An Integrated Strategy for Sustainable Underground Urbanization

THÈSE N° 5869 (2013)

PRÉSENTÉE LE 29 AOUT 2013

À LA FACULTÉ DE L'ENVIRONNEMENT NATUREL, ARCHITECTURAL ET CONSTRUIT
LABORATOIRE DE RECHERCHES EN ÉCONOMIE ET MANAGEMENT DE L'ENVIRONNEMENT
PROGRAMME DOCTORAL EN MANAGEMENT DE LA TECHNOLOGIE

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

POUR L'OBTENTION DU GRADE DE DOCTEUR ÈS SCIENCES

PAR

Huanqing LI

acceptée sur proposition du jury:

Dr P. Rossel, président du jury
Prof. Ph. Thalmann, Prof. A. Parriaux, directeurs de thèse
Prof. M. Finger, rapporteur
Dr J. Martelain, rapporteur
Prof. R. L. Sterling, rapporteur

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Suisse
2013

Abstract:

An increase in the functional diversity of infrastructure and buildings, driven by changing demands in industrial, commercial, and public service sectors, has contributed to the evolution and economic growth of cities around the world. Utilization of urban underground space is also undergoing a transforming and enhancing stage. The number of projects now being built beneath the city surface suggests a rising interest in underground infrastructure and underscores the need to sustainably plan further development. The Deep City research program at the Swiss Federal Institute of Technology in Lausanne puts forth a methodological framework for addressing the synergies and conflicts between underground resources in the urban planning process, in order to align underground urbanization with sustainable development paradigm. Through a contextual analysis of the four main underground resources - underground space, geomaterials, geothermal energy and groundwater – and a strategic model study of seven cities exemplary in their underground development practices, this dissertation proposes an integrated management process for the Deep City methodology and applies it to the Chinese case study of Suzhou. It develops strategies for creating decision-making criteria, for rating potential subsurface development projects by priority and for assessing their economic efficiency.

The process associating strategy making and operational measures, proposed solution packages to increase feasibility for a sustainable development of the four resources; it created an information system revealing urban underground potential, with the involvement of city level administrations; and it demonstrated priority development projects based on potential evaluation. At the end, a cost efficiency indicator taking into account underground space's supply potential and demand potential was applied to justify economic competitiveness of underground development projects.

Key words:

Underground urbanization, underground resources, sustainable cities, integrated management process, Deep City method

Résumé:

Une augmentation de la diversité fonctionnelle des infrastructures et des bâtiments en milieu urbain, poussée par l'évolution des besoins dans les secteurs des services industriels, commerciaux et publics, a contribué à l'évolution et la croissance économique des villes dans le monde entier. Le nombre de projets en cours de construction sous la surface de la ville suggère un intérêt croissant pour les infrastructures souterraines et souligne la nécessité de planifier leur développent durable. Le programme de recherches *Deep City* à l'Ecole Polytechnique Fédérale de Lausanne propose un cadre méthodologique pour aborder les synergies et les conflits entre les ressources souterraines dans le processus de planification urbaine, afin d'appliquer le paradigme du développement soutenable à l'urbanisation souterraine. A partir d'une analyse contextuelle des quatre principales ressources du sous-sol - espace souterrain, géomatériaux, géothermie et eau souterraine - et une étude des modèles stratégiques de sept villes exemplaires pour la gestion de leur sous-sol, cette thèse propose un processus de gestion intégrée pour la méthodologie *Deep City* et l'applique à la ville chinoise de Suzhou. Elle élabore des stratégies pour créer des critères de prise de décision, pour évaluer les projets potentiels de développent du sous-sol par ordre priorité et pour en évaluer la performance économique.

L'approche associe analyse stratégique et démarches pratiques, et propose un ensemble de solutions pour améliorer la faisabilité du développement soutenable des quatre ressources; La mise en place d'un système d'information associant la participation des administrations locales permet de révéler le potentiel d'urbanisation des sous-sols; Différents projets prioritaires sont proposés sur la base d'une évaluation de leur potentiel. Enfin, la création d'un indicateur de rentabilité prenant en compte les opportunités de cet espace tant au niveau de l'offre et de la demande, permet de justifier la compétitivité économique du développement des projets souterrains.

Mots-clés:

Urbanisation du sous-sol urbain, ressources souterraines, villes durables, procédure de gestion intégrée, méthodologie Deep City

Acknowledgements:

First and foremost, I would like to express my deepest gratitude to my supervisors Prof. Philippe Thalmann and Prof. Aurèle Parriaux, who gave me the opportunity to undertake the research of Deep City project in REME and GEOLEP. Working on a trans-disciplinary and international research project is an adventure for knowledge creation and skill integration. During this four-year doctoral study, I gained constructive advice and kind encouragement from my supervisors, who owned a long-term insight for scientific research and city development. They gave me lots of opportunities in participating into international academic conferences, where knowledge converged and expertise interacted. The fulfillment of my thesis could not have been possible without concrete internal research and active external exchange.

Furthermore, I would like to thank my entire thesis jury committee Prof. Pierre Rossel (EDMT), Prof. Matthias Finger (EDMT), Dr. Jacques Martelain (GESDEC) and Prof. Raymond Sterling (Louisiana University), for accepting to be on my committee, for taking the time to read my thesis, and for providing valuable input. I am particularly thankful for Prof. Raymond Sterling guiding my research during numbers of international conferences and workshops dedicated to the development urban underground space.

This project was supported by Sino-Swiss Science and Technology Cooperation (SSSTC). I sincerely acknowledge its funding support to enable scientific collaboration with the Chinese academic partner of Nanjing University. Success of the collaboration replied on the Deep City China team directed by Prof. Li Xiao-Zhao (IUSG-NJU), who facilitated important connection to local administrations in Jiangsu province and Suzhou city and developed an advanced thinking on underground resources management for Chinese urban context. I have to thank our team members Dr. Cao Liang, Mr. Wu Wenbo, Dr. Yan Yuru and Dr. Che Ping, who expressed their passions on working on Deep City China project and contributed their valuable expertise on geotechnical engineering and geographic mapping.

Further thanks go to my colleagues of Deep City Swiss team Dr. Pascal Blunier and Dr. Pierrick Maire. It was my pleasure to share delighted moments with Laurence, Marc, Michael, Cecilia, Anne-Kathrin, Camille, Philippe, Santosh, Yann, Sophie, Lucas and Nikolai in REME, as well as Alina, Séverine, Cornelia, Diana, Julien, Alain, Thomas, Yannick, and Laurent Tacher in GEOLEP.

Last but not least, I would like to thank deeply my family in China for unfailing encouragement and supporting my oversea study.

Table of contents:

List of figures :

List of tables :

INTRODUCTION OF THE RESEARCH

The concept of sustainable underground urbanization and pilot project in China

The present research was supported by Sino-Swiss Science and Technology Cooperation (SSSTC) during the year of 2009 to 2012. It is a second phase of Deep City project, following the first phase supported by Swiss National Research Program (PNR54). Originality of the research is to put forward four sustainable dimensions for underground urbanization, an emerging trend to provide alternative land supplies with below ground spaces. The four dimensions include underground space, geomaterials, geothermal energy and groundwater, composing a durable exploitation pattern of the urban underground, named as “Deep City method”. A holistic utilization of the urban underground calls for an integration of these dimensions, which are presented as four industrial segments as having long-term development potentials. Scarcities on space, material, energy and water have been constraining city growth; the same concerns also apply to subsurface resources. Chapter 1 will introduce in detail the current development stage, opportunity and feasibility of these segments, in order to identify unbalances among these segments. Development potential of each segment is evaluated from a framework of factors grouped into three categories of scores: current development score, opportunity score and feasibility score. This scoring system aims to identify gaps generated from current utilization and to identify barriers hindering future exploitation, a first step on strategy making for underground urbanization.

City leaders on underground urbanization are investigated in Chapter 2, classified on three strategic models based on respective development stage and motivation. In addition, the seven city leaders represent particular characteristics on using underground infrastructures and buildings, promoted by different administrative agencies and enabled through different demand side encouragement schemes. Supply side management in these benchmark cities varies from underground space reservation to legalized stratification to compact form facilitation. This strategic study will complement the contextual study of Chapter 1, by revealing instruments of best practices to increase feasibility level of underground urbanization, especially for the segment of underground space. This policy learning tool serves as a second step on strategy making for underground urbanization, by generalizing critical success factors for administrative arrangement, supply side management and demand side facilitation.

Since not all the cities own a full portfolio of these four resources dimensions, a selection of applicable cities for Deep City method was performed based on Swiss context and Chinese context. Since the first phase researching on Swiss context selected Geneva city as case study and developed a resources management methodology and a social-economic analysis. This second phase researching on Chinese context focuses on strategy making and operational measures implementation for the sustainable underground urbanization in Chinese big cities. The country will host one third of world big cities (population more than 5 millions) from the year of 2025, deserving for a forward thinking on developing underground resources for its increasing urbanization demand. The city of Suzhou is selected as case study, demonstrated by an integrated management process involving six steps from strategic level to operation level in Chapter 3. The integrated management process with participation of local administrations is a strategy prototype for sustainable underground urbanization in Suzhou city.

After a two-step strategy making using the framework of contextual analysis for the four segments (Chapter 1) and strategic study for implementation references (Chapter 2), specific solutions are formulated under a three-year collaboration project with Suzhou city government. An evaluative information system is developed for the case study, which will serve as a consulting tool for administrative use. This consulting tool used two categories of decision-making criteria including supply potential criteria and demand potential criteria: the category of supply potential criteria reflects factors determining feasibility score, while the category of demand potential criteria reflects factors determining opportunity score. This operational tool is to assess integrated development potential of underground space use beneath the city, serving as future administrative tool to manage underground urbanization of Suzhou city. High integrated development potential targets can be identified by this tool, linking supply capacity of underground resources and demand level of urban areas. Resource supply inventory is quantified and mapped by qualification, for four development layers deep to 100 meters. This city scale evaluation allows a practical implementation on project scale, which will be illustrated on the project type of mixed use underground complex in priority districts. An economic indicator is put forward at the end to lever investment competitiveness of underground development projects. This three-step operation at city scale, urban center scale and project scale helps to implement the Deep City method by instrumentalization. The sixth step on policy making by using the economic indicator links operational steps with strategic steps, creating a continuous improvement cycle for the integrated management process.

From Chapter 1 to Chapter 3, multidisciplinary domains are integrated, with a framework of contextual factors for four segments, a catalogue of strategic models for seven city leaders and a concrete case study for project implementation in Suzhou city.

CHAPTER 1

1 SEGMENTAL ANALYSIS OF SUSTAINABLE UNDERGROUND URBANIZATION

1.1 Introduction for Chapter 1

Underground construction & exploration can be defined as a new portfolio in the industrial sector. Development of the urban underground can produce new spaces for building sector, new mass transit solutions for transport sector, new utility infrastructures for public service sector, new renewable thermal source for energy sector, and new minerals resource for commodity sector. Production of these goods and services in the interdependent segments has been contributing to the economic performance of city growth. With participation of the urban underground to the production of building, transport, infrastructure, energy and raw material, various players in existing industries and services should be engaged to maintain this growing and converging sector.

Vitality of the segmental growth depends on its development effectiveness, potential contribution to the urban economy, and feasibility. Chapter 1 will give an overview of these new industrial segments' performance and contribution to the urbanization process.

1.1.1 Terminologies

Underground urbanization can be defined as an innovative concept for urban restructuring and transformational construction practice (Utudjian, 1972, Barles and Guillerme, 1995, Bélanger, 2007), aiming to increase mixed uses in urban centers by relocating space underground in order to release surface land, while safeguarding valuable groundwater, geothermal energy and geomaterial resources. This new concept is named "Deep City method", an interdisciplinary project based in Switzerland since 2009 (Parriaux et al., 2010). The four segments of underground urbanization are illustrated in Figure 1:1 below.

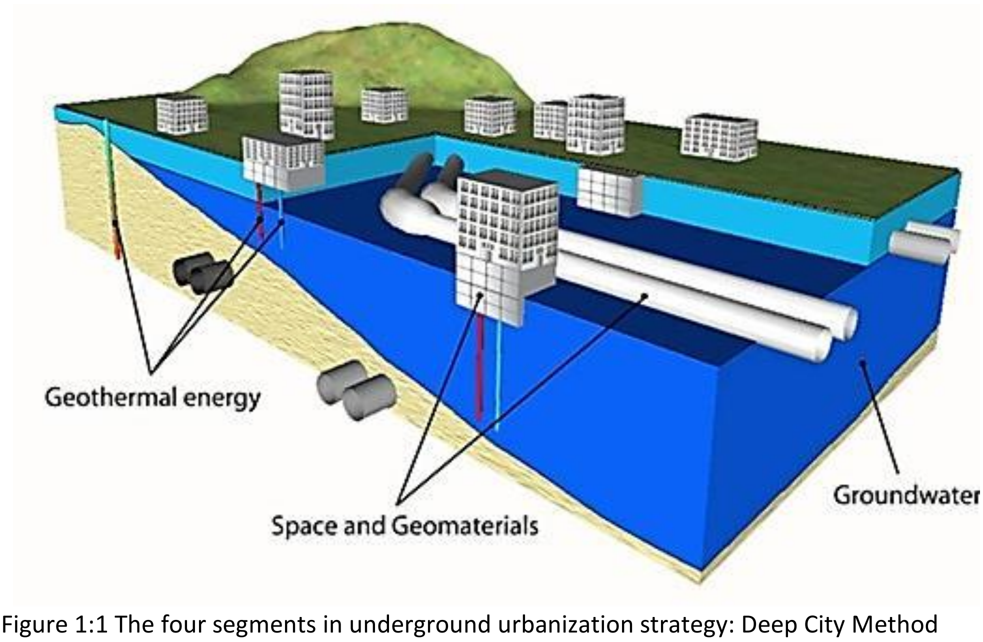


Figure 1:1 The four segments in underground urbanization strategy: Deep City Method

Segment 1: Underground Space

Land, as the main production factor of cities, is limited, nonrenewable and scarce. Cities are transforming from agricultural traders to industrial manufacturers to service providers. Their land use planning agenda is changing from industrial land oriented planning to commercial land oriented planning to residential land oriented planning, even to mixed use planning (O'Sullivan, 2009, Kivell, 1993). In a context of sustainable urban development, innovative spatial planning attempts to maximize land use value by mixing urban activities, linking urban mobilities and compacting the urban fabric. While more space is needed but more land leasing is frozen, space hunting is going to a three-dimensional trend. Density generates space, but over-densification is always restricted by planning regulations.

Another dimension is being stated by civil engineers, claiming that by going underground we can acquire more possibilities for construction. Emerging uses became attractive such as subway tunnels, road tunnels, buried utility lines, subterranean parking, deep storage, pedestrian pass, and large basement buildings (Bergman, 1986). Technological advancement makes these uses even more competitive (Goel et al., 2012), because going underground can mitigate surface constraints on land acquisition, from building height limits and from landscape control (Golany and Ojima, 1996a, Carmody and Sterling, 1993). Relocating space volume underground helps to equilibrate densification and revitalization. This is the first segment developed during underground urbanization: *underground space*.

Segment 2: Geomaterials

Availability of materials is one of the main factors influencing construction industry, a mainstay sector in the urban economy. As mining and quarrying areas become limited, provision of material is becoming more difficult. A recyclable material source from construction excavation sites could relieve material provision deficiency (Rochat et al., 2006). Excavation provides raw materials that may be able to aid in meeting higher demand. This is the second emerging segment: *geomaterial*.

Segment 3: Geothermal Energy

Energy provisioning is a challenge to modern societies. Transport and building count for more than half of the total energy demand, which is being intensified by rapid urbanization. Energy efficiency can be gained from technological innovation in transport systems and building structures. A subway, as a transport system of high efficiency, speeds up urban mobility and shortens travel time. The building sector is also undergoing continuous progress to save energy use. The ground source heat pump (GSHP) market is expanding around the world (Navigant Consulting, 2009, IEA, 2010), making this hidden resource developed as the third segment during underground urbanization: *geothermal energy (Parriaux et al., 2004)*.

Segment 3: Groundwater

Water, is another critical production factor for agriculture, industry and urbanization. The use of groundwater exceeds 70% of the total water consumption in most European countries, especially for domestic drinking water use (Zektser and Everett, 2004). In the post-industrial era, quality of life dominates our residential location choice. An abundant source of drinking water has a competitive advantage for sustaining urban growth. This is the fourth segment: *groundwater*.

Multi-segmental development as sustainability model:

Since innovation in the construction sector has been oriented towards a sustainable and multi-functional direction, synergetic development of these segments could be promoted. For example, during project design for underground infrastructure and building, other segments should be also considered: Firstly, construction site should be outside the volume of protected aquifers; secondly, geothermal energy walls and piles could be integrated into construction foundation; thirdly, material generated should be used as primary material instead of waste.

“Underground urbanization” focuses on the development of underground space, while “sustainable underground urbanization” has to cover all the four segments including underground space, groundwater, geothermal energy and geomaterial.

1.1.2 Segmental analysis and Factor-based review

Each segment will be analyzed and rated with three scoring categories: development score, opportunity score and feasibility score. They represent respectively the level of performance, motivation and feasibility. For sustainable underground urbanization, a segment with high potential for future development should be satisfied by three conditions: availability of geological resource, presence of opportunities from external environment, and feasibility to overcome barriers from internal environment, as shown in Figure 1:2.

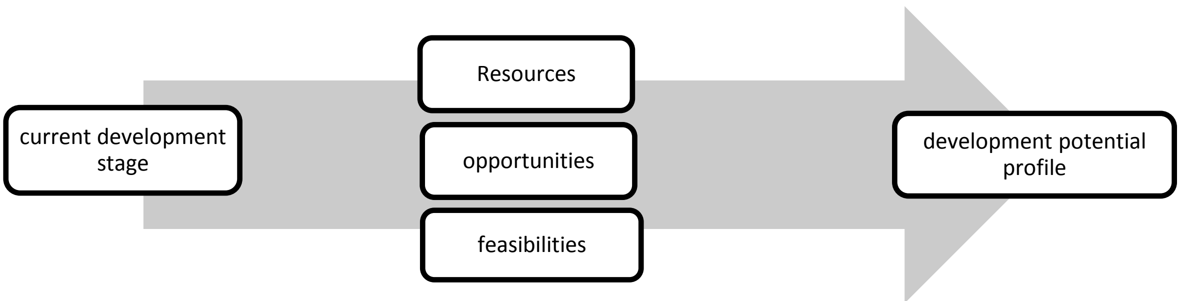


Figure 1:2 Segmental analysis categories in Development potential profile review

- Development score: three factors are selected to assess development score of each segment, including functional convergence, inner-segmental sustainability and inter-segmental sustainability. A segment gets a high development score if it is currently utilized in a variety of uses serving a broad range of users with changing demands, taking into account conflicts and synergies generated inside each segment and among the four segments;

- Resource score: availability of underground resources beneath the city determines its future development potential for underground urbanization. While some cities owns a full portfolio of the four resources (constructible underground space, extractable geomaterial, exploitable geothermal energy and drinkable groundwater), other cities possess a partial combination of these resources (such as absence of urban aquifer). This indicator is illustrated explicitly in Chapter 3, for the selection of pilot city having supply capacities of these four resources;

- Opportunity score: four factors are selected to assess opportunity score of each segment, including resource scarcity, increasing price effect, urban market growth and substitution effect for conventional resource on the surface. Motivation of discovering new usages is driven by external environment, including changing demands, economic forces and societal forces. Urban development has been requiring more and more resources for increasing demands. Driven by urbanization process, the segment addressing strong demand can be considered as with high opportunity;

- Feasibility score: nine factors are selected to assess feasibility score of each segment, including technology awareness, knowledge diversity, innovation speed, cost efficiency, property right flexibility, public acceptance, resource inventory prospection, anthropogenic risk mitigation and natural hazard adaptation. These factors determine technological, social and institutional conditions for underground resources supply. Feasibility of segmental application depends on its capacity to overcome technological, financial, legal, political, sociocultural barriers and to deal with resiliency issue. The segment with higher capacity to handle these constraints can be considered as more feasible.

- Development potential profile: combination of these scores can be weighted to give prospective on segmental future development.

Information illustrated in this section is based on literature reviews from academic journals and books, working papers from underground construction associations, technical reports from contractors, web sites from project developers, conference papers from the Associated Research Centers for the Urban Underground Space (ACUUS), interviews with private contractors and consulting groups, and field study through technical visits. Qualitative and quantitative arguments are employed to illustrate each factor in the scoring framework, which is rated from low to high (scored as 1 to 3) for a general assessment.

1.2 Segment 1: Underground Space for buildings and infrastructures

This section will draw a big picture for geo-space's utilization forms in the international context, especially multiple functional forms combining single usage in utility, transport, commercial space and industrial space. Driving forces are presented to understand why geo-space became an increasing interest for urban growth. Challenges including technological innovation, construction costs and physical risks are revealed to indicate current capacity for managing underground space development.

1.2.1 Development stage of underground space for infrastructures and buildings

1.2.1.1 Inner-segmental sustainability:

Increasing utilization of various forms has been inducing congestion problems among underground space users due to a lack of city scale planning policy, which is seen as a deficiency of inner-segmental sustainability and is harmful for a durable growth of urban subsurface. Therefore, we consider that inner-segmental sustainability is moderate (score=2).

1.2.1.2 Functional convergence:

Based on current development scale, underground space can be built deep to 100 meters. From abundant case studies of construction projects, spatial forms can be classified into three types:

1) *Tunnel form:* it is to facilitate mobility flows and material flows such as rail, vehicle, pedestrian, water, waste, energy, information, and electricity;

2) *Cavern form:* it is to store commodity such as oil, gas, minerals, water, food, shelter, and database;

3) *Basement form:* it is to connect the surface for spaces such as conference hall, research lab, parking, recreational and commercial center;

Those three underground forms can be also joined to shape an *underground complex from* containing tunnel, cavern and basement. Worldwide best practices of multi-functional underground projects in forms of tunnel, cavern, basement and complex are showed from point 1) to 4).

1) Tunnel form with multiple usages:

- *Multi-utility tunnel*: (Figure 1:3)

  Sustainable cities have to provide adequate infrastructural capacity on water, energy, electricity, sanitation and communication services. A tunnel form to manage these utility lines can ensure service quality of the infrastructure, can avoid leakage issue, facilitate maintenance and increase operational life of utility system. Grouping the utilities' right-of-way into a tunnel under public domain also avoid future relocation of pipelines due to redevelopment or new construction.

Figure 1:3 Example of Dutch multi-utility tunnel: Multi Utility Providing (MUP), Smart Link, The Netherlands[1]

- *Climate change risk adaptation tunnel*: (Figure 1:4[2], Figure 1:5[3])

  Capacity design of urban infrastructure has to take into account resiliency to potential risks, including manmade risks and natural hazards. Climate change related risks such as floods are becoming more and more frequent in cities worldwide and necessitate prompt response of existing infrastructures. Two flood mitigation tunnels are showed below:

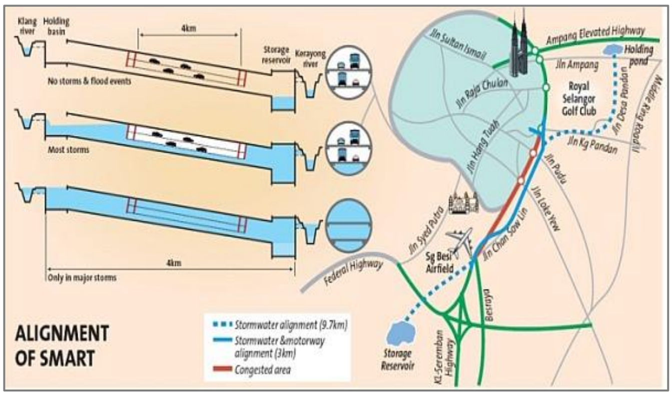


Figure 1:4 Example of Malaysian flood traffic SMART tunnel: Storm Management and Road Tunnel, Malaysia, Kuala Lumpur

[1] http://www.zeelandseaports.com/en/projects/project:hidden-connections.htm
[2] http://smarttunnel.com.my/
[3] http://www.ktr.mlit.go.jp/edogawa/gaikaku/index.html

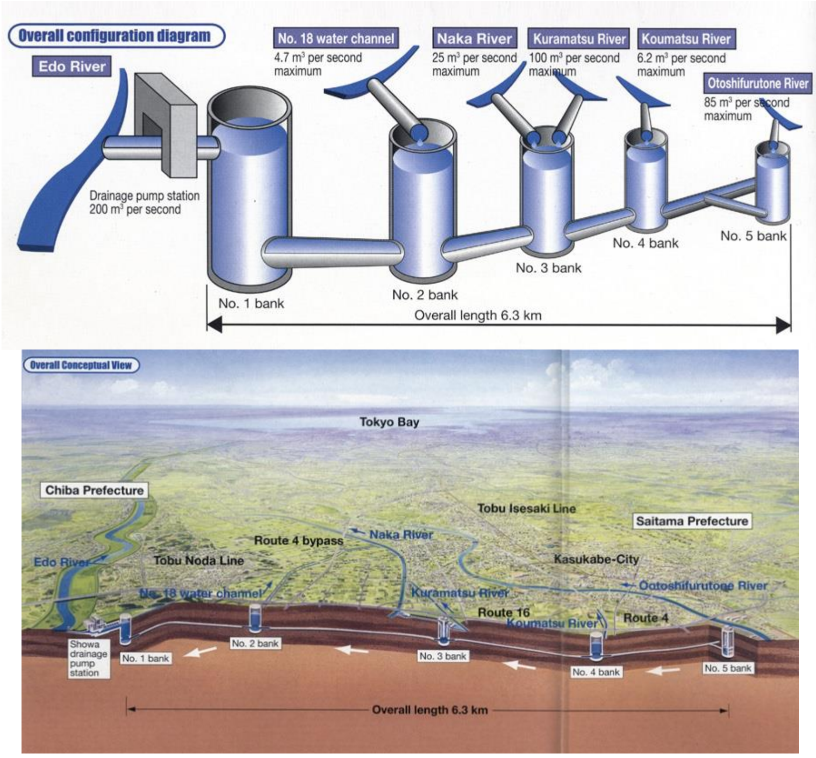


Figure 1:5 Tokyo Metropolitan Area Outer Underground Recharge Channel (Giant Cans)

- *Pedestrian utility tunnel*: (Figure 1:6 (Boivin, 1990))

  Tunnel form space can not only protect traffic flow and utility transfer, but also protect pedestrian from walking in cold weathers. Accommodating both users is another creative form of subsurface space use.

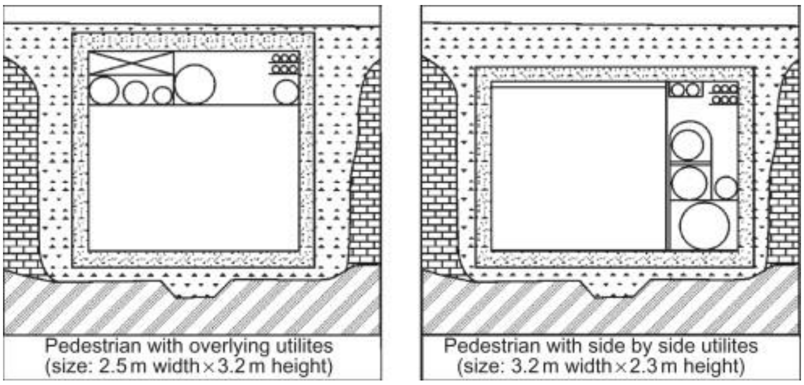


Figure 1:6 Example of Canadian campus pedestrian utility tunnel: Laval University campus, Quebec, Canada

2) Cavern form with multiple usages:

- *Carven cluster of data center and R&D center*: (Figure 1:7)

  The fast progressing sectors of information technology and life science asked for more and more data storage centers (such as Mount10 in Switzerland) and experimental research offices (such as Dusel Lab in the U.S.). While those spaces always require concealed environments and locate outside the city center, series of large cavern to host these particular working places can be built under wide open space. Future cluster development for I.T., life science and related manufacturing could choose this kind of cavern center near crowded city center, to ensure sufficient working places for industrial growth, and to avoid trans-city expansion or relocation of important R&D headquarters. Images below of Singapore Science city are extracted from (Chang et al., 2012, Zhao et al., 2001):

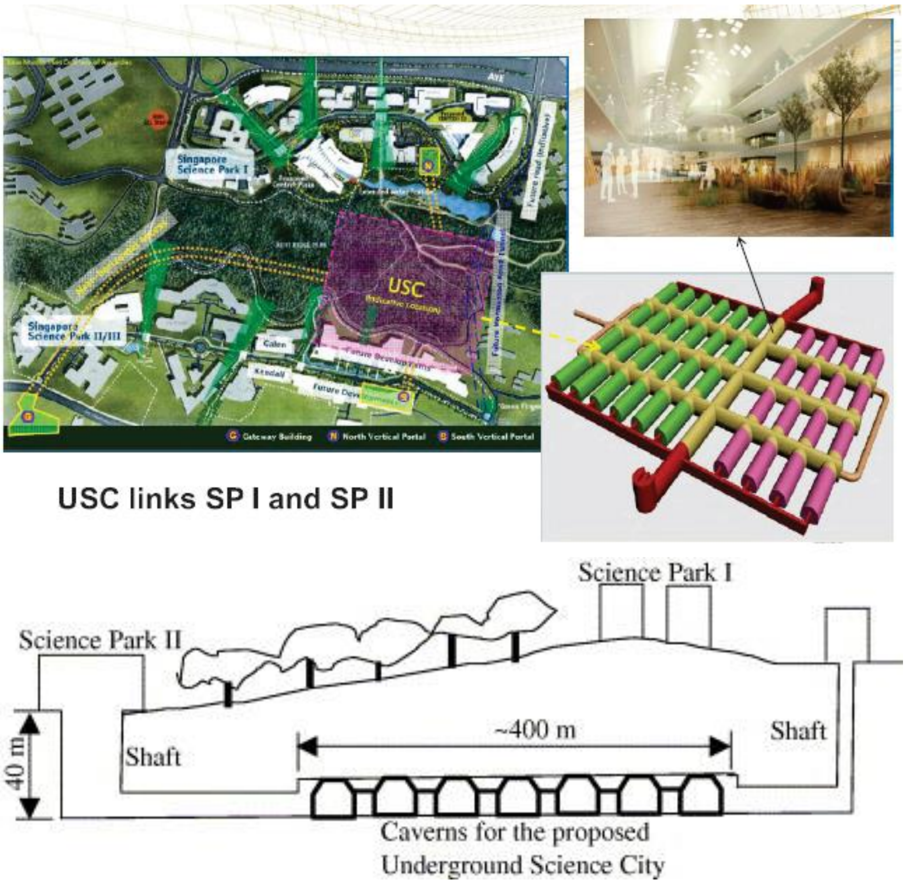
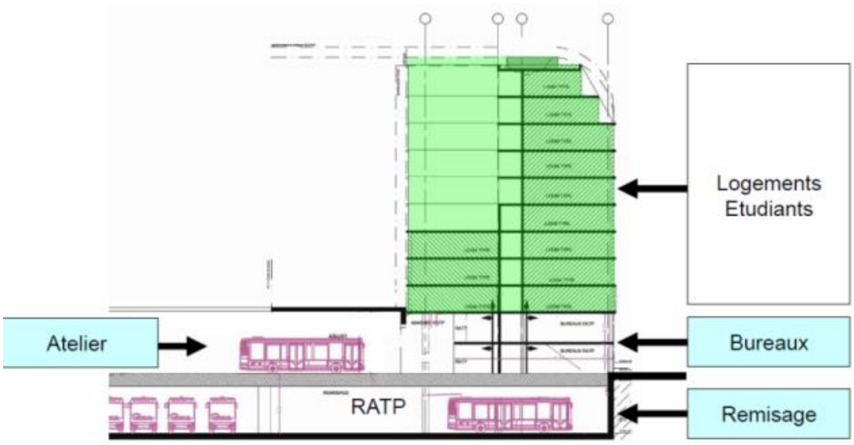


Figure 1:7 Example of Singapore Science Park technology cluster cavern city

3) Basement form with multiple usages:

- *Public use basement under residential building*: (Figure 1:8)

  Basement type building is normally used for private vehicle parking. With changing lifestyle, private vehicle usage in public transport promoted cities is becoming less encouraged. Private use of basement for parking can be converted to public use, such as public vehicle garage for bus or bicycle keeping. The image below of RATP[4]'s mixed land use is extracted from (Feredj, 2012):



Coupe de principe sur Logements étudiants / Atelier et Bâtiment administratif RATP

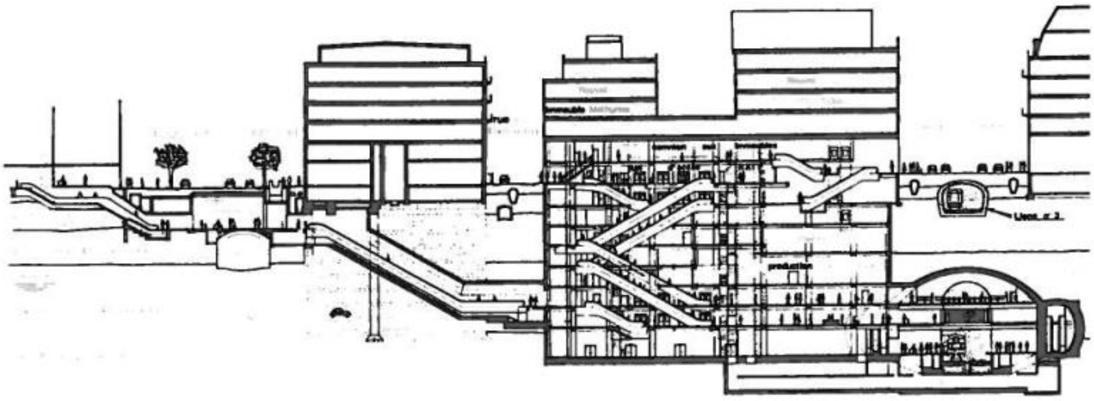
Figure 1:8 Example of Paris RATP Bus center under housing redevelopment

[4] RATP : Autonomous Operator of Parisian Transports

4) Underground complex form with tunnel, cavern and basement:

- *Transit center complex*: (Figure 1:9 (image provided by Pierre Duffaut))

  Transport tunnel, station cavern and building basement are linked together to provide the city center with seamless flow between pedestrian and rail transit.



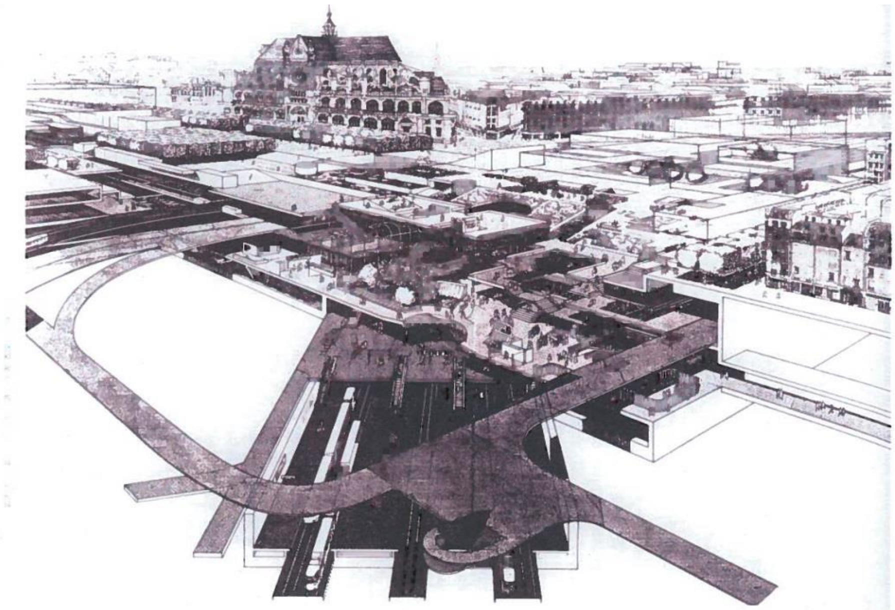
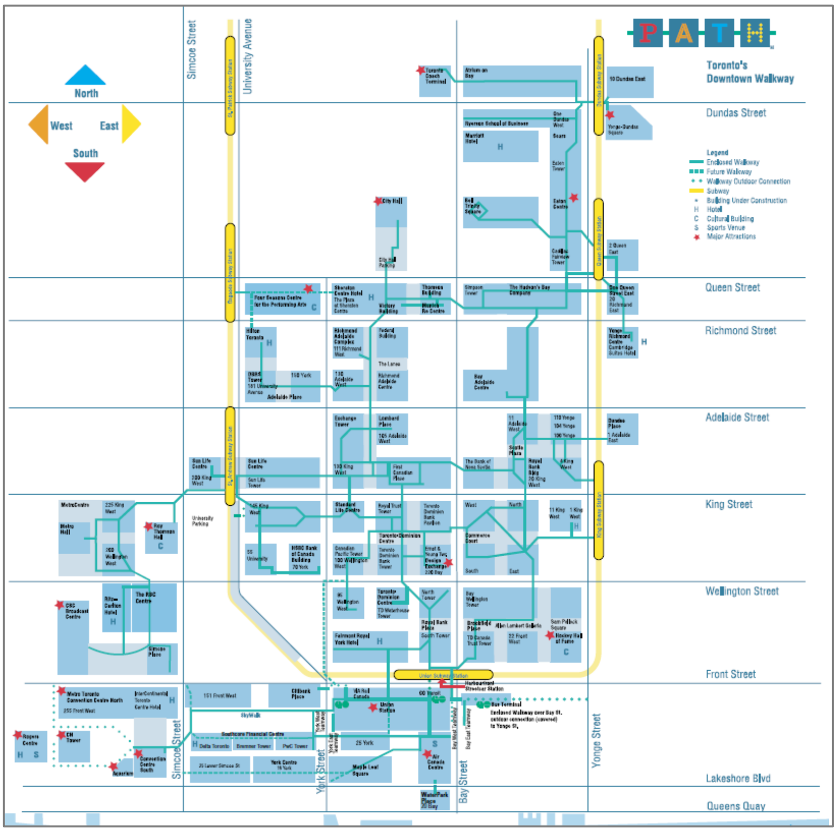


Figure 1:9 Example of Paris train station complex Auber and Les Halles

- *Retail complex in Central Business Center*: (Figure 1:10)

Basements of buildings sharing similar activities can be joined to create easy access for business flow and commercial exchange, such as commercial centers and financial centers. Below shows two Central Business District (CBD) networks of commercial basements and pedestrian tunnels: (blocks represent basement type buildings; blue links represent pedestrian & retail tunnels)



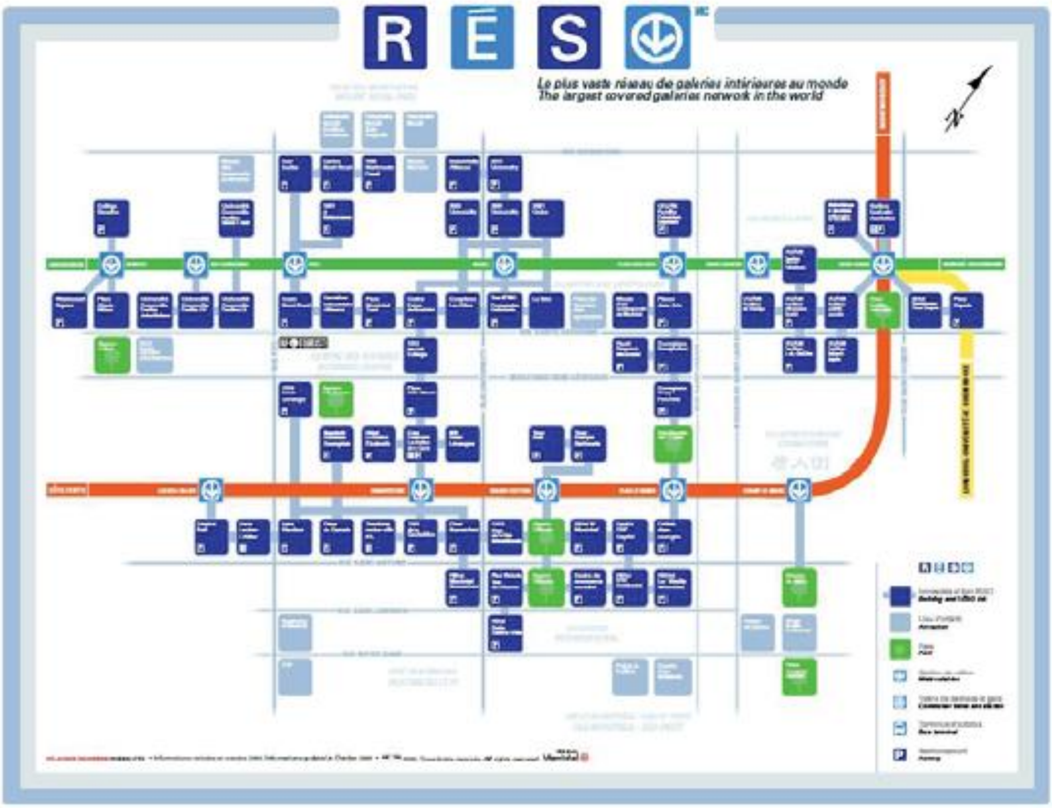


Figure 1:10 Example of Canadian Indoor cities: (above: Toronto PATH complex, down: Montreal RESO complex)

Promoting multi-functionality of underground construction helps to adapt the built environment for different demands in economic growth periods, as well as for different paradigms evolved in urban planning. A functional void type space formed beneath the surface should be considered as useful medium to serve changeable human needs and to provide flexible urban solutions. Based on the above mentioned diversifying usages of underground space, functional convergence factor can be scored as high (score=3).

1.2.1.3 Inter-segmental sustainability:

In addition, interactive impacts between underground space and other underground resources of geomaterials, geothermal energy and groundwater have not been fully integrated into project conceptualization, according to (Blunier, 2009). While geomaterial mining could offer a synergetic production for underground space, groundwater pumping and geothermal heat extraction could generate geotechnical conflicts for underground infrastructures and buildings, such as land subsidence caused by overexploiting groundwater. As a result, we consider the factor of inter-segmental sustainability as having low score (score=1).

1.2.1.4 Development score of underground space

Concluded from the classification above, utilization of underground space is undergoing a movement to functional convergence and adaptation for climate change. These two factors (convergence and adaptation) are considered as critical decision criteria for future infrastructure and building projects in urban areas. Current development stage of underground space segment can be considered as advanced in functional diversity but insufficient at sustainability level. Therefore, the segment of underground space can be rated as being at moderate development stage.

Factors	Scores
1.1 Inner-segment sustainability	2
1.2 Functional convergence	3
1.3 Inter-segment sustainability	1
Average score	2

(Factors are equally weighted; high: 3, moderate: 2, low: 1)

1.2.2 Opportunities for underground space development

Growing demand from urbanization is requiring expansion and rehabilitation of infrastructure networks for utility service and urging delivery of building floor space for living. Ongoing and predicted infrastructural and building works in cities are going to serve more than 6.25 billion of world's population in 2050 (Population Division, 2012), while 5.12 billion of these urban inhabitants living in less developed regions will need new construction projects in their cities. In the meanwhile, cities in more developed regions will need to renew their obsolete fixed assets.

During the transformational urbanization process, construction projects should be more adaptive, flexible and integrative with the changing urban demand. Green city movement advocates a resource efficient economic growth. Construction industry as a resource intensive sector should rethink the pattern of property development, in order to consume less land, less energy, less water and produce less waste. As showed in the section above, underground construction of infrastructure and buildings can be multi-functional and multi-layered, by using the same land area.

1.2.2.1 Land scarcity

One of the driving forces for underground construction is urban land scarcity, which is caused by either excessive construction volume inside urban boundary or strict zoning restriction from government. Urbanization scale usually has a limit to expand due to the national control for sufficient farmland area. Since continuous sprawl outside the city is an expensive choice for local government (Burchell, 1998), concentration of activities in urban area is challenging governors to explore other options for locating public and private property developments, in order to avoid construction site saturation. The phenomena of urban land scarcity can be translated by deliverable quantity of land use permit (construction permit allocation) in the city center.

It is pointed that a fixed supply of land in a dynamic urban economy could provoke speculative land bubble and damage welfare of the citizens. According to (Hui et al., 2006), urban land shortage exists in 58% of urban districts in Hong Kong. In South Korea's largest 171 cities, nearly 35% have problems of urban land shortage (Son and Kim, 1998), mainly due to greenbelt restriction policy. Underground space became a modernity to urbanize land area without demanding for more surface land supply, can be considered as an alternative planning policy direction for new land supplies. The factor of land resource scarcity can be scored as high (score =3), motivating utilization of the subsurface.

1.2.2.2 Increasing land prices

Land as a main production factor for construction project influences investment decisions, relating to land acquisition, property function and project scope. Land price is the main reason for high priced housing and commercial property. New York City's land value has amplified by 5 times in the period from 1984 to 2004, while construction cost has increased by 1.3 times, according to Lincoln Institute of Land Policy[5].

Urban land value is also linked to quality of public infrastructures, determined the capacity to provide functional interaction between urban dwellers with public services in utility, transport, school, hospital, commercial center, working center, open space, etc. Shortage in land supply constraints inadequate provision for these public services. Underground space helps to restructure land use pattern with downward layers. By economizing buildable land plots, creating new land supplies and releasing additional public land for infrastructures, it helps to recapture the value of built-up land in its surrounding environment. The factor of increasing land prices is also scored as high (score = 3), making land development move toward layered restructuring to save land acquisition costs.

1.2.2.3 Urban market growth

The strength of land demand is caused by agglomeration intensification in metropolitan areas, due to the fact that urban area is the hub for economic activity concentration with abundant production factors such as labor force, financial capital and working space. One of the indicators showing concentrating process is urban population density.

Until the year of 2011, 52.1% of world population has been living in cities, and this ratio will reach 67.2% by 2050. 37 Urban agglomerations with more than 10 million inhabitants are expected to emerge around the world by 2025 (Population Division, 2012), demographical intensification of these megacities is challenging the quantitative limit of urban land supply and the quality of built environment. So the factor of urban market growth is scored as high (score = 3), representing a growing demand for subsurface utilization.

1.2.2.4 Substitution effect for surface density

Density management of built-up area is an instrument to regulate urban land supply, based on existing infrastructure provision and spatial structure. Floor Area Ratio (FAR) as building density indicates capacity of land to develop living space. In the context of limited land and growing population, density should be enhanced in order to ensure sufficient living space per habitant. How to welcome higher density while to relieve building footprint remains a challenge for city planners and land administrators, who are facing dilemma to balance the supply on public infrastructure land (road, park, education, waste treatment plant, water supply plant, etc.) and real estate development land (housing, business, industry, tourism). A higher density profile could help the city to save additional land supply by 60% (Bertraud, 2007).

Underground densification can be an innovative policy instrument to fight against urban sprawl and land scarcity. A coordination with subsurface land survey and allocation helps to gain densities for existing land supply, as well as to release building footprint for surface open space and services.

[5] http://www.lincolninst.edu/subcenters/land-values/metro-area-land-prices.asp

Existing land plots can be retailored in size with surface densities and subsurface densities. An efficient densification measure is for land plots within mass rapid transit (subway, rail) catchment zones, having high land values given by high mobility capacity. Planning mixed use activities in the catchment zones is encouraged from paradigm of Transit-Oriented Development (TOD), a transport-urbanism coordinated solution to sustain development of public infrastructures, as well as to capture added value of infrastructural service into land value. Substituting surface density with underground space plot ratio offers a high opportunity (score =3) to fulfill space demand.

1.2.2.5 Opportunity scores for geo-space development:

The level of Opportunity score indicates a beneficial interest from exploitation. The benefit of developing urban subsurface helps to supplement surface building density, reduce land expansion, multiply the economic output of land resource, and to meet space demand in growing cities. Thus, these driving forces reflect a strong motivation for worldwide cities in underground space development.

Factors	Scores
2.1 Resource scarcity	3
2.2 Increasing price effect	3
2.3 Urban market growth	3
2.4 Substitution effect for the surface	3
Average score	3

(Factors are equally weighted; high: 3, moderate: 2, low: 1)

1.2.3 Feasibilities for underground space development

1.2.3.1 Technology awareness

Underground infrastructures:

Construction in the underground requires more technological progress of advanced equipment such as tunneling and piling than conventional construction, as well as specialized manpower for excavation and foundation, and higher capital investment. Since the first subway opened in London in 1863, a new era of underground space technology has begun with extensive networks of underground metro system around the world. Most of the underground infrastructure projects are invested from public sectors, for providing large scale utility pipelines, mass rail transits, cross-city transportations, large volume water and waste treatment plants and strategic resource storages. Those higher investments served for a large scale urban growth, with a long infrastructure service life (average 100 years) to ensure continuous benefits. Therefore, underground transport and deep infrastructure can be considered as one of the high-tech industrial sectors.

Underground buildings:

Compared to the enhanced share of transport and infrastructure placed underground, buildings have been less buried for living and working. While architectural technologies keep advancing, creation of surface alike environment in the underground building is not out of imagination. Numbers of underground commercial centers and institutional buildings have been developed in Japan and U.S. (Carmody and Sterling, 1983, Golany and Ojima, 1996a). However, livability of underground building space will be realized with a higher cost premium to enhance spatial design quality. Unlike the transport and infrastructure projects that are highly relied on public sector, buildings have been considered as a commodity linked to market behavior of private actors, who acquire the spatial right, build the property and trade it. This conventional production process goes on its cycle until one of the production factors become unavailable and call for a substitution. Most of the underground building projects serve to compensate the deficit of spatial right above ground, such as barriers from air rights and surface land acquisition. The first underground shopping mall in Japan was opened in 1932. Due to land scarcity in Japan's metropolitan area, there are currently 80 sites of underground mall in operation for 19 Japanese cities, with a total subterranean floor area more than 1.1 million m^2 (Nakamura et al., 2012).

European underground construction platform:

Construction sector is one of the main pillars of urban economic activities, European countries' average expenditure on construction industry is around 10% of GDP (Société Suisse des Entrepreneurs, 2011). Production factors of constructing building, transport and infrastructure include technology portfolio, competent manpower, fixed capital such as equipment and machinery, and financial capital. Research and development on underground construction has been recognized by European Construction Technology Platform as a strategic research area in the vision of Agenda 2030 (ECTP, 2005). The best technological achievements helped European cities of cultural importance to protect heritage landscape and to maintain advanced urban functions, such as mass rail transit under old city centers as well as tunnels beneath beautiful natural landscapes. Substantial European technologies related to underground urbanization have been transferred to Korea and Japan, creating a competitive international environment in this field. At the same time, underground construction industry is undergoing a sustainable development transformation including economic efficiency, safety, environmental friendly and social acceptability (ITA-CUS, 2010, ITACUS, 2012). Here are priorities of new research agenda for underground construction sector in the European context (ECTP, 2005) in Table 1:1.

Table 1:1 Research priorities for underground construction sector (European Construction Technology Platform)

Meeting Client Requirements by: - Efficient use of Underground City Space - Knowledge of the ground (geotechnical engineering)
Becoming sustainable by: - Reduce Resource Consumption - Reduce Environmental and Anthropogenic Impacts - Improve Safety and Security Transformation of the Construction Sector by: - Increase the competitiveness - A New Client-driven, knowledge-based Construction Process - ICT and Automation - High Added-value Construction Materials - Attractive Workplaces

The European research project named Technology Innovation in underground construction (TUNCONSTRUCT, Figure 1:11[6]) launched in 2005 was the biggest research project on underground construction worldwide, involved by a consortium joined by most of the players in Europe. The vision was to make underground construction more efficient in cost and time, and more resilient in risk prevention and environmental impact. With the increasing traffic flow, many tunnels in Europe were subjected to expansion. While construction cost and duration for major European tunnel projects is quite high (about 120 to 160 million Euros per km), various value-chain based innovations related to basic research, application, development, manufacturing and commercialization were examined with an integrated approach (Beer, 2010). Underground infrastructure as an important component of the city for tomorrow has a great potential to be a high-tech, exciting and attractive industry. The factor of technology awareness can be scored as high (score =3).

Figure 1:11 TUNCONSTRUCT project: city of tomorrow with underground infrastructures

[6] http://www.ifb.tugraz.at/tunconstruct/overview.htm

1.2.3.2 Knowledge diversity

The following information is showing a high knowledge diversity in underground space development (score = 3). Current technologies available for underground space development include the below categories: from (Goel et al., 2012c).

1) *Survey and design stage*: planning technology such as data system and information system, survey technology such as remote sensing and borehole investigation, design technology such as modeling and simulation, measurement technology such as ground monitoring;

2) *Construction and execution stage:* foundation technology, interior space technology, anti-disaster technology;

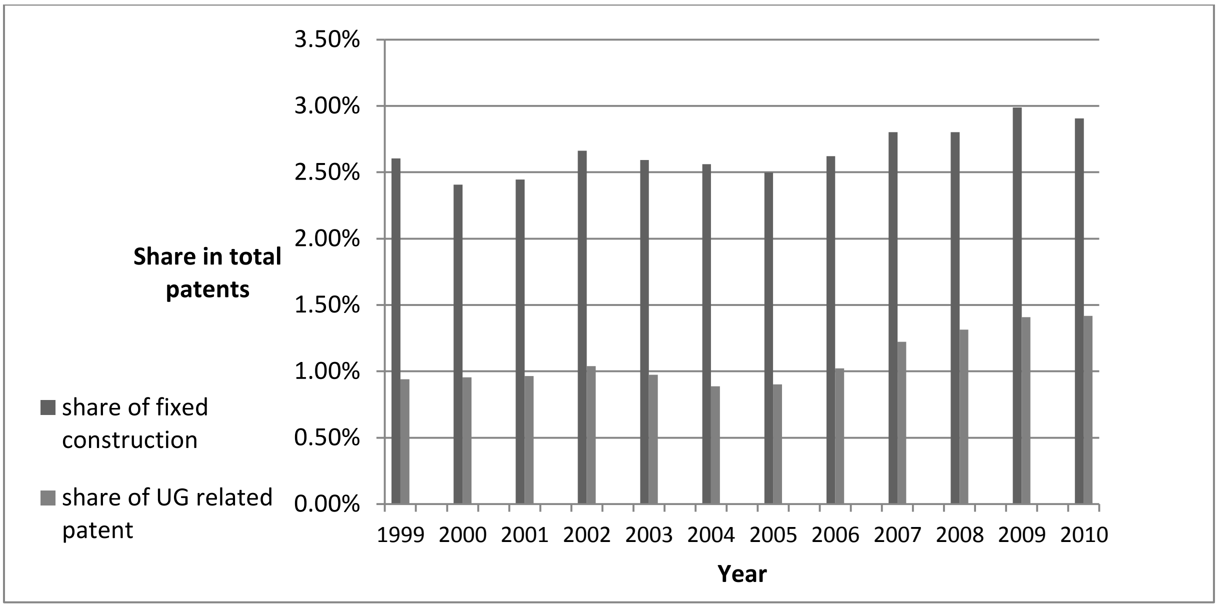
3) *Operation and control stage*: safety technology, interior facility technology, monitoring technology.

Different from the above ground condition, behavior of underground environment is difficult to observe and monitor. Therefore, investment on *survey and design technology (1)* is important for the performance of underground construction. General rules mentioned by International Tunneling Association (ITA-WG3, 2011) indicated that the more geotechnical data and interpretation available for contractual parties in the early stage, the greater is the certainty for meeting budgets and timely payments. Especially for the large scale transport and infrastructure network, an increasing effort on borehole investigation significantly decreased the costs of risk exposed to the project cycle (Westland et al., 1998). Quality of the survey was also considered to be critical to avoid cost overrun of underground projects (Panet, 1989).

Excavation and execution technology (2) for construction (tunneling and piling) has been developed among major actors in Japan, U.S. and Europe, with difference progress levels depending on their level of R&D input (Sterling, 1992). An industrial think tank The Warren Centre in Australia, based on collaborations among academia, industry and government, launched a research and development project in 1995. It looked at technological innovation, development barriers (finance, regulation, awareness) and marketing opportunities, in order to promote advanced underground space engineering for urbanization (Dobinson and Bowen, 1997).

1.2.3.3 Innovation speed

Some argued that underground construction methods are not progressing as far as other technologies (Hellsten, 2010). Based on OECD's statistics of world patents related to science and technology, share of underground related patents didn't exceed 1.5% among total technologies during ten years from 1999 to 2009. Since there is no particular patent inventory for underground space technology, a manual classification is done by compiling related IPC codes. Figure 1:12 below shows the share of fixed construction category patents and the share of underground construction related patents. Numbers of the three groups of underground construction patents (IPC codes: E21, E03, E02) are also detailed below. (Statistics from http://stats.oecd.org/: IPC code "E" refers to fixed construction, underground construction relates to IPC E02 engineering methods, E03 utility, E21 drilling and mining)



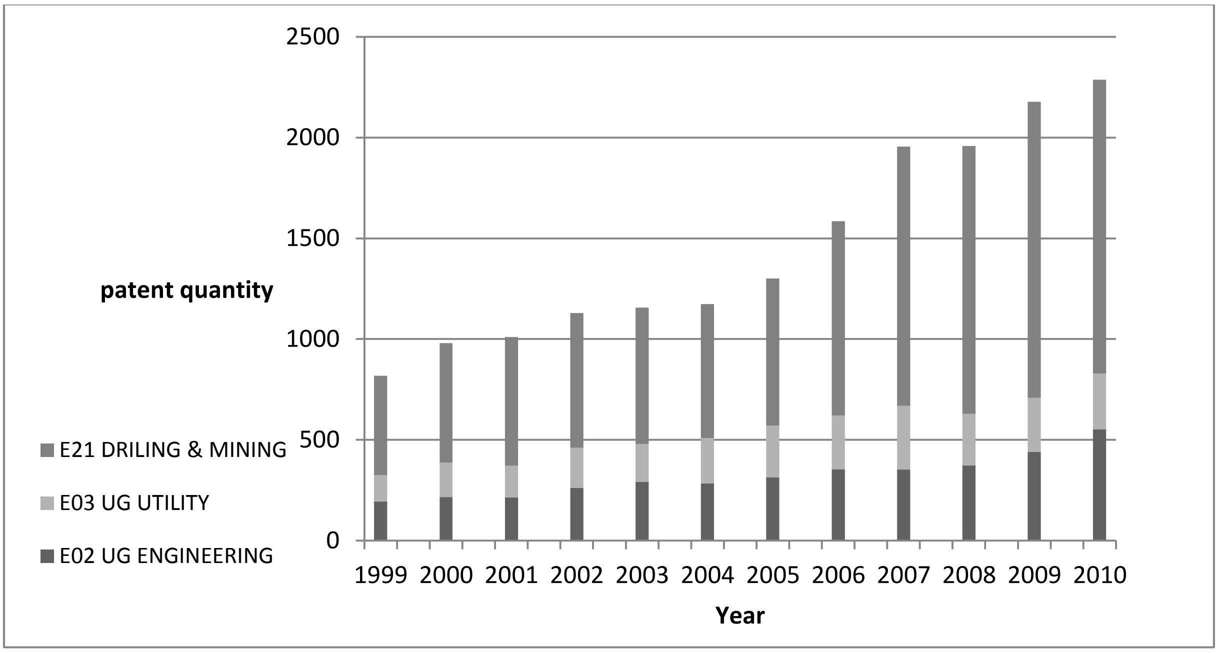


Figure 1:12 Share of underground construction related patent and distribution by IPC codes (data from WIPO)

Average innovation speed of underground related technologies is about 0.5%[7] during the recent decade. Although quantity of patents for the segment of underground space construction tripled in this ten-year period, the factor of innovation speed is considered as moderate (score = 2) compared to other technologies.

[7] Definition for innovation speed (based on patent data): variation of patent share during 1999 to 2010.

1.2.3.4 Construction cost efficiency

Technological progress has been contributing to reduce costs and duration in underground construction. A statistical research for 89 French tunnel projects have pointed that construction costs of tunnels were reduce by 3.5% per year between the period from 1975 to 1990 (Zhang, 1994). Construction time of underground subway station was reduced by one third thanks to innovative design separating building operations on station mezzanine level with tunneling operations on platform level (Brierley and Drake, 1995).

The main costs of underground construction are related to engineering executions in excavation and ground support foundation. Experiences From engineers (Goel et al., 2012i) indicated a relative steady growth of excavation price compared to construction price and land price:

"While comparing the cost, two trends are worth mentioning. First, the costs of excavation both aboveground and underground have increased much more slowly than the costs of construction. Second, the cost per capita of space required for public utilities increase aboveground and decreases underground as a function of the population in an urban community…In 1978, underground installations were economical when the cost of land was around US$85/m^2 "(quoted)

Here are examples of construction costs for the three underground forms in tunnel, cavern and basement, with function of usage, project dimension and land quality:

1) *Costs of tunnel construction:* factors of ground quality and space dimension can both determine construction cost of tunnel projects. Empirical cost functions are shown below in Figure 1:13 From (Goel et al., 2012g) :

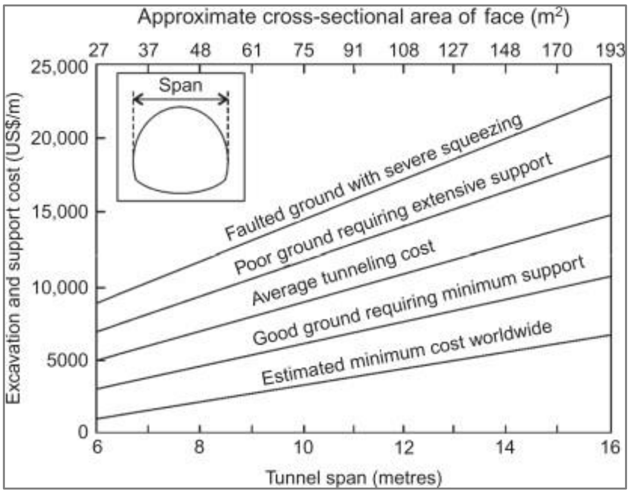


Figure 1:13 Tunnel construction costs with function of project dimension and land quality

Seen from the graphic above, based on different land quality from good to poor, excavation and support cost can range from 5,000$ to 23,000$ per meter of tunnel construction for a largest dimension, and range from 1,000$ to 9,000$ per meter for a smallest dimension. Therefore, knowledge level about the ground quality is essential for appraising underground space investment.

According to a statistical survey of 272 tunnel projects in the U.S. and Canada by (Rostami et al., 2013), construction cost of underground space in tunnel form depended on the size, ground condition, as well as function type. Examples below show the cost comparison of four tunnel function types: waste water tunnel (Figure 1:14), water tunnel (Figure 1:15), subway tunnel (Figure 1:16) and highway tunnel (Figure 1:17), based on tunnel diameter and land quality (hard rock or soft ground).

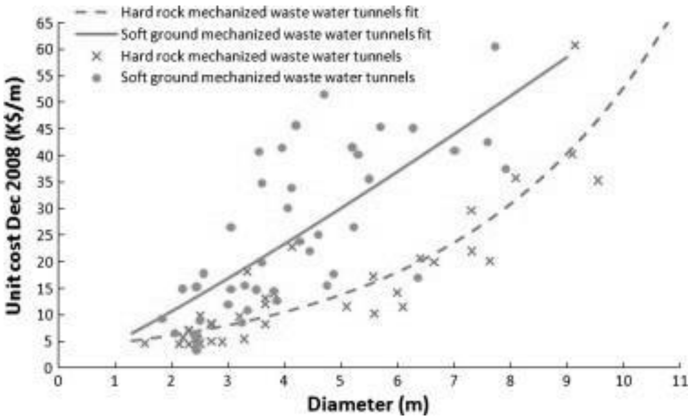


Figure 1:14 Construction costs of waste water tunnel with function of project dimension and land quality

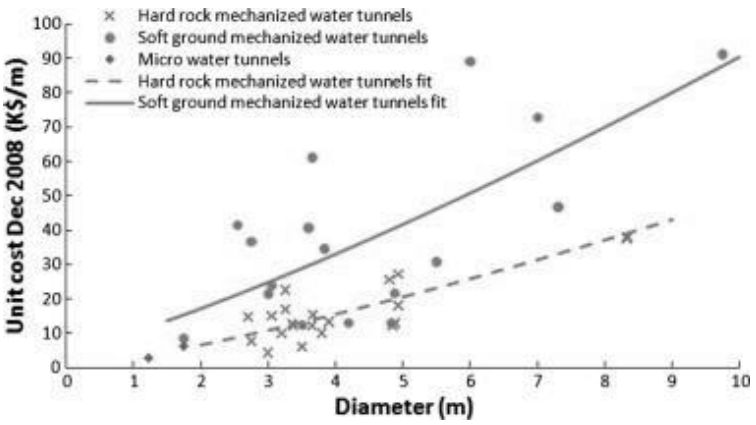


Figure 1:15 Construction costs of water tunnel with function of project dimension and land quality

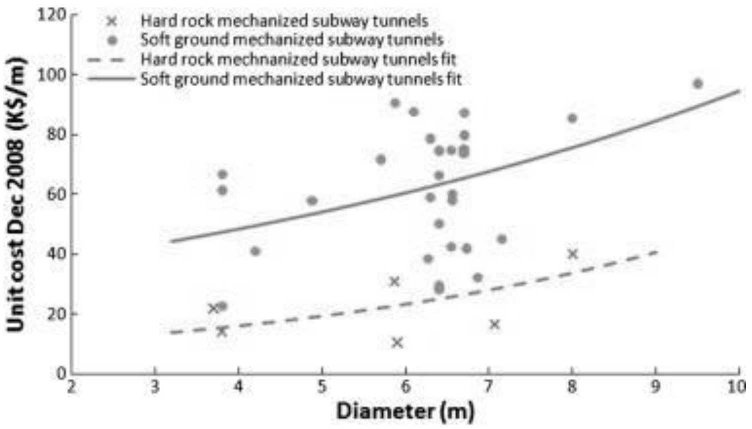


Figure 1:16 Construction costs of subway tunnel with function of project dimension and land quality

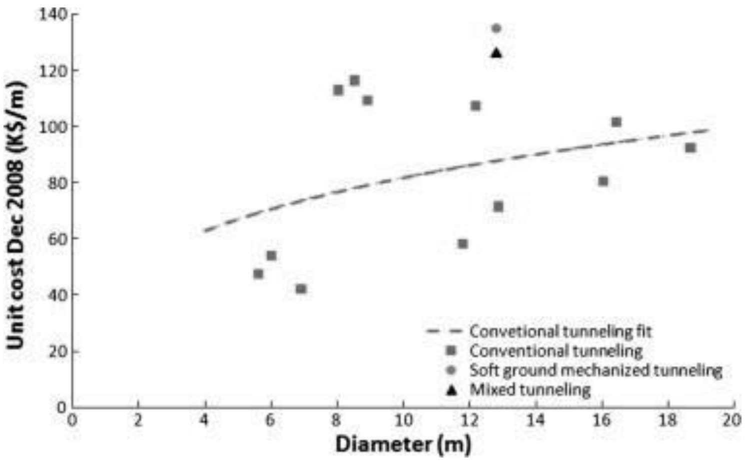


Figure 1:17 Construction costs of highway tunnel with function of project dimension and land quality

As seen, construction in soft ground land is generally more costly for tunneling excavation. A larger project dimension will have a greater cost difference between soft ground space and hard rock space.

2) *Costs of cavern construction:* cavern means rock space void. It is pointed by rock engineers that it is preferable to open larger cavern than smaller one, since unit construction cost will be lower with larger storage volume. Unit cost variation index according to space dimension is shown in the Figure 1:18, for strategic mineral storage facilities (Goel et al., 2012h).

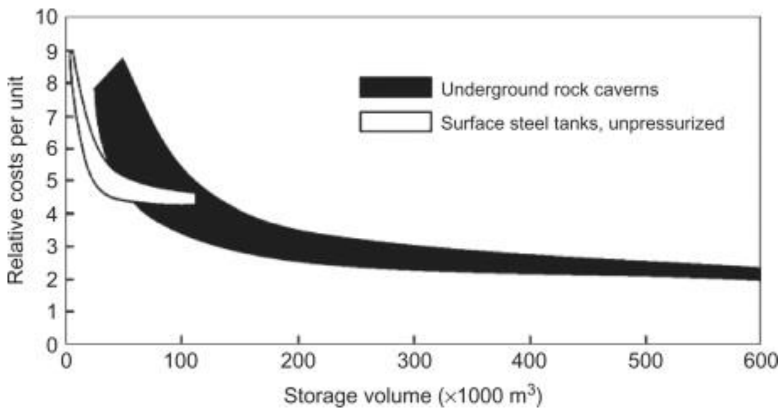


Figure 1:18 Construction costs of oil rock cavern with function of project dimension

3) *Costs of basement construction*: for underground car parks, per parking space cost reduced with parking capacity. Figure 1:19 below shows Japanese cases, built in subsurface of soft ground quality (Goel et al., 2012f).

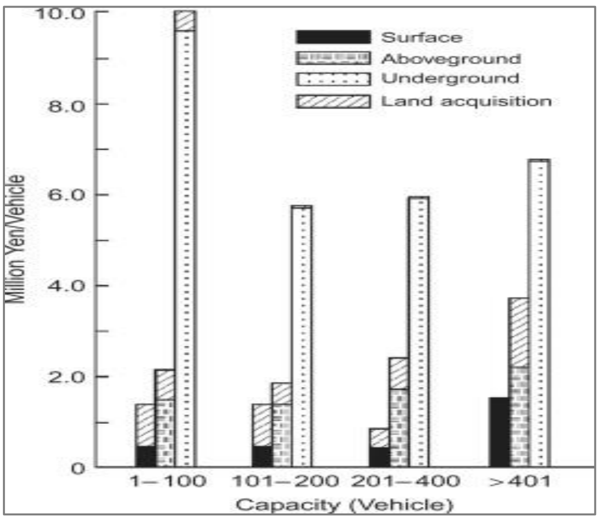


Figure 1:19 Construction costs of basement with function of project dimension (land quality class in Japan is considered as unfavorable)

The factor of cost efficiency can be considered as moderate (score = 2) due to engineering challenges. The challenge of high construction costs can be overcome by several ways:

- Know more about the ground, choose the best land quality for construction;
- For large scale linear underground infrastructure, try to align the tunnel with uniform ground condition;
- Adopt multiple functions to enlarge the dimension of underground facility (cavern and basement), making unit construction cost lower.

1.2.3.5 Property right flexibility

Human utilization of the land has been gone through agricultural production to industrialization. Horizontally, land has different functions ranging from rural zone to industrial zone to urban zone; boundaries among these functions are changing during different economic development eras with enhancing technological levels. Vertically, the interest to extend above or to below also depends on economic growth and technological levels. Invention of mechanical lift and shaft helped buildings to extend upwards or downwards, while invention of airplane and subway helped linear infrastructures to go across physical barriers (landscape constraint or congestion) on the surface. However, while horizontal land functions become a main concern in urban management, vertical land functions are still lacking regard.

Surface land value is based on its function and production. Land property right is highly respected and controlled in civil code, whose functional change such as rural to urban use implies a payment. In the case of airplane or subway construction, vertical space property right has been undergoing adjustments with landlords, such as limiting building heights in the flight path near airport to safeguard aviation operation (case of London city airport near CBD) and imposing strata resumption to safeguard subway operation (case of Hong Kong Mainland high speed rail). Instead of limiting or imposing the vertical space property right on a project-by-project basis, instruments in urban land management should be introduced to safeguard future air space and underground space development. Due to the fact that underground space presents in form of building basements and infrastructure network, both private property interest and public property interest are going to be involved in vertical land development process.

According to an international subsurface property right survey for 35 countries (Barker, 1991), for countries legitimizing private property right, delimitation of underground space under surface land property varies from shallow depth (to 6 meters) to an unlimited depth (to the center of the earth). There were only few countries (Germany, Italy, Japan and Switzerland) having administrative flexibilities in granting a significant depth interest for the surface landowner, which could help facilitating landowner’s will for underground space development. Based on these elements, we consider that property right flexibility is low (score = 1).

1.2.3.6 Space quality and public acceptance

Along with the progressing architectural technologies in lighting, interior physical design, ventilation, orientation, as well the enhancing safety standards imposed for indoor space, underground space’s attractiveness improvement has been given more and more effort by architects around the world (Von Meijenfeldt and Geluk, 2003, Von Meiss and Radu, 2004). It is pointed that the enhancement of interior space quality could help to increase public acceptance of using underground space (Maire, 2011). Public acceptance is scored as generally high (score = 3) as increasing utilization of underground buildings for commercial and entertainment uses.

1.2.3.7 Resource inventory prospection:

Constructability of the subsurface beneath a city required a comprehensive visualization for vertical layers, to identify appropriate construction sites below ground. Data availability will determine the prospection accuracy of underground space reserve. Application of information system and spatial analysis tools helped to establish a precise resource inventory for subsurface development. Mineral reserve prospection is part of natural resource management measures, but underground construction site inventory should be regarded as urban development measures. How to turn on the administrative transition remains uncertain due to moderate level of underground space resource inventory (score = 2). Therefore, it is part of the research in the thesis to reveal feasibility of mapping and quantifying permissible underground construction sites.

1.2.3.8 Risk exposures

Anthropogenic risks:

Underground construction related risks include quantitative loss and qualitative damage. Land subsidence and pollution in the subsurface are considered as significant anthropogenic risks caused by urbanization and industrialization.

The most concerning issue for underground urbanization is land subsidence induced by extraction and excavation. The reasons are mainly from over-extraction of groundwater and dewatering &excavating process. Rapid development of industrialization and urbanization has increased the volume of groundwater pumping and land excavation. In 1995, it is reported that there were more than 150 major cities in the world where subsidence was substantial, among which 45 cities in China had experienced costly damage to its environment and economy (R.L. Hua, 2004). The issue of land subsidence has been recognized by international organizations like UNESCO as one of major projects for scientific research and development[8].

Engineering excavation related risks appeared more often as increasing number of subway excavation projects undergoing in cities around the world (Zou and Li, 2010). Other disaster categories such as fire and gas also deserve high attention for different underground space types (Goel et al., 2012b). After spectacular tunnel accidents, ITA' guidelines on tunneling risk management integrated mitigation solutions for the entire project development process (Degn Eskesen et al., 2004). As mass transit system such as metro infrastructure plays an important role for providing energy efficient transport solution in future urban agglomerations, security and liability of large scale excavation works should be emphasized by both private developers and public legislators.

To sum up, risks of geotechnical subsidence and pollution are severe during the advanced development stage of underground space. As risk mitigation is still moderate (score = 2), capacities of the segment to deal with these risks still need to be scaled up.

[8] http://wwwrcamnl.wr.usgs.gov/rgws/Unesco/

Natural disasters and resiliency of underground infrastructures:

A study from the Center for International Earth Science Information Network (CIESIN) at Columbia University estimated that, of the more than 450 urban areas with 1 million inhabitants or more in 2011 (representing 1.4 billion people), 60% (about 890 million people) were living in areas of high risks of exposure to at least one natural hazard[9]. Cities with more than 5 million people facing more than one natural risk are listed in Figure 1:20, data from (Population Division, 2012).

CITIES AND URBAN AGGLOMERATIONS (WITH 5 MILLION OR MORE INHABITANTS IN 2011) EXPOSED TO AT LEAST ONE MAJOR NATURAL HAZARD (8-10TH RISK DECILES OF NATURAL DISASTERS)

		Population (in million)			*Risk decile*					
	City	*2011*	*Location*	*Type*	*Cyclones*	*Droughts*	*Earthquakes*	*Floods*	*Landslides*	*Volcanoes*
1	Tokyo, Japan	37.2	Coastal	Not Arid	8-10th	No hazard	5-7th	8-10th	No hazard	No hazard
2	Delhi, India	22.7	Inland	Semiarid	No hazard	5-7th	No hazard	8-10th	No hazard	No hazard
3	Ciudad de México (Mexico City), Mexico	20.4	Inland	Not Arid	No hazard	1st-4th	No hazard	8-10th	5-7th	No hazard
4	New York-Newark, USA	20.4	Coastal	Not Arid	5-7th	No hazard	No hazard	8-10th	No hazard	No hazard
5	Shanghai, China	20.2	Coastal	Not Arid	8-10th	No hazard	No hazard	8-10th	No hazard	No hazard
6	São Paulo, Brazil	19.9	Inland	Not Arid	No hazard	No hazard	No hazard	8-10th	No hazard	No hazard
7	Dhaka, Bangladesh	15.4	Coastal	Not Arid	1st-4th	1st-4th	No hazard	8-10th	No hazard	No hazard
8	Kolkata (Calcutta), India	14.4	Coastal	Not Arid	5-7th	8-10th	No hazard	8-10th	No hazard	No hazard
9	Karachi, Pakistan	13.9	Coastal	Arid	1st-4th	8-10th	No hazard	1st-4th	No hazard	No hazard
10	Buenos Aires, Argentina	13.5	Coastal	Not Arid	No hazard	1st-4th	No hazard	8-10th	No hazard	No hazard
11	Los Angeles-Long Beach -Santa Ana, USA	13.4	Coastal	Semiarid	No hazard	8-10th	8-10th	1st-4th	5-7th	No hazard
12	Rio de Janeiro, Brazil	12.0	Coastal	Not Arid	No hazard	No hazard	No hazard	8-10th	No hazard	No hazard
13	Manila, Philippines	11.9	Coastal	Not Arid	8-10th	1st-4th	8-10th	8-10th	No hazard	No hazard
14	Osaka-Kobe, Japan	11.5	Coastal	Not Arid	8-10th	No hazard	5-7th	5-7th	No hazard	No hazard
15	Istanbul, Turkey	11.3	Coastal	Not Arid	No hazard	1st-4th	8-10th	1st-4th	No hazard	No hazard
16	Guangzhou, Guangdong, China	10.8	Coastal	Not Arid	8-10th	No hazard	No hazard	8-10th	No hazard	No hazard
17	Shenzhen, China	10.6	Coastal	Not Arid	8-10th	1st-4th	No hazard	8-10th	No hazard	No hazard
18	Jakarta, Indonesia	9.8	Coastal	Not Arid	No hazard	5-7th	1st-4th	8-10th	No hazard	No hazard
19	Seoul, Republic of Korea	9.7	Inland	Not Arid	8-10th	1st-4th	No hazard	8-10th	No hazard	No hazard
20	Wuhan, China	9.2	Inland	Not Arid	1st-4th	1st-4th	No hazard	8-10th	No hazard	No hazard
21	Lima, Peru	9.1	Coastal	Arid	No hazard	1st-4th	8-10th	5-7th	No hazard	No hazard
22	London, United Kingdom	9.0	Coastal	Not Arid	No hazard	1st-4th	No hazard	8-10th	No hazard	No hazard
23	Chennai (Madras), India	8.8	Coastal	Not Arid	1st-4th	8-10th	No hazard	5-7th	No hazard	No hazard
24	Bogotá, Colombia	8.7	Inland	Not Arid	No hazard	5-7th	5-7th	8-10th	5-7th	No hazard
25	Lahore, Pakistan	7.6	Inland	Semiarid	No hazard	8-10th	1st-4th	8-10th	No hazard	No hazard
26	Tehran, Iran (Islamic Republic of)	7.3	Inland	Semiarid	No hazard	5-7th	8-10th	5-7th	No hazard	No hazard
27	Dongguan, Guangdong, China	7.3	Coastal	Not Arid	8-10th	No hazard	No hazard	8-10th	No hazard	No hazard
28	Hong Kong, China, Hong Kong SAR	7.1	Coastal	Not Arid	8-10th	1st-4th	No hazard	8-10th	No hazard	No hazard
29	Chengdu, China	6.7	Inland	Not Arid	No hazard	No hazard	No hazard	8-10th	No hazard	No hazard
30	Foshan, China	6.5	Coastal	Not Arid	8-10th	No hazard	No hazard	8-10th	No hazard	No hazard
31	Ahmadabad, India	6.4	Coastal	Semiarid	No hazard	8-10th	No hazard	5-7th	No hazard	No hazard
32	Thành Pho Ho Chí Minh (Ho Chi Minh City), Viet Nam	6.4	Coastal	Not Arid	No hazard	5-7th	No hazard	8-10th	No hazard	No hazard
33	Santiago, Chile	6.0	Inland	Semiarid	No hazard	8-10th	8-10th	8-10th	No hazard	No hazard
34	Philadelphia, USA	5.9	Coastal	Not Arid	5-7th	No hazard	No hazard	8-10th	No hazard	No hazard
35	Belo Horizonte, Brazil	5.5	Inland	Not Arid	No hazard	8-10th	No hazard	8-10th	No hazard	No hazard
36	Hangzhou, China	5.4	Coastal	Not Arid	5-7th	No hazard	No hazard	8-10th	No hazard	No hazard
37	Chittagong, Bangladesh	5.2	Coastal	Not Arid	5-7th	5-7th	5-7th	8-10th	No hazard	No hazard
38	Singapore, Singapore	5.2	Coastal	Not Arid	No hazard	No hazard	No hazard	8-10th	No hazard	No hazard
39	Luanda, Angola	5.1	Coastal	Semiarid	No hazard	8-10th	No hazard	1st-4th	No hazard	No hazard

Figure 1:20 Cities (with more than 5 million inhabitants in 2011) exposed to at least one natural hazard

A research group from ATKINS and University College London studied vulnerability of world growing developing cities face to future hazards and listed policy solutions according to an urban typology diagnostic framework[10]. Since the future of urbanization demand is in developing countries, resiliency oriented infrastructure solutions and civil protection space should be incorporated into city construction plan, in order to safeguard a durable urban growth.

[9] http://www.ldeo.columbia.edu/chrr/research/hotspots/

[10] http://www.futureproofingcities.com/

Certain types of natural hazards constrain the chance for underground construction, such as the risk of landslides and volcanoes; while others impose a necessity of using underground infrastructures to cope with uncertain natural risks, for providing shelters for evacuation, networks for water alteration and storage for critical reserves. Resiliency potential of underground infrastructures is investigated by (Sterling and Nelson, 2012), indicating advantages and disadvantages of underground facilities and buildings with respect to catastrophic events such as earthquake, hurricane, flood, fire, and radiation. The development pattern of urban underground should follow a resilient way, by inventing adaptable function portfolio and flexible solution for cities, based on location specific risk diagnostics.

Except the good protective performance during earthquake, underground infrastructures and buildings are still vulnerable facing flooding risk. Natural hazard adaptation capacity is considered as moderate (score = 2).

1.2.3.9 Feasibility score of underground urbanization

The Feasibility score indicates overall conditions required for promoting underground space construction for infrastructures and buildings, as well as resiliency considerations. We observed higher scores in technology awareness, knowledge diversity and public acceptance. Innovation speed is still low compared to other technologies, hindering a future cost efficiency improvement. Regulatory unconsciousness in subsurface space property right has been a challenge limiting a broader resource management extending to the third dimension. Resilient underground infrastructures and buildings have to be further promoted in order to ensure a capacity to mitigate risks, as well as to increase durability of underground construction which is usually considered as irreversible.

Factors	Scores
3.1 Technology awareness	3
3.2 Knowledge diversity	3
3.3 Innovation speed	2
3.4 Cost efficiency	2
3.5 Property right flexibility	1
3.6 Public acceptance	3
3.7 Resource inventory prospection	2
3.8 Anthropogenic risk mitigation	2
3.9 Natural hazard adaptation	2
Average score	2.22

(Factors are equally weighted; high: 3, moderate: 2, low: 1)

1.2.4 Synthesis for development potential profile: segment 1 underground space

Figure 1:21 summarizes three categories of factors, illustrating the development context, opportunities and challenges of underground space utilization during urbanization process. Implications are as follow:

Driven by urbanization growth, existing physical forms of underground are diversified and starting to converge together to form multiple functional complexes, but its innovation speed is slow compared to other technologies. More research and development input should be encouraged to keep pace with functional convergence and end user diversity generated from growing urban demand. Regulatory innovation by legalizing three dimensional extensions could help to activate hidden land supply of urban subsurface for more economic activities. Manmade risks may hinder the contribution of underground space and damage this vulnerable resource, which was mostly caused by inaccurate resource prospection and insufficient governmental monitoring. The vision of extending land value in a 3D way could transfer the administrative effort from resource management to construction planning, thus mitigating the avoidable conflicts and risks.

Overall development potential profile of the segment of underground space is rated as 2.41 (or 80.25% of full score). The segment can be regarded as having high opportunity but moderate capacity to deal with challenges. Sustainability issues were not well addressed in current development stage of underground urbanization, including inner-segmental congestion and inter-segmental interaction. Chapter 2 will explore practical measures and administrative instruments to overcome existing barriers and difficulties, in order to upgrade the feasibility of underground space development. Chapter 3 will study an integrated management process taking into account sustainability considerations for the four segments.

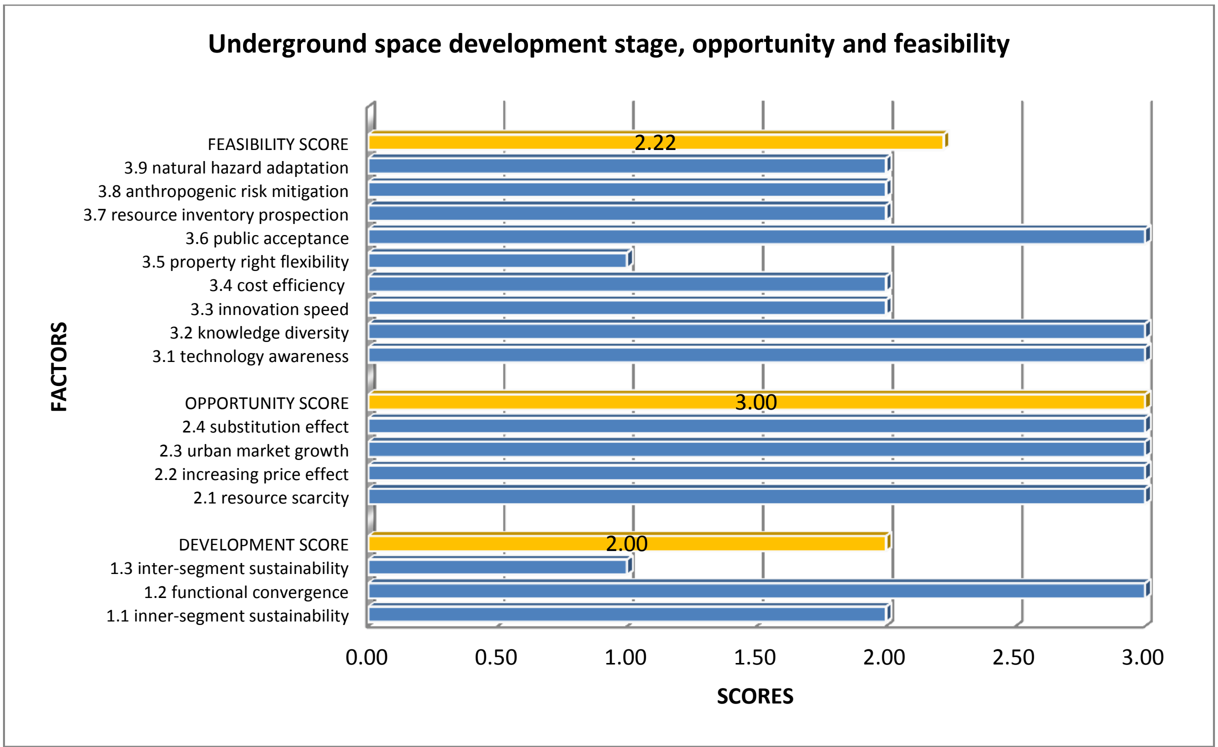


Figure 1:21 Overall rating for underground space segment

1.3 Segment 2: Geomaterials

1.3.1 Development stage of geomaterials

Waste produced from underground construction (rock, sand, gravel, clay, gypsum, slurry, etc.) can be recycled and reused for new raw material supply, providing an economical solution to recover excavation costs. This kind of eco-construction method is to avoid externalities related to waste transportation (pollution and energy consumption), as well as externalities related to land use (landfill disposal area).

Tunnel builders have been imposed by environmental regulators to reuse the excavated material generated from construction sites. As (Burdin, 2010) showed that, for tunnel project of Lyon, Gatthard, Loetschberg, Brenner and Nante, material valorization coefficients can reach a maximum of 24%, nearly one fourth of waste can be reused, which helped to reduce significant quantity of landfill and transport volume, as well as energy consumption. Figure 1:22 (Parriaux, 2009) shows a material handling method, a post-resource management pattern promoted by the new discipline of industrial ecology. The segment of geomaterials can be considered as having high functional convergence score (score = 3).

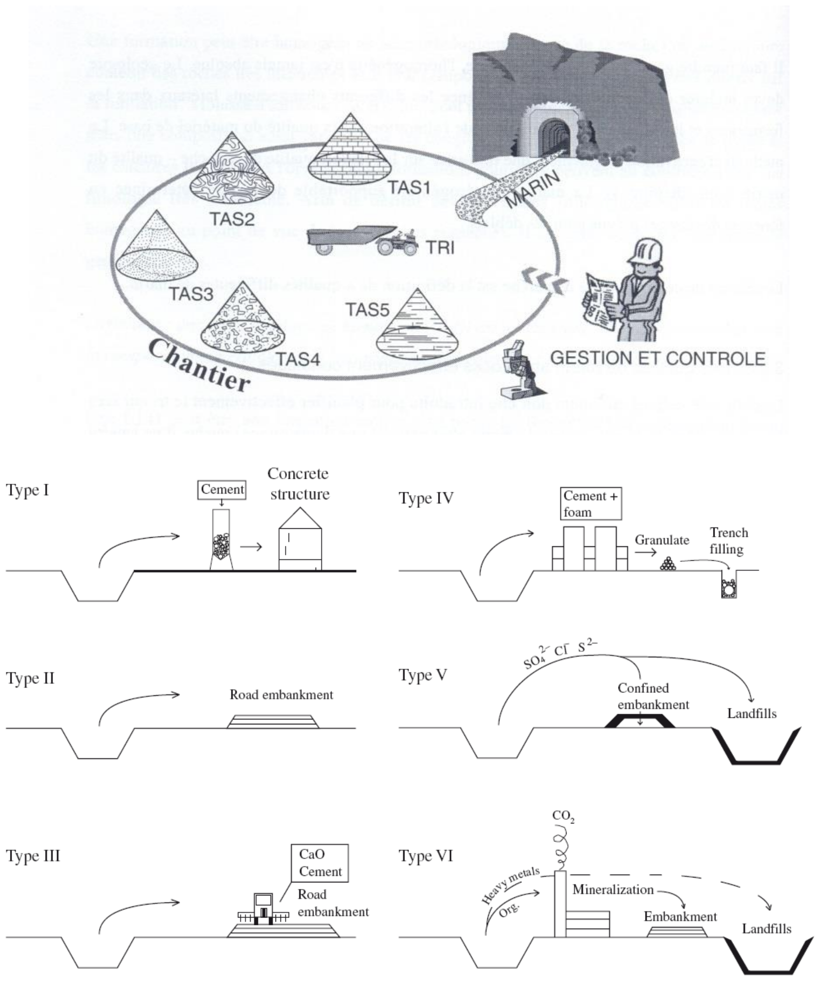


Figure 1:22 Sorting excavated material and reuse according to material types

For coastal cities relying on materials for embankment and land reclamation, excavated soil from construction sites is precious for urban land creation, like cities of Hong Kong (Hong Kong SAR, 2011), Singapore (Ong et al., 2009) and Toronto (Bélanger, 2007). Along with the growing trend of underground infrastructure and building construction, this resource will merit high attention to be handled timely, in order to extend the value chain of underground construction. However, for inland cities where land reclamation is limited, excavated soil with minor reusability causes problem for land fill discharge. While land fill cost is rising due to urban land scarcity, this negative impact from geomaterial discharge will harm economic attractiveness of underground space construction (inter-segmental conflict, factor of inter-segmental sustainability scored as 1, at low level). Reducing land fill volume by increasing geomaterial reusable fractions (extending recycled product portfolio) through technological breakthrough and administrative support will help to improve the sustainability performance of this segment. Conflict generated from groundwater segment is mainly pollutants diffusion from contaminated aquifers to soil layers. According to current research, internal conflicts between different geomaterial types are absent, making the factor of inner-segmental sustainability as high (score = 3).

Development score:

Reusing locally the excavated material is a sustainable trend combing waste reduction and raw material regeneration. Function portfolio is extending from land reclamation use to building material use. However, development score of the segment is rated as moderate, due to a lack of synergetic development with other segments, such as combing underground construction opportunity with geomaterial mining.

Factors	Scores
1.1 Inner-segment sustainability	3
1.2 Functional convergence	3
1.3 Inter-segment sustainability	1
Average score	2.33

(Factors are equally weighted; high: 3, moderate: 2, low: 1)

1.3.2 Opportunities for geomaterial reuse

1.3.2.1 Scarcity of surface quarry and landfill

With the increasing price of raw material and scarcity of quarrying sites, underground construction waste offers an alternative for vicinity construction material delivery. The Environmental Department of Geneva city estimated that[11], a 233% increase on reuse rate of excavated waste will help to save

[11] http://etat.geneve.ch/dt/environnement/ecomat/objectif-829-4383.html

58% of disposal waste and decrease 70% of natural quarrying extraction. The relationship between available aggregate supply land and urban intensification are shown in Figure 1:23, From (Robinson and Brown, 2002).

Surface rock quarrying and aggregate mining practices are limited due to non-renewable property of minerals. Reusing the outflow of underground construction can help to increase economic life cycle of mineral materials such as aggregates, and to reduce dependence on external construction material supply. A sustainable management manner of treating waste is to transform them to new resource. Solid waste landfill causes problems related to land use, transport, and pollution. Soil and rock waste can be considered as new material supply to save landfill area. The factor of quarry and landfill resource scarcity can be scored as moderate (score = 2), due to the fact of possible importation of material and exportation of landfill.

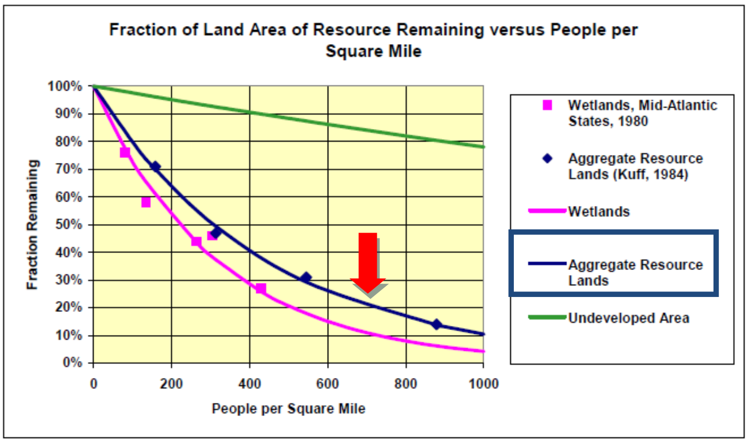


Figure 8. – Fraction of land area of resource remaining versus people per square mile. The fraction of aggregate resource lands available is calculated from data in Kuff (1984) and population data for Anne Arundel County, Maryland. The estimates of wetlands remaining in ntic States and fraction of land area undeveloped are derived from data published by the National Resources Conservation Service (2000) and county-level population data.

Figure 1:23 The relationship between urban intensification and aggregate supply capacity

1.3.2.2 Increasing material prices

As one of the production factors for construction, material prices are growing faster than labor price and construction costs. The factor of increasing material prices can be scored as high (score = 3). Figure 1:24 shows the evolution of material input prices (data from Eurostat).

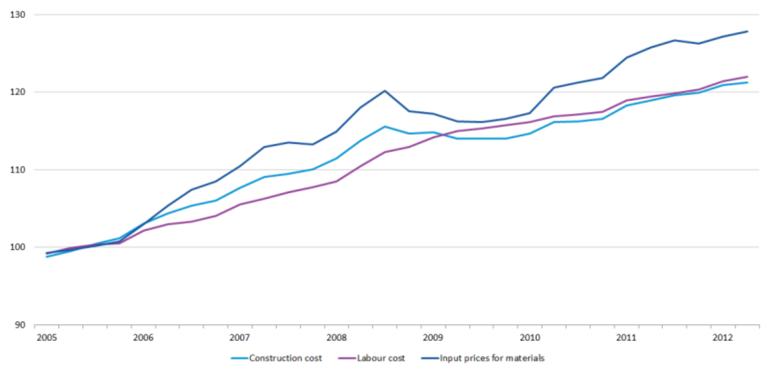


Figure 1:24 EU construction cost index and material input prices

1.3.2.3 Substitution effect for surface quarry

Since extraction of natural aggregates from the surface become limited due to urban intensification (Figure 1:23), considering underground mining or material extraction as a secondary product from underground urbanism offers an opportunity for resource revolution. Large scale underground mining can produce secondary resource as underground space, like the limestone caverns in Kansas City named SubTropolis[12], commercialized as the world's largest underground logistic business complex. Caverns formed by limestone extraction are developed as logistic center and commercial storage. Therefore, material extraction and land use can be planned at the same time to resolve material scarcity and land scarcity. Based on these arguments, substitution effect to surface material using geomaterial is high (score = 3).

1.3.2.4 Opportunity score for geomaterial reuse

The developing trend of underground construction will generate substantial quantity of material waste. The decreasing availability of surface quarry for material provision and land fill for waste disposal is imposing a circular exploration of this waste into resource. Large scale excavation work can be considered as underground mining, which could produce valuable primary material for various functions, from construction to land reclamation. Opportunity score of geomaterial reutilization can be rated as high.

Factors	Scores
2.1 Resource scarcity	2
2.2 Increasing price effect	3
2.3 Urban market growth	3
2.4 Substitution effect for the surface	3
Average score	3

(Factors are equally weighted; high: 3, moderate: 2, low)

[12] http://www.huntmidwest.com/subtropolis/index.html SubTropolis, the world's largest underground business complex

1.3.3 Feasibilities for geomaterial exploration

1.3.3.1 Technology awareness

Typical revalorization technologies can be seen in Figure 1:22. Onsite valorization technologies are developed to transform excavated underground waste into new material, an attempt to be used as green building material (J.C. Morela, 2001). As some Chinese building developers told the author that, the most difficult aspect to achieve national green building standard is the integration of local material for construction work. Future technological movement towards industrial ecology and material substitution can be encouraged to mainstream this kind of circular economy practice, in order to enhance material use efficiency and to relieve material intensity of construction sector (Newton et al., 2009). Small scale recycler can be installed near construction sites for efficient production (Miki et al., 2005), or large scale recycler can centralize small ones outside city centers for long-term operation (Mankelow et al., 2008). As a result, technology awareness in this segment can be seen as moderate (score = 2).

1.3.3.2 Innovation speed

From World intellectual property organization's IPC Green Inventory, reuse of waste materials as fillers (such as aggregate) for mortars and concrete is considered as one of the Environmentally Sound Technologies (ESTs). This innovation in waste management is registered in the area of chemistry, coded as C04B. Lacking diversity in patent class, this segment's knowledge diversity is considered as low (score = 1). Figure 1:25 shows the share of related patents among total technologies, the rate below 0.4% implies a significant research and development gap compared to other industrial technologies. Its innovation speed counts for only 0.05% (considered as low innovation speed, score =1), ten times slower than the segment of underground space.

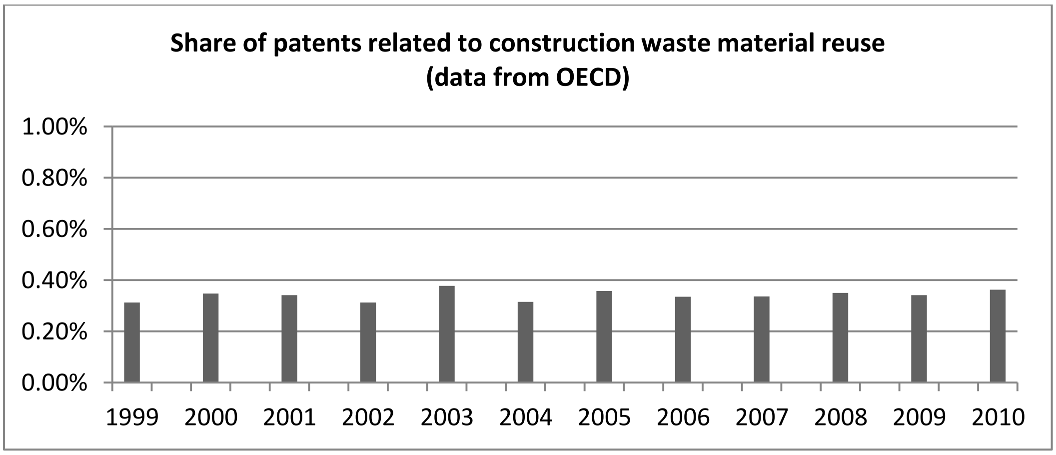


Figure 1:25 Share of aggregate waste reuse related patent (C04B)

1.3.3.3 Investment costs

According to types of waste generated from underground construction, material exploration ways can range from direct resale, onsite application to treatment process. Rock, sand and gravel can be sold directly as primary material after excavation to cover construction costs, or can be reused onsite to cover cement production need. Other polluted soils are more costly to be handled by contractors. As recycled aggregates are becoming more and more important to supplement total aggregate supply, production cost efficiency is critical for propagating this eco-construction method. A cash flow model to simulate investment cost and return was demonstrated by (Wilburn and Goonan, 1998), showing profitability levels of different production scales by aggregate recyclers in Denver, U.S.. From sensitivity analysis of this model, if average recycled aggregate price remains the same, increasing charges in landfill will help to increase attractiveness of recycling aggregate industry.

According to a UK's aggregate companies, underground mining (such as limestone and aggregate) costs 20% higher than surface quarrying. If increasing material scarcity drives up prices sufficiently, underground mining will become economically attractive (Mankelow et al., 2008). Recycled aggregate production counts for 20% of total aggregate supplies. Since half of the cost for aggregate supply comes from long distance transportation cost, reutilization of local excavation waste can reduce costs on material transport, disposal land use and environmental impact. Soft soil material usually needs chemical treatment to be recycled for new construction material. The factor of cost efficiency is considered as moderate (score = 2).

1.3.3.4 Property right flexibility

Economic value of the material can determine if its exploration right subjects to local mining law. From administrative investigations conducted by (Barker, 1991), minerals including oil, gas, coal and aggregate from the underground were owned and regulated by the central state in most of the countries around the world, with legislative facilitation such as concession and permission to endorse an exploration right. However, handling of excavated material is normally the responsibility of project contractors, property right flexibility can be scored as high (score =3). Therefore, underground space construction site management should take into account the disposal method for geomaterial.

1.3.3.5 Resource inventory prospection

Once geomaterial can be considered a resource for direct use, its utilization potential should be investigated before excavation. Kansas city's limestone cavern logistic center was originated from rock mining. The presence of good material could become the motivation for underground space creation. Since the profitability of material reuse depends on its requirement of treatment level (special valorization techniques for soft soil or polluted soil), economic viability of reusing geomaterial in the subsurface is related to the ground condition. A recycling planning should look at the planned construction sites in the city, in order to capture this opportunity. According to a study of construction material recycling in Geneva city, only 20% of planned construction sites have suitability to reuse excavated material for aggregate resource (Rochat et al., 2006). Current feasibility on material inventory is considered as low (score = 1).

1.3.3.6 Risks

Mineral extraction related subsidence and its substantial economic losses were well documented by the United States (Panel on Land Subsidence and National Research Council (U.S.), 1991). Mitigation measures such as information system, legal regulation, land use control, insurance and pricing instrument were proposed for different types of land subsidence. Capacities to deal with risks are viewed as moderate (score = 2), deserving for a higher attention to operate geomaterial mining.

1.3.3.7 Feasibility score for geomaterial reuse

Although the segment is listed as one of the environmentally sound technology application area, its low innovation speed and weak concern on city level recycling plan have discouraged contractors to integrate post resource management into construction projects. Information diffusion about available technical solutions for geomaterial valorization and material market prices should be improved by creating contractor communication platform, used to provide records on geomaterial production and acquisition.

Factors	Scores
3.1 Technology awareness	2
3.2 Knowledge diversity	1
3.3 Innovation speed	1
3.4 Cost efficiency	2
3.5 Property right flexibility	3
3.6 Public acceptance	3
3.7 Resource inventory prospection	1
3.8 Anthropogenic risk mitigation	2
3.9 Natural hazard adaptation	2
Average score	1.89

(Factors are equally weighted; high: 3, moderate: 2, low: 1)

1.3.4 Synthesis for development profile: segment 2 geomaterials

Development potential of this segment (rated as 2.32, 77.47% of full score) fails to follow the potential level of underground space, due to lacking capacity to overcome technological and administrative barriers (Figure 1:26). The public mobilization project called ECOMAT[13] in Geneva city can be a model for establishing a good information guidance platform of construction material reutilization. Technology providers and associated contractors are centralized by a communication platform established by Geneva city government, facilitating market information flow to enhance awareness.

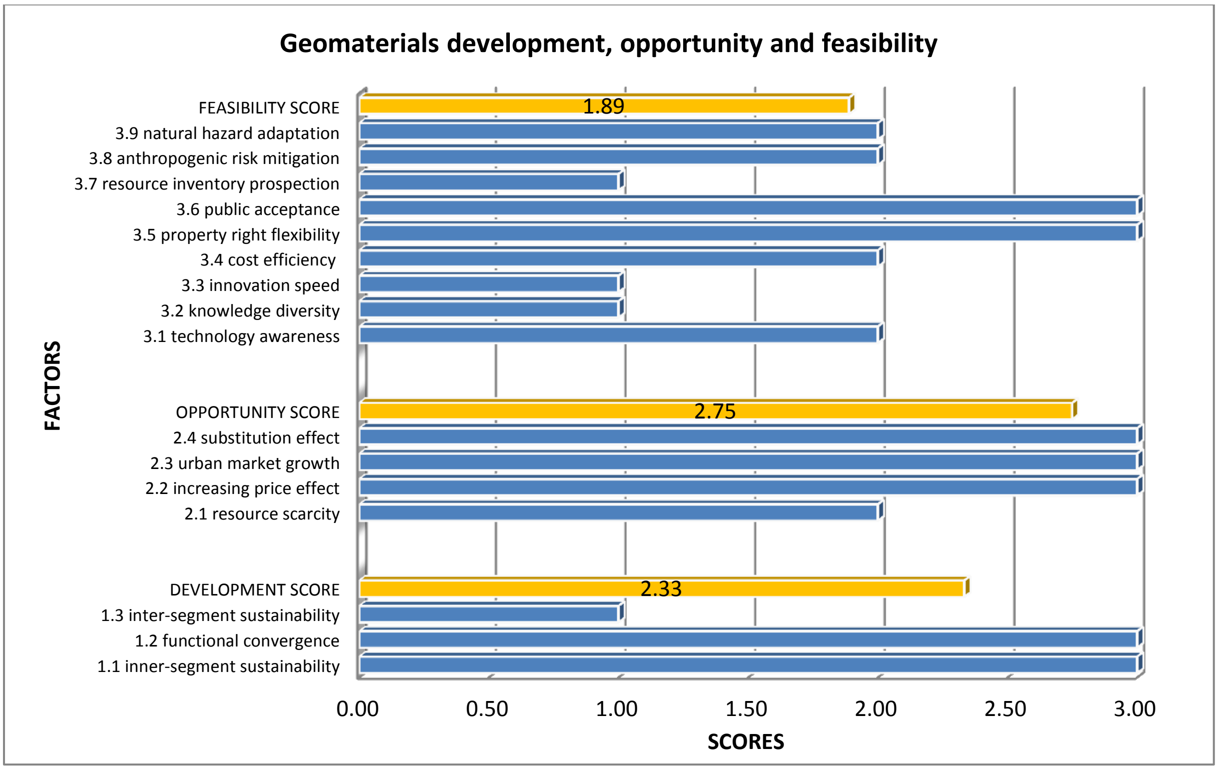


Figure 1:26 Overall rating of geomaterial segment

[13] http://etat.geneve.ch/dt/environnement/ecomat/ecomat-829.html

1.4 Segment 3: Geothermal energy

1.4.1 Development stage of geothermal energy

As one of the renewable energy explorations, geothermal energy infrastructures can be classified into direct heat extraction (from groundwater or soil) and electricity generation. Different types of geothermal energy exploration system are shown in Figure 1:27[14]. Inner-segmental sustainability is considered as high (score = 3) due to minor conflicts existing between different types of geothermal systems. According to International Energy Agency (OECD/IEA, 2010), for geothermal exploration around the world, shallow direct heat extraction capacity in 2009 was five times larger than electricity generation. The largest technology application of direct heat extraction is ground source heat pump (GSHP), contributing to 50% of shallow geothermal use.

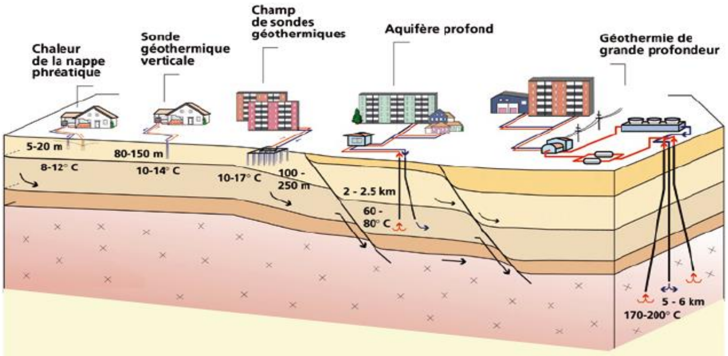


Figure 1:27 Typologies of geothermal energy system (direct heat use)

Utilization of geothermal energy system is becoming more and more compact with the integration of underground foundation structures and heat exchangers, and more and more flexible for buildings. Functional application can adapt to different building types, even for tunnel types (energy lining). Functional convergence can be scored as high (score = 3). Inter-segmental conflicts include spatial competition with underground space and hydrogeological impact with groundwater level modification. Therefore, inter-segmental sustainability can be scored as moderate (score =2).

Development score:

Current development stage of geothermal energy is rated higher than the two segments presented previously.

Factors	Scores
1.1 Inner-segment sustainability	3
1.2 Functional convergence	3
1.3 Inter-segment sustainability	2
Average score	2.67

(Factors are equally weighted; high: 3, moderate: 2, low: 1)

[14] http://www.geothermie.ch/index.php?p=geothermics

1.4.2 Opportunities for geothermal energy exploration

1.4.2.1 Energy scarcity

Facing energy crisis, the supply limit of fossil fuel resource and volatility of energy prices are accelerating the exploitation process of alternative energy supply. Extractable conventional oil reserves have been facing constraint according to the report of Energy supply (Climate Change 2007: Mitigation). International Monetary Fund also released a report on oil scarcity recently. The gap between supply and demand for liquid fuels in the next decades is shown in Figure 1:28[15]:

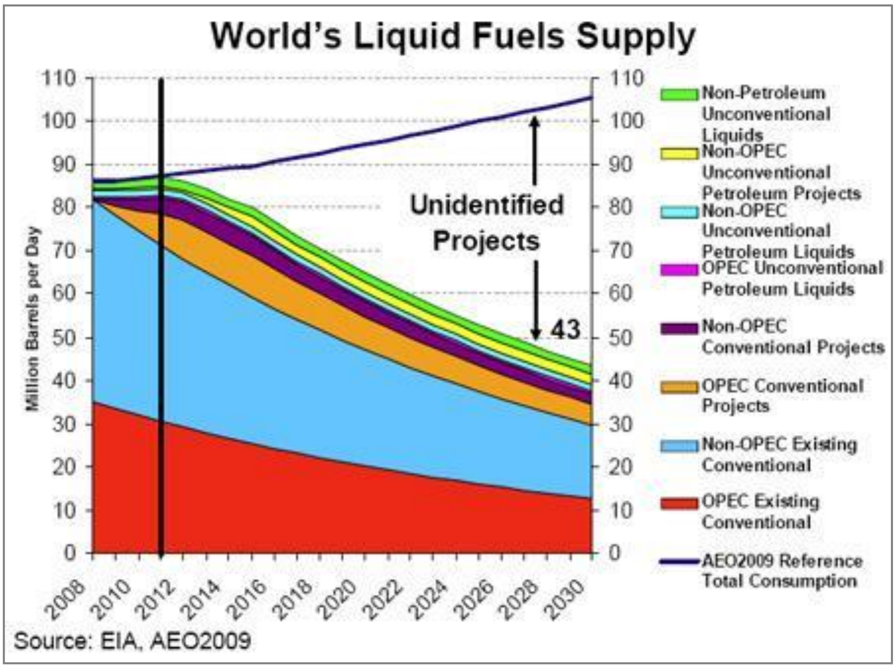


Figure 1:28 Prediction from Glen Sweetnam for world liquid fuels supply and demand gap

Instead of extracting, producing and transporting fossil fuels to heat our floors, geothermal energy beneath the city can be extracted locally as new heating and cooling source. The factor of energy resource scarcity can be considered as high (score = 3).

1.4.2.2 Increasing energy prices

Figure 1:29 shows the price evolution of fuel energy from 2003 to 2012. Overdependence on energy importation could threaten a city's durable growth. Storage of oil and gas reserve can only meet emergency demand. Transforming building to a self-reliance energy system with ground source heat pump could relieve the pressure on exogenous energy demand. The factor of increasing energy prices is considered as high (score = 3), pushing discovery of alternative energy source belowground.

[15] Source: Glen Sweetnam/US Energy Information Administration

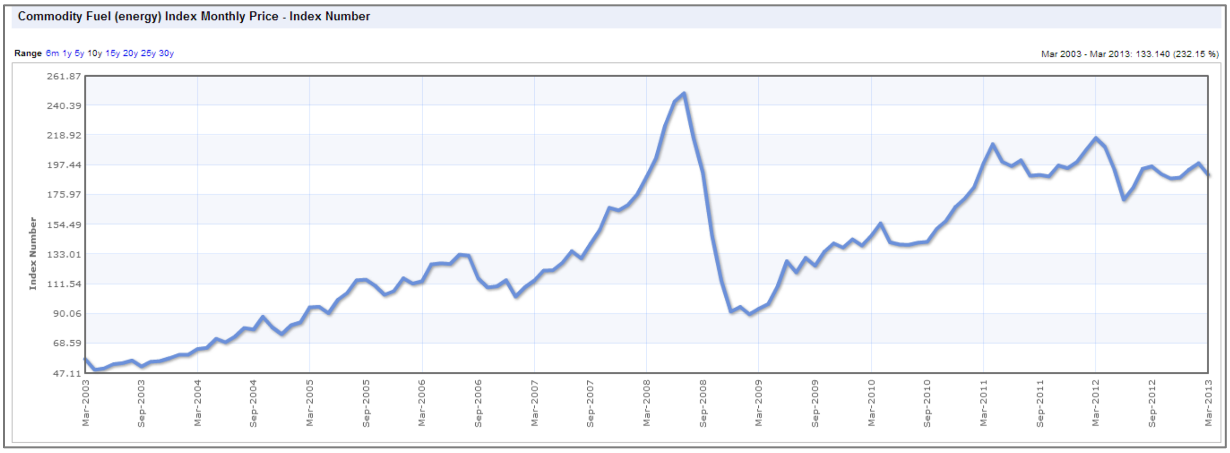


Figure 1:29 Commodity fuel (energy) index (International Monetary Fund)

1.4.2.3 Market growth

Shallow heat can be found everywhere in urban zones, therefore it owns a potential to contribute and replace conventional heating energy exploitation. Energy industry as a critical sector for urban economy, is calling for sustainable alternatives to support economic development with independent local resource supply. An increase of geothermal direct use is expected to reach 20 times in 2050 compared to the level in 2010. Urban market growth is scored as high (score =3), which induced increasing geothermal energy demand in the emerging cities. Global development of these two geothermal energy uses is shown in Figure 1:30 (OECD/IEA, 2010):

Geothermal electricity production		Geothermal direct use	
Country	GWh/yr	Country	GWh/yr*
United States	16 603	China	20 932
Philippines	10 311	United States	15 710
Indonesia	9 600	Sweden	12 585
Mexico	7 047	Turkey	10 247
Italy	5 520	Japan	7 139
Iceland	4 597	Norway	7 000
New Zealand	4 055	Iceland	6 768
Japan	3 064	France	3 592
Kenya	1 430	Germany	3 546
El Salvador	1 422	Netherlands	2 972
Costa Rica	1 131	Italy	2 762
Turkey	490	Hungary	2 713
Papua New Guinea	450	New Zealand	2 654
Russia	441	Canada	2 465
Nicaragua	310	Finland	2 325

** 1 000 GWh = 3.6 PJ*

Figure 1:30 Main producers of geothermal energy (electricity production and direct use)

1.4.2.4 Substitution effect for renewable energy on the surface

Extractable heat from subsurface is less variable than other surface renewable energy source such as solar, wind and tide. Taking advantage of basement foundation construction, energy walls and piles could be integrated as parts of building structure, saving additional land occupation for drilling from the surface. But performance of ground source heating depends a lot on the property of soil in terms of thermal conductivity. As a result, substitution effect for surface energy resource is scored as moderate (score = 2).

1.4.2.5 Opportunity score for geothermal energy use

Extracting underground heat resource helps to relieve conventional energy supply pressures and to complement the renewable clean energy portfolio. Along with the predicted market growth for geothermal heat use, this segment can be also considered as owning high opportunity for future development.

Factors	**Scores**
2.1 Resource scarcity	3
2.2 Increasing price effect	3
2.3 Urban market growth	3
2.4 Substitution effect for the surface	2
Average score	2.75

(Factors are equally weighted; high: 3, moderate: 2, low)

1.4.3 Feasibilities for geothermal energy exploration

1.4.3.1 Technology awareness

Technology portfolio of geothermal solutions for building sector can be classified in Figure 1:31[16], showing that technologies are well sensed at the international level (technology aware score = 3).

A highly innovative solution incorporating basement construction and energy foundation (energy walls and piles) was realized and demonstrated in **London's Knightsbridge hotel project**, which promoted a new concept of green building using multiple potentials of the urban underground, to save land use and energy demand (see Figure 1:32).

[16] http://www.skanska.co.uk/Services/Piling-foundations/About-us/Sustainability-/Energy-incorporating-Energy-Piles/

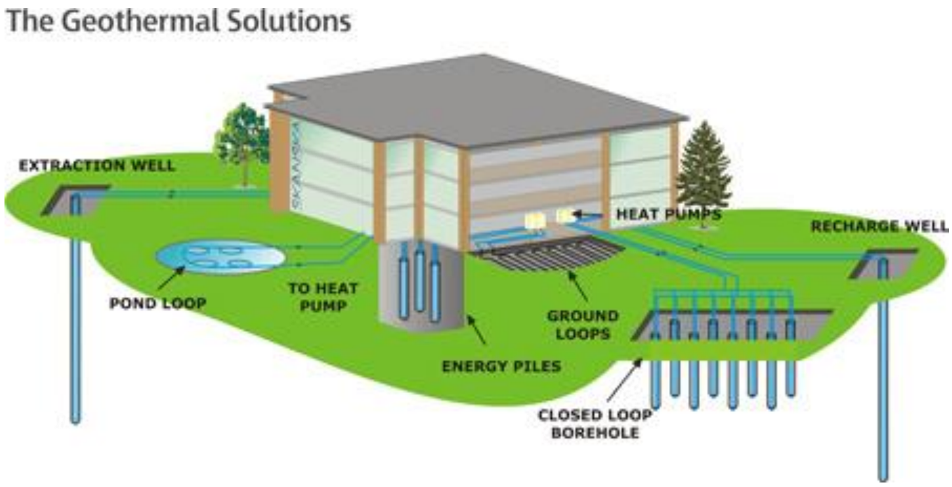


Figure 1:31 Heat extraction methods for buildings

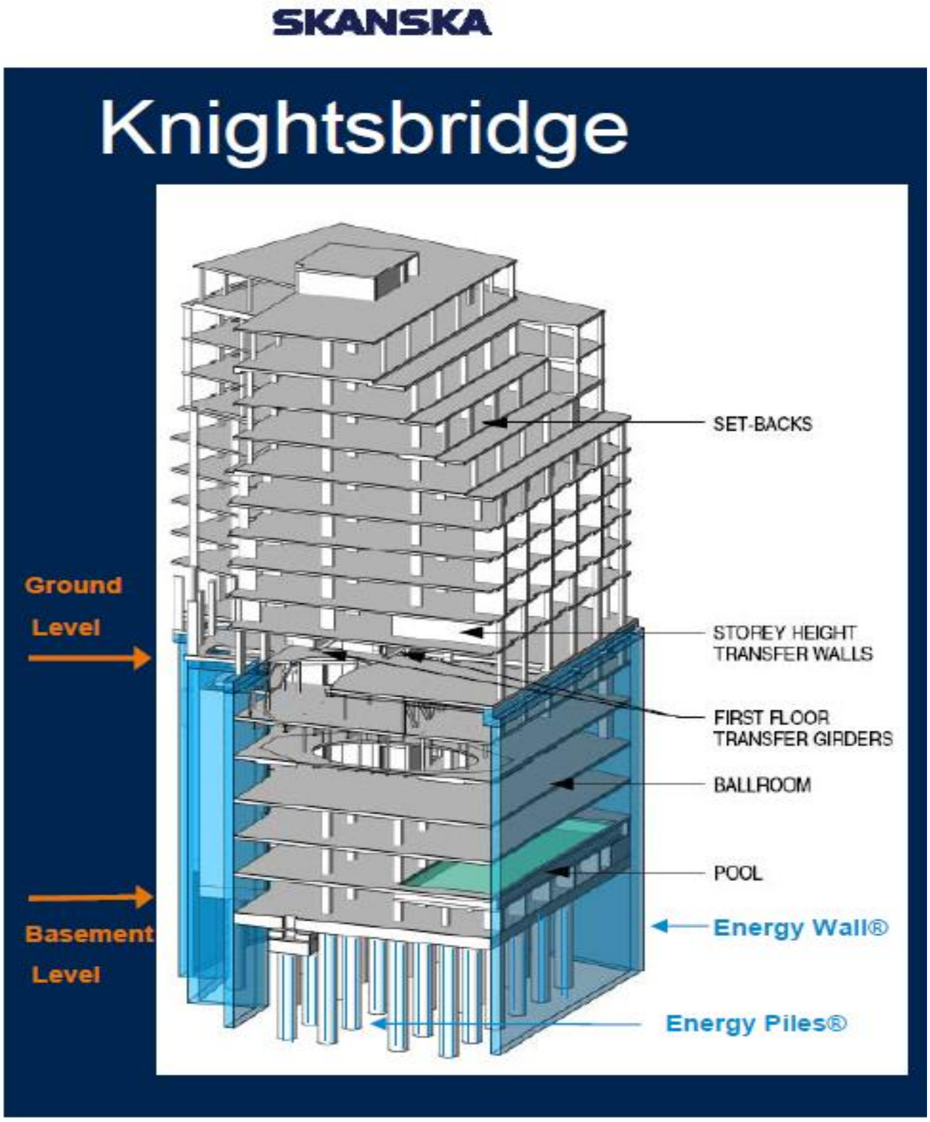
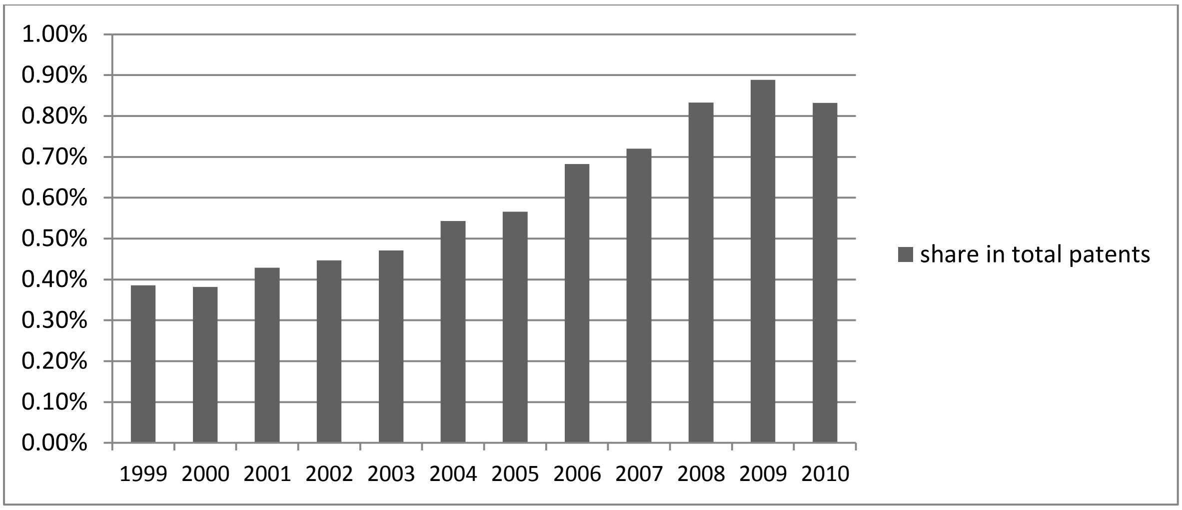


Figure 1:32 London Knightsbridge Hotel energy piles and walls (from SKANSKA UK)

1.4.3.2 Innovation speed

From World intellectual property organization's **IPC Green Inventory**, geothermal energy is considered as one of the Environmentally Sound Technologies (ESTs). Innovation scheme for geothermal heat use presents in the area of mechanical engineering (heating) and electricity, grouped by a series of patent codes (F01K, F24F, F24J, F25B, H02N). Diversity of patent class represent a high knowledge diversity in the segment (knowledge diversity score = 3). Share of patents related to this technology codes didn't exceed 1% of total patents (Figure 1:33), and innovation speed counts for 0.4% (innovation speed score = 2), indicating a necessity of encouraging more R&D effort in the future to promote technological progress of geothermal energy exploration.



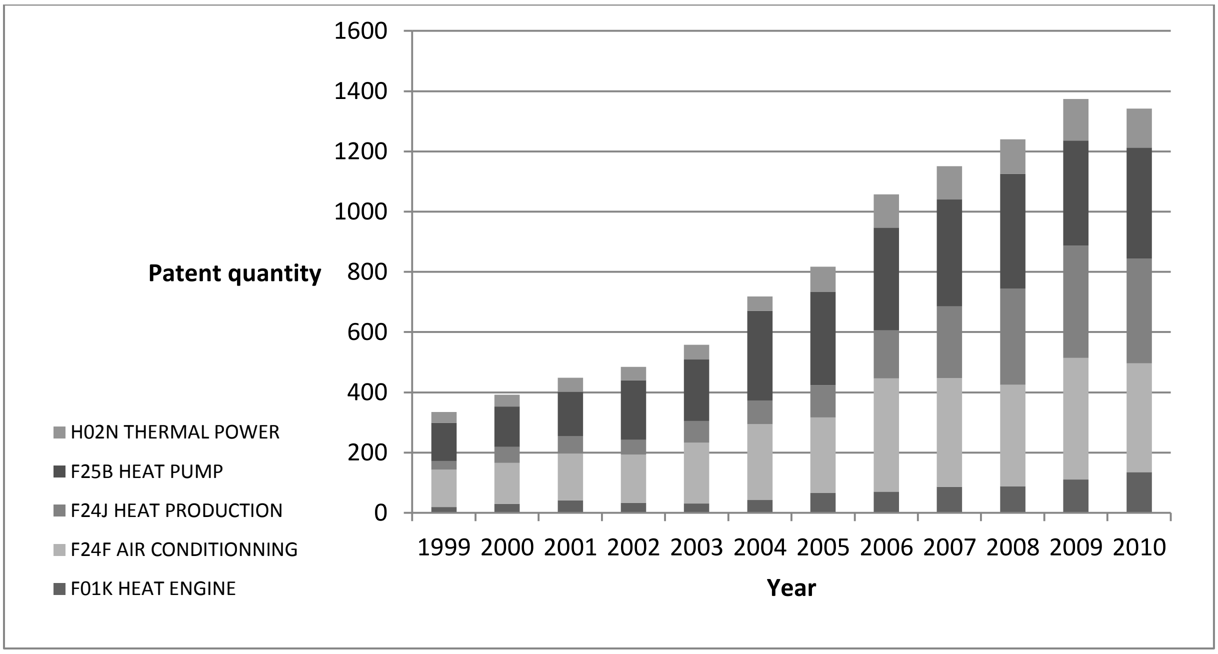


Figure 1:33 Share of geothermal heat use related patent and quantity distribution in IPC codes

1.4.3.3 Investment Cost and development cost:

International Energy Agency estimated that capital costs of ground source heat pumps (GSHP) amounted to USD 439-600/KW for China and India, USD 905-1190/KW for North America, and USD 1170-2267/KW in Europe. Operational cost is much lower than conventional heating system, with an average of USD 0.079/KWh, which is expected to decrease by 10% in the next twenty years with rapid global deployment scale.

A detailed cost comparison between GSHP and conventional heating system for residential building is showed in Figure 1:34[17], revealed from several demonstration projects in China. Investment efficiency of the system can be gained from lower operational cost in heating and cooling, as well as saved building floor space required for equipment. Cost efficiency score is high (score = 3).

Initial investment and operational costs of GHP system compared to a central air and heating system that runs on natural gas.

	GHP system		Natural gas-powered central air-conditioning and furnace	
	Unit price * CNY/m² USD/m²	Total cost (million=m)	Unit price CNY/m² USD/m²	Total cost (millions=m)
Equipment cost	CNY 224.0 USD 27.0	CNY 15.72 m USD 1.90 m	CNY 219.0 USD 26.46	CNY 15.34 m USD 1.85 m
Engineering cost	CNY 136.0 USD 16.4	CNY 9.52 m USD 1.15 m	CNY 147.0 USD 17.76	CNY 10.29 m USD 1.24 m
Total investment	**CNY 360.0 USD 43.5**	**CNY 25.24 m USD 3.05 m**	**CNY 366.0 USD 44.22**	**CNY 25.63 m USD 3.10 m**
Operational cost heating	CNY12.9 USD 1.6	CNY 1.50 m USD 181,353.00	CNY30.0 USD 3.63	CNY 2.64 m USD 318,968.00
Operational cost cooling	CNY 8.5 USD 1.0	CNY 748,000.00 USD 90,374.00	CNY 14.2 USD 1.72	CNY 1.25m USD 151,026.00
Cost of building space required for equipment	CNY 2500.0 USD 302.0	CNY 375,000.00 USD 45,308.00	CNY 2500.0 USD302.0	CNY 875,000.00 USD 105,719.00

* Conversion rate used: 1 USD = 8.28 CNY.

Figure 1:34 Cost comparison between GSHP and conventional heating&cooling system

For commercial and institutional buildings, life cycle cost savings by using GSHP compared to other Heating, Ventilation and Air Conditioning (HVAC) alternatives was proved to range from 22% to 38% (with a discount rate of 4.5%) (Bloomquist, 2009).

[17] From NREL International programs www.nrel.goc/international in 2002, an analysis of Beijing's International Mansions at the Jiaheli Garden using GSHP

Among all the renewable energy for heating and cooling, shallow geothermal technologies applied for both heating in winter and cooling in summer can be cost-competitive on a life cycle basis (IEA, 2007), as showed in the Figure 1:35.

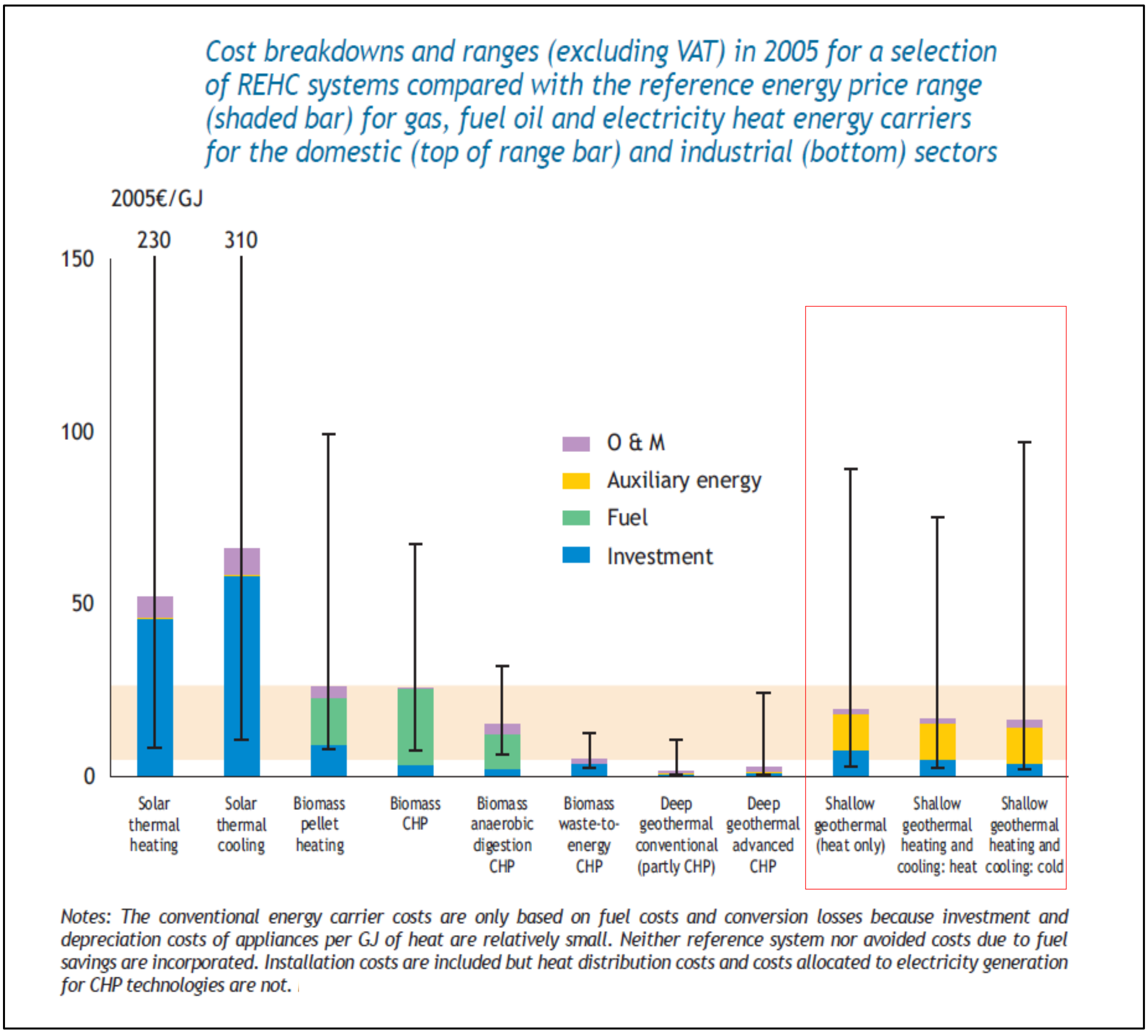


Figure 1:35 Cost breakdown comparison among renewable heating & cooling system types

1.4.3.4 Property right flexibility

Since development typologies of geothermal energy varies from shallow underground to deep underground, from ground source heat extraction to groundwater heat extraction, legal title of the thermal heat can be considered differently according to the extractable medium (air or water). In all cases, a permission of installing geothermal system should be granted by local regulators, who determine obligations for developers during authorization process. Property right flexibility score is high (score = 3).

1.4.3.5 Resource inventory prospection

Similar to mineral resource prospection, geothermal energy supply inventory has been investigated broadly and well documented by international and national energy departments. Among one of the renewable energy portfolio, its development has been stated as common concern at the political level. Geothermal energy resource inventory score is high (score =3).

1.4.3.6 Risks

Geothermal heat extraction induced environmental risks have been recognized by IEA, who set up a Geothermal Implementing Agreement[18]. Sustainability of geothermal extraction can be achieved based on comprehensive resource survey and potential zone protection policies. Compared to other segments, deep geothermal system may induce potential seismic risks, while low-temperature heating & cooling system installed in shallow layers (0-300m) has a lower risk profile. Capacities of geothermal industry to deal with risk is scored as moderate (score = 2).

1.4.3.7 Feasibility score for geothermal energy use

Feasibility of this segment's application is rated as at much higher level than the other two segments presented before (underground space segment feasibility score: 2.22; geomaterials segment feasibility score: 1.89). Geothermal energy exploration has been promoted and researched extensively during previous decades under the direction of increasing renewable energy utilization. **While political and technological supports are taking effect, economic viability disclosure is also helpful to raise the acceptance of its application.**

Factors	Scores
3.1 Technology awareness	3
3.2 Knowledge diversity	3
3.3 Innovation speed	2
3.4 Cost efficiency	3
3.5 Property right flexibility	3
3.6 Public acceptance	3
3.7 Resource inventory prospection	3
3.8 Anthropogenic risk mitigation	2
3.9 Natural hazard adaptation	2
Average score	2.67

(Factors are equally weighted; high: 3, moderate: 2, low: 1)

[18] http://iea-gia.org/ 2

1.4.4 Synthesis for development potential profile: Segment 3 geothermal energy

As seen in Figure 1:36, segmental development potential profile is rated to **2.69 (89.81% of full score).** Development potential of this segment is higher than the segment of underground space. One of the important factors is the political awareness and administrative effort on resource inventory prospection, in order to formulate energy supply planning and to safeguard self-reliance capacity.

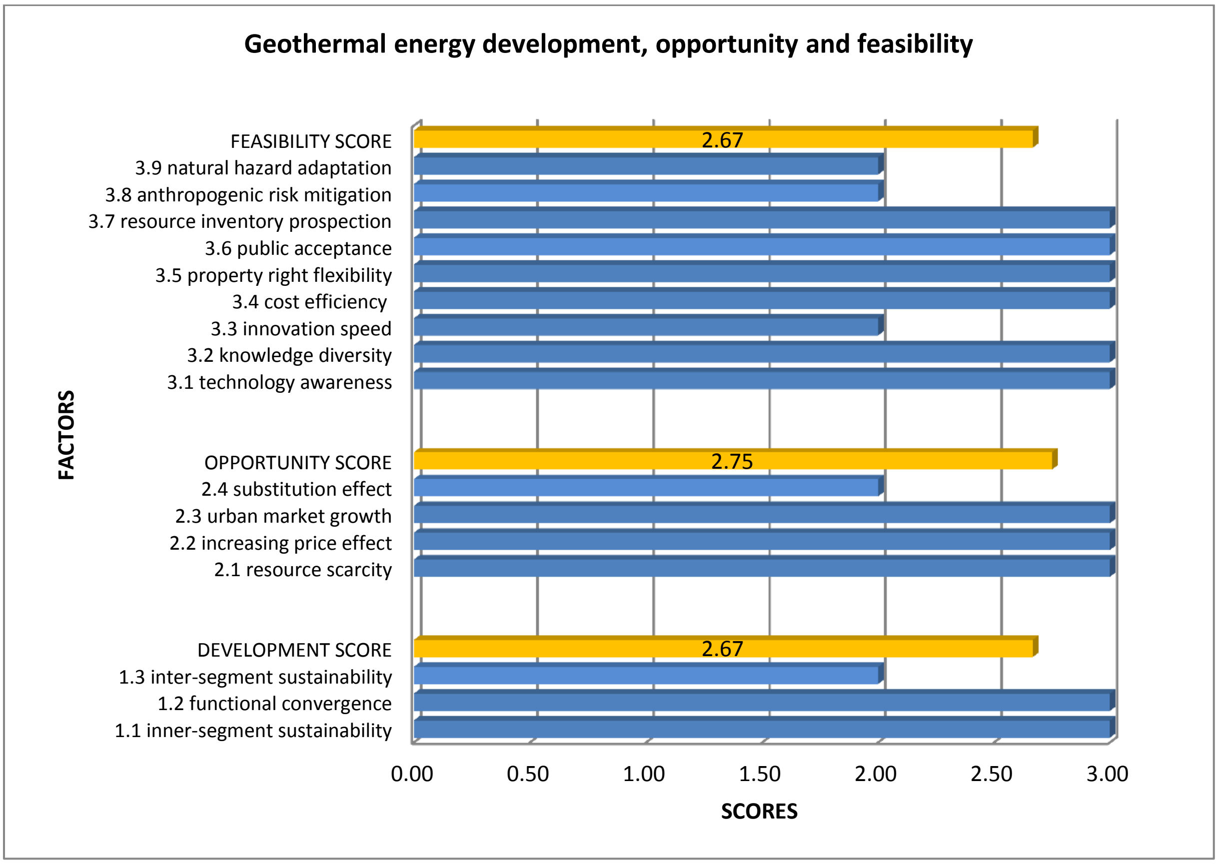


Figure 1:36 Overall rating for geothermal energy exploration

1.5 Segment 4: Groundwater

1.5.1 Development stage of groundwater

Different from resource of subsurface space and geothermal heat which are static in supply capacity, the resource of underground water (groundwater) is considered as variable in time and in location. Exploration potential of this water resource depends more on the geological property of the subsurface than the technology input, especially the parameter of permeability, an indicator showing quantitative recharge and storage capacity of aquifer layers. A city or a district owning a good aquifer system (sufficient groundwater recharge and storage, potable water quality) will help to reduce public expenditure on surface water transportation, distribution and treatment. It is considered as a sustainable exploration by using local resource instead of water importation. Exploration system can be classified as in Figure 1:37[19]. Generally, due to rational density of groundwater well installed in the city, inner-segmental sustainability score is high (score = 3).

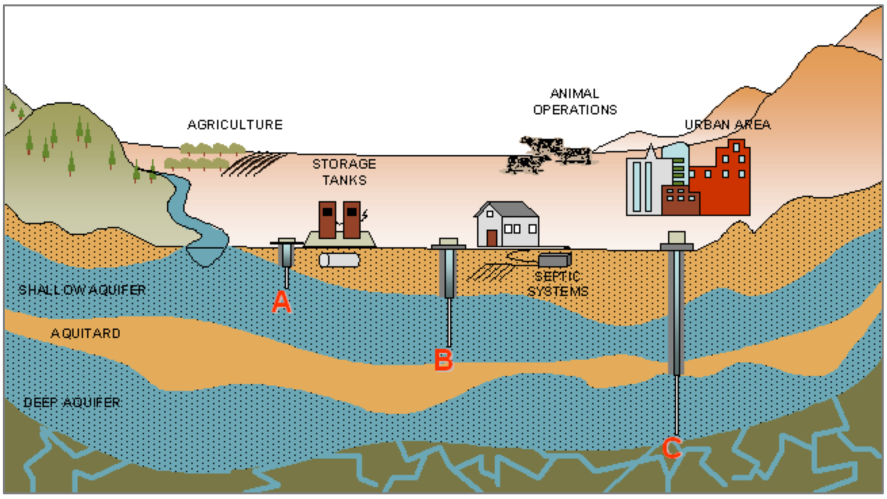


Figure 1:37 Groundwater well typologies: A: shallow well, B: intermediate well, C: deep well

Underground space construction and geothermal system installation cause both positive and negative effects on groundwater: for example, water drained from tunnels or heat pumps could be reused; but laying tunnels or drills across shallow and deep aquifers could facilitate pollutant diffusion between aquifers. Those synergies and conflicts across the segments should be taken into account for sustainability performance assessment. Inter-segmental sustainability score is low (score = 1) according to these elements.

Development scores:

Despite its high contribution to sustainable urban growth by localizing resource exploration, many cities around the world have been extracting substantial groundwater without guaranteeing its storage capacity. While extraction overpasses storage, this resource will deplete with insufficient

[19] From California water boards: http://www.waterboards.ca.gov/gama/geotracker_gama.shtml

renewability. This the reason for the segment to be given a moderate functional convergence score (score = 2). An over-withdraw practice also caused severe land subsidence problems for many cities around the world, reducing the development potential of underground space segment. Therefore, development context of this segment is rated as moderate level.

Factors	Scores
1.1 Inner-segment sustainability	3
1.2 Functional convergence	2
1.3 Inter-segment sustainability	1
Average score	2

(Factors are equally weighted; high: 3, moderate: 2, low: 1)

1.5.2 Opportunities for alternative water supply

1.5.2.1 Water resource shortage

Water access is a critical issue for economic performance in many sectors. Traditional surface water supply has a limit due to resource pollution, network leakage or climate change factors. The World Bank has published a study showing the global water supply deficiency up to the year of 2030, representing a gap of 40% (Figure 1:38). Water resource scarcity score is high (score = 3). This study also revealed cost of alternative supply measures, with groundwater related measures being among the most cost effective options for alternative water resource (Figure 1:39) (Addams et al., 2009).

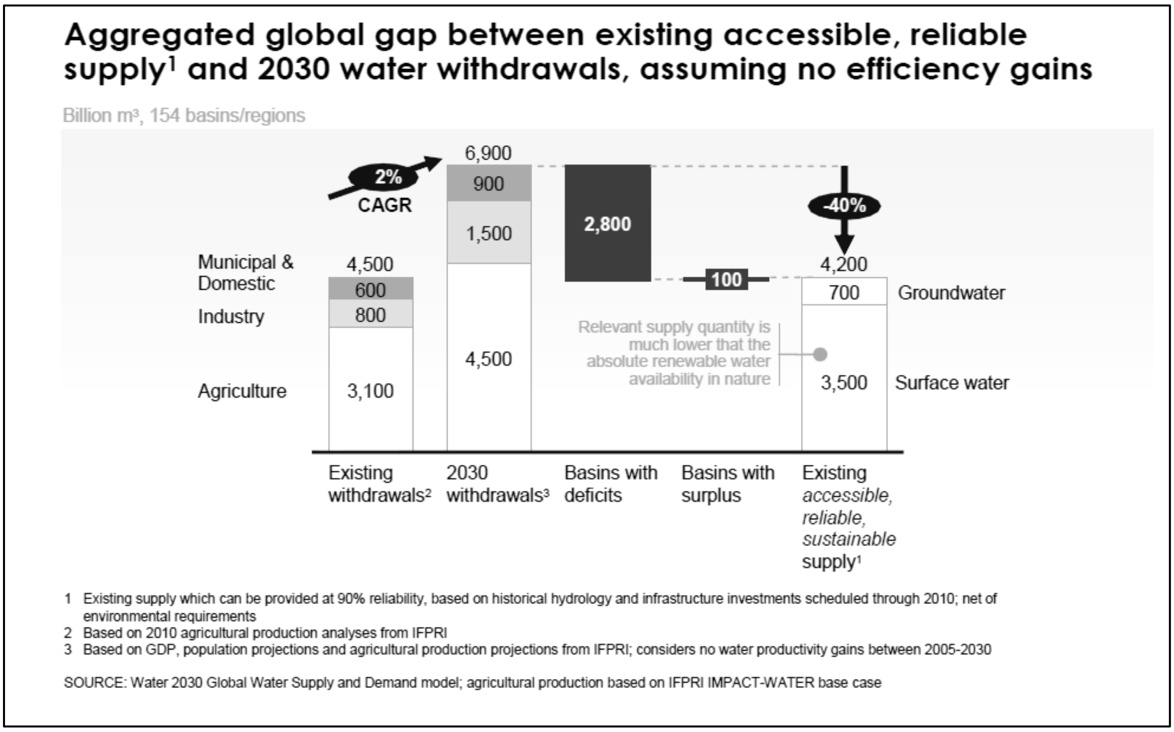


Figure 1:38 Global water supply and demand gap of water resource

1.5.2.2 Substitution effect for surface water

Distance between water extraction point and consumption point is always large, causing extensive construction of water conveyance pipelines for transportation. With increasing concerns about the quality of water utility system (leakage rate can reach 60%[20]), groundwater as a vicinity resource can be integrated into sustainable community development. Substitution effect is high (score = 3).

According to UNESCO's world groundwater use data (Zektser and Everett, 2004), groundwater is the world's most extracted raw material, contributing to 65% of drinking water supply and 35% of agricultural and industrial supply.

1.5.2.3 Opportunity score for groundwater exploration:

Due to the increasing urban population need (urban market growth score = 3) and insufficient surface water supply capacity, the market of using groundwater could be promising, despite the price of water remain relative low (increasing price score = 1), compared to other raw material. Opportunity for this segment can be considered as above moderate level.

Factors	**Scores**
2.1 Resource scarcity	3
2.2 Increasing price effect	1
2.3 Urban market growth	3
2.4 Substitution effect for the surface	3
Average score	2.5

(Factors are equally weighted; high: 3, moderate: 2, low)

[20] Data from US Environmental Protection Agency http://water.epa.gov/infrastructure/sustain/wec_wp.cfm

1.5.3 Feasibilities for groundwater exploration

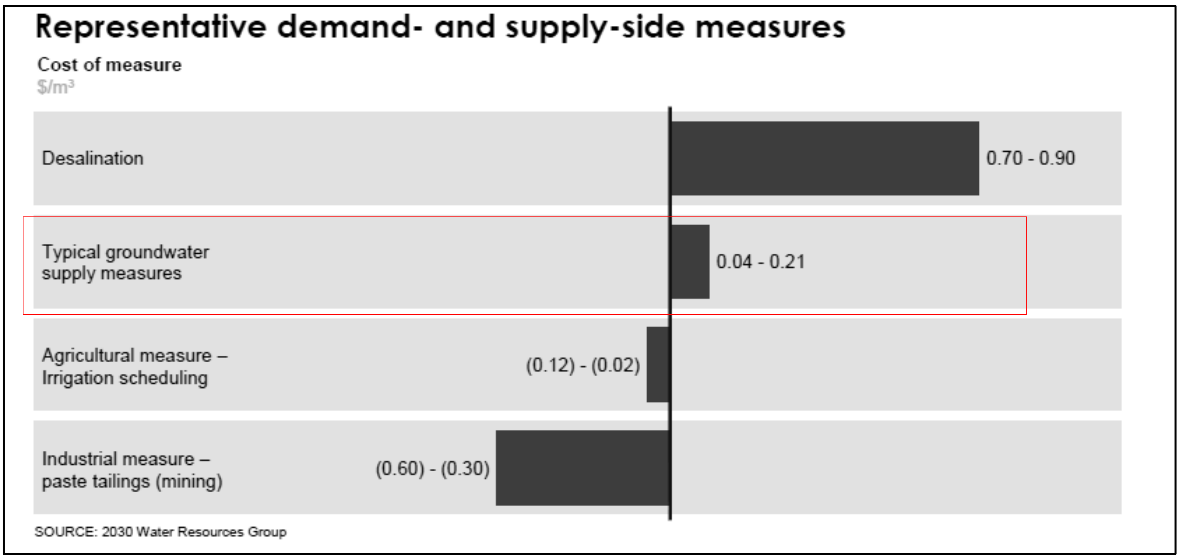
1.5.3.1 Technology awareness

Groundwater related technologies include monitoring, drilling, extraction, treatment and remediation. Extraction efficiency[21] of water well can attain 90% with current technologies. Extraction infrastructures range from shallow wells to deep wells, as showed in Figure 1:37. Advanced design and construction technologies will enhance water well efficiency performance and therefore help to reduce cost of pumping and energy consumption (Fulton et al.). Technology awareness is moderate (score = 2), the same for knowledge diversity and innovation speed according to general assumption.

1.5.3.2 Exploration costs

Due to high costs for upgrading quality of surface water intake by installing water treatment plants, groundwater is considered as a cost effective alternative for public water supply. It is estimated[22] that total cost of groundwater exploration (well construction cost, integration cost to existing water distribution system and operational pumping cost) was about 15% of the estimated cost of a treatment plant for surface water exploration. Cost efficiency is moderate (score = 2), compared to the other segments.

Compared to energy intensive measures such as desalination of sea water to complement traditional surface water supply, cost of groundwater supply measures is much lower, Figure 1:39 below estimated by (Addams et al., 2009): (in $\$/m^3$ water)



[21] Water well efficiency is defined as the ratio of theoretical drawdown in the soil of the actual drawdown in the well.
[22] http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/gwbc/C136_Smithers.html

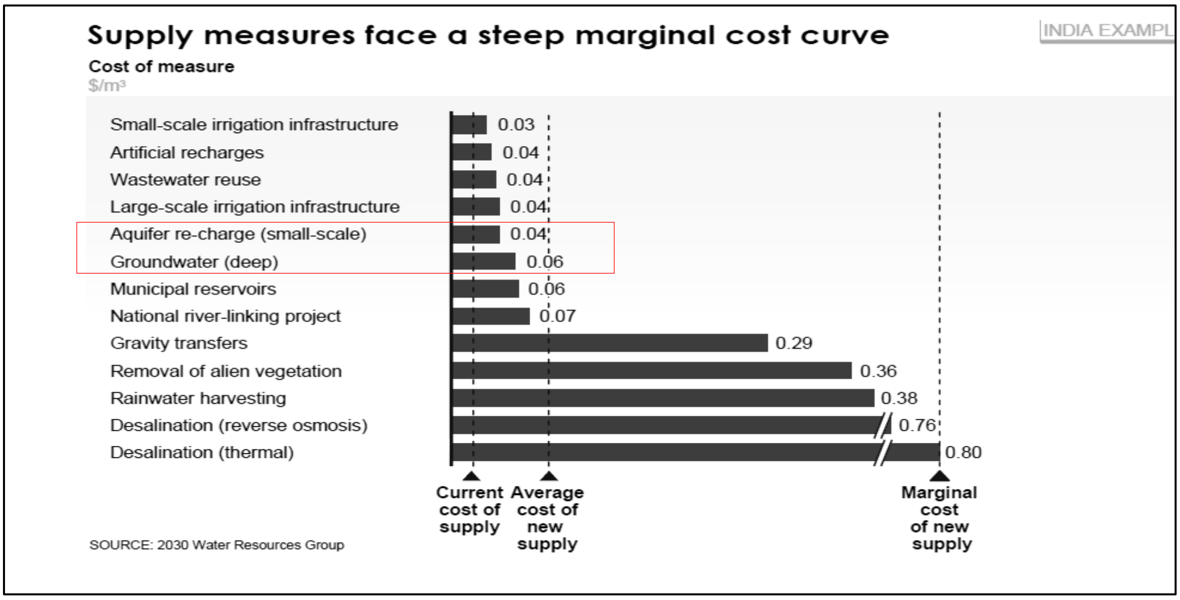


Figure 1:39 Cost comparison between water supply alternatives

1.5.3.3 Property right flexibility

Extractable volume (water flow) of an aquifer could define its service catchment boundary, thus its public property right limit. Despite of some juridical cases legitimizing landowners' holding on groundwater property right (Owen, 2013), substantial government regulation is predominant in groundwater resource development around the world. Water well installation and resource capturing subjected to supervision of local government through licensing procedure and royalties collection. Property right flexibility score is high (score = 3).

1.5.3.4 Resource inventory prospection

To integrate groundwater extraction into part of urban water supply planning, annual extractable volume should be defined based on recharge and storage capacity of urban aquifers. This resource prospection helps to locate exploitable aquifers, where underground construction sites should be restricted in a protective buffer zone. Location of public wells is strictly protected within a radius to limit any polluting activities from the surface. Groundwater resource inventory capacity is scored as high (score = 3). While most of the cities have investigated their own groundwater resource, administrative effort is insufficient to avoid conflicting activities around the protectable buffer zone.

1.5.3.5 Risks

Groundwater pumping related land subsidence and subsurface pollution is correlated with urbanization demand, investigated from studies by (Taniguchi et al., 2008, Jago-on et al., 2009) for several metropolitan areas in Asia, where most of megacities are located. Long term monitoring measures and environmental regulations are critical for groundwater dependent megacities (Endo, 2011). It is important to mention that, underground urbanization will have potential impacts on urban aquifers, bring surface pollutions below ground by excavation and drilling. This kind of anthropogenic risk can be avoided by a forward control and permission of subsurface construction sites, as well as technical solution to improve waterproofing quality of physical structures. Generally speaking, the capacity to mitigate risks is scored as moderate (score = 2).

1.5.3.6 Feasibility score for groundwater exploration

Vulnerability of groundwater resource necessities a combination of resource reservation, environment regulation and land use permission, in order to ensure its long-term supply capacity. Technological solution should be also upgraded to safeguard the long-term exploitability value of groundwater and to prevent damages.

Factors	Scores
3.1 Technology awareness	2
3.2 Knowledge diversity	2
3.3 Innovation speed	2
3.4 Cost efficiency	2
3.5 Property right flexibility	3
3.6 Public acceptance	3
3.7 Resource inventory prospection	3
3.8 Anthropogenic risk mitigation	2
3.9 Natural hazard adaptation	2
Average score	2.33

(Factors are equally weighted; high: 3, moderate: 2, low: 1)

1.5.4 Synthesis for development potential profile: segment 4 groundwater

Figure 1:40 shows a global profile of groundwater exploration segment, which is rated as **2.28 (75.93% of full score)**. The segmental profile is the lowest graded segment, implying a highest concern in the sustainable development of underground urbanization. Despite the long history of groundwater exploration, performance of this segment in the world wide context is not on a high level, due to the sectoral utilization pattern. Storage and reservation of urban aquifers for future need still need to be highlighted by local authority. The relative low price of water resource discourages to discovery a more rational water supply structure, imposing minor motivation for groundwater supply planning. Management capacity has to be upgraded to tackle with technical and political barriers, in order to improve feasibility level of groundwater development.

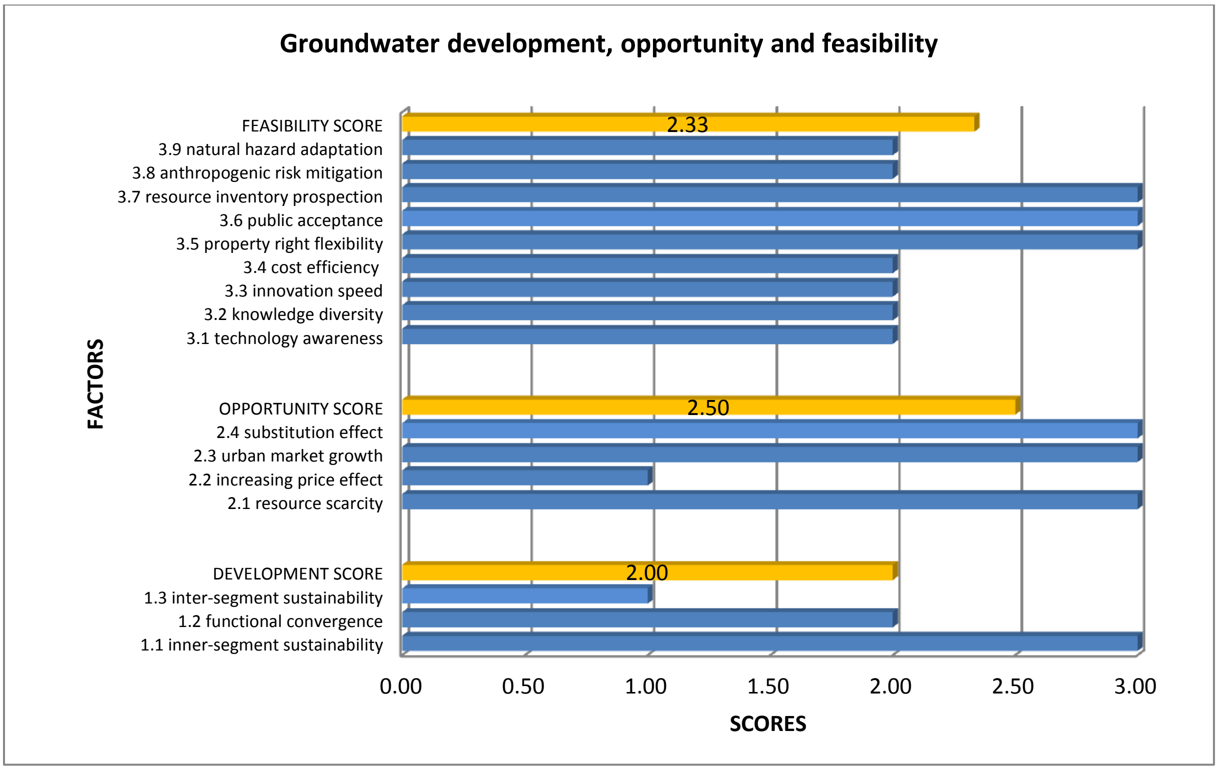


Figure 1:40 Overall rating for groundwater exploration segment

1.6 Comparison among the four segments

After a thorough examination of segmental development stage, opportunity and feasibility, major internal factors and internal factors were investigated to lever their contributions to segmental development potential. From Table 1:2 and Figure 1:41, the highest development potential profiles are for segments of underground space and geothermal energy. Underground space development owns a full score in opportunity assessment, driven by acceleration of urbanization demand. Experiences of city level strategies for underground urbanization will be illustrated in the next chapter.

The Deep City method aims to promote a holistic development of these four segments for a sustainable underground urbanization. Comparing the three scoring categories including development stage, opportunity and feasibility, the segment of groundwater is rated the lowest in development score and opportunity score due to its insufficient functional convergence and low resource prices. The segment of geomaterial exploration is rated the lowest in feasibility score, because of the low innovation speed and lack of resource inventory measures. Those two low rated segments (groundwater and geomaterial) need to be further integrated into strategic level policy making for sustainable underground urbanization. The application of Deep City method in a pilot city under collaboration of local administration will be detailed in Chapter 3.

Table 1:2 Scores for the four segments in Deep City method (international overview)

Segments	**Development score**	**Opportunity score**	**Feasibility score**	**Development potential profile**
Geo-space	2.00	3.00	2.22	2.41
Geomaterial	2.33	2.75	1.89	2.32
Geothermal energy	2.67	2.75	2.67	2.69
Groundwater	2.00	2.50	2.33	2.28
Average	2.25	2.75	2.28	2.43

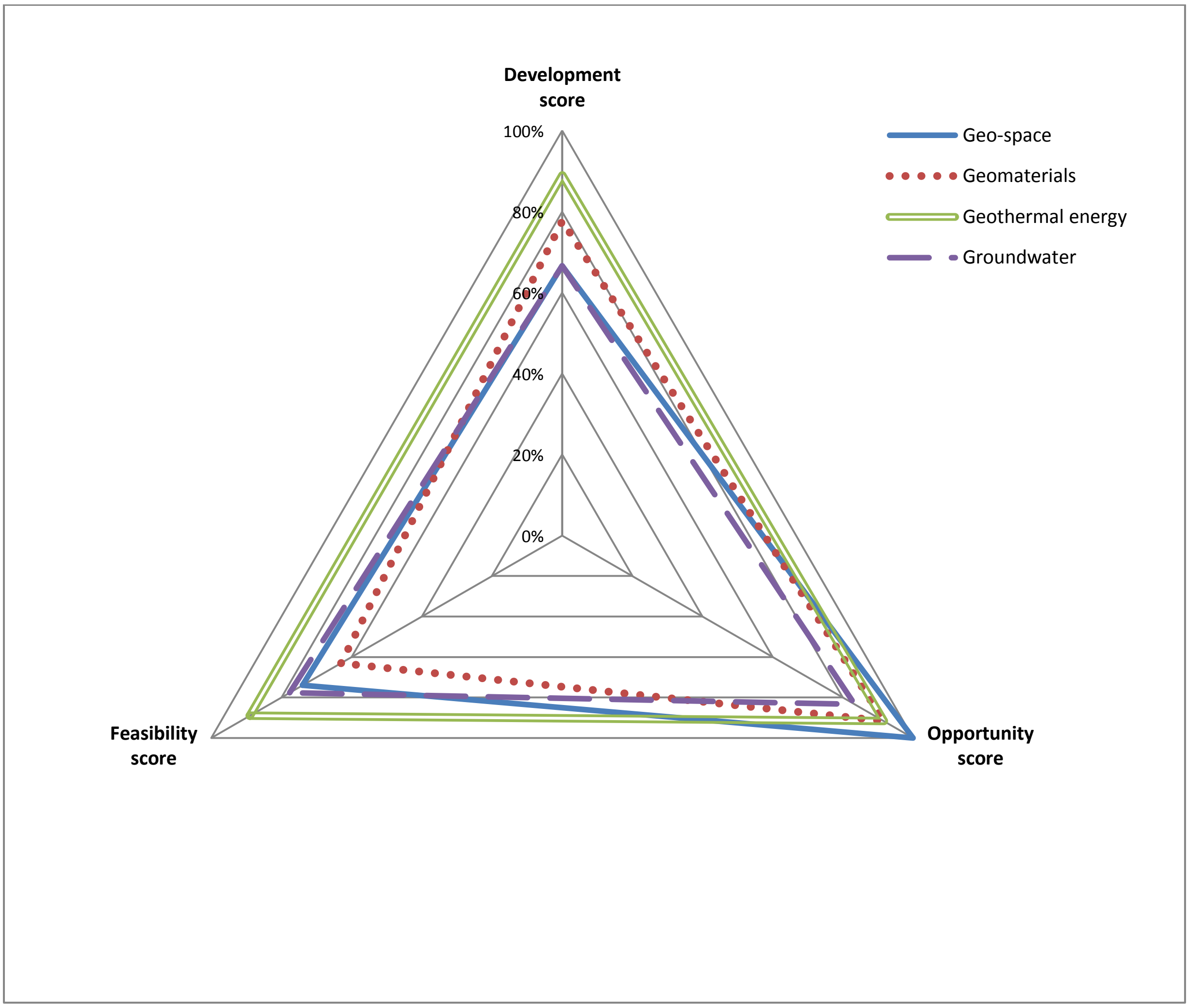


Figure 1:41 International overview: segmental development potential profile

CHAPTER 2

2 BENCHMARKINGS OF CITY LEVEL STRATEGY FOR UNDERGROUND URBANIZATION

2.1 Introduction for Chapter 2

This chapter is to showcase worldwide best practices in the management of underground space development, including administrative framework, supply side strategies and demand side development. Three models represent different city level strategies in response to the increasing use of underground infrastructures and buildings. Critical success factors are summarized for each model, in order to formulate a global city learning guide for underground urbanization.

2.1.1 Benchmark cities

Cities advancing in underground urbanization are selected, according to their high performances of using diversified functions in form of tunnel, cavern, basement-type building and complex. They are Helsinki, Singapore, Hong Kong, Minneapolis, Tokyo, Shanghai and Montreal. These cities have been well documented by international and local research centers in urban underground space use. By attending international conferences from the year of 2009 to 2012, documentary knowledge have been completed with personal interviews and discussions with city planners and engineers from these cities. Selection of these cities was also based on the traceability of their policy histories, which usually started from feasibility study to concrete administrative formulations.

2.1.2 Strategic model analysis and critical success factors

Strategic models are classified into three categories (model 1, 2, 3), according to motivation orgins of using the urban subsurface and according to development stages in function and scale:

Model 1	Model 2	Model 3
• **opportunity**: good rock resource • **development stage**: from industrialization to urbanization • **case study**: Helsinki, Singapore, Hong Kong, Minneapolis	• **opportunity**: land scarcity • **development stage**: from shallow construction to deep construction • **case study**: Tokyo, Shanghai	• **opportunity**: mixed social forces • **development stage**: from blocks to horizontal expansive network • **case study**: Montreal

The reasons to choose these three models are:

- Firstly, from the segmental analysis in Chapter 1, functions of the urban subsurface have been evolving from infrastructures to buildings due to the growing demand from urbanization process, which also intensified the scale of underground construction across vertical and horizontal dimensions. This interesting evolution can be observed in these cities and can be elaborated separately;

- Secondly, motivation origins will determine the strategic direction of policy making. Discovery of good subsurface resource (such as rock) will generate additional utilizations and economic activities, which allows more administrative efforts on resource management and exploitation control. In the other hand, scarcity of land resource will urge local governments to improve the output of limited land by multiplying functions and property rights. While motivations from public sector and private sector coincide, common function can be realized and shared among mixed actors based on agreements and obligations. These different types of motivation origins have been influencing the spatial planning of underground space in the selected case studies.

Therefore, three city level strategic models are put forward based on the reasons mentioned above.

Each case study will be presented with the structure of three questions below, related to city's capacity to manage underground urbanization by overcoming technological, financial and administrative barriers:

- Origins and administration: list historical initiation for policy making and organizational chart of related regulatory bodies;
- Supply side management: show resource management measures and 3D land use planning;
- Demand side development: introduce function diversities and development scales.

At the end of each model analysis, similarities and particularities of case studies are summarized. Two critical success factors per question are extracted from each model analysis. In the final section, comparison across the three models is performed to formulate strategic guidance for cities around the world.

2.2 Strategic model 1: from industrialized to urbanized underground space

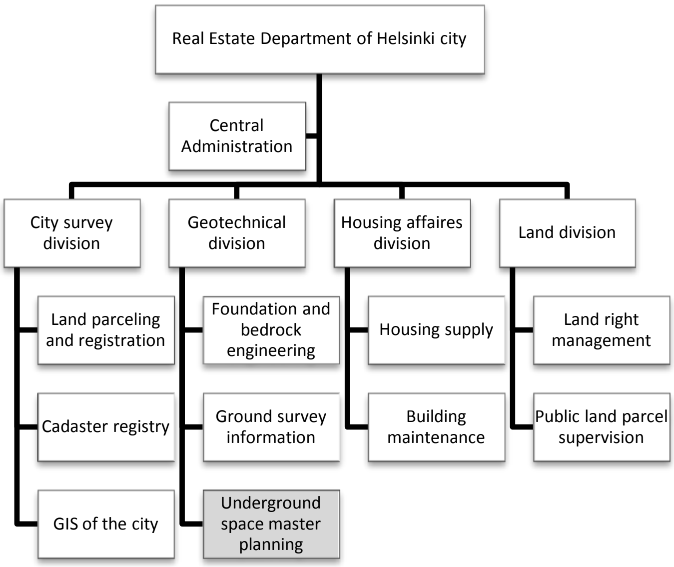
Tracing the political and institutional innovations in Helsinki, Singapore, Hong Kong, and Minneapolis, this section is to describe their histories of policy making for underground urbanization, as well as their performances of functional convergence in underground infrastructure and building.

Model 1	Model 2	Model 3
• **opportunity**: good rock resource • **development stage**: from industrialization to urbanization • **case study**: Helsinki, Singapore, Hong Kong, Minneapolis	• **opportunity**: land scarcity • **development stage**: from shallow construction to deep construction • **case study**: Tokyo, Shanghai	• **opportunity**: mixed social forces • **development stage**: from blocks to horizontal expansive network • **case study**: Montreal

2.2.1 Case study in Model 1: Helsinki

2.2.1.1 Origins and Administration

Underground space development has been initiated from Real Estate Department of Helsinki city[23], who grouped five divisions including central administration, city survey, geotechnical, housing affaires and land. Leading agency for underground urbanism is its Geotechnical Division. Integration of underground space development planning inside Real Estate Department helped to facilitate a centralized process of developing fixed underground assets. The organization chart in Figure 2:1 shows the parallel decision levels of these five divisions, which enables a timely implementation of underground space plan (rock space plan) by transferring rock survey information to land reserve system, then permitting operation of land leasing and real estate property supply. Decision makings on surface land use and underground space use are permitted to be performed at the same administrative level, avoiding eventual vertical conflicts.



(readapted by the author)

Figure 2:1 Organizational chart of Real Estate Department of Helsinki

Historical institutional innovation for promoting subsurface urbanization can be observed at strategic level and operational level:

- From 1988 to 1994 - strategic level decision: (Narvi et al., 1994)

A special committee was established in 1988 for a legislative survey on the feasibility of underground building permits and ownership issue, investigated from local officers and international experiences. The governmental study ended in 1994 proposed the applicability of existing legislation to underground projects, with amendments to the Building Act and Land Parcelling Act. Under a clear

[23] http://www.hel.fi/hki/Kv/en/Geotechnics/CaseBank information page of urban underground space development progress

political view of using underground space efficiently, the city has incorporated subsurface development into its city planning system since the 1980s, using existing planning procedures for underground space activities. In order to enhance administrative competence, a survey was conducted in 1991 to investigate knowledge level of city planners and capacity building measures were proposed for planning department (Finnish Tunnelling, 1992).

- From 1994 to 1996 - operational level measures: (Rönkä et al., 1998)

In order to provide concrete instruments to support underground development strategy, operations at different administrative levels were studied. Serials of output included demand survey and forecast for underground facilities, rock space supply potential inventory, environmental assessment, social cost-benefit estimation and decision making process.

2.2.1.2 Supply side management

The whole policy implementation has gone through nearly 30 years, from initiation of underground allocation plan to legally adopted master plan. The aim of the policy is to create alternative land supplies for public facilities and to enable joint use of utilities in form of network. This urban development policy combines two aspects of resource revolution: firstly, improving resource efficiency by functional convergence of infrastructures; secondly, expanding new supplies prospection of alternative land resource.

Two development stages are designated:

- The first priority was given to the already developed city center. The first underground development plan was designed for its densely built Central Business District. Projected below ground facilities are planned to extend existing underground infrastructures according to functional demand. The plan is trying to link relevant facilities together in order to ensure service continuity and land use compactness;

- Future expansion stage was projected for the expandable suburban area. Besides 100 new locations registered, about 40 unnamed rock premises are reserved for future use, with a standard-sized measurement cave (90'000 m^3 per cave space) to define reservation parcels. Future additional land supply in cavern space counts to 14 km^2, equalized to a gain up to 6.5% of Helsinki's urban land area.

An accurate resource prospection enables a sound resource management by ensuring sustainable resource supply. Observed from extensive literature review, **development stages of Helsinki's urban underground have been demonstrated with quantitative data (in volume, in floor space and in depth) and qualitative information (in function, in price and in ground type).** The city of Helsinki developed its data management since 1955, including geotechnical survey, data registration, information platform building[24], and data commercialization. Helsinki model of underground

[24] http://ptp.hel.fi/soili/Default.aspx

urbanization is based on a sound data management (data collection and digitalization), which offers "the best soil and rock map in the world", indicated by its director of Geotechnical division (Vähäaho et al., Real Estate Department and Geotechnical Division, 2005).

Availability of land information is useful for underground construction project appraisal. Substantial geotechnical support expenditure is required for bad quality land, inducing a higher construction cost. Existing facilities in the subsurface constraint excavation work and induces utility pipeline relocation costs, which can be prevented by centralizing pipeline data into land registration system. High performance of its data system made it possible for the municipal enterprises to assess public underground projects with exact cost information (Narvi et al., 1994), providing pertinent information in decision-making.

Translating construction potential data into land information can be realized by administrative coordination between Geotechnical Division and City Survey Division. The vertical land information can be passed to Land Division, who supervises potential building plots for subsurface construction, and arranges land right acquisition. Since the city of Helsinki owned 65% of its land including greenfield and brownfield, realization of public underground facilities becomes more flexible under public domain.

Other alternative land supply strategies such as land reclamation in seashore area and low quality land improvement. Excavated material production from underground projects has been beneficial to land reclamation, being the cheapest way to reclaim land from the sea.

2.2.1.3 Demand side development

Large-scale utility network:

Helsinki's underground energy tunnel network consists of 60 km of tunnels, including main transfer lines of district heating & cooling, household water, electricity, and communication cables. This energy tunnel grouping utilities is located deep enough to avoid spatial disturbance to other buried facilities. Combined with the energy distribution tunnel, power plants, waste water treatment plants and water storages are usually located near the distribution infrastructures under public areas.

Famous projects can be found such as: the world's largest underground heat pump plant located at 25 m depth under Katri Vala Park[25]; a centralized waste water treatment plant under Viikinmäki residence[26]; and the world's greenest data center beneath Uspenski Cathedral[27]. These underground solutions for infrastructural construction saved substantial public expenditures in two sectors (Satola and Riipinen, 2011, Vähäaho): firstly, financial savings in utility supply, because expenses of the energy tunnel were shared by several operators, and the large underground treatment plant replaced numbers of smaller treatment plants; secondly, financial gains in land supply, because surface lands were released for housing and open space amenities. In total, there are over 200 km of

[25] http://helen.fi/ymparisto_eng/katrivala.html underground heat pump center under Katri Vala park
[26] http://www.hsy.fi/en/waterservices/wastewater_treatment/Pages/viikinmaki.aspx centralized waste water treatment plant under Viikinmäki residence
[27] http://news.cnet.com/8301-11128_3-10405955-54.html underground data center under Uspenski Cathedral

technical tunnels and 24 km raw water tunnels built underground within the 215 km^2 urban center of Helsinki.

Underground buildings for business and organization:

The city of Helsinki already had more than 400 premises (locations) built underground, including car park[28], shopping malls and sports halls. In the recently passed Underground Master Plan(VÄHÄAHO, 2009), more than 200 new locations are reserved for future underground projects. This innovative urban morphological design attracts planners from worldwide cities to learn from Helsinki[29].

In order to supplement existing land survey regime, underground property right is defined as subsurface below 6m under land parcel. Underground property locations are indicated in the Underground Master Plan, a legal document to reserve and register potential underground building lots under existing land parcels, according to rock quality, existing land use and accessibility value. Underground land right can be established through voluntary transactions, agreements or redemption.

The city also offers a reduced rental charge for underground space users with about 50% of corresponding ground-level rent. According to Global Property Guide, Finland is among the top ten European countries with the highest property prices, its capital city of Helsinki is encountering land scarcity and increasing housing prices[30]. Helsinki's 21.1km metro system enables the built-up zone to densify floor space near public transport, it is evaluated that land properties in the vicinity of metro station are likely to capture values of mobility advantage provided by the metro lines (Laakso, 1992).

Existing overall underground space volume counts for 10 million m^3, averaging an annual growth of 250'000 m^3 during 22 years between 1989 and 2012. This high utilization rate is mainly due to easy resource access for rock cavern construction, with most of hard bedrock not far below the ground surface. Construction price is around 100 €/m^3, including excavation, rock reinforcement, grouting and drainage (VÄHÄAHO, 2011). Since minimum technical support is required by rock cavern construction, it provides a cost efficient solution to extend public facilities underground.

In addition, the good quality excavated rock has been reused or sold as construction material (aggregates for concrete and road construction) and land reclamation material to offset capital costs, combining land supply with material supply.

[28] European Parking Award for Helsinki: http://www.prnewswire.com/news-releases/q-park-winner-of-prestigious-european-parking-awards-130115358.html

[29] International attention for underground construction: http://www.hel.fi/hki/Helsinki/en/international/news/underground_construction

[30] Helsinki's Preposterous property prices http://yle.fi/uutiset/helsinkis_preposterous_property_prices/6468761

2.2.2 Case study in Model 1: Singapore

2.2.2.1 Origins and Administration

Despite of the well-known land scarcity problem in Singapore, underground urbanism is in its early stages compared to Helsinki. Urban Redevelopment Authority (URA) of Singapore has also centralized public services of land use planning and real estate development. All the services are integrated and accessible through an information platform[31]. Organizational chart of URA is showed in Figure 2:2.

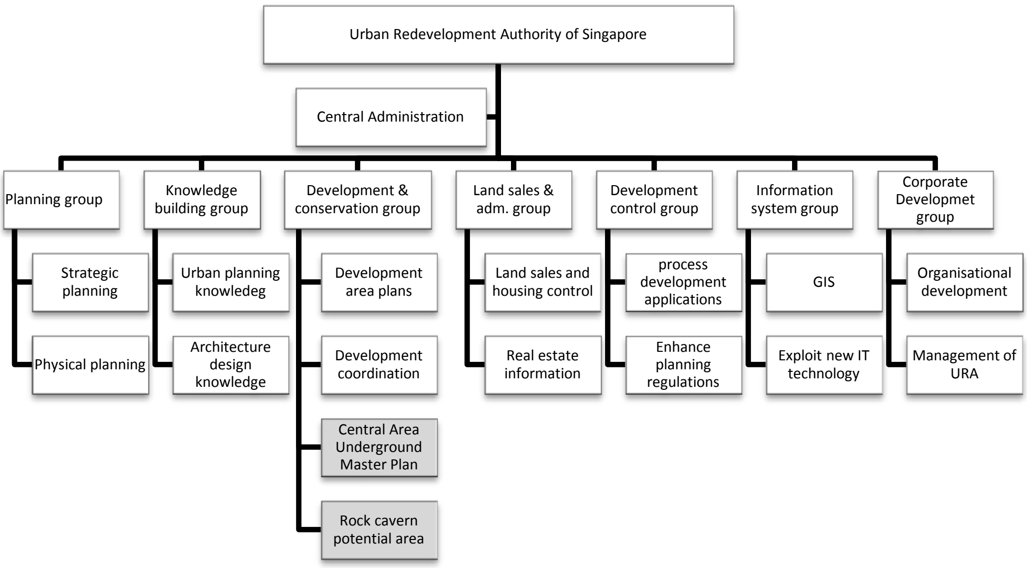


Figure 2:2 Organizational chart of Urban Redevelopment Authority in Singapore (readapted from URA annual report 2011/12)

Several policy studies and political attempts have been initiated in recent decades:

A first government commissioned study took place in 1996, looking at rock cavern space supply for public and industrial facilities. Output of the study included land quality information (Zhao, 1996), planning guidelines and GIS platform building (Zhao and Lee, 1996), development functions and cost estimation (Zhao et al., 1996). The importance of integrating underground urbanism into URA's administrative assignment was revealed in this study.

Ministry of Finance in Singapore released a report of Economic Strategies Committee[32]in 2010, the content announced the strategic importance of using underground space as new land supply and addressed the needs: to promote creation of underground network, to allocate basement space in land reserve bank, to develop master plan, to establish geology office to collect information, to

[31] http://www.ura.gov.sg/uramaps/
[32] http://app.mof.gov.sg/esc.aspx MOF report on the use of underground space resource to resolve land scarcity

establish land right and pricing, and to invest in R&D for cavern technology. A geological office was then set up in 2010 by the Building and Construction Authority (BCA) to create a database of subsurface quality information[33].

2.2.2.2 Supply side management

For central area built-up use:

A public private joint research group studied potential land supply for underground urbanization in central area[34], with feedbacks given to URA's co-location concept. Land's quality (geology, flood risk, existing structures) and economic value (added value with a proximity to metro station and park) were integrated into a 3D information platform to identify potential mixed use land plots for underground development.

Central Area Underground Master Plan (CAUMP): as a first attempt to implement this plan, 20 Underground Pedestrian Links (UPL) in the CBD and retail zone are proposed to be built from 2012 to 2016 with financial incentives. Linking existing commercial building basements and subterranean metro stations, it aims to improve business exchange and pedestrian accessibility. A revised URA circular in 2012 informed a reimbursement scheme for UPL's construction cost, with Cash Grant Incentive Scheme[35] to encourage developers for participating UPL construction. These proposed UPLs are allowed to develop retail business adjacent to pedestrian walkway by the building owners, a win-win solution for public and private sector. URA's Urban planning & design group (renamed as Development & Conservation group in the chart above) was the project initiator, under coordination with Development Control group for regulatory upgrades.

For suburban area industrial use:

Industrial land takes up more than 10% of the city's land stock. Large scale industrial facilities can be hosted underground, combined with mineral extraction activity. Economic feasibility was estimated for different underground infrastructures such as oil storage (500,000 m^3) and warehouse (210,000 m^3) in rock cavern (Zhao et al., 1996). Quality of subsurface plays a crucial role in construction cost variation (including excavation and reinforcement costs). Accurate land quality information is useful for pertinent cost appraisal. Since capital cost of rock cavern can be offset partially by resale of excavated rock aggregate, and land cost is absent for cavern option, it is a viable chose for the city to use subsurface for industrial facilities.

Combining facility's long term operational cost, the underground option was proved as more cost competitive. US Department of Energy claimed that it was roughly 10 times cheaper to store oil below the surface with the added advantage of no leaks and constant temperature[36]. In addition, for

[33] http://niegtms.wordpress.com/introduction/ GTMS team, National Institute of Education
[34] http://niegtms.wordpress.com/analysis/ potential land plots for underground development
[35] http://www.ura.gov.sg/circulars/text/dc12-12.htm central area underground master plan with UPL
[36] http://en.wikipedia.org/wiki/Strategic_Petroleum_Reserve_(United_States) US strategic petroleum reserve

oil storage caverns with a capacity exceeding 50,000 m^3, unit volume capital cost of oil cavern is lower than surface steel tanks and continues to decrease with volume expansion. With the rising prices of commodities such as oil and food, storage capacity for these strategic reserves may increase in demand from industrial sector, making the investment more viable. Studies also revealed the increased capacity of material generation and mineral storage is linked to political will, which tried to decrease reliance on importation[37,38].

A proposal for an underground science city[39] (Figure 1:7) with floor space area of 290,000 m^2, was studied since the year of 2001, regarding a large scale space creation for R&D cluster and data center under Kent Ridge park (Zhao et al., 2001). Based on 16 quantitative and qualitative criteria for a selection among 12 project scenarios, the project scenario with a central open atrium was selected for implementation, taking into account cost efficiency and psychological benefits for occupants. Further research has been carried out within a Swiss-Singapore consortium (Chang et al., 2012), looking into functional configuration and commercialization potential. It was estimated that 95% of its total space can be put on the property market, considering the growing trend of industrial sector and R&D activities in Singapore. This project will have a potential to release surface building footprint of 20 hectares. While national park can be conserved by the proposal, possible expansion of the multi-cavern science city is also envisaged for future demand.

2.2.2.3 Demand side development

Large scale public infrastructures:

Singapore's Common service tunnel (CST) stored water pipes, power cables, utility service, and refuse conveyance, saving 1.6 hectares of land in the central area. To ensure water supply for the next 100 years, a Deep Tunnel Sewage System (DTSS)[40] was conceived with a length of 80km, to replace 139 pumping stations and reduce water reclamation plants, saving 990 hectares of land for the city suburban. Numbers of industrial storage included underground storm water ponds, ammunition facility, oil reserve caverns, etc.

Underground buildings and complex:

Land plot ratio (density) is usually high in the vicinity of metro lines (currently 4 lines with a length of 149 km)[41], where most buildings near major transfer hubs are observed to be extended downwards with basements. The metro network offered opportunity to expand its station to nearby buildings, such as the underground complex of Raffles Place station, which connected 19 buildings. A network style of underground spaces is beneficial for business exchange and pedestrian convenience.

[37] http://www.atimes.com/atimes/Southeast_Asia/EG31Ae01.html Sand war in Singapore
[38] http://www.eco-business.com/news/khaw-boon-wan-on-recycling-excavated-materials/ waste to material
[39] Press release http://www.youtube.com/watch?v=Rn4ET1_dCiw
[40] http://www.pub.gov.sg/dtss/PublishingImages/DTSS_Animation.swf Deep Tunnel Sewage System
[41] http://www.ura.gov.sg/uramaps/ integrated map with land plot density and underground infrastructure information

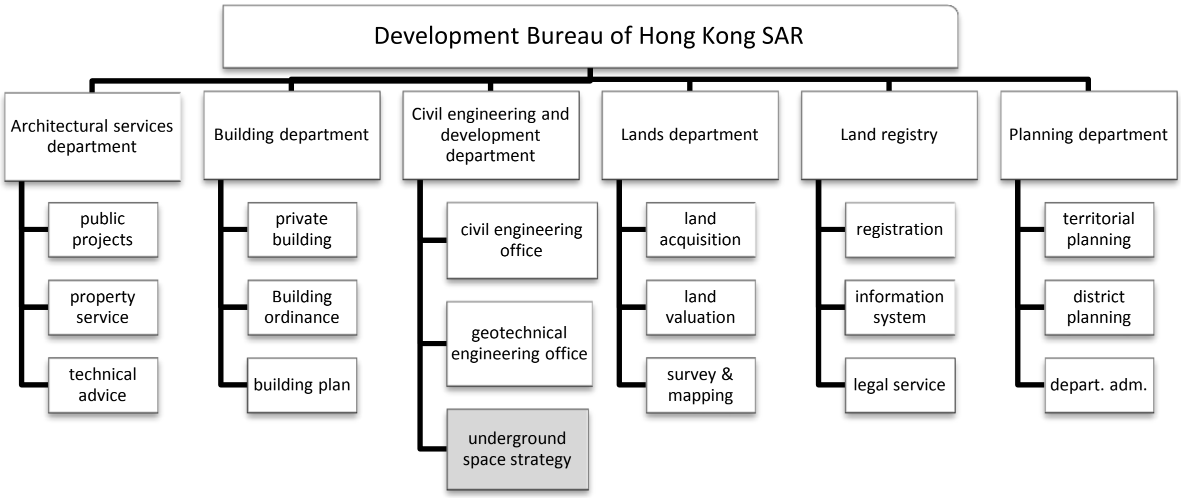
2.2.3 Case study in Model 1: Hong Kong

2.2.3.1 Origins and Administration

Also as a city well-known for its land scarcity (Bertaud, 1997) and rapid economic growth, Hong Kong Special Administrative Region has been addressing underground space development, from a "potential prospection stage" begun in the 1980s to the current "enhanced development stage", that was symbolized from the official policy agenda in 2009[42].

Administration related to urban development is centralized under Development Bureau, in charge of buildings, infrastructures and land use issues. Its organizational structure is showed in Figure 2:3. Based on the clear political will addressed from the top administration level (Lam, 2011), operational procedures have started to take effect, including infrastructure survey, underground space supply inventory, planning guideline establishment and a public consultation program granted with a budget of HK$300 million (Chan, 2011).

In 1991, Hong Kong Planning Standards and Guidelines (HKPSG) integrated rock cavern development[43] (Howells and Chan, 1993), which was revised in 2008. The procedure to integrate rock cavern solution for governmental facilities is indicated by the Planning department[44]. Engineering and fire safety guides were also provided by the city for cavern construction in 1992 and 1994.



(adapted from HK government department website http://www.gov.hk/en/about/govdirectory/govchart/index.htm, departments of Electrical&Mechanical service, Drainage service and Water supplies are also part of the Development Bureau)

Figure 2:3 Organizational chart of Development Bureau of Hong Kong SAR

[42] http://www.policyaddress.gov.hk/09-10/eng/agenda.html see policy agenda 2009 chapter 1
[43] http://www.pland.gov.hk/pland_en/tech_doc/hkpsg/full/ch12/ch12_text.htm#2 Planning guidelines rock cavern ch.12
[44] http://www.pland.gov.hk/pland_en/tech_doc/hkpsg/full/ch12/ch12_fig_1a.htm project planning for gov. projects

Initiated by Civil Engineering and Development Department (CEDD), a first strategic study took place in 2010 (CEDD. and ARUP., 2011), taking inventory of more than 400 governmental facilities on the surface and targeting potential land plot supplies to receive transferable facilities below ground. A forthcoming long-term strategic study will extend the study to additional private facilities, ownership separation issue, cavern master plan and land valuation.

According to the director of Planning Department (Ling, 2011),the Strategic Planning 2030 of Hong Kong didn't specially address the potential of underground space. But the Planning department has pointed out flexibility of planning control instruments to favor strategic underground projects. Beside rock cavern development, basement type underground building was also called for consideration by the Planning Department to renew guideline amendments. Long-term strategy will focus on comprehensive underground space development for both public and private uses.

2.2.3.2 Supply side management

Quality of Hong Kong's underground rock space belongs to the highest level, similar to Helsinki and Singapore. According to a land supply inventory inspected by Civil Engineering and Development Department (CEDD. and ARUP., 2011), 64% of the land area owns high quality for subterranean space exploitation in form of rock cavern.

For central area:

Potential land supply for underground space development was classified for central Kowloon district, a densely built urban center with numbers of existing tunnels. Criteria including geotechnical properties and existing land use were taken into account. Open space and green belt zone were preferred for future underground space construction, in order to avoid land resumption or acquisition. Within this central area of 43.8 km^2, 30% was considered highly suitable for underground construction in form of cavern (Roberts and Kirk, 2000).

For suburban area:

Combining geological criteria and social-environmental criteria, 12 strategic land plots are identified for multiple use cavern construction. These land plots will be provided for containment of facilities into rock space, meanwhile revitalizing the released land surface for housing supply or educational land supply[45], in order to maximize value of public land (average land plot area estimated to be 20 hectares). Application of the Helsinki model is being tested in Hong Kong, by placing large scale public infrastructures beneath residential area. Rock cavern strategy for land supply was put on public discussion[46] to investigate social readiness and community acceptance for this solution before definite implementation.

According to the Mines division in CEDD, local aggregate supply from main quarries in Hong Kong will be suspended by 2014, imposing a higher reliance on mineral importation. Reusing aggregate from underground space excavation works is highly recommended by the government.

---

[45] http://www4.hku.hk/cecampus/eng/enews/article.php?id=5 co-location of water reservoir and Centennial Campus

[46] http://www.landsupply.hk/preview/index.php?lang=eng Hong Kong land supply public engagement

2.2.3.3 Demand side development

Large scale public infrastructure:

Cavern facilities in Hong Kong have gone through evolution in size and in function (Malone, 1996). Significant land acquisition savings by using cavern options was disclosed in subsurface construction project appraisals. The scale of extensive tunnel networks is expected to reach more than 600 km in 2017, hosting facilities of water, sewage, cables, road, and rail. The city has a metro network with a length more than 200 km, operated by a privatized but government owned rail and metro company, who is also a main property developer and landlord in Hong Kong. Its business model named “Rail + Property” is a successful case for Transit-oriented Development (TOD). Large scale residential projects were developed along metro lines capturing some 10-30% of housing price premium (Cervero and Murakami, 2009), which ensured a sustainable financial mechanism for the mass transit infrastructure.

Underground building:

Most of the building basements in Hong Kong city are large scale and deep to 25m with more than four stories below ground (Wong, 2002). Despite engineering challenges in dense urban area, constraints of land supply have been forcing the developers to build high rise buildings and deep basements.

2.2.4 Case study in Model 1: Minneapolis

2.2.4.1 Origins and Administration

In 1985, the Minnesota Mined Underground Space Development Act was written into law (H.F.922, S.F.925), a first essay to legalize underground space development in urban area (Nelson and Rockenstein, 1985b). The achievement was realized after a study of legal and economic feasibility of mined underground space development, pointing out a legislative gap in enabling mined space utilization for industrial and commercial purposes. With this act, cities in the state were authorized to apply existing planning laws to reserve potential subsurface land supply. This legislative movement demonstrated the importance of knowledge level of legislators on underground space’s benefits to urban economy, because their capacities of passing the law by preparing the right information for public hearings were based on active participation to academic activities and industrial cooperation.

After approval of the development act from state level, operational steps were able to be carried out by existing divisions in municipal department in Minneapolis, complied existing administrative procedures. Centralized urban development services are structured in Figure 2:4[47]:

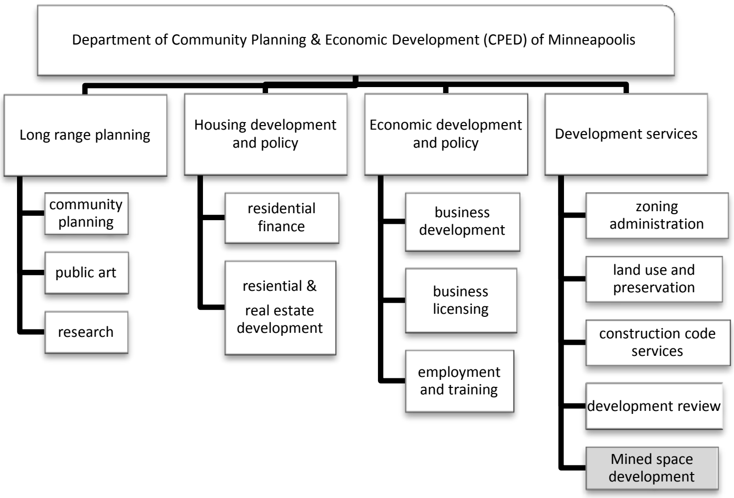


Figure 2:4 Organizational chart of Community Planning & Economic Development in Minneapolis

According to the study on underground space development guidelines conducted by planners and engineers (Sterling and Nelson, 1982) for the city of Minneapolis, data harmonization by complying engineering feasibility criteria with information from Minnesota Geological Survey played a critical role on understanding distribution of potential subsurface construction sites throughout the city and its relation to existing surface uses.

Development typologies in the city included independent mined space in rock and basement space linked to surface use (such as earth-sheltered space and cut-and-cover space in soil). These two typologies involved different sets of assessment criteria for development potential appraisal, as well as different zoning categories in existing regulations.

A Minneapolis law firm was employed by the city for institutional instrument study (Rockenstein, 1985c), unfolding legal barriers and gaps for the promotion of mined underground space use for commercial and industrial estates. Relevant issues and concrete recommendations were presented in the Legislative Policy Discussion Document, including: real estate leasing, mineral rights, subsurface parcel registration, fiscal incentive, new agency assignment, public land condemnation, vertical zoning control, drilling control, building code, and environmental quality control. The law firm participated to draft the Mined Underground Space Act 1985 after submitting this policy document.

[47] Adapted from CPED organizational chart http://www.ci.minneapolis.mn.us/cped/cped_about

2.2.4.2 Supply side management

Potential of Minneapolis's underground space potential was quantified in 1982, revealing cost competitiveness of using subsurface created from mining industry. Potential areas for mined space typology and basement space typology were mapped for the city of Minneapolis and can be found in the report of Underground Space Center (Sterling and Nelson, 1982). It is estimated that about 24,000,000 m^2 (6000 acres) of mined underground space could be created in Minneapolis without dewatering permission (Subspace Associates, 1990a). Groundwater appropriation permit is required if dewatering is needed for excavation (Subspace Associates, 1990b).

In the industrial redevelopment area, a pilot land plot was designated for implementing Mined Underground Space Master Plan (Subspace Associates, 1990a, Sterling, 2012). Based on land quality investigation, the land plot can provide 90,000 m^2 mined space for a high technology corridor. As manufacturing sector is an important economic contributor for the city, there exists a high potential to add new land supplies for industrial and R&D functions from mined underground space. Since the city has been fully developed on the surface and restrained industrial land use in the 1980s, an erosion of the city's economic base and loss of development pushed the officials to search other alternatives such as mined space to maintain the tax basis of manufacturing sector.

2.2.4.3 Demand side development

Public infrastructure network:

Downtown Minneapolis has the world largest combined skyway & underground walking system of 8 miles length, connecting major buildings in the city center. However, this expanding above ground bridge system have been criticized for the impacts on urban landscape and business segregation (Maitland, 1992). Montreal's indoor city, a subterranean pedestrian network connecting subway stations and buildings in central city, has been expanding along with subway lines and urban redevelopment (El-Geneidy et al., 2011, Daniel J, 1991). The transport planning of Minneapolis favoring above ground light rail, didn't offer the same degree of freedom for urban revitalization.

Underground building for business, organization and housing:

Earth-sheltered building is one of the Green Building types, with advantages of cost competitiveness and energy efficiency (Wells, 2009, Harrall, 2012). Earth-sheltered homes were highly promoted by the state's Legislative Commission on Minnesota Resources (LCMR). In 1983, a national earth-sheltered and underground building survey was conducted by (Carmody and Sterling, 1983), with detail disclosure on energy consumption, construction cost, material use, design concerns and performance evaluation for 20 representative commercial and institutional buildings, including functions of libraries, schools, offices, commercial centers, manufacturing and storage facilities, visitor centers, etc. Some famous underground buildings in U.S and their construction costs are listed in Table 2:1 below, between the 1970s and 1980s.

A market potential survey was conducted by a public private collaborative group in 1985 (Nelson and Sterling, 1985a), which listed potential business sectors to use mined space in the city with existing standard industrial codes. Within the 600 suitable firms selected, 150 were from high-tech sector, others were from manufacturing and service sector. From questionnaire results, many of the firms with an interest on mined space use were among the largest multinational firms in the U.S, especially the interest from manufacturing firms. A demand for more than one million sq. ft. (92,900 m^2) of mined space was indicated by the responders for a period of seven years. Estimated average development costs for mined space ranged from \$19.50 to \$25.50 per square feet in the 1985s, compared to a range from \$20.10 to \$83.70 per square feet for surface industrial buildings.

Table 2:1 List of earth-sheltered buildings in the U.S. (name, function, costs, floor space)

BUILDING NAME	CITY IN U.S.A	TECHNOLOGY	TOTAL COST	FLOOR SPACE (sq.ft)	UNIT COST ($/m2)	YEAR
LIBRARY						
NATHAN MARSH PUSEY LIBRARY	CAMBRIDGE, MASSACHUSETTS	R.C	$5 600 000	87 000	692,87	1976
LAW LIBRARY ADDITION	ANN ARBOR, MICHIGAN	R.C	$9 500 000	77 000	1328,06	1981
WALKER COMMUNITY LIBRARY	MINNEAPOLIS, MINNESOTA	R.C	$1 437 000	18 500	836,12	1980
EDUCTIONAL INSTITUTIONS						
CIVIL AND MINERAL ENGINEERING BUILDING	MINNEAPOLIS, MINNESOTA	R.C, rock mining	$12 900 000	150 000	925,73	1982
BLUE RIDGE ELEMENTARY SCHOOL	WALLA WALLA, WASHINGTON	R.C	$5 057 720	70 135	776,25	1982
TERRASET ELEMENTARY SCHOOLS	FAIRFAX COUNTY, VIRGINIA	R.C	$2 863 000	69 000	446,64	1977
TERRA CENTRE ELEMENTARY SCHOOL	FAIRFAX COUNTY, VIRGINIA	R.C	$3 190 389	74 000	464,08	1980
OFFICE AND COMMERCIAL BUILDINGS						
WILLIAMSON HALL	MINNEAPOLIS, MINNESOTA	R.C	$3 468 458	86 500	431,62	1977
CALIFORNIA STATE OFFICE BUILDING	SACRAMENTO, CALIFORNIA	R.C	$18 500 000	264 000	754,31	1982
NATIONAL ART EDUCATION ASSOCIATION	RESTON, VIRGINIA	R.C	$258 818	4 000	696,50	1976
MUTUAL OF OMAHA HEADQUARTERS ADDITION	OMAHA, NEBRASKA	STEEL AND R.C	$12 330 830	184 000	721,37	1979
TERRATECH CENTER	ST PAUL, MINNESOTA	STEEL AND R.C	$1 100 000	14 750	802,76	1979
MANUFACTURING AND STORAGE						
GREAT MIDWEST UNDERGROUND	KANSAS CITY, MISSOURI	raw rock mining	$926 950 000	18 539 000	50,00	1979
HOLADAY CIRCUITS	MINNETONKA, MINNESOTA	MASONRY WALL	$2 163 000	35 000	665,23	1981
VISITOR AND INTERPRETIVE CENTERS						
	BLUE EARTH, MINNESOTA	R.C	$160 000	1 100	1565,71	1979
HIGHWAY REST AREA BUILDINGS	ANCHOR LAKE, MINNESOTA	R.C	$232 000	1 800	1387,39	1979
	ENFIELD, MINNESOTA	R.C	$166 000	1 700	1051,10	1980
KELLEY INTERPRETIVE CENTER	ELK RIVER, MINNESOTA	R.C	$429 296	6 000	770,18	1981
SPECIAL USE FACILITIES						
BENEDICTINE MISSION HOUSE	SCHUYLER, NEBRASKA	R.C	$3 000 000	40 000	807,32	1979
YATES FIELDHOUSE	GEORGETOWN, WASHINGTON	MIXED	$7 197 200	152 275	508,77	1979
MOSCONE CONVENTION CENTER	SAN FRANCISCO? CALIFORNIA	R.C	$100 710 000	650 000	1667,80	1981
MINNESOTA CORRECTIONAL FACILITY	OAK PARK HEIGHTS, MINNESOTA	R.C	$30 631 275	330 000	999,16	1982
AVERAGE			**$52 174 772**	**947 989**	**834,04**	

(R.C : reinforced concrete)

2.2.5 Implications from Model 1

Strategic model 1 demonstrated solutions for the administrative integration of underground urbanization into existing agencies, for resource management and for project delivery facilitation. The four cities discussed above have developed extensive cavern space and tunnel network for public infrastructures, which were considered as main strategic targets for functional convergence. Strong political support led by historical or recent concerns on industrialization and urbanization helped administrators of those cities to raise the potential of urban underground space as alternative land resource supply. Institutional innovations were observed from strategic level decision to operational instrument implementation. A benchmark synthesis including similarities in each strategic question and particularities in local instruments is shown in Table 2:2.

Table 2:2 Synthesis for Strategic model 1

BENCHMARK FACTORS	HELSINKI	SINGAPORE	HONG KONG	MINNEAPOLIS
Administration: Integration and coordination				
Leading agency	Real Estate Department, Geotechnical Division	Urban Redevelopment Authority, Urban Planning & Design Group	Development Bureau, Civil Engineering and Development Department	Department of Community Planning & Economic Development, Development Services
Legal basis	Underground Space Master Plan 2009	Central Area Underground Space Master Plan 2012	Planning Guidelines for Rock Cavern 2008 revised	Mined Underground Space Development Act 1985
Strategic decision	Integration into existing administrative and legal system	Economic policy agenda, new agency on geology, R&D input on technology	Development policy agenda	Integration into existing administrative and legal system
Operational instrument	Demand survey, supply inventory, environmental regulation, valuation	Potential project identification	Facility relocation survey, supply inventory, public consultation	Development typology identification, supply inventory, valuation
Supply side management: Reservation and diversification				
Policy orientation	Alternative land supply, functional convergence, facility network formation	Alternative land supply, commercial network formation	Alternative land supply, functional convergence	Alternative land supply for industrial expansion
Development stage	From redevelopment stage to expansion stage	From industrialization stage to urbanization stage	From industrialization stage to urbanization stage	From industrialization stage to urbanization stage
Supply inventory	Indication in volume, floor space, depth, function, price and ground type	Indication in location for central area	Indication in location for central area and entire city	Indication in volume, depth, function and ground type
Data management performance	High	Moderate	High	High
Material handling	Direct rock trading, land reclamation	Direct rock trading, land reclamation	Aggregate reuse, land reclamation	Direct rock trading
Demand side development: Convergence and facilitation				
UG infrastructure	Deep energy tunnel, plants, storages, data center, subway	Common service tunnel, deep sewage tunnel, storage, subway	Utility tunnel, cavern facility, storage, subway	Mined space for industrial use, pedestrian tunnel
UG building	Car park, shopping mall, sport hall, church	Basements and pedestrian pass near subway stations	Deep and large commercial basements	Basements, earth-sheltered buildings
Public private alignment	Voluntary transaction, agreement, redemption	Cash grant for private participation	Development right of released surface	Fiscal incentive for qualified private projects
Land price level	High	High	High	Moderate
Space registration	10,000,000 m^3	None	None	None
Motivation	Good quality resource, construction cost efficiency, valuable material	Land shortage, good quality resource, construction cost efficiency	Land shortage, good quality resource, cost efficiency in land saving	Industrial land shortage, good quality resource, construction cost efficiency

(UG: Underground)

2.3 Strategic model 2: underground urbanization in megacities

Tracing the trend of institutionalization for underground space development in the two megacities of Tokyo and Shanghai, this section is to describe their advancements in underground space legislations, as well as their increasing development scales of underground buildings and complexes.

Model 1	**Model 2**	Model 3
• **opportunity**: good rock resource	• **opportunity**: land scarcity	• **opportunity**: mixed social forces
• **development stage**: from industrialization to urbanization	• **development stage**: from shallow construction to deep construction	• **development stage**: from blocks to horizontal expansive network
• **case study**: Helsinki, Singapore, Hong Kong, Minneapolis	• **case study**: Tokyo, Shanghai	• **case study**: Montreal

2.3.1 Case study in Model 2: Tokyo

2.3.1.1 Origins and Administration

From 1988, Japanese Cabinet decided to promote effective land use, resulting to an acceleration stage of using the urban subsurface. However, subsurface under limited public domain made the projected facilities difficult to be implemented, due to the congestion at already occupied shallow layers. The city of Tokyo was not only busy on the surface, but also crowed in the subsurface.

In 1995, an advisory committee in the Prime Minister's office for Deep Underground Space Use was formed for studying legal and administrative issues and for building a new legal system for deep underground space. The policy proposal attempted to transform the urban land into a three dimensional system, reserving deep underground for public roads, water facilities, railways, cables and sewages.

Public right of using underground was set in the "**Law on Special Measures related to Public Use of Deep Underground**"[48] with specific executive procedures, co-executed by **Deep Underground Use Council** and Ministry of Land, Infrastructure and Transport (MLIT). This law aimed to benefit reduction on construction cost by shortening length of underground infrastructural networks and to benefit avoidance on compensation issue caused by land strata resumption. It was officially in effect since 2001[49] with "**Basic Policy on Public Use of Deep Underground**" approved by the Cabinet

[48] http://www.mlit.go.jp/english/2006/d_c_and_r_develop_bureau/01_deep/02_smooth.html Ministry of Land, Infrastructure, Transport and Tourism
[49] http://www.mlit.go.jp/toshi/daisindo/index.html Deep Underground Law

Office [50]. Technical guidelines were published for public consultation, demonstrated with comprehensive solutions to guarantee infrastructure projects' reliability (type of technologies, safety distance, ground capacity, monitoring), to ensure geotechnical feasibility (groundwater protection, subsidence prevention, excavated soil treatment) and to increase social acceptability (accessibility for aged population, interior comfort). For underground buildings, strict regulations were implemented into the Basic Policy by addressing high safety standards[51].

Legal domain of Deep Public Underground was defined depending on existing building basement and foundation layers, starting from the depth of 40 m to more than 80m. Two types of ownership delimitation are shown in Figure 2:5:

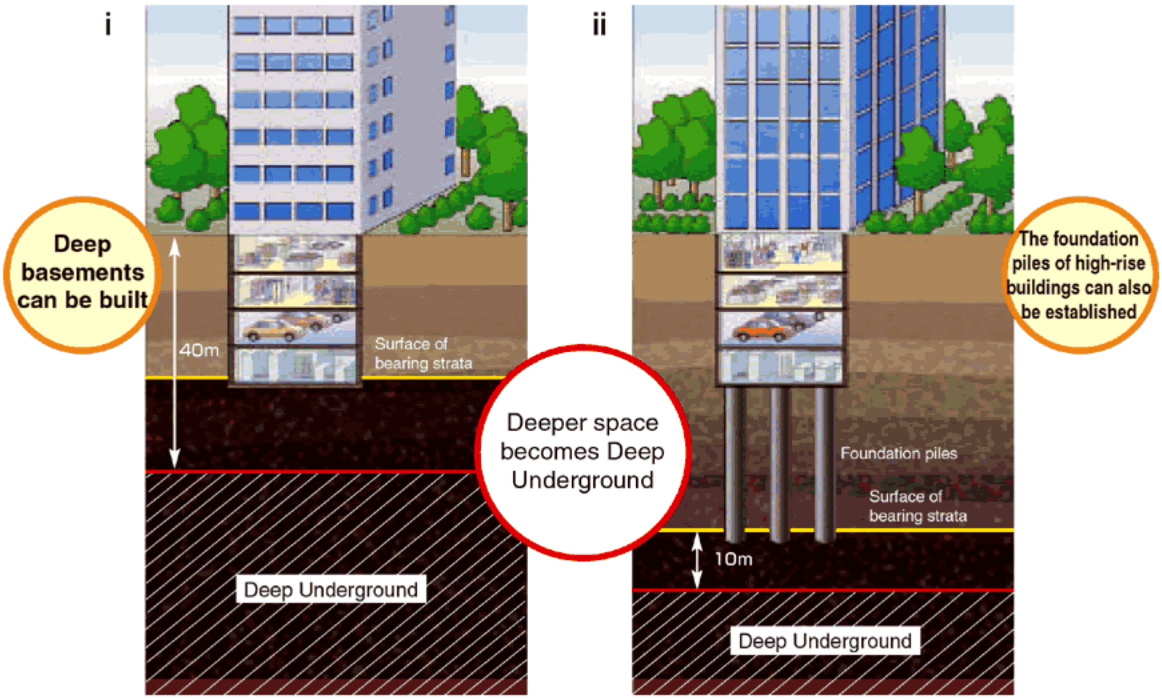


Figure 2:5 Japan Deep Underground Space law

National administration of city development is showed on the organizational chart in Figure 2:6[52], including state level divisions, offices and regional level councils dedicated for Deep Underground Space. The "**Law**" and "**Basic Policy**" measures were transferred from national level to local level, limiting to three main application regions defined by the Law (Regions of Kanto, Kinki and Chubu).

[50] http://www.mlit.go.jp/toshi/daisei/crd_daisei_tk_000008.html Basic Policy for the Public Deep Underground
[51] http://www.mlit.go.jp/english/2006/d_c_and_r_develop_bureau/01_deep/07_safety.html basic policies for safety
[52] adapted and translated from: http://www.mlit.go.jp/toshi/crd_fr1_000002.html

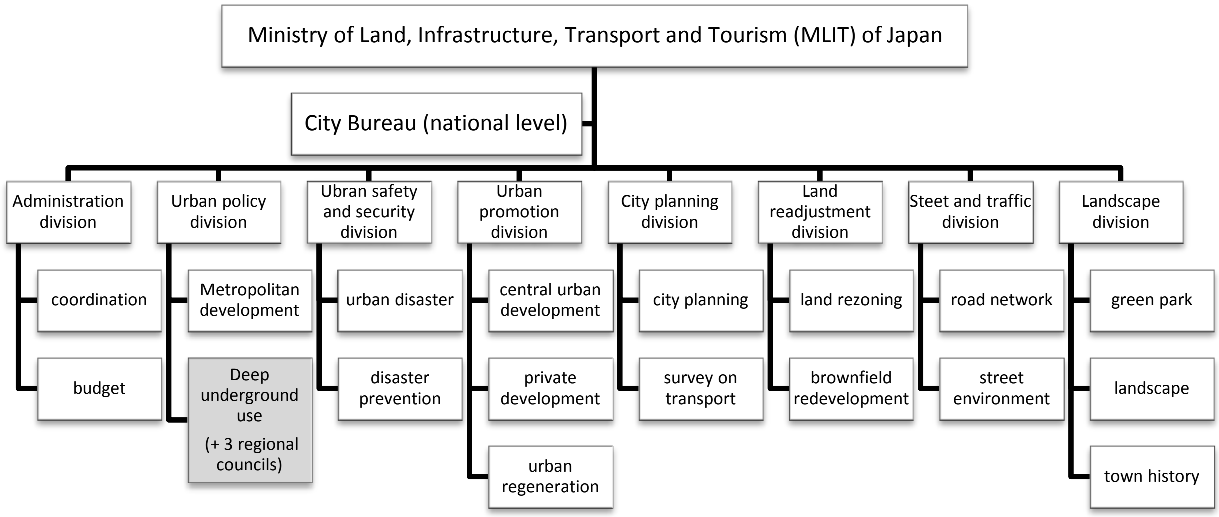


Figure 2:6 Organisational chart of City Bureau in Japan and Deep Underground Use Council

Activities of the **National Deep Underground Use planning Council Office** can be consulted from a central platform[53]. Its responsibilities are as follow:

- Define legal limit of Deep Underground for public use,
- Demonstrate benefits of using deep underground,
- Inform administrative procedures,
- Establish the "Law on Special Measures related to Public Use of Deep Underground",
- Integrate guidelines into the "Basic Policy",
- Information system management.

Each of the three local regions has their own Deep Underground Use Council. **Tokyo Metropolitan Deep Underground Use Council** was integrated into Regional Development Bureau of Kanto, with specific council management guidelines and administrative procedures for public underground projects[54].

Authorization procedures[55] for public deep underground projects are showed in Figure 2:7. According to different scopes of underground space project, authorization bodies are different. Large scale underground infrastructures are within the administrative competences of the **Regional Deep Underground Use Council**, while other smaller scale projects such as shallow underground buildings and complexes remain in the authority of prefectural governors. The delimitation of vertical property right defined by the "Law" served as a basis for authority decentralization, from national level to prefectural level.

[53] http://www.mlit.go.jp/toshi/daisindo/index.html
[54] http://www.ktr.mlit.go.jp/city_park/shihon/index00000024.html Kanto (Tokyo) metropolitan Deep Underground Use Council information webpage
[55] http://www.mlit.go.jp/english/2006/d_c_and_r_develop_bureau/01_deep/02_smooth.html project authorization procedure

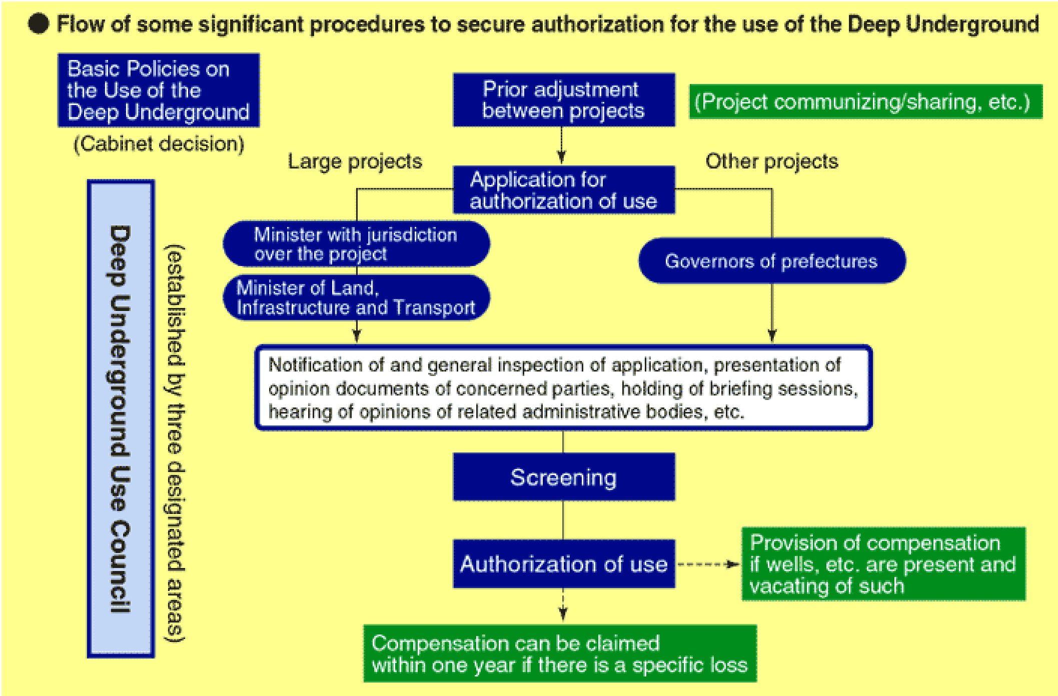


Figure 2:7 Authorization procedures for Deep underground space use

Data management was recognized as a critical tool to provide efficient administrative services. Tokyo Metropolitan Government has implemented a centralized Geotechnical Data Information System[56] since 1986 (Ishii et al., 1992). Subjected to frequent and severe earthquakes, as well as land subsidence risks due to groundwater extraction (Hayashi et al., 2009), geological information became one of the important parts of the data for disaster prevention in Tokyo. Access to information of existing underground infrastructures can be viewed through official request, with corresponding department in charge of information delivery.

2.3.1.2 Supply side management

For underground construction, the general depth limit with current technological feasibility is 100 m. According to Deep Underground Use Council, deep underground in most of Tokyo's central area is located below the depth of 50m (Figure 2:8[57]), where large public infrastructural networks can be located. This is due to the sea-shore alluvial geology of the city and existing deep building piles below urban area.

[56] http://doboku.metro.tokyo.jp/start/03-jyouhou/geo-web/00-kushichoson.htm Tokyo web geo-data
[57] http://www.mlit.go.jp/english/2006/d_c_and_r_develop_bureau/01_deep/01_definition.html deep underground map

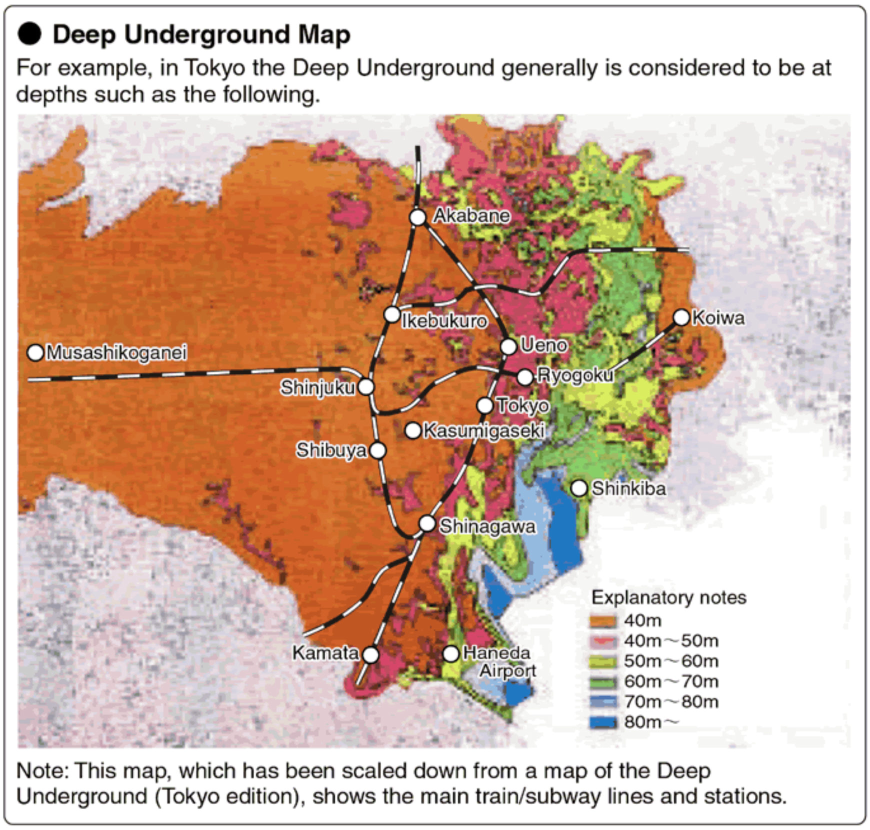


Figure 2:8 Supply inventory map for Deep Underground Space in Tokyo city

Underground construction in Tokyo city generated mud or sludge from tunnel excavation or foundation piling. In 2007, they counted for 8.2% of industrial waste source and 10.8% of industrial waste disposal (data from Tokyo Bureau of Environment). Technologies for soil treatment for recycling excavated material into new material supply are advanced in Japan (Miki et al., 2005), supporting to reuse over 30% of excavated soil for construction industry. In total, nearly 98% of waste concrete produced from engineering and construction works is recycled in Tokyo, which is limited to be used as recycled aggregate for road type construction. Since the demand for road will decline in the future, the government is urging to develop technologies for recycling waste concrete into aggregate for building projects rather than road type civil engineering projects, in order to expand the recycled material market.

Groundwater extraction has been strictly prohibited due to overexploitation induced aquifer level declines and land subsidence before the 1970s. Since the 1980s, aquifer level has been recovered gradually and rising higher than the sea level in some area in Tokyo, causing damages to the expanding underground infrastructures beneath the city (Jago-on et al., 2009). Therefore, prudent exploitation of these water resources should be envisaged, to complement surface water supply and reduce obstacles for future underground infrastructures.

2.3.1.3 PPP model for underground complex development

Underground utilization for commercial function is particular to Japan, which developed the largest number of underground shopping centers in the world. Beside basement-type buildings, underground commercial network are also well developed in Japan. It was a gradual transformation from single use underground passages under busy roads, into prosperous underground shopping streets.

Since 1930s, enhanced utilization of rail transit in its large cities enabled another spatial transformation: expansion of subway station space took advantage of overwhelming passenger flow to generate business opportunities. Since office buildings were situated near transport hub to facilitate accessibility, a linkage between basement-type buildings and underground stations was viewed by private developers as a business opportunity for attracting passenger flow at one hand, and viewed by urban planners as a convenience to integrate station entrances into these buildings at the other hand. This "win-win" benefits motivated private developers to participate into underground commercial network construction and expansion. This kind of "**Multi-use Urban Complex**" can be regarded as a successful example for private public partnership (PPP). It is investigated that most of the underground shopping centers in Japan were private invested or jointly invested from mixed funds (Golany and Ojima, 1996a).

Therefore, different from high rise building which can only expand its own vertical scale; underground space can expand in a horizontal way for a much larger scale. Pedestrians and commuters can circulate from working places to stations, through the car-free and commercial lively underground network, under any kind of weather condition. It is important to notice that, since these underground commercial networks are under public domain like park or road, they are required to have characteristics of above ground public facilities, to ensure sufficient passage using the public network. Due to the horizontal large scale and functional complexity of these underground networks, facility management becomes critical (Golany and Ojima, 1996a), including maintenance for pedestrian passages, restaurants, shops and parking.

- PPP project case: OMY redevelopment

In the strategic redevelopment project of **Otemachi-Marunouchi-Yurakucho (OMY)** area around Tokyo station, which covers 120 hectares, a large scale underground plaza is on construction. It is linking Tokyo station and extending horizontal underground commercial streets under roads nearby. A private sector led organization (named the **Project Council**) founded by 70 landowners and other members, was integrated into the District Redevelopment Committee (a PPP organization). The organization developed common vision, method and rules with landowners, Railway Company, district government and metropolitan government. Maintenance of the public spaces over ground and underground is expected to be outsourced to private sector by the organization (Nakamura et al., 2012, Otemachi-Marunouchi-Yurakucho District Redevelopment Project Council, 2008).

- Mixed legal arrangement to facilitate public private collaboration:

Urban underground facilities can be developed by public or private entities on public or private land. A classification of these facilities and legal arrangement were proposed by Japan Urban Underground Space Center (Kunitomi et al., 2012), according to investor entities and land ownership.

For public invested projects (infrastructures), the “Law on Special Measures related to Public Use of Deep Underground” and its “Basic Policies” can provide legal and administrative guidelines, subjected to the control of Deep Underground Use Council.

For private invested projects (buildings and complexes), existing acts on urban redevelopment, land readjustment, road, river and park can be applied by local municipality to private underground space. While investor entity and landlord differ, **flexible solutions (agreement, concession), legal relaxations (leasehold, permission) and planning innovation (3D land zoning)** are called for to facilitate an effective development.

Examples of mixed arrangements are showed in Table 2:3. Instruments of occupancy permission, leasehold and agreement will be also demonstrated in detail for the development process of Indoor City in the Montreal model (section 2.4.1.3).

Table 2:3 Mixed legal arrangements for underground facilities

Mixed arrangement	Underground Facility	Title of underground space	Legal system
Public investment under private land	Road, passage, rail, parking, sewage, reservoir, flood pond	• Land use right, • condominium leasehold, • Co-ownership	• Urban re-development act, • Land readjustment act, • Deep Underground Space law, • 3D land zoning
Private investment under public land	Shopping mall, parking, passage, utility infrastructures	• Occupancy permission, • Land leasehold, • Individual agreement, • PFI projects, • concession	• Road act • River act • Park act

2.3.1.4 Demand side development

As the biggest megacity around the world, opportunities for underground space use were raised from Tokyo city’s growing demand from urbanization. In addition, technological and financial feasibilities can be considered as triggers for underground space development, including: breakthrough of advanced technology (especially for soft soil construction technology) and thriving financial investment from both public and private sectors (Hanamura, 1990).

Close collaboration with private construction industry initiated by Ministry of International Trade and Industry (MITI) accelerated the progress of technology innovation and advanced project conceptualization, such as "Alice City Network"[58] and "Urban Geo Grid"[59] (Miyake and Denda, 1993). A public private entity Geo-space engineering Center (GEC)[60] was established by **MITI and private enterprises** in 1989, for enhancing R&D input for advanced utilization of underground space in the area of planning, construction technology and information system.

Since the 1990s, subsurface use has been tightly boosted by the demand from **urbanization**, an over 70% of population moving to urban area from 2000 to 2025. Population density of Tokyo is among the highest around the world cities. Population level of Tokyo metropolitan area has been standing on top of the megacity list from the past to future decades until 2025 (Population Division, 2012). Claims for more office spaces and public facilities have not only pushed underground use for infrastructures, but also for working spaces. Therefore, research and development related to underground building architectural quality, users' perception and working environment improvement were also incorporated into national land policy and institutional program (Nishi et al., 1990, Okuyama, 2007, Nishida et al., 2007, Okuyama, 2012). Underground space has been regarded as **development and regeneration tool** for Tokyo city.

It was reported that underground space in Japan's urban area was also facing problem of **congestion**, similar to the existing congestion on the surface. With the broadening uses on public facilities, public infrastructures (water, power, sewage, utility), transport, flood control ponds, commercial buildings, and oil storage, land shortage issue had been expanding downwards according to the City Bureau [61], driving a strategy for deep underground expansion. Due to the special soil quality in its urban area near coastal area, building foundations are usually very deep to reach the bedrock, forming a dense piling layer below ground. According to a survey done by Tokyo City Bureau of the Ministry of Construction in 2000, highest **underground space development rates** were registered for facilities of subway (77.4%), power utilities (85.6%) and car parks (89.2%) (Takasaki et al., 2000).

Diversity of underground space function is illustrated from section 2.1.1.1.1to 2.1.1.1.3:

2.1.1.1.1 Risk mitigating underground infrastructures:

Tokyo Metropolitan area has one of the World's largest underground discharge systems with a 6.3 km channel connecting 5 giant sink tanks (Figure 1:5) for flood water transportation from rivers[62]. The tunnel system is located 50 meters below the city, ended in a Parthenon-type subterranean reservoir (180 long, 80 wide and 18 m high) with a capacity to pump 200 tons of water per second. It helped the city to reduce 80% of flood impact on urban area.

[58] http://www.cee.nagasaki-u.ac.jp/~jiban/text/concept/con9/con9.html Alice city network by Taisei Corporation
[59] http://www.shimz.co.jp/english/theme/dream/underground.html Urban Geo-Grid by Shimizu Corporation
[60] http://www.enaa.or.jp/EN/activities/gec.html Geo-space engineering Center (GEC)
[61] http://www.mlit.go.jp/english/2006/d_c_and_r_develop_bureau/01_deep/10_progress.html Ministry of Land, Infrastructure, Transport and Tourism
[62] http://www.ktr.mlit.go.jp/edogawa/gaikaku/index.html The metropolitan outer underground discharge channel

2.1.1.1.2 Dense public infrastructures and effect on land prices:

According to City Bureau, average length of pipelines beneath 1 km of national highway is 33.3 km, including cables, electricity lines, water tubes and sewage lines. Depth of Tokyo's metro lines has been extended from 10 m to 50 m from the year 1936 to 2006[63]. Total length of the subway system is 328.8 km, including 13 lines.

The relationship between average commercial land prices and proximity to subway is shown in Figure 2:9, measured by distance to the nearest station (data based on 226 standard commercial land parcels in Central Tokyo, provided by Land property department of MLIT in 2012). Within a catchment area of subway stations of 500 meters, an average land price premium can reach 34.49% by a proximity improvement of 100 meters. Inside the radius of 100 meters around the station, maximum premium can attain 75.86% of commercial land value.

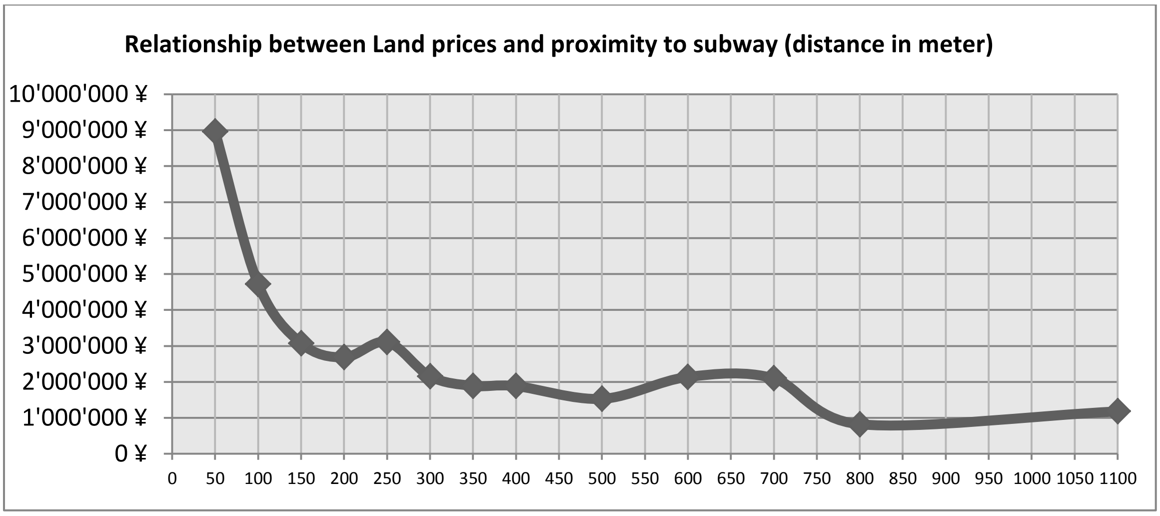


Figure 2:9 Relationship between land prices and transit accessibility

2.1.1.1.3 Advanced development of underground buildings and complexes:

1) *Status and statistics for basement type buildings:*

The first underground shopping street connecting subway stations emerged in Tokyo in 1927. After the first underground shopping mall built in 1932 in Japan, nearly 1,100,000 m^2 floor areas of underground shopping malls have been built in Japanese cities until 2010 (Nakamura et al., 2012). From Tokyo Statistic Yearbook 2010, buildings with more than four stories counted to 152,835 in total, while buildings with basements of more than one level counted to 67,476, a share of 44%. Tokyo Fire Department published annual data of high rise buildings (>4 stories) and deep basements

[63] http://www.mlit.go.jp/toshi/daisei/crd_daisei_tk_000007.html Deep Underground Law information webpage

(>1 level)[64]. Evolution of high rise buildings and deep basements from 1977 to 2010 are showed in Figure 2:10, indicating that this megacity has been constructing substantially upwards and downwards.

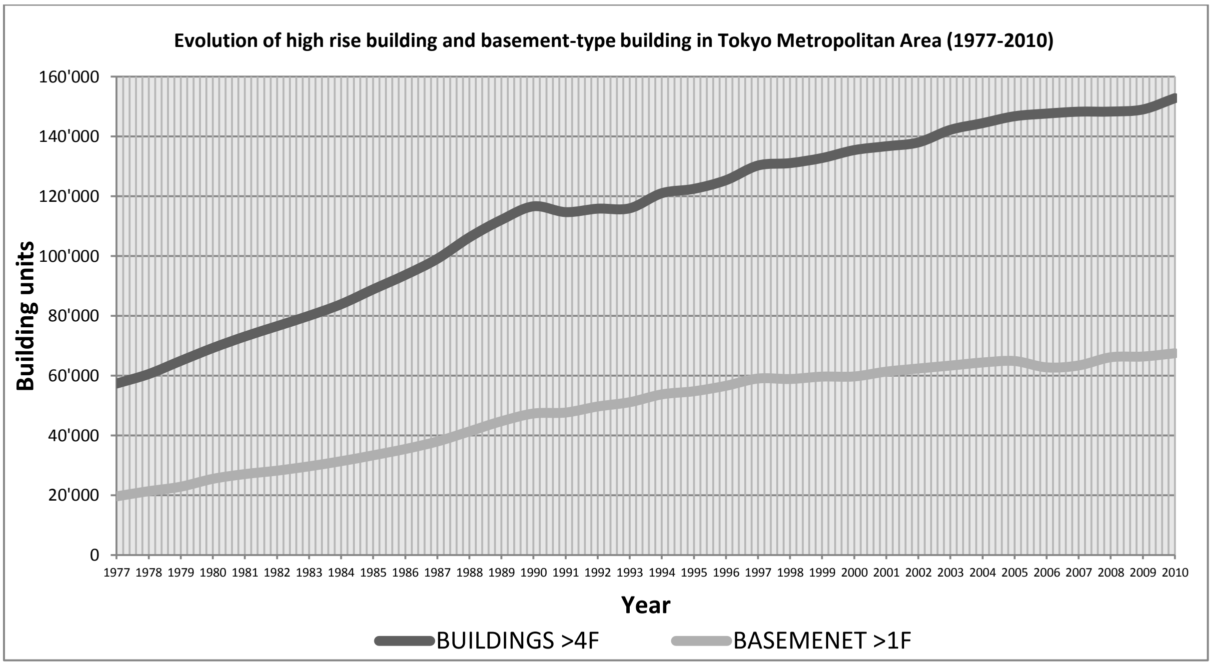


Figure 2:10 Evolution of high rise building and basement-type building in Tokyo Metropolitan Area (1977-2010)

In addition, quantity of two-level basements tripled from 1977 to 2010, with more and more deep basements extended below four levels, as showed in Figure 2:11:

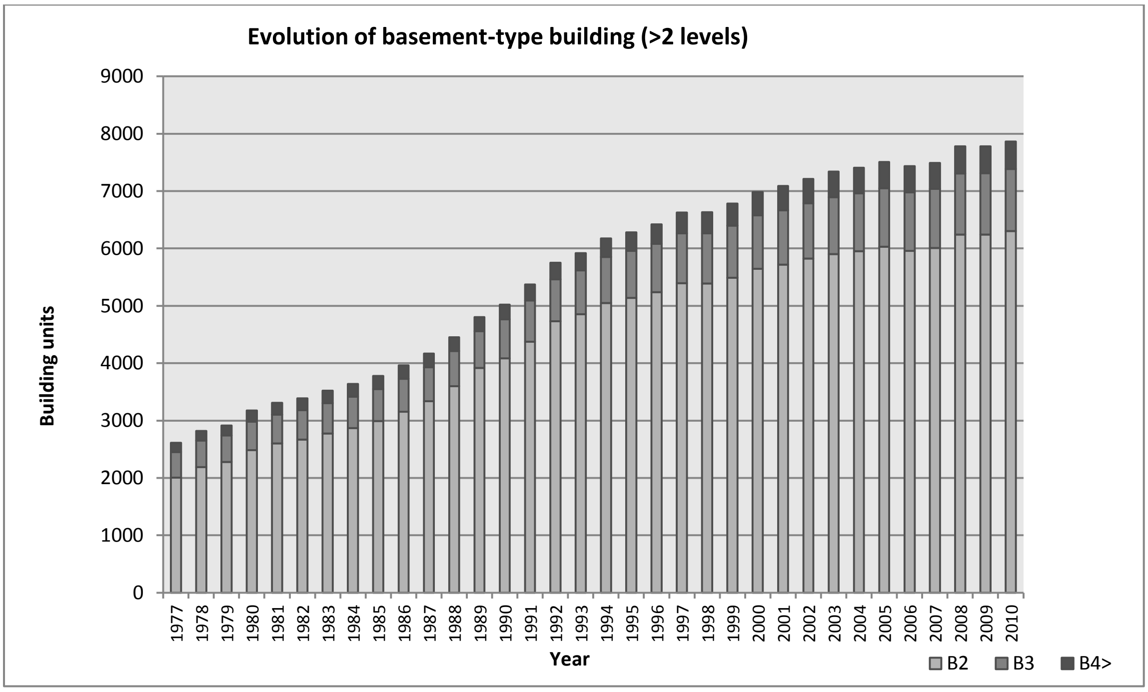


Figure 2:11 Evolution of basement-type building (B>2 levels)

[64] http://www.toukei.metro.tokyo.jp/tnenkan/tn-eindex.htm#2009 Tokyo Statistical Yearbooks

2) Driving forces for basement type building development:

According to Tokyo Urban Development Department, in 1991, 85% of the urban redevelopment projects designed basement type buildings, with the deepest design having four levels (Nishida and Uchiyama, 1993): Among the 207 urban redevelopment projects in this survey, 52% of the basement type buildings were developed in districts with more than 200,000 population, and mostly for commercial and mixed use functions; Also, there existed a correlation between land prices and basement levels, showing that **basements were commonly built for land plots priced more than 400'000 yen/m^2**. Creation of underground network linking subway stations and adjacent buildings requires at least a two-level basement type, implying that the closer a building near a subway station, the higher potential can be forecasted for basement-type redevelopment.

Combing the three factors of population, land price and station proximity, basement-type buildings can be projected for redevelopment districts or land plots.

According to a series of underground architectural survey (Okuyama, 2007, Okuyama, 2012) from 1990 to 2008, various functions of underground buildings were observed in Japan, such as museum, community facility, residence, art studio, education, religion, hotel, conference, shopping, restaurant and transport station. His investigations showed that half of the underground building projects were driven by high land prices, and one third of these buildings were built below ground level due to building height limit standard, while others were restricted by landscape and historical scenery protection.

Below demonstrates the **correlation between land prices and basement levels**, based on 226 standard commercial land parcels in Central Tokyo, located in five central districts: Chiyoda (46,413 inhabitants), Chuo (118,730 inhabitants), Minato (218,482 inhabitants), Shinjuku (319,857 inhabitants) and Shibuya (203'522 inhabitants) (data published by MLIT in 2012). The Table 2:4 shows land parcels having a value more than 10 million yen/m^2, their average basement level is 3.2 and average distance to station is 148 m. Average basement level is 3.8 for land priced higher than 20 million yen/m^2, and those lands are all situated face to the subway station (distance to station < 50 m). From the diagram of Figure 2:12[65], **it is observed that most of the deepest basement sites were constructed for the highest priced land parcels**.

[65] Data from http://tochi.mlit.go.jp/english/land-prices/land-market-value-publication (publication on land market valuation)

Table 2:4 Central Tokyo commercial land prices and basement levels

Land Parcel N°	LAND PRICE (yen/m2)	LAND PRICE ($/m2)	BASEMENT LEVEL	PROXIMITY TO STATION (m)	Floor area ratio(%)
Chiyoda5-42	27'000'000	346'154	4	50	1300
Chuo5-22	27'000'000	346'154	2	50	800
Chuo5-41	23'900'000	306'410	6	50	800
Chiyoda5-21	20'800'000	266'667	3	50	1300
AVERAGE	**Price category (> 20 million yen/ m2)**		**3.8**	**50**	**1050**
Land Parcel N°	LAND PRICE (yen/m2)	LAND PRICE ($/m2)	BASEMENT LEVEL	PROXIMITY TO STATION (m)	Floor area ratio(%)
Chuo5-49	19'700'000	252'564	1	50	800
Chiyoda5-19	19'500'000	250'000	3	580	1300
Chiyoda5-49	19'500'000	250'000	4	50	1300
Shinjuku 5-35	19'300'000	247'436	3	50	900
Shinjuku 5-24	18'200'000	233'333	1	50	800
Chuo5-5	15'900'000	203'846	5	220	800
Chuo5-43	15'400'000	197'436	2	180	800
Chuo5-18	14'800'000	189'744	3	50	800
Shibuya 5-22	14'500'000	185'897	2	150	800
Chuo5-48	14'000'000	179'487	4	50	800
Chiyoda5-25	13'700'000	175'641	4	100	900
Chiyoda5-23	13'500'000	173'077	4	700	900
Chuo5-33	12'000'000	153'846	6	100	800
Shinjuku 5-17	11'400'000	146'154	2	100	800
Shibuya 5-14	11'200'000	143'590	2	230	800
Shinjuku 5-5	11'100'000	142'308	5	50	1000
Chuo5-2	10'800'000	138'462	2	400	700
Shinjuku 5-15	10'000'000	128'205	2	50	800
AVERAGE	**Price catergory (10 to 20 million yen/ m2)**		**3.2**	**148**	**878**

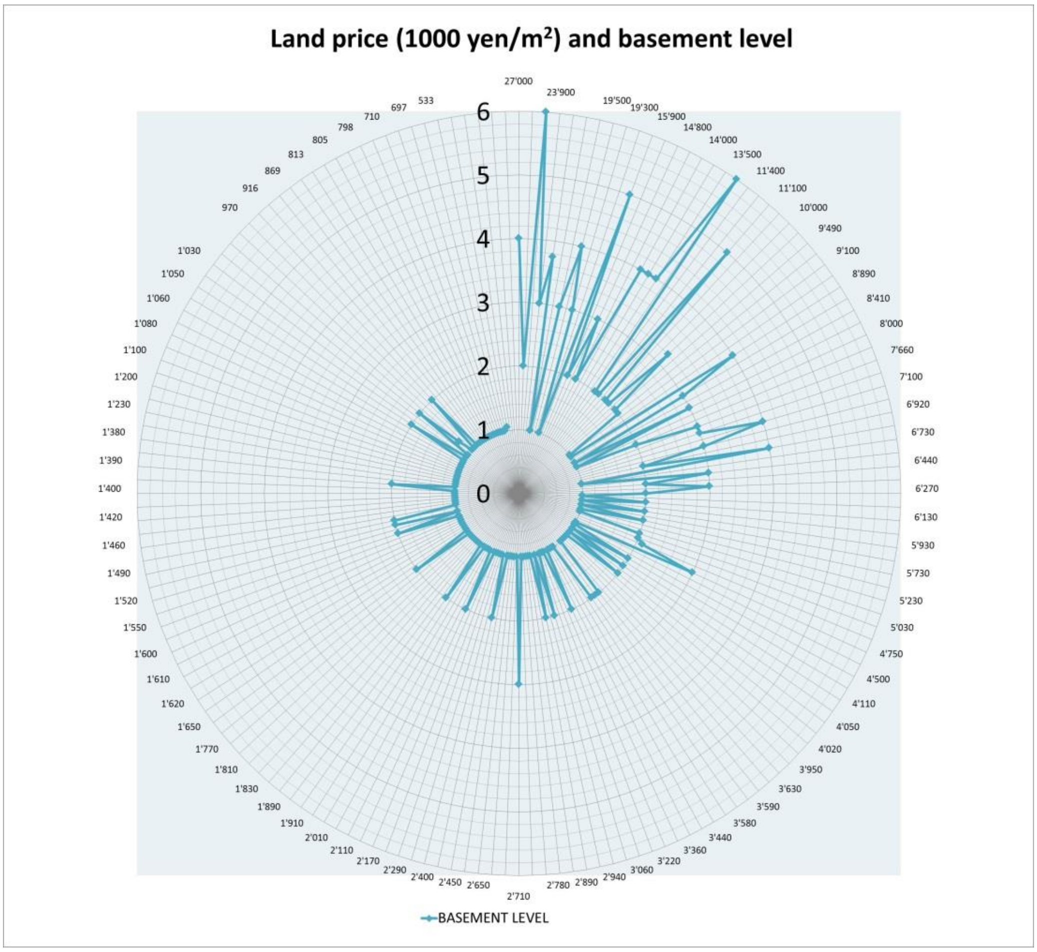


Figure 2:12 Central Tokyo commercial land prices and basement levels

2.3.2 Case study in Model 2: Shanghai

2.3.2.1 Origins and Administration

Underground spaces in Chinese cities have been constructed in early decades for civil defense use, which are undergoing redevelopment for commercial use in the modern rapid economic development stage (SHU et al., 2006). The national policy on "**Management regulation of the development and utilization of urban underground space of China**" was addressed in 1997 by State Ministry of Construction. Currently there are over 40 cities in China studying development strategies of urban underground space.

In the megacity of Shanghai, a first attempt to study urban underground space development was initiated by its Civil Defense office, which formed a **Municipal Joint Committee of Underground Space** with 17 administrative agencies in 2006. This committee aimed to formulate an integrated management of urban underground space, by creating horizontal coordination with parallel administrative agencies (commission, bureau and office levels) and vertical coordination with **District Joint Committees of underground space**. District Joint Committees are decentralized decision platforms at local level, having their own rules and organizational management guidelines. Organization structure of Shanghai city government is shown in Table 2:5 below.

A short term executive plan of underground space development was established by the Municipal Joint Committee for the period from 2007 to 2012 and integrated into the social-economic strategies of the 12th Five-Year-Plan, focusing on measures to create underground network between subway stations and nearby basements in priority development zones. The committees also performed safety inspections for existing underground buildings, and established safety guidelines for underground facilities with other urban agencies. An information platform has been built and upgraded regularly[66], offering public consultable information about land quality, groundwater, subsidence risk and urban geology.

Table 2:5 Administrative agencies in Shanghai municipal government

Structure	Municipal agency	New institution for UG space
Commission (strategic level)	- Development and reform - Population and family planning - Science and technology - State-owned assets supervision - Urban and rural construction and transportation - Others	
Bureau (operational level)	- <u>housing and real estate service</u> - Planning, Land and Resources - Transport and port - Water - Environmental protection - Greenery and public space - Others	<u>Underground building registry</u>
Office (special operational level)	- <u>Civil defense</u> - Others	<u>Joint Committee of underground space (municipal and district)</u>

(Adapted from shanghai government agency information)

[66] http://www.sigs.com.cn/sigsonlines/ Shanghai geo-information sharing platform

Creation of this Municipal and District level Joint Committee of Underground Space has been relevant to improve political awareness and to mobilize urban agencies into administrative coordination. However, concrete operational instruments have to be developed inside each agency according to their management procedures. Example is taken below for the Bureau of Housing and real estate service.

Different from Tokyo metropolitan government, underground buildings (basement level) were not fully registered in the municipal administrative system except civil shelter space, like all the Chinese cities. In 2006 and 2007, the government released the **regulation and implementation guide** on "**Urban Underground Building Construction Approval and Property Registration**", which required existing and future commercial use underground buildings to be fully registered by the Bureau of Housing and Real Estate Service. This instrument served as a basis to integrate underground space into conventional **building administrative system**. It also enabled the Bureau of Planning, Land and Resources to upgrade **land administrative system** by creating an urban subsurface cadastre or an underground space density map, and helped to guide future land use planning taking into account of existing underground building assets.

In China, the definition of "underground space" was interpreted differently in local laws by local governments, with a confusion between **belowground land resource** and **belowground buildings** (Xu and Zhu, 2012). Article 136 of the revised **Chinese Property Rights Law 2007** (page 130) indicated a layered property right system for construction land, combined with surface, aboveground and underground land use rights (leaseholds). With an analogy to air right, underground space should be classified to another spatial right (geo-space right) separated from surface land use right.

Therefore, **underground space is defined by national law as part of land resource**. Delimitation of underground land use rights should adapt to existing regulations on surface land use (Planning administration), building code (Real estate administration), subsoil quality (Environmental protection), aquifer depth (Water authority) and geological risk constraints (Land Resources administration). Compliance among these urban agencies should be ensured in order to avoid administrative conflicts and to safeguard potential value of urban subsurface.

2.3.2.2 Supply side management

Land quality in Shanghai is similar to Tokyo, having challenging underground engineering conditions with thick alluvial soil layer and high aquifer level. Land quality information indicated a scarcity of good quality subsurface in central urban area, due to density of existing underground infrastructures and high water content. Sludge type material has been reused as reclamation for low lying lands near coastal area.

Water-withdrawal induced land subsidence caused substantial economic loss for the city. Since groundwater resource was highly prohibited from extraction and artificial recharges were carried on by the city, land subsidence has been controlled since 1965. From 2011, groundwater was redefined as strategic water reserve for future utilization.

2.3.2.3 Demand side development

Public infrastructures:

There are overall 12 subway lines in Shanghai, with a total length of 420 km, ranking as the longest among all world cities, compared to 408 km in London and 368 km in New York[67]. Millions of utility lines were located beneath the city, as well as numbers of water storages and power plants. Strategic energy storage is anticipated in its deep underground space.

Underground buildings:

According to the data of 2008 (He et al., 2012), its urban area and inner suburban area, including 12 districts and covering 1920 km^2, had a total underground building floor space of 43,959,000 m^2, used for public, commercial and industrial facilities. Average per capita underground space is 3.52 m^2, representing 14% of standard per capita living space in China (25 m^2). Its old city center (Jiang'an district) had the highest density of underground commercial building: 247,638 m^2 belowground floor space per unit land area (km^2), with an average per capita underground space of 7.31 m^2 (counting for 29% of per capita living space).

According to the annual report of Municipal Joint Committee of 2010, 15,000,000 m^2 of underground space was expected to be constructed in urban area during 2007 and 2012, including underground network linking subway stations, civil shelters and building basements. The deepest building basement is 71 meters below ground level, an underground complex of subway station.

[67] http://www.thetransportpolitic.com/2010/04/15/shanghais-metro-now-worlds-longest-continues-to-grow-quickly-as-china-invests-in-rapid-transit/

2.3.3 Implications from Model 2

Strategic model 2 demonstrated solutions for administrative decentralization, for underground space regeneration and for incentive adoption. The two megacities presented above housed more than 20 million population in their urban areas, located in coastal zone exposed to relative high natural hazard risks, including cyclones, earthquakes and floods (Population Division, 2012)(see section 1.2.3.8). The city of Tokyo and Shanghai both developed extensive flood discharge tunnel system for risk prevention, as well as well-maintained civil shelters for disaster protection. Urban underground infrastructures and basement type buildings in these two cities are exceptionally large at horizontal scale and deep at vertical scale, owning longest subway lines and deepest basements in the world. In spite of their challenging ground quality for construction and frequent subsidence risks, advanced technologies including slurry shield tunneling and deep piling enabled them to develop world class infrastructures and buildings for urban growth and resilient development. Similarities and particularities between Tokyo and Shanghai in underground urbanism are shown in Table 2:6:

Table 2:6 Synthesis for Strategic model 2

BENCHMARK FACTORS	TOKYO	SHANGHAI
Administration: Institutionalization and decentralization		
Leading agency	City Bureau, Urban Policy Division, Metropolitan Deep Underground Use Council	Municipal Civil Defense Office, Joint Committee of Underground Space
Legal basis	Law and Basic Policies on Public Use of Deep Underground Space 2001	Regulation and Guide on Underground Building Construction Approval and Property Registration 2006/2007
Strategic decision	Creation of a new permanent agency, decentralized regional Deep Underground Use Councils	Creation of a new temporary agency, decentralized district Joint Committees of Underground Space
Operational instrument	3D land zoning, supply inventory, public private decision platform	Demand forecast, supply inventory, trans-institutional decision platform
Supply side management: Expansion and regeneration		
Policy orientation	Alternative land supply, infrastructural network and building network expansion	Subterranean pedestrian network expansion, and common utility tunnel
Development stage	From shallow development stage to deep development stage	From civil defense stage to urbanization stage
Supply inventory	Indication in depth and location	Indication in ground type and location
Data performance	High	High
Material handling	Soil reused to build roads, expand material market	Soil reused for embankment to form lands
Demand side development: Adaptation and cooperation		
UG infrastructure	Flood discharge tunnel and reservoir, utility tunnel, storage, plants, road tunnel, subway	Offshore discharge tunnel, storage, plants, road tunnel, subway
UG building	Shopping mall, pedestrian network, deep basement, public facility, civil shelters	Civil shelters, commercial basements, industrial basements
Public private alignment	Participative project council, legislative relaxation and flexible agreement	Development incentive, private use right of defense shelters
Land price level	Very high	High
Space registration	1,100,000 m^2 (only shopping mall)	43,959,000 m^2 (total)
Beneficial enabler	Land shortage, advanced technology, financial investment	Land shortage, existing defense shelters

(UG: Underground)

2.4 Strategic model 3: Central business district underground space

Tracing the private public synergy in the city of Montreal, this section is to describe histories of the emergence of Indoor city in the Central Business District (CBD), as well as its performance of functional convergence and horizontal expansion.

Model 1	Model 2	**Model 3**
• **opportunity**: good rock resource	• **opportunity**: land scarcity	• **opportunity**: mixed social forces
• **development stage**: from industrialization to urbanization	• **development stage**: from shallow construction to deep construction	• **development stage**: from blocks to horizontal expansive network
• **case study**: Helsinki, Singapore, Hong Kong, Minneapolis	• **case study**: Tokyo, Shanghai	• **case study**: Montreal

2.4.1 Case study in model 3: Montreal

2.4.1.1 Origins and Administration

In the city of Montreal, an **Indoor City** made up of more than fifty **underground commercial complexes** has been developed in the Central Business District Ville-Marie since 1962. This Indoor City covers a land footprint of 12 km^2 inside its district boundary of 16.50 km^2. Its total length is 32 km, being one of the longest covered commercial networks in the world. Formation of the Indoor City was initiated from a project-by-project basis, with regulatory adaptation and flexible agreement from the city. Development vision of private developers and collaborative mechanism permitted by public administrators were two importation enablers for the development of Indoor City (Besner, 1997, Besner, 2007a).

Integration of Indoor City development into city level strategies took place in 2002, with general guidelines indicated in Master Plan Section 4.23. Administrative structure and related institution for underground urbanism are showed in Table 2:7[68].

[68] Adapted from municipal organisational chart
http://ville.montreal.qc.ca/portal/page?_pageid=5977,88899589&_dad=portal&_schema=PORTAL

Table 2:7 Administrative agencies of City Council in Montreal

Structure	Municipal agency	New institution
City Council		
Executive Council	- General control - Department of institutional affaires - Department of finance - Department of human capital and communication - Department of legislation and land valuation - Department of land use development - Department of district consultation - Department of quality of life - Department of information technology - Department of infrastructure, transport and environment - Department of water - Department of civil safety (police and fire) - District council of Ville-Marie (CBD)	Indoor city development plan

Regulatory foundation for Indoor City's expansion is based on various types of incentivizing **by-laws** granted by the City Council. In order to encourage and facilitate developers to use underground space under public domain, the granted by-laws (regulations) included long-term leases, occupation permission, laneway granting, density bonus and development agreements. Some of these instruments were constrained by availability of public land hold by the city, such as available quantity of leasehold, occupation permission and laneway. The instrument of density bonus was simply a legislative loophole in planning laws, which ignored underground building floor space area in the calculation of total building Floor Area Ratio (FAR) before 1990 and was subject to modification in new planning rules in 1992. Therefore, the last instrument named **development agreement** was considered as the most powerful tool to stimulate the expansion of Indoor City, making most of the Indoor City projects achieved in downtown area. The agreement with zoning derogation was decided by the City Council for projects having a benefit to the development of Indoor City (such as linkage between metro stations with nearby basements). The project demand was requested by developers and negotiated between public and private stakeholders.

In addition, beside strategic guidelines and facilitating instruments, existing standards and rules (such as safety, water, utility, spatial design quality, facility maintenance, etc.) from other departments were required to be complied in the obligations of public private land use contracts. Therefore, the three-level administrative instrument (**Guidelines, Incentives and Standards**) ensured the development of Indoor City a long-term continuous and multi-consensual process.

2.4.1.2 Supply side management

From land quality investigation for underground construction, underground space was considered in favorable condition in Canadian cities, similar to most of Scandinavian rock spaces (Durand and Boivin, 1985). Excavated earth material (15 million tons of rock) during metro construction in 1965 were used to build the artificial island of Notre-Dame, which served for the events of World Expo 1967 and Olympics 1976 in the city of Montreal.

A methodology for establishing three-dimensional land use management was proposed by (Boivin, 1989, Boivin, 1990), who suggested a vertical land reservation policy for future urban development in Canadian cities, and a data registration system for creating underground building cadastre.

2.4.1.3 PPP model for Indoor City development

Real-estate managers reported that, since the development of the metro and Montreal's interior city, the number of legal deeds and agreements registered between the city and the private sector in relation to the underground had increased exponentially (Escobar, 2002). **This real estate planner also argued the determinant factor of real-property law stratification to the evolution of Indoor City.** According to a working paper from Indoor City Lab (L'Observatoire de la Ville Intérieure) (Boisvert, 2004a): due to the multi-functionality of Montreal Indoor City, it is difficult to restrict private construction into private domain and public function into public domain. A flexible regulatory arrangement should be favored, in order to improve negotiation between public and private sector and find out "win-win" solution. Several incentive instruments were proposed and implemented before (Besner, 2007b), among which public domain occupation permission and development agreement were considered as useful instruments to give **a legal title to underground space** invested by private developer beneath public domain.

- PPP project case: Quartier International redevelopment

A success project is showed below for the indoor network extension in Quartier International, supported by an integrated decision platform for private public engagement, instead of individual negotiation solution.

The strategic redevelopment project in Quartier International was launched in 2000, accompanied with an extension and consolidation with the existing Indoor City located beneath the CBD of Montreal. The project has been managed by a non-profit organization QIM (Quartier International de Montréal) and a **project team**, composed of **financial partners** from the government, land owners and private investors[69]. 14 major land owners of hotels and enterprises founded an **investment platform**, named ARQIM (Quartier International de Montréal Adjacent Landowner Association) in 1998. A private fund of more than $8 million were collected as a voluntary local improvement tax, used to improve the public space environment. It was marked that this private sector participation had revealed a confidence level of the business community in the redevelopment project, whose aim was to improve public environment of working centers.

[69] http://qimtl.qc.ca/en/societe-qim/ca QIM organisation information

Administrative support was in form of a **development agreement** in the Plan Particulier d'Urbanisme (**PPU**), granting developers the occupation permission beneath public land, in order to extend the underground pedestrian and commercial network.

- Indoor City evolution process under mixed social forces:

Evolutionary process of underground city illustrated in Figure 2:13[70] below by (Boisvert, 2004b). This development model is formed by a hybrid arrangement of public and private titles of underground space, based on common visions to raise the potential of underground urbanization, as well as to promote innovative strategies for urban growth.

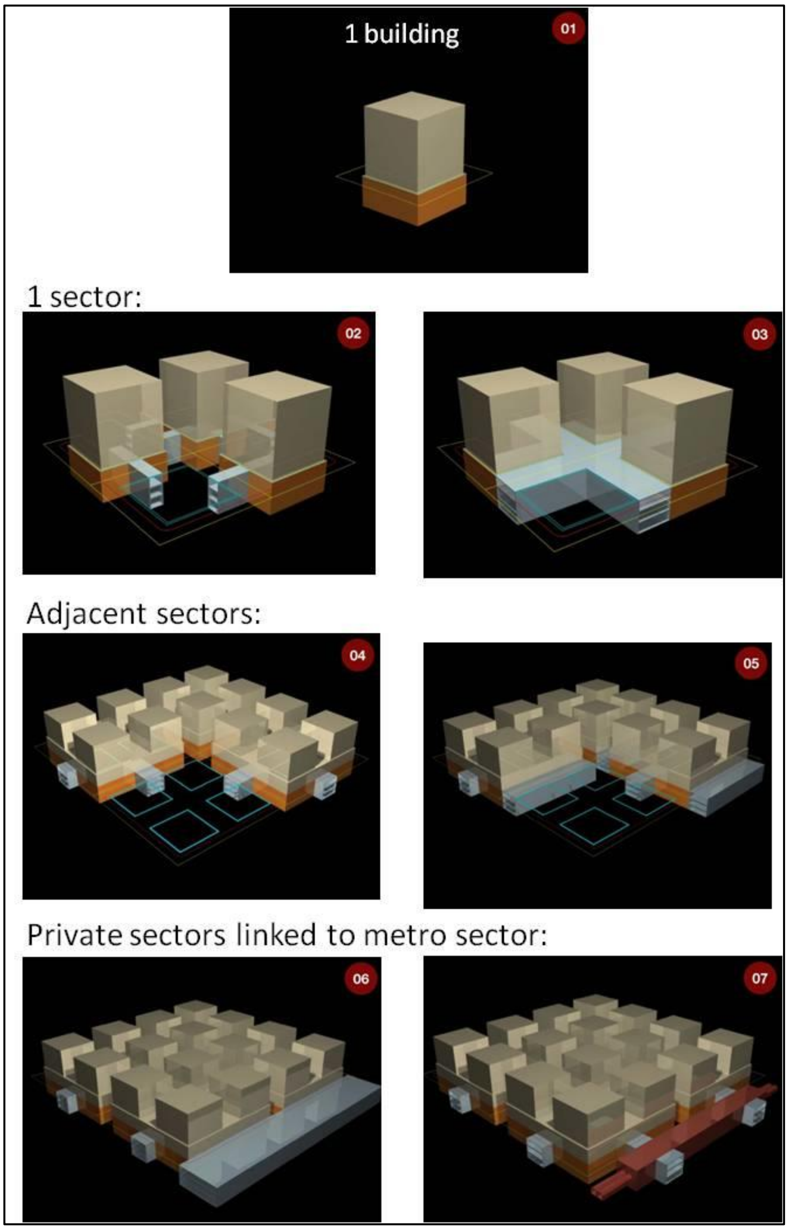


Figure 2:13 Montreal Indoor city expansion

[70] Proposed by Manuel Escobar

2.4.1.4 *Demand side development*

Underground complex network of public infrastructure and u*nderground buildings*:

Montreal city's metro system had a length of 69.2 km, including four lines. The subterranean pedestrian network named RESO (Figure 1:10), connecting 63 commercial and institutional buildings, 8 underground subway stations, 9 hotels, 17 museums, 43 underground parking, 5 rail stations, and 258 entrance accesses. 80% of the central city offices and 35% of commercial activities were linked by the underground complexes in this Indoor City[71]. In 2007, the city of Montreal owned about 10% of floor space in the Indoor City, while the remaining 90% split over 60 private owners.

Evolution of Indoor City's horizontal scale was studied by (El-Geneidy et al., 2011), indicating three growing cycles from conception to expansion and maturity in the 1960s, 1970s and 1980s. These three development stages were also linked to the economic context of the city, which affected its investment scale in urban infrastructures. This author also put forward an **indicator of "variation in accessible retail space"** to evaluate the benefit of Indoor City expansion to retail sector. His empirical study indicated that, for certain land use sectors, improving connectivity to Indoor City's pedestrian networks can generate an increase of 30,000 m^2 accessible retail space.

According to a survey about Indoor City's building network (Boivin, 1991) in 1988, there were 1300 tenants in the 14 km central link of Indoor City, with 52.7% occupied by retail stores, 19.8% by offices and service, and 12.3% by restaurants. In 1990, it was reported that nearly 50% of the rented retail floor spaces were located in the Indoor City: total number of retail shops in central city was 1600 compared to 1800 surface retail shops. This subterranean retail cluster had a total building floor space of 363,034 m^2 in 2006, with continuous extension projects inside the CBD. The development model of Montreal Indoor City was also transferred to the megacity of Toronto in Canada (Figure 1:10) (Barker, 1986, Boisvert, 2011).

[71] http://www1.ville.montreal.qc.ca/banque311/content/ville-int%C3%A9rieure City of Montreal information bank

2.4.2 Implications from Model 3

Strategic model 3 implied the feasibilities on public private partnership, on underground space expansion and on stimulus assignment. The unique historical and modern developments of Montreal's Indoor City demonstrated a processing method to join private development with public infrastructure construction to form a large scale "**multi-use urban complex**", similar to the ongoing central station redevelopment in Tokyo. Since underground space beneath urban center can't be expanded horizontally without legal stratification of urban land, the achievement of Montreal Indoor City represented feasibility of sharing property right between private and public sectors based on reciprocal benefits. Benchmark factors of administration, supply side management and demand side development are shown in Table 2:8:

Table 2:8 Synthesis for Strategic model 3

BENCHMARK FACTORS	MONTREAL
Administration: Integration and coordination	
Leading agency	Department of Land Use Development
Legal basis	Master Plan Guidelines for Indoor Pedestrian Network 2004
Strategic decision	Integration into existing administrative and legal system
Operational instrument	public private partnership, trans-institutional standard harmonization
Supply side management: Expansion and diversification	
Policy orientation	Infrastructural and building network expansion
Development stage	From segmented development stage to expansive development stage
Supply inventory	Indication in location for central area
Data performance	High
Material handling	Land reclamation
Demand side development: Cooperation and facilitation	
UG infrastructure	Rail tunnel, road tunnel, utility lines, subway
UG building	Basements, pedestrian networks, public space
Public private alignment	Development agreement, bonus, public land leasing
Land price level	High
Space registration	363,034 m^2 (the entire Indoor City)
Beneficial enabler	Visionary developers, administrative adaptation

(UG: Underground)

2.5 Cross model analysis and critical success factors

Drawn from the world wide best practices in the Chapter, we can observe the development processes of underground urbanization in these cities. Common motivation was driven from the intensifying urban growth demand. Performances of city specific underground infrastructures and buildings have been improved in terms of functional convergence with increasing user diversity, as well as functional adaptation to changing social-economic and environmental challenges.

City level feasibility study was carried out in the Chapter, including administrative framework establishment, underground resource management, underground space planning, and regulatory facilitation. Below summarizes feasibility implications from the three strategic models:

- Strategic model 1:

Model 1: from industrialized to urbanized underground space

Opportunity: good rock resource
Development stage: from industrialization to urbanization
Case study: Helsinki, Singapore, Hong Kong, Minneapolis

Feasibility concern:	Instrument application:
Administrative arrangement	- Legal basis and implementation guidelines - Integration into existing agencies
Supply side management	- Reservation for underground construction sites - Convergence of industrial land use with urban land use
Demand side development	- Substitution for surface land supply - Contractual and fiscal incentives

- Strategic model 2:

Model 2: underground urbanization in megacities

Opportunity: urban land scarcity
Development stage: from shallow construction to deep construction
Case study: Tokyo, Shanghai

Feasibility concern:	Instrument application:
Administrative arrangement	- Legal basis and implementation guidelines - Creation of new agencies and decentralization
Supply side management	- Stratification to enable vertical intensification - Incorporation into urban regeneration scheme
Demand side development	- Adapt to surface context and encourage complex form - Regulatory relaxation and private side attraction

- Strategic model 3:

Model 3: Central Business District underground space

Opportunity: mixed social forces Development stage: from blocks to horizontal expansive network Case study: Montreal

Feasibility concern:	Instrument application:
Administrative arrangement	- Implementation guidelines and standard extension - Integration into existing agencies
Supply side management	- Stratification to enable horizontal expansion - Compactness of land use in CBD
Demand side development	- Encourage linkage between underground complexes - Contractual incentive and facilitation agreement

A classification of critical success factors (CSF) by comparing across these strategic models is shown below:

- For administrative feasibility:

	Administration CSF
Legislative level	Law and guidelines
Administrative level	Coordination with existing or new agencies

Megacities' urban scale required for a decentralized administrative structure to manage underground space development projects at local levels, like the cases of Tokyo and Shanghai in model 2. Other benchmark cities deployed an integration of underground urbanism policy into existing governance, led by one existing agency as leader and coordinated with other agencies.

- For underground space provision feasibility:

	Supply side CSF
Subsurface resource management	Reservation by quality, stratification by depth
Interaction with surface land use plan	Encourage mixed use and compactness

Land shortage is considered as common problem for all the cities mentioned in the Chapter. For cities with good quality resource, it is beneficial to reserve suitable underground space for future exploitation and to choose diversified project functions for long service duration. For cities with limited and unfavorable resource but expansive urbanization demand, careful selection for suitable land is critical in supply inventory scheme. Exploiting additional underground space helped cities to store alternative land supply for development need. The same land supply opportunity can be offered by renewing and connecting existing underground space (such as civil shelters, commercial basements, and subterranean stations).

- For demand side promotion and orientation:

	Demand side CSF
Functional convergence	Synergize public use and private use
Investment facilitation	Contractual and fiscal incentives

Industrial utilization had dominated some cities' underground space, which are undergoing transformational stage into urban facilities. Risk threatened metropolitans had to develop preventive infrastructures underground for adaptation. All the benchmark cities have initiated regulatory mechanisms to encourage private investment, using contractual arrangements. Some cities have founded public private project organization to enable participative decision making.

After an examination of model specific feasibility study and classification of critical success factors according to the three strategic questions (administration, supply side, demand side), this chapter is to give other emerging cities a learning tool to formulate their own development processes of underground urbanization. This tool can be applied by cities with high development potential profile, defined by the factors mentioned in Chapter 1 Section 1.2 "Segment 1: underground space".

In order to combine development potential analysis and feasibility study, a demonstrative city will be presented in the next chapter for strategic analysis and implementation recommendation.

CHAPTER 3

3 AN INTEGRATED MANAGEMENT PROCESS FOR A SUSTAINABLE DEVELOPMENT OF UNDERGROUND URBANIZATION: PROJECT DEMONSTRATION IN CHINA

3.1 Introduction for Chapter 3

3.1.1 Methodological conceptualization

In order to balance the development potential profile of the four segments including underground space, geomaterials, geothermal energy and groundwater, city level strategies learnt from Chapter 2 should be further reformulated and applied for a sustainable trend of underground urbanization.

Section 3.2 will start by putting forward an integrated management process for sustainable underground urbanization, involved by various agencies acting in six administrative steps. This integrated strategy framework will take into account the three strategic questions illustrated in Chapter 2, including instruments for administrative arrangement, supply side management and demand side development.

3.1.2 Project demonstration

This research supported by an international joint research project supported by Sino-Swiss Science & Technology Cooperation (SSSTC), investigated the Chinese context in underground urbanization and its sustainability performance. This project lasted for three years and was carried out by Deep City China Project team (named “Project team” in the following text), composed by two laboratories in EPFL and a technology center in Nanjing University. General context of Chinese underground urbanization will be presented in section 3.3.

After a screening process for Chinese big cities, the city of Suzhou in Jiangsu province was finally selected for case study. The detailed selection process for candidate cities will be presented in section 3.4. Supported by provincial government of Jiangsu and prefectural government of Suzhou, official meetings and personal interviews were organized between the Project team and administrative bodies. Overall communication program will be presented in section 3.5.

From section 3.6 to section 3.7, the city of Suzhou will be interpreted as a growing big city with high development potential profile in underground urbanization. Feasibility study in administrative arrangement, supply side management and demand side development will be presented. These three strategic questions will be further formulated into the integrated management process, in order to create relevant instruments for final implementation.

3.2 The trans-institutional integrated management process

Learnt from the benchmark cities cases, administrative arrangement for the development of urban underground space can be integration into existing agencies or creation of new agency under a particular authority. In both cases, coordination within overall urban management bodies is required, to ensure underground infrastructure and building projects compatible with economic development goal, land use plan, spatial planning, and construction standards. Institutions involved in the development process are:

- Economic planning institution:

Opportunity of discovering new usages is driven by economic forces such as market demand induced by demographic growth. While these forces can be identified by Economic Planning institution, underground urbanization having a high development potential profile (combining current development stage, opportunity and feasibility, see Section 1.2.4) can be incorporated into urban development agenda. Since the scale of underground space has been expanding, and its capital cost will become substantial, public investment on underground assets should be evaluated based on financial feasibility and global cost-benefit analysis.

- Land resource institution:

Land supply and development control is administered by Land resource institution, who authorizes land use types (commercial, residential, industrial, educational, infrastructural, agricultural and mixed use), allocates land use rights (freehold or leasehold), and monitors land parcel utilization. Along with the functional convergence trend of urban underground space, more and more land use types are being built below the surface, such as infrastructural, commercial, industrial and mixed use. Absence of legal title for these subsurface uses will hinder long-term utilization, as the infrastructure congestion problem found beneath Tokyo city. A legal title granted to underground space can also help to improve the acceptability by financial institutions and facilitate private capital input.

- Urban spatial planning institution:

Spatial forms of infrastructure and building are designed by Urban Planning institution, which controls physical dimension of buildings, location of infrastructures and development form in land parcels. Although spatial forms of underground space have evolved from infrastructure type to building type and to complex type, its functions have not been integrated into urban planning considerations. Planning guidelines for underground building and complex have to be upgraded by taking into account spatial forms below ground, in order to enhance spatial compatibility between surface and subsurface buildings.

- Construction institution:

Construction institution supervises construction market activities, including construction project permission, construction quality control, housing supply, infrastructure supply, and real estate services. Besides civil shelter being part of urban construction plan, the increasing floor spaces of underground buildings have not been taken into account as part of floor space production plan. Along with the enhancing quality requirement for underground space, building code standards should be extended to underground buildings and complexes, in order to enable underground space's contribution to the increasing space demand from commercial and mixed activities.

- Relation between public and private sector:

Construction project authorization procedures will pass through all these institutions for investment approval, spatial design approval, project planning approval and land use right delivery. Revision of these procedures to find out administrative gap related to underground construction is important to increase feasibility of underground urbanization.

Since more and more private capitals are coming into financial participation of underground space utilization, such as Japanese underground shopping malls (Golany and Ojima, 1996a) and Montreal's Indoor city (Boisvert, 2007), private developers' vision during the project conception stage can be of consequence to make the land development project approved by regulatory bodies.

As seen from the city level strategic analysis, the balance between regulatory bodies and private sector differs among the strategic models. Model 1 type cities (Helsinki, Hong Kong) stated a relatively strong regulatory initiative on assigning underground construction sites for future development; Model 3 city (Montreal) chose a flexible collaboration pattern to synergize private aim with public use; Model 2 cities (Tokyo, Shanghai) deployed a strategy in between, by setting legal basis to safeguard the authorization power of regulatory bodies while giving development incentives to private developers.

Since legislative framework differs in world cities, there are no universal standards for writing related legal terms into existing laws to clarify the responsibility of regulatory bodies on the development of underground urbanization. The case study demonstrated in this Chapter will base on Chinese context and will use the Chinese institutional system as executors for the integrated management process. Table 3:1 propose new missions for city level institutions and private sectors regarding the promotion of sustainable underground urbanization.

Table 3:1 Institutional involvement in underground urbanization

Organizations	**Responsibility in sustainable underground urbanization**	**Administrative boundary**
Municipal People's Congress	Revision of legislation, political innovation	Municipal region
Development and Reform Commission	Forecast economic demand for underground resource exploitation (four segments)	Municipal region
Land and Resource Bureau	Prospect resource supply, allocate exploitable sites, monitor utilization	Urban region
Urban Planning and Design Bureau	Conceive underground space functions in exploitable sites, maximize land use value	Urban center
Urban Housing and Construction Bureau	Provide technical guidance and service for underground infrastructure and building	Urban center
State-owned and private developers	Choose the optimal project scope based on planning and technical guides	Individual project

Figure 3:1 below illustrates the trans-institutional management process involved from city level strategy definer to project developer. Beside the indispensable coordination inside governmental bodies, the smooth feedback from private sector to public sector helps to improve political awareness on emerging issues, such as the new utilization forms of the urban subsurface. Since the Municipal People's congress is composed of hundreds of individual representatives from various economic sectors, who could submit motions to resolve institutional barriers restricting the promotion of sustainable underground urbanization.

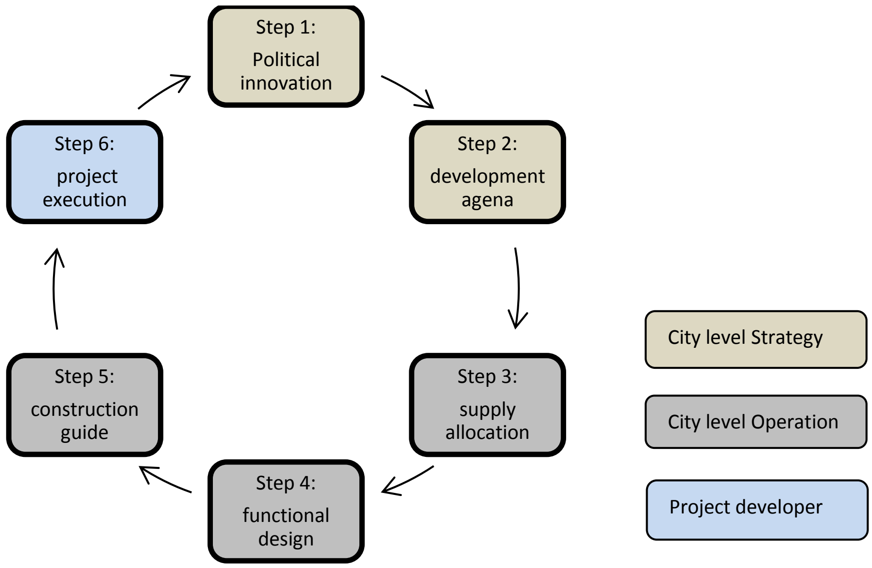


Figure 3:1 An integrated management process for sustainable underground urbanization

Current development of underground space in cities is facing coordination dilemmas: on one side public infrastructures are growing fast and going deep, congestion and disorder hinder future development (Sterling, 2005, Sterling et al., 2010); on the other side, private developers are playing a major role in property development but lack of guidance of subsurface potential and comprehensive decision-making. The 6-step process proposed in Figure 3:1 is a facilitating procedure to frame a comprehensive decision platform, linking public and private sectors into new subsurface urbanism plans. It is also a value chain of underground development by linking multi-disciplinary capitals to create long-term growth, aiming to meet urban demand while optimize the use of underground space in the city.

This new strategic and operational process dedicated to urban underground development, is based on the classical theory of rational model for policy implementation (Patton and Sawicki, 1993). The integrated management process helps to develop a long-term vision and planning methodology for sustainable subsurface use in urban centers. Implication for innovative underground management is an "integrated planning" linking multiple spatial scales (international, national, municipal, local, parcel), linking multiple institutional levels (political, strategic, scientific, economic, private) and linking specific analytic methods to the whole framework. Detail analytic methods will be demonstrated in section 3.6 with a city case study.

3.3 Chinese context in development potential of sustainable underground urbanization

This section is to give insights on Chinese cities' underground development, looking at their current development stages, opportunities, and feasibilities. Applying the segmental analysis introduced in Chapter 1, development potential profile of the four segments in Chinese underground urbanization will be evaluated.

3.3.1 Segment 1: underground space in China

3.3.1.1 Development stage of underground space

1) *Underground Infrastructures:*

Agricultural and industrial sector:

Underground grain storage of granary has been used since ancient Chinese histories. In the year 606 A.D. the Chinese capital had 3000 underground facilities for food storage, with a capacity of 500,000 tons. This solution helped to avoid substantial grain loss after harvest due to weather issues. The largest underground power plant was constructed in the Three Gorges Project, with a total capacity of 4.2 million KW.

Underground container transport systems are undergoing research and development, which will be applied for urban cargo logistic sector in coastal port megacities like Shanghai. Driven from fossil fuel resource scarcity in the recent decades, crude oil storage cavern facility began to be built underground, to supplement aboveground strategic oil reserves.

Transport and Utility network sector:

Reported by (Freeman et al., 1982), since 1955, an average of 100 km of railroad tunnels have been constructed annually in China. The first subway was constructed in Beijing city in 1965, a 24 km long section with 17 stations, operating at a maximum speed of 80 km/hr. Nowadays, there are 16 Chinese cities operating subway system[72], with overall 64 metro lines counted to a total length of 1,980 km.

Utility infrastructures (including water, waste, energy distribution and telecommunication) in Chinese big cities tend to be more and more crowded and complex, causing difficulties for new utility construction due to problems of information inadequacy and maintenance deficiency (Ma and Zeng, 2009). The first multi-utility tunnel was built in Beijing in 1959, which improved the utility performance, facilitated maintenance and reduced public expenditure. Opportunities for utility

[72] Data source : http://www.chinametro.net

corridor construction lie on forward land reservation in the subsurface under public domain, usually within 10 meters' depth.

2) Underground Buildings:

Residential earth-sheltered buildings:

Earth sheltered homes have been widely built in the region with loess soil in Western China, housing millions of dwellers in the atrium-style houses (Carmody and Derr, 1982). Reasons for this living pattern came from lack of suitable building materials in the region and good self-supporting loess soil for cave construction. However, this kind of housing form failed to provide a more desirable housing density in urban areas, except in places where farming was carried out on the rooftops of the underground houses.

Institutional and commercial buildings:

Hospitals, factories, recreation center, meeting room were built in basement level of conventional buildings since the 1980s. The increasing construction of underground buildings for commercial use have driven the State Administration of Taxation to impose a 50% land use tax[73] for the subsurface space occupied by detached underground buildings (totally buried buildings without surface development) from the year of 2009. This kind of underground buildings is subject to regulation of local Real Estate Department in Construction Bureau.

Civil defense property's commercial development:

Since the 1960s, civil shelters have been an integral part of urban planning practice, constructed by self-organizing associations of neighborhood or by working units (Golany, 1989). National standard for per capita emergency shelter provision is 1 square meter, or 3% of building floor space. Annual shelter construction space attains 20 million square meters in China.

Modern trend of underground shelter development promotes a functional fusion of emergency protection in critical period and commercial center in stable period, in order to balance financial investment of shelter construction and provide alternative land supply for commercial sector. This business model named "civil defense property development" (different from conventional real estate development), attracted private developers to participate into a partnership form of special property development with local Civil Defense Office, who offered investors a **reduced land acquisition cost** of subsurface space for commercial street development below urban road area or public plaza area.

Construction and management of this kind of property are required to be complied with double standards of shelter protection and commercial facility, with strict legal right arrangement between private developer and local government. According to a survey from Underground Space Research Center of PLA University of Science and Technology (Yu et al., 2012), this special property

[73] Land use tax (yuan per square meter): 1.5 to 30 (big cities); 1.2 to 24 (midsized cities); 0.9 to 18 (small cities); 0.6 to 12 (counties).

development in China had increased from 4.6 million square meters to 8.5 million square meters from 2003 to 2010. Due to the special legal arrangement, this kind of property is not categorized as real estate property. Therefore, there is not a uniform regulatory body to supervise both civil defense commercial property and real estate property, requiring coordination between Civil Defense Office and Real Estate Department to safeguard effectiveness of this critical property.

3) Underground complexes and mega-complexes

Combining function of rail transit hub and business centers, complexes in forms of tunnel and basement started to emerge in Chinese big cities, where subway became one of the important transport modes. There are currently more than 200 underground complexes in China, with construction floor space over 10,000 square meters for each complex. In addition, there are about 100 large-sized underground complexes with single scale of over 20,000 square meters floor space (Li, 2012). In Chinese megacities like Beijing and Shanghai, average scale of underground complex surpassed 100,000 square meters. They can be called “Mega Underground Complex”.

According to (Qian), one of the Mega Underground commercial Complexes is in Beijing city’s Zhongguancun high-tech business center, providing 500,000 square meters space in an underground complex linking two subway lines, subterranean bus stops, parking areas, commercial tenants, and utility corridors. Another mega complex is in Beijing city’s Wangfujing shopping district having 600,000 square meters of commercial underground space.

Figure 3:2 shows one of the mega underground complexes in Beijing city, with functional indications at different vertical layers (image from personal communication with Beijing urban planner Shi Xiaodong)

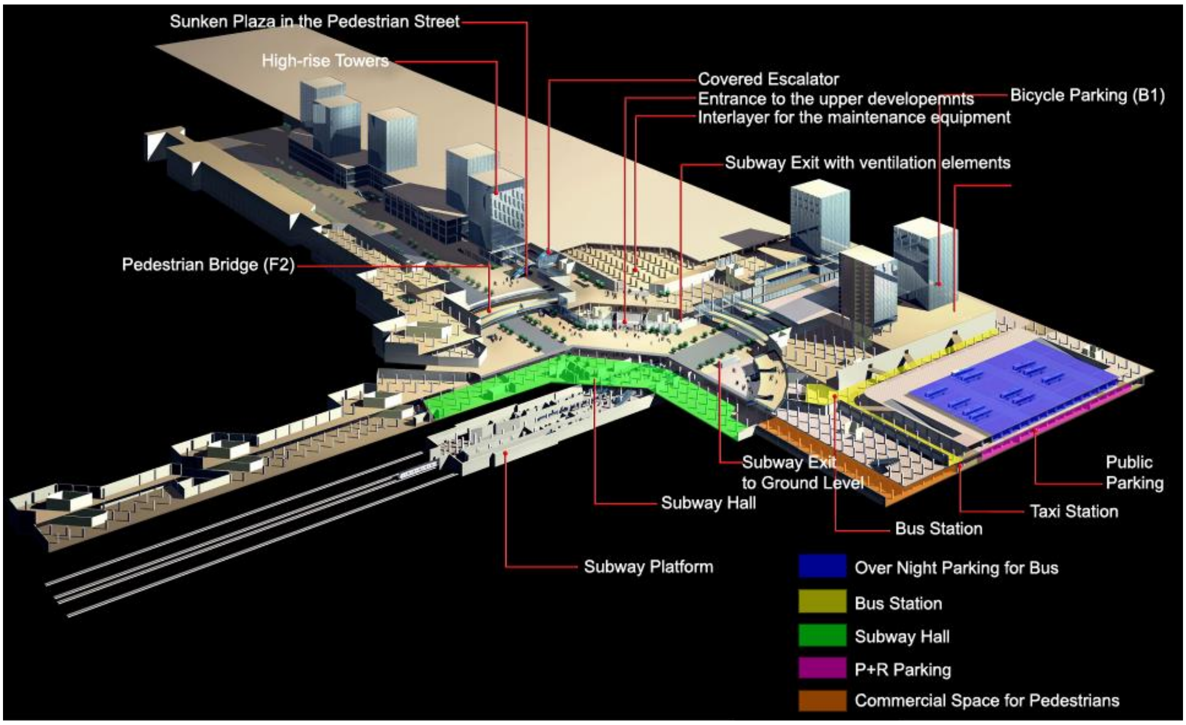


Figure 3:2 Beijing megacity: a mega underground complex in Guo-gong-zhuang metro station of metro line 9 (200,000 square meters of underground floor space)

The capital city of Beijing had built 30 million square meters of underground space; with an annual incremental quantity of 3 million (10% of total building floor space), its future underground space scale will attain 90 million square meters in 2020 (Qian, 2009).

3.3.1.2 Opportunities of underground space development

According to Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (Population Division, 2012), urbanization rate of our planet has reached a level of 51.6% since the year of 2010. Cities are becoming bigger and bigger to house increasing urban inhabitants. The Table 3:2[74] shows the number of cities at three population levels: one to five million, five to ten million and over 10 million. In ten years, nearly one third of the "5 to 10 million"-populated cities will emerge in the territory of China. Total number of Chinese big cities (more than one million inhabitants) will attain 163 in 2025, compared to 35 in Europe.

Table 3:2 Growth of midsized city, big city and mega city in the world and in China (from 1950 to 2025)

POP. LEVEL	1 TO 5 MILLION (Midsized city)			5 TO 10 MILLION (Big city)			OVER 10 MILLION (Mega city)		
REGION	WORLD	CHINA	*ratio*	WORLD	CHINA	*ratio*	WORLD	CHINA	*ratio*
1950	69	8	*12%*	4	0	*0%*	2	0	*0%*
1955	75	9	*12%*	9	1	*11%*	2	0	*0%*
1960	94	11	*12%*	10	1	*10%*	2	0	*0%*
1965	114	13	*11%*	12	1	*8%*	2	0	*0%*
1970	128	14	*11%*	15	1	*7%*	2	0	*0%*
1975	144	15	*10%*	14	1	*7%*	3	0	*0%*
1980	173	18	*10%*	19	2	*11%*	4	0	*0%*
1985	197	23	*12%*	20	2	*10%*	7	0	*0%*
1990	237	32	*14%*	19	2	*11%*	10	0	*0%*
1995	270	45	*17%*	19	2	*11%*	13	1	*8%*
2000	311	57	*18%*	27	5	*19%*	17	2	*12%*
2005	340	67	*20%*	33	7	*21%*	19	2	*11%*
2010	388	80	*21%*	38	10	*26%*	23	4	*17%*
2015	449	97	*22%*	40	9	*23%*	29	6	*21%*
2020	506	121	*24%*	48	11	*23%*	35	7	*20%*
2025	572	139	*24%*	59	17	*29%*	37	7	*19%*

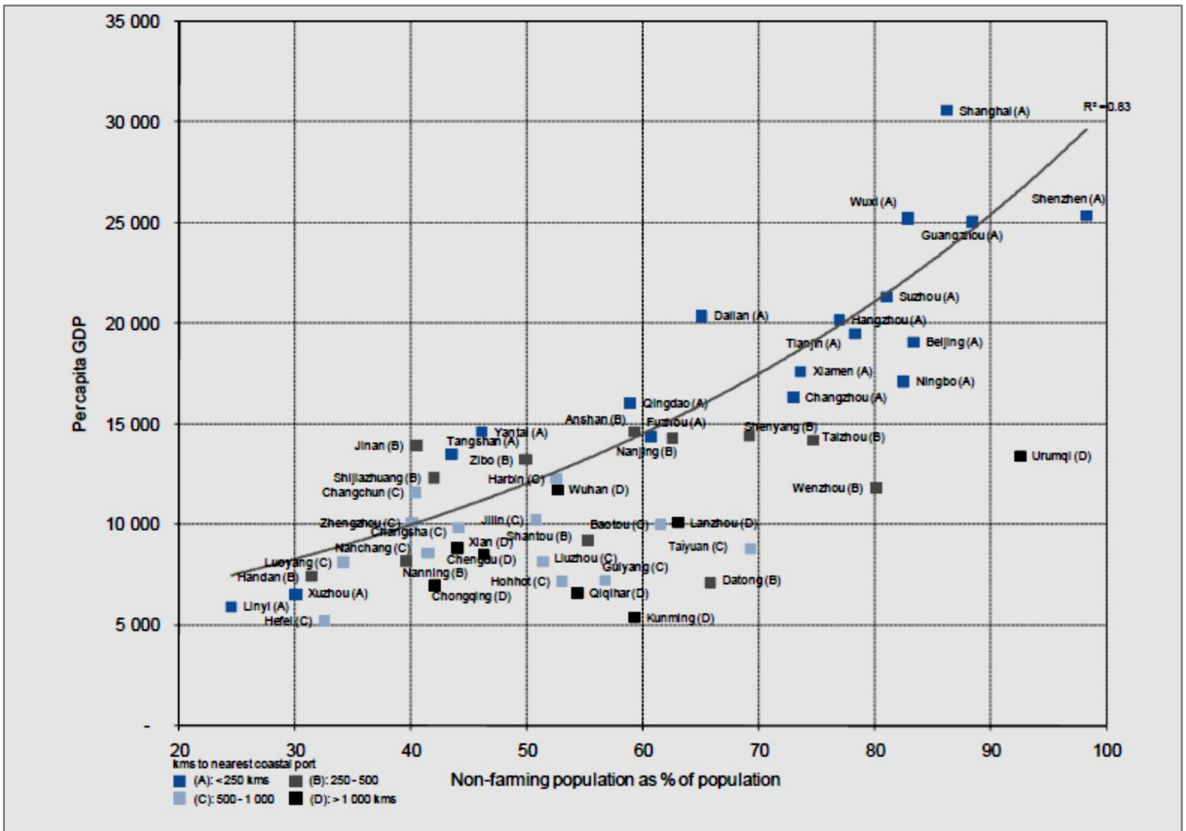
Chinese cities have been undergoing an urbanization specializing process, started from industrializing (small city expanding land to attract business), to transforming (midsized city commercializing land to finance infrastructures), finally to modernizing (mega city focusing on service sector). The specializing process is moving city level policies for denser land uses, larger scale infrastructures, higher value-added sectors, higher skilled labor and better quality of life for citizens.

According to a study simulating Chinese urbanization scenarios, the scenario of "concentrated urbanization" will bring the following benefits: an increase of 20% for per capita GDP, a reduction on

[74] *Source: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2010 Revision and World Urbanization Prospects: The 2011 Revision Wednesday, April 10, 2013; 8:37:33 AM*

public spending equivalent to 2.5% of 2025's annual GDP, and a saving in energy bill for private sector equivalent to 1.7% of 2025's annual GDP (Woetzel et al., 2009). The "concentrated urbanization" model can be an optimal path by generating less pressure on urban production factors, such as land, labor, capital, and natural resources. Densification with underground space offers this opportunity to concentrate economic activities inside urban cores, to maximize land value and economize public expenditure on infrastructure. A higher urbanization rate asks for a stronger motivation for underground urbanization.

The relationship between per capita GDP and urbanization rate (percentage of urban population) is shown in Figure 3:3, for 53 metropolitan regions in China (Kamal-Chaoui et al., 2009). Economic performance increased with urbanization rate for major coastal cities (dark blue points are cities having the best accessibility to ports). The indicator of per capita GDP can serve as one of the demand forecast criteria for the development of urban underground.



Source: Analysis of data from Provincial Statistical Yearbooks, 2001.

Figure 3:3 Urbanization and prosperity (per capita GDP) in China's 53 metropolitan regions (year 2000)

According to the 2011 annual report of land price monitoring in China[75], average urban land price has doubled during the decade of 2000 to 2011 (Figure 3:4). The highest land price growth was in the big cities of Shenzhen (index in 2011: 408), Kunming (index in 2011: 383), Ningbo (index in 2011: 380), Haikou (index in 2011: 311) and Beijing (index in 2011: 275).

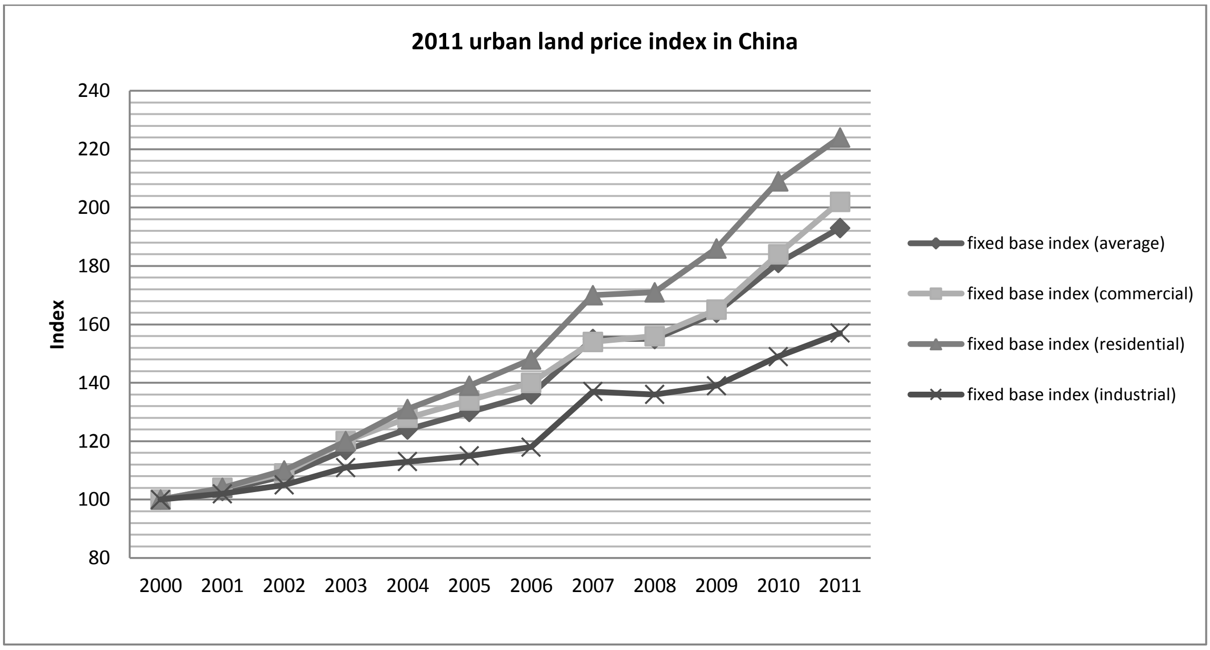


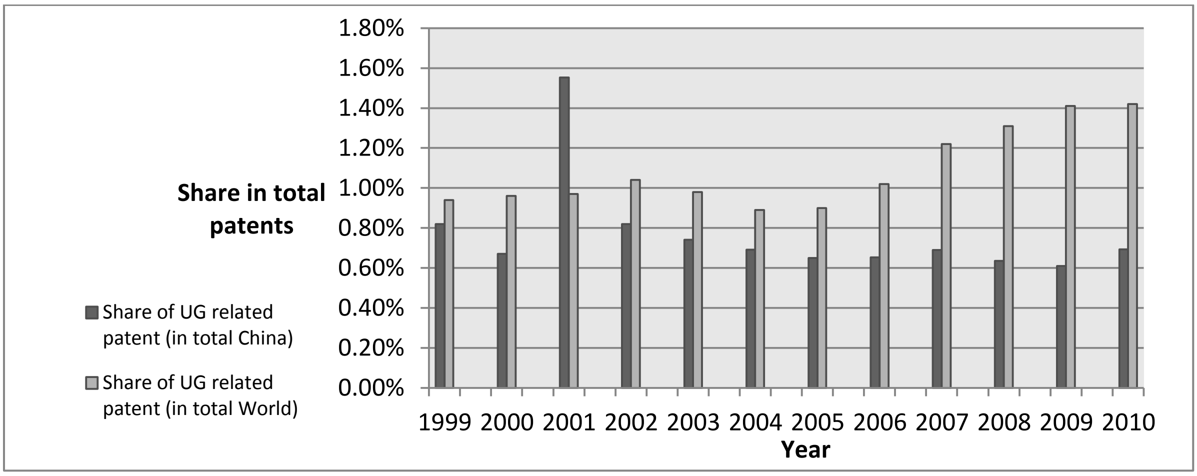
Figure 3:4 Urban land price index in China from 2000 to 2011 (average, commercial, residential, industrial use)

3.3.1.3 Feasibilities of underground space development

1. Technological capacity

Innovative tunneling technologies have been developed in cities like Shanghai to overcome challenging geo-engineering conditions in soft soil, for projects of subway tunnels, road tunnels, and offshore discharge tunnels. Innovation landscape of underground construction is shown in Figure 3:5 (data from WIPO and OECD). Total Chinese patent quantity has increased significantly during the year 1999 to 2010, standing for an advancing trend in technological development. However, when compared to the international level, Chinese national level innovation speed in underground construction has been quite slow (< 0.2%). Underground construction related technologies are lagging behind of other technologies (international level of average UG patent share: 1.09%, Chinese level: 0.77%).

[75] http://www.mlr.gov.cn/tdsc/djxx/djjc/201208/t20120801_1127356.htm Ministry of Land and Resources of China, 2011 urban land price monitoring report (in Chinese)



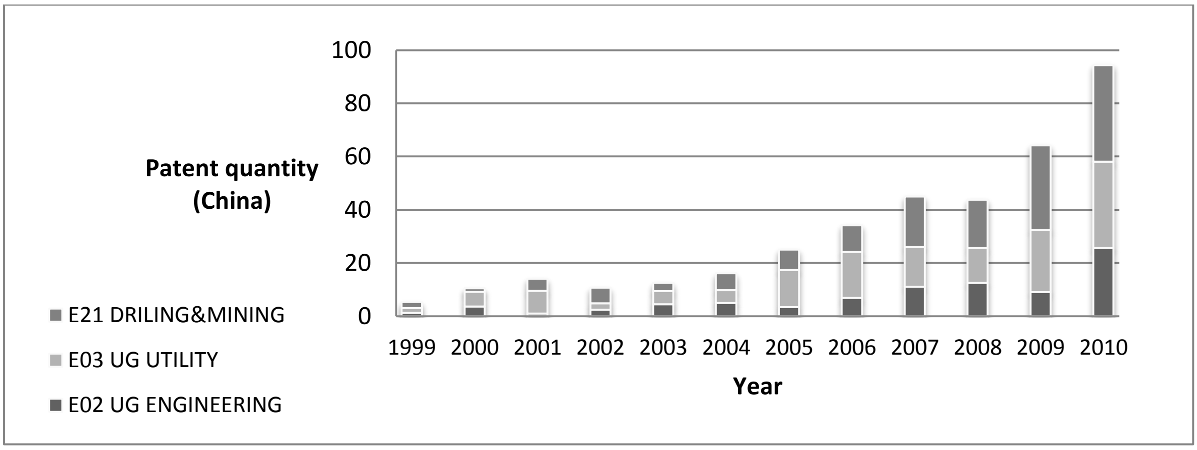


Figure 3:5 Share of underground construction related patent and quantity distribution by IPC codes (China)

2. Between technology and policy making in developing countries:

Out of 6.97 billion urban inhabitants in the world, 5.73 billion people live in less developed regions (Population Division, 2012). Potential contribution of subsurface to the urban development in these nations has been recognized by the United Nations. In the late 1970s and early 1980s, the United Nations' Committee on Natural Resources developed a topic on managing subsurface space as vital natural resource. A formal concern was addressed and formalized in 1981, following by adopting a resolution on "Utilization of subsurface space" in 1983 (Lemley, 1986).

A focus on developing countries' utilization of subsurface space also became an urgent subject, where the resources are often scarce and the needs are great. A special study was devoted to this subject in 1982 with collaboration of United Nations, International Tunneling Association and Swedish government (Bergman, 1982, Bergman, 1986), in order to promote technology transfer from north to south. Potential function portfolio, planning, technology and financing issues were investigated by this study, which tried to bridge a communication between technology and policy making.

The importance of coordinating surface and subsurface development in national level planning was stated by this UN report, declaring a need to expose the growing potential of subsurface space to administrators and planners in developing nations and to raise their awareness for policy making. Ignorance for urban underground management was caused by lacks of knowledge on subsurface resource potential and available data related to technological feasibility and economic benefit.

As one of the developing countries, China has been undergoing a transitional period by learning from international experiences and developing its own administrative actions to manage underground urbanization, as presented in the following section.

3. Institutional capacity

According to the revised Property Law adopted by the National People's Congress in 2007, construction land use right includes right to use of the land's surface, ground and underground. But there is not specific implementation guidelines to authorize the stratification with underground land use right.

Property Rights Law of the People's Republic of China (2007)[76]

Chapter XII Right to the Use of Construction Land

Article 135
The owner of the right to the use of land for construction use shall, according to law, be entitled to possess, utilize and obtain profits from the State-owned land, and have the right, by utilizing such land, to build buildings and their accessory facilities.

Article 136
The right to the use of land for construction use shall include right to the use of the land's surface, ground or underground. The newly-established right to the use of land for construction use may not infringe upon the rights of already-established usufructuary right.

Article 137
The right to the use of land for construction use may be established by means of assignment or transfer. Such operation lands as for industrial, commercial, tourism, entertainment and commercial use and one land with two or above intentional users shall be assigned by auction or invitation to bid. The establishment of the right to the use of land for construction use by way of transfer is strictly restricted. Where the way of transfer is adopted, provisions relating to land use stipulated by laws, administrative regulations shall be observed.

In China, construction of the urban underground has been diversifying from agricultural and habitation uses to industrial and commercial uses, in forms of infrastructures and buildings. In 1997, a national level policy on "**Management regulation of the development and utilization of urban underground space**" was released by the State Ministry of Construction and was revised in 2001. A decentralized administrative system for urban subsurface use from central level to local levels was established, giving city administrators instructions to manage their own underground urbanization process.

In 2007, MOHURD[77] released a first "**Urban Underground Space Planning Guidelines" for Medium-to-Large cities**, which compiled national standards and authorization procedures for underground

[76] Source: legal terms cited from China government website, translated by the law firm of Lehman Lee & Xu

development in urban areas, in order to lead local city level implementation by providing a methodological framework. **This Guidelines 2007 indicated the need to plan subsurface use for city centers, CBDs and mass transit hubs.**

Currently there are nearly 20 Chinese cities trying to formulate and implement urban subsurface space utilization strategies and planning, based on local conditions and specific investment models. Major Chinese megacities (Shanghai, Beijing, Shenzhen, and Hangzhou) have formulated their own urban underground space development regulations and strategies (Zhang and Liao, 2009, Liu et al., 2009, Jin and Huang, 2009, Dai et al., 2009, Shi, 2009).

International technology transfer and knowledge diffusion had a critical influence in shaping Chinese subsurface urbanization process, especially for underground infrastructures and buildings. Advancement in tunneling and excavation techniques accompanied with policy reinforcement from administrative bodies has been speeding up the development stage for the segment of geo-space.

3.3.1.4 Development potential profile of underground space development

Development potential of underground space in Chinese context is slightly higher than that of average international level, with an overall rating of 2.44/3 (81%). The revised property right law and increasing regulatory interventions on urban underground development reflected that the nation is moving towards an enhancing stage of underground urbanization by improving institutional feasibilities. Scores for factors are shown in Figure 3:6.

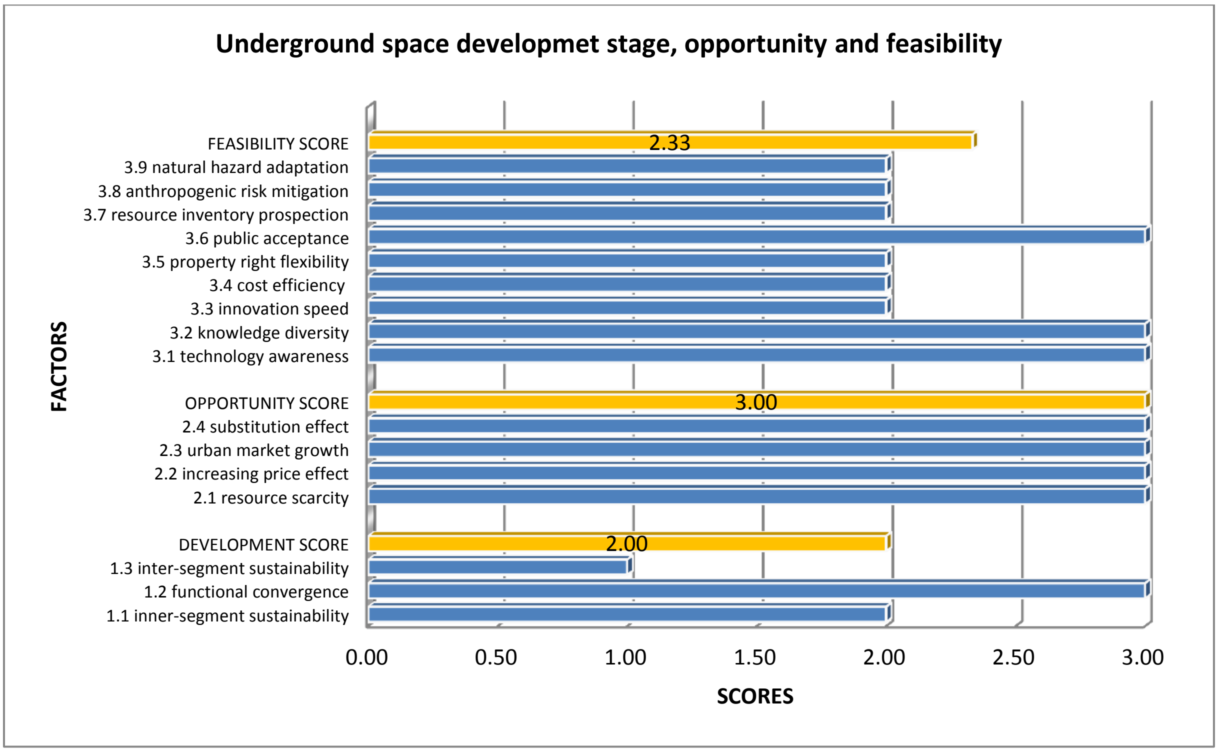


Figure 3:6 Chinese context: underground space segment

[77] Ministry Of Housing and Urban-Rural Development of the People's Republic of China (MOHURD)

3.3.2 Segment 2: geomaterials in China

3.3.2.1 Development stage of geomaterials

According to Beijing city's statistics on Construction and demolition waste (CDW) during 1994 to 2004, excavated soil constituted more than 88% in total CDW generation (Hu et al., 2010b). For major raw materials used in Beijing's residential building development, the highest utilization intensities belong to sand and gravel, ranging from 400 to 1200 kg per square meter building space, much higher than cement, steel, wood and brick. A similar study for Beijing city showed the raw material intensity of gravel and sand ranged from 33 to 66 tons per 100 square meters (Hu et al., 2010a).

Most of the excavated soil was used as embankment and land reclamation for low-lying land. Current reutilization rate of construction waste is lower than 10%, compared to 50% in European countries and 97% in Japan and Korea. A special science and technology promotional plan for waste reutilization was launched and integrated in to the national 12th Five-Year-Plan, supported by seven ministries, considering construction waste recycling as one of the prioritized development area[78].

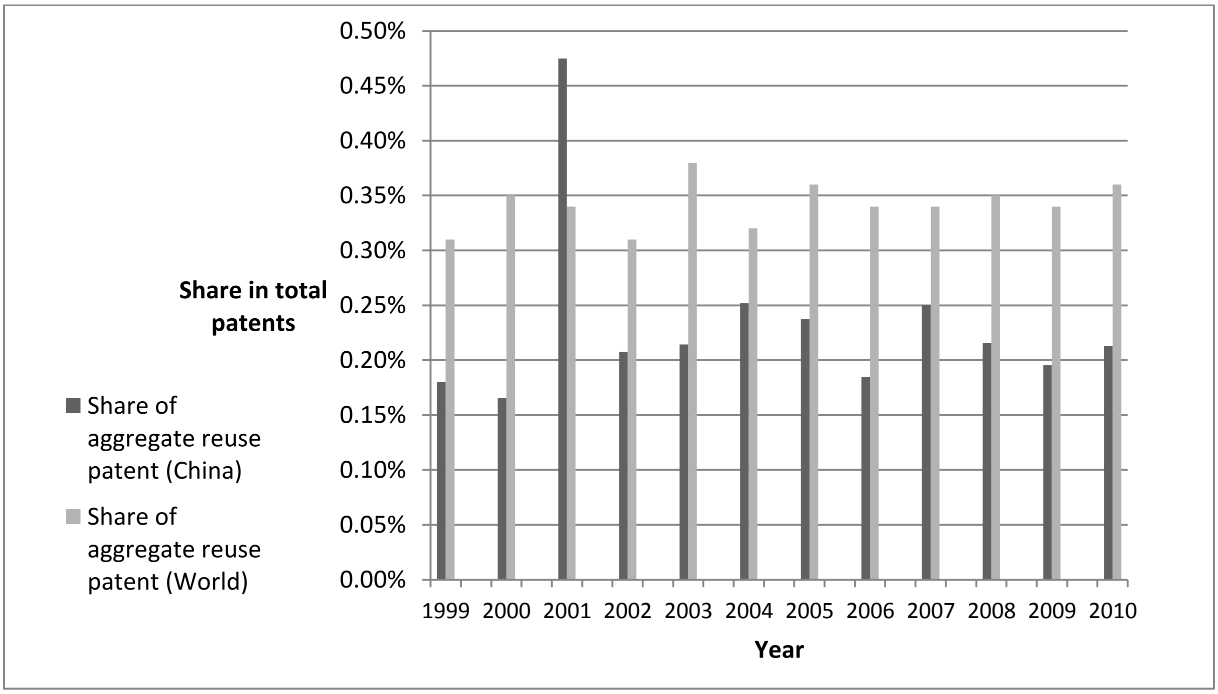
3.3.2.2 Opportunities of geomaterials development

Urban economy of China will generate over 90% of GDP for the country in 2025, increased from 75% in 2009. This urbanization trend represents a huge potential for infrastructural development: 5 billion m^2 of road will be paved, 28,000 km of metro rail could be built; and a substantial demand for building construction: 40 billion m^2 of floor space will be built in 5 million buildings (Woetzel et al., 2009). Those future projects are about to induce and intensify resource pressures on land, energy, water and raw material.

3.3.2.3 Feasibilities of geomaterials development

Based on the WIPO IPC green inventory's classification on "Use of waste materials as fillers for mortars, concrete"(IPC code: C04B), technological development in this segment has been escalated quantitatively as shown in Figure 3:7. Its innovation speed is similar to the international level (0.05%). Average patent share among all the technology categories is 0.23%, compared to the world level of 0.34%.

[78] http://www.miit.gov.cn Press release from Ministry of Industry and Information Technology of China



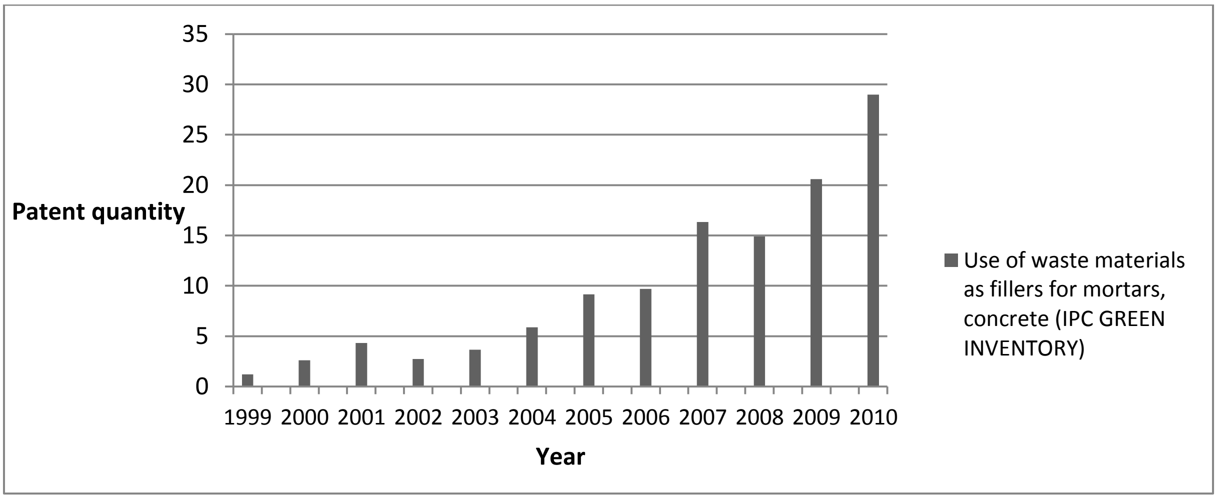


Figure 3:7 Share of aggregate reuse related patent and patent quantity (China)

To promote sustainable development and increase resource utilization efficiency, China's national congress adopted the "**Circular Economy Law**" in 2008. This law addressed measures of reducing raw material extractions and imports, as well as using wastes as valuable raw materials. In 2012, MOHURD released an official technical guide (GB/T50743-2012) for urban construction waste recycling.

3.3.2.4 Development potential profile of geomaterials

Due to the low performance of construction waste recycling and lack of material reuse diversity, geomaterials' development potential is rated lower than international level (rated as 2.10/3, 70%). However, the high opportunity of construction material demand, accompanied with increasing technological input and administrative awareness could upgrade the current utilization condition for excavated material generated from underground construction sites. Scores for factors are shown in Figure 3:8.

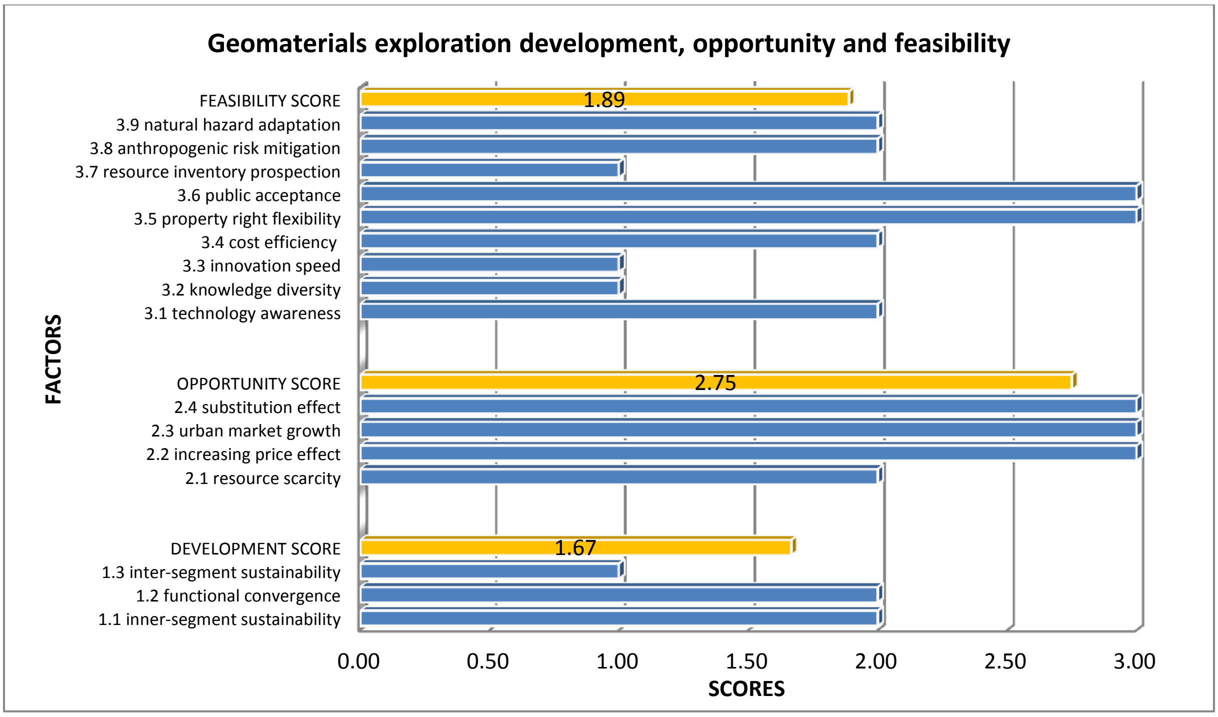


Figure 3:8 Chinese context: geomaterials segment

3.3.3 Segment 3: geothermal energy in China

3.3.3.1 Development stage of geothermal energy

The first building using shallow geothermal heating system was constructed in 1989 in Shanghai, covering 4,305 square meters of heated space with 135 boreholes of 35m depth. Since 1996, international technological cooperation between China and overseas helped to scale up performance of domestic geothermal heating system (Gao et al., 2009). Research on GSHP technologies has been incentivized financially at the national level, with increasing patent applications and demonstrative projects in several pilot cities. Until 2007, total floor space area with GSHP heating system reached 80 million square meters (Yang et al., 2010).

According to a market survey for Ground source heat pump (GSHP) with 160 projects in China, 39% of project portfolios were for office buildings, 19% for hotels, 12% for residential buildings, 9% for factories, 7% for villas, 6% for supermarkets and 8% for schools and hospitals. Half of these building projects had operational floor space between 10,000 to 50,000 square meters.

Northern cities in China have been using hot groundwater for heating use, causing severe land subsidence problems. Inter-segmental sustainability between geothermal energy and groundwater deserves a great concern in underground resource management.

3.3.3.2 Opportunities of geothermal energy development

The increasing living standard and growing urban population in China make it the biggest energy consumer around the world, indicated from Figure 3:9 (from World Energy outlook 2012, IEA). As mentioned in section 1.4.2.3, China is the one of the main producers for geothermal direct heat with 20 932 GWh per year. Motivation of developing geothermal energy has been well addressed by the State in the "Renewable energy law".

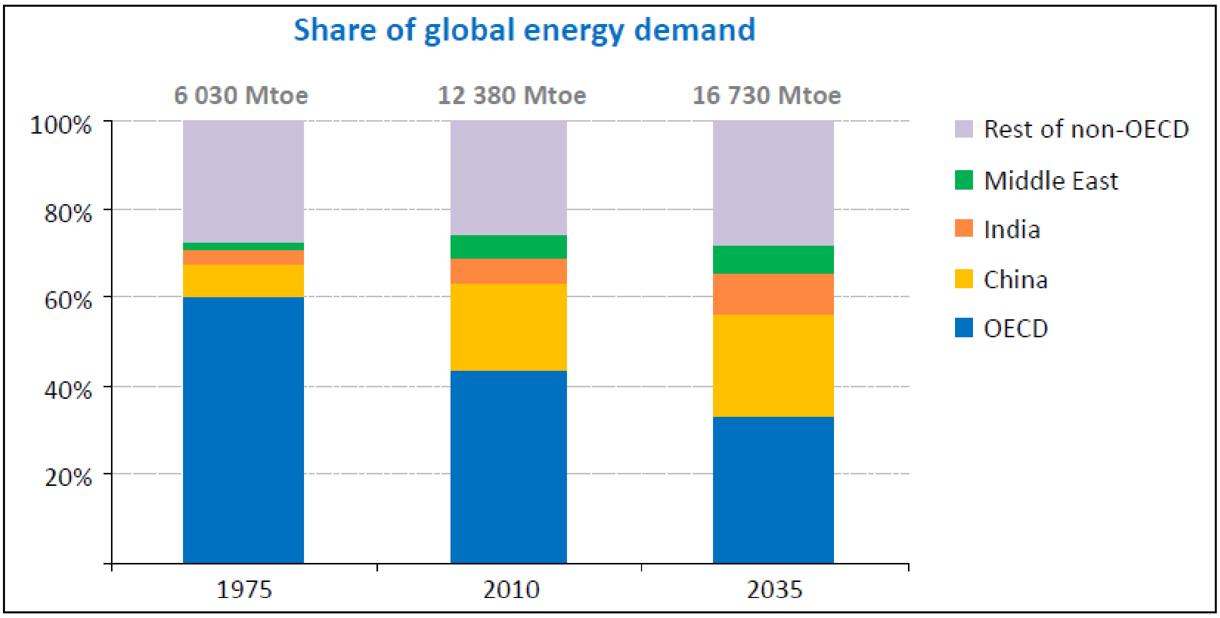
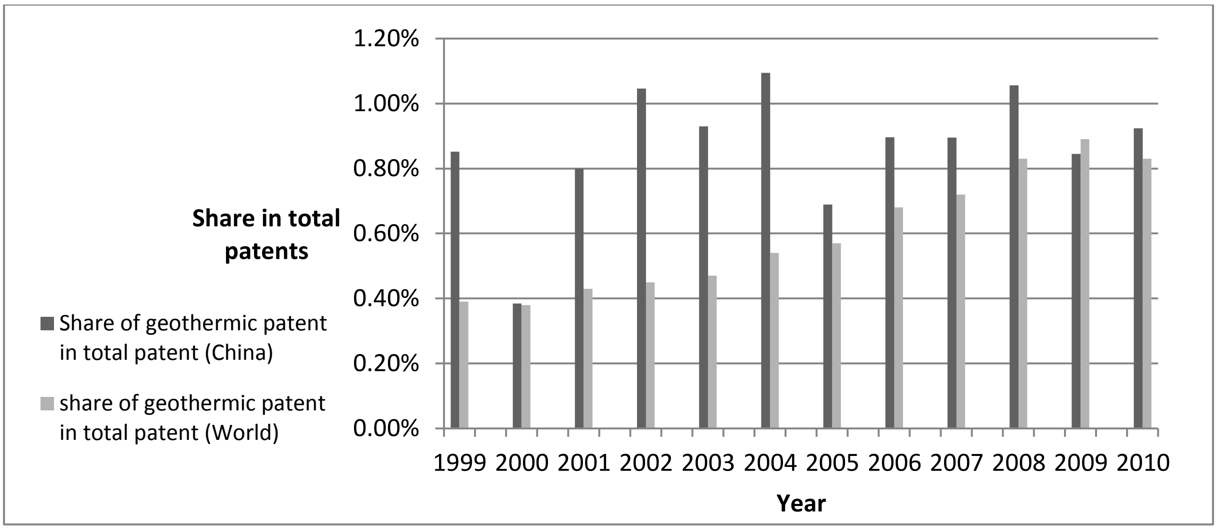


Figure 3:9 Increasing energy demand of China

3.3.3.3 Feasibilities of geothermal energy development

The technological advancement in geothermal energy exploration (IPC green inventory classification for geothermal direct heat use: H02N, F25B, F24J, F24F, F01K) can be observed with a quantitative escalation (Figure 3:10). Chinese innovation speed in geomaterial reutilization has been higher than the international level (China level 0.6% versus world level 0.4%). Therefore, this high technological capacity of the segment of geomaterial will help to upgrade the development potential profile at the national scale. Average share of geothermal direct heat use technologies is 0.87%, compared to 0.60% at the international level.



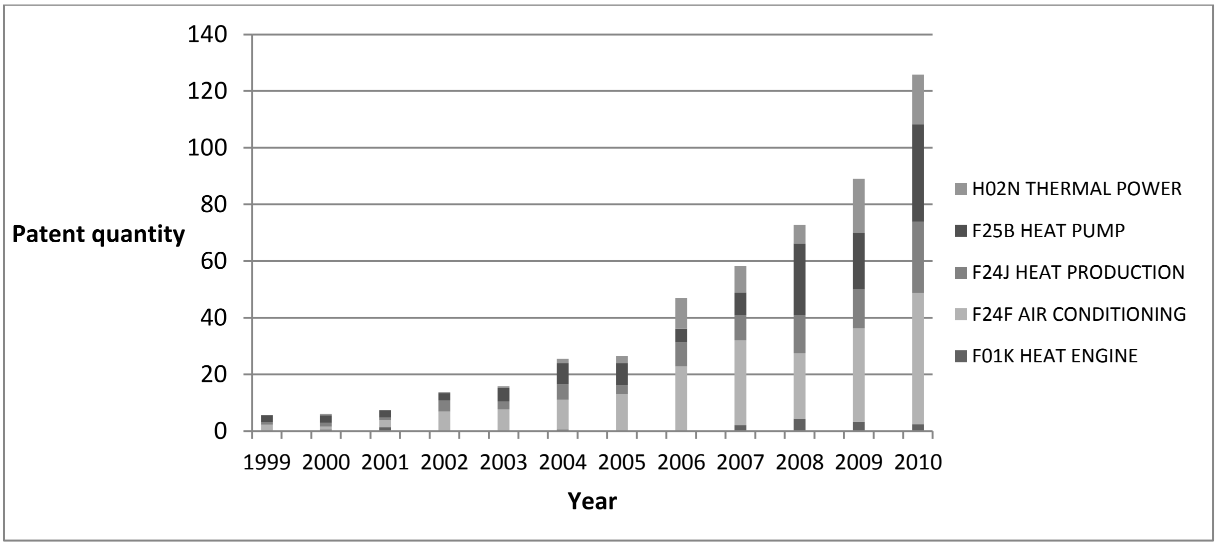


Figure 3:10 Share of geothermal energy exploration patents and quantity distribution with IPC codes (China)

Ministry of Land and Resources (MOLR) has initiated geothermal energy surveying, mapping and exploration projects during the 12th Five- Year- Plan (2011-2015), which listed geothermal energy as renewable clean energy with a goal to supply heating for 350 million square meters of building floor space during the five-year period. “Technical Code for Ground Source Heat Pump System (GB50366-2005)” took effect in 2006. The code plays a significant role for the development of geothermal heat pump industry.

3.3.3.4 Development potential profile of geothermal energy development

Innovation speed of geothermal heating use in China surpassed international level, making the feasibility score relatively higher (Figure 3:11). Having a total development potential score of 2.73 (91%), geothermal energy can be considered as an indispensable segment in sustainable underground urbanization. Coupling with the enhancing use of underground infrastructures and buildings in the country, synergetic development of geothermal system and underground foundation structures (energy piles and energy walls, Figure 1:32) could be promoted to upgrade its inter-segmental sustainability performance.

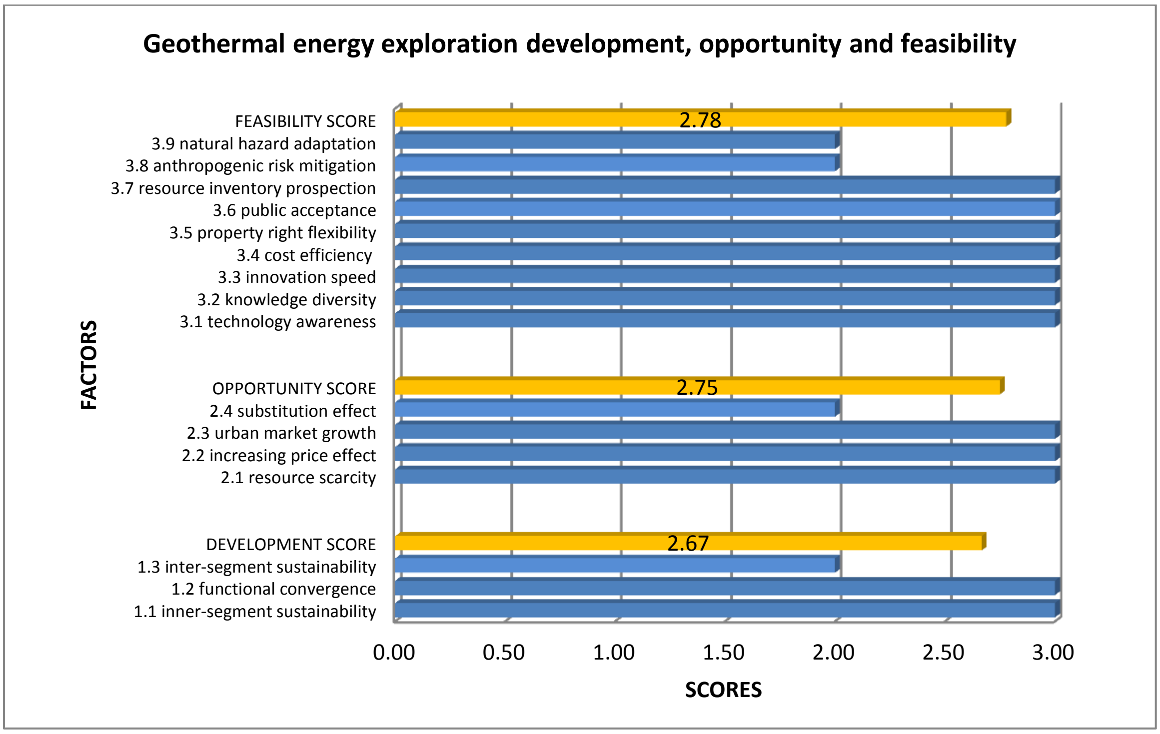


Figure 3:11 Chinese context: geothermal energy segment

3.3.4 Segment 4: groundwater in China

3.3.4.1 Development stage of groundwater

According to a survey from Ministry of Water Resources, there are 440 Chinese cities (61% of overall 657 cities) exploring groundwater for drinking water need, among which **70 cities are classified as "Sinking Cities"**, meaning cities suffering from land subsidence of more than 2 meters caused by over exploiting groundwater. Based on groundwater quality monitoring data in 2011 for 200 Chinese cities, **55% of monitoring points indicated a bad quality level of groundwater**, based on national groundwater quality standard (GB/T 14848-93).

3.3.4.2 Opportunities of groundwater development

Groundwater as strategic water reserve could supplement surface water supply, which has been suffering from increasing pollution problems around the country. In addition, the unbalance water resource distribution in the nation has been a constraining factor for national wide economic growth. A huge trans-provincial water transportation infrastructure network from south to north was constructed across Chinese main cities. With increasing urban demand for water resource, local aquifers can be considered as valuable resource to support economic growth while safeguarding municipalities' resource independency and security.

3.3.4.3 Feasibilities of groundwater development

The first Management regulation of urban groundwater exploration and protection was released by Ministry of Construction in 1993, who defined administrative procedures for licensing water well development. In 1998, this responsibility was transfer to Ministry of Water Resources (MOWR). To tackle the severe exploration problems, the State Council passed a political approval on the National Groundwater Protection Plan (2011-2020), requiring local Environment Department to coordinate with other departments in surveying, monitoring, controlling, repairing and managing groundwater exploration.

3.3.4.4 Development potential profile of groundwater development

A low performance level of inner-segmental sustainability (groundwater pollution) for groundwater development graded its development potential profile to be the lowest among all the four segments (2.06/3, 69%). The inter-segmental sustainability factor between groundwater and underground space should be improved to ensure geotechnical stability of underground infrastructures and buildings. Considering the high opportunity to supplement surface water supply for supporting increasing urban demand, protecting and managing groundwater resource during this enhancing era of underground urbanization is essential. Scores for factors are shown in Figure 3:12.

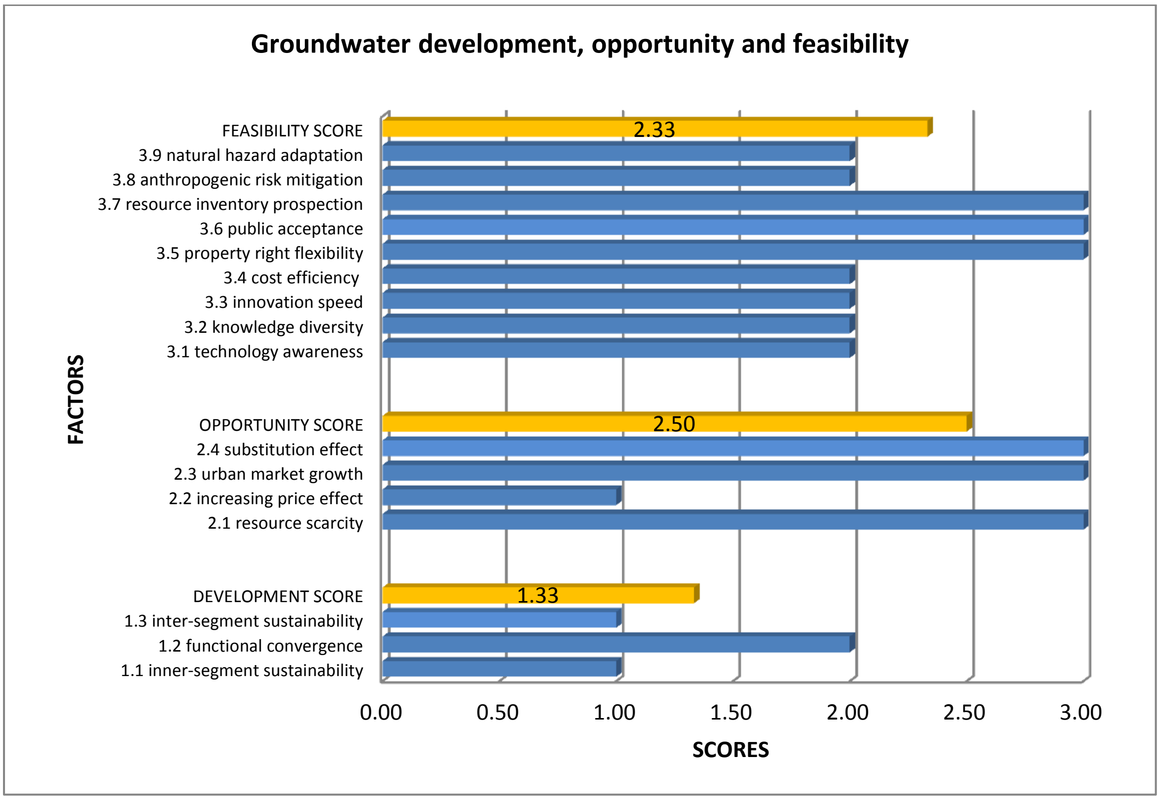


Figure 3:12 Chinese context: groundwater segment

3.3.5 Comparison among the four segments in China

Overall scores for the four segments in China are shown in Table 3:4, with radar chart illustration in Figure 3:13. Development potential of the four segments is unbalanced in Chinese context:

- ***High development potential profile: underground space and geothermal energy***

Driven by the world highest growth of medium-to-mega cities, underground urbanization in the Chinese territory has been spread from early civil defense function to mega urban transit complex development in recent decades. The development profile of geothermal energy exploration for direct heat use is also promising with higher innovation speed than the international level.

The good performances of underground space segment and geothermal energy segment are also reflected in domestic qualification innovations (domestic patent data from SIPO, applied technology patent type). With the same grouping for the three patent segments, annual patent quantities in 2011 are shown Table 3:3. The share of 2.30% in domestic Geo-space patent group is higher than the world wide average (1.50%). Domestic Geo-thermal heating patent share is also higher than the world average, 1.23% to 0.80%. Geomaterials reuse related patent share is slightly higher than international level.

Table 3:3 Domestic patent applications for the three segments (data in 2011)

Segment	IPC codes	Quantity	Share % in total patents 2011
Geo-space	Manual classification E02, E03, E21	23,239	2.30% (world level: 1.50%)
Geo-thermal heating	Green inventory F01K, F24F, F24J, F25B, H02N	12,435	1.23% (world level: 0.80%)
Geo-material reuse	Green inventory C04B	4,099	0.41% (world level: 0.36%)
TOTAL		39,773	3.94%

(Total domestic patent application quantity in 2011: 1,008,844)

- ***Moderate development potential profile: geomaterials and groundwater***

Material and water resource managements and their functional convergences are falling behind. Performances and feasibilities for these two segments are low, calling for broader geomaterial resource usage discoveries during underground development process, as well as wider political awareness for groundwater resource protection.

Table 3:4 Scores for the four segments in Deep City Method (China context overview)

Segments	Development score	Opportunity score	Feasibility score	Development potential profile
Geo-space	2.00	3.00	2.33	2.44
Geomaterials	1.67	2.75	1.89	2.10
Geothermal energy	2.67	2.75	2.78	2.73
Groundwater	1.33	2.50	2.33	2.06
AVERAGE SCORE	1.92	2.75	2.33	2.33

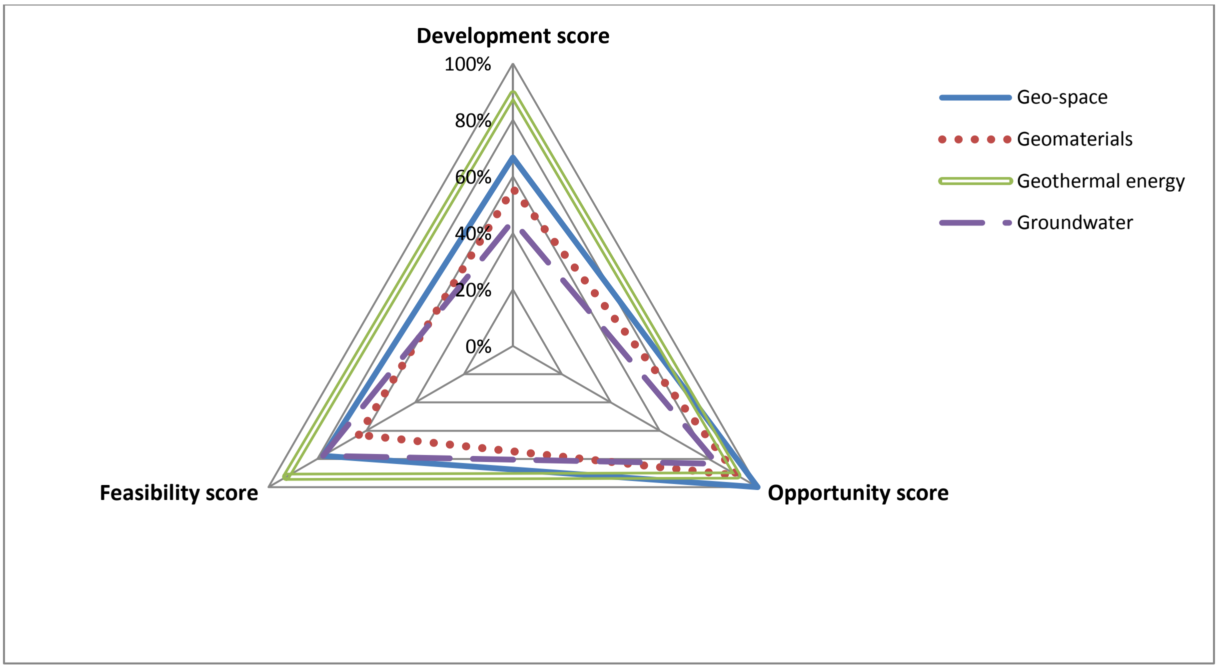


Figure 3:13 Chinese context: segmental development potential profile

3.4 Selection of a Chinese city to demonstrate sustainable underground urbanization with the integrated management process

3.4.1 City selection tool: "Deep City Applicability Score"

Numbers of candidate Chinese cities were examined with general criteria of geography, geology and population. Finally four representative cities were selected for further examination, according to their significant population size and diversity of geo-resources. These four candidate cities are Beijing, Shanghai, Nanjing and Suzhou. The comparison by rating in this section serves to identify a particular city which deserves an imminent management of the urban underground.

The economic importance of underground resources is determined by combining the value of resources and the macro-economy, which in turn aids in defining the applicability of underground urbanism for a particular city. "**Deep City Applicability Score**" is the potentiality of the urban underground to provide reliable building space, good-quality drinking water, safe geothermal energy and usable construction material, in response to urbanization demand.

3.4.2 Qualification criteria

It is supposed that, the level of potentiality can reveal to decision-makers the urgency of the city to manage its underground resources. Table 3:5 shows the criteria structure used in developing the score. Capacity of resources (A1) addresses the global potential of natural underground resources by qualifying geological characteristics. The macroeconomic context (A2) determines the quantitative demand scheme of using these resources along with urbanization, which induces increasing need in living space, water, energy and material supply.

Distribution of importance to the three level criteria is formulated by following arguments:

1) First level criteria: supply and demand (A)

We considered equal importance between geo-resources' supply capacity and urban demand in macro-economic growth, meaning urban underground's sustainability can't be achieved by overexploiting available geo-resources.

2) Second level criteria: supply potentials and demand driving forces (B)

According to (Dobbs et al., 2011), emerging opportunities in land, energy, water and material should be captured to support rapid urbanization by expanding alternative supply source and increasing resource productivity. At the developing stage of the urban underground, opportunities and potentials of exploiting these four subsurface resources define a supply capacity of underground urbanism. This is the reason of choosing sub-criteria from 1.1 to 1.4, representing potential types for underground resource supply.

Among the four criteria of supply, groundwater especially for drinking use is considered as the most important sub-criteria for the supply criteria, due to the increasing deficiency of drinking water supply in urban areas (Zektser and Everett, 2004). Since location of protected aquifer is considered as a spatial expansion limit for subsurface construction and geothermal drilling in the Swiss environmental regulations, subsurface construction potential zoning has to be compatible with aquifer protection zoning.

Urban population and living density as driving forces for underground development has been recognized by (Bobylev, 2009, Golany and Ojima, 1996b). An empirical study for Shanghai city showed both population density and Per capita GDP have positive correlations to the future demand of underground space (He et al., 2012). Therefore, three driving forces are included into demand sub-criteria from 2.1 to 2.3. Densification demand is weighted as the most important sub-criteria for demand side.

3) Third level criteria: quantitative and qualitative standard (C)

Information about the status of four resources and three driving forces was collected for cities selected below, from municipal geological department websites and statistic yearbook of these four cities. Quantitative and qualitative data is treated and classified on three standards (from most preferable to least preferable) for each sub-criteria. Classification of geological resources is based on previous research results on geo-resource potential evaluation by Deep City team (Blunier, 2009).

4) Final weighting (Table 3:6) and grading for selected cities (Figure 3:14)

Weights of sub-criteria are evaluated based on facts mentioned above, using pairwise comparison with Expert Choice Comparison Suite. Final score for each city is calculated as:

$$Deep\ City\ Applicability\ Score = A1 \sum_{i=1.1}^{1.4} (Bi \times C) + A2 \sum_{i=2.1}^{2.3} (Bi \times C)$$

Selected cities are placed in Table 3:5 according to their local contexts.

For example, the final score for Beijing city is calculated as:

$$0.5 \times (0.30 \times 0.69 + 0.45 \times 0.80 + 0.15 \times 0.21 + 0.10 \times 0.25) + 0.5 \times (0.22 \times 0.64 + 0.41 \times 0.65 + 0.37 \times 0.07) = 0.535$$

3.4.3 Selection of pilot city

Table 3:5 Criteria structure of "Deep City applicability score" and attributed weights

	A	Bi	C	Cities
Applicability criteria	**A1.** Capacity of resources – criteria of supply (0.50)	**1.1** Subsurface geotechnical quality (0.30)	- favorable condition (0.69)	Beijing, Suzhou
			- unfavorable condition (0.23)	Shanghai
			- presence of special risks (0.08)	Nanjing
		1.2 Groundwater quality and quantity (0.45)	- drinking water aquifer (0.80)	Beijing, Nanjing, Suzhou
			- low quality aquifer (0.12)	Shanghai
			- no aquifer under city (0.08)	
		1.3 Geothermal energy quality (0.15)	- high quality reserve (0.70)	Shanghai
			- conditional exploitation (0.21)	Beijing, Nanjing, Suzhou
			- restricted exploitation (0.09)	
		1.4 Geomaterial quality (0.10)	- valuable mines (0.68)	Shanghai, Suzhou
			- reusable material (0.25)	Beijing, Nanjing
			- material needed treatment (0.07)	
	A2. Macroeconomic context – criteria of demand (0.50)	**2.1** Urban population (0.22)	- over 5 million (0.64)	Beijing, Shanghai, Nanjing
			- between 1 and 5 million (0.27)	Suzhou
			- below 1 million (0.09)	
		2.2 Living density (0.41)	- over 5000 per/km^2 (0.65)	Beijing, Shanghai, Nanjing, Suzhou
			- 2000 to 5000 per/km^2 (0.22)	
			- below 2000 per/km^2 (0.13)	
		2.3 GDP per capita (0.37)	- over 50K USD (0.74)	
			- between 20K to 50K USD (0.19)	Suzhou
			- below 20K USD (0.07)	Beijing, Shanghai, Nanjing

The rating method enables a first insight into cities' urban underground diversity and current economic development level. The final choice for applicability test can be the highest-scored city; more considerations can also be taken such as significance of new emergence and outstanding economic achievement.

Table 3:6 Rating the Deep City Applicability Scores for four Chinese cities

Criteria	Beijing	Shanghai	Nanjing	Suzhou
1.1 subsurface geotechnical quality	0.11	0.04	0.01	0.11
1.2 groundwater quality	0.18	0.03	0.18	0.18
1.3 geothermal energy	0.02	0.06	0.02	0.02
1.4 geomaterial quality	0.02	0.04	0.02	0.04
2.1 urban population	0.07	0.07	0.07	0.03
2.2 living density	0.14	0.14	0.14	0.14
2.3 GDP per capita	0.02	0.02	0.02	0.04
Final scores	**0.54**	**0.37**	**0.44**	**0.54**

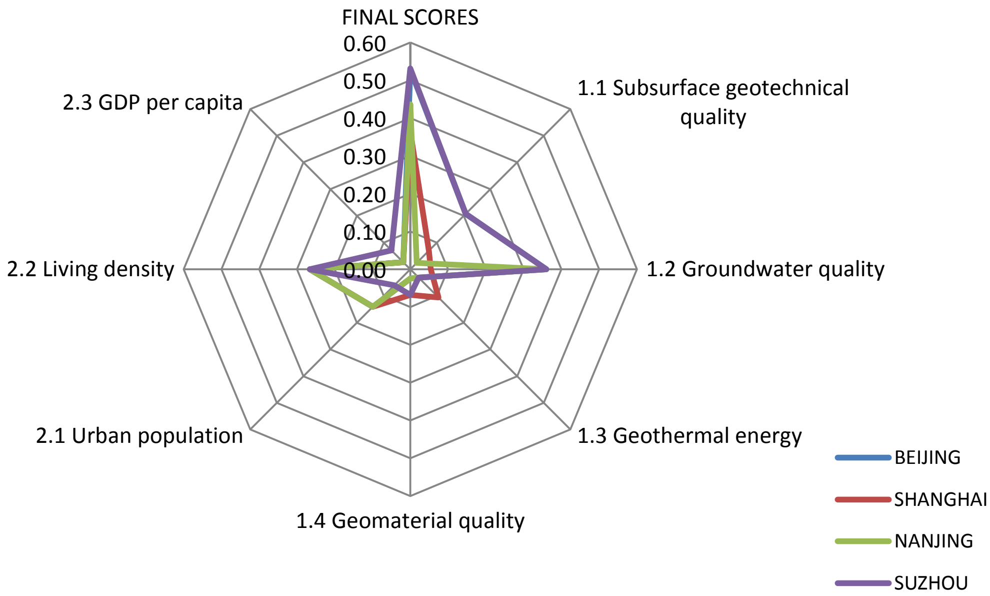


Figure 3:14 Deep City Applicability Scores of Chinese big cities

From the contextual analysis: Beijing and Suzhou are rated the highest applicability level, with high geo-resource capacity and a very high population demand. In China, the city of Suzhou is the earliest prefectural level city operating metro system. Its distinct economic achievement (highest per capita GDP: $25,500) allows us to use it as a case study city for demonstration and strategic analysis. The city of Suzhou also represents one of the new big cities coming up in China in the current urbanization stage. Figure 3:15 shows the ranking of economic contribution from 53 metropolitan regions in China (Kamal-Chaoui et al., 2009), with Suzhou city region being one of the most dynamic contributor ranked higher than Beijing and Nanjing.

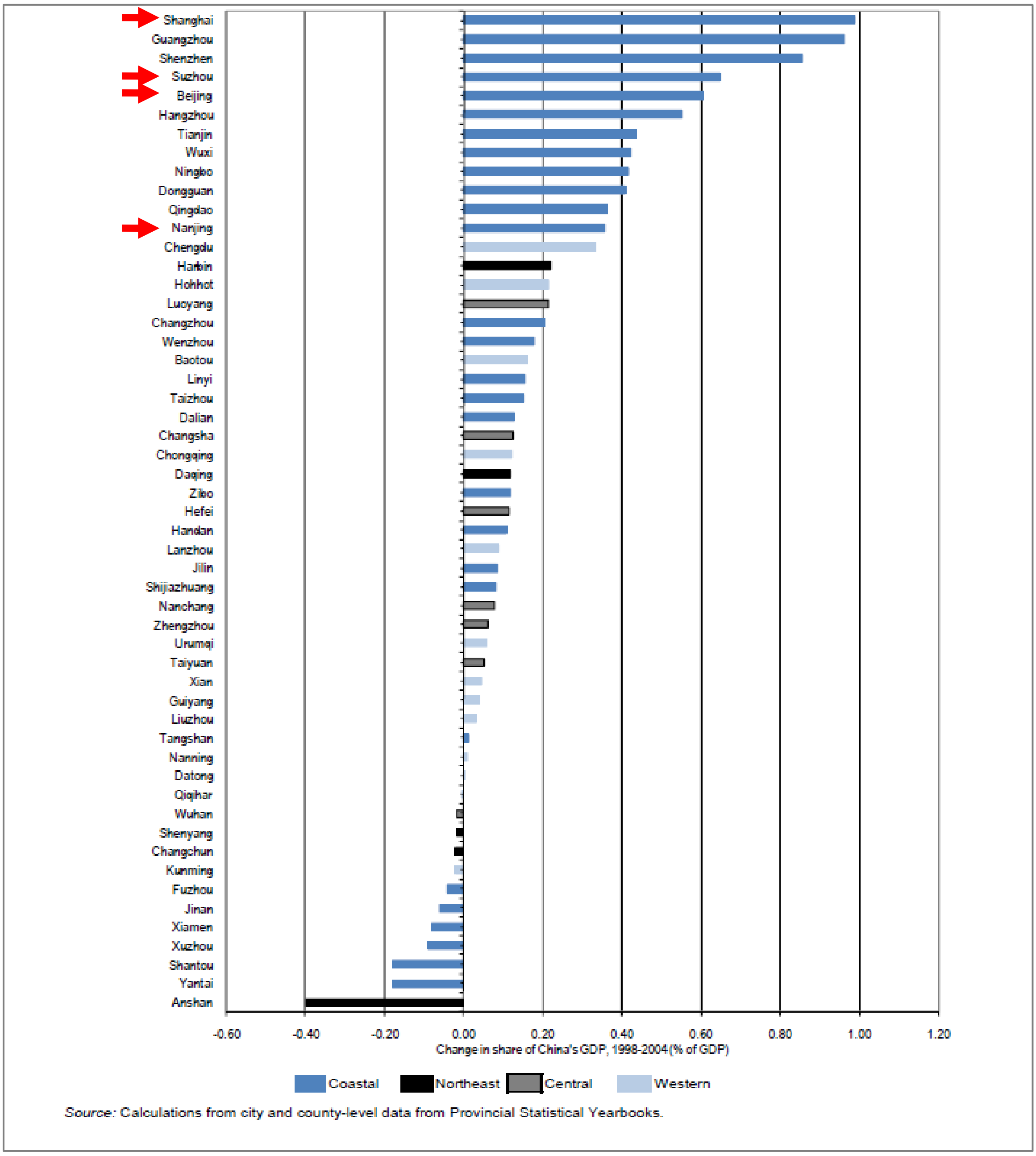


Figure 3:15 Change in metropolitan region's share of China's GDP (variation between 1998 to 2004)

3.5 The Deep City China project: a trans-institutional collaboration

3.5.1 Project team

Activities of the present research were initiated from 2009, supported by a joint venture between Swiss and Chinese governments: the Sino-Swiss Science and Technology Cooperation (SSSTC) and by Ministry of Science and Technology of China (MOST). As one of the major funding instruments to support innovative scientific research and to promote private sector involvement, the collaborative form in Joint Research Project (JRP) favored several priority areas, one of which was "Urban Development and Sustainability".

The present project named "Underground Resources Management for Urban Sustainable Development: Comparison between Swiss and Chinese Contexts" was completed in 2012 ((Li et al., 2013a, Li et al., 2013b) , with active academic exchanges and local city involvements. It was a trans-disciplinary study linking engineering, geology, economics, urbanism and administration. 37 scientific publications were diffused internationally, while three patents and one software copyright were certified in China during the project execution. The pilot project focused on Suzhou city's underground development in Central Business Districts, aiming to formulate a strategic framework and an operational process in the transformational era of a midsized city to big city. The Project team and involved institutions are shown in Figure 3:16.

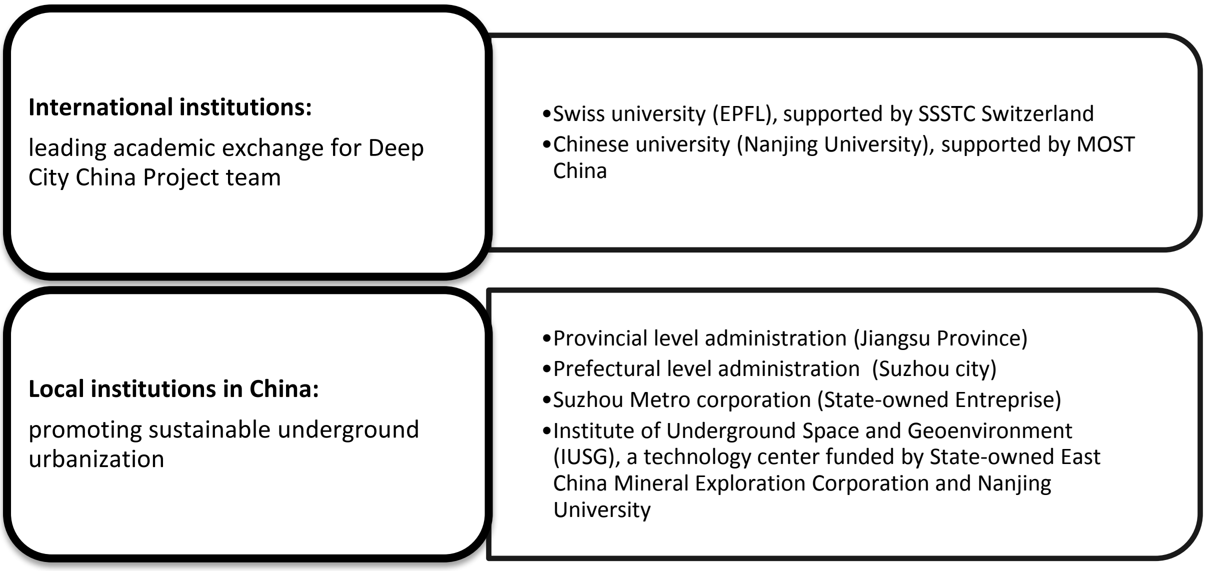


Figure 3:16 Deep City China Project team and local city involvement

As one of the Chinese cities advocating underground space use, the typicality of the case study can be reflected from an alignment between advanced technology application and policy making by creating trans-institutional interlocution. Purpose of the research to align technology with policy making was coordinated with opinions from United Nations' resolution in 1983, on the utilization of subsurface space in developing countries. Since strategic levels and operational levels of urban development involved both provincial and prefectural institutions, communication program including several governmental meetings and individual interviews were carried out from 2010 to 2012.

3.5.2 Interactions with local administration

Within the Deep City China project team composed of Swiss and Chinese researchers (EPFL and IUSG), there were three short-term periodical academic visits organized between the two universities partners, enabling to share international experiences and develop complementary knowledge package for sustainable underground urbanization. After the pilot city selection made during project start-up period at the end of 2009, the technology center of IUSG (a private public institute hosted by partner University) was commissioned by the Jiangsu Provincial Department of Land and Resource, on a two-year mandate for urban underground resources prospection and evaluation in Suzhou city region. Table 3:7 below lists activities between Deep City China team with local administrative bodies.

Observations from various governmental meetings and exchanges indicated advantages and disadvantages of local context on developing and managing the urban subsurface:

- Advantages and potentials:

  Promising technology level and increasing R&D input in underground construction and exploration; growing demand for underground space and resources due to rapid urbanization; functional convergence between tunnel, basement and complex became feasible; conventional resource scarcity became a constraining factor for urban growth; enhancing quality of underground space while broadly accepted by the public; encouraged joint development of civil shelter space and commercial property.

- Disadvantages and challenges:

  Insufficient knowledge diversity for resources exploration; insufficient consideration of the notion of sustainability into subsurface development; higher investment costs due to shallow subsurface congestion caused by dense foundation and utility layers; strong control of public ownership; frequent geotechnical accidents in soft soil engineering; recovery stage from land subsidence risk; increasing concerns on pollution incurred from the surface to subsurface.

Table 3:7 Deep City China project team and pilot city: communication program from the year of 2010 to 2012

Year/Month	FORMAT & PURPOSE	INSTITUTIONS & FIRMS
2010.03	**<u>Symposium</u>**: Improve political awareness of administrators and initiate capacity building of planners for underground sustainable urbanization and geo-resources management	• Leading party: IUSG and EPFL • **Jiangsu Provincial level institutions**: -Development and Reform Commission -Housing and Urban-rural Construction Department -Land and Resources Department -Civil Defense Bureau • Domestic and oversea research institutes
2010.07	**<u>Workshop</u>**: Professional training for Deep City Method	• Leading party: EPFL • **Jiangsu Provincial level institution**: -Land and Resources Department, Geology Office
2011.05	**<u>Official Meeting</u>**: City level investigation on operational feasibility of Deep City Method	• Leading party: Provincial Land and Resource Department and IUSG • **Suzhou Prefectural level institutions**: -Population and family planning Commission -Land and Resources Department -Water Department -Transport Department -Housing and Urban-rural Construction Department -Civil defense Department -Urban planning Department -Utility Service Department -Cultural heritage Department • **State-owned Enterprises (SOE):** -Suzhou Metro Corporation -Suzhou Power Supply Company
2011.06	**<u>Field Study</u>**: Project level survey of underground infrastructures and buildings, soil reclamation site, subsidence monitoring center	**Construction sites and soil disposal site:** -Suzhou city metro line 2 *tunnel* -Land reclamation site (tunneling soil from metro line 2) -Suzhou land subsidence monitoring center -Suzhou city Wanda commercial *basement* and pedestrian network -Suzhou city metro line 1 station CBD *underground complex* (linked to landmark building: the Orient Gate) -Nanjing city south railway station *mega underground complex*
2011.06	**<u>Interview:</u>** Provincial level policy making feedback	**Public administrators**: -Provincial urban spatial planner -Provincial Civil Defense Bureau director
2012.02	**<u>Interview:</u>** Project level survey of underground complex in CBD	**Project developer**: Suzhou city CBD SSIP state-owned land developer

Relationship between Deep City China Project team (EPFL and IUSG) and local administrations are shown in Figure 3:17. Interactions between the multidisciplinary project team and local administration attempted to transfer international knowledge and testify robustness of the Deep City Method in a demonstrative city.

- Strategic level: political awareness and administrative readiness should be developed through knowledge transfer and capacity building. The symposium and workshop targeted to provincial level administration helped to diffuse Deep City Method and establish institutional consensus.

- Operational level: development feasibility and potential should be investigated through local decision makers and project executors. The local meeting and field study involved by prefectural administrators and public-private entrepreneurs (SOE) helped to specify stakeholders' interests and to align local regulations with technological feasibility.

- Coordination: implications from demonstrative project should be channeled to policy makers for administrative coordination and managerial instrument upgrade, in order to generalize the strategy for other cities.

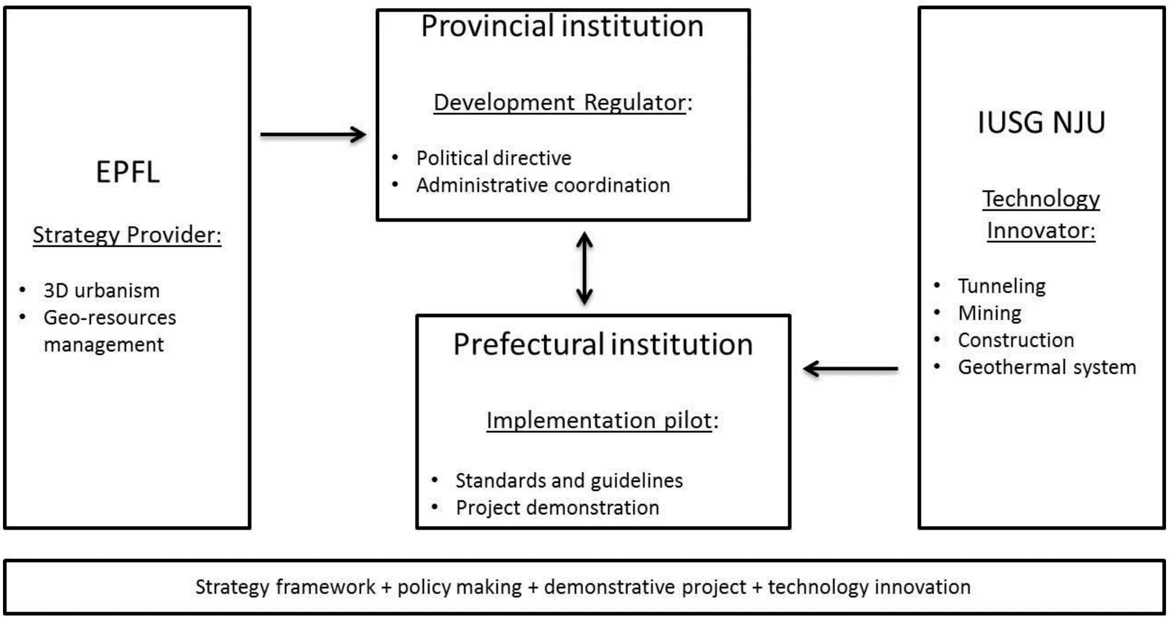


Figure 3:17 Interactive relationship between Project team and local administration

3.6 Project demonstration and methodological application: case study in Suzhou city

This section devotes to apply the Deep City Method in a demonstrative case study for a Chinese city. Since the city of Suzhou was selected on the merit of its resource diversity and its economic potential, the four segments of sustainable underground urbanization will be firstly investigated in section 3.6.2, to have an insight on a global development potential profile, by analyzing the motivation from urbanization, segmental performance and feasibility challenge.

And then in section 3.7, the integrated management process (Figure 3:1) will be used to demonstrate how the Project team followed each step in this process through the communication program (Table 3:7), in order to give recommendations on city level policy making and project level evaluation. Feasibility of proposed instruments was discussed through personal interviews of planner and developer for validation.

3.6.1 City profile of Suzhou

Suzhou city, producing the second-largest economic output in the cluster of Yangtze-River Delta (YRD) Megalopolis (location shown in Figure 3:19), will be a 5 million populated city before 2020 (Population Division, 2012). Demographic growth in urban area is shown in Figure 3:18. Its key industries are ICT, Chemicals, textiles, electronics and machinery (37.9% of urban economy). Tertiary sector (finance, trade, services) counts for 34.2% of urban economy. Current urban population is 3.248 million (with registered urban residence), being 54% of total inhabitants.

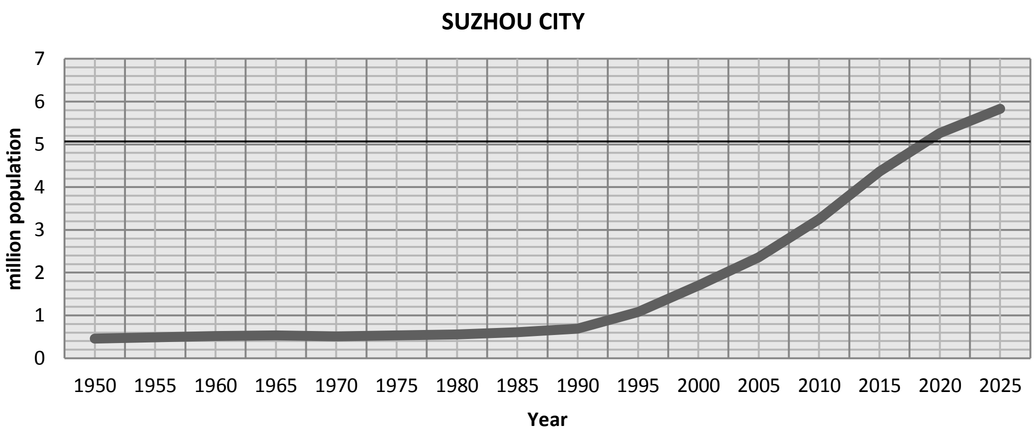
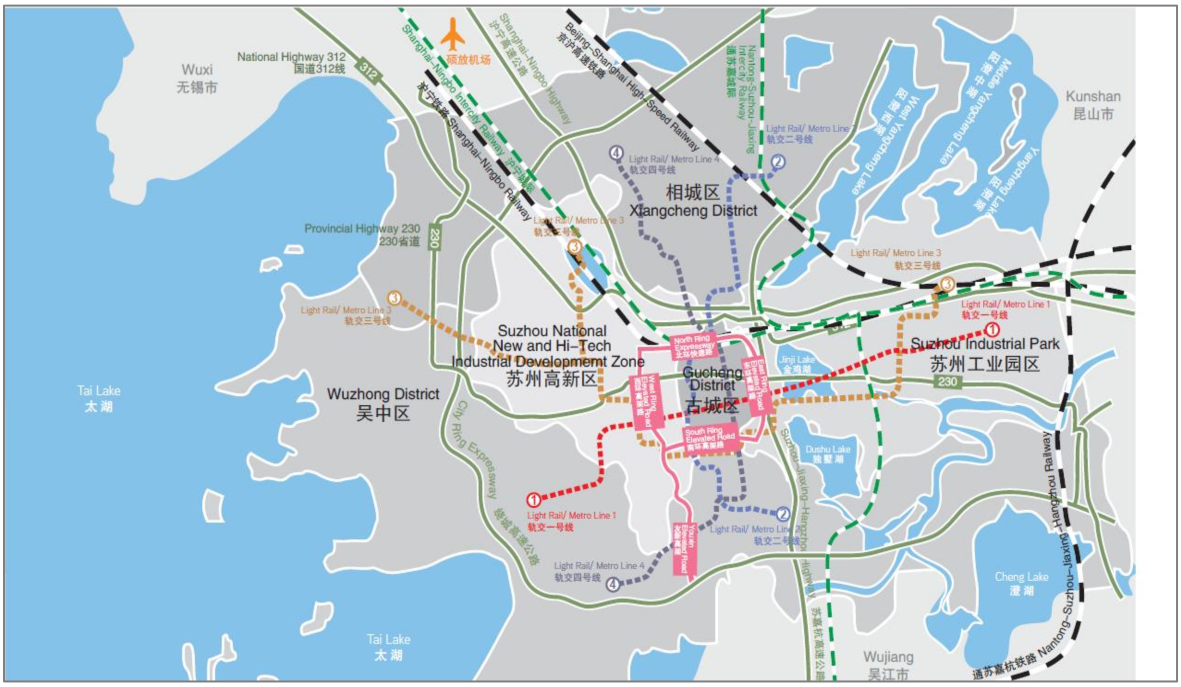


Figure 3:18 Urban population growth in Suzhou city from 1950 to 2025

Figure 3:19 Location of Suzhou city region in Yangtze-River-Delta megalopolis

It is a city undergoing specializing process from small city industrialization to big city transformation, putting more and more focus on providing pubic infrastructures and better quality of life. According to the annual report from China Institute of City Competitiveness (CICC) in 2012[79], Suzhou city was scored as the first livable city in China, considering by performance index on local governance, economy, environment and culture. Transport infrastructures have been built with escalated scale to serve rapid urbanization demand, as shown in Figure 3:20.



(Land area colored in grey, water surface colored in blue)

Figure 3:20 Suzhou city: administrative divisions (Gucheng, SSIP, SND, Xiangcheng and Wuzhong), transport infrastructures (metro lines, railways, ringroads, highways, airport)

79 http://www.china-citynet.com/yjh/en/fyphb_show.asp?id=2255 CICC Ranking list

The annual report 2011 of the State Intellectual Property Office of China (SIPO) showed that, Jiangsu provincial invention patent application number stood on top of all the other provinces and regions (84678 in 2011, sharing 20% of annual invention patent application in the country). From Suzhou Statistical Yearbook 2010, prefectural invention patent application has increased with an average of 56% annually from 2000 to 2009. But there is not detailed data found for each technology type. R&D expenditure of Suzhou city was 2% of annual GDP in 2009, producing the highest patent quantity among overall Medium-to-Large cities in China.

3.6.2 Suzhou city's segmental underground development potential profile

Understanding the segmental potential profile of Suzhou city's underground development could serve as a basis for city level strategic management, by analyzing external opportunity, internal performance as well as implementation capacity, to guide policy initiation and operational program establishment (Hunger and Wheelen, 2011). Implementation barriers and challenges were investigated through the official meeting in 2011 (communication program in Table 3:7), by collecting feasibility issues for segmental development.

This section will group the segmental analysis into two parts, including general opportunity outlook for urban underground development and segmental feasibility insights. The city of Suzhou was selected by its full portfolio of the four geo-resources, as evaluated in section 3.4. Since the city is in early stage of underground urbanization, its demand driven development path raised series of technical issues and led to regulatory adjustments by local administrations. Coupling observations on current development stage and feasibility insights, implementation issues are classified based on the three strategic questions (administrative arrangement, supply side management and demand side development) for the four segments.

3.6.2.1 Opportunities for using the urban underground

3.6.2.1.1 Resource scarcity

The evolution of urbanized land is shown in Figure 3:21, with annual urban land growth rate of 16%. Built-up area surface quadrupled in less than ten years after the land reform policy. Farmland resource has been reduced by 23% during the decade from 2001, with an average annual decrease of 3.16%. This farmland reduction rate was five times higher than the rate of 0.65% in the last decade (Li and Yang, 2005). According to the land value monitoring report in 2007, construction land supply was reduced by 30% from 34.6 km^2 in 2006 to 24.2 km^2 in 2007, especially commercial land supply (18% annual reduction) and industrial land supply (74% annual reduction). Farmland preservation and housing land provision became the priority of land resource management. Housing land supply increased by 107% annually, while affordable housing land was the major land use supply with an incremental rate of 188%.

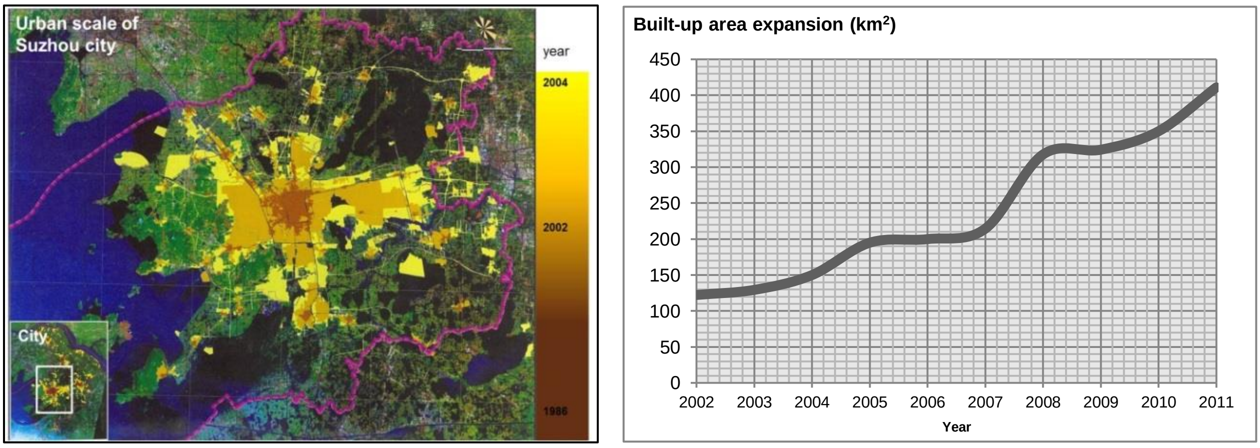


Figure 3:21 Spatial expansion of Suzhou city from 1986 to 2004 (from Suzhou urban planning bureau) and built-up area expansion from 2002 to 2011 (from Suzhou statistical yearbooks)

According to (Zhang et al., 2009), the urban growth elasticity index[80] in Suzhou was 2.01 during the period of 2000 to 2005, compared to 0.53 during the period of 1995 to 2000. The national level rational standard is 1.12. Considering the urbanization trend (Figure 3:18) during the period of 2010 to 2025, urban growth elasticity index will rise to 3.0, causing more and more pressure on urban land supply. An empirical study showed that GDP and urbanization rate were the main drivers of the expansion of construction land in Suzhou (Li et al., 2007). In order to maintain the rapid urban economic growth and urban livability, a "concentrated urbanization" mode has been proposed for the development of Suzhou city (Ngo, 2011).

Resource supply in material, water and energy are mainly from importation. Intensifying urbanization generates substantial demand for construction material. However, surface quarrying activities have been abandoned from 1999 in order to protect mountain landscapes, addressed by a regulation approved by Suzhou Prefectural People's Congress. Water consumption volume in the city has been increased by 61% from 2000 to 2011. Annual water supply report of 2011 indicated that, 37% of total water supply was from importation. It was reported that Suzhou city's local energy stock was nearly zero in 2005, with energy imports supporting overall consumption (Liang et al., 2010). Prospecting reliable local resource supply becomes urgent for the city to fulfill future resource demand.

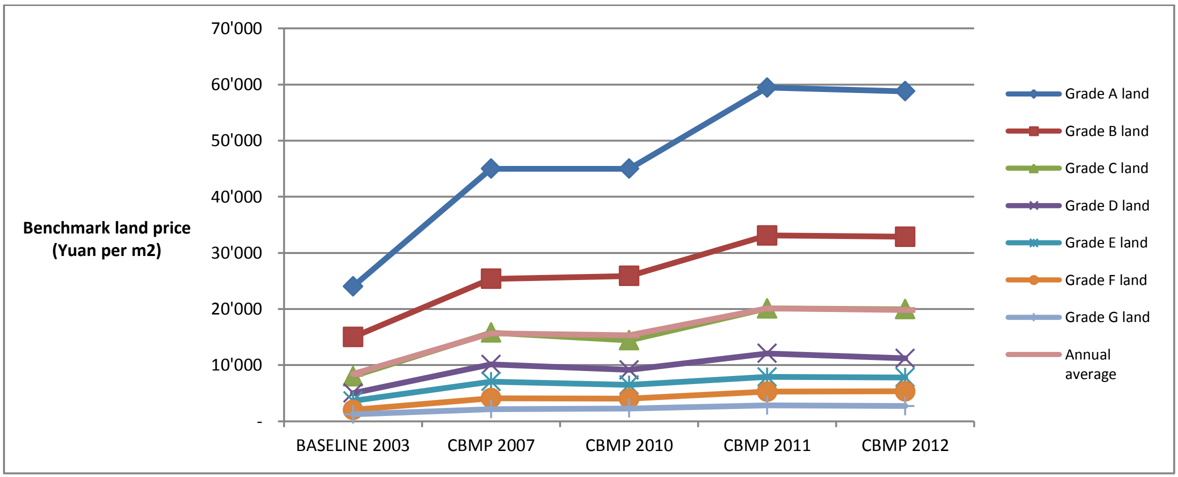
3.6.2.1.2 Increasing land prices

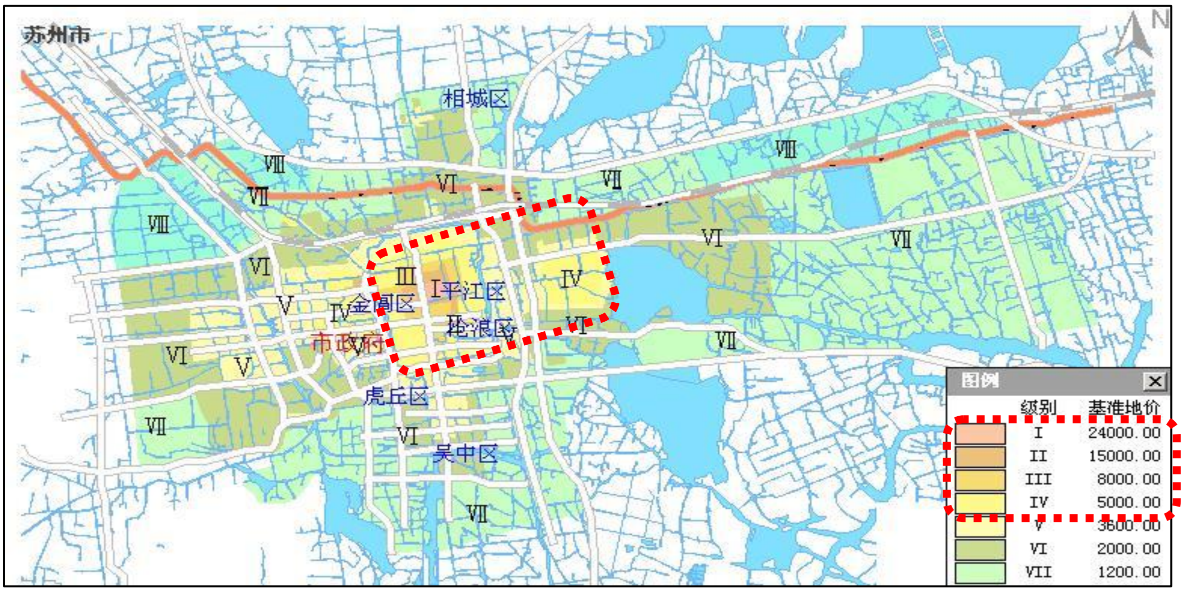
From urban land price monitoring data offered by Land and Resource Bureau, who selected 200 market monitoring land parcels for long-term observation from 2003, indicated a high increase in commercial land price in the city of Suzhou (Figure 3:23). The commercial benchmark land price index was 235.72 in 2011, 40% higher than the national level in 2011[81] (Figure 3:4). Land price value was classified on 7 grades from A to G, defined by criteria of physical form, density limit, accessibility, utility infrastructure and land use right terms related to land parcels. Spatial

[80] Urban growth elasticity index = annual growth rate of urban land / annual growth rate of urban population

[81] National level commercial benchmark land price index used 2000 as baseline index, here we use the year of 2003 for Suzhou city.

classification of these land grades is shown in Figure 3:22, with price evolution from 2003 to 2012. The highest price levels are in Old City core (Gucheng district) and SSIP CBD area.





(Spatial monitoring for baseline year 2003 CBMP: I for Grade A, II for Grade B…VII for Grade G)

Figure 3:22 Suzhou Commercial Benchmark Land Price (CBMP) growth and spatial monitoring results

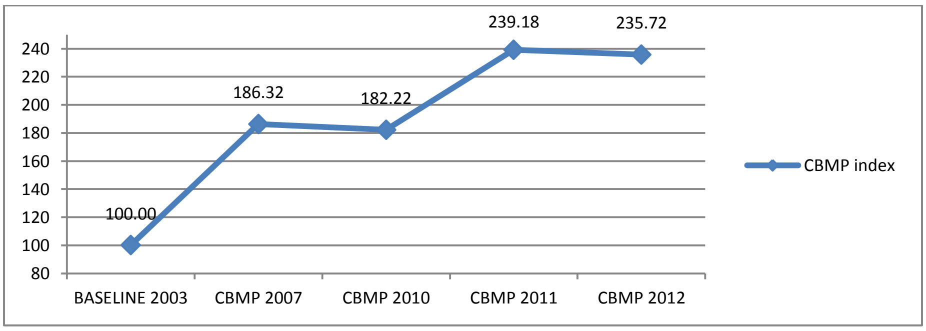


Figure 3:23 Suzhou CBMP index growth from 2003 to 2012 (average price of the 7 land grades)

3.6.2.1.3 Urban market growth

Building sector:

A survey from Jones Lang Lasalle studied cities' economic competitiveness and real estate business potential (Jones Lang LaSalle, 2006) and graded Suzhou city as one of the competitive cities for business sector in China. As one of leading destinations for Foreign Direct Investment in China (16,810 foreign invested firms including 107 Multinationals in Fortune 500), the city expanded its urban boundary by zoning two industrial parks outside the Old City Core (Gucheng district) including: the Suzhou National High-tech Industrial Development Zone (SND) and the Suzhou Singapore Industrial Park (SSIP). The latter has been undergoing transformation into a Central Business District (CBD) of Suzhou city, providing 75% of the total office buildings and most of the retail properties in the city. According to Colliers International's reports of 2011 and 2012, average annual growth of real estate investment in Suzhou city was 24% from 2006 to 2010, while average annual retail sales growth is 19.4% for the same period. Vacancy rate of high quality office decreased from 24% to 13% from 2008 to 2012.

Infrastructure sector:

With respect to urban infrastructure, the transportation network includes ten highways, four metro lines (two in service and two in construction), and five railways (three in service and two in construction). Along with the opening of metro line 1, five large retail projects were launched in 2012 with direct connection from basement level to metro stations. An underground complex named Central Station (see Figure 3:54 in section 3.7.3.3) was launched to supply 50,000 square meters of retail space in 3 basement levels above a subway station, with nearly 90% of these retail space have been leased. This wave of retail projects linking to metro stations symbolized an expansive trend of underground space use in Suzhou city.

3.6.2.2 Segmental development and feasibility investigation

3.6.2.2.1 Segment 1: Underground space

1. Underground infrastructures:

<u>Rail transit system:</u>

Suzhou Metro line 1 covered 25 km, having 24 subterranean stations. It cost 9'357 million Chinese Yuan, an average cost of 419 million Yuan per km length. Compared to other metro lines in Beijing and Shanghai, which spent about 15% to 30% of total costs on relocation of existing urban infrastructures, relocation costs in Suzhou Metro line 1 covered only 4.2% of total expenditure (Jie and Wang, 2008), thanks to a more careful redevelopment plan along transit lines. Land around all the subway stations was zoned to a catchment circle with 300 to 500m, where mixed use property development around transit lines is promoted to maximize the value of land and transport system.

Because this transit line passed through the Old City core, where located numbers of historic gardens listed in UNESCO and hundreds of city level listed protected buildings, the choice for underground transit line instead of elevated or surface network helped to safeguard the heritage conservation purpose and save additional land allocation. It was estimated that land supply savings reached 2,657,000 square meters by choosing the option of underground rail transit system.

In order to economize the construction volume of subterranean station, the Metro operator chose small-sized rolling stocks (vehicle) with higher service density to maintain passenger flow demand. It was estimated that cutting one metro vehicle (20 m length) could reduce subterranean station construction costs by 10 million Yuan. Construction of buried station buildings employed Soil Mixing Wall, a new technical method costing 6200-6800 Yuan/m^2, which is one third of the price for conventional deep diagram wall technologies. Combined technology of shield tunneling and station mining helped to reduce overall construction costs. Benefiting from the fast growing industrial innovation in the country, 74% of the equipment of the metro system was produced domestically and was less costly than imported equipment.

Total metro line length planned and approved by State Development and Reform Commission reached 173.6 km, with most of the metro stations built below ground. Passenger traffic volume carried by the operating line 1 was 38,502,300 person-times.

- ***Challenges pointed by Suzhou Metro Corporation:***

1) Technical issue:
   Due to the complexity of Suzhou city's geological environment, more geotechnical information should be obtained through city scale resource survey, in order to optimize metro line alignment, avoid engineering uncertainty and project over cost. The boundaries of protected aquifer layers beneath the city were not well defined, and there are no specific regulations to restraint spatial conflicts related to underground resources. Surface drinking water protection area has been considered into environmental assessment before construction operation.

2) Functional design issue:
   Coordination with Urban planning department will help to avoid relocation expenditures for existing utility infrastructures and to redevelop the construction land around. Since the protection buffer of metro lines is around 60 meters in both sides (stated in Suzhou rail transit management regulation 2011), construction of the four lines will cover an urban land footprint of 20.76 km^2 (5% of built-up zone). The Corporation owns the development right of this land area for mixed use utilization.

3) Financial issue:
   Subway capital costs are 10 times higher than that of surface road system. The Transport Department mentioned that, financing the ring road elevated system has already suffered from severe debt problem, with annual revenue only enough to pay one third of bank loan interest. **According to the regulation 2011, land parcels inside the metro station catchment radius of 500 meters can be sold by the Corporation through auctions, in order to finance the metro construction and operation.**

4) Heritage and landscape preservation issue:
   Due to the density of urban heritage in Suzhou city (310 conservation units), tunnel construction operation had to pass through authorization of Cultural Heritage Department when excavating near the old city core. Strict preservation regulations required advanced engineering solutions to reduce damages on existing heritage buildings, which were usually with weak foundation and quite dense along narrow roads in the old city. Some metro line sections will pass below national ecological protection zones, impacts had to be justified by environmental assessment.

<u>Multi-utility tunnel:</u>

After a demonstrative utility tunnel of 1 km built in 2008, another large multi-utility tunnel of 10km was planned for offices and hotels in the CBD area (Wang, 2012). Combined with a road tunnel construction (3 km) under the lake in SSIP district, a multi-utility tunnel was built inside the road tunnel, housing various pipelines while limiting subsurface exploitation volume. Type and quantity of pipelines determined the dimension of utility corridor, which is not only a functional system but also an accessible space for maintenance work and renewable infrastructural system.

Suzhou city is among the few Chinese cities operating common utility tunnel infrastructure, including Shanghai, Beijing, and Shenzhen. Under-utilization of this utility form in Chinese cities is mainly due to administrative consensus failure and high investment cost. Average construction costs are 100,000 Yuan per meter of utility tunnel, compared to an average cost of 2,000 Yuan per meter for conventional single pipeline. Therefore, the functional convergence with utility tunnel and road tunnel under SSIP district helped to maximize unit underground space value.

- ***Challenges pointed by Suzhou Underground Pipeline Service Office:***

1) Technical issue:
   There are currently 166 underground pipelines with a total length of 3600 km, providing utility services in water supply, sewage, gas, electricity and communication by 18 pipeline property owners (rights-of-way). Most of the lines are located within 5 meters depth under road surface, with the deepest sewage down to 10 m and the deepest electricity cable down to 20 m. Density

of utility infrastructures is: 600 km length of underground pipelines per 1 km of road. During underground construction process, utilities of high priority protection are water related pipelines (rain, tap water, sewage), due to the high capital costs for relocation. The complexity of utilities made this infrastructure form difficult to be realized in the already dense old city core.

2) Institutional issue:
   There is not a centralized platform to collect and monitor operation and maintenance of these pipelines. An information system is being established inside the office for public use. The newly released Suzhou urban underground pipeline management regulation (2007) did not impose the development of multi-utility tunnel at a city scale and there was no a technical guide for project execution.

2. Underground buildings and complexes:

<u>Commercial basement and underground complex:</u>

Most of the high rise buildings own deep basement structure, due to the reason that basement foundation can be deep enough to rest in the geotechnical bearing layer (hard soil or bedrock) making the building more stable, preventing from vertical and lateral geological movements (Chew, 1999). Another advantage of basement foundation is to create room for many purposes, such as parking, maintenance, sports center, art hall, etc. Two-level basement type buildings became common in the CBD of Suzhou city, where an average building height reaches over 100 m. Local regulations for Old City area redevelopment have restricted the expansion of existing buildings including downward extension, complied to old town conservation laws.

Construction technique selection for basement foundation depends on multiple factors such as safety, environment, duration and costs. According to a report of China Construction Bank (Suzhou branch) on value engineering method for decision making, demonstrated with a project with basement foundation (12 m depth, 32% of total building space), safety criteria and waterproofing criteria have higher importance than duration and constructability. Thus, technical feasibility will play a critical role for the basement type project.

The tallest building in Suzhou city (The Orient Gate, 278 m height, image in Figure 3:24) has five basement levels deep to over 20 meters and links to a metro station of three basement levels, forming an underground complex. Basement level 1 and 2 are used for retail leasing and station entrances, level 3 and 4 as parking and level 5 for private wine storage. According to its main contractor Shanghai Construction Group, this construction work was graded as high level geotechnical complexity according to national civil engineering standard. Various foundation techniques were deployed to maintain the co-stability of the deep basement and subterranean station (Peng, 2010).

Figure 3:24 The Orient Gate underground complex: commercial basement + subterranean station + metro tunnel (total floor space: 500,000 square meters)

➢ ***Challenges pointed by Suzhou Urban Planning Department and Construction Department:***

1) Technical issue:

   Lack of information about geotechnical bearing layers influenced the basement dimension design of high rise buildings. City level geotechnical survey could serve to select location and dimension for underground buildings. The planning department needs to know restricting factors in the subsurface to plan construction sites, such as aquifer boundaries, heritage preservation zones and subsidence risk zones.

   The construction department mentioned the importance of investigating operational performance of existing underground space in the urban center, with concrete floor space data of underground buildings collected from owners. This knowledge basis will serve as technical guide for future underground space construction and utilization. Coordination with all the agencies is critical to know the current utilization performance of underground space, including infrastructure and building type space. Status investigation and performance monitoring serve to update regulatory terms in existing building codes and facility management rules for underground space.

2) Institutional issue:
Development of underground buildings was initiated by private developers, motivated by the fact that underground floor space has not been accounted into density calculation. With the increasing scale of basement and complex space, development right of underground space should be stratified in general land use right, in order to avoid functional conflicts with other users in the subsurface. Underground construction projects beneath public open space were not regulated by related laws such as park act and road act.

According to a study conducted by Construction Department in 2012, building type has been transformed from low rise to high rise, with more and more basement foundation construction. Overall building project in the city covers 25,000,000 square meters of floor space areas annually, with 2,500,000 square meters underground. Including infrastructure project, annual total underground space construction reaches 5,000,000 square meters. **The rate of development attains 20% in total fixed assets.** Despite this expanding trend, there was no regulatory instrument to supervise the whole development process, as well as no incentives to attract developers' interest in using the underground to maximize land use value. The department is drafting a provisional underground space construction regulation, by collecting instrument references from other cities in China and oversea.

<u>Civil shelter property converted to commercial use:</u>

According to "**Management regulation of civil defense construction in Suzhou city**" released in 2008: civil defense facility should be part of the annual public construction plan; per capita shelter space should be an important evaluative index for city development. Construction standards were defined in this regulation and were further detailed in the Basic Measures added to the regulation in 2012:

- Eligibility: buildings over 10 stories and over 3 m deep below ground should have shelter space equivalent to **2-4% of the surface floor space**;

- Alternative 1: **other underground space function (like parking) other than shelter space can be accountable** into this ratio for residential buildings;

- Alternative 2: if land quality is unsuitable for basement construction, an ex-situ construction fee (2000 to 2500 Yuan per square meters) should be paid by developers to Civil Defense Department for alternative relocation (like in the subsurface beneath park and public space);

- Civilian use: all the shelter spaces are owned by the State, a "**civilian use certificate of civil defense shelter**" can be requested by the building owners to Civil Defense Department, in order to convert into other uses such as parking, retail, storage, recreation, etc.

- **Underground building**: for underground buildings covering over 6000 square meters, per employee shelter space should have at least 1 m^2 and pedestrian shelter space should have at least 1 m^2 per 5 persons.

According to statistics in 2012, 720,000 square meters of shelter space were constructed for civil defense protection. Based on the Suzhou City Civil Defense Construction Plan (2008-2020), shelter space in urban area has to reach 4,800,000 m^2 (excluding tunnel form), with per capita space of 1.33 m^2; short term objective is to build 2,645,000 m^2, a per capita space of 0.94 m^2. Each district has different demand quantity of shelter space construction according to population level. The maximum depth of shelter basement is 20 meters.

The plan also prioritized the sheltering protection development within 100 m's distance around metro stations and it encouraged pedestrian connections. Seen from the short term civil shelter property projects, **main function for civilian use is parking** which usually covers more than 10,000 m^2 floor space per project.

The drafted Underground Space Development Plan (2020) was coordinated with this civil defense plan, in order to integrate protection use into large scale underground property development such as underground complex.

- ***Challenges pointed by Suzhou Civil Defense Office:***

  In order to relieve the budgetary burden of civil shelter construction and maintenance, various private financing mechanisms were encouraged by the government. Development right could be granted by Civil Defense Department to private developers to convert shelter space into commercial property, bringing tax revenue for local governments. However, a legal gap for this kind of **converged underground property** has restrained the private sector from project financing, due to the fact that state-owned civil shelter facility **can't be registered and legalized with private real estate property right**, a requisite for bank loan application. The absence of real estate service supervision on this converted property had also an effect on its business operation performance, which could prevail at the launching stage with property leasing but weaken its business attractiveness in the operating period (observed from the case of "Renhe" Commercial Holdings Company, the biggest underground shopping mall developer in China[82]).

[82] http://www.xcf.cn/newfortune/texie/201212/t20121218_388322.htm "Renhe" underground commercial mirage: the secret behind an alternative business model (in Chinese)

3. Segmental development potential profile and feasibility insight: underground space in Suzhou city

Figure 3:25 shows the segmental analysis indicating feasibility gaps, which could be resolved by implementing specific measures related to three strategic questions detailed in Table 3:8.

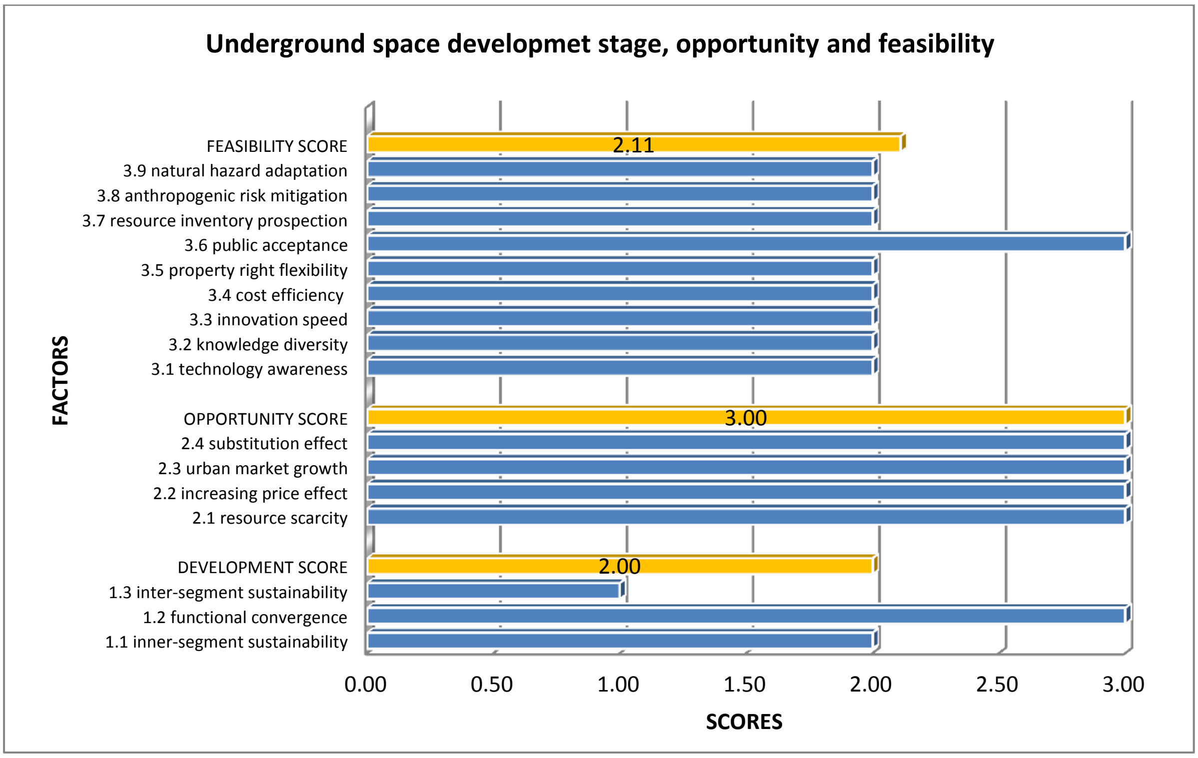


Figure 3:25 Suzhou city context: underground space segment

Table 3:8 Suzhou city context: underground space segment feasibility issues and solutions

Segmental Feasibility issues	Segment 1: Underground space
Related agencies in Suzhou city government	Metro Corporation, Pipeline service office, Urban planning department, Construction department, Civil defense office
ISSUE 1: **Administrative arrangement**	• Construction regulation, • Technical guide, • Information platform for built up subsurface, • Development right stratification, • Authorization procedure, • Real estate property registration for underground buildings
ISSUE 2: **Resource supply management**	• Land quality inventory, • Water protection zoning, • Knowledge on risks, • Utility protection zoning, • Development depth guidance
ISSUE 3: **Functional demand development**	• Transit oriented development for reserved metro lands, • Building space performance monitoring, • Public private collaboration, • Convergence of civil defense use with civilian use

3.6.2.2.2 Segment 2: Geomaterial reutilization

In coastal Chinese cities like Suzhou**, land reclamation in low-lying area** by soil backfill demands substantial quantity of excavated soil, from lakes, abandoned farmlands or construction sites. Excavated soil waste from metro tunneling projects was reused for soil reclamation for low-lying lands in the suburban area. For instance, all the excavated soil from tunneling work of metro line 2 was disposed in a special spoil soil backfill site, situated at the lowest topographical level in the city. This transportation and disposal project (investigated by the Project team) was commissioned to a state-owned construction enterprise, which handled over 1,600,000 cubic meters of spoil soil during 931 days, with 50 soil-conveying heavy vehicles.

Material reutilization technology has been one of the scientific promotion areas. However, information gap between waste generators and construction material recycler is the main barrier to create value chain for recyclable material.

According to a construction project consulting company, soil excavation and disposal costs can reach 40% of total civil engineering costs. The case below shows a basement project in a similar coastal Chinese city, covering 7,870 square meters floor space area and generating 39,350 cubic meters of soil to be excavated and transported: (From Yang 2009, Fuzhou city)

Cost item	Price in Yuan
Total civil engineering cost	3,570,000
Material excavation and transportation (13km)	1,490,000 (2.92 Yuan per m^3 per km)
Share of material related costs	42%

According to Suzhou Construction Price Information Platform, evolution of Jiangsu province's construction material price is shown in Figure 3:26: Aggregate (5-20mm), Sand (midsized). The increasing trend of material price will urge developers to integrate the revalorization process of extracted material into construction project management.

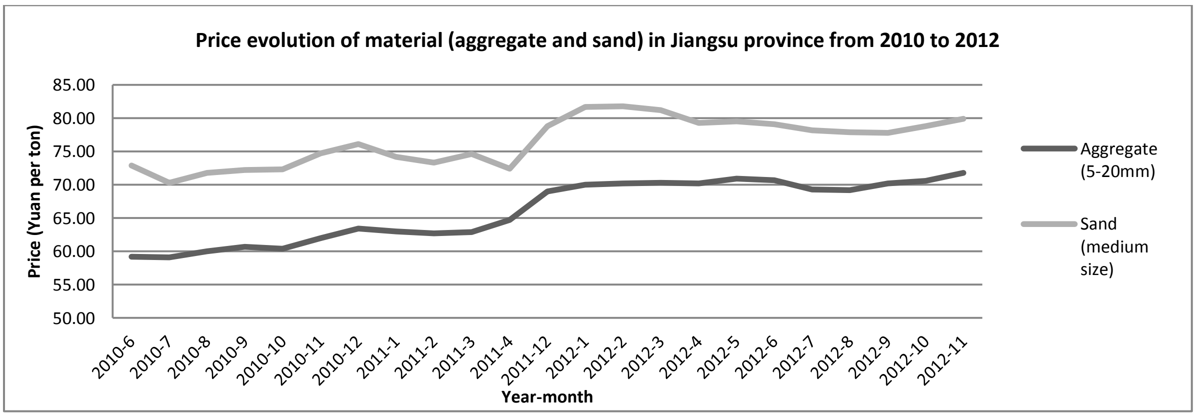


Figure 3:26 Price evolution of material (aggregate and sand) in Jiangsu province from 2010 to 2012

➢ ***Challenges pointed by Suzhou Construction Department and Environmental Sanitation agency:***

Along with the growing construction activities in the city, volume of engineering excavation soil has been increased significantly. However, there is no information available regarding its source, disposal and environmental impacts. Thus, recyclers had difficulties to source material output from construction sites. The city is building an information platform to centralize engineering soil transportation data and to control air pollution induced by soil transfer. A technical guide released in 2009 for construction waste disposal suggested that, the treatment method for engineering excavation soil can be used as backfill soil for low-lying lands, which has been the only reutilization method so far. But this technical guide didn't inform possible revalorization options to transform geo-material into raw material. These challenges are scored in Figure 3:27. Practical operations to improve the feasibility of using geomaterials are suggested in Table 3:9.

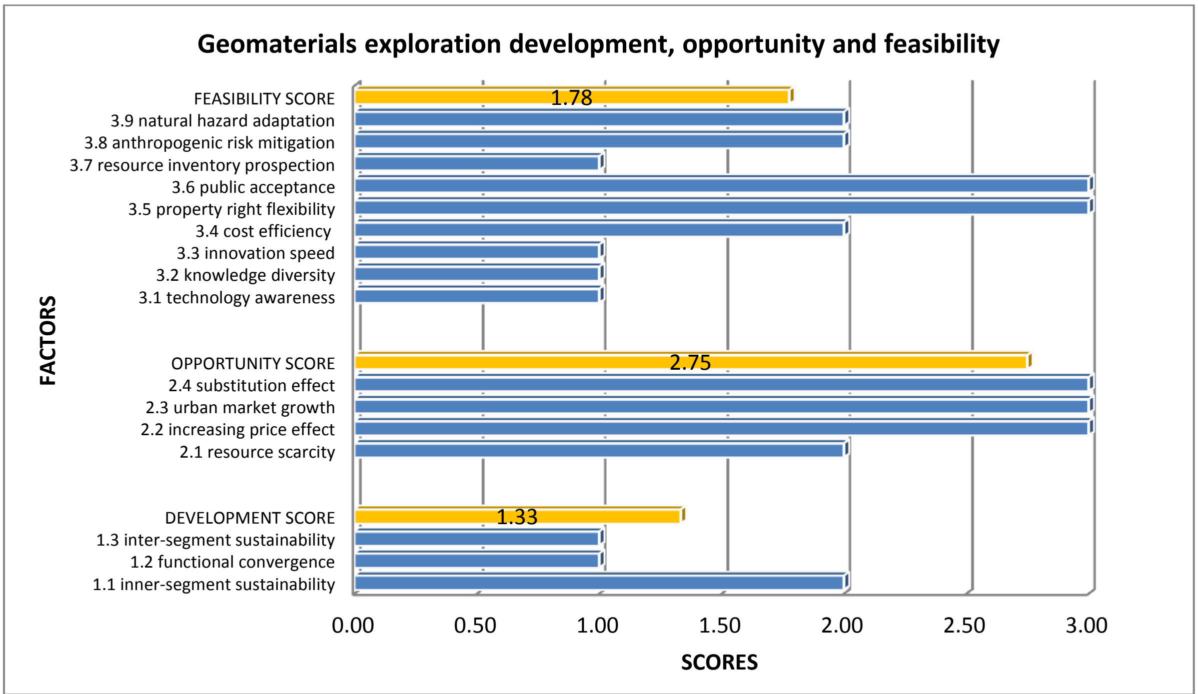


Figure 3:27 Suzhou city context: geomaterials segment

Table 3:9 Suzhou city context: geomaterials segment feasibility issues and solutions

Segmental Feasibility issues	**Segment 2: Geomaterials**
Related agencies in Suzhou city government	Construction department, Environmental sanitation agency
ISSUE 1: Administrative arrangement	• Information platform for output source, • Technical guide
ISSUE 2: Resource supply management	• Underground construction site as output source, • On site material sorting
ISSUE 3: Functional demand development	• Knowledge on revalorization options, • Recycled product portfolio development

3.6.2.2.3 Segment 3: Geothermal energy exploration

According to the provincial energy efficiency standards (released in 2010), public buildings with more than 20,000 m^2 floor space area should be equipped with renewable energy exploration system (three options: ground source heat pump, solar heating and Photovoltaic power generation). This compulsory regulation was implemented with governmental subsidy incentives to attract developers' interests. In Suzhou city, the representative public building equipped with GSHP is the renovated railway station with 40,000 m^2 of floor space. Drilling costs in Suzhou city's soft soil are lower than other cities around, due to its thick layer up to 100 meters, convenient for geothermal borehole operation. A first residential project using GSHP served 1,800,000 square meters of floor space in SSIP district. Compared to ordinary air-conditioning, the geothermal system consumed 56% less energy.

A project appraisal is shown below for an industrial building in Suzhou city (information from a local technical report). Despite a higher capital cost of 23% compared to conventional boiler and air conditioner, annual operation costs can be saved by more than 27% with GSHP.

GSHP parameters	Cost comparison
Total served building space: 4500 m^2	1. *Ground source heat pump:*
Land quality: 83% soft soil	Capital costs: 2,784,000 Yuan
	Annual operation costs: 389,800 Yuan
Cooling load: 960 KWH (120 days)	
Heating load: 540 KWH (120 days)	2. *Air-to-air heat pump:*
	Capital costs: 2,064,000 Yuan
Borehole depth: 95 meters	Annual operation costs: 624,500 Yuan
Borehole distance: 4 meters	
Borehole drilling quantity: 151 drills	3. *Gas boiler and air conditioner:*
	Capital costs: 2,256,000 Yuan
Land footprint of drilling area: 1359 m^2	Annual operational costs: 537,300 Yuan

(Price of resource: water 2.8 Yuan per cubic meter; natural gas 3.2 Yuan per cubic meter; electricity 0.8 Yuan per KWH)

- ***Challenges pointed by Suzhou Urban planning department and Power supply company:***

  Despite of the growing number of industrial players on ground source heat pump installation, legal procedure to authorize and supervise the installation and operation is missing in the administrative system.

  According to local professionals, the main technological challenge for GSHP application is its cooling performance, which is much lower than heating in several demonstrative projects. Since there are more cooling days than heating days in Suzhou city, air conditioning in buildings consumed 40% of total power grid supply, with industrial buildings being the major demand sector. Technological breakthrough on system's cooling performance plays a critical role to enhance the utilization of ground source heat pump as renewable local energy supply.

If innovation speed of geothermal direct use is catching up, the overall development potential will be comparable to the national level. The profile shown in Figure 3:28 reveal a promising development trend of the segment with highly scored factors for Suzhou city context. In order to improve the readiness of stimulating geothermal energy use, implementation suggestions for the city are listed in Table 3:10.

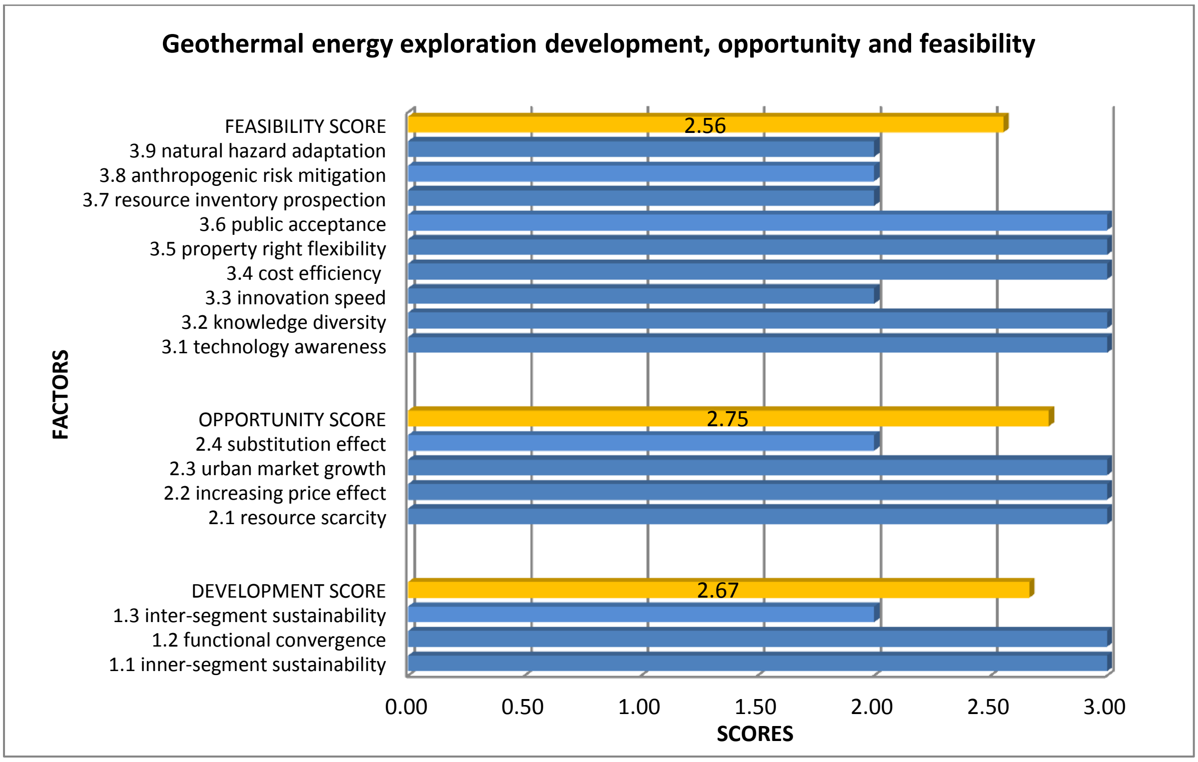


Figure 3:28 Suzhou city context: geothermal energy segment

Table 3:10 Suzhou city context: geothermal energy segment feasibility issues and solutions

Segmental Feasibility issues	Segment 3: geothermal energy
Related agencies in Suzhou city government	Urban planning department, Construction department, Power supply company
ISSUE 1: Administrative arrangement	• Authorization procedure for installation, • Energy planning combined with production auditing
ISSUE 2: Resource supply management	• Shallow ground heat distribution inventory, • Deep ground heat for electricity production potential
ISSUE 3: Functional demand development	• Cooling performance challenge, • Convergence of GSHP with building structure

3.6.2.2.4 Segment 4: Groundwater exploration

According to the data from Water Department in 1998, urban regional groundwater exploration volume was 200,550,000 m^3 (70% industrial use). The lower groundwater price (0.55 Yuan per ton for industry, 0.50 Yuan per ton for household) compared to surface tap water price (0.95 Yuan per ton for industry, 1.18 Yuan per ton for household) drove individual users to construct their own water wells, extracting substantial volumes of groundwater.

In 2000, provincial congress released a compulsory restriction on deep groundwater exploration, due to severe land subsidence disasters. **In total, 2798 water wells in Suzhou city were closed from 2000 to 2005.** There were only 47 deep water wells kept for exploration, granted with licenses of Special Industry Water Extraction, each well zoned by a 30 meters' radius as protection zone restricting all construction projects in the vicinity.

- ***Challenges pointed by Suzhou water department:***

  In 2006, aquifers in Suzhou city were recovered gradually to the depth of 30 meters, from the subsided depth of 52.7 meters before 2000. Land subsidence scale was reduced from 30 mm per year to nearly 2 mm per year. Overall aquifer system is in stable recovery stage. A lack of long-term resource management was the main reason for over exploration in the city. The pure restriction measure can only be a temporary solution. Sustainable management of water resource should base on comprehensive resource inventory for provision planning and demand side regulation. Increasing surface water pollution in Yangtze River Delta urged the government to reconsider groundwater resource to be a strategic reserve for emergency supply.

  Since deep groundwater has been restricted from extraction for land stability, feasibility and technological readiness for shallow groundwater exploration was investigated in the city. Easy access and sufficient natural recharge are advantages of shallow groundwater resource. However, a resilient exploration manner should be established, by formulating long term resource supply planning and monitoring to avoid over exploration and pollution. With respect to technological requirement, shallow groundwater's extraction required alternative techniques for improving output of pumping well while maintaining soil stability. Shallow groundwater resource prospection and demonstrative water well projects were launched by Provincial Geology Office and Prefectural Water Department, proposing a supply capacity inventory of shallow aquifers and adaptive pumping technologies.

The prohibition policy of over exploitation in the last decade enabled the city of Suzhou to retain its groundwater resource, which helps to improve the inner-segmental sustainability score, making the current development status scored higher than national level (Figure 3:29). However, future utilization of groundwater for increasing urban demand should be prepared by upgrading innovative technical solutions to optimize the capacity between water extraction and subsidence risk prevention, as suggested in Table 3:11.

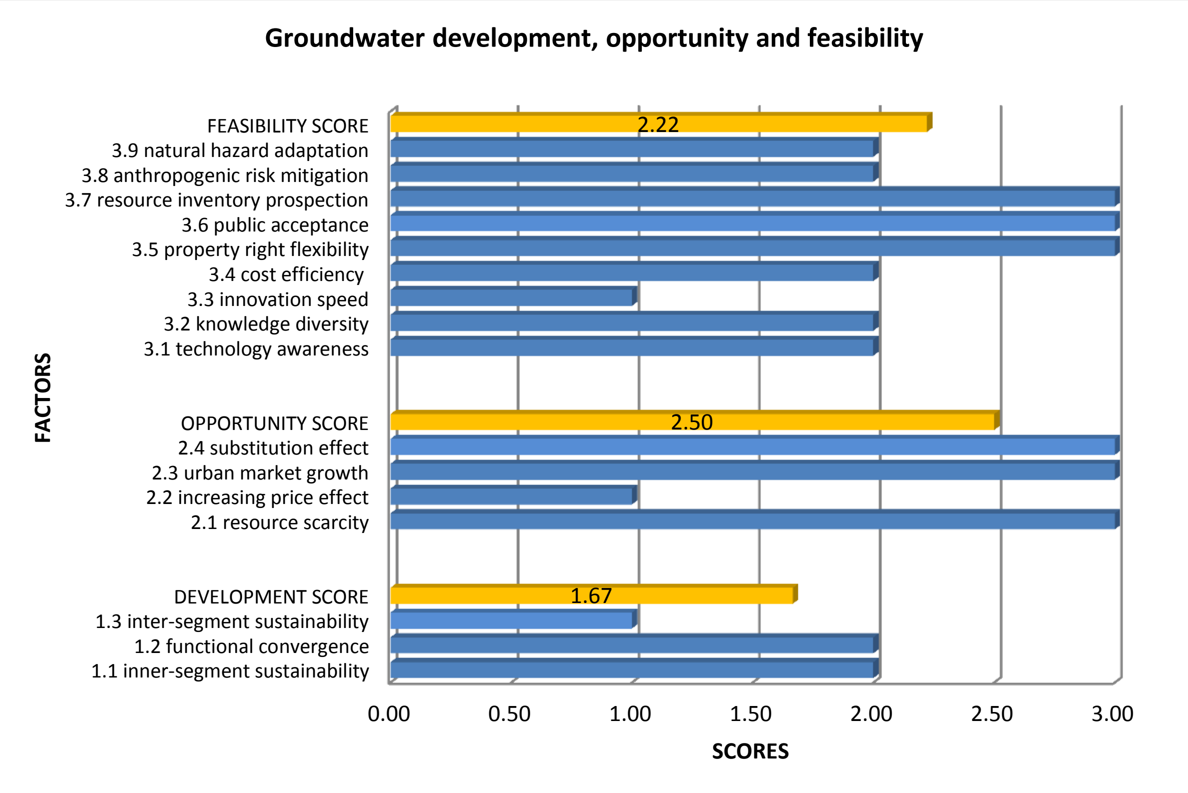


Figure 3:29 Suzhou city context: groundwater segment

Table 3:11 Suzhou city context: groundwater segment feasibility issues and solutions

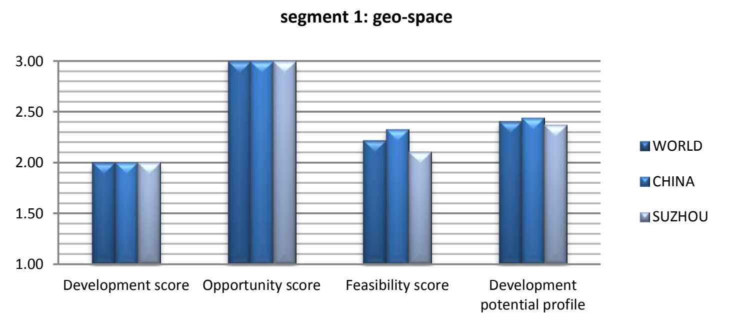
Segmental Feasibility issues	**Segment 4: groundwater**
Related agencies in Suzhou city government	Water department
ISSUE 1: Administrative arrangement	• Groundwater resource protection regulation, • Groundwater extraction licensing
ISSUE 2: Resource supply management	• Shallow aquifers extractable quantity prospection, • Long-term land subsidence monitoring
ISSUE 3: Functional demand development	• Knowledge on water well construction and operation, • Effective allocation among groundwater users

3.6.2.3 Development potential profile for the four segments in Suzhou city

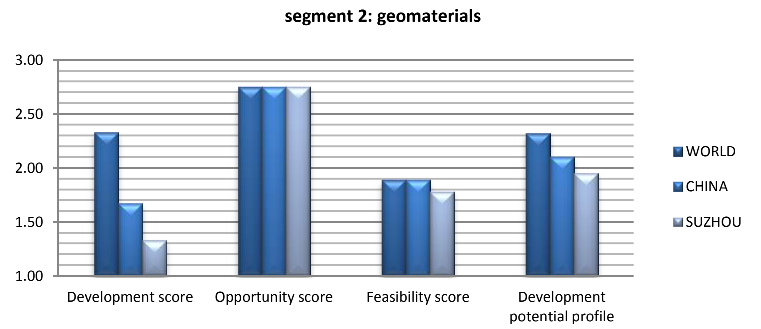
After a thorough examination of Suzhou city's underground development opportunity, development stage and feasibility, development potential profile for the four segments can be summarized in Figure 3:30. Compared to international level overview in segmental analysis (Table 3:12), Suzhou city's underground urbanization performance (current stage) and feasibility level still have room to be upgraded, especially for the segments of geomaterial and groundwater.

Table 3:12 The four segments of sustainable underground urbanization in Suzhou city (comparison with international and national level)

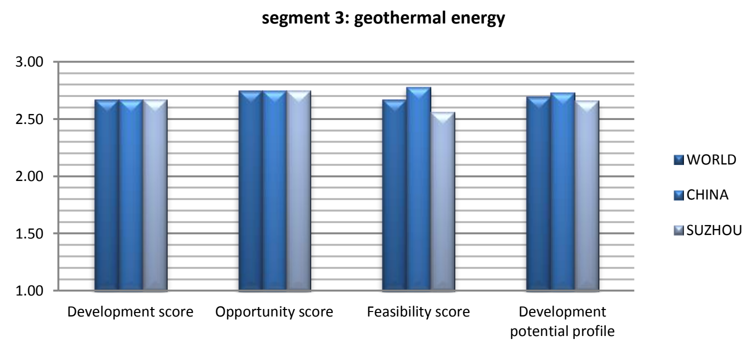
Segment 1	Development score	Opportunity score	Feasibility score	Development potential profile
Geo-space	2.00	3.00	2.11	2.37



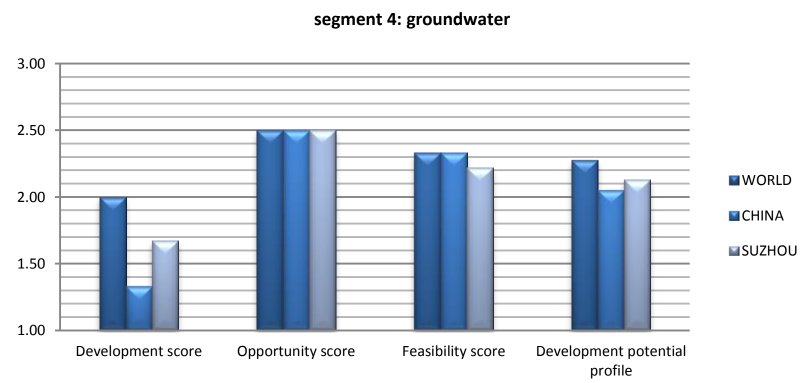
Segment 2	Development score	Opportunity score	Feasibility score	Development potential profile
Geomaterials	1.33	2.75	1.78	1.95



Segment 3	Development score	Opportunity score	Feasibility score	Development potential profile
Geothermal energy	2.67	2.75	2.56	2.66



Segment 4	Development score	Opportunity score	Feasibility score	Development potential profile
Groundwater	1.67	2.50	2.22	2.13



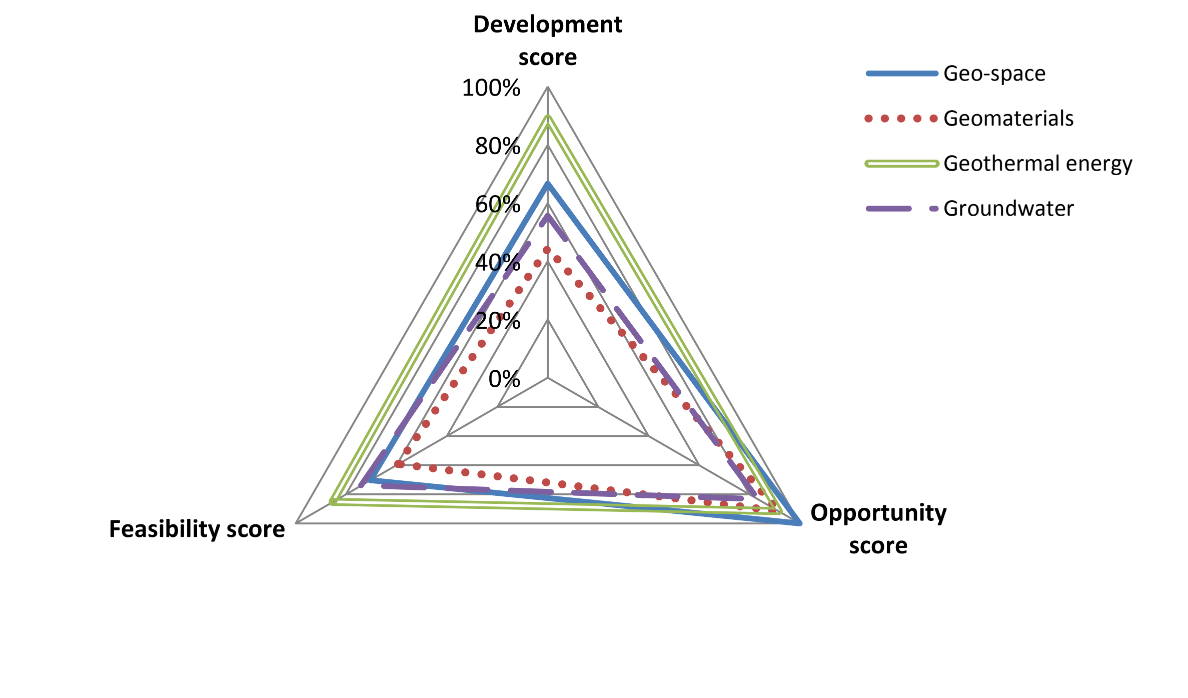


Figure 3:30 Suzhou city context: segmental development potential profile

Capacities of related urban administrative agencies to overcome legal, financial and technological barriers were investigated though governmental meetings and field studies in Suzhou city. Solutions to upgrade feasibilities of sustainable underground urbanization were listed in Table 3:8 (underground space), Table 3:9 (geomaterials), Table 3:10 (geothermal energy), and Table 3:11 (groundwater). They listed “must-do” elements as solutions in response to three strategic questions, in order to advance and manage the development process. Difficulties and management gaps observed from the case study could be overcome by improving existing regulations and by implementing specific instruments. Administrators’ consciousness about the development barriers and interactive constraints of the four segments helps to speed up the capacity building process of local government, as well as to incorporate operational measures into urban development agenda.

Solutions listed for each segment will be further developed in the next section, with strategic and operational planning at the city level. The Project team put forward a **Geographical Planning System for Urban Underground Resources** (registered as software copyright in China[83]) taking into account supply side management and demand side development, a tool for sustainable underground urbanization in the city of Suzhou. The planning system could indicate permissible underground construction sites and areas with high demand potential. Two underground complex project cases in the central city will be used for economic appraisal, using the indication from the planning system.

[83] Computer Software registration number (protected by Copyright Law): 2012SR018316 “Urban Underground Resources Evaluation System V.1.0”

3.7 Suzhou city level strategic model and operational study: application of integrated management process

When making strategies to change a city's development agenda or to enhance its competitive advantages, the first step should study the current strategy and draw a learning process from benchmark strategic models. Existing administrative system of a city could evolve by enrichment of new visions and new responsibilities. City specific development goals could be renewed based on political willingness and economic motivations. Section 3.7.1 will start by reviewing the benchmark strategic models, aiming to propose an applicable **strategy prototype** for the city of Suzhou. The newly shaped strategy can be revised over time, with operational feedbacks and changing objectives.

The operational steps developed in the integrated management process are to overcome the barriers and to fill the gaps revealed in the last section. Challenges pointed by the communicated departments were treated with an integrated point of view, by putting forward a **Geographical Planning System** for the four segments in Deep City method in the section 3.7.2. It is a personalized platform to centralize information and to guide underground development plans.

3.7.1 Strategy making for sustainable underground urbanization

Compared to the benchmark city studies in Chapter 2, Suzhou city's development potential profile for the segment of underground space thrives in terms of motivation, functional performance and feasibility. The main opportunity for its utilization of underground space is land scarcity induced by intensifying urbanization rate, which is expected to be 70% in 2015 according to the Municipal 12th Five-Year-Plan of social-economic development agenda (2011-2015). Functional performance of Suzhou city's underground space transformed from civil defense space oriented to urbanized space oriented, represented by the construction and operation of first metro lines and multi-utility tunnels, as well as the wave of large scale commercial basement linkages to metro stations. This development stage resembles to that of the Chinese mega city Shanghai, another city in the same economic cluster of Yangtze-River-Delta. There are two points of critics regarding its learning process from the strategic model 2 (underground urbanization in megacities Chapter 2, section 2.3.2):

- Lack of operational instruments:
  Administrative phase for Shanghai city's underground urbanization remains in strategic level by drafting regulation of underground building construction right and planning guidelines. Operational levels with specific instruments remain limited, about defining permissible

construction sites (supply side instrument) and encouraging public private collaboration (demand side instrument) during the development process.

- Lack of sustainability consideration:
  As one of the megacities with land subsidence risk, Shanghai city's experience on mitigating this anthropogenic hazard by technological advancement and regulatory control on groundwater extraction offers an important resiliency lesson for the city of Suzhou. Sustainability performance has to be integrated into the development process, by taking into account the four segments instead of the exclusivity on the segment of underground space.

By combining these arguments above, a local specific strategy prototype is studied in this section, based on legislative feasibility and objective of urban development agenda.

3.7.1.1 Origins and Administration

From the year of 2003, Housing and Construction Bureau has initiated feasibility study on urban underground space construction and utilization. While the regulation on underground construction is still under drafting stage, a regulation on underground building construction right and property registration has been approved by Prefectural People's congress in 2011. This new legal document was released by Land and Resource Bureau, based on the new property rights law announced in 2007 by National congress. It is applicable for spatial forms of underground building and not for underground infrastructures. Major underground infrastructures were regulated by Transport Bureau and Utility service Bureau. Historical legacy protection with underground relics in particular, required all excavation activities under designated conservation area to be announced by constructors to Cultural heritage Bureau for investigation. Due to the historical function of the subsurface, civil defense construction has been an obligation for surface buildings and it is going to be an integral part of underground urbanization. Civil defense Bureau required shelter construction to reserve linkage access for underground buildings nearby, encouraging network form of subsurface.

Table 3:13 shows administrative agencies related to urban development. New responsibilities on the development of urban surface have been assigned to main leading agencies, including Bureau of Construction, Land & Resource, Transport, Water, Utility service, Civil defense and Cultural heritage.

Table 3:13 Administrative agencies in Suzhou prefectural government

Administrative levels	Urban Agencies	New responsibilities related to subsurface
Government	Prefectural People's congress	Legislative acceptance
Commission (Strategic level)	Development and Reform	
	Population and Family planning	
	State-owned assets supervision	
Bureau (Operational level)	Housing and Construction	Drafting Regulation of Underground construction (2012)
	Land and Resource	Regulation of Underground building construction right and property registration (2011)
	Urban Planning	Drafting master plan for urban underground space for horizon to 2020 (2009)
	Transport	Regulation of rail transit development (2011)
	Water	Notice on groundwater well management (2006)
	Environmental Protection	
	Garden and greenery	
	Science and technology	
	Utility service	Regulation of urban underground pipelines (2007) Regulation on engineering soil transportation (2011)
	Civil defense	Regulation of civil defense construction (2008)
	Cultural heritage conservation	Regulation of underground archeological protection (2006)

According to the revised technical guide on urban planning released by Jiangsu provincial government in 2011: prefectural level government should establish city scale master plan for underground space utilization; and should formulate fiscal instruments for commercial underground space. There is no obligation to account underground building floor space into permissible density limit, and Prefectural Urban Planning Bureau owns the right to assign an underground space density for particular project plans. In the drafted master plan of underground space (a planning study conducted by China Academy of Planning), priority development zones with underground space demand were indicated but there was no functional design specification with underground space density assignment, due to technical barriers of recognizing constructible volume and location in the subsurface (challenges pointed in 3.6.2.2). The ongoing underground construction had no planning control aid for location selection and dimensional design. Therefore, further operational actions have to be performed for construction capacity survey for priority zones.

Besides policy makings for the segment of underground space, other segments such as groundwater and geomaterial were also considered in sectoral regulations. The expansive trend of underground space utilization in the city without a sustainability objective could harm its long-term development. The ongoing learning and drafting process for strategy making offered a good timing for Deep City method application, in order to consider the four segments into underground development process.

3.7.1.2 Current city level development agenda

According to the 12th Five-Year-Plan of Social-Economic Development agenda (12th FYP) released by Prefectural Commission of Development and Reform, investment on metro line development will be part of priority public expenditures until the horizon to 2020. It is to resolve traffic congestions in central city and save land use supply on infrastructure. The plan addressed a reinforcement of central city's urbanization process and restricted development projects on farmland area. Due to the fact that land supply in central city has been frozen, especially in old city core, a "Concentrated Urbanization" pattern could be favored to meet increasing urban demand. Land development rights around metro stations transferable by Suzhou Metro Corporation could be assigned with permissible underground space density, maximizing land value by redevelopment and creating a sustainable financing mechanism for metro infrastructure projects.

The importance of reserving urban aquifers for emergency water supply was stated in the 12th FYP, since the main objective for groundwater resource management is restricting exploitation and controling land subsidence.

3.7.1.3 A strategy prototype for Suzhou city

Like the surface type urban development, urbanizing the urban underground needs to involve various actors for entire coordination, as mentioned in section 3.2. Since existing coordination is missing in administrative system, the integrated management process could help to align actions of different administrators (Figure 3:1). A strategy prototype proposed below combined the concept of integrated management process for administrative coordination, with instrumental solutions for overcoming feasibility barriers. The six-step process (Figure 3:31) starts from reviewing baseline context to setting development vision/objective, then though multi-level operations to making pertinent policies.

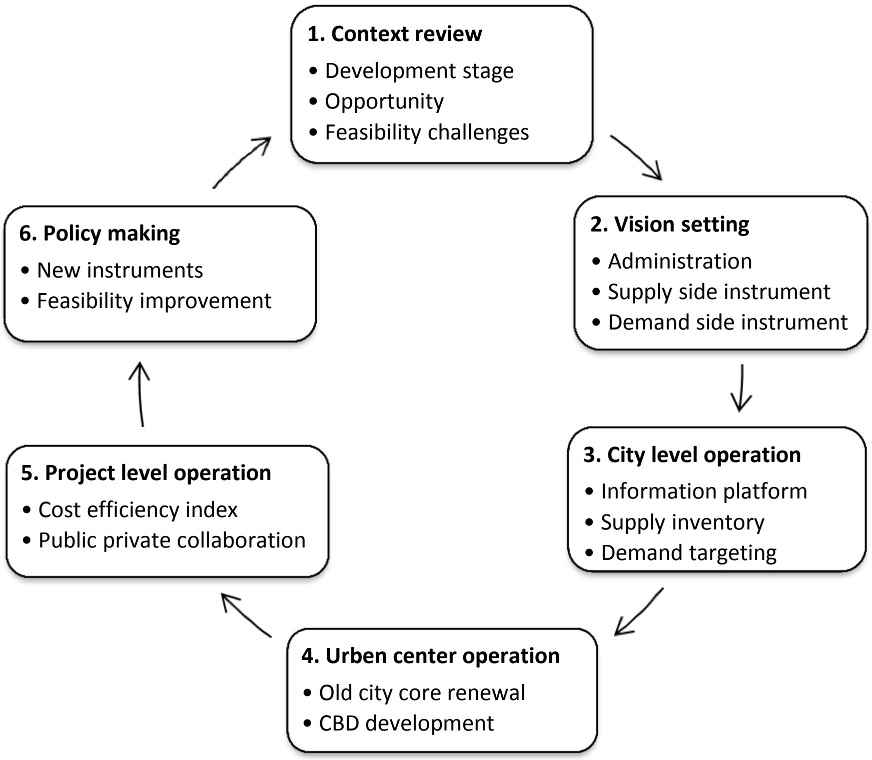


Figure 3:31 Strategy prototype for sustainable underground urbanization in Suzhou city

Based on the context review conducted in section 3.6.2, feasibility challenges pointed out by administrators and developers necessitate a resolving process for institutional adaptation and supply-demand justification. The second step in the strategy prototype is to set up development visions and goals for sustainable underground urbanization, by learning and extending from benchmark cities' referential instruments (strategic model 2 in Chapter 2, page 107), as follows:

- Administrative decentralization: to enable **central districts** execute their own projects based on city level regulations on the four segments;
- **Stratified planning** of subsurface supply: to enable vertical growth beneath the city, taking into account layered distribution of the four segments;
- Functional convergence: to enable mixed functions and **compact form** of underground urbanization, by merging public use with private use.

Following sections will present operational steps at the levels of city, urban center and project.

3.7.2 City level operation: information platform, supply inventory, demand targeting

Due to diversity of underground resources and complexity of restraining factors, an information platform helps to centralize resources database, evaluate development potential and identify permissible underground construction and exploration sites. Structure of the information system for data management and for Suzhou city subsurface planning is shown in Figure 3:32. Creation of the system and three-level potential evaluation reports will be illustrated in this section.

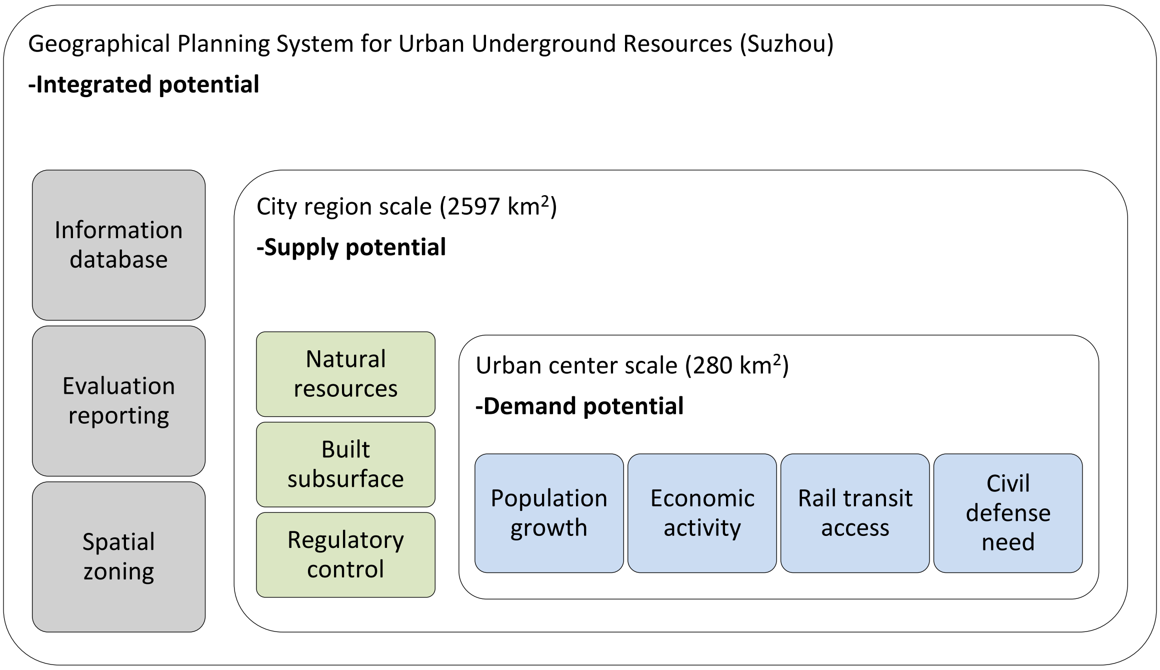


Figure 3:32 Information management and planning system for sustainable underground urbanization

3.7.2.1 Information platform and reporting system

A comprehensive underground urbanization strategy requires a significant amount of information on the urban scale: land quality related to geological foundation, groundwater reserves, construction material and energy sources, existing built environment layout (buildings, transports, utilities, and greenery), land use plan, district level zoning rules, housing capacity, functional space demand, land parcel inventories and real estate marketability.

The quality of information can influence project implementation. While a good understanding of the urban underground depends on substantial geological investigation, the land management institution should add administrative issues to the resources survey. Previous geological surveys have been concentrated on mineral resources prospection (metal, gold, oil, gas, coal, rare earth, etc.), which were driven by their increasing value as primary material supply (Salisbury and Salter, 1941a, Salisbury and Salter, 1941b). An accurate estimation of underground mineral resources helps to project future exploitation according to technological level and economic demand. The same principle is applied in urban subsurface development (Paul et al., 2002), which requires a comprehensive knowledge basis for understanding the truth of natural assets beneath the cities.

Technological advancement enabled our deep vision of using the subsurface, including prospection methods and construction techniques. Innovations in tunnel design and construction process have been helping reduce costs and time of project execution (Brierley and Drake, 1995, Sterling, 1992, Beer, 2010, Goel et al., 2012). Contribution of geothermal exploitation for heat and power generation has been increasing since 2010 (OECD/IEA, 2011), while capital cost is expected to decrease by 2020 (OECD/IEA, 2010). Challenges for using subsurface and energy resources are linked to higher investment costs and development risks such as subsidence. Substantial R&D input should be promoted for accurate resources potential prospection and for upgrading related equipment.

A resilient city needs urban services to adapt to human demands in the context of population growth or de-growth. For the new megacities around the world, intensification of urban demands in housing, working, commuting and networking can be relieved by using underground infrastructures for providing services (utility, transport and civil protection) and spaces (commercial and residential). Infrastructure planning should be coordinated with land use planning, in order to serve the right place with the right resources in an economically viable way (Jenks et al., 1996, Jenks and Jones, 2010, Kivell, 1993).

A Geographical Planning System for Urban Underground Resources was developed by the Project team during 2010 to 2012, for reporting supply potential and demand potential at the city level to aid policy making. Procedures of creating the geographical planning system are as follows:

1) Criteria selection, data collection and standard level classification:

Based on existing studies in subsurface evaluation from Chinese major cities of Shenzhen, Guangzhou, Shanghai and Beijing, general criteria and local specific factors were put together. From 2009 to 2011, local data from geological survey and economic statistics was collected and treated. A 3D geological model is created with an internally invented software GEOLEP3D (Cao et al., 2011), showing the four segments in a three dimensional way.

In order to define standards for the selected criteria, ten municipal departments were invited to give advice on resources management and infrastructure development, as shown in the communication program in Table 3:7. Those discussions helped to form a constructive framework for underground development standards, which is one of the major challenges in planning coordination (Narvi et al., 1994, SHU et al., 2006).

2) Weighting criteria with questionnaires and interviews:

A group of local professionals in geological engineering, building construction and urban planning was interviewed and gave weights for overall criteria to indicate importance level from 1 to 9. From 2010 to 2011, numbers of joint meetings were organized by the Chinese Deep City Team with the provincial geological department and municipal land use administration, to gain updated legislative information and political guidance in order to readjust the weighting results.

3) Analytic diagnostic for supply and demand and mapping for integrated potential:

Analytic Hierarchy Process (Saaty, 2001) and GIS are used for data treatment and geographic mapping (Li et al., 2012, WU, 2012). The combination of information technologies helps to translate decision making criteria into zoning maps as planning instruments.

Output from the planning system is divided in three themes: supply inventory report, demand targeting report and integrated potential report. Following sections will present detail methodologies and reporting results on these three themes.

3.7.2.1.1 Reporting on supply inventory evaluation for underground space

The city subsurface in Suzhou city was stratified into four layers, including two shallow layers (0-15 meters, 15-30 meters) and two deep layers (30-50 meters, 50-100 meters). According to its Construction Bureau, current and short-term utilization layers are shallow ones deep to 30 meters. Experiences drawn from the megacity of Japan showed the maximum depth feasible for underground construction is 100 meters.

Other engineering solution related considerations were also included for the layered division: Firstly, shallow layers (15m, 30m) are usually used for different basements of buildings, where additional land acquisition is unfeasible on the surface; large linear public infrastructures occupy deeper layers below 30m (Nishioka et al., 2007). Secondly, technological investment is different for shallow and deep underground: the cut-and-cover excavation method works for the shallow subsurface while deep underground projects (subway, tunnel, and large utility lines) requires high level tunneling technologies. In its local context of China, the subsurface construction costs around 3000 CNY/m^2 and deep tunneling costs above 100 million CNY/km. After defining vertical divisions, supply capacities of the four segments were evaluated according to engineering feasibility and regulatory control. Therefore, shallow subsurface (0-30 meters) supply inventory serves the development forms of basement type buildings and subterranean metro stations, while deep underground (30-100 meters) supply inventory serves the development forms of tunnels.

The exploitable underground space quantity is **limited** due to the natural quality of land resource and legal restrictions to preserve the landscape, while the supply value of the asset in terms of high construction capacity could be **variable** due to the technological progress of builders and financial means of the developers. Number of restraining factors determines challenge level for underground construction. Current technological level in the city determines that shallow layers could be easily built, while deep layers' supply capacity will be reduced from 30% to 50% (depth restraining factors).

For the context of Suzhou city, eight categories of criteria (Table 3:14, Table 3:15) were identified as relevant challenging factors for prospecting underground construction sites. The inventory of potential subsurface supply could be classified on **five standards (very high, high, moderate, low and very low)** according to the five standards for each criteria category. Statistics in graphical form and geographical form could be generated from the planning system.

Figure 3:33 shows a users' guide for using this reporting system. The supply inventory covers the city region of 2597 km^2, in order to provide a broad vision for the whole urban territory.

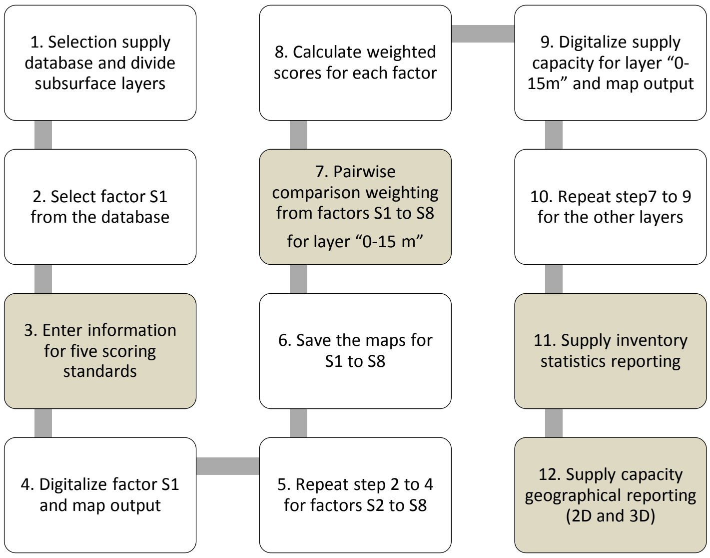


Figure 3:33 Users' guide for the Geographical planning system: reporting on supply inventory (colored parts are illustrated steps in the text, other steps for manual manipulation in the computer system is not illustrated here)

Illustration for information input (Users' guide step 3)

Table 3:14 Supply potential evaluation criteria and standards for Suzhou city

Supply potential criteria:	**Technical/legal basis**	**Standards and scores**				
		Very high (0.8-1.0)	**High (0.6-0.8)**	**Moderate (0.4-0.6)**	**Low (0.2-0.4)**	**Very low (0.0-0.2)**
S1: Geo-risks (subsidence)	Monitoring center data	No risk	No risk	<5mm/a	5-10mm/a	>10mm/a
S2: Sensitive soil thickness	Borehole data	0	0-5m	5-10m	10-15m	>15m
S3: Sensitive aquifer outflow	Water well data (1st aquifer)	Absent	<50t/d	50-150t/d	150-300t/d	>300t/d
	Water well data (2nd aquifer)	Absent	<100t/d	100-1000t/d	1000-3000t/d	>3000t/d
S4: Existing foundation	Suzhou underground planning 2020	No	No	6-10m	10-30m	>30m
S5: Archeology discovery	Suzhou city planning 2020	Absent	Absent	Absent	Present	Present
S6: Ecology protection level	Suzhou city planning 2020	Non sensitive	District level	City level	Province level	National level
S7: Topography (altitude)	Suzhou DEM model	>5.8m	4.8-5.8m	3.8-4.8m	2.8-3.8m	<2.8m
S8: Faults buffer	National standard 2010	>200m	>200m	>200m	>200m	<200m

Illustration for factor weightings (Users' guide step 7)

Table 3:15 Supply potential criteria weighting for the four layers

Supply potential index	Vertical layer division:	15m	30m	50m	100m
	Depth feasibility factor	**1**	**0.9**	**0.7**	**0.5**
Criteria S1 to S8	S1: Geo-risks	0,193	0,173	0,144	0,117
	S2: Sensitive soil thickness	0,186	0,181	0,166	0,078
	S3: Hydrogeology	0,173	0,233	0,242	0,172
	S4: Existing foundation	0,166	0,140	0,000	0,000
	S5: Archeology	0,101	0,093	0,000	0,000
	S6: Eco-sensitivity	0,092	0,080	0,078	0,057
	S7: Topography	0,089	0,000	0,000	0,000
	S8: Faults	0,000	0,000	0,071	0,077

(weights are already multiplied by depth feasibility factor; absence of factor in certain layers is marked with 0.000)

Reporting is in forms of statistical, graphical, geographical and 3D model, as shown from Figure 3:34 to Figure 3:36:

Illustration for supply inventory graphical reporting (Users' guide step 11)

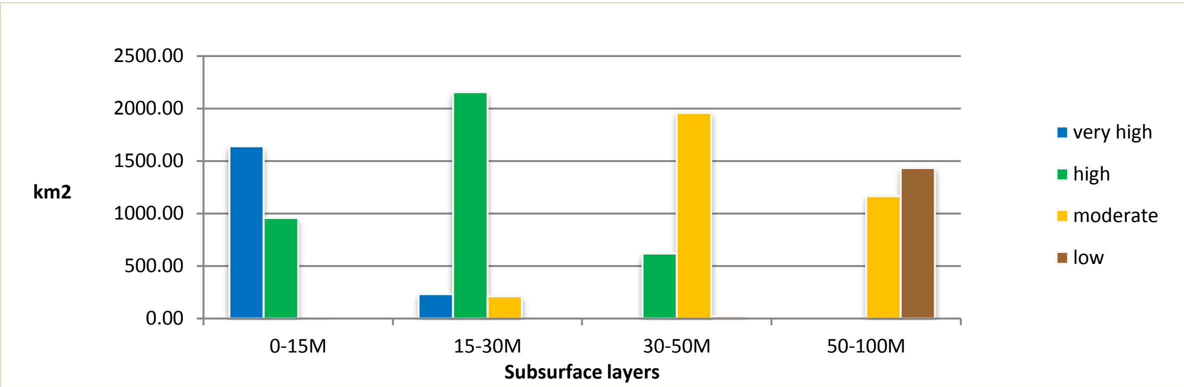


Figure 3:34 Graphical reporting: supply inventory of underground space in land area (by layers and by capacity levels)

Illustration for supply inventory geographical reporting (Users' guide step 12)

2D visualization

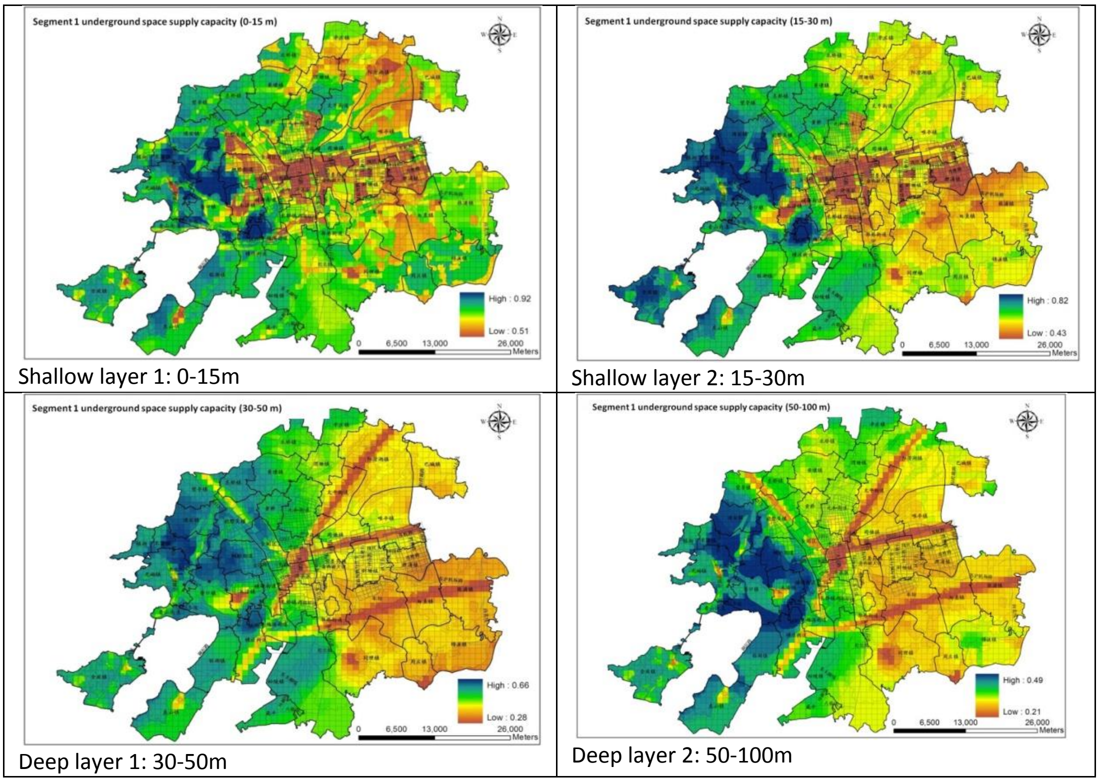


Figure 3:35 Geographical reporting: supply capacity distribution (by layers and by capacity levels)

3D visualization

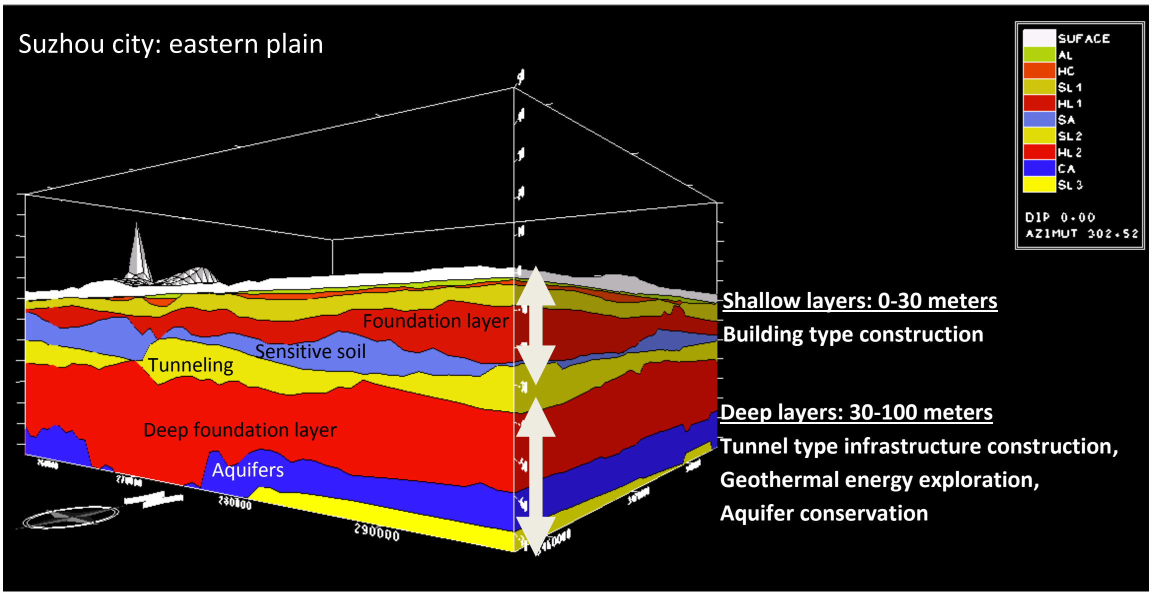


Figure 3:36 3D geo-engineering model with resources layers division deep to 70 meters, developed by (Cao et al., 2012)with Geolep3D[84] (color legends: red-bearing layers for building foundation; blue-aquifers; yellow-suitable tunneling construction layers)

---

[84] Geolep3D is an internally developed software for three dimensional modeling for cities by Laurent Tacher (GEOLEP)

From the statistics report, good underground space resource covers an average 27% of the whole city region territory deep to 100 meters. Higher capacity could be found at shallow layers within 30 meters, due to technological feasibility. However, the factor “S4 existing foundation” is dynamic and will be weighted higher along with intensifying urbanization on the surface and shallow subsurface. Monitoring of existing foundation and existing underground structures enables a timely renewal for its weighting degree, which could change the picture of supply inventory for shallow layers.

Deep layers’ supply capacity is lower, due to the reduced depth feasibility factor. If economic development agenda boosts technological progress and financial assistance for underground construction, like the case of Tokyo city, feasibility of building in the deep underground will be increased to host more large scale underground infrastructures. In this case, supply inventory for deep layers will be also changed.

Complexity of geotechnical setting is shown in the 3D model (Figure 3:36), with multiple technical and environmental restraining factors limiting underground urbanization. Three types of functions are showed in the 3D model: building foundation layers (colored in red), tunneling layers (colored in yellow) and aquifer layers (colored in blue). The main aquifers deep to 60 meters were drinking water source in the city before the groundwater extraction restriction from the year of 2000.

While the city region subsurface supply inventory serves as global insight for underground urbanization, specific development forms require more accurate indication for construction site selection. According to local engineers, underground construction costs are mostly influenced by the presence of sensitive soil layer in the construction site, with high risk of fine sands intrusion. The planning system could generate difficulty mappings for risk prevention, as shown in Figure 3:37. Critical subsurface locations with high engineering difficulties (due to the sensitive soil layer) are indicated in dark parts, for basement building form and tunnel form. Land development with underground construction in these critical locations will significantly increase the investment costs for engineering solutions.

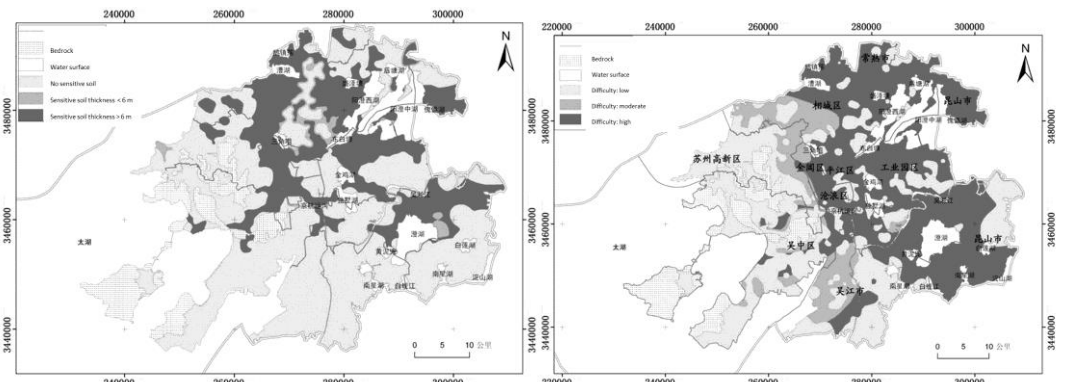


Figure 3:37 Geo-engineering difficulty mapping by (Cao, 2012): basement construction (10m) and tunneling (10-20m) (dark parts remarked as high difficulty zones)

3.7.2.2 Reporting on demand targeting evaluation for underground space

With the aim to develop a "concentrated urbanization" pattern for Suzhou city, underground densification in the built up area is promoted. Within the central city of 280 km^2, opportunities for underground urbanization vary in different central districts according to the level of economic activities. After interviewing local urban planners, seven categories of criteria (Table 3:16) were identified as relevant opportunity indicators for developing underground space. Four planning specialists were invited to give weights for these criteria, averaged weights shown in Table 3:17. Demand targeting reporting is also classified on five standards (very high, high, moderate, low and very low) according to the five standards for each criteria category. Statistics in graphical form and geographical form could be generated from the planning system.

Demand potential reporting is only presented on the surface layer, due to the fact that the value of underground space is still not included into surface land value. In addition, criteria of demand potential (land prices, population density, land use type, transport network, civil defense plan, and development stage) are presented on the surface layer. However, demand potential on the surface will be extended into the four layers defined in the planning system, with shallow layers having higher opportunity factor and deep layers having lower opportunity factor based on current economic context. Underground space development potential form shallow to deep dimensions will be revealed by combing supply capacity and demand potential, presented in the last reporting theme.

A users' guide for using the reporting system is shown in Figure 3:38.

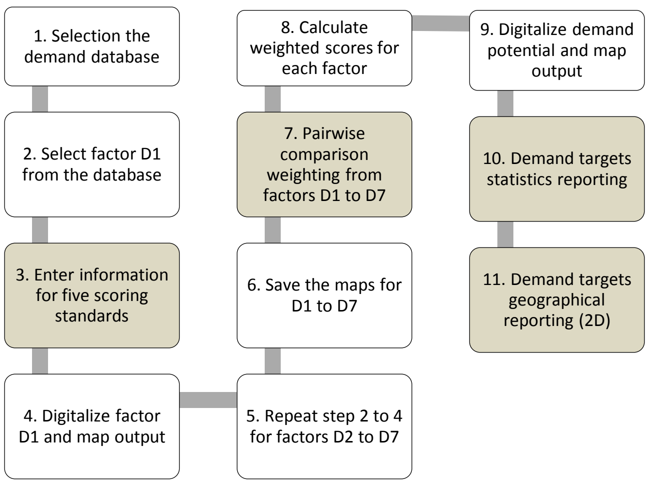


Figure 3:38 Users' guide for the Geographical planning system: reporting on demand targeting (colored parts are illustrated steps in the text; other steps for manual manipulation in the computer sytem are not illustrated here)

Illustration for information input (Users' guide step 3)

Table 3:16 Demand potential evaluation criteria and standards for Suzhou city

Demand potential criteria:	Technical/legal basis	Standards and scores				
		Very high (0.8-1.0)	High (0.6-0.8)	Moderate (0.4-0.6)	Low (0.2-0.4)	Very low (0.0-0.2)
D1: Civil defense need	Civil defense planning 2020	Old city	SSIP	SSND	Xiangcheng	Wuzhong
D2: Commercial land prices	Land valuation report 2007	>26K RMB/m^2	14K-26K	6K-14K	3K-6K	<3K
D3: Residential land prices	Land valuation report 2007	>6K RMB/m^2	3K-5K	1K-3K	675-1K	<765
D4: Land use type	Suzhou land use plan 2005	Commercial	Education	Residential	Industrial	Farmland
D5: Population density	The 6^{th} Population Census	11K-15K/km^2	2414-7860	1774-2218	1561-1667	1083-1195
D6: Transport accessibility	Suzhou city planning 2020	Metro hub	Metro station	Bus stop	Road	Other
D7: Development stage	Suzhou underground planning 2020	1	2	3	3	4

Illustration for factor weighting (Users' guide step 7)

Table 3:17 Demand potential criteria weighting for the four layers

Demand potential index	Vertical layer division:	Surface	15m	30m	50m	100m
	Depth opportunity factor	1	1	0.9	0.7	0.5
Criteria: D1 to D7	D1: Civil defense need	0.083	0.083	0.075	0.058	0.042
	D2: Commercial land prices	0.110	0.110	0.099	0.077	0.055
	D3: Residential land prices	0.110	0.110	0.099	0.077	0.055
	D4: Land use type	0.114	0.114	0.103	0.080	0.057
	D5: Population density	0.144	0.144	0.130	0.101	0.072
	D6: Transport accessibility	0.218	0.218	0.196	0.153	0.109
	D7: Development planning stage	0.222	0.222	0.200	0.155	0.111

Illustration for demand targeting graphical reporting (Users' guide 10)

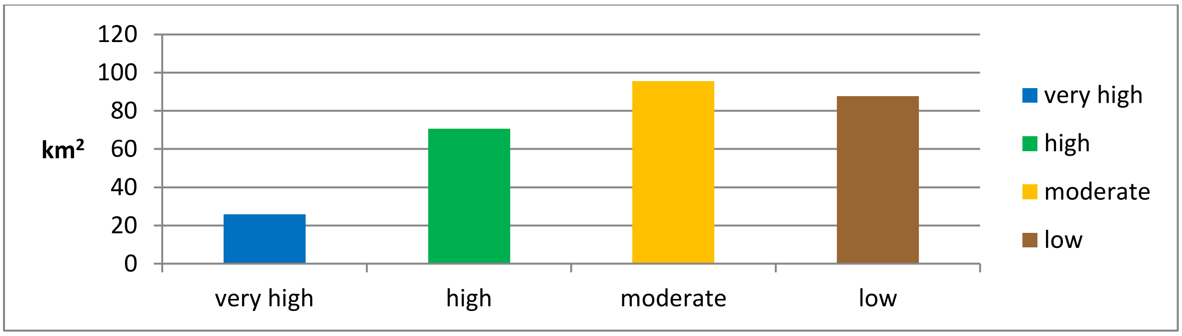


Figure 3:39 Graphical reporting: demand potential of underground space in land area (by potential levels)

Illustration for demand targets geographical reporting (Users' guide step 11)

2D visualization (only surface layer)

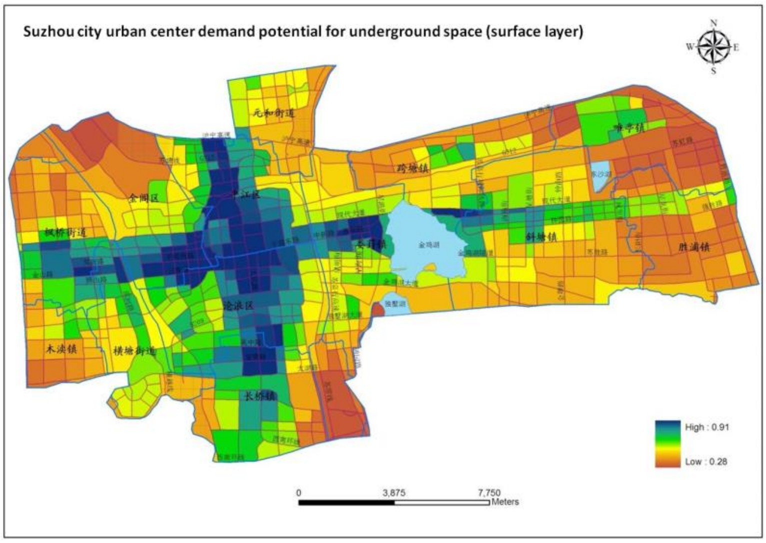


Figure 3:40 Geographical reporting: demand targets distribution from the surface (by levels)

From the reporting results shown in Figure 3:39 and Figure 3:40, around 35% of the central city area owns high to very high demand potential, covering 97 km^2 concentrated in the Old city core of Gucheng district and CBD of SSIP district. Higher land prices, denser population and better access to rail transit are main factors making these areas motivated to develop underground space.

3.7.2.3 Reporting on integrated potential evaluation for underground space

In order to know whether the supply capacity of underground space in central city could meet the demand potential for development, a third reporting theme was developed in the planning system: integrated potential for underground urbanization. Users of the system could give weights to define importance level of supply index and demand index for the four layers, as shown in Table 3:18. According to local planners' point of view, for short-term development period with shallow layers, the importance of meeting the demand for underground urbanization was weighted much more higher than overcoming engineering difficulties and regulatory control (Figure 3:42); deep layers utilization scheme is still beyond the development agenda due to technological limit, with their integrated potentials influenced by major engineering difficulties (Figure 3:43). Supply capacity index will be combined with demand potential index extended from surface evaluation, to generate an integrated inventory for the four layers (in land coverage Figure 3:44 and in volume Figure 3:45). Statistical inventory by volume is shown in Table 3:19, indicating that 65% of total underground volume having above moderate quality of integrated potential in central city area. More than 50% of total shallow underground volume owns above moderate integrated development potential for short-term development; for deep underground space, only 26% of volume is inventoried as exploitable resource. Geographical reporting for zoning instrument guide can be referred to Figure 3:46, showing that high development potential for shallow construction concentrates in old city core and CBD of SSIP near Jinji Lake in the eastern plain, while deep construction development potential concentrates in the western high elevated area.

Figure 3:41 presents the users' guide for integrated potential reporting exercise.

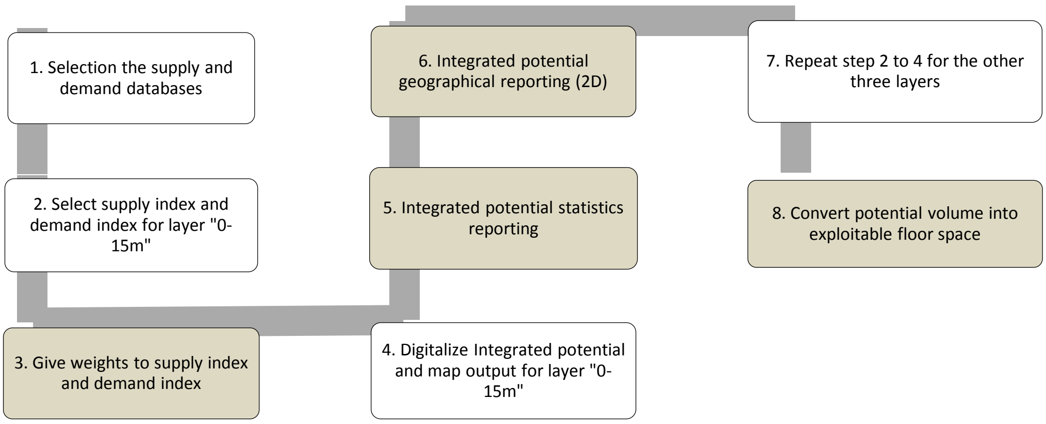


Figure 3:41 Users' guide for the geographical planning system: reporting on integrated potential zoning (colored parts are illustrated steps in the text)

Illustration for index weighting (Users' guide step 3)

Table 3:18 Integrated potential weighting for the four layers

Vertical layer division:	15m	30m	50m	100m
Supply capacity index	0.200	0.300	0.700	0.800
Demand potential index	0.800	0.700	0.300	0.200

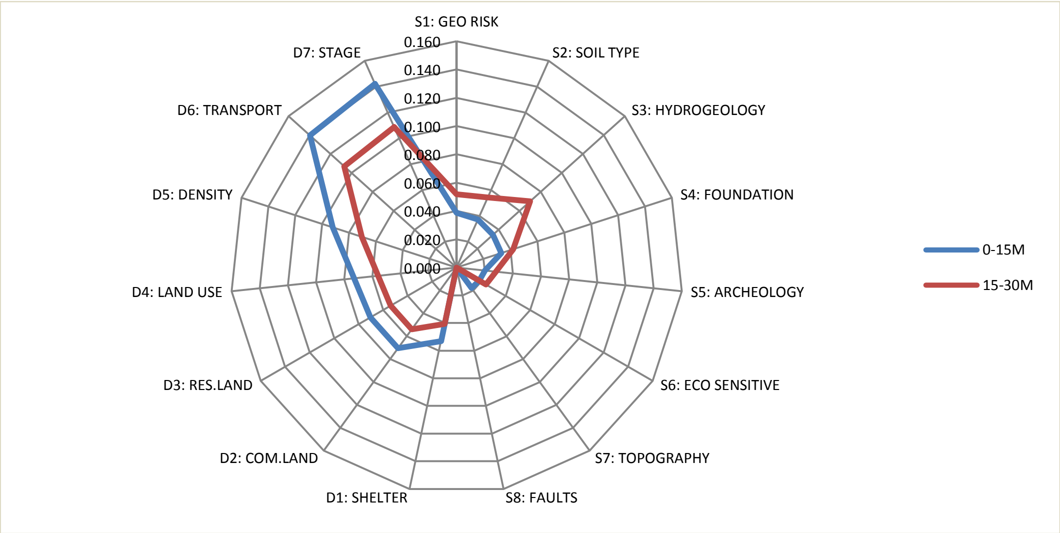


Figure 3:42 Integration potential criteria weighting (shallow layers)

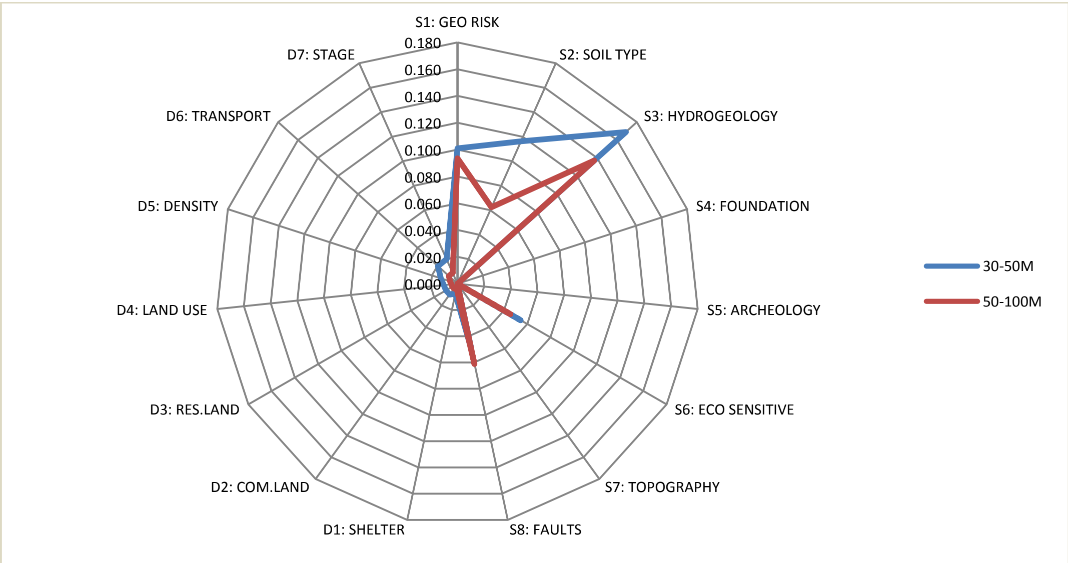


Figure 3:43 Integrated potential criteria weighting (deep layers)

Illustration for integrated potential graphical reporting (Users' guide step 5)

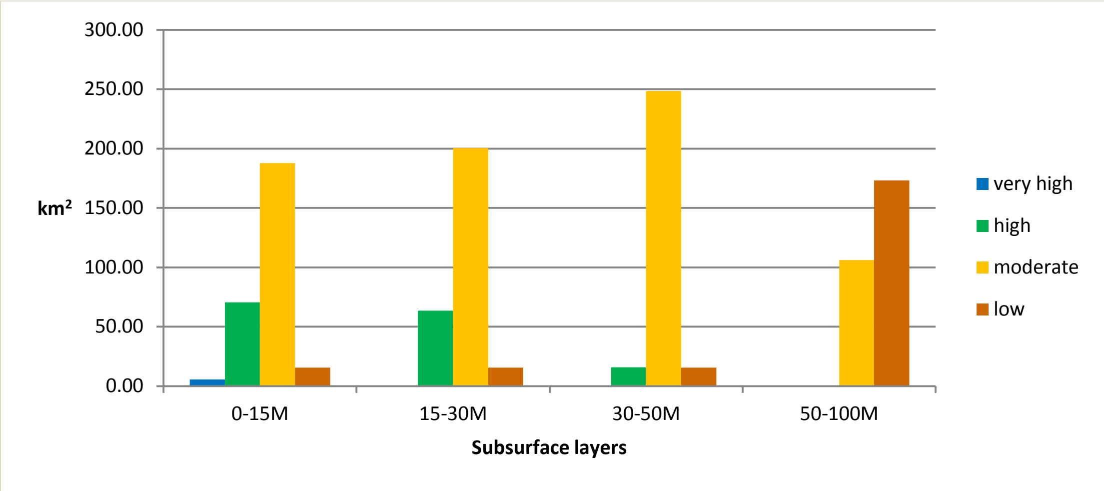


Figure 3:44 Graphical reporting: integrated potential of underground space in land area (by layers and by potential quality)

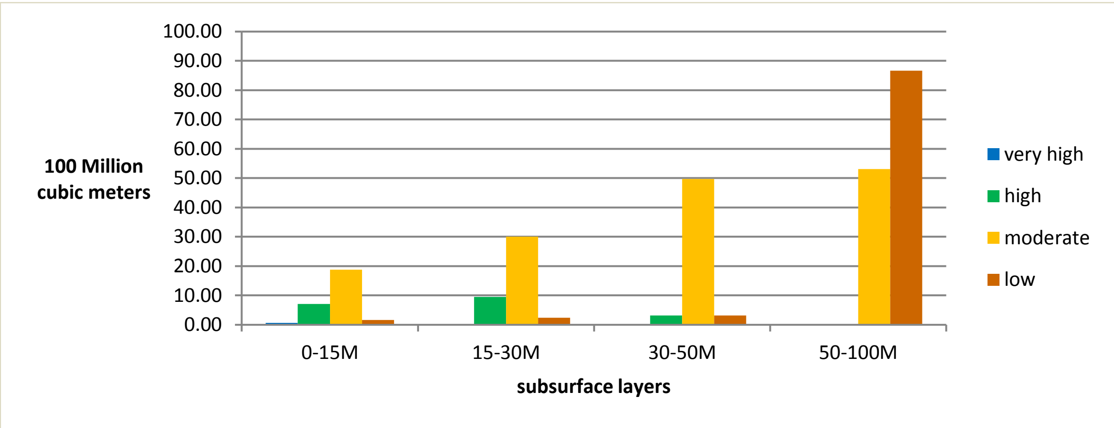


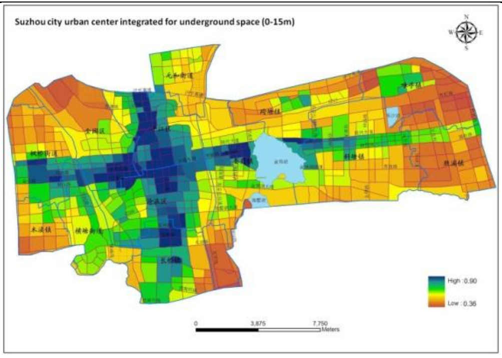
Figure 3:45 Graphical reporting: integrated potential of underground space in volume (by layers and by potential quality)

Table 3:19 Statistical reporting on integrated potential inventory (in volume)

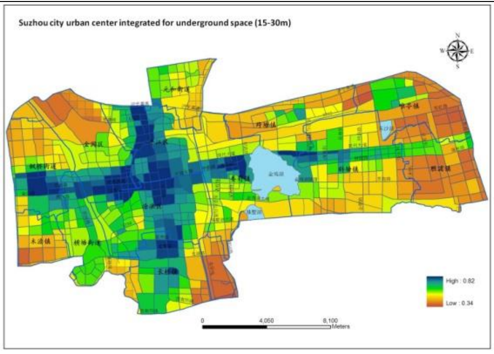
(unit: 100 million cubic meters)	Very high	High	Moderate	Low	TOTAL BY LAYER
0-15M	0,56	7,05	18,78	1,56	27,95
15-30M	0,04	9,52	30,05	2,32	41,93
30-50M	0,00	3,13	49,68	3,09	55,90
50-100M	0,00	0,00	53,11	86,64	139,75
TOTAL BY QUALITY LEVEL	0,60	19,70	151,62	93,61	265,53

Illustration for integrated potential geographical reporting (Users' guide step 6)

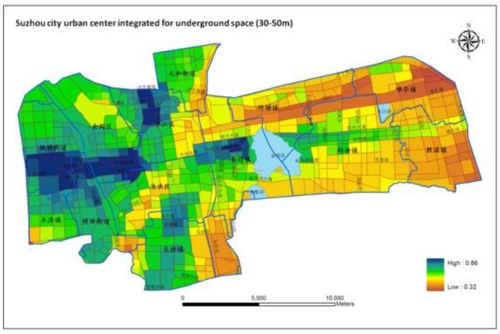
2D visualization



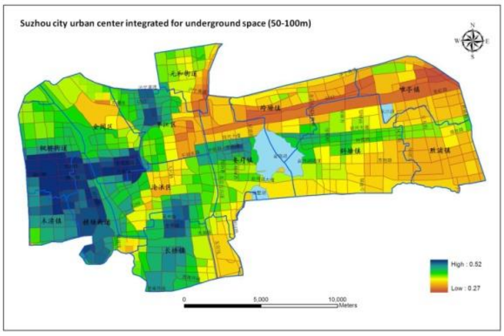
Shallow layer 1: 0-15m



Shallow layer 2: 15-30m



Deep layer 1: 30-50m



Deep layer 2: 50-100m

Figure 3:46 Geographical reporting: integrated potential distribution (by layers and by potential levels)

Statistical reporting results indicates that, 26% of central city area owns high to very high integrated potential, concentrated at shallow layers beneath Old city core and CBD area, due to the fact that demand potential is highly distributed in these areas and engineering difficulties are considered as manageable in the shallow urban underground. Realistic buildable floor space is subject to effectiveness of shallow underground construction, represented with an effectiveness factor by quality level.

As mentioned before, the urban underground is stratified into shallow and deep layers to facilitate building form construction and tunnel form construction. Shallow effective development potential can be converted from volume in to building floor space in statistical reporting. Table 3:20 shows estimation results, considering future underground building floor height upgraded to 4 meters. **In total, more than 300 million square meters of floor space could be built deep to 30 meters, a supply limit with current economic context and feasibility level.** Developing underground space will help to **save more than 150 km^2 of additional surface land supply** (current FAR is 2), equivalent to the half of central city. Therefore, this potential zoning and supply limit should be integrated into city level construction land supply plans, to make sure that underground urbanization will take place at the right location with the right development quantity.

Illustration for converting volume into exploitable floor space (Users' guide step 8)

Table 3:20 Conversion of effective development volume into floor space

Integrated potential level	0-15m	Effectiveness Coefficient	15-30m	Effectiveness Coefficient	Total volume by level	Useful ratio by level
very high potential	0,336	0,6	0,016	0,4	0,35	**0,50%**
high potential	2,820	0,4	1,904	0,2	4,72	**6,76%**
moderate potential	3,756	0,2	3,005	0,1	6,76	**9,68%**
low potential	0,156	0,1	0,116	0,05	0,27	**0,39%**
useful volume_100mio m^3	7,07		5,04			
total volume_100mio m^3	27,95		41,92		69,87	
useful ratio by depth layer	**25,29%**		**12,03%**		**37,31%**	
equivalent floor land_m^2	**176 700 000,00**	**2,5 floors**	**124 344 666,67**	**3,7 floors**	**301 044 666,67**	*(if floor height = 4m)*
Intensity of underground space (floor space/land area)	**0,63**		**0,44**		**1,08**	

Supply capacity is static for short-term, with unchangeable natural resources, existing built subsurface and historical regulatory control. But demand potential could be dynamic with growing economic activities, and could be expansive with rail transit accessibility. Estimation performed in the section considered a time horizon to 2020 based on development agenda and demographical trend.

3.7.2.4 Reporting on supply inventory for geomaterial, geothermal energy and groundwater

3.7.2.4.1 Geomaterial:

Volume of geomaterial is linked to underground construction. According to local geotechnical survey, 60% of shallow layers' materials are silt and fine sands, the rest are clay material. Those high water content materials are conserved substantially by the city, for land reclamation in low-lying lands to maintain surface land supply (average elevation below 3 meters). Therefore, urbanizing the central subsurface will produce valuable derivative product of reclamation material for the city region.

Based on the reporting results on effective development volume of underground space at shallow layers shown (Table 3:20), overall geomaterial reserve counts for 1.21 billion cubic meters. It can be estimated that, **0.93 billion tons of fine sands and 0.78 billion tons of clay can be produced along with shallow underground construction**[85]. This quantity is equivalent to half of the national annual aggregate production (1.5 billion tons of stone and sands in 2001), and one third of national annual clay production (2.24 billion tons of clay for brick production in 1995). Since aggregate quarrying

[85] Conversion units: fine sands: 1 cubic meter = 1.28 tons; stiff clay: 1 cubic meter = 1.6 tons

and mining have been threatening river environment and farmlands, synergizing the opportunity of underground construction and geomaterial production will help to increase the sustainability performance of underground urbanization.

3.7.2.4.2 Geothermal energy:

The Project team conducted a shallow geothermal energy potential study with the help of technology center IUSG in 2010, with installation of 19 monitoring boreholes in Suzhou city for observation. Monitoring results showed a constant temperature of 17.8 °C at the depth of 10 meters, being 2 °C higher than annual average temperature in the city. This study only evaluated the potential for ground source heat pump utilization (GSHP), due to the strict regulatory control of groundwater extraction.

Suitable areas for ground source heat pump installation are shown in Figure 3:47 (IUSG-NJU and Jiangsu geology office, 2012). Despite the large potential of geothermal resource, operable area in Old city core is limited to 10% of land, due to spatial conflicts with existing building blocks. Development zones could have 30% of land available for ground source heat pump drillings. For the whole urban scale, only 12.5 % of land is operable for geothermal borehole drilling. The study indicated that: exploitable shallow geothermal source (100 meters depth) has a potential of producing **3.6 million KW of thermal energy** for the building sector, representing 18 times of urban household electricity need in the year of 2009 (0.2 million KW). Due to the unbalance of heating and cooling performance (Table 3:21), summer cooling will need complementary energy system unless technological advancement in the industry of GSHP.

In order to unlock the energy potential of underground to serve the long term demand of the built environment, coordination of construction land and energy preservation zones should be taken into account to promote a synergetic use of energy and space. However, geothermal drills should be only permitted outside the protected groundwater zone.

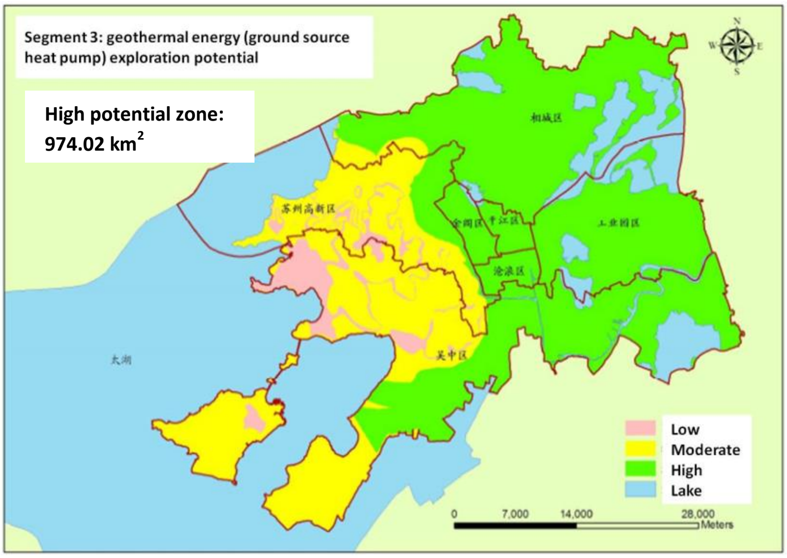


Figure 3:47 Geographical reporting result: Supply potential of shallow geothermal energy in form of GSHP (map extracted from internal report)

Table 3:21 Statistical reporting result: ground source heat pump energy supply

	GSHP LOAD (W/m2)	OPERATIONAL FLOORA SPACE (m^2)
WINTER HEATING	98	36 487 098
SUMMER COOLING	180	19 865 198

3.7.2.4.3 Groundwater:

Production potential of the main aquifer for drinking use is shown in Figure 3:48, indicating mean well output (IUSG-NJU and Jiangsu geology office, 2012), with the most productive sector situated beneath Central plain area, from the depth of 90 meters. This main aquifer suffered from over exploitation and was prohibited from extraction. Future deep infrastructure construction site should avoid the protection boundary to make sure that this valuable resource can be well protected for strategic water reserve. It is estimated that, exploitable deep groundwater reserve could reach 22 million cubic meters per year, if a moderate extraction rate is employed to insure a natural recharge of the aquifers and to avoid over exploitation. Future location of groundwater well can be selected based on the potential evaluation (red colored zone as priority location), then zoned with a protection radius according to national groundwater well regulation.

Shallow groundwater resource above this aquifer has been a new target for groundwater exploitation, due to high natural recharge rate. However, shallow groundwater well's water output is relatively low (< 300 m^3 per day), enhanced technical solutions could help to increase supply potential of shallow groundwater resource for future water demand.

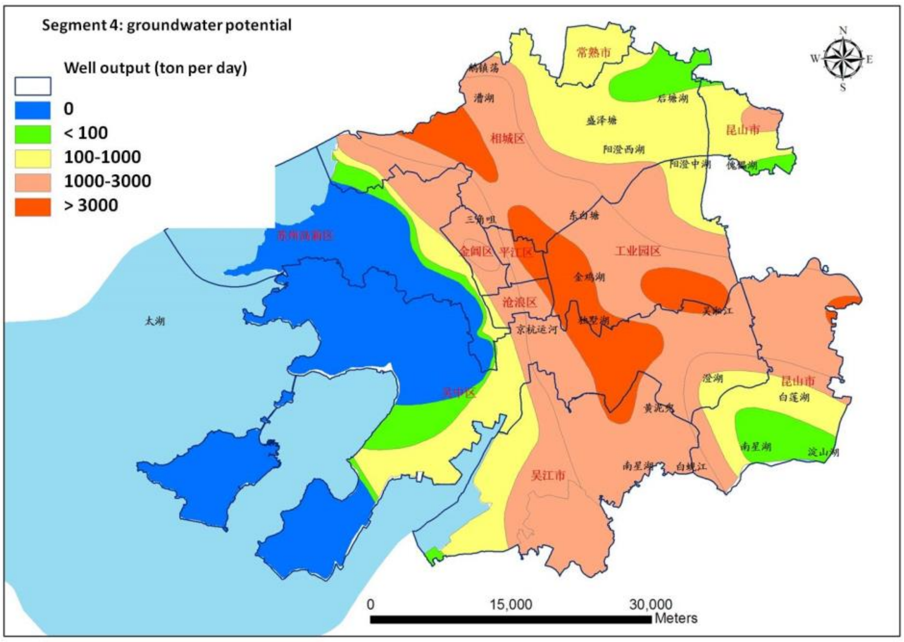


Figure 3:48 Geographical reporting result: drinking water aquifer supply inventory (map extracted from internal report)

3.7.3 Urban center operation: Old city core renewal and CBD development

Based on the city level inventory on urban subsurface' supply potential, demand potential and integrated potential, three dimensional land use planning can be formulated using reporting results drawn from the Planning system. Underground space resource can be allocated for urban zones with high integrated potential. This land management tool changed the pattern of developer-driven underground space utilization to a pattern of potential-driven utilization under governmental guidance. As indicated by reporting results, supply capacity of underground space has a limit, due to technological level and regulatory control. Increasing construction in the subsurface without planning directive will also decrease the capacity of underground densification. **Underground space development intensity or density is potential underground floor space divided by land area** (as shown in Table 3:20). As a complement for surface density, which influences the value of construction land, underground space development density can be considered as a new coefficient to adjust urban land utilization value.

This section is to introduce firstly a new method for valuing three dimensional land prices, which are driven by underground space development intensification. This method is then applied on district level case studies, in Old city regeneration projects and Central Business District development projects.

3.7.3.1 3D land valuation method

This new planning tool for using underground space as alternative land supply serves to reorient conventional urban expansion trend from surface sprawling to subsurface intensifying, by placing development intensities beneath existing built-up lands. While additional underground space development intensities/densities could be assigned to potential construction land, surface land prices could be readjusted with the increased intensities/densities. Therefore, a new economic index "**3D land value**" is put forward in this section, to renew surface land value by using the integrated potential evaluation performed in the last section.

Academic contributions on underground space pricing have been focusing on methods to evaluate "subsurface land value" for underground infrastructures expropriation costs (Pasqual and Riera, 2005, Riera and Pasqual, 1992, Barles, 2000) and for underground commercial space leasehold price in business district (Chen, 2010, Wang and Cheng, 2006, Wang et al., 1995). For example, along with national policy initiations to cope with increasing use of urban subsurface in China, several Chinese real estate researchers have developed methods to calculate the "*correction coefficient for subsurface use right*" by different underground floors (Tang and Yang, 2011). The aim is to serve future policy of "*underground construction right certificate*" assigned to underground building developers with a reduced tax compared to surface land use right (Wang et al., 2009).

Planning regulations will give land parcels specific market values, linked to the permitted density (FAR), authorized use (facility, industrial, commercial, residential), infrastructure level (utility, transport, and services), etc. While a planning policy is being formulated for urban underground space, ***3D land valuation* process** should also be merged into policy making practices.

Although researchers pointed out that there will be a subsurface land market in the future due to increased use of subsurface in urban areas (Pasqual and Riera, 2005, Barles and Guillerme, 1995), this solution is not a simple administrative tool but involved with lots of legal issues and fiscal feasibility uncertainties. Since the legal context of land property rights differs among countries (Barker, 1991), there is not yet a universal solution to deal with subsurface property rights, apart from some cities initiated a specific depth and ownership for underground public infrastructures (e.g. Helsinki and Tokyo). For underground building projects, workable valuation methods have to align with existing surface land regulations and adapt to existing market rules.

According to land value monitoring in Suzhou city, there exists a linear correlation between land price premium and permitted development density (Floor area ratio): an example for commercial land price index is shown in Figure 3:49. In order to integrate the subsurface value into existing land prices, the potential underground space intensity can be embedded into land market value. The tradable land parcels on the market can be restructured according to their land price and their exploitable underground potential. This land value restructuring helps to incorporate the economic potential of using underground space into market land price. It gives implication to the land owners about how to develop an underground property project in a rational way.

For high potential area in general, their land parcels to be developed can have different interpretation of real value. The hidden value of developing subsurface can be incorporated into existing land price (here is about commercial land or mixed use land), with a coefficient/premium to reveal the differences of subsurface economic returns. Low “supply capacity” indicates higher construction costs for underground space, decisions on land acquisition can combine supply capacity index with demand potential of the location, and developers can also adapt the real estate project plans to the **3D land value class**, corresponding to the four integrated potential levels (Table 3:20).

There are two approaches for 3D land valuation:

1) Supply approach: underground space intensity can be estimated by dividing the estimated total underground space potential by the area of built-up zone. Through regression model of land price and density level, 3D land value can be deducted. This approach is applicable for cities with a comprehensive supply inventory of underground urbanization.

Table 3:20 converted effective usable underground space volume into floor space, indicating that fully development of underground space at the first shallow layer (0-15m) contributes an intensity ratio of 0.63 for total construction land in central city, equivalent to 31.5% of surface building density (FAR of 2.0 in current stage). Using analogical relationship between FAR and land price premium shown in Figure 3:49 (data from land valuation report of Suzhou city 2007), **maximum 3D land value premium could reach 119% due to alternative space supply with an underground intensity of 0.63 in the short-term future**.

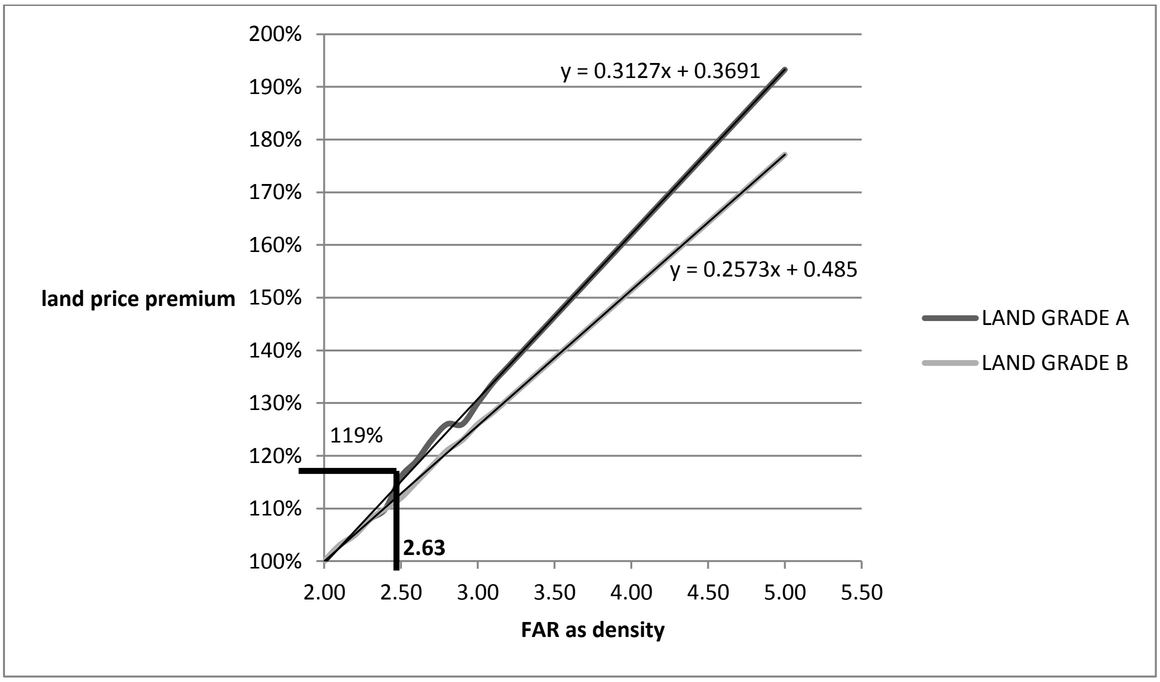


Figure 3:49 Land price premium with density variation for Suzhou commercial land prices (Land grade A and B) (data from Suzhou land value monitoring report)

2) Demand approach: existing commercial land price could indicate the potential level for underground space intensity, based on megacity experience of Tokyo. This approach is applicable for cities with enhanced technological and financial capacity for overcoming supply capacity limit in order to meet escalated demand on underground urbanization.

According to an empirical research on the relationship between intensity of underground space (IUS) and four land use indicators: land prices, FAR, distance to subway, land use types (Liu and Zhu, 2009) (for 4 central districts in Tokyo, covering 60.38 m^2), significant correlations were observed between land price with the other indicators. For commercial land, the coefficient of correlation between IUS and land prices is 0.788, and it is 0.745 between IUS and FAR. Average intensity in commercial land is 0.2 (within 290 land parcel samples), much higher than housing land (0.015) and industrial land (0.008).

The section 2.1.1.1.3 presenting central Tokyo's basement type building development has revealed a relationship between central commercial land prices with basement levels (Figure 2:12), as shown in the linear equation below:

$$\text{Number of basement levels} = 0.0001 \times \text{Land price} + 1.0251$$

The above equation helps to predict potential underground space development expressed in basement level according to land price categories, as shown in Table 3:22. It is estimated that, current commercial land price level implies that building development projects could have an average basement level of 3 floors, indicating that development depth could reach 15 meters for commercial land use type.

Table 3:22 Basement level prediction for Suzhou commercial land parcels

Commercial land GRADE	Benchmark land price 2012 (Yuan per m^2)	BASEMENT LEVEL (ANALOGY TO TOKYO)
Grade A land	58 790	6,90
Grade B land	32 860	4,31
Grade C land	19 950	3,02
Grade D land	11 195	2,14
Grade E land	7 810	1,81
Grade F land	5 310	1,56
Grade G land	2 690	1,29
AVERAGE	19 801	3,01

According to Suzhou city's commercial development agenda, main economic activities in the commercial sector will be located in the Old city zone and in the CBD of SSIP district. Contribution of underground intensification will be evaluated in these two areas, by showing their 3D land values and implementation strategies.

The remaining section will present district level strategies at shallow underground development layers (0-15m, 15-30m). Main administrative districts in Central city are shown in Figure 3:50.

Figure 3:50 Location of five administrative districts in Old city zone and development zone

(Gusu Old City zone: 1 Pingjiang district, 2 Canglang district, 3 Jinchang district;

Developing zone: 4 SND district, 5 SSIP district)

Reporting results for integrated potential evaluation for these five districts are shown in Table 3:23. It is estimated that 57% of Old city zone has high to very high level of integrated potential for underground space development to the depth of 15 meters, with the deeper underground rich in groundwater and geothermal energy supply. Development zone's high underground urbanization potential is concentrated in the CBD area in SSIP district, with richer groundwater resource and geothermal energy potential than the Old city zone.

Table 3:23 Sustainable underground urbanization potential for five urban districts

DISTRICTS	**AREA (km^2)**	**DENSITY (per/ km^2)**	**POP. GROWTH**	**UNDERGROUND SPACE INTEGRATED POTENTIAL (very high to high)**				**MAIN AQUIFER**	**GEOTHERMAL ENERGY**
				0-15M (Km^2)	**ratio**	**15-30M (km^2)**	**ratio**	**WATER SUPPLY (ton/day)**	**ENERGY SUPPLY (KW)**
PING_JIANG	23	11682	3,52%	16,90	73%	4,50	20%	3000	84,436
CANG_LANG	26	15191	2,15%	20,30	78%	2,40	9%	2000	95,229
JIN_CHANG	37	7860	1,05%	6,70	18%	1,60	4%	2000	113,804
OLD CITY ZONE	86	11098*	2,24%*	43,90	57%*	8,50	10%*	2333*	293,469
SND	258	2218	4,65%	11,90	5%	0,00	0%	100	494,389
SSIP (CBD incl.)	288	2414	11,48%	19,90	7%	0,40	0%	3000	2,097,820
DEVELOPMENT ZONE	546	2322*	8,07%*	31,80	6%*	0,40	0%*	1550*	2,592,209

(* average value)

3.7.3.2 Old city zone: underground space for revitalization

District of Ping-Jiang has the highest land prices and highest population growth. As the city's historical development center, this district owns most of the cultural heritages in the city. This dense urban center 23 km^2 is an important transport hub with train station and metro stations. Three subway lines will pass through the district, with two largest central transfer stations located beneath the district. According to land administrators, there have been no available land supplies in the Old city zone in the recent decade.

For underground urbanization, supply capacity in the district is constrained by existing below ground structures and numerous protected building sites. However, the high level land price and social-political role of the district allow it to be one of the important targets for underground space development.

From Table 3:24, potential supply of underground space helps to relieve land use pressures in the center up to 63.09% of current building footprint, leaving more spatial freedom for this historical center to preserve cultural and landscape capital (gardens, museums, water canals, old bridges, listed historic buildings for rehabilitation). Spatial relocation and functional adaption helps to preserve this historical city while providing better social services.

Table 3:24 Inventory of underground space supply (0-30m depth) for Ping-Jiang district

Indicators	Planning reference (Ping-Jiang)	Space and land (Ping-Jiang)
Housing sector space demand	268,686 habitants	9,404,010 m^2 living space[86]
Commercial sector space demand	285,200 employees[87]	7,130,000 m^2 working space[88]
Built-up area	23 km^2	
Green space	40% of built-up area	9,200,000 m^2 (9 km^2)
Building footprint	60% of built-up area	13,800,000 (13.8 km^2)
Densification demand	Floor area ratio	3.0
Underground space supply (0-15m)	16.90 km^2	21,125,000 m^2 (2.7 floors)
Densification input (current trend)	Underground space density	0.92
Underground space supply (15-30m)	4.5 km^2	4,995,000 m^2 (3.7 floors)
Densification input (short term trend)	Underground space density	0.22
Building footprint release	Underground space / density	8.71 km^2 (63.09 %)

(The layer of 0-15m subjects to an effectiveness coefficient of 0.5, for the layer of 15-30m is 0.3 as technical limit; Technological evolution could increase the effective use coefficient and enable more supply quantity of underground space.)

From geographical reporting results shown in Figure 3:46 (page190), high integrated potential for underground space development at shallow depths is concentrated near rail transit lines. Regeneration projects in the district can be located near main metro hubs, where development rights will be allocated for mixed use projects according to Rail transit development regulation (2011). Underground space density supply within 15 meters' depth reaches 0.92, being 31% of total development density demand. If existing land value is corrected by the underground space density coefficient, a 29% of value premium can be gained for a maximized utilization of the subsurface (Figure 3:51). This regression model can be used to adjust single land parcel's 3D land value in Ping Jiang district, by integrating underground space density.

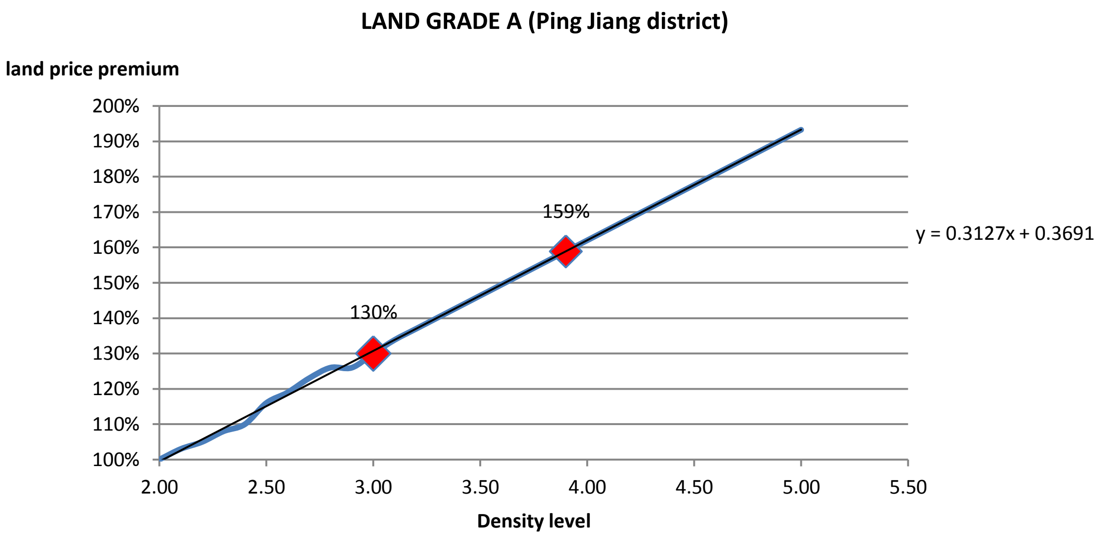


Figure 3:51 Regression model: Land price index with density level in Ping Jiang district

[86] According to the municipal objective in 2010: per capita living space reaches 35 m^2.
[87] Adapting to international planning standard for Transit-Oriented land development: 1.24 employees per 100m^2 space near subway catchment area.
[88] Assuming that per employee working space is 25 m^2.

Although land supply has been saturated in this district, the rail transit induced redevelopment projects creates alternative land reserve owned by the Suzhou Metro Corporation. Since densification in the old city zone is restrained by building height limits (9 meters for residential land use and 24 meters along main avenues), placing commercial and mixed land use functions in the subsurface could help to revitalize the district while respecting planning codes and urban landscape regulations.

Functional demonstration for redevelopment projects are shown in Figure 3:52. Redevelopment projects for the three rail transit hubs in the district have potential to construct more than 270,000 square meters of underground space for commercial use and public use functions. 90,000 square meters of surface land can be released for green space and public space, to improve quality of life in this historic district. This functional design is similar to the regeneration projects in Central Paris and Central Tokyo, by intensifying underground space development near rail transit hub and creating large scale green space on top of public infrastructure land.

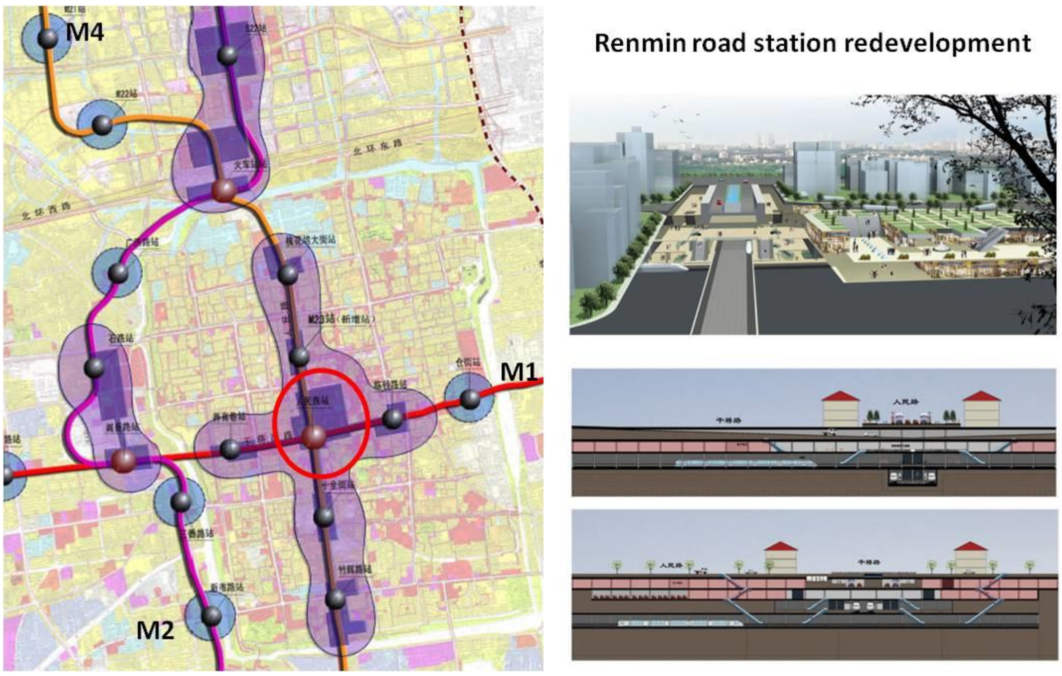


Figure 3:52 Combined redevelopment with metro lines and adjacent lands in Ping Jiang district (image from Suzhou urban planning bureau)

3.7.3.3 Central Business District: underground space for densification

The CBD of Suzhou city is the first in China introducing a preliminary subsurface leasing regulation. According to official data in 2009, land supply in the district decreased by 30%, while the district GDP increased by 15%. Land scarcity of the CBD zone pushes its urbanization upward to reach an average building height of 150 m and downward to depth of 20m. With the improved accessibility to rail transit (three subway stations to be serving the CBD), other uses including subterranean pedestrian ways, parking, and shopping centers are gradually planned to release more surface space for housing and office (80% of Grade-A office in the city will be located in SSIP CBD).

Due to the unfavorable soil quality, the foundation of this development zone was built artificially from earth fill to increase its elevation and to prevent flooding (Chen, 2006). A cautious land development pattern is critical to maintain its role as business and financial center by providing sufficient working space. An abundant groundwater resource reserve beneath the district also helps to sustain its urbanization need in the long-term future. From 2003, groundwater exploitation in Suzhou city has been totally prohibited, due to land subsidence from over-exploitation. The groundwater level is increasing significantly, offering a potential long-term reserve for future generations under rational exploitation.

Contribution of underground space densities and land savings is shown in Table 3:25. Utilization of the shallow subsurface helps to release 24.08% of surface land supply. Maximum intensity with underground urbanization deep to 30 meters could reach 0.69, being 17% of total density demand.

Table 3:25 Inventory of underground space supply (0-30m depth) for CBD in SSIP district

Indicators	Planning reference (SSIP CBD)	Space and land (SSIP CBD)
Predicted space demand		12,000,000 m^2
Built-up area		5 km^2
Building footprint	70% of built-up area	3.5 km^2
Densification demand	Floor area ratio	4.05
Underground space supply (0-15m)	2.20 km^2	2,970,000 m^2 (2.7 floors)
Densification input (current trend)	Underground space density	0.60
Underground space supply (15-30m)	0.4 km^2	444,000 m^2 (3.7 floors)
Densification input (short term trend)	Underground space density	0.09
Building footprint area release	Underground space / density	0.84 km^2 (24.08%)

(The layer of 0-15m subjects to an effectiveness coefficient of 0.5, for the layer of 15-30m is 0.3 as technical limit; Technological evolution could increase the effective use coefficient and enable more supply quantity of underground space.)

By integrating underground space density, land value in the Central Business District can have 12% of price premium by densification effect, indicated by the regression model shown in Figure 3:53.

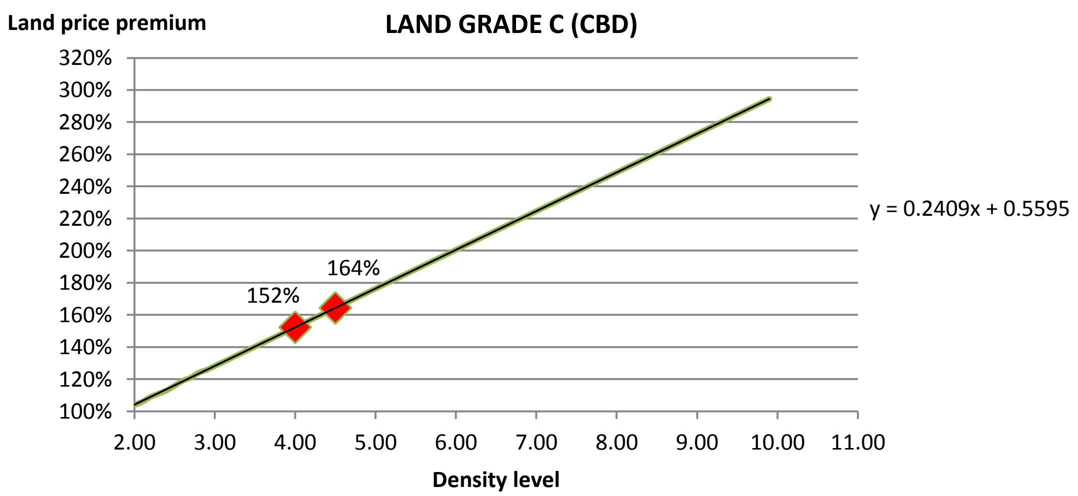


Figure 3:53 Regression model: land price index and density level in Central Business District

According to urban planner of Central Business District, 90% of the high rise buildings have developed underground space, with the deepest scale to four basement levels. Referring to other Central business Districts with aboveground and underground space ratio around 3 to 3.6 (Table 3:26), it is predicted that using an average ratio of 3.4, future underground space development could attain 1,150,000 square meters. This demand quantity is feasible under the reporting results (Table 3:25) estimated by the Planning system.

Table 3:26 Comparison of Central Business District on underground space development ratio

World CBDs	Shanghai	Paris	Chongqing	Suzhou
Overground space (m^2)	3,090,000	2,500,000	4,000,000	4,000,000
Underground space (m^2)	890,000	830,000	1,120,000	1,150,000
Ratio OG:UG	3.5:1	3.0:1	3.6:1	3.4:1

Feasibility and opportunity of large scale underground space development determine a high development potential profile for underground urbanization in Suzhou city's CBD. Supply capacity and demand opportunity are detailed as follows:

- Supply capacity:
  As part of development zone in the city, this district has been planned and built since the year of 1995. Different from Ping Jiang district built in ancient periods, there are more spatial freedoms for underground urbanization with less existing structures occupying its subsurface and there is no protected urban heritage on the surface to restrain underground construction.

- Demand opportunity:
  Since most of the high rise buildings in the district have basement levels, horizontal expansion of underground space can be feasible by linking subterranean stations and adjacent basements. Demographical growth in the CBD is expected to reach 11.48% annually, but surface land supply has been reduced by 30% annually. Besides increasing parking demand, retail business and recreational activities are expected to increase significantly in the district.

  About 60% of inhabitants will use rail transit system, which necessitates large scale of public space in the metro station for pedestrian use and related services. Combined development with rail transit stations and adjacent subsurface is shown in Figure 3:54. Total scale of the combined development in the subsurface cover 350,000 square meters of floor space.

- Administrative arrangement:
  Underground building functions beneath the CBD include public properties such as pedestrian pass, parking and plaza, as well as private properties such as commercial centers. Those subterranean commercial use lands (red colored parts in the figure) were leased on the land market with specific development rights defined by SSIP district government.

According to the urban planner in SSIP district construction bureau, when subsurface commercial land development rights are transferred to private developers, specific underground space floor space and density will be indicated precisely in the leasehold contract. In addition, district urban planning bureau will impose ceiling height and access to public space for private underground construction projects. This compulsory development requirement helped to orient developers on subsurface land development.

Fiscal encouragement for using the urban underground in the district is in form of reduction on land acquisition costs. Since the year of 2009, district government has released a regulation on underground building construction right and property registration[89]. Underground building units were registered into development rights of construction land parcel, considered as part of overall building density in the land parcel. In 2011, district financial bureau released a notice on fixing the price of underground construction land (with and without surface building). Floor price[90] assigned to underground part of commercial land can be reduced by 70% to 90% of basic floor price. Commercial buildings can be constructed fully below ground, granted with stratified leasehold rights.

Financial advantage under this regulatory term is shown below, for an underground commercial center in the complex of "Central Station".

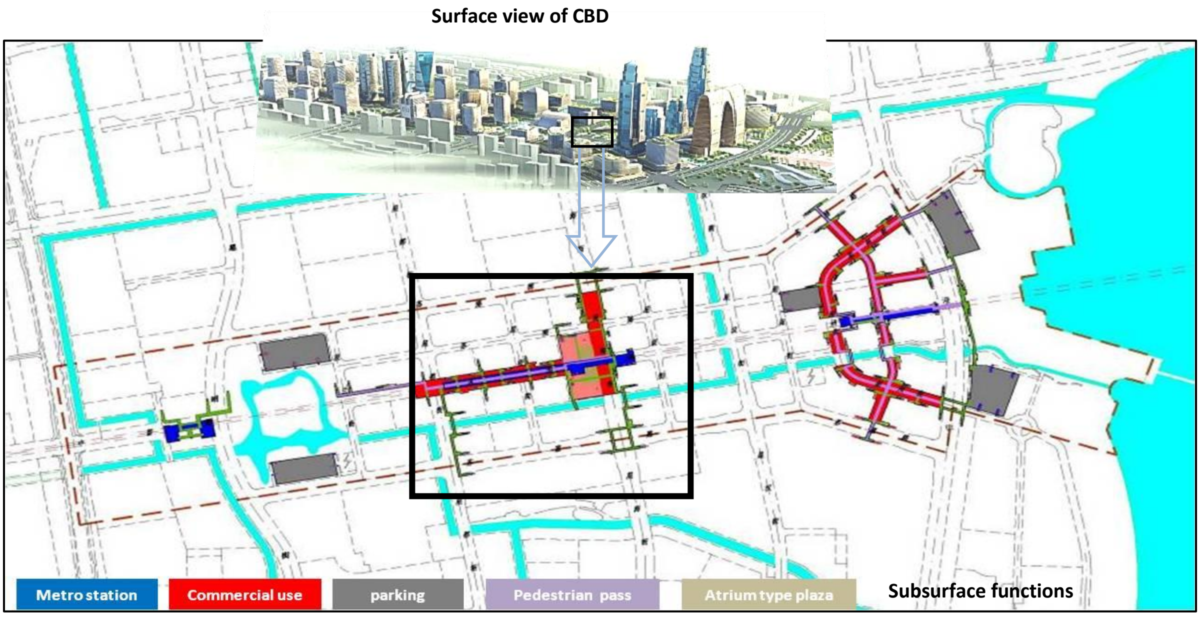


Figure 3:54 Combined development of rail transit and adjacent subsurface in central business district in Suzhou city (the circled area is "Central Station" underground complex) (image from SSIP land development company)

89 Legal document code: EL100-C0500-2009-001 (Suzhou SSIP district)

90 Floor price is land value distributed in floor space unit, it is calculated as:

Floor price = land price / (overground space + underground space) = land price / (FAR × land area).

This underground commercial complex was invested, developed and managed by the State-owned land developer of SSIP[91] in 2011 and it is currently under operation. Deep to 16 meters with three underground floors, development functions are mainly retail shops and parking service adjacent to the subterranean metro station (Figure 3:55). Compared to basic land acquisition costs for the 18,000 square meters of commercial space, underground development can save about 90% of land acquisition costs, as illustrated in Table 3:27.

Table 3:27 Central Station commercial estate information, underground space leasing price calculation

Project name:	**Central Station**		
Location:	CBD in SSIP district		
Land area:	14,400	m^2	
Total building floor space:	54,000	m^2	
Underground building floor space: (commercial use)	18,000	m^2	(level 1,2)
Underground building floor space: (public parking use)	27,000	m^2	(level 3)
Unit land price:	19,950	Yuan per m^2	Land price index 2012
Total land price:	287,280,000	Yuan	
Basic Unit Floor price: (UFP)	5,320	Yuan per m^2	
Underground unit floor price: (stratified leasehold)	1,064	Yuan per m^2	(level 1: 20% of UFP)
	532	Yuan per m^2	(level 2: 10% of UFP)
Total basic land acquisition costs:	95,760,000	Yuan	(commercial use)
Total underground land acquisition costs:	9,585,532	Yuan	(commercial use)
Savings in land acquisition costs:	-89.99%		

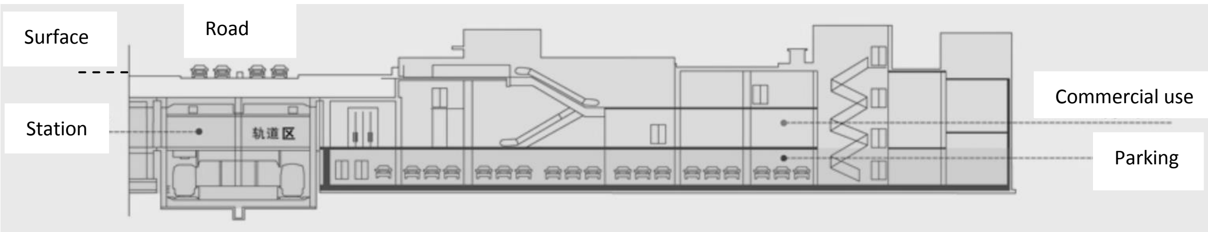


Figure 3:55 Vertical profile of Atrium type underground plaza and commercial center (image from SSIP Central station commercial presentation booklet)

[91] http://www.siplm.com/

3.7.3.4 Conclusion for urban center operations

Central city owns high integrated potential on underground space development, especially at shallow layers. While this potential is converted into buildable floor space, contribution of underground densification can be expressed by a price premium for existing land values, forming a 3D land value.

Urban centers near rail transit infrastructures were identified as having high integrated potential for shallow underground urbanization (Figure 3:46). By quantifying potential underground building densities for an old district and a modern district, functional utilization in complex forms were presented including revitalization type for historic center and densification type for business center. Benefits of compact development in adjacent lands to transit stations also helped to relieve financial burden of the underground transport system, by capturing the real estate price premium around catchment area. While both types of underground complex offered additional land supplies for commercial sector and public service sector, financial investment still need to be justified with cost efficiency analysis.

3.7.4 Development project evaluation: Cost efficiency analysis

This section is to apply the findings from city level operation and urban center operation into project level evaluation, in order to guide development project investment. Underground densification could generate price premium for utilization value of land resource. Since underground space functions have been diversified and serving a broad range of users, single underground buildings are being extended horizontally into mixed use network, and being extended vertically into stratified layers.

Despite technological advancement, current underground construction feasibility still asked for a higher capital costs. While land price is taken into account, the landscape of total investment costs will change significantly due to absent or lower price of the subsurface. Financial advantage was illustrated for a commercial project in the CBD of Suzhou city (Table 3:27). However, this fiscal incentive didn't take into account the construction cost, which is a main constraining factor to attract private developers' participation into underground urbanization. The construction cost factor was considered by Singapore government in the formulation of Central area underground master plan (section 2.2.2), putting forward a cash grant incentive scheme to encourage private capital participation.

The cost efficiency analysis applied to the case study of Suzhou city will combine the factor of land cost and construction cost, as well as the intensity evolution of underground space use.

3.7.4.1 Land price in the city

According to statistics of land price evolution in 46 American metropolitan areas[92], the land cost share in housing projects has increased by 20% from 1984 to 2008, with land price having increased by 490% during 22 years. In Chinese emerging urban land markets, housing land price in the city has been going through an incremental rate of 125%, while commercial land price was observed with a 100% incremental rate, during a 12-year period starting from its national land reform in the year of 2000 until now[93]. This value increase is often more crucial in the Old City core than in development zones outside the city center. Evidence could be found for the above mentioned districts in Suzhou city: Ping-Jiang district's commercial land price is 58,790 CNY/m^2 (9,436 USD/ m^2)[94]; CBD's commercial land price is 19,950 CNY/m^2 (3,202 USD/ m^2).

Land acquisition right is managed by various building codes such as Floor Area Ratio (FAR) or building height, building footprint (built-up density), greenery rate, leasehold duration[95], land use, etc. All these codes have significant impacts on project implementation. In the current context, general fixed codes include land use (commercial, housing, education or industrial use), building footprint (50% for commercial land and 20% for housing land), greenery rate (40%), leasehold duration (40 years for commercial land and 70 years for housing land). Floor Area Ratio or building height could be flexible according to specific need (high-rise building projects), but generally it is also subjected to strict regulations (e.g. building height limits to 24m in Geneva's old city district and 9m in Suzhou's old city district). Although current regulations don't embrace underground space into the FAR calculation, unlimited extension below the ground is not a wise plan, which will be explained by the factor below.

92 http://www.lincolninst.edu/subcenters/land-values/metro-area-land-prices.asp
93 Urban land price report, China Ministry of Land Resources http://www.mlr.gov.cn
94 http://www.szgtj.gov.cn (1 USD = 6.23 CNY)
95 Leasehold is a common practice in Chinese land market, while most of developed countries applied freehold in land trading.

3.7.4.2 Construction cost of underground space

According to these 46 American metropolitan areas, the observation of house building costs showed an increase over 130% in 22 years. Material price keeps climbing (cement, concrete, aggregate, steel), with a percentage recorded in Switzerland as 48% (1998-2008). Technology in the construction industry is giving impetus to scale up the performance of developers in terms of bringing efficient equipment, shortening project duration and forming skilled builders (Newton et al., 2009). Underground construction especially tunneling technology is one of the important areas of continued innovations in this industry (Sterling, 1992). However, underground buildings still have higher construction costs compared to surface buildings. Savings in operational costs in terms of life-cycle energy consumption were quantified for an underground commercial center in Switzerland (Maire, 2011). Compared to the Swiss “Minergie” standard eco-building, this underground commercial center can help to reduce emission of 1.5 kg CO^2 per square meters per year.

1) Cost coefficient 1: Supply capacity level

Construction cost for underground space is determined by underground supply capacity, which was illustrated in section 3.7.2.1.1 (page 179) by a comprehensive evaluation method using geographical planning system. Geo-engineering difficulty, risk prevention and technological limit are main determinants for high construction costs and limited exploitation effectiveness. Developing the subsurface of lower supply capacity land requires larger volume of ground support or longer duration for ground acquisition (due to utility relocation, specific authorization request, archeological discovery, pollution treatment, etc.). These costs related to engineering, risk prevention, relocation and time delay will influence the project delivery process and should be well identified during conceptualization and appraisal stage, with the eight supply capacity criteria considered in the evaluation method (Table 3:14). Based on the supply capacity standards, the analysis in this section will consider three quality levels: good, moderate and bad, with corresponding cost coefficients.

Quality of the ground modifies ground treatment engineering solutions, inducing a cost premium for specific construction condition. According to the bill of quantities estimated by Institute of construction economics (IEC, Lausanne) for an underground commercial building in Geneva city (project plan shown in Table 3:30): based on Swiss referential price index in 2002, physical engineering element of ground preparation (CFE code: B) for good quality ground (Molasse rock) cost 229 fr. per square meter space, which increased to 577 fr. per square meter space for bad quality ground (Moraine soil). The cost coefficient can be considered as 2.52 to 1 for bad to good quality level. Avoiding execution in bad construction site will help to save up to 60% of ground engineering costs. Considering conventional surface building as baseline value, cost coefficients 1 related to supply capacity level are shown in Table 3:28.

Table 3:28 Unit price for ground engineering and cost coefficients (provided by IEC, Lausanne)

	Unit price for ground preparation (CFE code: B)	**Cost coefficient 1 Supply capacity**
Baseline level (surface building)	56 fr. per m^2	1.00
Good quality level (UG building)	229 fr. per m^2	4.09
Bad quality level (UG building)	577 fr. per m^2	9.95

2) Cost coefficient 2: Development scale

Current development depth of underground buildings in Suzhou city is 20 meters. As observed from the case studies in benchmark cities worldwide (Chapter 2), expansion of underground space is not only vertical but also horizontal. Subsurface vertical stratification and horizontal connection can be realized by overcoming technical barriers and property right barriers. While surface building can only be extended upward, underground building can be extended both downward and sideward, until all the underground space forms (tunnel, basement, and cavern) can be connected as exchangeable spaces with the surface.

Development depth of underground buildings determines foundation engineering solutions, inducing a cost premium for larger volume of excavation. Table 3:29 shows unit price of foundation and excavation work for three development scale from shallow to deep and corresponding cost coefficients.

Table 3:29 Unit price of foundation excavation and cost coefficients (provided by IEC, Lausanne)

	Unit price for foundation excavation (CFE code: D)	**Cost coefficient 2 Development scale**
Baseline level (surface building)	667 fr. per m^2	1.00
shallow level 16m (UG building)	1511 fr. per m^2	2.27
Mid-depth level 24m (UG building)	1853 fr. per m^2	2.78
Deep level 36m (UG building)	2366 fr. per m^2	3.55

3) A cost evaluation model for an underground commercial building with deepening scale for different ground quality

The evaluation model is based on three development scales, ranging from conventional surface development to underground space development at increasing depths. Project types are presented in (Table 3:30). Using Swiss construction quantity surveying standard (CFE: codes des frais par élément), four project scopes were selected for detail construction cost appraisal, including a surface commercial building of 6 levels, and three underground commercial building with increasing levels (Ugo, 2011). Besides variation in developing scale, quality of the ground was taken into account to investigate the influence of subsurface supply capacity on construction cost. Detail cost breakdown is shown in Table 3:31 for good quality underground and in Table 3:32 for bad quality underground.

For underground commercial buildings, incremental costs for bad quality underground compared to good quality underground increase proportionally with basement levels, being 11%, 12% and 13% for 4-level, 6-level and 9-level underground buildings. The factor of ground quality influences ground preparation costs by requiring special soil treatment, while the factor of development depth influences excavation costs by digging larger volume of geomaterial. However, lower quality underground didn’t have a significant impact on project duration. Enhancing development scale requires longer duration for project delivery, with 16 to 20 weeks more for adding two underground floors and 40 to 50 weeks more for adding five underground floors, compared to the 4-level underground building project. In addition, unit construction cost for subterranean commercial building decreases with development depth, as shown in Figure 3:56 and Figure 3:57.

Table 3:30 Overview of four commercial projects (underground development scale extended from surface to deep underground)

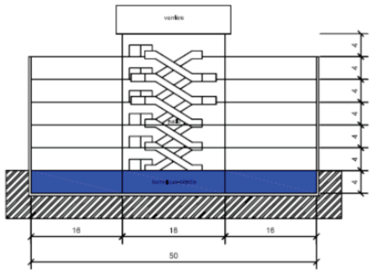
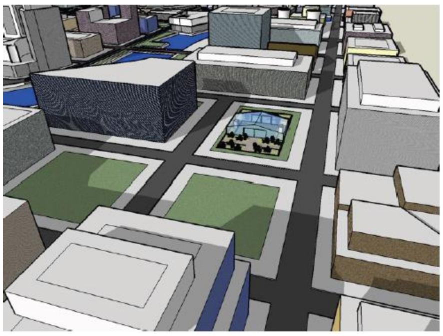
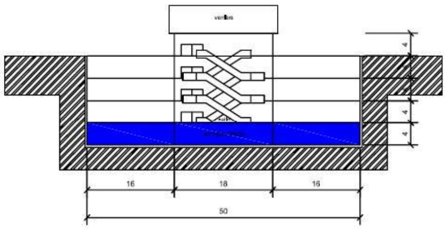
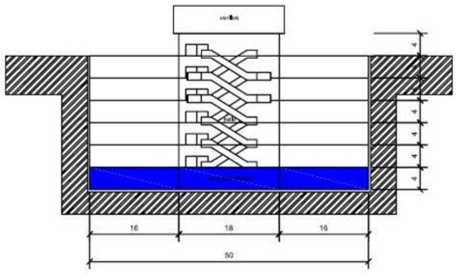
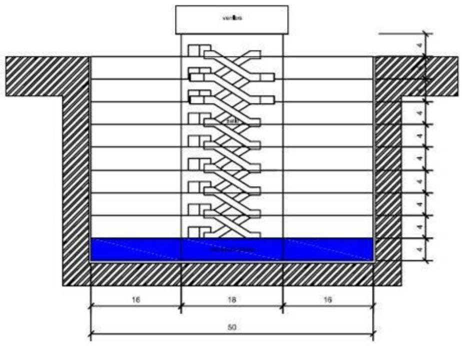
Surface view of commercial building	**Vertical profile (from surface to deep space)**
	 Project 1 : Surface 6F MINERGIE 6 levels above ground (0% underground rate) Total floor space: 8915 m^2
 (Project plan conceptualized by Prof. Architect Pierre Von Meiss)	 Project 2 : Underground B4 4 levels below ground (100% underground rate) Total floor space: 5943 m^2
	 Project 3 : Underground B6 6 levels below ground (100% underground rate) Total floor space: 8915 m^2
	 Project 4 : Underground B9 9 levels below ground (100% underground rate) Total floor space: 13372 m^2

Table 3:31 Construction costs for surface commercial building (6 levels) and three underground commercial buildings (4 levels, 6 levels and 9 levels below ground) in the good quality underground (Molasse rock)

CFC CODE	CFE CODE	TASK	Surface 6 F MINERGIE	Underground B 4	B 6	B 9
1	B	Ground treatment	500'000	1'360'000	2'040'000	3'060'000
Preparation work						
2	C	Site setting	412'000	250'000	250'000	250'000
	D	Foundation	1'000'000	2'267'000	2'780'000	3'549'000
	E	Structure	7'465'000	5'108'000	6'550'000	8'713'000
	I	Facility	5'560'000	4'077'000	5'490'000	7'610'000
	M	Interior	4'900'000	3'266'000	4'900'000	7'350'000
Construction work						
5	V	Taxes	1'000'000	818'000	1'103'000	1'529'000
	W	Consultancy	4'875'000	4'052'000	5'462'000	7'576'000
	X	Accounts	2'600'000	2'120'000	2'858'000	3'964'000
	Z	TVA	2'152'000	1'772'000	2'389'000	3'314'000
Fees						
Total Construction costs (good quality underground)			30'464'000	25'090'000 *(-18%)*	33'822'000 *(+11%)*	46'915'000 *(+54%)*
Unit construction costs (Swiss francs per square meter)			3417	4222 *(+24%)*	3794 *(+11%)*	3508 *(+3%)*
Unit construction costs (Swiss francs per cubic meter)			762	896 *(+18%)*	846 *(+11%)*	809 *(+6%)*
Engineering work duration for task B to E (weeks)			50	54	70	95

(Values in Swiss francs, % indicating over cost percentage compared to surface 6F building)

Table 3:32 Construction costs for surface commercial building (6 levels) and three underground commercial buildings (4 levels, 6 levels and 9 levels below ground) in the bad quality underground (Moraine soil)

CFC CODE	CFE CODE	TASK	Surface 6 F MINERGIE	Underground B 4	B 6	B 9
1	B	Ground treatment	500'000	3'427'000	5'140'000	7'710'000
Preparation works (additional ground treatment for bad quality underground)						
2	C	Site setting	412'000	250'000	250'000	250'000
	D	Foundation	1'000'000	2'267'000	2'780'000	3'549'000
	E	Structure	7'465'000	5'108'000	6'550'000	8'713'000
	I	Facility	5'560'000	4'077'000	5'490'000	7'610'000
	M	Interior	4'900'000	3'266'000	4'900'000	7'350'000
Construction works						
5	V	Taxes	1'000'000	925'000	1'263'000	1'769'000
	W	Consultancy	4'875'000	4'252'000	5'700'000	8'026'000
	X	Accounts	2'600'000	2'297'000	3'100'000	4'383'000
	Z	TVA	2'152'000	1'965'000	2'653'000	3'751'000
Fees						
Total Construction costs (bad quality underground)			30'464'000	27'834'000 *(-9%)*	37'826'000 *(+24%)*	53'111'000 *(+74%)*
Unit construction costs (Swiss francs per square meter)			3417	4683 *(+37%)*	4243 *(+24%)*	3972 *(+16%)*
Unit construction costs (Swiss francs per cubic meter)			762	994 *(+30%)*	946 *(+24%)*	916 *(+20%)*
Engineering work duration for task B to E (weeks)			50	54	74	105

(Values in Swiss francs, % indicating over cost percentage compared to surface 6F building)

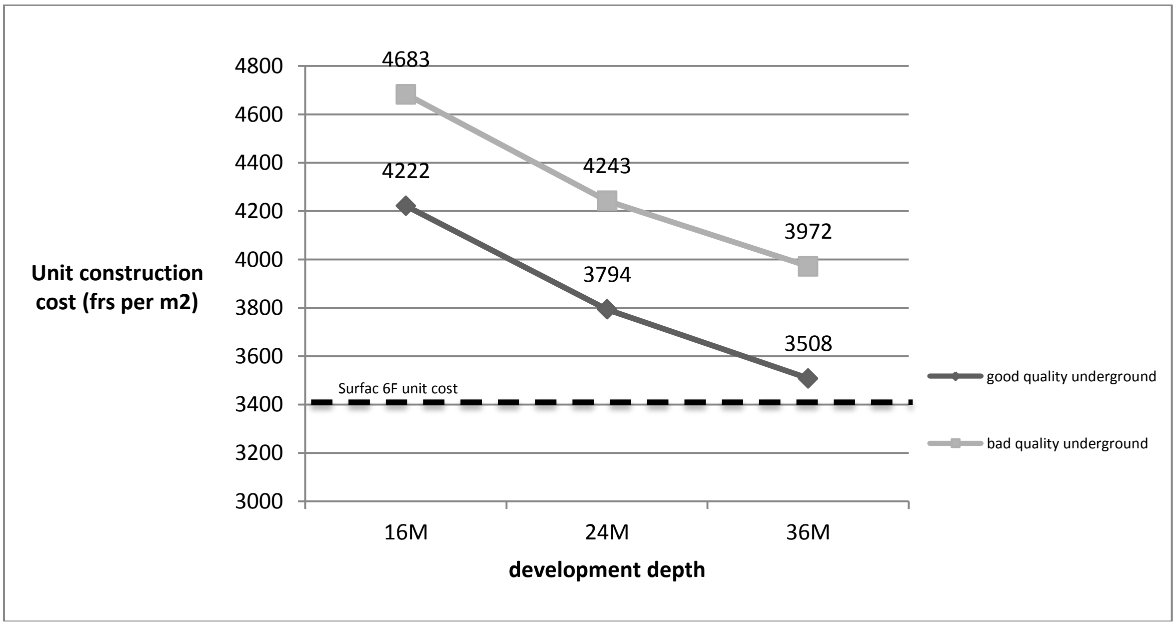


Figure 3:56 per square meter unit construction cost with the function of development depth (underground commercial building in Switzerland)

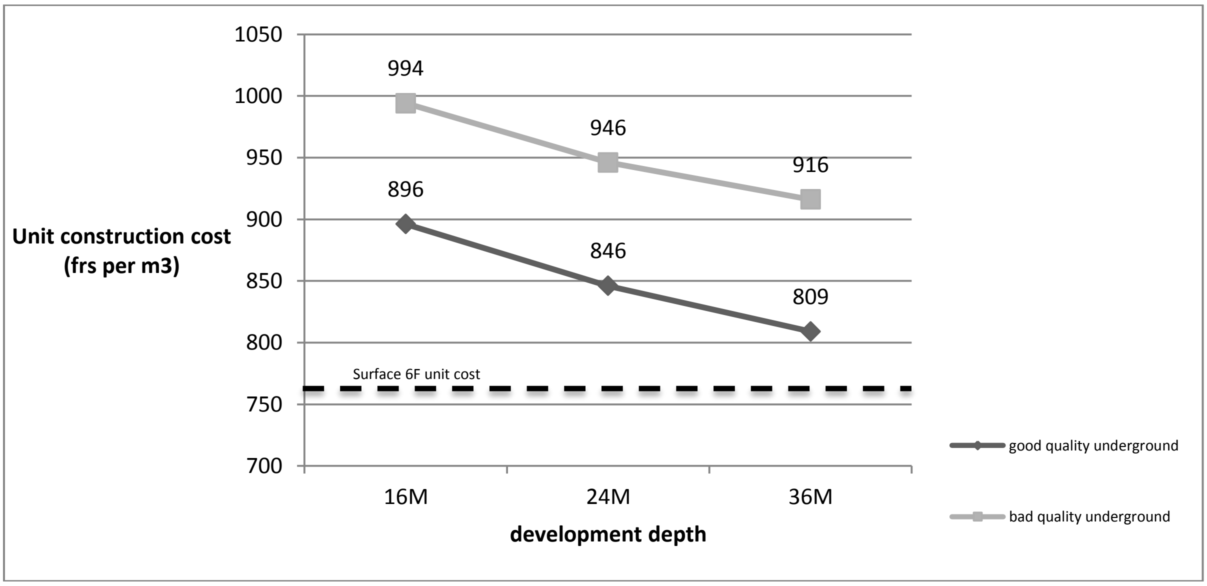


Figure 3:57 per cubic meter unit construction cost with the function of development depth (underground commercial building in Switzerland)

According to the construction cost index in Geneva city, price index of excavation work has been increased sharply from the year of 1997 (index: 90.2) to 2002 (index: 156.2). This continuous price trend will decrease competitiveness of underground urbanization. Commercialization of the geomaterial generated from excavation could help to compensate the cost of excavation. Excavation price include onsite excavation and off site evacuation, 45.4 fr. per cubic meter for soft soil and 104.5 fr. per cubic meter for rock. Aggregate price in the city is around 30 to 40 fr. per cubic meters, which is able to cover a large part of excavation work cost. Future underground construction cost model should integrate market value of geomaterial (soil and rock) into the balance sheet, making the operation of geomaterial handling an offsetting tool for civil engineering costs.

3.7.4.3 Investment cost efficiency analysis

Land price on the market represents surface economic context, and construction cost will represent subsurface constructability. These two main investment cost components of building projects are generally sharing around 70% of overall capital costs. In order to reveal competitiveness of underground building projects, a new index is put forward by the authors, named "**Underground development cost efficiency ratio**": proportion of total investment cost (land and construction) of a building that can be saved by burying part of it. We can obtain a series of investment scenarios by varying the burying rate, defined as underground space rate from 0% to 100% (the rate of underground floor space in total building floor space). A 100% of underground space rate is supposed to save 100% of land acquisition costs.

The economic model developed in this section is based on the hypothesis of contractual arrangement between public and private sectors: with the aim to encourage underground space development, project developers purchase the land footprint of surface building part and benefit an exemption for subsurface land use cost. Enhancing the underground space rate will reduce surface building part, leading to a minimization trend for land footprint purchase. The released land footprint area could be resold or conceded to the public sector for other surface developments (such as pedestrian lanes, cycling lanes, green spaces, public spaces, etc.). Evolution of underground space scale will change conventional land use allocation, by increasing more public domain on the surface and making private developers save land acquisition costs proportionally with the burying rate. In addition, the condition of using this legal arrangement to separate surface and subsurface ownership should be designated by the economic model, which indicates a rational burying rate to make the investment costs of underground scenarios breakeven compared to surface scenarios.

Estimation method for "underground development cost efficiency ratio" is as follow:

1) Select building project scope with development function, total floor space (FS), permitted density (FAR), and land use footprint (LF);

2) **Baseline surface scenarios**:

- Define surface development form as baseline scenario, using construction cost index to fix surface unit construction cost (SUCC) and baseline total construction cost (BTCC);
- Apply benchmark commercial land price value (LP) and classify into three levels (high price, medium price and low price), calculate baseline total land cost (BTLC) with the three price levels;
- Aggregate baseline total construction and land cost into baseline total investment cost (BTC).

Thus: (BTC) = (BTCC) + (BTLC) = (SUCC) × (FS) + (LP) × (LF)

3) **Underground scenarios**:

- Estimate the cost coefficients (K) for different underground space supply capacity standards (good, moderate and low levels), using the baseline cost coefficient as 1.00. Underground unit construction cost (UUCC) = (K) × (SUCC);
- Extend underground space rate (R) from 2% to 100%, meaning total floor space (FS) is composed of surface floor space (SFS) and underground floor space (UFS). It can be expressed as (FS) = (UFS) + (SFS) = R × (FS) + (1-R) × (FS);
- Total construction cost (TCC) with extending underground space rate equals to surface total construction cost (STCC) plus underground total construction cost (UTCC);
- With unit construction cost, cost coefficient, underground space rate, total construction of the project can be calculated as:

(TCC) = (STCC) + (UTCC) = (SUCC) × (FS) × (1-R) + (UUCC) × (FS) × R

= (SUCC) × (FS) × (1-R) + (K) × (SUCC) × (FS) × R

- Increasing underground space rate helps to save land use footprint on the surface, reducing initiate land cost for the same floor space quantity. Savings on land footprint can be estimated by space density (D). Total land costs (TLC) for underground scenarios can calculated as:

(TLC) = (LP) × (LF)' = (LP) × [(LF) – LF savings] = (LP) × [(LF) – (UFS)/D]

= (LP) × [(LF) – (R) × (FS) / (D)] = (LP) × [(LF) – (R) × (LF)] = (1-R) × (LP) × (LF)

= (1-R) × (BTLC)

- Total investment costs of underground space development project include total construction cost and total land cost, expressed as: TC = TCC +TLC.

4) Underground space development Cost efficiency ratio (CER %) is the cost saving by developing various rate of underground space, compared to baseline scenario:

$$CER\ \% = \frac{(BTC - TC)}{BTC}$$

This investment indicator reveals viability level of underground space developments. A higher cost efficiency ratio indicates higher integrated potential and better competiveness of underground scenarios compared to surface scenarios. A negative cost efficiency ratio implies a low integrated potential of land development scenario.

A breakeven cost analysis is also illustrated, to justify a viable level of underground space rate in building projects according to different levels of land quality and land price. Similar analysis has been done previously by (Carmody and Sterling, 1993) who evaluated competitiveness of underground facility to surface facility in terms of capital costs, indicating a favorable cost efficiency of underground facility construction in high priced land parcels with limited density authorization.

Estimation of the cost efficiency ratio will be applied on 2 project scopes (shopping mall project and mixed-use complex project), using three indicators (land price, subsurface quality and underground space rate). For each project scope, nine scenarios combining subsurface quality and surface land price will be evaluated and compared to the baseline scenario.

The baseline scenario is conventional surface building with an underground space rate of 0% and a cost coefficient of 1. Table 3:33 displays the reference data for the project scopes. All the price references are from Suzhou city Land Use Bureau and Construction Statistics Bureau.

Table 3:33 Reference of project scopes, land prices and construction cost coefficients

Project types	**Scope 1**	**Scope 2**	**Parameter**
Underground space function	Shopping mall	Mixed-use Complex	
Total floor space (m^2)	20,000	100,000	FS
Permitted FAR (floor area ratio)	5	8	FAR
Land area (m^2)	4000	12500	
Building footprint (50%) (m^2)	2000	6250	LF
Space density in the buildable footprint	10	16	D=FS/LF
Baseline scenario (surface development)			
Construction cost (Yuan per m^2) **Index 2011 Suzhou**	2’517	1’826	SUCC
Baseline total construction cost (Yuan)	50’340’000	182’600’000	BTCC
Land price indicator			
Surface land price (Yuan/ m^2)	(Low) 2800	(Low) 2800	LP1
Index 2011 Suzhou	(Medium) 12080	(Medium) 12080	LP2
	(High) 59435	(High) 59435	LP3
Underground quality indicator			
Subsurface construction cost coefficient:	(Good) 1.33	(Good) 1.33	K1
Baseline cost coefficient as 1.00	(Moderate) 2.66	(Moderate) 2.66	K2
	(Bad) 5.32	(Bad) 5.32	K3

3.7.4.3.1 Project scope: Shopping mall

In the city of Suzhou, commercial land supplies have been reduced to favor residential land and public infrastructure land provision. In order to maintain business vitality in central city, commercial sector development can be planned in a three dimensional way to save land use footprint. Since increasing land prices in megacities have been driving shopping malls to extend beneath limited urban lands, higher land value implies stronger demand for commercial space. Increasing underground space rate have an effect on resizing dimension of land parcels, thus decreasing land acquisition costs.

Underground space rate (R)	Underground floor space (UFS)	Surface floor space (SFS)	Saving in land footprint	Land parcel dimension %
0% (baseline)	0	20000	0	100%
10%	2000	18000	200	90%
20%	4000	16000	400	80%
30%	6000	14000	600	70%
40%	8000	12000	800	60%
50%	10000	10000	1000	50%
60%	12000	8000	1200	40%
70%	14000	6000	1400	30%
80%	16000	4000	1600	20%
90%	18000	2000	1800	10%
100%	20000	0	2000	0%

1) Baseline total investment costs: (in Yuan)

	LP1	LP2	LP3
BTCC	50’340’000	50’340’000	50’340’000
BTLC	5’600’000	24’160’000	118’870’000
BTC	55’940’000	74’500’000	169’210’000

2) Underground scenarios’ total investment costs and cost efficiency ratios:

Table 3:34 shows total investment costs for underground project scenarios for ten development scales (from 10% to 100%), with corresponding cost efficiency ratios. For good quality underground, fully development of underground space generates a cost efficiency of 60.43% on the highest priced land parcels and 10.13% for land parcels of medium land value grade. Compared to the surface development scenario, developing underground shopping mall in low value land use zone will be less competitive, with a negative ratio increasing with underground space rate. This analysis implies that, for the same underground development scale, higher land value enables a better efficiency in terms of investment cost.

However, supply capacity of the underground is an important constraint factor for the economic viability of underground commercial projects. Comparing Figure 3:58, Figure 3:59 and Figure 3:60, lower quality level of the underground increased significantly total construction costs, to an extent that even the absence of land acquisition costs could not improve its financial performance. The relative high construction cost of commercial centers (normally more expensive than offices) makes this functional development sensitive to underground quality. Underground urbanization in commercial sector should consider the supply capacity of the underground as critical determinant for its financial performance, for the impact of over cost will be harmful for long-term operation of the project.

Table 3:34 Total investment costs and cost efficiency levels for underground project scenarios (Shopping mall, Good quality underground)

Underground space rate (R)	Total Construction Cost (K1) good quality level	Total investment Cost in Yuan and cost efficiency ratio %		
		Low price land	Medium price land	High price land
0% (baseline)	50'340'000	55'940'000	74'500'000	169'210'000
10%	52'001'220	57'041'220 (-1.97%)	73'745'220 (1.01%)	158'984'220 (6.04%)
20%	53'662'440	58'142'440 (-3.94%)	72'990'440 (2.03%)	148'758'440 (12.09%)
30%	55'323'660	59'243'660 (-5.94%)	72'235'660 (3.04%)	138'532'660 (18.13%)
40%	56'984'880	60'344'880 (-7.87%)	71'480'880 (4.05%)	128'306'880 (24.17%)
50%	58'646'100	61'446'100 (-9.84%)	70'726'100 (5.07%)	118'081'100 (30.22%)
60%	60'307'320	62'547'320 (-11.81%)	69'971'320 (6.08%)	107'855'320 (36.26%)
70%	61'968'540	63'648'540 (-13.78%)	69'216'540 (7.09%)	97'629'540 (42.30%)
80%	63'629'760	64'749'760 (-15.75%)	68'461'760 (8.11%)	87'403'760 (48.35%)
90%	65'290'980	65'850'980 (-17.72%)	67'706'980 (9.12%)	77'177'980 (54.39%)
100%	66'952'200	66'952'200 (-19.69%)	66'952'200 (10.13%)	66'952'200 (60.43%)

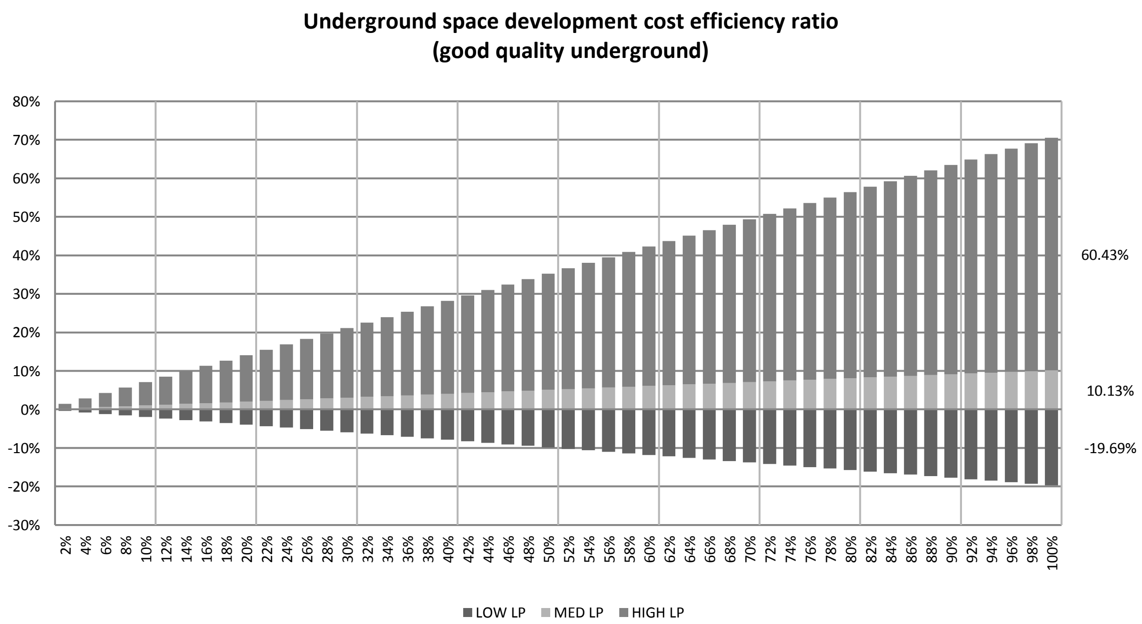


Figure 3:58 Underground shopping mall cost efficiency ratio (Good quality underground)

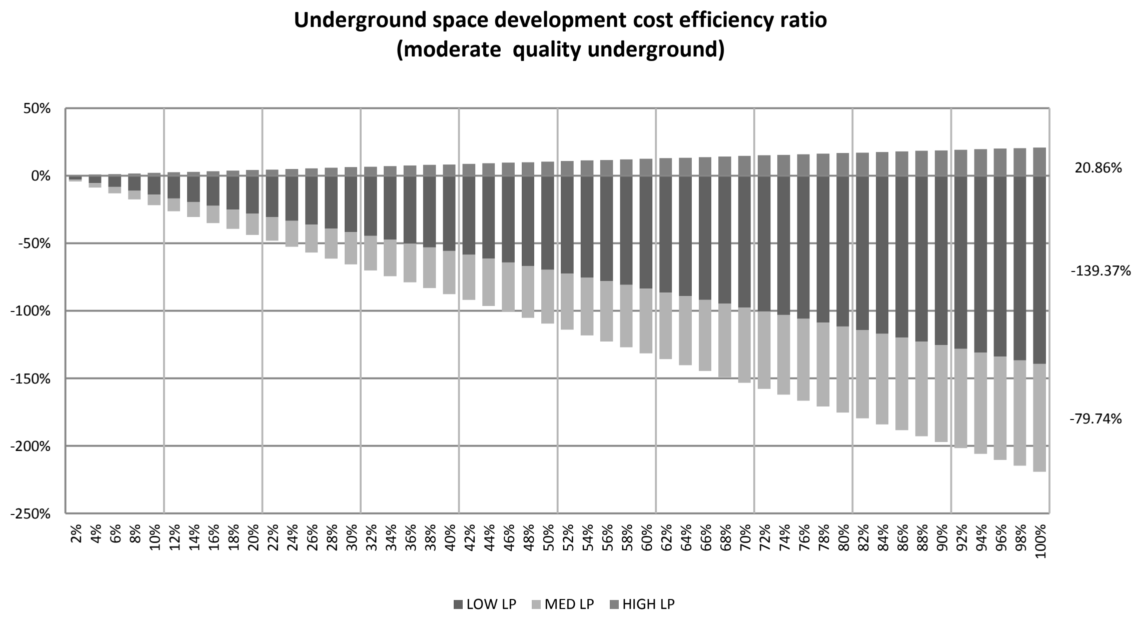


Figure 3:59 Underground shopping mall cost efficiency ratio (Moderate quality underground)

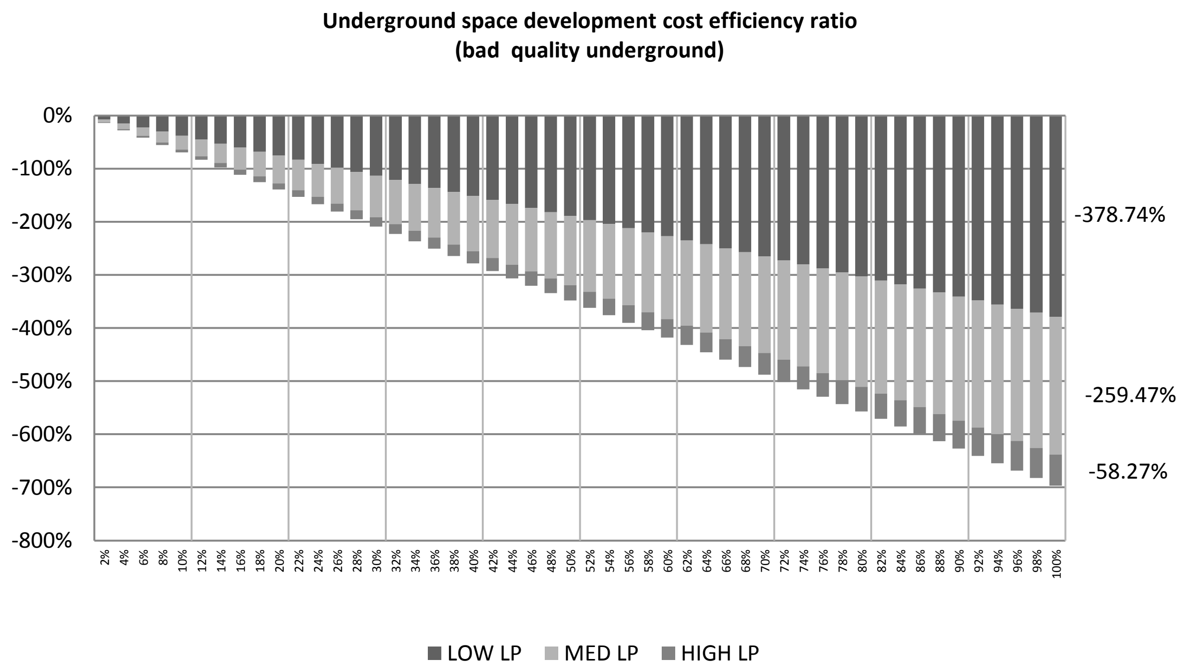


Figure 3:60 Underground shopping mall cost efficiency ratio (Bad quality underground)

3) Breakeven analysis for cost efficiency:

In order to ensure viability of underground space development, cost efficiency ratio should be positive. Since land value and construction cost both have critical effects on investment decision making. It is useful to indicate an acceptable level of underground quality as supply capacity requirement, based on the level of land use demand. In addition, the rate of underground space development will have intensification effect on the cost efficiency analysis, combing the impact of increasing construction cost and decreasing land acquisition cost.

Relationship between those three indicators (land price, underground quality and development scale) is illustrated in Figure 3:61. Each land price level has a regression model to interpret the limit of underground space rate according to a cost coefficient level, or the limit of construction investment premium for a 100% rate of underground floor space.

The highest commercial land price level of Suzhou city is highlighted in red color in the figure, indicating that construction investment of totally buried underground shopping malls should below the 3.42 times of baseline option. For better quality underground (such as a cost coefficient of 2.02), a 42% rate of underground space could enable the project to attain investment breakeven point with surface scenario. Referring to the reporting results on city level supply capacity in Suzhou, subsurface cost coefficient is around 3 times to surface construction costs, meaning that the parcels with the highest commercial land price can attain a maximum underground development rate of 89%.

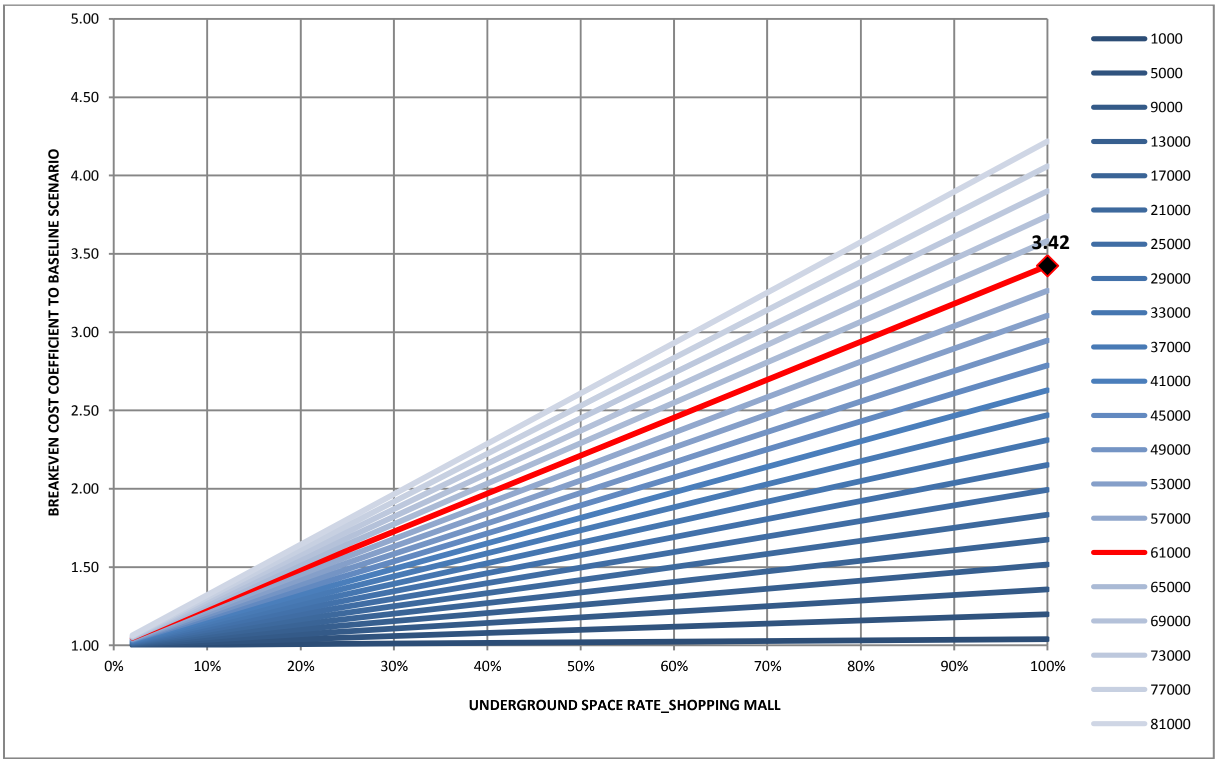


Figure 3:61 Breakeven cost coefficient of underground project to surface project (shopping mall)

Commercial land value can be integrated with potential of subsurface to formulate the 3D land value, combining the "supply approach" and "demand approach" mentioned in section 3.7.3.1.

3D land value = surface land price × (1 + CER %)

Instead of giving subsurface layers separate prices with reduced premium to promote underground urbanization, overall potential of the underground can be aligned with existing land price appraisal system based on the function, dimension, scale and permitted density. A negative cost efficiency ratio downgrades existing land value, which implies an unwise solution of using the underground space, due to lowered demand potential or supply capacity. A positive cost efficiency ratio will upgrade existing land value by offering high integrated potential combing urban demand and resource supply.

In the case of 100% underground development rate, 3D land value of the three commercial land price levels can be adjusted and shown as in Table 3:35.

Table 3:35 3D land value adjustment for three land value grade with different underground qualities (Suzhou city context, commercial land use type)

Land value grade	**Good quality (k=1.33)**	**Moderate quality (K=2.66)**	**Low quality (K=5.32)**	**Breakeven model K=f(R)(Figure 3:62)**	**Breakeven point (R=100%) K limit**
2800	2249	-1102	-7805	K=0.1112R+1	K=1.11
CER%	*-19.69%*	*-139.37%*	*-378.74%*		
12080	13304	2448	-19265	K=0.4799R+1	K=1.48
CER%	*10.13%*	*-79.74%*	*-259.47%*		
59435	95353	71836	24802	K=2.3613R+1	K=3.36
CER%	*60.43%*	*20.86%*	*-58.27%*		

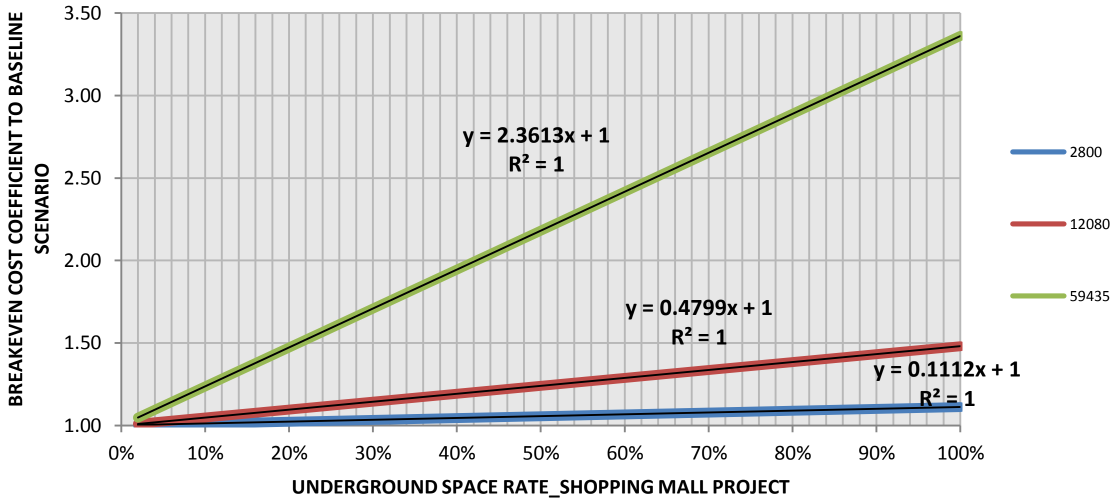


Figure 3:62 Breakeven models for three land value grade: cost coefficient with function of underground space rate (shopping mall project)

3.7.4.3.2 Project scope: mixed-use urban complex (office, hotel, transport, retail, recreation)

This is one of the most common development patterns of underground space in metropolitan areas, which serve to connect the subway transport hub with commercial activities nearby. Examples can be found in megacities like Montreal, Tokyo, Paris, Shanghai, Beijing, etc. Higher land prices make the capital investment more feasible facing unfavorable land conditions, which might require stronger foundations, relocation of existing utility lines, compensation for nearby users, etc. Observations show that underground space rate is increasing for this kind of project scope, due to growing pressures of land acquisition in urban centers and due to more severe green space regulation codes in city planning. The zero land use pattern with 100% underground space rate helps the city to densify land development through three dimensional restructuring, as well as to revitalize the city by saving more building footprint and releasing more walkable surface. The land parcel redimensioning effect is as follows:

Underground space rate (R)	Underground floor space (UFS)	Surface floor space (SFS)	Saving in land footprint	Land parcel dimension %
0% (baseline)	0	100000	0	100%
10%	10000	90000	625	90%
20%	20000	80000	1250	80%
30%	30000	70000	1875	70%
40%	40000	60000	2500	60%
50%	50000	50000	3125	50%
60%	60000	40000	3750	40%
70%	70000	30000	4375	30%
80%	80000	20000	5000	20%
90%	90000	10000	5625	10%
100%	100000	0	6250	0%

1) Baseline total investment costs: (in Yuan)

	LP1	LP2	LP3
BTCC	182’600’000	182’600’000	182’600’000
BTLC	17’500’000	75’500’000	371’468’750
BTC	200’100’000	258’100’000	554’068’750

2) Underground scenarios’ total investment costs and cost efficiency ratios:

Table 3:36 shows total investment costs for underground project scenarios for ten development scales (from 10% to 100%), with corresponding cost efficiency ratios. For good quality underground, fully development of underground space generates a cost efficiency of 56.17% on the highest priced land parcels and 5.91% for land parcels of medium land value grade. Compared to the surface development scenarios, investing underground mixed use complex in low value land use zone will be less competitive, with a negative ratio increasing with underground space rate. This analysis implies that, for the same underground development scale, higher land value (higher demand potential) enables a better efficiency in terms of investment cost.

However, supply capacity of the underground is also an important constrain factor for the economic viability of underground mixed complex projects. Comparing Figure 3:63, Figure 3:64 and Figure 3:65, lower quality level of the underground increased significantly total construction costs, to an extent that even the absence of land acquisition costs could not improve its financial performance. The much larger volume of floor space (100,000 for common underground complex) than conventional commercial building makes this functional development sensitive to underground quality. The sensitivity is higher than the demonstrated project scope of shopping mall (section 3.7.4.3.1). Underground urbanization in mixed use sector (linking transit hub to business activities) should consider the supply capacity of the underground as well as the demand scale (floor space quantity) as critical determinants for its financial performance. For Suzhou city's expanding underground urbanization in urban centers (section 3.7.3.2 for old city center and 3.7.3.3 for CBD), the decision of developing transit related underground complex could be justified from Figure 3:64 below (moderate quality underground in Central city), given by a viability level of 12.34% (revitalization type in old city, R=100%) and 2.71% (densification type in CBD, R=22%).

Table 3:36 Total investment costs and cost efficiency levels for underground project scenarios (Mixed use complex, Good quality underground)

Underground space rate (R)	Total Construction Cost (K1) good quality level	Total investment Cost in Yuan and cost efficiency ratio %		
		Low price land	Medium price land	High price land
0% (baseline)	182'600'000	200'100'000	258'100'000	554'068'750
10%	188'625'800	204'375'800 (-2.14%)	256'575'800 (0.59%)	522'947'675 (5.62%)
20%	194'651'600	208'651'600 (-4.27%)	255'051'600 (1.18%)	491'826'600 (11.23%)
30%	200'677'400	212'927'400 (-6.41%)	253'527'400 (1.77%)	460'705'525 (16.85%)
40%	206'703'200	217'203'200 (-8.55%)	252'003'200 (2.36%)	429'584'450 (22.47%)
50%	212'729'000	221'479'000 (-10.68%)	250'479'000 (2.95%)	398'463'375 (28.08%)
60%	218'754'800	225'754'800 (-12.82%)	248'954'800 (3.54%)	367'342'300 (33.70%)
70%	224'780'600	230'030'600 (-14.96%)	247'430'600 (4.13%)	336'221'225 (39.32%)
80%	230'806'400	234'306'400 (-17.09%)	245'906'400 (4.72%)	305'100'150 (44.93%)
90%	236'832'200	238'582'200 (-19.23%)	244'382'200 (5.31%)	273'979'075 (50.55%)
100%	242'858'000	242'858'000 (-21.37%)	242'858'000 (5.91%)	242'858'000 (56.17%)

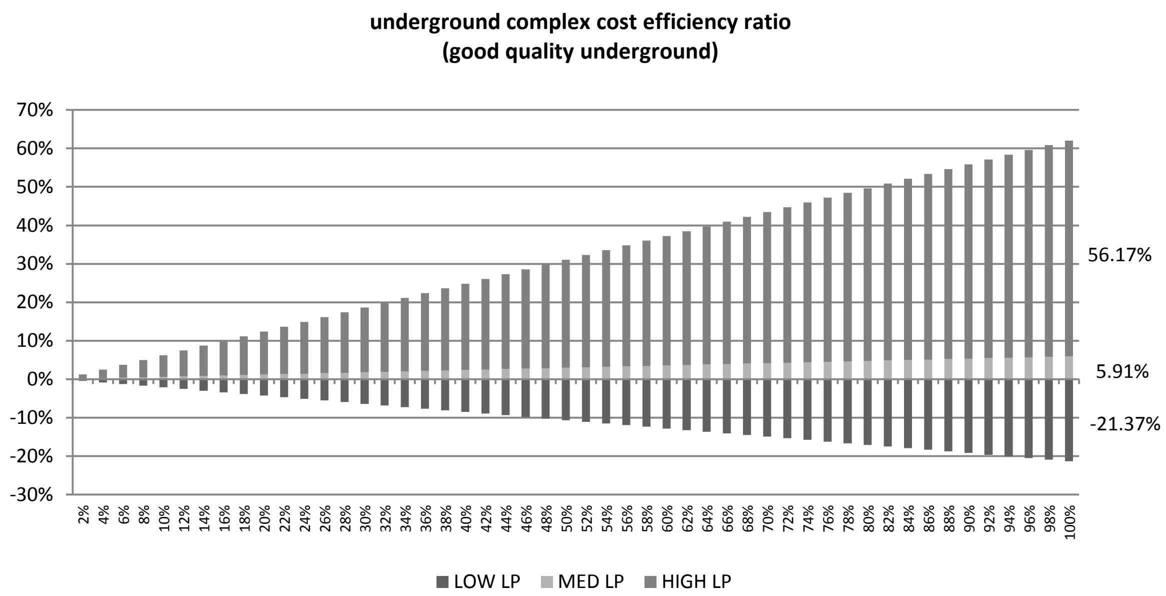


Figure 3:63 underground complex investment cost efficiency ratio (Good quality underground)

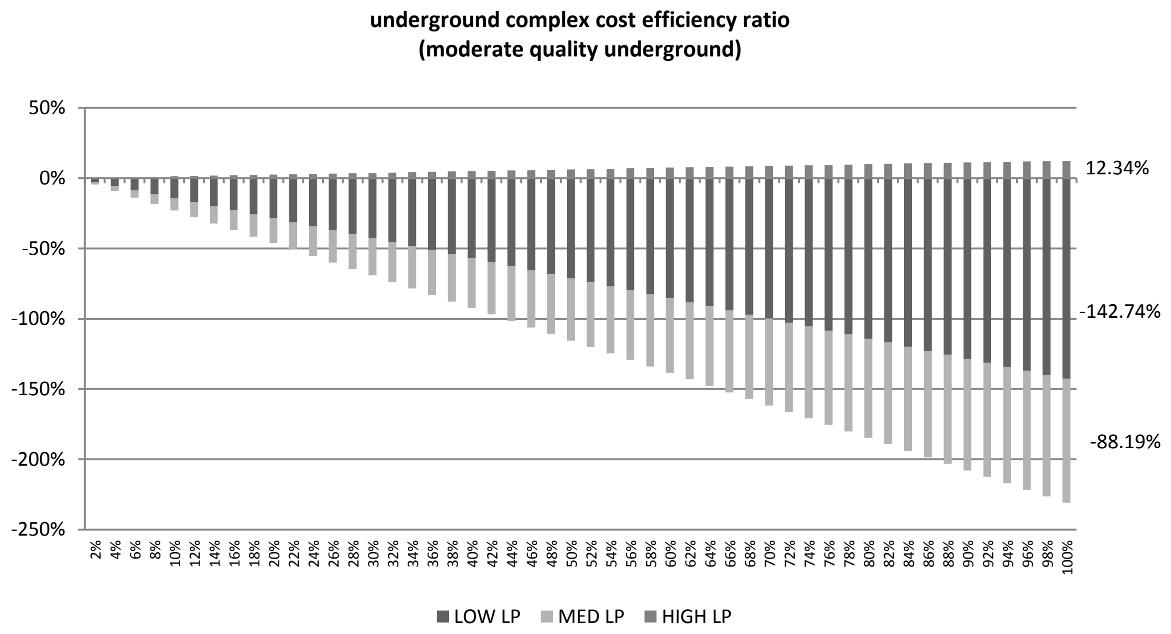


Figure 3:64 underground complex investment cost efficiency ratio (Moderate quality underground)

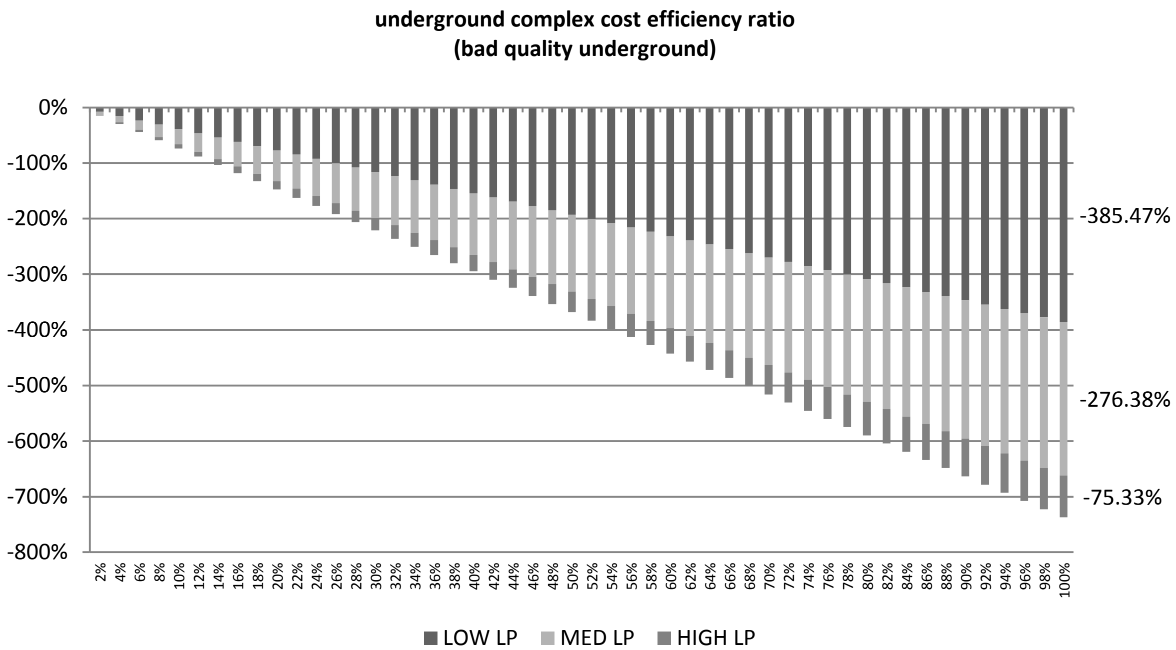


Figure 3:65 underground complex investment cost efficiency ratio (Bad quality underground)

3) Breakeven analysis for cost efficiency:

In order to ensure viability of underground space development, cost efficiency ratio should be positive. Since land value and construction cost both have critical effect on investment decision making. It is useful to indicate an acceptable level of underground quality as supply capacity requirement, based on the level of land use demand. In addition, the rate of underground space development will have intensification effect on the cost efficiency analysis, combing the impact of increasing construction costs and decreasing land acquisition costs.

Relationship between those three indicators (land price, underground quality and development scale) is illustrated in Figure 3:66. Each land price level has a regression model to interpret the limit of underground space rate according to a cost coefficient level, or the limit of construction investment premium for a 100% rate of underground floor space.

The highest commercial land price level of Suzhou city is highlighted in red color in the figure, indicating that construction investment for totally buried underground complexes should below the 3.09 times of baseline option. This requirement for underground quality is even higher than the demonstrated project scope of underground commercial building. For better quality underground (such as a cost coefficient of 2), a 48% rate of underground space could enable the project to attain investment breakeven point with surface scenario. Referring to the reporting results on city level supply capacity in Suzhou, subsurface cost coefficient is around 3 times to surface construction costs, meaning that the parcels with the highest commercial land price can attain a maximum underground development rate of 83%, for mixed use complex.

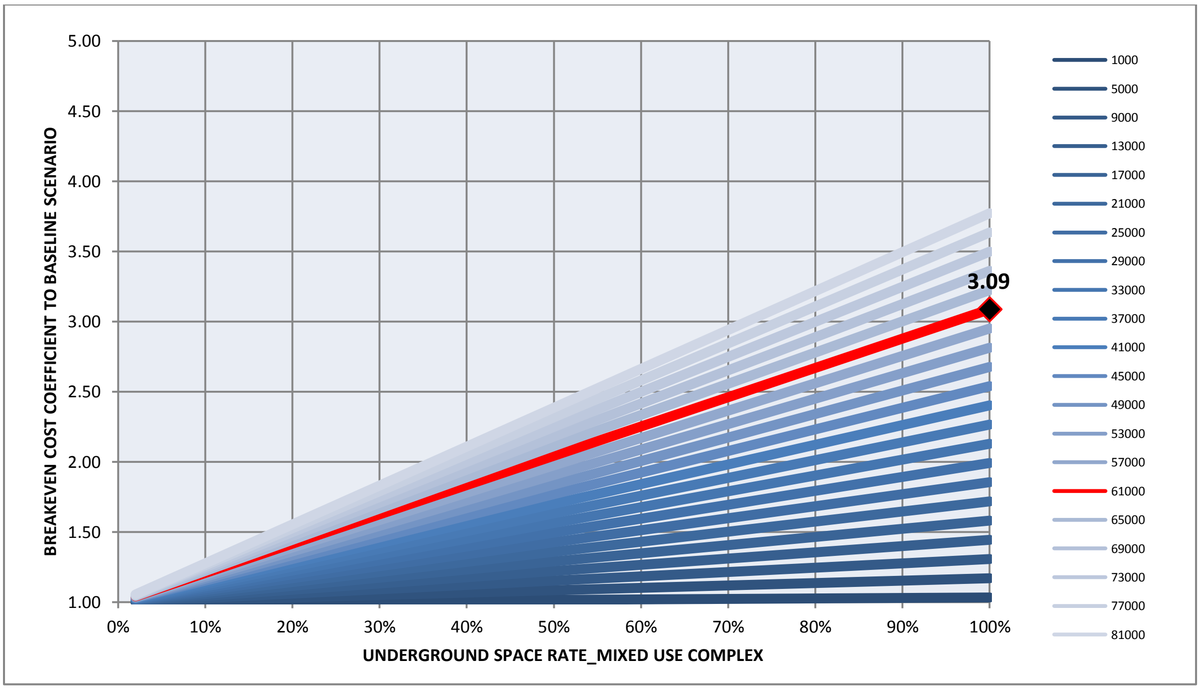


Figure 3:66 Breakeven cost coefficient of underground project to surface project (mixed use complex)

Commercial land value can be integrated with potential of subsurface to formulate the 3D land value, combining the "supply capacity approach" and "demand approach" mentioned in section 3.7.3.1.

3D land value = surface land price × (1+ CER %)

Instead of giving subsurface layers separate prices with reduced premium to promote underground urbanization, overall potential of the underground can be aligned with existing land price appraisal system based on the function, dimension, scale and permitted density. A positive cost efficiency ratio will upgrade existing land value by offering higher integrated potential combing urban demand and resource supply.

In the case of 100% underground development rate, 3D land value of the three commercial (mixed use) land price level can be adjusted and shown as in Table 3:37.

Table 3:37 3D land value adjustment for three value grades with different underground qualities (Suzhou city context, infrastructure and mixed land use type)

Land value grade	Good quality (k=1.33)	Moderate quality (K=2.66)	Low quality (K=5.32)	Breakeven model K=f(R) (Figure 3:67)	Breakeven point (R=100%) K limit
2800	2202	-1197	-7993	K=0.0958R+1	K=1.10
CER%	*-21.37%*	*-142.74%*	*-385.47%*		
12080	12793	1427	-21306	K=0.4135R+1	K=1.41
CER%	*5.91%*	*-88.19%*	*-276.38%*		
59435	92819	66767	14664	K=2.0343R+1	K=3.03
CER%	*56.17%*	*12.34%*	*-75.33%*		

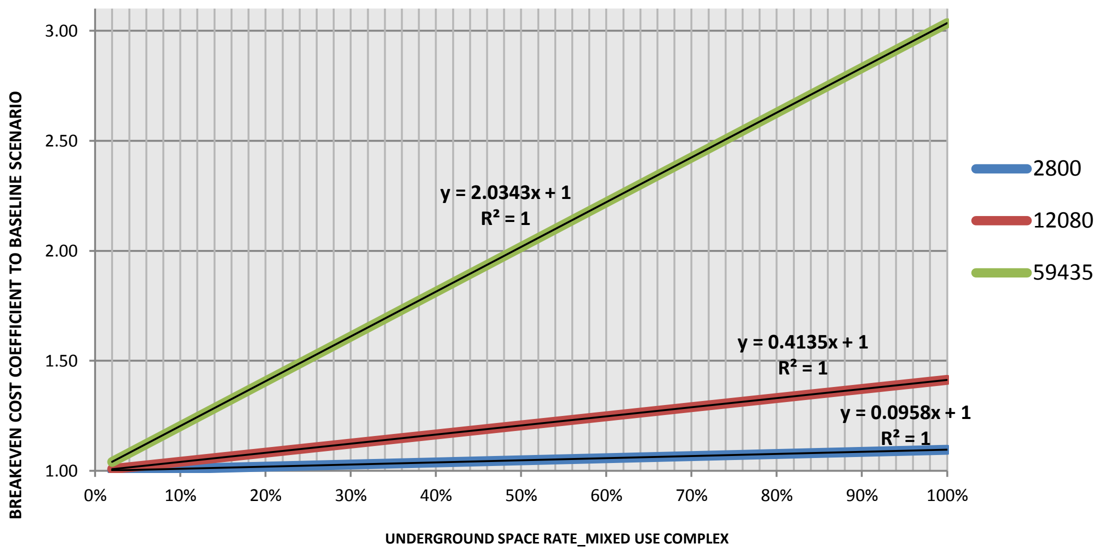


Figure 3:67 Breakeven models for three land value grades: cost efficiency with function of underground space rate (mixed use complex project)

3.7.5 Implications for policy making

The aim of introducing this simple economic index "3D land value" is to reveal the viability level of different project scopes projected in different urban zones. Application of this economic index to guide policy making includes two parts:

1) For short-term planning: land parceling practice

A sustainable underground urbanization is based on an orderly development pattern, by prioritizing high integrated potential areas at the early stage of underground space use. Since land asset allocation by municipalities is facing a dilemma between land supply coordination (housing land, commercial land, mixed development land) and urban demand growth (more floor space for living, working, commuting and relaxing), a rational approach of using underground space could be vital to relieve the dilemma. However, misusing a subsurface land portion can be harmful, not only to the geological environment, but also to the investment side. Applying this index based on asset integrated potential (price and quality) can avoid project risks such as over budget, unforeseen damages, and claims from other users. Considering that high quality subsurface is scarce at an urban scale, a first level selection of land parcels is critical for city governors in order to protect the asset and develop a resilient 3D city.

2) For long-term planning: dynamic instrument adaptation

The index of "3D land value" can be considered as a long-term monitoring tool to supervise economic competitiveness of underground development scenarios compared to surface development scenarios. It is possible to improve viability level of underground space projects by enhancing technological capacity to increase supply potential or by regulating urbanization plans to increase demand potential. Two trajectories including supply side policy and demand side policy are shown in Figure 3:68.

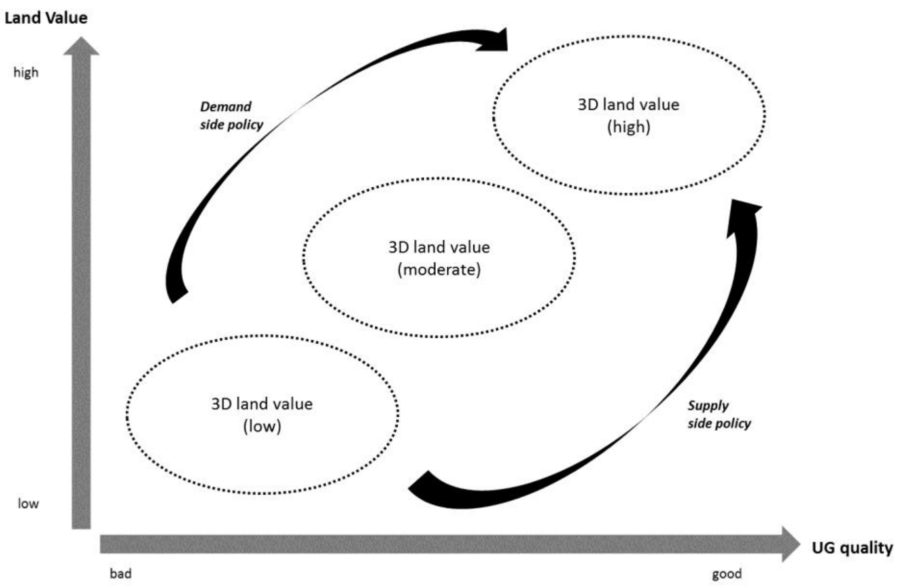


Figure 3:68 Using 3D land value for policy making: supply side policy and demand side policy

3.8 Conclusion for Chapter 3

Going from contextual study at the international scale, to strategic insight at the specific city scale, epistemological research from Chapter 1 and Chapter 2 is further developed in this Chapter with a case study in China. Chinese cities have been undergoing a critical transformation process induced by intensifying urbanization, diversifying economic activities, and changing institutional interventions. The scaling up stage of underground space development in Chinese big cities has been illustrated in the Chapter with feasibility insight, compared to international context. Urbanizing the underground should take into account sustainability issues, related to underground resources' protection, reservation, exploitation and reutilization. An integrated strategy for the sustainable underground urbanization was presented and applied for the Chinese context, to facilitate strategic making, to guide development operation and to innovate implementation.

Knowledge research has to associate with pragmatic study for the aim of adopting innovation. The case study in Suzhou city was not only a theoretical development for Deep City method, but also an interactive execution process with local administrations. Difficulties and management gaps for sustainable underground urbanization were identified, related to three questions in administrative arrangement, resource supply management and demand side encouragement. Under the positive political support of the city, the Project team developed an integrated planning system for the city, which involved the intervention of ten urban departments for standard establishment, information centralization, and instrument formulation. According to the reporting results from the integrated planning system, current technological level and economic demand allowed the development on the shallow underground deep to 30 meters, which enabled the city to inventory more than 301 million m^2 of floor space while saving 150 km^2 land provision for the horizon of 2020. Since the city of Suzhou was selected based on both construction potential and resource potential, available resource reserves were also estimated. Construction sites deployment in the urban underground could be synergized with material, geothermal source and groundwater exploration, making functional value of the subsurface comparable to that of the surface. Prospecting the overall potential of supply capacity is useful for three dimensional urban planning in long-term horizon.

Operations at the city scale helped to identify priority target for project demonstration and implementation. By incorporating the supply capacity level into existing land value, benefit of developing the urban subsurface can be disclosed explicitly. Multiple functions have been emerging into an expandable subterranean form, the underground complex with infrastructures and buildings. Having advantages to densify and revitalize urban centers, this development form represents a transformation of commercial underground space to mixed use underground space. Therefore, a sustainable underground urbanization is not only changing the paradigm of urban management, it is also advancing the connection of economic sectors.

Putting forward a 3D land valuation method, underground development projects such as commercial building and mixed use complex were appraised based on the level of investment cost efficiency. The economic viability analysis will help to formulate further operation on investigating financial mechanisms and fiscal instruments, in order to foster the development and regulate its performance.

CHAPTER 4

4 CONCLUSIONS AND PERSPECTIVES

The present research aims to put forward an integrated strategy to facilitate a sustainable pattern of underground space utilization in urban areas. The three previous chapters illustrated four segments developed by Deep City method, three strategic models in existing cities leading underground urbanization, and a concrete case study in China for methodological application.

4.1 Conclusions of integrated strategy

Conclusions can be drawn based on five integrated dimensions, including integration of four segments, integration of contextual factors, integration of strategic models, integration of strategic & operational levels and integration of surface & subsurface values:

1. Integration of four segments:

Underground space, geomaterials, geothermal energy and groundwater

Based on segmental analysis at international, national and city levels, there exists an unbalanced development trend among these four segments, contributing with different potential scores to the sustainable underground urbanization for worldwide cities. Comparing the three geographical levels, segments with the highest development potential score are underground space (2.41) and geothermal energy (2.71), having 80% and 89% of full score in average. Segments of geomaterials (2.13) and groundwater (2.15) are scored around 70% of full score in average, with moderate development potential. An overview of segmental development from global level to local level enables cities to position their current development stage and to study solutions for feasibility improvement, in order to meet intensifying urbanization demand.

Ultimate objective of sustainable underground urbanization is to unlock overall development potential of the four segments, which provide alternative supplies in infrastructure, building, material, energy and water sectors. Cities having a full portfolio of the four resources and rising urban demands are qualified as Deep City method applicable targets, as shown in section 3.4.

A demonstrative city case study conducted by a multidisciplinary Project team justified that: overall development potential of the four segments can be quantified in supply capacity and stratified by demand promotion schedule. An “integrated potential” indicator helped the pilot city to decide strategic districts for initiating sustainable development of the subsurface. Since utilization of underground space is moving towards a mixed function oriented development (underground complex), integration of other geo-segments (material, energy and water) will allow this utilization form aligned with green city development paradigm.

2. Integration of contextual factors:

Development stage, resource, opportunity and feasibility

The framework of factors in segmental analysis was categorized by current status, changing context and long-term vision (Table 4:1). The long-term vision was determined by current status and changing context, which were influenced by natural forces and social-economic-political divers.

Table 4:1 Framework of factors for segmental analysis and Deep City applicability

Categories	Current status (resource)	Current status (development stage)	Changing context (opportunity)	Changing context (feasibility)
	Deep City applicable case	1	2	3
Factors	Segment 1 underground space Segment 2 geomaterials Segment 3 geothermal energy Segment 4 groundwater	1.1 inner-segmental sustainability 1.2 functional convergence 1.3 inter-segmental sustainability	2.1 scarcity 2.2 price increase 2.3 market growth 2.4 substitution effect	3.1 technology awareness 3.2 knowledge diversity 3.3 innovation speed 3.4 cost efficiency 3.5 property right flexibility 3.6 public acceptance 3.7 inventory prospection 3.8 anthropogenic risk mitigation 3.9 natural risk adaptation
Long-term development vision for sustainable underground urbanization: a fulfillment with four categories				

- **Current status** includes development stage and resource portfolio. Variation of resource portfolio determines applicability degree of Deep City method (segment 1 to 4). Examination of factor 1.1 to 1.3 is the first step for knowing current potential of each segment: Inner-segment sustainability is the perceived potential for exploitation; functional convergence represents services provided for broad range of users; inter-segmental sustainability means conflict avoidance across the four segments. Segment 3 geothermal energy owns the highest score on current development stage (score: 2.67), followed by segment 1 underground space (score: 2.00), arguing that perceived exploitation potential and service range are greater for the sectors of energy and space. However, neither of them obtains full score for holistic development, due to ignorance on cross-segment interdependence.

- **Changing context** includes opportunity and feasibility. Opportunity for underground urbanization is imposed by scarcity, price increase, market growth and substitution effect (factor 2.1 to 2.4). Feasibility is conditioned by technological capacity, institutional intervention and risk sensibility (factor 3.1 to 3.9). Assessment of the changing context is the second step for predicting future potential.

- **A long-term vision** for sustainable underground urbanization is a fulfillment of having current development potential and positive changing conditions. Comparing international level, national level (China) and city level (Suzhou), overall development potential covering the four segments is rated as moderate (average score of three levels covering four segments: 2.35, see Table 4:2). While opportunity has been highly imposed by social-economic forces, feasibility performance should be further stimulated through techno-political interventions.

Table 4:2 Scoring for the framework of factors and overall development potential profile

WORLD (section 1.6)	Development score	Opportunity score	Feasibility score	Development potential profile
Geo-space	2.00	3.00	2.22	2.41
Geomaterials	2.33	2.75	1.89	2.32
Geothermal energy	2.67	2.75	2.67	2.70
Groundwater	2.00	2.50	2.33	2.28
			Average (world level)	2.43
CHINA (section 3.3.5)	**Development score**	**Opportunity score**	**Feasibility score**	**Development potential profile**
Geo-space	2.00	3.00	2.33	2.44
Geomaterials	1.67	2.75	1.89	2.10
Geothermal energy	2.67	2.75	2.78	2.73
Groundwater	1.33	2.50	2.33	2.05
			Average (China level)	2.33
SUZHOU (section 3.6.2)	**Development score**	**Opportunity score**	**Feasibility score**	**Development potential profile**
Geo-space	2.00	3.00	2.11	2.37
Geomaterials	1.33	2.75	1.78	1.95
Geothermal energy	2.67	2.75	2.56	2.66
Groundwater	1.67	2.50	2.22	2.13
			Average (Suzhou level)	2.28
Overall average	2.03	2.75	2.26	2.35

3. Integration of strategic models:

Administrative arrangement, supply side management, demand side development

Feasibility insight and implementation strategy are main themes of the present research. Learnt from best practices about city level strategy presented in Chapter 2, public management models of underground urbanization was classified to three types, grouped by similar development stage and opportunity driver. Factors determining feasibility performance (factor 3.1 to 3.9) were translated into operational solutions related to three strategic questions: administrative arrangement, supply side management and demand side development. Although there is no universal strategy prescription for underground urbanization, feasible measures have been demonstrated in these three strategic models deployed by seven big cities around the world and they could offer a benchmark guide for future cities having potential for underground development.

- **Administrative feasibility**: giving underground space a legal title is the policy mainstream of selected benchmark cities. Formulation of the legal title varies from master plan to regulation to specific law. Leading administrative agency is also different depending on respective policy history. Megacities deployed a decentralization arrangement by creating specific local level agencies to deal with underground management, while other benchmark cities approved the feasibility of coordinating existing agencies for using below ground space. Therefore, it is important to investigate government's organizational scheme and adopt pertinent titling forms, before assigning the task of underground development to local administrators.

- **Supply side management**: according to utilization form (cavern, tunnel, basement, complex, mega complex) at current development stage in benchmark cities, supply inventory method of underground space differs depending on resource reservation need. While good rock resource can be easier quantified and registered in land reserve, urban underground with challenging geotechnical properties requires more effort on development suitability survey. Existing and expanding underground infrastructure and building constrain future subterranean space use, which should be kept in record of fixed asset property registration, an administrative basis for construction regulation and real estate market supervision.

- **Demand side development**: opportunities imposed by social-economic forces will change functional type of underground space, in order to serve a broader range of users. Going from industrial use to commercial use, from public domain to private domain, from infrastructure to building, users from various economic sectors are merged into the redevelopment and expansion of underground space. Besides property right relaxation, contractual and fiscal incentives were transferred by public sectors of benchmark cities, to private developers having motivations to place additional economic activities in high demand subsurface locations.

4. Integration of strategic level and operational level:

Solution framing, information system, project demonstration

Collaborating with local administrations in Suzhou city helped the Project team to identify implementation difficulties and management gaps for promoting sustainable underground urbanization, which supplemented the contextual study on segmental development potential. A strategy prototype was put forward to establish an integrated management process, including six steps from central strategy making to multi-level operations, specifying actions at city level, urban center level and project level. These steps are context review, vision setting, city level operation, urban center operation, project level operation and policy making (Figure 3:31). Main outputs of the process include:

- **Solution framing:** through contextual study and location administrative survey, feasibility issues related to the three strategic questions (administration, supply side and demand side) were identified, followed by solution formulations to improve feasibility of developing the four segments of underground development. The four packages of solution reflected segmental analysis factors, referred to benchmark strategic models, and covered the four segments of Deep City method. This level of strategy making and solution framing is revisable over time with operational feedbacks and changing visions.

- **Information system:** managing complexity of the urban underground requires a competent database and evaluative reporting system, a basis to provide management intelligence on policy making and designating new public instruments. An information system for underground planning developed in the research is a new administrative tool with involvement of ten local administrative agencies in Suzhou city, which offered multiple functionalities including data standardization, geographical visualization, spatial analysis, criteria evaluation, quantitative calculation and potential reporting. Output of the planning system includes supply inventory of underground resources, demand levering of urban zones and integrated potential estimation, presented in geographical and statistical formats.

- **Project demonstration**: high potential zones were identified as priority development targets, including a historical district and a central business district. Functional demand for underground space use is different for these two districts: historical district needed to preserve cultural heritage and green space on the surface by moving infrastructures and commercial space underground; central business district had to host increasing inhabitants and growing business sectors by extending mixed use developments underground and connecting adjacent economic activities into network form. Changing demands and expanding users of underground space allowed the city to develop several underground complexes, linking rail transit infrastructures and mixed use buildings. This development form symbolized a compact underground urbanization trend, a complementary paradigm for compact city development.

5. Integration of subsurface value and land value:

3D land valuation method

Urbanizing the underground is beneficial to reduce building footprint on the surface, having a potential to economize land acquisition costs in project investment. Higher construction cost compared to surface development has been a financial barrier to increase attractiveness of underground space use. A cost model for deepening floor space scale built in different ground quality indicated that, unit construction costs decreased with increasing subterranean floor space quantity. For a 9-level underground commercial building (36 m depth, deep underground with good quality), unit construction cost exceeded only 3% of that for surface building.

If building footprint was reduced proportionally by the percentage of burying rate, as shown in cost efficiency analysis for a shopping mall and underground complex in Suzhou city, land cost savings could allow total investment cost much more viable than conventional surface development scenarios. However, a positive cost efficiency ratio is determined by both land prices and construction cost levels, two main components in investment decision making. For different land price categories, development scale of underground space will determine the breakeven construction cost level, as shown in the breakeven models in Chapter 3 section 3.7.4.3. This cost efficiency analysis aims to rationalize project investment based on supply capacity and demand level of land parcels. Land parcels with higher supply capacity (lower construction cost) and a higher demand level (higher land price) have greater cost efficiency ratio, a monetary indicator for integrated potential of underground space.

With this economic indicator of underground development cost efficiency ratio, a 3D land value was created by integrating underground development potential into existing benchmark land prices. Variations of 3D land value compared to existing benchmark land prices indicated competitiveness level of underground space development. It is also a cost-benefit valuation tool to judge viability level of underground projects. In addition, supply side management and demand side development measures will change the 3D land value by renewing cost level and price categories.

4.2 Limitations of the research and Perspectives for further study

- Limitations of the present research include two points:

Firstly, the segmental analysis using a scoring framework in Chapter 1 presented a general assessment tool for underground development potential, which should have been completed with the help of experts specialized in each segment for the rating process. Since the segmental analysis was applied to international, national and municipal scales, personal judgment with qualitative and quantitative data become limited to rate the factors across different geographies. A more robust approach should be employed to increase applicability level of segmental analysis in Deep City method;

Secondly, the benchmarking case studies on city level policy demonstrated in Chapter 2 were clustered into three strategic models as policy typologies. This qualitative research still lacked of a standardized approach adopted in the field of social science and political science, such as application of cluster analysis method.

- Perspectives for further research include four points:

Firstly, a green project grading tool can be developed with Deep City Method for sustainable underground infrastructures and sustainable underground buildings;

Secondly, fiscal instrument can be studied for promoting underground urbanization with 3D land value created in the present research;

Thirdly, a new paradigm can be researched on compact deep city development with the objective to avoid vertical sprawling underground, by converging public use with private use for horizontal expansion of underground space;

Fourth, the integrated strategy can be generalized to more cities around the world, based on different contexts of administrative arrangement, resources management and development promotion.

References

ADDAMS, L., BOCCALETTI, G., KERLIN, M. & STUCHTEY, M. 2009. Charting Our Water Future: Economic Frameworks to Inform Decision-making. *In:* 2030 WATER RESOURCES GROUP & MCKINSEY&COMPANY (eds.).

BARKER, M. 1991. Legal and administrative issues in underground space use: a preliminary survey of ITA member nations. *Tunnelling and Underground Space Technology,* 6**,** 191-209.

BARKER, M. B. 1986. Toronto's underground pedestrian system. *Tunnelling and Underground Space Technology,* 1**,** 145-151.

BARLES, S. 2000. La Valeur du tréfonds. *Etudes foncières,* 85**,** 28-32.

BARLES, S. & GUILLERME, A. 1995. *L'urbanisme souterrain,* Paris, Presses Universitaires de France.

BEER, G. 2010. *Technology Innovation in Underground Construction,* Graz, Taylor & Francis Group.

BÉLANGER, P. 2007. Underground landscape: The urbanism and infrastructure of Toronto's downtown pedestrian network. *Tunnelling and Underground Space Technology,* 22**,** 272-292.

BERGMAN, S. M. 1982. Special Report: The utilization of subsurface space in developing countries (a United Nations Workshop in Stockholm, Sweden). *Underground Space,* 7**,** 230-317.

BERGMAN, S. M. 1986. U.N. Progess Report: The development and utilization of subsurface space. *Tunnelling and Underground Space Technology,* 1**,** 115-144.

BERTAUD, A. 1997. Measuring constraints on land supply: The case of Hong Kong (report published in www.alain-bertaud.com).

BERTRAUD, A. 2007. Urbanization in China: land use efficiency issues (report published in www.alain-bertaud.com).

BESNER, J. 1997. Genèse de la ville intérieure de Montréal. *The 7th International Conference of the Associated research Centers for Urban Underground Space (ACUUS1997).* Montréal.

BESNER, J. 2007a. Develop the underground space with a Master Plan or Incentives. *The 11th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2007)* Athens: NTUA Press.

BESNER, J. 2007b. Develop the underground space with a Master Plan or Incentives. *Underground Space: expanding the frontiers, proceeding of 11th ACUUS International Conference, 2007, Athens*.

BLOOMQUIST, R. G. 2009. The economics of geothermal heat pump system for commercial and institutional buildings. *In:* INTERNATIONAL COURSE ON GEOTHERMAL HEAT PUMP (ed.). Washington State University.

BLUNIER, P. 2009. *Méthodologie de gestion durable des ressources du sous-sol urbain.* Ph.D, EPFL.

BOBYLEV, N. 2009. Mainstreaming sustainable development into a city's Master plan: A case of Urban Underground Space use. *Land Use Policy,* 26**,** 1128-1137.

BOISVERT, M. 2004a. Le développement de la ville intérieure et la révision en cours du Plan d'urbansime. Montreal: Observatoire de la ville intérieure.

BOISVERT, M. 2004b. U3D: Contributions de la ville intérieure. *In:* INSTITUT D'URBANISME DE L'UNIVERSITÉ DE MONTRÉAL (ed.) *Les 5 à 7 de l'urbanisme.*

BOISVERT, M. 2007. Extensions of Indoor Walkways into the Public Domain - A Partnership Experiment. *The 11th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2007).* Athens.

BOISVERT, M. 2011. *Montréal et Toronto: Villes intérieures,* Montréal, Presses de l'Université de Montréal.

BOIVIN, D. 1989. De l'occupation du sous-sol urbain à l'urbanisme souterrain. *Cahiers de géographie du Québec,* 33.

BOIVIN, D. J. 1990. Underground Space Use and Planning in the Quebec City Area. *Tunnelling and Underground Space Technology,* 5.

BOIVIN, D. J. 1991. Montreal's underground network: A study of the downtown pedestrian system. *Tunnelling and Underground Space Technology,* 6**,** 83-91.

BRIERLEY, G. S. & DRAKE, R. D. 1995. Cost-reduction strategies for subway design and construction. *Tunnelling and Underground Space Technology,* 10**,** 31-35.

BURCHELL, R. W. 1998. The costs of sprawl--revisited. *In:* BURCHELL, R. W. (ed.) *Transit Cooperative Research Program.* National Academy Press.

BURDIN, J. 2010. La valorisation des matériaux d'excavation générés par les grands travaux souterrains. *Colloque Franco-Suisse sur la gestion de l'espace sous la ville: des géosciences à l'urbanisme.* Lausanne: EPFL.

CAO, L. 2012. *Geological Environment Identification and Evaluative Modeling Method for Urban Underground Resources Development.* PhD, Nanjing University.

CAO, L., LI, X., TACHER, L. & YANG, R. 2012. Three-Dimensional Geological Modeling Based on Division of Engineering Geological Strata Units. *Advanced Science Letters,* 5**,** 510-514.

CAO, L., LI, X., WU, W., YANG, Y. & LI, H. 2011. Geological modeling research of Suzhou City based on the identification of urban underground resources. *2011 International Conference on Remote Sensing, Environment and Transportation Engineering (RSETE).*

CARMODY, J. & DERR, D. 1982. The Use of Underground Space in the People's Republic of China. *Underground Space,* 7**,** 7-11.

CARMODY, J. & STERLING, R. 1983. *Underground building design: commercial and institutional structures,* University of Minnesota, Underground Space Center, Van Nostrand Reinhold Co.

CARMODY, J. & STERLING, R. L. 1993. *Underground Space Design: Part 1: Overview of Subsurface Space Utilization Part 2: Design for People in Underground Facilities*, John Wiley & Sons.

CEDD. & ARUP. 2011. Enhanced Use of Underground Space in Hong Kong - Executive Summary of feasibility study. Hong Kong.

CERVERO, R. & MURAKAMI, J. 2009. Rail and Property Development in Hong Kong: Experiences and Extensions. *Urban Studies,* 46**,** 2019-2043.

CHAN, R. K. 2011. Planning Future Cavern Development in Hong Kong. *The Joint HKIE-HKIP Conference on Planning and Development of Underground Space: bridging planners, engineers and the public on innovative use of underground space.* Hong Kong.

CHANG, A., NG, K. W., SCHIMID, H., TAN, W. L., SEETOH, K. C., WONG, D., SEOW, J. H., WONG, F. & AUDI, N. C. 2012. Feasibility Study of Underground Science City Singapore: Part 2 Planning, Architectural, Engineering, Fire Safety and Sustainability. *In:* SRMEG (ed.) *The 13th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2012).*

CHEN, J. 2010. Pricing methodology research for urban underground space use (in Chinese). *World Economic Outlook*.

CHEN, S. 2006. *Shaping the Suzhou CBD in the Suzhou Industrial Park: a Case Study of Chinese Urban Planning Reform.* Master of Arts (Architecture), National University of Singapore.

CHEW, Y. L. M. 1999. *Construction technology for tall buildings*, Singapore University Press, National University of Singapore.

DAI, Q., FAN, X. & SUN, Y. 2009. Solution to Planning Management of Connection between Rail Transit Stations and Around Underground Space - Taking Shenzhen as an example. *The 12th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2009).* Shenzhen, China.

DANIEL J, B. 1991. Montreal's underground network: A study of the downtown pedestrian system. *Tunnelling and Underground Space Technology,* 6**,** 83-91.

DEGN ESKESEN, S., TENGBORG, P., KAMPMANN, J. & HOLST VEICHERTS, T. 2004. Guidelines for tunnelling risk management: International Tunnelling Association, Working Group No. 2. *Tunnelling and Underground Space Technology,* 19**,** 217-237.

DOBBS, R., OPPENHEIM, J., THOMPSON, F., BRINKMAN, M. & ZORNES, M. 2011. Resource Revolution: Meeting the world's energy, materials, food, and water needs. *In:* MCKINSEY GLOBAL INSTITUTE & MCKINSEY SUSTAINABILITY & RESOURCE PRODUCTIVITY PRACTICE (eds.).

DOBINSON, K. & BOWEN, R. 1997. Underground Space In The Urban Environment Development and Use. *In:* THE WARREN CENTER FOR ADVANCED ENGINEERING (ed.) *Technical papers.* The University of Sydney.

DURAND, M. & BOIVIN, D. J. 1985. Underground Construction in Canada: Some Aspects of a Promising Avenue in Geotechnical Engineering. *Geoscience Canada,* 12 Dec.

ECTP 2005. Strategic research agenda for the European underground construction sector. *In:* EUROPEAN CONSTRUCTION TECHNOLOGY PLATFORM (ed.).

EL-GENEIDY, A., KASTELBERGER, L. & ABDELHAMID, H. T. 2011. Montréal's Roots: Exploring the Growth of Montréal's Indoor City. *Journal of Transport and Land use,* 4.

ENDO, T. 2011. Sinking Cities and Governmental Action: Institutional Responses to Land Subsidence in Osaka and Bangkok. *In:* TANIGUCHI, M. (ed.) *Groundwater and Subsurface Environments.* Springer Japan.

ESCOBAR, M. 2002. The next urban frontier: The inner city and role of the evolution of real-property law in the 21st century - a Montreal perspective. *The 9th International Conference: Urban underground space - a resource for cities (ACUUS2002)* Torino, Italy.

FEREDJ, R. 2012. A New Economy for a New Habitat (RATP real estate project). *INTA36 Conference "Suitable urban development unlocking economic urban value".* Paris.

FINNISH TUNNELLING, A. 1992. City planners' notions of rock spaces. *Tunnelling and Underground Space Technology,* 7**,** 399-405.

FREEMAN, S. T., HAMBURGER, R., LACHEL, D. J., MAYO, R. S., MERRITT, J. L. & SMITH, B. L. 1982. Tunneling in the People's Republic of China. *Underground Space,* 7**,** 24-30.

FULTON, A., DUDLEY, T., MCMANUS, D. & STATON, K. Water well design, construction and development: important consideration before making the investment. University of California.

GAO, Q., LI, M., YU, M., SPITLER, J. D. & YAN, Y. Y. 2009. Review of development from GSHP to UTES in China and other countries. *Renewable and Sustainable Energy Reviews,* 13**,** 1383-1394.

GOEL, R. K., SINGH, B. & ZHAO, J. 2012. *Underground Infrastructures: Planning, Design, and Construction*, Butterworth-Heinemann ElSEVIER.

GOEL, R. K., SINGH, B. & ZHAO, J. 2012b. Chapter 3 - Important Considerations. *Underground Infrastructures.* Boston: Butterworth-Heinemann.

GOEL, R. K., SINGH, B. & ZHAO, J. 2012c. Chapter 4 - Underground Space Planning. *Underground Infrastructures.* Boston: Butterworth-Heinemann.

GOEL, R. K., SINGH, B. & ZHAO, J. 2012f. Chapter 7 - Underground Parking. *Underground Infrastructures.* Boston: Butterworth-Heinemann.

GOEL, R. K., SINGH, B. & ZHAO, J. 2012g. Chapter 8 - Underground Metro and Road Tunnels. *Underground Infrastructures.* Boston: Butterworth-Heinemann.

GOEL, R. K., SINGH, B. & ZHAO, J. 2012h. Chapter 9 - Underground Storage of Crude Oil, Liquefied Petroleum Gas, and Natural Gas. *Underground Infrastructures.* Boston: Butterworth-Heinemann.

GOEL, R. K., SINGH, B. & ZHAO, J. 2012i. Chapter 10 - Civic Facilities Underground. *Underground Infrastructures.* Boston: Butterworth-Heinemann.

GOLANY, G. & OJIMA, T. 1996a. *Geo-space urban design*, John Wiley.

GOLANY, G. S. 1989. *Urban underground space design in China: Vernacular and Modern Practice,* USA, Associated University Presses, Inc.

GOLANY, G. S. & OJIMA, T. 1996b. *Geo-Space Urban Design,* New York, John Wiley & Sons.

HANAMURA, T. 1990. Japan's New Frontier Strategy: Underground Space Development. *Tunnelling and Underground Space Technology,* 5.

HARRALL, J. 2012. A Demonstration of the Viability and Growing Acceptability of Earth-Sheltered Buildings in the UK. *In:* SRMEG (ed.) *The 13th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2012).* Singapore.

HAYASHI, T., TOKUNAGA, T., AICHI, M., SHIMADA, J. & TANIGUCHI, M. 2009. Effects of human activities and urbanization on groundwater environments: An example from the aquifer system of Tokyo and the surrounding area. *Science of The Total Environment,* 407**,** 3165-3172.

HE, L., SONG, Y., DAI, S. & DURBAK, K. 2012. Quantitative research on the capacity of urban underground space – The case of Shanghai, China. *Tunnelling and Underground Space Technology,* 32**,** 168-179.

HELLSTEN, M. 2010. More infrastructure for the money. *Sustainability Journal from the Swedish Research Council Fromas*.

HONG KONG SAR 2011. Reuse, Reduction and Recycle of Construction and Demolition Waste.

HOWELLS, D. J. & CHAN, T. C. F. 1993. Development of a regulatory framework for the use of underground space in Hong Kong. *Tunnelling and Underground Space Technology,* 8**,** 37-40.

HU, D., YOU, F., ZHAO, Y., YUAN, Y., LIU, T., CAO, A., WANG, Z. & ZHANG, J. 2010a. Input, stocks and output flows of urban residential building system in Beijing city, China from 1949 to 2008. *Resources, Conservation and Recycling,* 54**,** 1177-1188.

HU, M., VAN DER VOET, E. & HUPPES, G. 2010b. Dynamic Material Flow Analysis for Strategic Construction and Demolition Waste Management in Beijing. *Journal of Industrial Ecology,* 14**,** 440-456.

HUI, E., LAM, M. & HO, V. 2006. Market Disequilibrium and Urban Land Shortages: Analysis of Policy and Patterns in Hong Kong. *Journal of Urban Planning and Development,* 132**,** 80-88.

HUNGER, J. D. & WHEELEN, T. L. 2011. *Essentials of Strategic Management: International Version*, Prentice Hall.

IEA 2007. Renewables for heating and cooling: untapped potential. *In:* RENEWABLE ENERGY TECHNOLOGY DEPLOYMENT (ed.). Paris: International Energy Agency.

IEA 2010. Annex 30 Retrofit Heat Pumps for Buildings - final report. Sweden: IEA Heat Pump Center.

ISHII, M., ISHIMURA, K. & NAKAYAMA, T. 1992. Management and application of Geotechnical Data: The Geotechnical Data Information System of the Tokyo Metropolitan Government. *Environmental Geology and Water Sciences,* 19**,** 169-178.

ITA-CUS 2010. ITA Committee on Underground Space White paper #2 "Planning the use of underground space".

ITA-WG3 2011. The ITA Contractual Framework Checklist For Subsurface Construction Contracts. Internation Tunnelling and Underground Space Association.

ITACUS 2012. Training course: Seminar on Underground Space Use. Sinagpore.

IUSG-NJU & JIANGSU GEOLOGY OFFICE 2012. Report on Suzhou city underground space and resources development potential evaluation (in Chinese). Institute of Underground Space and Geoenvironment, Nanjing University.

J.C. MORELA, A. M., M. OGGEROB, P. WALKERC 2001. Building houses with local materials:means to drastically reduce the environmental impact of construction. *Building and Environment,* 36**,** 1119–1126.

JAGO-ON, K. A. B., KANEKO, S., FUJIKURA, R., FUJIWARA, A., IMAI, T., MATSUMOTO, T., ZHANG, J., TANIKAWA, H., TANAKA, K., LEE, B. & TANIGUCHI, M. 2009. Urbanization and subsurface environmental issues: An attempt at DPSIR model application in Asian cities. *Science of The Total Environment,* 407**,** 3089-3104.

JENKS, M., BURTON, E. & WILLIAMS, K. 1996. *The Compact city: a sustainable urban form?,* London, E & FN Spon.

JENKS, M. & JONES, C. 2010. *Dimensions of the Sustainable City,* London, Springer.

JIE, M. & WANG, S. 2008. Discussion on cost reduction for rail transit construction: the case of Suzhou subway (in Chinese). *Public Utilities,* 22.

JIN, Y. & HUANG, W. 2009. Thoughts on the Underground Space Planning and Construction, the Core Area of QianJiang New CBD, Hangzhou. *The 12th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2009).* Shenzhen, China.

JONES LANG LASALLE 2006. World Winning Cities Profiles: China Suzhou. *World Winning Cities Research.*

KAMAL-CHAOUI, L., LEMAN, E. & ZHANG, R. 2009. *Urban Trends and Policy in China,* Paris, OECD publishing.

KIVELL, P. 1993. *Land and the City: Patterns and Processes of Urban Change*, Routledge.

KUNITOMI, T., KASUYA, T., TANIKAGA, N. & SHIRANE, T. 2012. Study of ideal development and management of underground networks (role sharing between public and private sectors). *In:* SRMEG (ed.) *The 13th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2012).* Singapore.

LAAKSO, S. 1992. Public transport investment and residential property values in helsinki 1. *Scandinavian Housing and Planning Research,* 9**,** 217-229.

LAM, C. 2011. From HK Secretary of Development: Optimal Use of Underground Space in Hong Kong –the New Era. *The Joint HKIE-HKIP Conference on Planning and Development of Underground Space: bridging planners, engineers and the public on innovative use of underground space.* Hong Kong.

LEMLEY, J. K. 1986. ITA and the U.N.: Cross-cultural forum for communication. *Tunnelling and Underground Space Technology,* 1**,** 113.

LI, G., CHEN, J. & SUN, Z. 2007. Non-agricultural land expansion and its driving forces: a multi-temporal study of Suzhou, China. *International Journal of Sustainable Development & World Ecology,* 14**,** 408-420.

LI, H.-Q., PARRIAUX, A., THALMANN, P. & LI, X.-Z. 2013a. An integrated planning concept for the emerging underground urbanism: Deep City Method Part 1 concept, process and application. *Tunnelling and Underground Space Technology*.

LI, H., LI, X., PARRIAUX, A. & THALMANN, P. 2013b. An integrated planning concept for the emerging underground urbanism: Deep City Method Part 2 case study for resource supply and project valuation. *Tunnelling and Underground Space Technology*.

LI, X.-Z., ZHAO, X.-B., WU, W.-B., CAO, L. & LI, H.-Q. 2012. Evaluation of Geo-environmental Suitability for the Development of Underground Space in Suzhou. *In:* SRMEG (ed.) *The 13th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2012).*

LI, X. 2012. Resources of Urban Underground Space and Sustainable Development - progress and lesson from China. *International Forum on Underground City 2012.* Saint Petersburg, Russia.

LI, Z. & YANG, G. 2005. Correlation analysis between cultivated land use change and economic development in Suzhou city over the past 50 years (in Chinese). *Resources Science,* 27.

LIANG, S., WANG, C. & ZHANG, T. 2010. An improved input–output model for energy analysis: A case study of Suzhou. *Ecological Economics,* 69**,** 1805-1813.

LING, K.-K. 2011. Towards an underground development strategy for Hong Kong. *The Joint HKIE-HKIP Conference on Planning and Development of Underground Space: bridging planners, engineers and the public on innovative use of underground space.* Hong Kong.

LIU, J. & ZHU, W. 2009. Empirical research on correlation between intensity of urban underground space and indexes of land-traffic characteristics. *The 12th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2009).* Shenzhen.

LIU, K., PENG, F. & SHU, Y. 2009. Ideas and Practices on Urban Underground Space Planning in Business District in Shanghai. *The 12th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2009).* Shenzhen, China.

MA, B. & ZENG, C. 2009. The Development of Underground Infrastructure Asset Management in China. *The 12th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2009).* Shenzhen, China.

MAIRE, P. 2011. *Étude multidisciplinaire d'un développement durable du sous-sol urbain : aspects socio-économiques, juridiques et de politique urbaine.* Ph.D, EPFL.

MAITLAND, B. 1992. Hidden cities: The irresistible rise of the North American interior city. *Cities,* 9**,** 162-169.

MALONE, A. W. 1996. The use of underground space in Hong Kong. *Tunnelling and Underground Space Technology,* 11**,** 57-64.

MANKELOW, J. M., BATE, R., BIDE, T., MITCHELL, C. J., LINLEY, K., HANNIS, S. & CAMERON, D. 2008. Aggregate resource alternatives: options for future aggregate minerals supply in England. *In:* BRITISH GEOLOGICAL SURVEY (ed.).

MIKI, H., IWABUCHI, J. & CHIDA, S. 2005. New soil treatment methods in Japan. *TREMTI 2005 – Communication C189*.

MIYAKE, N. & DENDA, A. 1993. Utilization of underground spaces in urban areas: Urban geo-grid plan. *Engineering Geology,* 35**,** 175-181.

NAKAMURA, H., SHINYA, K., KOBAYASHI, K. & TAKAMI, Y. 2012. A Study on the Formation of Underground Network in Japan. *In:* SRMEG (ed.) *The13th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2012).* Singapore.

NARVI, S., VIHAVAINEN, U., KORPI, J. & HAVUKAINEN, J. 1994. Legal, administrative and planning issues for subsurface development in Helsinki. *Tunnelling and Underground Space Technology,* 9**,** 379-384.

NAVIGANT CONSULTING, I. 2009. Ground-Source Heat Pumps: Overview of Market Status, Barriers to Adoption, and Options for Overcoming Barriers. U.S. Department of Energy.

NELSON, S. & ROCKENSTEIN, W. H. I. 1985b. Legislating underground space use: Minnesota's Mined Underground Space Development Act. *Underground Space,* 9**,** 289-292.

NELSON, S. & STERLING, R. 1985a. Legal and Economic Feasibility of Mined Underground Space in Minneapolis, Minnesota. *Underground Space,* 9**,** 143-147.

NEWTON, P. W., HAMPSON, K. D. & DROGEMULLER, R. 2009. *Technology, Design and Process Innovation in the Built Environment,* Oxon, Spon Press.

NGO, V. 2011. Globalizing Suzhou: Exogenous Growth and Chinese Urban Development. University of British Columbia.

NISHI, J., KAMO, F. & OZAWA, K. 1990. Rational use of urban underground space for surface and subsurface activities in Japan. *Tunnelling and Underground Space Technology,* 5**,** 23-31.

NISHIDA, Y., FABILLAH, H., ICHIHARA, S., NISHI, J. & DUK CHO, K. 2007. The Underground Images in Japan, Korea and Indonesia. *The 11th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2007).* Athens.

NISHIDA, Y. & UCHIYAMA, N. 1993. Japan's use of underground space in urban development and redevelopment. *Tunnelling and Underground Space Technology,* 8**,** 41-45.

NISHIOKA, S., TANNAKA, Y. & MINEMURA, T. 2007. Deep Underground Usage for Effective Executing of City Facility Construction. *The 11th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2007).* Athens - Greece.

O'SULLIVAN, A. 2009. *Urban Economics,* New York, Douglas Reiner.

OECD/IEA 2010. Renewable energy essentials: geothermal.

OECD/IEA 2011. Geothermal heat and power roadmap.

OKUYAMA, K. 2007. A Study for the Construction Method, Site Environment and it's Usage of Newly Built Underground Architecture in Japan. *The 11th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2007).* Athens

OKUYAMA, K. 2012. A Study of the Construction Factor and its Scale of Newly Built Underground Architecture in Japan. *The 13th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2012).* Singapore.

ONG, K. C. G., ANGGADJAJA, E. & SOH, S. L. 2009. Sustainable Construction Strategies: A Singapore Perspective. *Lifecycle design of buildings, systems and materials.* Enschede, The Netherlands.

OTEMACHI-MARUNOUCHI-YURAKUCHO DISTRICT REDEVELOPMENT PROJECT COUNCIL 2008. Council booklet (http://www.otemachi-marunouchi-yurakucho.jp/index.html).

OWEN, D. 2013. Taking groundwater. *Washington University Law Review*.

PANEL ON LAND SUBSIDENCE & NATIONAL RESEARCH COUNCIL (U.S.) 1991. *Mitigating Losses from Land Subsidence in the United States,* Washington. D.C., National Academy Press.

PANET, M. 1989. Maîtriser les coûts et les délais des ouvrages souterrains par la qualité des études. *In:* THESAURUS (ed.) *L'Economie Des Travaux En Souterrain.* Paris.

PARRIAUX, A. 2009. *Geology: Basics for Engineers*, Taylor & Francis.

PARRIAUX, A., BLUNIER, P., MAIRE, P., DEKKIL, G. & TACHER, L. 2010. Rapport de recherche PNR54: Projet Deep City – Ressources du sous-sol et développement durable des espaces urbains. Fonds National Suisse ed.

PARRIAUX, A., TACHER, L. & JOLIQUIN, P. 2004. The hidden side of cities—towards three-dimensional land planning. *Energy and Buildings,* 36**,** 335-341.

PASQUAL, J. & RIERA, P. 2005. Underground land values. *Land Use Policy,* 22**,** 322-330.

PATTON, C. V. & SAWICKI, D. S. 1993. *Basic methods of policy analysis and planning*, Prentice Hall.

PAUL, T., CHOW, F., KJEKSTAD, O. & EUROPEAN COUNCIL OF TOWN PLANNERS 2002. *Hidden aspects of urban planning: surface and underground development*, Thomas Telford.

PENG, P. 2010. The combined construction design of metro station and high building basement in Suzhou city (in Chinese). *Transportation Science & Technology,* 10.

POPULATION DIVISION 2012. World Urbanization Prospects: The 2011 Revision. *In:* UNITED NATIONS DEPARTMENT OF ECONOMIC AND SOCIAL AFFAIRS (ed.).

QIAN, Q. Evaluation of the Status and Outlook of the Urban Underground Space Development and Utilization in China Chinese Academy of Engineering.

QIAN, Q. 2009. The development of risk management research on the exploitation of underground space in China. *The 12th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2009).* Shenzhen.

R.L. HUA, Z. Q. Y., L.C. WANGA, S.J. WANG 2004. Review on current status and challenging issues of land subsidence in China. *Engineering Geology,* 76**,** 65– 77.

REAL ESTATE DEPARTMENT & GEOTECHNICAL DIVISION 2005. "Deeper than Skin" Geotechnics of the City of Helsinki's Real Estate Department since 1955. Helsinki.

RIERA, P. & PASQUAL, J. 1992. The importance of urban underground land value in project evaluation: a case study of Barcelona's utility tunnel. *Tunnelling and Underground Space Technology incorporating Trenchless,* 7**,** 243-250.

ROBERTS, K. J. & KIRK, P. A. 2000. Cavern area study of Kowloon, GEO report No. 101. *In:* GEOTECHNICAL ENGINEERING OFFICE, C., HK SAR (ed.).

ROBINSON, G. R. & BROWN, W. M. 2002. Sociocultural dimensions of supply and demand for natural aggregate - Examples from the Mid-Atlantic Region, United States. *In:* U.S. GEOLOGICAL SURVEY (ed.).

ROCHAT, D., ERKMAN, S. & CHAMBAZ, D. 2006. Le Recyclage des Matériaux de Construction à Genève. Geneva: GESDEC.

ROCKENSTEIN, W. H. 1985c. The city of Minneapolis' Authority to Develop Mined Underground Space: A Case Study of the Development of Legislative Policy in Minnesota. *Underground Space,* 9**,** 148-152.

RÖNKÄ, K., RITOLA, J. & RAUHALA, K. 1998. Underground space in land-use planning. *Tunnelling and Underground Space Technology,* 13**,** 39-49.

ROSTAMI, J., SEPEHRMANESH, M., GHARAHBAGH, E. A. & MOJTABAI, N. 2013. Planning level tunnel cost estimation based on statistical analysis of historical data. *Tunnelling and Underground Space Technology,* 33**,** 22-33.

SAATY, T. L. 2001. *Decision Making with Dependence and Feedback: The Analytic Network Process : the Organization and Prioritization of Complexity*, Rws Publications.

SALISBURY, J., JR. & SALTER, L. A., JR. 1941a. I. Subsurface Resources and Surface Land Economics. *The Journal of Land & Public Utility Economics,* 17**,** 270-279.

SALISBURY, J., JR. & SALTER, L. A., JR. 1941b. II. Subsurface Resources and Surface Land Economics. *The Journal of Land & Public Utility Economics,* 17**,** 385-393.

SATOLA, I. & RIIPINEN, M. 2011. Energy Tunnel Network in Helsinki. *In:* REAL ESTATE DEPARTMENT & HELSINKI ENERGY (eds.). Helsinki.

SHI, X. 2009. Development and Utilization of Underground Space Based on Large-scale Infrastructure Construction of Beijing. *The 12th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2009).* Shenzhen, China.

SHU, Y., PENG, F., WANG, X. & ZHU, H. 2006. Study and Practice of Urban Underground Space Planning in China (in Chinese). *Chinese Journal of Underground Space and Engineering,* 2.

SOCIÉTÉ SUISSE DES ENTREPRENEURS 2011. La construction suisse 2011: faits et chiffres.

SON, J.-Y. & KIM, K.-H. 1998. Analysis of Urban Land Shortages: The Case of Korean Cities. *Journal of Urban Economics,* 43**,** 362-384.

STERLING, R. 2012. Other Planning Issues and Examples. *ITACET Seminar on Underground Space Use.* Singapore: SRMEG.

STERLING, R., ADMIRAAL, H., BOBYLEV, N., PARKER, H., GODARD, J.-P., VÄHÄÄHO, I., ROGERS, C. D. F., SHI, X. & HANAMURA, T. 2010. Sustainability issues for underground space in urban areas. *Proceedings of the Institution of Civil Engineers*.

STERLING, R. & NELSON, P. 2012. City Resiliency and Underground Space Use. *In:* SRMEG (ed.) *The 13th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2012).* Singapore.

STERLING, R. & NELSON, S. 1982. Practical Guidelines and A Case Study of Minneapolis: Planning and Development of Underground Space. *Underground Space,* 7**,** 086-103.

STERLING, R. L. 1992. Developments in excavation technology: a comparison of Japan, the U.S. and Europe. *Tunnelling and Underground Space Technology,* 7**,** 221-235.

STERLING, R. L. 2005. Urban Underground Space Use Planning: A Growing Dilemma. *The 10th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2005).* Moscow.

SUBSPACE ASSOCIATES 1990a. A mined underground space master plan for Minneapolis, Minnesota—Part I. *Tunnelling and Underground Space Technology,* 5**,** 233-243.

SUBSPACE ASSOCIATES 1990b. A mined underground space master plan for Minneapolis, Minnesota—Part II. *Tunnelling and Underground Space Technology,* 5**,** 375-377.

TAKASAKI, H., CHIKAHISA, H. & YUASA, Y. 2000. Planning and Mapping of Subsurface Space in Japan. *Tunnelling and Underground Space Technology,* 15**,** 287-301.

TANG, Y. & YANG, W. 2011. Research Summary of the Evaluation of Underground Space (in Chinese). *Chinese Journal of Underground Space and Engineering,* 7.

TANIGUCHI, M., BURNETT, W. C. & NESS, G. D. 2008. Integrated research on subsurface environments in Asian urban areas. *Science of The Total Environment,* 404**,** 377-392.

UGO, M. 2011. Construction en souterrain: Comparaison des coûts de construction en fonction de la géologie et du nombre d'étage d'un centre commercial (Master project report written in French). Lausanne: EPFL.

UTUDJIAN, É. 1972. *L'urbanisme souterrain*, Presses Universitaires de France.

VÄHÄAHO, I. Technical Services and Utility Tunnels in Helsinki: Reliable and optimised large-scale networks in bedrock. *In:* DEPARTMENT, R. E. (ed.). Helsinki.

VÄHÄAHO, I. 2009. Underground Master Plan of Helsinki: A city growing inside bedrock http://www.hel.fi/hki/Kv/en/Geotechnics/CaseBank. City of Helsinki.

VÄHÄAHO, I. 2011. Four Lessons by Vähäaho in Workshop on "Use of Underground Space" in Hong Kong, 26 September 2011 http://www.hel.fi/hki/Kv/en/Geotechnics/CaseBank Helsinki: Real Estate Department.

VÄHÄAHO, I., KORPI, J., SATOLA, I., VAN ALBOOM, G. & VERGAUWEN, I. Geotechnical and geological data management in urban underground areas. *In:* REAL ESTATE DEPARTMENT (ed.). Helsinki: Geotechnical division.

VON MEIJENFELDT, E. & GELUK, M. 2003. *Below Ground Level: Creating New Spaces for Contemporary Architecture*, Birkhäuser.

VON MEISS, P. & RADU, F. 2004. *Vingt mille lieux sous les terres: Espaces publics souterrains,* Lausanne, Presses Polytechniques et Universitaires Romandes.

WANG, J. 2012. Study on planning and design of a multi-utility tunnel in Suzhou Singapore Industrial Park. *The 13th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2012).* Singapore.

WANG, R., CAO, C. & WANG, C. 2009. Land right instauration and management of urban underground space in Shanghai (in Chinese). *Shanghai Geology,* 3.

WANG, X., YANG, L. & SHU, Y. 1995. Rearch on pricing the land use right transfer of urban underground space (in Chinese). *Tongji University Journal - Humanities and Social Science Section,* 6.

WANG, Z. & CHENG, L. 2006. Primary Exploration of Practical Evaluation Approach to Urban Underground Space Usufruct (in Chinese). *Journal of Taiyuan University,* 7.

WELLS, M. 2009. *The Earth-Sheltered House: An Architect's Sketchbook*, Chelsea Green Publishing Company.

WESTLAND, J., BUSBRIDGE, J. R. & J.G., B. 1998. Managing subsurface risk for Toronto's rapid transit expansion program. *North American Tunneling 1998.*

WILBURN, D. R. & GOONAN, T. G. 1998. Aggregates from Natural and Recycled Sources: Economic Assessments for Construction Applications—A Materials Flow Analysis. *U.S. Geological Survey Circular 1176.*

WOETZEL, J., MENDONCA, L., DEVAN, J., NEGRI, S., HU, Y., JORDAN, L., LI, X., MAASRY, A., TSEN, G. & YU, F. 2009. Preparing for China's urban billion. *In:* MCKINSEY GLOBAL INSTITUTE (ed.).

WONG, R. W. M. 2002. The construction of deep and complex basements under extremely difficult urban environment—3 representing projects in Hong Kong. *In:* ANSON, M., KO, J. M. & LAM, E. S. S. (eds.) *Advances in Building Technology.* Oxford: Elsevier.

WU, W. 2012. *Research on the Evaluation for Underground Space Resources in Suzhou Urban Planning Area* Master, Nanjing University.

XU, S. & ZHU, X. 2012. Research on current legislation for urban underground space in China. *In:* SRMEG (ed.) *The 13th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2012).* Singapore.

YANG, W., ZHOU, J., XU, W. & ZHANG, G. 2010. Current status of ground-source heat pumps in China. *Energy Policy,* 38**,** 323-332.

YU, R., CHEN, Z. & YE, Q. 2012. Review on the Development of Underground Shopping Mall in China. *Studies in Sociology of Science (CSCanada),* 3**,** 7-11.

ZEKTSER, I. & EVERETT, L. 2004. Groundwater Resources of the World and Their Use. *In:* UNESCO (ed.).

ZHANG, C. 1994. Etudes des coûts des tunnels de métro français. *Tunnels et Ouvrages souterrains,* 121**,** 46-58.

ZHANG, L., PU, L. & TU, X. 2009. Ecological-environment effect during urban growth in Suzhou, China. *Urban Remote Sensing Joint Event.*

ZHANG, T. & LIAO, Z. 2009. The Discussion on Regulatory Plan for Underground Space in Key Urban Areas — with underground space plan for Beijing Central Business Districts (CBD) as the case. *In:* GROUP, C. P. (ed.) *The12th International Conference of the Associated research Centers for Urban Underground Space (ACUUS2009).* Shenzhen, China.

ZHAO, J. 1996. Construction and utilization of rock caverns in Singapore Part A: The Bukit Timah granite bedrock resource. *Tunnelling and Underground Space Technology,* 11**,** 65-72.

ZHAO, J., CAI, J. G. & HEFNY, A. M. 2001. *Creation of the Underground Science City in Rock Caverns Below the Kent Ridge Park in Singapore,* Singapore, Nanyang Technological University, Geotechnical Research Centre.

ZHAO, J., CHOA, V. & BROMS, B. B. 1996. Construction and utilization of rock caverns in Singapore Part B: Development costs and utilization. *Tunnelling and Underground Space Technology,* 11**,** 73-79.

ZHAO, J. & LEE, K. W. 1996. Construction and utilization of rock caverns in Singapore Part C: Planning and location selection. *Tunnelling and Underground Space Technology,* 11**,** 81-84.

ZOU, P. X. W. & LI, J. 2010. Risk identification and assessment in subway projects: case study of Nanjing Subway Line 2. *Construction Management and Economics,* 28**,** 1219-1238.

CV

Li Huanqing
01/12/1982
Tel.: +41 (0)76 750 6177
Email: huanqing.li@gmail.com
Address: Av du 24 Janvier, 30, 1020 Renens

ACADEMIC BACKGROUND:

2009-2013 Research assistant, Doctoral School in Management of Technology, Ecole Polytechnique Fédérale de Lausanne, Switzerland
Research LAB on the Economics and Management of the Environment
Project: Underground Resources Management for Urban Sustainable Development-Comparison between Swiss and Chinese Contexts (Deep City Project)

2006–2008 Master Degree in International Project Management and NTIC (New Technology of Information and Communication), Paris Dauphine University
English courses: Project management, Consulting skills, Change management, Cross-culture management, Transformation, business cases, project in supply chain, e-commerce

2005–2006 Master Degree in Ecology and Environment, South Paris University, *by the exchange program MS10 of French embassy in China*
French Courses: Ecology, Biostatistics, French environmental law, Economy and environment, scientific modeling. Field study: CNRS, Laboratory in Roscoff.

2001–2005 Bachelor Degree in Science and Technology of Environment, East China Normal University
With the scholarship on merit from the year 2001 to 2004
Courses: Environmental science, Environmental planning, Environmental governance, Biodiversity, Urban ecology, Industrial pollution, Engineering design, GIS.
Field study: Soil quality analysis for the field of Universal Exhibition 2010 in Shanghai

PROFESSIONAL BACKGROUND:

2008 (July to December) **Consultant**, Division Industry & Service, *ATOS ORIGIN INTEGRATION, Paris*

- Consulting mission in a pre-sales project, IS migration of department store *BHV*, analysis of client requirement and core-business strategy, active participation to build the commercial proposal, reply to the call for bids, help to coordinate the external and internal partners
- Project study for Product Information Management, data-synchronization of *Carrefour,* conception document analysis and information searching for the solution WPC
- Business process modeling with UML

2006/2007 (Internship 6 months) **International trading** (construction products) *SAMEXPORT, Monaco*

- In charge of the purchasing project for *Castorama (Group Kingfisher),* market prospect in Asia, leading a team (10 persons) to coordinate the supplier relationship, logistics service, quality control and budget planning, cooperation with *Kingfisher Asian Limited* in Hong Kong
- Mission in sustainable development: follow-up the report of enterprise social responsibility for the Chinese suppliers, sourcing the certificated green construction products

2004/2005 (Internship 7 months) Thesis in **Environmental Management**, *Shanghai government*

- Industrial investigation, statistics analysis, indicator synthesis in the Geographic Information System, analyze the air pollution situation and strategy proposal research
- Finalization of the Chapter of air environment in the official annual report, Shanghai 2004

LANGUAGES:

French: fluent; English: fluent (TOEIC 905/990); Chinese Mandarin and Cantonese: mother tongue

COMPUTER SKILLS:

MS Office, MS Project, Internet, AutoCAD, WIN Biz (accounting)

HOBBIES AND INTERESTS:

Travelling, film, sports, cultures

Personal publications and communications:

2013

Li, H.-Q., et al. An integrated planning concept for the emerging underground urbanism: Deep City Method Part 1 concept, process and application. Tunnel. Underg. Space Technol. (2013), http://dx.doi.org/10.1016/j.tust.2013.04.010

Li, H., et al. An integrated planning concept for the emerging underground urbanism: Deep City Method Part 2 case study for resource supply and project valuation. Tunnel. Underg. Space Technol. (2013), http://dx.doi.org/10.1016/j.tust.2013.04.009

Li, H. (2013) An integrated strategy for a sustainable Deep City. International forum on underground space and modern urban center (a post-expo low-carbon eco-technology application forum), Shanghai, China, July 17-19, 2013.

2012

Li, H., A. Parriaux, et al. (2012). The Way to Plan a sustainable "Deep City": The Economic Model and Strategic Framework. The 13th World Conference of the Associated research Centres for the Urban Underground Space (ACUUS). Singapore.

Li, H. (2012). The Way to Plan a sustainable Deep City: From Economic and Strategic aspects. 17th International Conference on Urban Planning, Regional Development and Information Society (REAL CORP 2012: Re-Mixing the City). AUSTRIA, CORP – Competence Center of Urban and Regional Planning.

Li, H. (2012). Deep City for Urban Sustainability: economic and strategic aspects (keynote speaker in the session of "Law, Economics and Investments"). International Forum on Use of Underground Space as a Public Policy Tool for Sustainable Urbanisation. Saint Petersburg, Russia.

2011

Li, H., A. Parriaux, et al. (2011). The way to plan a viable Deep City: from economic and institutional aspects (keynote speaker in "Town planning concepts and tools for use of underground space"). The Joint HKIE-HKIP Conference on Planning and Development of Underground Space. Hong Kong, The Hong Kong Institution of Engineers & The Hong Kong Institution of Planners: 53-60.

Li, H. (2011). Sustainable 3D urban governance: The Deep City concept from Switzerland to China. Ecocity World Summit 2011. Montreal, Canada.

Li, H. and A. Parriaux (2011). Urban sustainable underground resources management: the Deep City concept. The 13th AFTES International Congress: Underground Space for Tomorrow. Lyon, France.

2010

Li, H. (2010). Un marché caché sous la ville. École thématique du CNRS. Aussois, France.

Li, H. (2010). Urban underground resources management for sustainable development. The 9th NCCR Climate Summer School 2010 "Adaptation and Mitigation: Responses to Climate Change". Grindelwald, Switzerland.

Li, H. (2010). Project Deep City in China. Chinese - Swiss workshop on Geomatics Technology for the Monitoring of Natural Hazards. EPFL, Lausanne, Suisse.

Parriaux, A. and H. Li (2010). La méthodologie Deep City. Colloque Franco-Suisse 2010 sur La gestion de l'Espace Sous la Ville: des géosciences à l'urbanisme. EPFL, Lausanne, Suisse.

2009

Li, H. (2009). Deep City Project : A multi-use integrated approach for urban underground space planning. The 12th International Conference of Associated research Centers for Urban Underground Space (ACUUS), ITACUS open meeting. Shenzhen, China.