Opportunities for Technological Innovations in Current Construction Practices

by

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ABSTRACT

The focus of this investigation is to study the factors that influence the development of innovative technologies and methods in the construction industry. A study of the construction industry is provided to help understand how the industry has evolved in different parts of the world, particularly the United States (along with Europe) and Japan. In order to frame the investigation, basic concepts having to do with innovation in construction that are common to all geographical areas are defined and investigated.

A review of the professional literature, in particular the Journal of Construction Engineering and Management of the American Society of Civil Engineers provides some insight as to what are today's current trends for innovative implementations in the United States. Several case studies are included to complete the overall global picture.

It appears that technological innovation flourishes in booming construction markets. Thus history leads us to believe that economic hot spots fuel technological innovation in construction. It happened in the United States at the turn of the century, Japan followed after World War II, while the next hot spot will most probably be China.

Thesis Supervisor: Dr. Yehiel Rosenfeld
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Acknowledgments

First of all, I would like to thank Dr. Yehiel Rosenfeld for introducing me to such an interesting and gripping subject. Without your help, this paper would only be a collection of technological innovations from around the world without any insight as to how or why they have come about. The coursework and lectures of your class helped shape a global perspective in my mind of how the construction industry has evolved and continues to evolve around the world. The pattern repeats itself and we have yet to take advantage of it.

I never would have gotten the chance to work on this project, let alone be here at MIT had it not been for the sacrifice and support of my parents and my family. To them I give thanks for over 27 years of unconditional love and support.

To my fiancée who has stuck with me despite all the time I've left her back home planning a wedding and taking care of business, I thank you from the bottom of my heart. I promise I will make it up to you.

Finally, to all those who have struggled with me here at MIT, I sincerely hope you all reach your goals and may the world give you many triumphs.

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Introduction

This project has been the result of several months of investigation on technological innovation in the construction industry. The construction industry in Japan was studied in an effort to determine what drives technological innovation and then compared to the development of the industry here in the United States. A review of the professional literature and books on the construction industry was done to create a collage of ideas that might give some insight into the future of the industry.

Hopefully, this compilation of information will illustrate how technological innovations have changed the construction industry and will continue to reshape it into the future. Will Japan continue to be a crib for technological, method oriented innovations with a long-term outlook, or will it change to a more short-term managerial focus like the United States? What about China's emerging economy? What role will it play in the global development of the industry?

Let us take a look into the past and explore how the industry has change in the 20th century and maybe this will help us see what lies ahead.

In some cases the author's works have been partially transcribed, in others quoted. Sometimes the wording has been changed slightly to better accommodate the ideas into a complete and easy to read text. A just effort has been made to give credit to all those involved, and their works are referenced at the end.

Chapter 1 – The Construction Industry and Geography

According to Henry Kelly, National President of the Associated Builders and Contractors, "the United States construction industry will ease into its tenth straight year of expansion in 2001. ABC represents over 22,000 merit shop construction and construction related firms in over 80 chapters across the United States" [Kelly, 2000]. Here we find the first indication as to the structure of the industry and the large degree of fragmentation that characterizes it, not only in the United States but also in most of the industrialized world.

"As U.S. construction firms place emphasis on improving information technology systems, training the construction workforce and strengthening safety programs, both productivity and profitability steadily increase" [Kelly, 2000]. As will be shown later on, workforce productivity is closely dependent on proper motivation. In the United States and around the world, the skilled construction craft worker is still regarded as the most important asset to the continued strength of the U.S. construction economy [Kelly, 2000]. In contrast, the increasing cost of human labor and the higher levels of education being provided to the Japanese workforce have made human labor a quite expensive commodity. Also, trends show that a large number R&D projects in Japan are focused on decreasing the dependency of the industry on human labor.

Technological innovation in construction practices comes about because of different reasons in different countries. Here in the United States for example, we find that technological innovations are usually a byproduct of a specific project. This is due mainly to the nature and complexity of today's civil engineering projects and the fact that civil engineers build "prototypes." This means that very few construction projects are a copy of one another. When confronted with a new situation or a complex problem, engineers try to find the most economical and unobtrusive way to overcome it.

As will be shown, in many cases these situations can be solved by teamwork among "quality circles." The quality circle approach to solve production related problems was introduced by U.S. consultants in Japan after World War II. The concept was successfully implemented in the United States mainly in the manufacturing and service industries in the early 1980's, but somehow failed to take root in the construction industry. Impressed by the results, the Japanese took to the task of adapting the concept to the construction industry in Japan [Rosenfeld et al. 1992].

Webster [Webster, 1994] explains that research and development (R&D) of new technologies here in the United States is usually carried out by government organizations or by companies working on large government projects. Seldom do we see significant company resources being devoted to R&D inside a particular construction company. However, this is not true in Japan. Japanese construction companies have a very different approach and mentality when it comes to the advancement of technology in the construction industry. "Zenecons" (large Japanese construction firms with R&D departments) try to constantly develop new and efficient ways of doing everyday construction tasks. Within every Zenecon, we find large and well-funded R&D departments. Japan's commitment to R&D is not limited to its construction companies. Both the national government and Japan's higher education system have a very strong commitment to research and development.

He adds that R&D is not the only difference between U.S. and Japan's construction industry. While the U.S. construction industry continues to depend heavily on construction workers and craftspeople, Japan is seeking new ways to lower the demand of labor in the industry. Large construction companies are also leaning more towards design build projects where they can carry out both the architectural and civil design in house. This approach helps reduce friction between consultants in a project and improves constructability of the design.

There are many reasons to this disparate mentality with respect to R&D between the Japanese firms and the rest of the world. Perhaps one of most importance is their shared belief that obtaining new technologies, over the long haul, is as important to maintaining a competitive edge and continued growth as nurturing existing clients [Webster, 1994].

There are many areas for technological development in the construction industry. There is innovation in materials, methods, equipment and technology. Many believe that there is room for improvement in any construction activity used today. It is only necessary to dedicate a long enough period of time to find an infinite number of opportunities for improvement. Studies have revealed that sometimes, simple changes in the way an activity is carried out may yield very large gains in efficiency and lower construction costs.

Chapter 2 – Innovation Concepts

In a publication in the Journal of Construction Management and Economics, Dr. Yehiel Rosenfeld identifies three major barriers to innovation in the construction industry. He states that the greatest barriers, to innovation in construction methods lay in its unique combination of three major characteristics: capital intensiveness, legal responsibilities and great fragmentation [Rosenfeld, 1990].

"Since construction is usually the largest fixed investment made by individuals, corporations and public authorities, it is no wonder that most risk-aware decision makers feel more comfortable when investing in structures built through mainstream, well-tested designs, materials and methods, rather than through some "promising" innovative ways that may not live up to their promises in the long run. People usually prefer – both in private and public decisions – to give up potential savings (especially if they are merely in the range of single–digit percentage points) for the cozy feeling of security, confidence and experience they have with well-performing existing products (Burbridge, 1989)" [Rosenfeld, 1994].

There are also legal responsibilities that persuade innovators to abandon their goals. "No designer, engineer, construction manager and to a less extent, political figure, need be afraid of being sued for applying well-tested (though not very efficient...) practices in their construction projects while, whenever a new method fails, they are exposed to criticism and to liability claims for "experimenting" with new methods instead of using common practice" [Rosenfeld, 1994].

"The third major barrier to innovation is great fragmentation of the industry, its great fragmentation (Hasegawa, 1987), creates a situation in which the prime beneficiary from successful innovations is usually the owner of the project, whereas the primary losers in case of some failure of the innovation are the constructors, who carry the liability of fixing the faults, and the designers, who have to spend time and money on the corrective actions and suffer from damage to their reputation. This imbalance between risk and profit discourages inventiveness" [Rosenfeld, 1994].

An increase in productivity drives the vast majority of construction innovations. Webster [Webster, 1994] defines productivity as the act of producing in abundance. The idea of producing more "units" or completing more operations in less time and at a lower cost is what drives innovation in construction. It does not matter if the project is a $4.3 billion dollar bridge in the Akashi Strait in Japan or a $10 million dollar office park in Costa Rica. The fact remains that those involved in the design and construction of the project are looking for a faster, cheaper method of construction that will yield at least the same quality as traditional methods.

In a lecture on Innovation in Construction at MIT, Dr. Rosenfeld identified four elements of the construction industry as possible areas for innovation. Known as "the four M's," they are manpower, machines, materials and methods. Warren writes that motivation and productivity go hand in hand. He says that it is not that labor today "just isn't as good as it was in the old days," but rather that this decrease in productivity is attributable to a slip with regards to how the resource is managed. "Motivation is characterized as a combination of influences that causes the craftsman to want to do the job as quickly as possible consistent with safety and quality goals while cooperating, on a larger scale, with his fellow craftsmen in execution of the project as a whole" [Warren, 1989].

Within the four elements identified by Rosenfeld, perhaps one of the most important in determining productivity is manpower. Productivity as it relates to manual labor is influenced by four key factors: ability, motivation, external factors (equipment, materials, tools, weather, etc.) and job perception [Rosenfeld, 2001].

- The ability factor has to do with the laborers skill, experience and training. It is his ability to carry out his trade in a short time and maintaining a high level of quality. A worker that is able to complete many work units but with a sacrifice in quality has an overall negative impact on the project. Later on, this low quality work will have to be redone, sometimes by a more skilled employee, that represents an additional investment in both time and money.

- Second in this list of factors is motivation. As we have seen before, motivation is very closely related to productivity through Maslow's theory. Having a well thought of and equal motivation plan in a job site can significantly improve productivity and safety. It is important to make construction workers feel proud of their work and feel that the project belongs to them. In a way, nobody on the site deserves to feel more self-gratitude than those who have built projects from the ground up with their bare hands.

- External factors like equipment materials, tools, timely supplies and weather play a very important role in a work crew's productivity. Faulty equipment in a job site may not only decrease productivity but also poses a potential safety hazard. Construction equipment tends to be bulky, heavy and extremely powerful. Their power to weight ratio is such that it is easy to forget the power and danger associated with operations involving this type of equipment. Just because a crane can lift a ton of bricks effortlessly does not mean that it is safe to walk beneath the load. Many have died because they have left their guard down when it comes to working with heavy construction equipment. Modern construction however, would not be possible without these machines. Well-maintained equipment and trained operators can dramatically improve job site productivity. Construction crews that take advantage of this resource are much more productive than those who don't. This scenario is further investigated in subsequent chapters.

- The last factor that influences productivity is job perception. Many say that the problem in today's construction sites is that the available labor is not as good as in the old days. Actually, the quality and training of the construction work force is much better than thirty years back. The problem is actually one of communication. Faulty communication between management and field personnel opens the door to many mistakes that in turn lead to a large amount of do-over type of operations. Studies have shown that it is better to do it well the first time than to do a quick, inaccurate job that later on must be checked, rejected and rebuilt. Spending a small amount of time upfront to explain and make sure that those in charge of building have a clear picture of what they are about to build, and how exactly they are going to build it pays off by diminishing the need for repairs.

Warren's book on Motivation and Productivity [Warren, 1989] has a good description of Abraham H. Maslow's theory of human behavior. Maslow describes human behaviour in terms of psychological needs. "This theory suggests that human beings are driven by a series of psychological needs that manifest themselves as goals." In his hierarchy, Maslow identified five levels of needs presented here in ascending order:

1. Physiological needs
2. Safety needs
3. Belongingness needs
4. Esteem needs
5. Self-actualization needs

- "Physiological needs may be characterized as those necessary for survival of the body. They include the need for food, water, shelter, warmth, and sleep."

- "Safety needs pertain to the individual's concerns for safety and the causes that ensure or jeopardize it. Characteristic of these needs are the desires for security, for stability in relationships with others, for freedom from harm, fear, anxiety, and chaos, for the presence of a strong protector, for a structured environment, for predictability of events, and for law and order."

- When individuals are concerned with where the next meal is coming from, where they are to sleep at night, or whether they will be fired from their job, love and belonging are unimportant to them. Their preoccupation is with survival.

- Esteem needs have two components: self-esteem and the esteem of others. A person seeking self-esteem exhibits a desire for the achievement and mastery of some quality or skill.

- Finally, self-actualization needs are the individuals' motivation to become what he feels he must be. "He wants to become what he believes he is best suited to be and all that he is capable of becoming." If his dream is to become one of the best welders, this is what he will strive to be [Warren, 1989].

Satisfying worker's needs in today's construction industry can prove rather complicated. In the past, when workers were poorly educated and their primary goals were to satisfy the most basic of Maslow's needs, motivation came in the form of making a minimum wage. With the higher level of education required in modern construction industry, manager's have to satisfy higher needs of a higher level like esteem and self-actualization. This is where "Using Quality Circles to Raise Productivity and Quality of Work Life" by Rosenfeld and others comes in handy.

"A "quality circle" is basically a small group of employees from the same working environment that meets regularly to identify and analyze work-related problems or deficiencies, suggest solutions, and implement them. Typically, quality circles meet for one hour per week, either during working hours or afterwards, on paid time. Participation is voluntary, but regular attendance is essential to the process" [Rosenfeld et al. 1992].

The prototypical nature of construction projects makes quality circles seem unsuitable for the construction industry. "Unlike manufacturing industries, which produce large quantities of similar products, and unlike most service industries, where people perform limited sets of tasks over and over again, the construction industry usually produces one-of-a-kind large units, in which low repetition obviously negates the multiplicative effect of method improvement."

"The physical environment of construction sites is highly dynamic, making for very short-term relevancy of problems. The shape of the constructed facility and the pattern of operations change continuously, and so do the production problems related to them. Apparently the thorough, multiple-stage, lengthy procedure of quality circles cannot fit into the fast-paced environment of construction projects."

Since quality circles rely on group dynamics, the instability of the work force poses a challenge to this problem solving approach. However, the low initial efficiency of construction operations is evidence of a large opportunity to implement this type of problem solving procedure and increase in site productivity. Even though the global project output is a prototype, the day-to-day operations in the construction site are highly repetitious.

Another great advantage of quality circles is that they help spot problems early [Rosenfeld et al. 1992].

Chapter 3 – Japanese Construction Industry and Technology

Webster's book [Webster, 1994] on the "Technological Advance in Japanese Building Design and Construction," contains a good description of Japan's construction industry and how it varies significantly from that of western countries. This source has been primarily chosen because of its completeness in terms of history, economics and examples. Throughout this chapter and the next, references are made repeatedly to Webster's text in an effort to credit the author with his extensive research on the Japanese construction industry. Webster's development of the subject mater is an excellent source for those interested in getting a complete picture of the Japanese construction industry without having to undergo extensive bibliographical research.

In an article published in 1998 in "News and Views from Japan," Eiji Aoki of the Japanese Mission to the EU, states that one of the most important differences between Japan and other developed countries is that for a developed country, the percentage of public investment is large. The typical public investment of countries like the U.S., the UK, France and Germany has been from 2 to 4 % of the Gross Domestic Product (GDP). In Japan, this figure is more like 5 to 7 %. If we factor in the private investment, the figure is a staggering 16 to 18 % of the GDP. That is more than twice that of Europe and the United States showing that in Japan, not only the public but also the private sector invest heavily in construction [Aoki, 1998].

Benefiting from these investments, Japan's construction industry employs more than 6 million workers. This enormous employment sector amounts to 1 % of the island's total industrial work force. "Since the end of the 80's, the employment in the sector has continued to increase" [Aoki, 1998], hitting the 7 million mark in the summer of 1993. This growing trend is also evident in the number of construction companies, which kept growing through the 90's [Aoki, 1998].

Japan's construction industry differs as well from that of the west in the nature of its urban landscapes and the engineering details of it buildings. Japanese commercial high-rise buildings are usually shorter than those containing the same square footage in the United States. Structural frame sections like beams and columns, tend to be much more massive and are “short and stubby.” This is due in part to the ever-present threat of an earthquake in the Japanese archipelago [Webster, 1994].

However, the Japanese and U.S. construction industries do have many similarities. Construction technology and methods used in Japan are usually recognizable variations or refinements of U.S. equivalents. “Except in a few areas, such as construction automation and hybrid structural systems, the industries in both countries are following similar evolutionary paths, although the level of evolution varies, and each country is more sophisticated than the other in some areas. Exotic structural systems and construction materials are almost as rare in Tokyo as in New York; the materials and methods employed in Japan are for the most part very similar to those used in the U.S” [Webster, 1994].

Even though the products of the Japanese and American building construction industries are similar, there are important differences in the type of companies that design and erect each country’s major urban structures. The relationships between academia, the government, and industry are also quite different. A clear example of these differences is the commitment of Japan’s largest construction companies, as well as the national government, to research and development.

Here in the United States, two independent firms specializing in engineering and architecture usually carry out the design of large-scale, commercial and residential buildings. Once the design has been approved by the client an all pertinent permits have been obtained, the project will go out to bid and a third company will join the team in the form of a general contractor. This last party is ultimately responsible for the construction of the project. There are however large “design-build” and “engineer-constructor” firms like M.W. Kellogg and Bechtel Corporations that have added to America’s urban landscape, although their contributions to commercial and residential buildings has been limited. In contrast, large construction design-build firms in Japan have made significant contributions to the commercial and residential architecture of its cities, and they have engineered and built many buildings designed by Japan's leading independent architects [Webster, 1994].

Another important difference between Japan's construction industry and that of the U.S is the existence of Japan's "Big Six." The Big Six is a group made up of Japan's six largest construction companies. They are: Shimizu, Takenaka, Obayashi, Taisei, Kajima, and Kumagai-Gumi Corporations). These companies enjoy significantly higher sales volumes than the next six companies with the largest incomes. These six companies single-handedly control roughly 10 % of Japan's total design and construction market. With the exception of the Takenaka Corporation, all of these firms design and build major bridges, dams and other civil engineering works in addition to conspicuous architectural projects. The sales of these Japanese companies were rivaled only by those of Bechtel and Flour Daniel's when they recorded higher sales volumes than the Shimizu Corporation for 1991 [Webster, 1994].

As mentioned in the previous chapter, the construction industry is very fragmented both in the United States and Japan. There are roughly half a million construction related firms in each Japan and the U.S. Out of these, only 2,900 are approved by Japan's Ministry of Construction as "Specialized License Contractors." The SLC classification is required for firms to bid on Japan's largest civil engineering and building commissions. "Approximately 1,000 of the largest SLCs are capitalized at more than 1 billion yen and control 27 percent of the industry's contracts." The Japanese often refer to these firms as "Zenecons," or "general contractors." "The Zenecons aggressively pursue design-build contracts, and prefer these commissions to other methods of design and construction" [Webster, 1994].

"The Zenecons' pervasive role in urban architectural design and construction distinguishes them from the smaller, more specialized companies performing the same functions in the U.S. In designing and building high-end architectural commissions, the

Zenecons single-handedly perform the roles of America's specialized architectural, engineering, and building-construction firms" [Webster, 1994].

Besides their preference towards design-build projects, Japan's Big Six companies also have extensive R&D divisions, as do the next largest twenty-four or so Zenecons. Unlike U.S. based firms where R&D is vaguely heard of if at all, the research and development facilities of these firms are quite impressive. They are typically "larger and better equipped than the largest university-based labs in the U.S. or elsewhere"; and their funding averages almost one percent of sales [Webster, 1994].

Here in the U.S. firms that do have R&D divisions fund them with roughly 0.1 percent of sales. Firms in Japan staff these state-of-the-art R&D divisions with graduates holding Ph.D. or master's degrees from Japan's best universities and their work is measured with the frequency with which their research is published in prestigious American engineering journals. Their research spans everything from design and construction, to developing new building materials and prototype building systems. Just as in the United States, most R&D is geared towards quickly marketable products and techniques, though a significant number of projects do have an extended timeline of several years. "This commitment to protracted research reflects the corporations' emphasis overall on long-term planning over short-term market gains" [Webster, 1994].

The thirty or so largest Zenecons tend to work together, often on joint ventures and have similar plans for corporate growth. The similarities among them make them the most important force in shaping the future of Japan's construction industry. A commitment to high quality, contained costs and project completion are crucial cornerstones to their long-term success.

The government regulates Japan's construction industry but it also helps the industry develop. The Ministry of Construction, which oversees the construction industry, encourages the creation of new technologies, particularly for automated construction. Though the funding levels for the Ministry's Building Research Institute are not as large as that of the top Japanese construction companies, it initiates collaborative R&D efforts between government and industry on an annual basis. The Building Research Institute also pursues its own independent research, and collaborative projects with universities. Like those of the largest Zenecons' individual R&D efforts, many of the building Research Institute's initiatives are long-term projects, with no marketable results expected for a decade or more [Webster, 1994].

Many cultural factors, such as the Japanese emphasis on team effort over individual performance, help shape the unique face of Japan's construction industry. Possibly the most important factor is the pervasive belief in technological solutions to a wide range of problems – both technical and social. This notion encourages the continual development of new technologies for building design, construction and operation; it also encourages these multi-faceted companies (known as comprehensives), the government and universities to strive for technical solutions to problems as diverse as labor shortages and the thermal performance of building facades [Webster, 1994].

"Competition in quality and technology remains strong in Japan. In addition, Japan's construction economics is cyclical, and the comprehensives remain healthy enough to respond quickly to the next upturn." Even now, these companies are continuing to improve and broaden their technological capabilities faster than most American firms [Webster, 1994].

"Japan's higher education system, its belief in technology's ability to help solve a wide range of problems, the legitimate relationships between its government, universities, and its construction industry, and the industry's demographics and long-term focus, all continue to fuel the comprehensives' technological development. When the international real-estate markets recover, these factors may help the comprehensives leapfrog the technical capabilities of America's leading building design and construction firms. Concomitant increases in efficiency could dramatically increase the financial success of these firms in Japanese and global markets" [Webster, 1994].

As stated before, these Japanese companies prefer building commissions for complete design and construction services, and the number of contracts they receive for these services is increasing. They like design-build contracts, not just because of their large scope of work but also because of the non-adversarial relationships between designer and contractor inherent in this system. These companies execute design-build projects by using in-house teams that include all the professionals required for both design and construction. By having designers and builders work together throughout a project, the companies assert that jobs can be completed more quickly and economically, problems of constructability are often foreseen and resolved before construction begins, and quality control is more easily assured. The design-build system demonstrates some potential advantages over the prevalent bid system employed here in the U.S. These types of commissions illustrate the overall technological capabilities of these multi-faceted companies.

“Some of the comprehensives are working on ways to reduce the weight of façade systems in order to minimize structural requirements and therefore costs.” Pre-manufactured tiled façade panels are very popular in Japan. “These panel systems are often made of inexpensive but heavy reinforced concrete, significantly adding to a structure’s dead load and necessitating a stocky, expensive structural system. Kajima Corporation (among others) has recently developed tile-clad, carbon fiber reinforced concrete (CFRC) panels to reduce façade weights and thereby decrease the required strength and cost of a building’s structural system” [Webster, 1994].

“One of the biggest challenges facing Japan’s construction industry is finding enough laborers to build its buildings. Construction work – from excavating for foundations to applying building finishes – has the reputation of being difficult (kitsui), dirty (kitanai) and dangerous (kiken). These three perceived characteristics, known commonly as the three K’s in Japanese, have driven much of Japan’s semiskilled workforce to safer, “cleaner” jobs in the manufacturing and service industries. Compounding the labor problem is Japan’s education system, which produced young adults whose levels of literacy and mathematical proficiency naturally guide them toward more highly skilled positions" [Webster, 1994].

The comprehensives are responding to the problems of worker safety and discontent with a variety of technologies that either streamline the construction process or reduce the amount of manual labor required in the field. "Structural and nonstructural components are prefabricated whenever possible into subassemblies that are as large as can be practically shipped to the construction site. Shear walls and nonstructural partitions are often made of partially prefabricated assemblies. Steel columns are often delivered to the construction site in three-story-tall sections, and reinforcing cages and beam connections for hybrid structures are frequently fabricated on the ground before being erected. HVAC equipment is pre-mounted whenever possible on steel building girders before they are lifted into place. Japan's steel industry has recently developed a line of rolled steel shapes with constant flange depths, which helps speed detailing and aids in the standardization of the architectural and mechanical systems that must work around it. The process of construction is often made more efficient through the design of buildings and construction methods that let workers perform exactly the same tasks each day, as if they were working in a factory. Mitsui's "One Day One Cycle" system is typical of such efforts" [Webster, 1994].

"The success of the car industry's automated assembly plants, combined with the construction industry's worker shortage, has helped spur the development of Japan's automated and robotic construction operations. Although the trend toward automation itself has produced some gains in productivity, the primary goal is to do a specific task with fewer people in a safer setting" [Webster, 1994].

As has been said before, the most striking feature of the comprehensive construction companies is their large, well-staffed and funded research and development (R&D) divisions. "Unlike their American counterparts, which generally do not have sizable R&D operations, the comprehensives are committed to R&D as both a means of increasing their short-term profitability, and as an essential part of their long-term growth strategy." "R&D divisions are not only flourishing in Japan's Big Six firms – virtually all of Japan's large general contractors have R&D divisions with their own permanent facilities, budget and full-time staff" [Webster, 1994].

"The reasons for the comprehensives' commitment to R&D are many and complex, but most important is their shared belief that obtaining new technologies, over the long haul, is as important to maintaining a competitive edge and continued growth as nurturing existing clients." "Unlike American firms that tend to view themselves as implementers and installers of technologies developed by others, Japanese contractors take pride in developing their own technologies for improved building materials and aiding the construction process" [Webster, 1994].

"The comprehensives' commitment to technological development has its roots in Japan's reconstruction period following World War II, when the first of their R&D divisions were founded. While rebuilding Japan after a war that destroyed 40 percent of its urban structures and left it with very little capital, the construction firms were under great pressure to build quickly and efficiently. During the war, successful Western corporations had shown how R&D could help reinvigorate and industry. American fighter planes, for example, were arguably the worst among industrialized nations at the onset of the war, but largely due to successful R&D efforts, were by 1945 almost unsurpassed. The benefits of corporate R&D were quickly recognized by Hazama-Gumi, which initiated an R&D division in 1945" [Webster, 1994]. This type of drive towards innovation is also evident in Israel after the fall of Soviet Union, where large numbers of immigrants pressured the construction industry to provide affordable housing in a very limited amount of time.

Chapter 4 – Current Innovative Technologies

> *"Innovation is defined as an idea, practice, or material artifact perceived to be new by the adopting organization [Zaltman et al. 1973]" [Mitropoulos et al. 1999].*

A study of recent professional papers submitted to the Journal of Construction Engineering and Management sheds some light into new and developing innovations in the construction industry. While Japanese firms have focused primarily on robotizing tedious and dangerous jobs, U.S. based firms and others around the world have specialized in improving productivity itself.

"In general, construction automation systems are being developed slowly in Japan, and are being used to automate only the simplest construction tasks. The development of automated machines for building inspection and maintenance has produced better results" [Webster, 1994]. State-of-the-art finishing robots are successfully being developed in Israel and in several other European countries [IAARC, 2001].

"One reason for the success of the automated building maintenance and inspection systems is that the jobs they are asked to perform, like the work of their cousins in the auto industry, are simpler and more repetitive than the complex, unpredictable, often-similar-but-never-identical tasks that comprise most construction activity. The comprehensives have used this fact as the basis for developing their most striking automated building construction research, which has no analog in the U.S. Unlike robotizing traditional construction tasks (or maintenance operations), automated building construction systems set out to transform the construction site into a place of automated assembly. The proposed process would be similar to a large manufacturing plant, whose product is the extension of itself. Robots inside this plant would fabricate a building's primary technical systems, including structure, building envelope and environmental control, from pre-manufactured pieces, Obayashi's "ABCS" (Automated Building Construction System), which is among the most advanced in the industry, illustrates the idea. In this scheme, an automated all-weather factory would sit on jacks on top of a building's main columns, performing all the work required to assemble the structure, façade, and environmental control systems for the floor directly below it. After a floor is completed, the factory would jack itself up one floor and repeat the process. Obayashi has tested portions of this system, including automated placement of structural steel and jacking of the factory, on its Sumida Bachelor Dormitory in Tokyo in 1993. The company expects to expand the use of this system in constructing Arata Isozaki's Kashii Twin Towers in Fukuoka City, Kyushu" [Webster, 1994].

"The Shimizu Corporation tested portions of a similar system (called Shimizu Manufacturing System by Advanced Robotics Technology, or SMART) on its Nagoya Juroku Building in Nagoya in 1991 and 1992. The Nagoya Juruku prototype featured a self-jacking weather enclosed factory, which was used for automated placement and welding of the building's steel skeleton, and for remote-controlled placement of some façade and floor panels. In 1993, Taisei also tested a self-jacking, semi-enclosed platform for the erection of a building's structure. Called T-UP, Taisei's apparatus was used for erecting the steel skeleton frame of the Yokohama Building of Mitsubishi Heavy Industries. Cranes mounted on the factory floor performed steel erection; welding of connections was performed manually" [Webster, 1994]. Up to date information along with detailed descriptions and video clips on any of these innovative systems may be found at the respective companies websites. The interested reader is encouraged to visit these sites on the World Wide Web.

"A complete automated factory system would at a stroke solve many problems plaguing Japan's construction industry today and would resolve many difficulties the Japanese have encountered trying to automate the construction piecemeal. By erecting the structural, cladding, and most of the HVAC systems with robots, the need for construction workers would be significantly reduced, helping to alleviate Japan's labor shortage. The savings from reduced labor (depending on the cost of developing and maintaining the required robots) could be enormous. Productivity would also be boosted by incorporating all major assembly operations in the weather-protected roof-shed, and by the system's ability to easily function around the clock. Shimizu estimates that when completed, its system will reduce on-site construction labor and erection time by 50 percent. The work of automated machines, as the example of the auto industry shows, also produces consistently higher levels of quality than found in manual construction. Most important, because the system would transform the construction site into a manufacturing plant, jacking itself upward a floor at a time, the robots working in the plant would not need to be very mobile. This greatly simplifies their design and makes the system conceivable with technologies similar to those Japan already uses in its auto industry" [Webster, 1994].

"The system also has some drawbacks. Because it does not envision the inclusion of a heavy crane, the system could not install chillers and other heavy or bulky equipment without their first being broken into pieces. As these pieces are unique and complex, they would have to be assembled by hand at the site, reducing some efficiency gained by automation. A bigger problem is that the automated assembly machines would have limited mobility. This would require that the building plan, and to a lesser degree its section would need to be regular. Indeed, Obayashi's proposed system envisions a circular or rectangular-plan building, and Shimizu's and Taisei's prototypes were based on a square building plan. This severely limits the application of the system for general use" [Webster, 1994].

"The main differences between the two countries' building design and construction R&D efforts are that significantly more R&D is being done in Japan, and that it is performed in different types of institutions in the two countries. Although the types of research done in each country are generally similar, there are some important fields of research that if not uniquely Japanese, are not being aggressively pursued in the U.S. Most prominent among these areas is automated building construction, as exemplified in Obayashi's, Shimizu's and Taisei's systems. Because the scale of this research is so large, and because it involves virtually every discipline involved in building design and construction, it stands out as something that would be difficult to duplicate in the West" [Webster, 1994].

"Even given its limitations, automated building construction would be a revolutionary technology with the potential to produce awesome results. Its development says much about the forward-looking technical prowess of the comprehensives; its lack of development in the U.S. also underscores the highly specialized, fragmented organization of our industry, and its inability to envision systems and methods embracing a variety of professional disciplines and construction trades" [Webster, 1994].

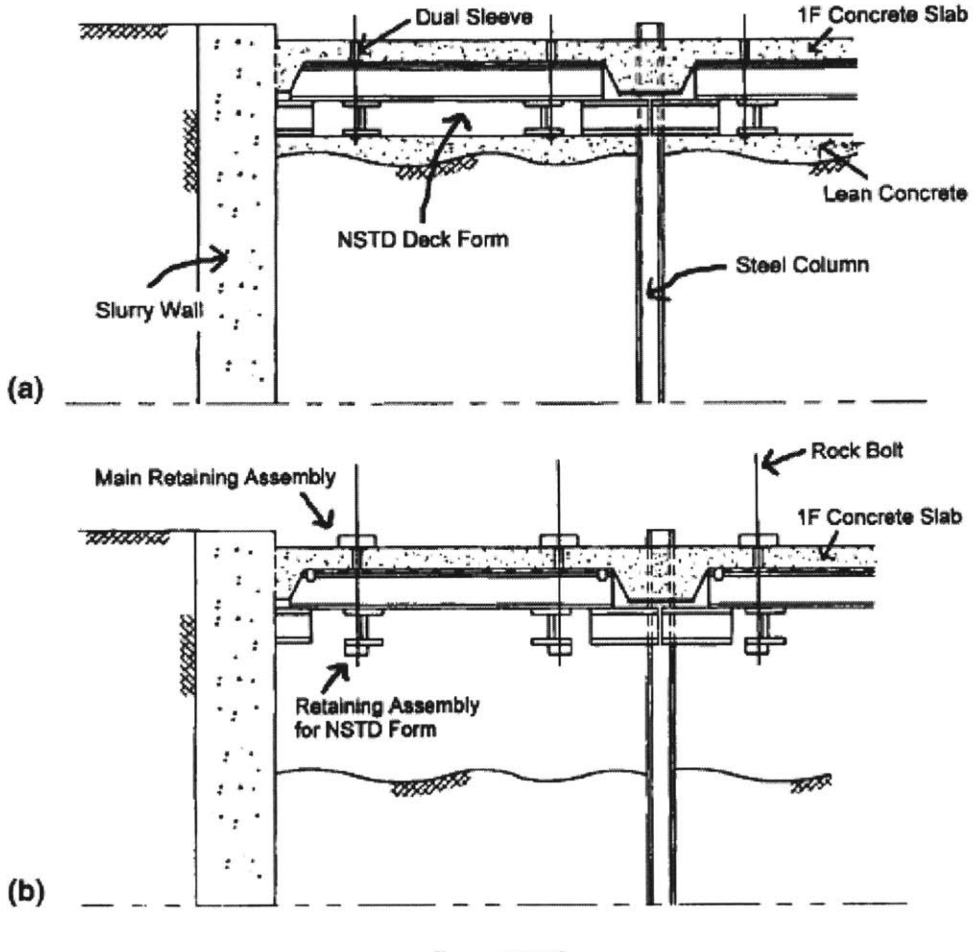
Non-Shored Formwork System for Top-Down Construction

Research is currently being conducted on the development of a "Non-Shored Formwork System for Top-Down Construction" (NSTD). "The main objective of this research is to propose a new formwork system that enables the underground excavation work to be executed in safe conditions, while still providing significant savings in the overall project schedule. The feasibility of the new formwork system is presented in terms of both time-savings and cost-effectiveness" [Lee et al. 1999].

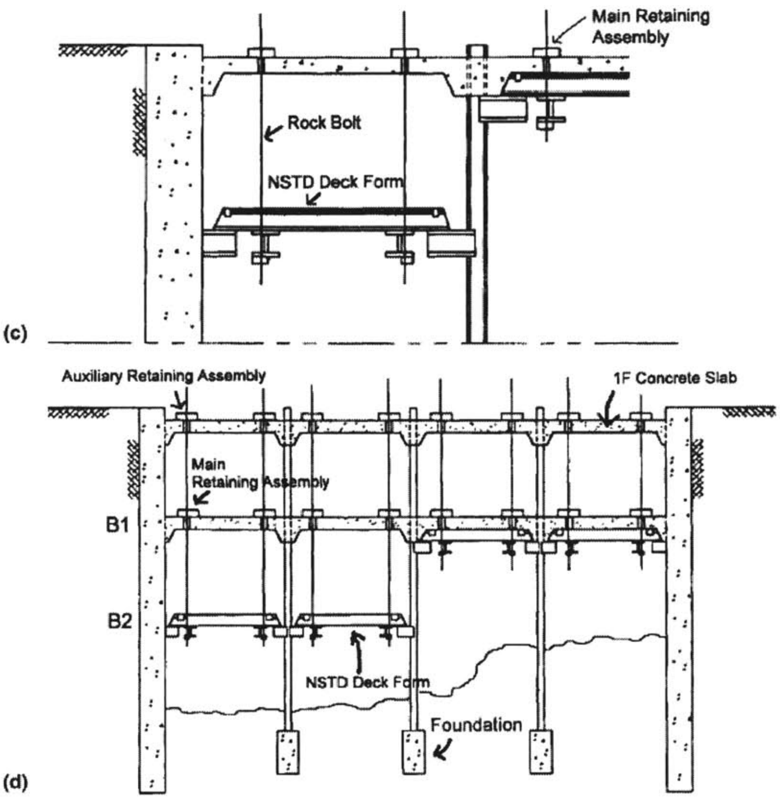
"In typical top-down methods, excavation is not possible during concrete curing. That is, the excavation work must wait until the completion of curing, resulting in schedule delays and discontinuity of the work process. Therefore, the overall project schedule is delayed, causing an increase in the total project cost. In addition, the safety of the concrete slab cannot be guaranteed when the forms are removed early" [Lee et al. 1999].

The proposed NSTD method provides sufficient workspace for excavating under the suspended forms. Upon completion of the concrete placement and the curing of the ground level concrete slab, the forms of the NSTD are lowered to the next lower floor and the process is repeated down to the lowest floor. The proposed construction sequence is as follows:

1. After the concrete slurry walls (retaining walls) are constructed, steel columns are installed in the sub-grade.
2. Ground surface is stabilized for lean concrete pour.
3. The NSTD forms are fabricated on top of the lean concrete.
4. Rebar is placed on the forms and rock bolts are installed through dual sleeves.
5. Concrete is place over the forms, and excavation continues.
6. Once excavation is complete, the forms are lowered to the next level.
7. The main retaining assembly is installed on the ground floor and the forms are fixed on the first basement floor.
8. Rebar is place and the process repeats itself.

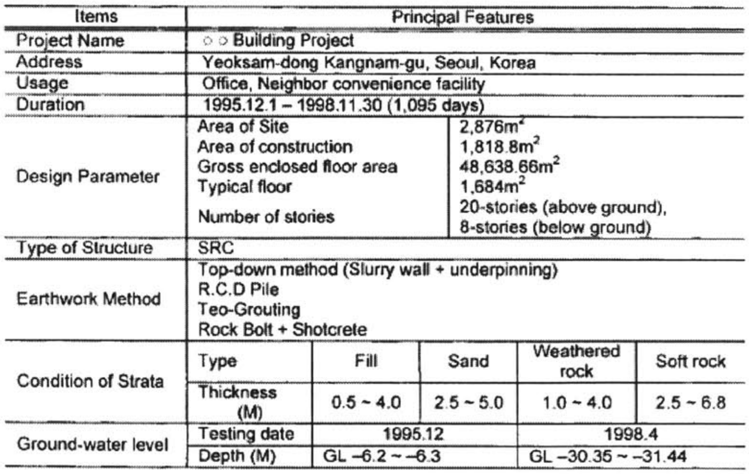


[Lee, 1999]



[Lee, 1999]

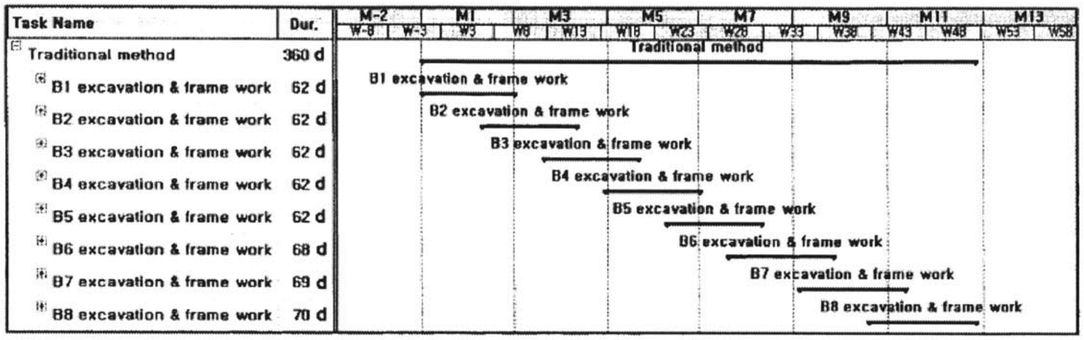
To illustrate and validate the NSTD method, an actual project was built and selected for a case study. The building is located at Yeoksam-dong, Kang-nam-gu in Seoul, Korea. The original construction process was planned using top-down construction and underpinning techniques. The next figure summarizes the project specs.



Items	Principal Features				
Project Name	○ ○ Building Project				
Address	Yeoksam-dong Kangnam-gu, Seoul, Korea				
Usage	Office, Neighbor convenience facility				
Duration	1995.12.1 – 1998.11.30 (1,095 days)				
Design Parameter	Area of Site	2,876m^2			
	Area of construction	1,818.8m^2			
	Gross enclosed floor area	48,638.66m^2			
	Typical floor	1,684m^2			
	Number of stories	20-stories (above ground), 8-stories (below ground)			
Type of Structure	SRC				
Earthwork Method	Top-down method (Slurry wall + underpinning) R.C.D Pile Teo-Grouting Rock Bolt + Shotcrete				
Condition of Strata	Type	Fill	Sand	Weathered rock	Soft rock
	Thickness (M)	0.5 ~ 4.0	2.5 ~ 5.0	1.0 ~ 4.0	2.5 ~ 6.8
Ground-water level	Testing date	1995.12		1998.4	
	Depth (M)	GL –6.2 ~ –6.3		GL –30.35 ~ –31.44	

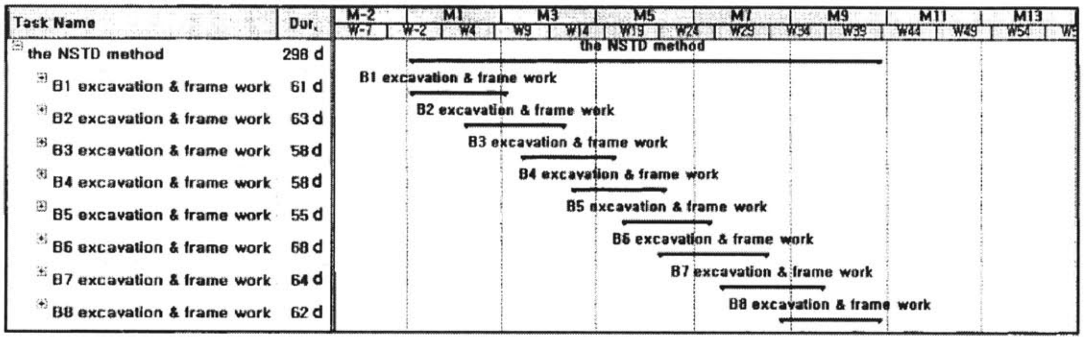
[Lee, 1999]

The actual NSTD method was compared with the original plan to investigate the effects on time and total construction costs. As seen below, the actual project schedule was cut short by over 60 days and the construction costs were reduced by 12.6%.



Task Name	Dur.
Traditional method	360 d
B1 excavation & frame work	62 d
B2 excavation & frame work	62 d
B3 excavation & frame work	62 d
B4 excavation & frame work	62 d
B5 excavation & frame work	62 d
B6 excavation & frame work	68 d
B7 excavation & frame work	69 d
B8 excavation & frame work	70 d

(a)



Task Name	Dur.
the NSTD method	298 d
B1 excavation & frame work	61 d
B2 excavation & frame work	63 d
B3 excavation & frame work	58 d
B4 excavation & frame work	58 d
B5 excavation & frame work	55 d
B6 excavation & frame work	68 d
B7 excavation & frame work	64 d
B8 excavation & frame work	62 d

(b)

[Lee, 1999]

TABLE 2. Cost Estimates: Traditional versus NSTD

Item (1)	Construction cost (2)	Cost of temporary work (3)	Job site overhead (4)	Sum (5)
Traditional method (A) (U.S.$)	1,856,841	2,019,637	2,468,882	6,345,360
NSTD method (B) (U.S.$)	1,311,500	1,905,284	2,329,092	5,545,876
Reduced cost (A and B) (U.S.$)	545,341	114,353	139,790	799,484
Reduction (%)	29.4	5.7	5.7	12.6

Note: Exchange rate is based on US$ 1 = 1,000 KRW (Korean Won).

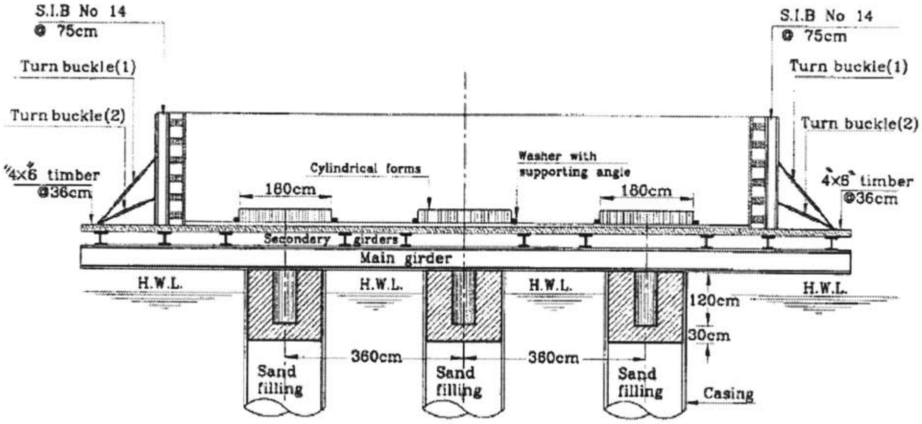
[Lee, 1999]

Adapting Lift-Slab Technology to Construct Submerged Pile Caps

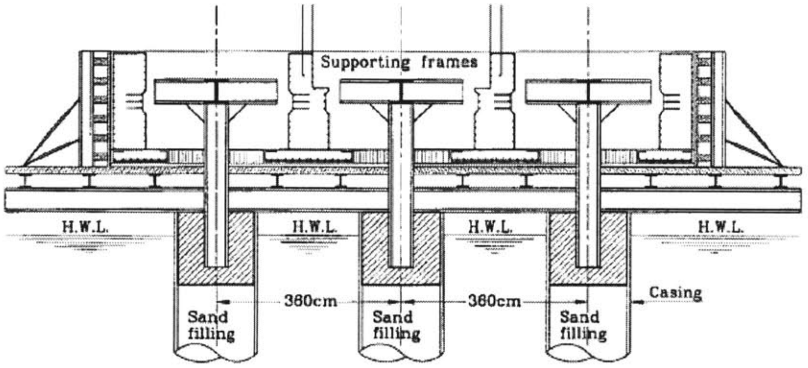
This innovative technique is based on the experience of adapting lift-slab technology to construct submerged pile caps in the Nile River. By lying immersed, the caps cause no obstruction to waterway traffic. The method is to partially construct the pile caps above water level, and then they are sunk in place, and monolithically joined to the pile group under water. The idea is to work most of the time above water in dry and safe conditions, hence eliminating the need for cofferdams. This technology has already been used in the construction of pile caps for several bridges along the Nile River in the 1990's [Elazouni et al. 2000].

The procedure is as follows:

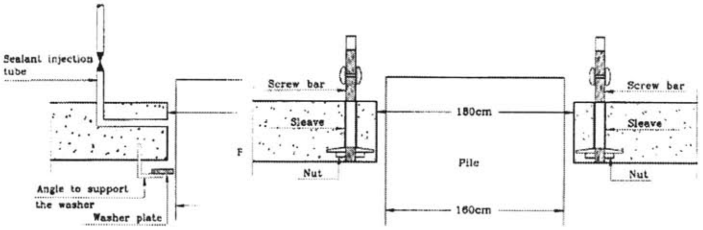
1. Preparation of temporary system of casting and the pile cap.
2. Erecting frames and fixing steel reinforcement of bottom and sides of pile cap.
3. Details of Sealing of space between pile casing and pile cap.
4. Details of anchorage of screw bars to bottom of pile cap.
5. Pouring the bottom, forming working rooms, and pouring around working rooms.
6. Lifting the pile cap, stripping off side and bottom formwork, and taking apart the temporary platform.
7. Sinking the pile cap to permanent position.
8. Pouring of some pile caps monolithically with pile cap.
9. Pile cap after pouring the rest of the pile caps.



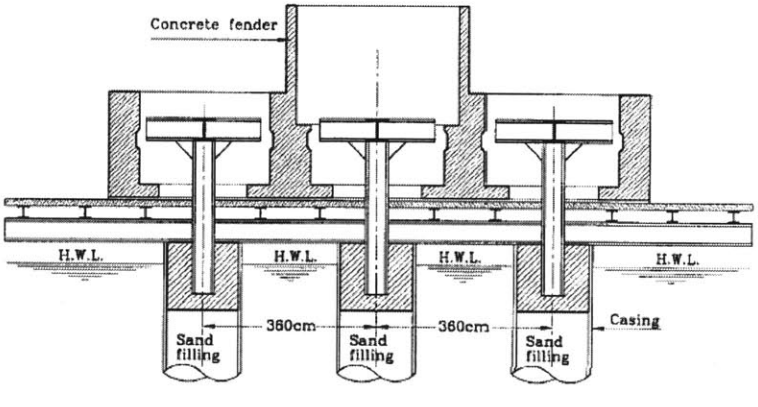
[Elazouni et al. 1999]



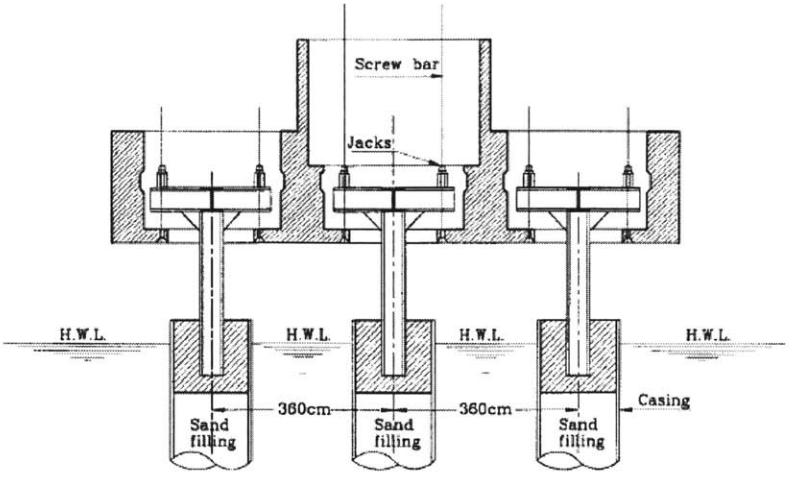
[Elazouni et al. 1999]



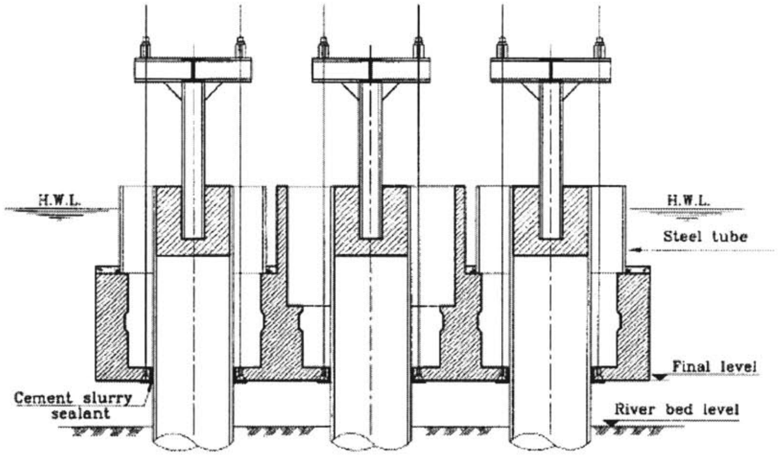
[Elazouni et al. 1999]



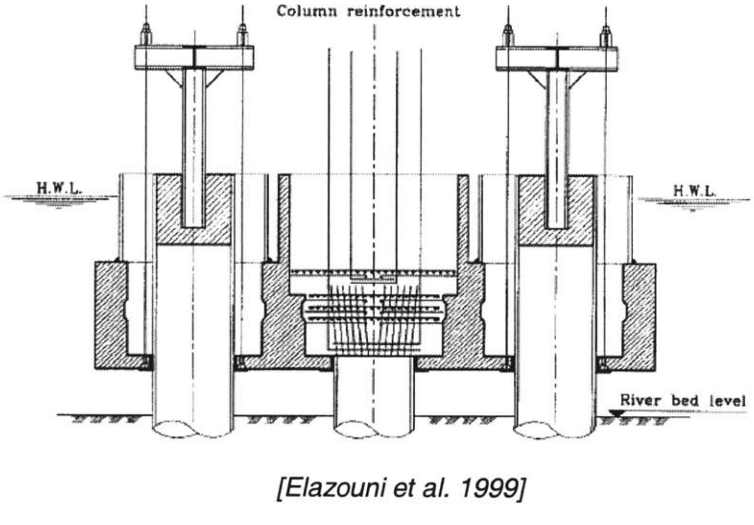
[Elazouni et al. 1999]



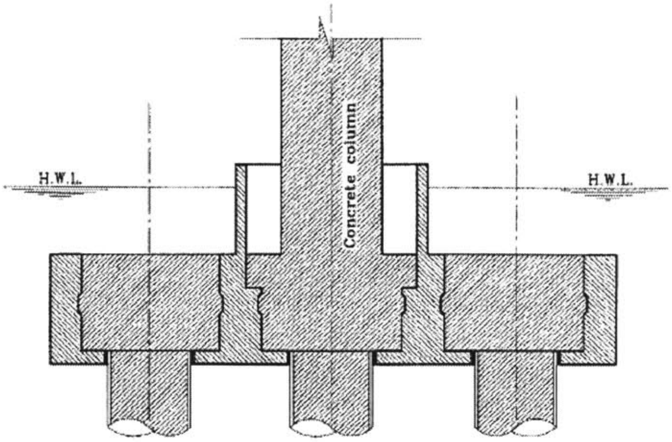
[Elazouni et al. 1999]



[Elazouni et al. 1999]



[Elazouni et al. 1999]



[Elazouni et al. 1999]

This type of construction had positive impacts both in cost and schedule. According to Elazouni and others, constructing pile caps using the adapted lift-slab technology consumes about one-third of the time required to complete the same operation using sheet-pile cofferdams. He also studied the effects on cost and found that the total cost per cubic meter of pile cap constructed was approx. $522 at 1994 exchange rates. Using the new method cut costs in almost half to $276 [Elazouni et al. 2000].

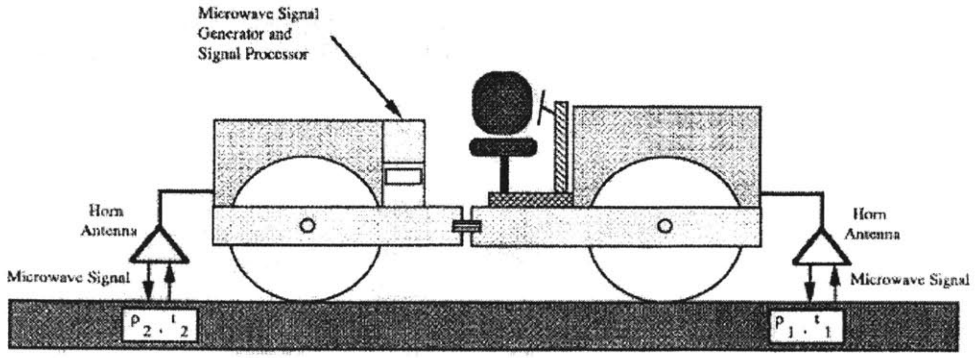
As has been stated throughout this investigation, there is room for technological innovation in materials, methods, manual labor and machines. The previous two examples have had to do mostly with methods. The next examples will have to do with equipment, machines and materials.

Status of Roller Mountable Microwave Asphalt Pavement Density Sensor

“Currently, there are several techniques for determining asphalt pavement density. Core sampling is one common technique extensively used by departments of transportation for ensuring satisfactory specification compliance. Also, extensive effort has been devoted to nondestructive evaluation of asphalt density characteristics. Nuclear density gauges, for example, have been used for several years to measure bulk density of hot asphalt mixtures (Burati and Elzoghbi 1987). The capacitance energy dissipation method is another technique that is relatively new to the paving industry. This approach measures changes in the electrical impedance of the asphalt pavement material matrix and correlates them to density (Apkarian and Piascik 1997)" [Jaselskis et al. 2001].

This proposed new method employs an approach to measure the density of asphalt in real time using dual microwave signals. "Two antennas, one in fron of a roller and the other behind it, measure reflected microwave signals from the asphalt, and the change in signal variability reveals to the operator the optimal compaction and density of the pavement" [Jaselskis et al. 2001]. The pavement before compaction is less dense, and reflected microwave signals exhibit higher variability. A significant rise in signal variability occurs when the pavement has reached its optimal level of compaction [Jaselskis et al. 2001].

"This new technique minimizes the need to quantify the hot mix asphalt (HMA) properties that change during the compaction process. This is because the asphalt pavement properties are similar in front of and behind the roller (e.g., temperature, binder chemistry, and mix design). Once operational, the new sensor will continuously provide the roller operator with real-time pavement density information. It will also be non-contact, roller mountable, and safe" [Jaselskis et al. 2001].



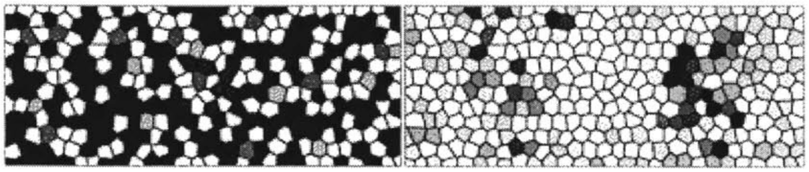
[Jaselskis et al. 2001]

Underwater Concrete Casting Operations

"Modern construction projects require the use of state of the art construction technologies and materials. Any particular project may call for the use of high strength materials like HSC mixtures or very high strength steel, while another may require the use of composite materials and lightweight sections. Underwater foundations are a very particular type of construction operation. They can be made out of steel, pre-fabricated concrete sections or cast-in-place concrete. It is this last method of construction that this paper will investigate" [Ortiz, 2001].

"Until recently, underwater casting operations were plagued with problems like material separation and loss of cement. Admixtures like Mellose have significantly reduced the problem, hence allowing for large scale underwater casting to be accomplished. Mellose is a viscose agent based on underwater Cellulose (Hydroxy Propyl Methyl Cellulose). This product is currently being developed by MECA Engineering Co. in Korea. Underwater cellulose is more commonly used as a self-leveling agent that increases viscosity when dissolved in water. Concrete mixtures containing similar products are known as anti-washout concrete or non-dispersible concrete mixtures. These types of admixtures are an essential component of today's high performance underwater concrete construction operations" [Ortiz, 2001].

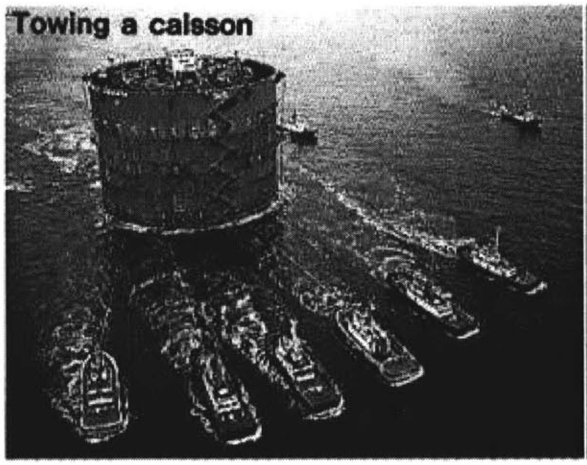
When subjected to an underwater medium, concrete mixes suffer the separation of particles due mostly to water flow. Changes in water pressure and the difference in material densities accelerate the segregation process. Underwater cellulose interacts with water before cement and other small concrete particles have time to separate from the matrix, hence stabilizing the concrete mixture.

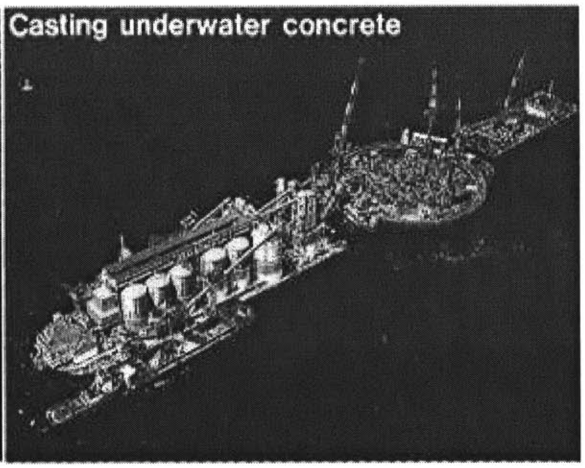


Concrete particles without MELLOSE *Concrete particles adding MELLOSE under water*

(Water pictured as black dots)

“The Akashi-Kaikyo Bridge in Japan is the longest cable stayed bridge in the world.” “The main tower foundations were built using caissons using the “setting down method.” The caissons were manufactured of site at a shipyard and then were towed using six high-powered tugboats to overcome the challenging currents and waves. Construction was limited to a small window between tides every day. The Akashi strait is 4 kilometers wide and currents of 4.5 meters/sec are not unusual. A circular cross section having no directional properties was chosen for the caissons that once towed were submerged into place and filled with underwater and standard concretes” [Ortiz, 2001]. This underwater casting operation is a clear example of how new innovative material technologies are shaping today’s construction industry by allowing us to do things that were previously not possible.





http://www.hsba.go.jp/bridge/e-akasi.htm

Chapter 5 – Decision Making Process Behind Innovation in Construction

Many technological innovations are never adopted, not because they are not worthy in terms of improving some aspect of the construction industry, but because key players have the important task of making calculated decisions on the matter. Dr. Rosenfeld once lectured that with 20% of the time, decision makers can have up to 80% of the information needed to make an educated decision with respect to any particular project. Construction project managers live in an environment of constant dynamics where time is a valuable commodity and decisions must be taken without less than 100% of the required information. With this in mind, Mitropoulos and others attempt to describe the factors that influence the decision-making process necessary for the adaptation of technological innovations in the construction industry.

"Advances in technology are widely regarded as major sources of improvement in the competitive position of firms and industries and major factors for increased national economic growth and standards of living (Ansoff 1965; Andrews 1971; Rosenberg 1982; Porter 1985; Alder 1989). However, the benefits from technological advances depend on the extent to which these technologies are utilized" [Mitropoulos et al. 1999].

"Our understanding of how managers in construction organizations make decisions to adopt new technologies is very limited. Several important questions remain. How does the need for technological change emerge? How do managers select and justify new technologies? Is innovation driven by company goals, powerful internal or external organizational actors, or does it happen only when some organizational and environmental conditions simply allow it? And how do the managers deal with the uncertainties involved in the adoption of a new technology" [Mitropoulos et al. 1999]?

"Innovation is defined as an idea, practice, or material artifact perceived to be new by the adopting organization (Zaltman et al. 1973). A decision-making process is a set of actions that begins with a stimulus for action and ends with the specific commitment to action (Mintzberg et al. 1976)" [Mitropoulos et al. 1999].

“Contractors historically have emphasized the ability to manage labor and subcontractors as the key element in competitive pricing. However, key changes in the industry are forcing a shift in the basis of competition from managerial to technological issues (Tatum 1988a). These changes include the increased technical complexity of facilities, competitive pressures to owners who demand “more construction for the money” (Business 1982), and increased international competition” [Mitropoulos et al. 1999].

“Construction researchers have investigated the barriers (Paulson et al. 1977; Paulson and Fondahl 1980), the processes, and the conditions for technological innovation (Tatum 1986a; Tatum and Funke 1988; Nam and Tatum 1989, 1992) but have not examined the decision-making process” [Mitropoulos et al. 1999].

Studies have shown that managers make decisions based on one of four perspectives: rational, behavioral, political and temporal. “These perspectives are based on different assumptions about organizations and provide different explanations about how managers make decisions” [Mitropoulos et al. 1999].

“The rational model of choice is based on the fundamental assumption that human behavior is driven by some purpose. According to this model, actors enter a decision situation with known objectives. These objectives determine the value of the possible consequences of an action. The actors gather relevant information, develop a set of alternative actions, select the optimal alternative, and implement the solution” [Mitropoulos et al. 1999].

“The behavioral (or bounded rationality) theory of decision-making emphasizes the differences between the rational theory and the actual decision-making behavior of managers (March and Simon 1958; Cyert and March 1963; March and Olsen 1976)” [Mitropoulos et al. 1999].

"The temporal model describes decision-making in highly ambiguous settings called "organized anarchies" (Chohen et al. 1972; March and Olsen 1976). These organizations are characterized by three main attributes: unclear objectives, unclear understanding of the ends-means relationship, and fluid participation (decision participants come and go from the decision-making process)" [Mitropoulos et al. 1999].

"The political perspective views organizations as political coalitions where decisions are influenced by the power of the actors (March 1962; Pfeffer 1981). Organizational actors may acquire power because they have decision authority, because other actors depend on them for resources (Pfeffer 1981), or because they can cope with uncertainty (Cyert and March 1963; Thompson 1967). The basic assumption of this perspective is that organizations are coalitions of people with conflicting interests. The decision-making process is one of negotiations and conflict resolution, and decisions reflect the preferences of the most powerful people (March 1962; Salancik and Pfeffer 1974)" [Mitropoulos et al. 1999].

It is evident that technological innovations not only have to cope with the barriers described in previous chapters but also once they have been developed, one last hurdle must be conquered before an innovation may ever be implemented. With so many different perspectives and views influencing the mind of the project manager, it is remarkable that any innovation has ever seen the light of day.

Chapter 6 - Conclusions

This study has covered some background of how the construction industry has evolved both in the United States (along with Europe) and Japan during the last few decades, following two very distinct approaches to technological innovation. It is fair to say that in the United States, the industry has focused more on solutions to short-term problems and has mainly utilized the managerial approach. This means that solutions are found in terms of better managing the existing resources to increase productivity and reduce overall project costs. Workforce motivation is kept under close scrutiny to control labor productivity and quality.

In Japan, technological innovations focus more on methods and alternative structural systems. This type of innovation requires much more time and money to yield appreciable positive results. This type of innovative technologies may only be pursued in an environment in which the commitment to long-term, capital intensive R&D is a top priority. It is not clear which of the two approaches is better since they are tailored to two very distinct markets. What is evident is that there are some innovative technologies, particularly in the realm of building construction systems (e.g. SMART, T-Up, ABCS, etc.) that are almost uniquely Japanese.

According to the research, the construction industry in all geographical areas is very fragmented, making it rather unprofitable to pursue long-term R&D projects. In Japan, this situation is mitigated by the large contributions of the national government and top-notch universities. Perhaps, this is one important aspect to keep in mind if one wishes to further develop the construction industry here in the United States.

“Historically, profit margins in the construction industry have been known to be large. Large to the point that productivity was assumed to be whatever the trades people were willing to provide. The tight bidding market that developed in the early 1990’s has created a need to control costs even more. Globalization has played a critical role in the way we view construction these days. Japanese and other foreign construction firms have started to do business in American soil bringing even more competition to an ever-shrinking world, economically speaking that is. Globalization opens the door to opportunity – either lost or found" [Webster, 1994].

At the heart of China's impressive economic development since 1978, we find an enormous construction industry. According to Ahmad in "An Overview of the Construction Industry in China," "today, the whole of China could be described as one large construction site." With an impressive average annual growth rate of 10% since 1979, China's construction industry employs more than 24 million people and has an annual output of over 90 billion dollars. This is more than 5% of the country's total labor force and more than 6% of the GDP. With numbers rivaling those of developed countries, it is clear that China's construction industry has a very strong potential for the future [Ahmad, 2001].

"In contrast to the U.S. and Japan's construction industry, China's growth has spurred from the successful introduction of reforms to attract foreign investment. In fact these reforms led to a record $43.2 billion in 1994, which translates to an annual increase of 28.1% from 1986 to 1994. There are also no private contractors in China. Instead, there are three distinct construction categories, namely, state owned enterprises, urban and rural collectives, and rural construction teams. State owned enterprises used to have the largest share of the industry and have done most of the work in China's infrastructure projects. Some notable progress has been made in an effort to reform these state owned enterprises in terms of commercial behavior, operational autonomy and competitive bidding. However, they still employ an excessive labor force, use traditional technology and do not have a well-structured management [Ahmad, 2001].

We have seen how innovations flourish in strong financial markets like post WWII Japan and Israel during the 1990's due to immigration influx after the collapse of the Soviet Union. If technological innovation in construction favors this type of economic environment, what can we predict is likely to happen in China? Will this be the new crib for new technological innovations both in the methods and managerial branches of the industry? If the literature covered in this investigation can be used as a guide, it appears that the economic boom in China's construction industry is likely to pose new challenges and situations that will require the development of many technological innovations of the type that we have seen both in Japan and the United States in the last 50 years.

Resources

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