Designing urban deep basements in South East England for future ground movement: Progress and opportunities for experimental simulation of long-term heave

Deryck Y.K. Chan
University of Cambridge, U.K.

Prof. Gopal S.P. Madabhushi
University of Cambridge, U.K.

Abstract (max 500 words)

In recent years, there has been a boom in urban infrastructure projects in and around London that require deep basements to be excavated, such as underground railway stations and shopping malls. The permanent removal of topsoil due to basement construction inevitably causes upward movement of the remaining soil. In London clay and other over-consolidated clay strata, this upward movement continues over many years after the basement structure's completion, a process known as long-term heave.

Urbanisation causes more and more of such deep basements to be constructed to greater depths and sizes than before. This has renewed interest in research on the long-term behaviour of base slabs in over-consolidated clay, because the basement structure must be designed to accommodate these long-term heave movements. The drive towards green construction techniques in next-generation infrastructure will require the methods of design need to be updated to allow more efficient use of material.

This paper reviews a range of current techniques used in the design of deep basement slabs where significant long-term heave deformations are expected. While current design guidance is sufficient in ensuring the safety of construction and operation of underground urban spaces, there is a strong feeling within the construction industry that the design criteria are inefficient and need to be improved with the help of experimental data.

Geotechnical centrifuge simulation is the main technique for physical modelling of long-term heave behaviour, as artificial gravity allows a year of real-life movements of soil to be replicated in a small-scale model in an hour of laboratory time. This paper reviews recent research in geotechnical centrifuge simulations on heave behaviour of deep excavations in over-consolidated clay, identifying key findings and pointing out areas that will require further research. These experimental simulations will allow the effect of long-term heave to be quantified more accurately in future design guidance, thereby addressing the need to conserve construction material as the requirement for urban underground space increases.

Key Words

underground construction, deep basement, heave, London clay, experimental modelling, geotechnical centrifuge

Demand for urban underground space

Urbanisation is a growing worldwide phenomenon. The United Nations estimated that the global urban population surpassed 50% of total population in year 2008 and the proportion of city-dwellers is projected to rise to 61% by year 2030. This social change puts significant pressure upon infrastructure planners and the emerging consensus is that cities ought to remain compact.[1] In practice, urban infrastructure of the next generation will require the creation of new subterranean caverns among existing buildings and utilities, to provide space for railway stations, shopping malls, and other public spaces.[2]

The development of urban underground space is an interdisciplinary problem as it involves both the social aspects of land use allocation and the technical aspects of architectural design and geotechnical engineering. Industry bodies such as the Associated Research Centers for the Urban Underground Space (ACUUS) and the International Tunnelling and Underground Space Association (ITA) have striven in recent decades to bring together professionals from different disciplines involved in the design and utilisation of underground space and tackle interface challenges.[3]

Recent ITA activities have identified a list of threats to the sustainability of urban underground space, most of which are social and political issues, but there are also two issues on the list that are fundamentally engineering problems that require engineering solutions. First, an underground structure affects ground conditions in its vicinity through changes in soil pressure, groundwater conditions, and temperature, creating an exclusion zone that limits future use of nearby space. Second, basements and tunnels are typically constructed using materials like steel and concrete that have a large ecological footprint, so their sustainability depends on efficient geotechnical design to save material.[1] These challenges are universal, but their solutions vary internationally because of climatic and geological conditions.

South East England is a prime example of this global demand for urban underground space. Recent infrastructure projects such as Crossrail have created deep excavations among existing structures and the demand for deep basements will continue with forthcoming projects such as HS2. However, deep excavations in London and surrounding areas pose an additional challenge because of the over-consolidated clay strata underlying this region, such as London clay, have a tendency to heave slowly over many years after structural completion. This paper will discuss the complexities caused by this phenomenon, review existing design methods, and advocate the use of geotechnical centrifuge simulations as a means to predict heave movements and to develop effective mitigation measures.

---

[1] Sterling, R. *et al.* Sustainability issues for underground space in urban areas. *Proceedings of the Institution of Civil Engineers - Urban Design and Planning* **165,** 241–254 (2012).

[2] ICE. *Growing cities and building resilience*. (Institution of Civil Engineers, 2016).

[3] Besner, J. Underground space needs an interdisciplinary approach. *Tunnelling and Underground Space Technology* **55,** 224–228 (2016).

Origin of long-term heave

The creation of underground space inevitably leads to some movement of the surrounding soil because the process of excavation relieves in-situ stresses. In the case of deep basement construction, significant relief of both horizontal and vertical stresses occur, with different effects upon the surrounding soil. The relief of horizontal stresses causes inward movement of soil towards the excavation and leads to surface settlement around the excavation. These movements generally occur during the time-span of construction and are controlled by providing adequate lateral excavation support.[4]

The relief of vertical stresses, on the other hand, is caused by the permanent removal of soil above formation level due to the need to create underground space. This causes a relaxation of average effective stress of the soil beneath the basement, allowing the soil to swell. Such swelling movements are inevitable as long as there is net vertical unloading; its magnitude depends on both the stress history of the soil and the basement's geometry.[5] (Figure 1)

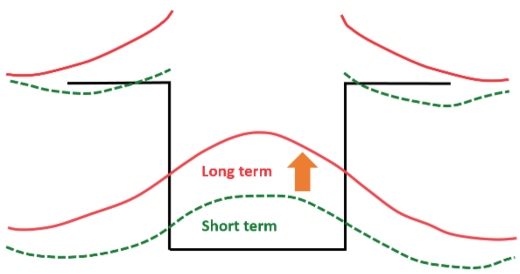

Figure 1: Exaggerated illustration of short-term and long-term heave movements, after Burland et al[4]

In many geological units, these upward movements happen before the structure is complete, allowing the application of corrective measures in later stages of construction. However, in stiff clays such as London clay, the low permeability of the soil means that negative excess pore pressure develops during construction and dissipates slowly to cause swelling (primary consolidation); creep movements may take even longer to approach completion (secondary consolidation). This process of swelling continues well beyond the period of construction. This behaviour is known as "long-term heave"[6] or "time-dependent heave".[7] For example, a basement structure in Horseferry Road, London recorded upward movement 21 years after structural completion which could be attributed to the dissipation of suction pressures generated during construction. Engineers must predict and design the substructure to withstand the pressure or accommodate the movements, many years before the anticipated critical conditions actually occur. This has led to much conservatism in existing designs of base slabs in over-consolidated clay.

Current design practices

As a fail-safe estimate, some structural engineers assume that the full overburden pressure of the excavated soil would manifest itself as heave pressure upon the base slab in the long term. Some structural solutions, particularly those of open shafts in tunnelling projects, carry the entire heave load by building

---

[4] Burland, J. B., Simpson, B. & St John, H. D. Movements around excavations in London clay. *Design parameters in geotechnical engineering. Proc. 7th European conference on soil mechanics and foundation engineering, Brighton, 1979. Vol. 1, (British Geotechnical Society; distributed by T. Telford, London)* 13–29 (1979).

[5] McNamara, A. M. Influence of heave reducing piles on ground movements around excavations, 8–10. (City University, 2001).

[6] Cheney, J. E. 25 years heave of a building constructed on clay, after tree removal. *Ground Engineering* **21,** (1988).

[7] O'Brien, A. S., Sharp, P. & MacDonald, M. Settlement and heave of overconsolidated clays - A simplified non-linear method of calculation. *Ground Engineering* **34,** 28–32 (2001).

an inverted arch shell at formation level.[8] However, most public underground spaces are rectangular with a flat base slab for architectural and buildability reasons, so each bay of the slab will hog in response to load and this upward movement in turn relaxes the heave pressure. Hence, the full-overburden estimation, while being safe, is grossly conservative for most purposes, causing many existing basements to have very thick and heavily reinforced concrete basement slabs.

The most basic approach to account for the relaxation of heave pressure with deformation is by ascribing a linear-elastic stiffness to the soil. This generally involves treating the substrate soil as a bed of springs or an elastic continuum, with representative values of linear-elastic stiffness. For simple structural and load geometries, Hemsley[9] presented analytical solutions that can either be used directly in design, or as building blocks of finite-element models. In Hemsley's recommendations, interactions within the soil are precomputed into a matrix of interactions on the soil-structure surface using the surface element method. Non-linear soil stiffness can be built into finite element calculations using iterative methods. Similarly, heave can be introduced into the model iteratively as an upward load.

The ICE Manual of Geotechnical Engineering on rafts and piled rafts[10] recognises the limitations of Hemsley's simplification of soil behaviour into a bed of springs or an elastic continuum and highlights differences between the two. Nevertheless, the manual recommends Hemsley's methods for simplified soil-structure analyses and provides procedures for using them in design. It recommends an iterative approach that applies springs to the structure to represent the soil and obtain an initial estimate of contact forces, then applies those forces to a soil continuum model to estimate ground movements and adjust the spring stiffness, allowing for variations of spring stiffness along the soil-structure interface. A design is chosen when the spring stiffness converges, as outlined in Figure 2.

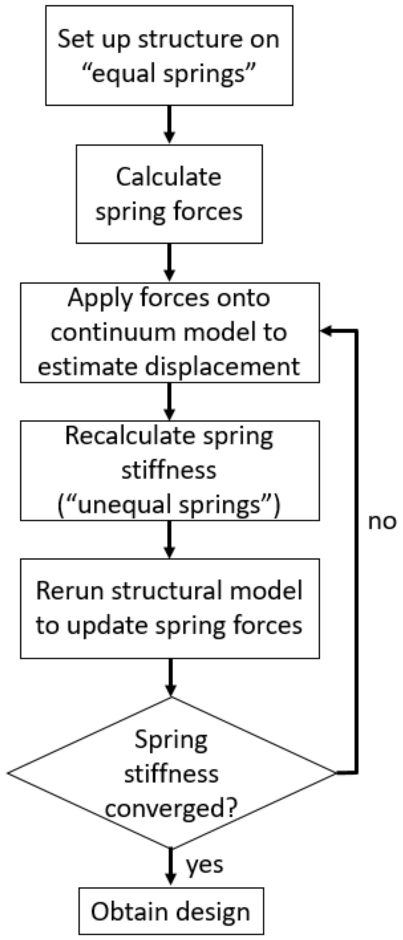

Figure 2: Iterative linear-elastic design flowchart, abridged from ICE Manual of Geotechnical Engineering, Ch. 56 [10]

In reality, all soils exhibit non-linear stress-strain behaviour, though the error introduced by the use of a linear approximation is acceptably small for many types of soil and secant stiffness values are used in these cases. However, over-consolidated clays exhibit highly non-linear stress-strain behaviour; furthermore, the stiffness values in loading and unloading differ substantially. This causes a wide range of "linear-elastic" moduli to be reported in technical literature even for similar types of clay, and the errors introduced by assuming linear-elasticity are so large that the same

[8] Schwamb, T., Elshafie, M. Z. E. B., Soga, K. & Mair, R. J. Considerations for monitoring of deep circular excavations. *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering* **169,** 477–493 (2016).

[9] Hemsley, J. A. *Elastic Analysis of Raft Foundations*. (Thomas Telford, 1998).

[10] O'Brien, A. S., Burland, J. B. & Chapman, T. Chapter 56 Rafts and piled rafts. in *ICE manual of geotechnical engineering* 853–886 (Thomas Telford Ltd, 2012).

assumed stiffness generally cannot predict both the total heave of a basement and the surface settlement around the basement accurately.[7]

O'Brien et al[7] thus proposed the "simplified non-linear method" for calculating settlement and heave for design purposes. This method allows the incorporation of nonlinearity in soil behaviour in calculations without resorting to non-linear finite-element analyses which are often complex and time-consuming. Their method divides the design scenario into "undrained settlement/heave" and "total settlement/heave" cases, and divides the over-consolidated clay stratum into multiple arbitrary layers. The stiffness parameters of each layer are given approximate secant values but allowed to vary independently from each other and are different between the "undrained" and "total" cases. Given a set of applied loads, the strains of each clay stratum are calculated and the stiffness parameters of that stratum are adjusted using the relevant non-linear soil behaviour model. The calculations are iterated until the stiffness parameters converge and the magnitude of time-dependent heave or settlement is then calculated as the difference between the undrained displacement and the total displacement. This process is outlined in Figure 3.

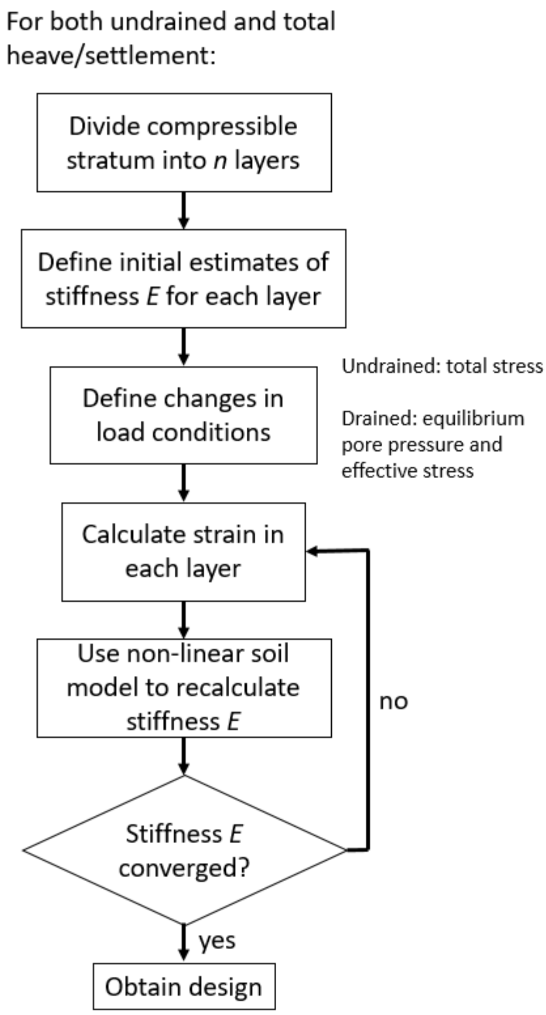

Figure 3: Simplified non-linear method, abridged from O'Brien et al[7]

The simplified non-linear method can be implemented into a base slab heave analysis, either as a constituent soil model of a numerical simulation, or as an approximate analytical method of design. One such analytical method is the "relaxation ratio" method. This method has gained much currency in the last few years among design procedures for deep basements in the parts of South East England where significant long-term heave deformations are anticipated. A simplified description of the procedures is as follows:[11] (Figure 4)

1. Using an appropriate soil behaviour model, plot a curve of heave displacement versus "relaxation ratio". The relaxation ratio is the proportion of original soil overburden pressure that will remain after construction, which by the principle of equilibrium will be equal to heave pressure.

2. Select discrete, salient locations on the base slab. For each location, plot a curve of structural displacement versus the magnitude of a uniform heave pressure applied upon the slab. This creates a family of curves.

[11] Courtesy to Yu Sheng Hsu of Mott MacDonald for providing the details about this method.

3. The intersection between the soil curve and the curve for each structural location provides an estimate of the heave displacement and pressure at that point.

4. If necessary, re-plot the structural displacement curves using the estimated profile of heave pressures obtained from the previous step. Iterate until results converge.

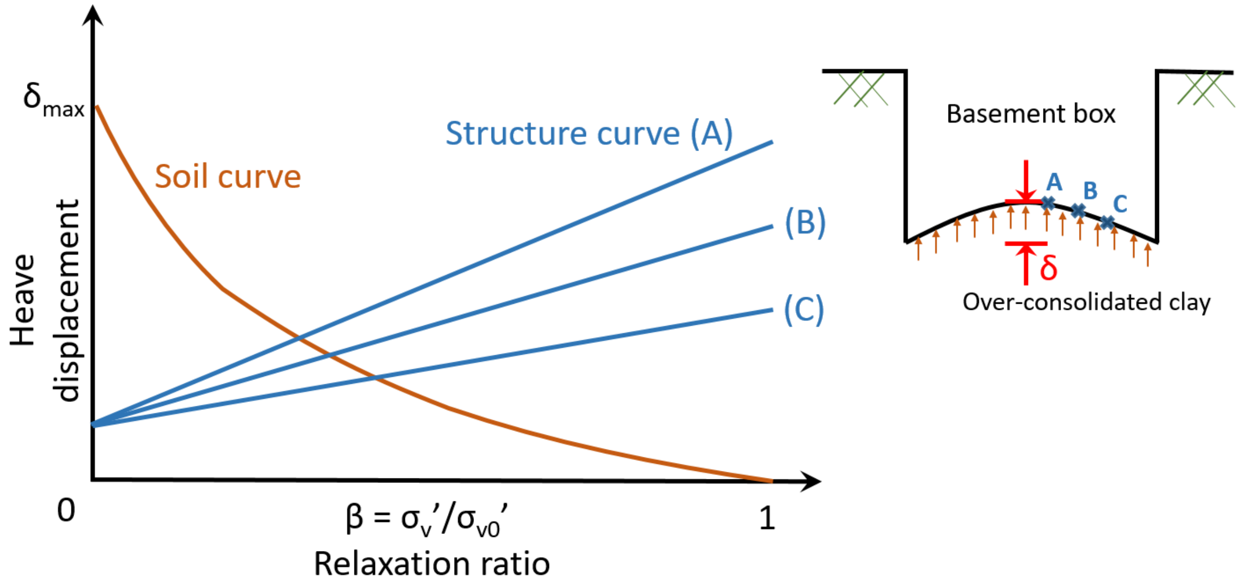

Figure 4: Illustration of relaxation ratio method

Although this method does not account for end effects, it is a quick solution that provides realistic estimates of heave pressure and displacement, so it is often used in recent designs of deep basement slabs in over-consolidated clay.

Where accurate predictions of heave displacement and pressure are required, advanced finite-element analyses are undertaken. This typically involves a consolidation analysis with a small-strain hardening soil model as the constitutive model of the over-consolidated clay.

Verification of model

Regardless of method, a design prediction is only ever as good as the underlying model and input parameters, which need to be verified and calibrated with data. Instrumentation of real-life excavations would be the best source of such data, as the predicted heave pressures and deformations can be cross-checked against actual values. In order to discern long-term heave behaviour, site monitoring would need to continue beyond practical completion. This section will present three case studies in South East England where such long-term monitoring data are available.

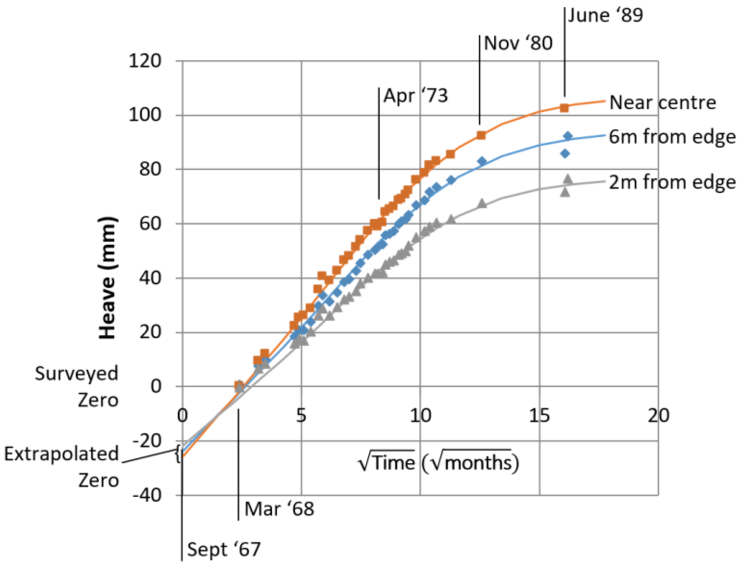

Figure 5: Heave measurements of three points on the base slab of the Horseferry Road site

A 10m-deep basement was built on Horseferry Road, London in 1966-67. The accompanying superstructure was never built due to a change of plan and engineers monitored the heave movements of the basement slab for 21 years until the site was redeveloped in 1989. The data showed that the evolution of heave agreed closely with predictions using one-dimensional consolidation theory. The findings from this site are widely used in industry for designs of deep basements in London until today.[12] (Figure 5)

A new 20-m deep underground vault was built in the British Library campus on Euston Road, London in 1984-86. Monitoring of movements in and around the site continued until 1992 and the data were published in 2014.[13] (Figure 6) The dataset is extensive but the British Library vault has complicated geometry and spans multiple geological units, making it a good test for models of ground movement but relatively unhelpful as a source dataset for the development of such models.

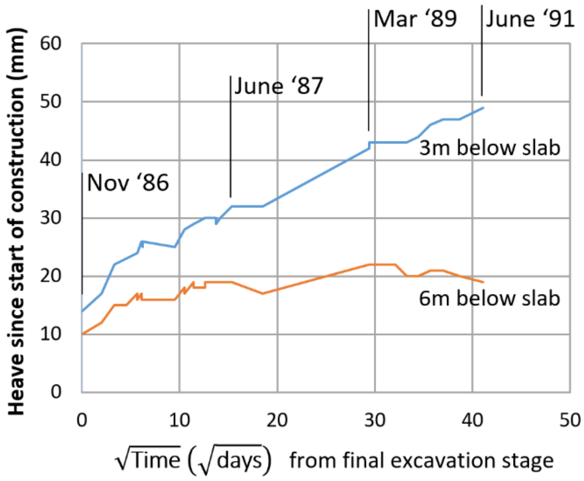

Figure 6: Extensometer data from the deepest part of the British Library vault

In 1989-90, a 10m-deep underground car park was built in Lion Yard, Cambridge to provide parking space as part of a shopping precinct renovation project. This car park is now known as Grand Arcade car park while the northern portion of the precinct continues to carry the Lion Yard name. The construction site was extensively monitored, partly to assist construction work and partly because its location in uniform Gault clay provided a valuable research opportunity. Monitoring continued until 1992 and the data and analysis were published in subsequent years. The primary research aim of the site monitoring was to investigate the soil-structure interaction associated with the retaining wall, thus there were relatively few instruments to measure heave deformations. However, Lion Yard was a rarity in heave monitoring in that there were records of both pore pressure and displacement beneath the base slab. Ng[14] analysed the data and proposed a "two-phase" understanding

---

[12] Courtesy to Sergio Solera of Mott MacDonald for providing information about this site. Data from 1975 and before were published in: May, J. Heave on a deep basement in the London clay. *Settlement Structures* (1975).

[13] Simpson, B. & Vardanega, P. J. Results of monitoring at the British library excavation. *Proc. Inst. Civ. Eng. Geotech. Eng.* **167,** 99–116 (2014).

[14] Ng, C. W. W. Observed Performance of Multipropped Excavation in Stiff Clay. *Journal of Geotechnical and Geoenvironmental Engineering* **124,** 889–905 (1998).

of stiff clay, whereby pore pressures along fissures react quickly to changes in applied load, and then soil lumps absorb water and swell over a much longer time-scale. This finding may have influenced later designers' separation of undrained heave and total heave in calculations.

These three case studies represent some of the most extensively monitored cases of long-term heave in South East England in the last few decades. In general, monitoring data is only available for a tiny proportion of construction sites because most clients are averse to their buildings' being used as living laboratories and it is expensive to monitor a site for many years after construction. Furthermore, complications with each underground structure's local geological conditions and bespoke structural layout means that monitoring data from each site are only useful as spot checks of the design assumptions of that particular site. There is a need for physical simulations to complement site data and shed light on the general trends and mechanisms involved in soil-structure interaction scenarios. One such method of physical simulation is geotechnical centrifuge modelling.

Experimental simulation using geotechnical centrifuge

Geotechnical centrifuge modelling is a form of scale modelling. It allows the behaviour of a large prototype to be simulated using a small-scale model. Geotechnical centrifuges achieve dimensional similarity by testing a *1/N* scale model at *N* times Earth's gravity so that the self-weight stresses at a given location in the model will be the same as the equivalent location of the prototype. Centrifuge models help with geotechnical design by providing realistic simulations of soil and structure behaviour where the soil conditions are difficult, the anticipated loads are unusual, or there is uncertainty about the constitutive models.[15]

Table 1 shows the advantages of centrifuge testing with respect to the simulation of long-term heave: a centrifuge model at *N* times Earth's gravity is able to simulate the behaviour of a prototype that is *N* times as big as a model over a timescale of N^2 times the duration of the simulation. At 100*g*, the scale model only takes an hour to replicate a year of prototype heave deformation. This is appropriate for the investigation of long-term heave in over-consolidated clay because the time it takes for a real-life basement to heave is usually in the order of years.

Centrifuge modelling was used extensively in the last two decades to investigate the related phenomenon of soil-structure interaction in tunnelling. In both tunnel and basement excavations, a major risk is the movement of existing structures in response to a new excavation. Engineers want to understand and make accurate, quantitative predictions of this interaction, to minimise the extent of exclusion zones around existing infrastructure. Dozens of researchers have worked together over the last few decades to produce a database of field measurements, centrifuge models, and computational simulations on how the stiffness of a vulnerable structure affects its settlement and damage when a tunnel is constructed in its vicinity. This culminated in a non-dimensionalised design chart which relates the stiffness of a building to the settlement

[15] Madabhushi, G. *Centrifuge Modelling for Civil Engineers*. (CRC Press, 2014).

that it will experience as a result of the new tunnel. Since its publication, the chart has been used widely to assess the safety of existing buildings in the design of proposed tunnel excavations.[16]

Parameter	Model scale	**Prototype scale** (prototype/model)
Gravity - g (ms^{-2})	N	1
Length - L (m)	1	N
Volume - V (m^3)	1	N^3
Force - F (N = $kgms^{-2}$)	1	N^2
Density - ρ (kgm^{-3})	1	1
Stress - σ (Pa = Nm^{-2})	1	1
Strain - ε (dimensionless)	1	1
Axial stiffness - EA (N)	1	N^2
Bending stiffness - EI (Nm^2)	1	N^4
Time - t (s)	1	N^2

Table 1: Selected geotechnical centrifuge scaling laws

A similar approach is being taken to study long-term heave of deep basements and researchers from various continents have reported centrifuge tests on swelling and heave of over-consolidated clays. Zornberg et al[17] performed centrifuge permeameter tests on Eagle Ford clay, an expansive clay from Texas, to measure its swelling behaviour. They compared the results of tests at *1g* (Earth's gravity) with tests in the centrifuge (*N g*) and concluded that the swelling characteristics of expansive clays behave as expected in elevated gravity.

The experiments by Zornberg et al used a natural expansive clay but did not include any structural model. In contrast, among the few centrifuge simulations of heave in stiff clay, most focused on methods to mitigate heave due to deep excavations rather than to stimulate heave and quantify it. Ohishi et al[18] performed centrifuge experiments to investigate the effect of ground improvement on heave movements of a deep braced excavation. Their study involved Isogo clay, a stiff clay stratum found near Tokyo, and the experimenters locally strengthened the clay beneath the base slab of the excavation with cement and fly ash. The ground improvement had unsurprisingly led to significant reductions in heave movements upon excavation. McNamara[5] studied the effect of piles as a means of stiffening the ground to reduce heave deformations in over-consolidated clays and found that the piles acted both in tension to resist upward heave movements and in bending to resist the horizontal movement of soil.

McNamara recommended that further research be done on the effect of other structural variations on heave deformations, but recent centrifuge model studies on deep excavations in clay generally focused on settlements around the excavation or means of stiffening the ground beneath the base slab. Simulations of the effect of the basement structure's stiffness on heave deformations are still noticeably rare.

---

[16] Mair, R. J. Tunnelling in urban areas and effects on infrastructure – advances in research and practice. in Muir Wood Lecture (2011).

[17] Zornberg, J. G., Kuhn, J. A. & Plaisted, M. D. *Characterization of the Swelling Properties of Highly Plastic Clays Using Centrifuge Technology*. (University of Texas at Austin, 2008).

[18] Ohishi, K., Azuma, K., Katagiri, M. & Saitoh, K. Deformation behaviour and heaving analysis of deep excavation. in *Geotechnical Aspects of Underground Construction in Soft Ground,* (2000).

A centrifuge modelling study is currently underway at Cambridge University to fill this research gap. A rectangular basement corresponding to a prototype depth of 15m is underlain by 15m of over-consolidated clay with a high swell capacity. The basement is initially filled with a fluid of the same density as the surrounding soil. The fluid is drained to empty out the basement, to simulate excavation of soil. This reduces the vertical stress on the clay beneath the basement, causing it to swell. Instrumentation on the basement records the development of heave movement of the basement with time and transducers in the clay record the changes in pore pressure. (Figure 7) The structural configuration and stiffness are varied between tests, so the mechanism of soil-structure interaction can be better understood.

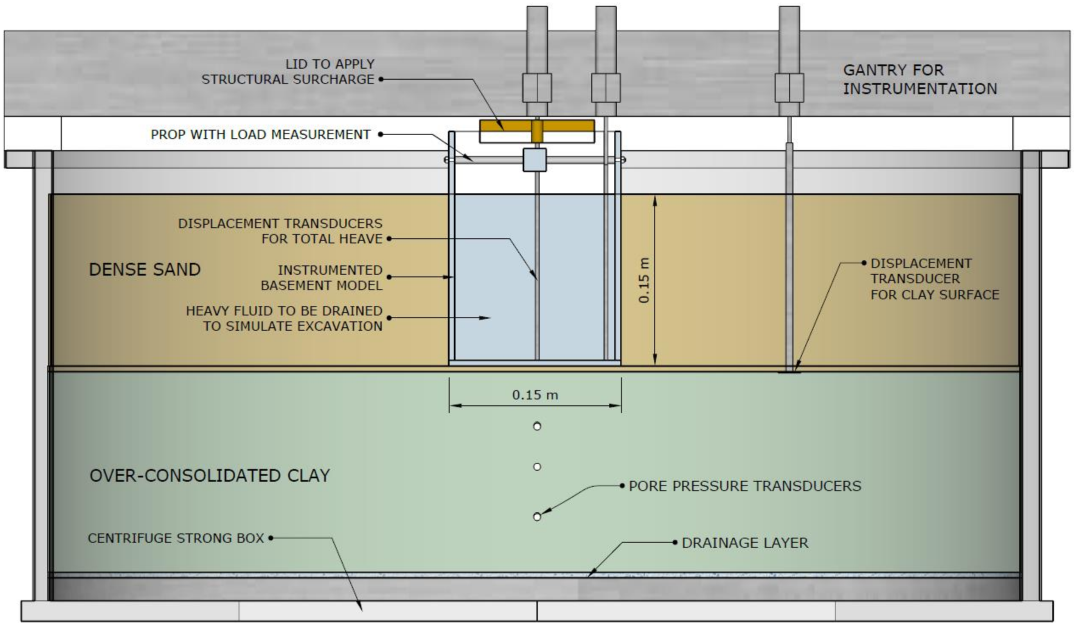

Figure 7: Cross-section drawing of centrifuge model to investigate soil-structure interaction in long-term heave

An improved understanding of the mechanisms of long-term heave will provide increased confidence in design predictions of post-construction movement. This will allow leaner designs to be used in deep basement construction in over-consolidated clay strata and precious underground space to be utilised more efficiently. While the research described in this paper has London and the South East of England in mind, advances in this field will be applicable to any city around the world with similar geotechnical challenges. This will help to address the sustainability issues in the exploitation of underground space as urbanisation continues globally over the forthcoming decades.

Acknowledgements

The authors would like to thank Yu Sheng Hsu, Hock Liong Liew, and Sergio Solera of Mott MacDonald; and Wilson Kesse, Adam Locke, and Corin Walford of Laing O'Rourke for their provision of past site data and information about current design practices.

This research project is supported by the EPSRC Centre for Doctoral Training in Future Infrastructure and Built Environment in the University of Cambridge.