

Experimental study of structural movements and swelling pressures on deep basements caused by long-term heave in over-consolidated clay

Etude expérimentale des mouvements structurels et des actions de gonflement sur les sous-sols profonds, dus au soulèvement long-terme des sols argileux surconsolidés

D.Y.K. Chan (corresponding author), S.P.G. Madabhushi
University of Cambridge, UK

Y.S. Hsu, A.S. O'Brien, S.A. Solera, M.G. Williamson
Mott MacDonald, UK

ABSTRACT: Urban growth has necessitated the construction of many large, deep basements in city centres. In many places, most notably London and South East England, these basements are founded upon stiff, over-consolidated clay strata. These clays exhibit long-term heave over many years after the construction of the basement structure, producing additional heave-induced soil stresses and movements. However, scarcity of site monitoring data has led to much conservatism in the design of basements subjected to long-term heave loading.

This paper presents the results of a series of geotechnical centrifuge tests, which model the three-dimensional heave behaviour of a rectangular deep basement structure underlain by over-consolidated clay. The tests are carried out at a centrifuge acceleration of 100 times Earth's gravity. A heavy fluid of the same density as the soil is drained from the basement cavity, to model the excavation process in the field. An actuator subsequently applies a vertical load on the structure's walls to simulate the construction of an over-site development.

The model structure is instrumented to monitor the evolution of vertical displacement at various points on the base slab, structural bending strains in the basement slab and in the walls, and the contact pressures between the structure and the soil. The results show good agreement with monitoring data from a site in London where a basement slab was allowed to heave without any building on top for over 20 years. These findings aim to provide guidance on heave magnitude for future construction projects.

RÉSUMÉ: La croissance urbaine a nécessité la construction de plusieurs sous-sols larges et profonds dans les centres villes, pour subvenir à la demande d'espace souterrain. Notamment à Londres et dans le Sud-Est de l'Angleterre, ces sous-sols sont souvent bâtis sur une strate d'argile raide et surconsolidée. Après un déchargement dû aux travaux d'excavation du sol, ces argiles démontrent un gonflement long-terme qui dure plusieurs années après la construction de la structure souterraine, mais qui produisent aussi un soulèvement additionnel induit par la contrainte effective de la terre dont les ingénieurs doivent tenir compte. Cependant, le manque de données de campagnes d'essais géotechniques a donné lieu à beaucoup de conservatisme dans la conception des sous-sols qui pourraient être sujets à un soulèvement du sol long-terme.

Les résultats présentés dans cet article proviennent d'une série de tests dans des centrifuges géotechniques qui représentent ce soulèvement en trois-dimensions, avec un modèle d'un sous-sol profond et rectangulaire reposant sur de l'argile surconsolidé. Les tests ont été effectués dans un centrifuge avec une accélération de 100 fois la

gravité de la Terre. Le déchargement du sol argileux dû à une excavation d'un sous-sol fut représenté par le drainage d'un liquide lourd, de la même densité que la terre, à travers un trou dans le sous-sol. Un actuateur fut ensuite appliqué comme charge verticale contre les murs de la structure pour simuler la construction du développement au-dessus du site.

L'instrumentation du modèle visa à mesurer le déplacement vertical à plusieurs endroits sur la dalle de base, ainsi que les déformations structurelles dues à la flexion sur la dalle et les murs. Les pressions de contact entre la structure et le sol argileux furent aussi mesurées pour une période de 4 ans après l'excavation. Les résultats sont comparés contre les données d'une campagne d'essai à Londres, où une dalle de base a subi un soulèvement pendant plus de vingt ans, sans construction dessus, et dont l'ampleur du soulèvement a été mesurée pour guider de futurs projets de construction.

Keywords: centrifuge modelling; deep basement; London Clay; long-term heave; over-consolidated clay

1 INTRODUCTION

As cities expand, it is common to construct basement structures to accommodate urban infrastructure, such as underground railway stations and shopping mall cellars. Constructing such basements requires the removal of soil above formation level, causing relief of total earth pressures. While the relief of horizontal stresses can be controlled by the provision of adequate lateral excavation support, the relief of vertical confining stresses at formation level is generally inevitable. This reduction of confining stress causes the remaining soil to heave into the excavation (Burland et al, 1979).

In many geological units, this heave either occurs within the time-frame of the excavation or is small in magnitude, so they are not detrimental to the finished structure. However, in over-

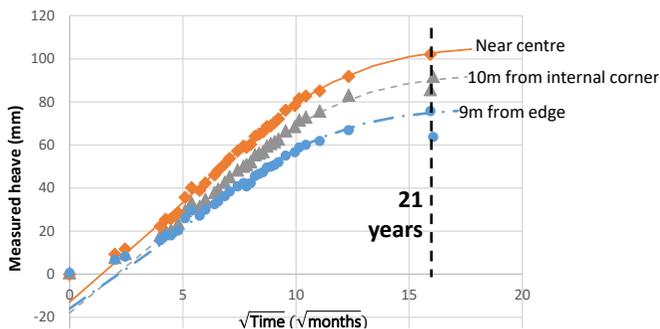


Figure 1: Heave monitoring data from Horseferry Road basement, London

consolidated clay strata, most notably the clays of London and South East England, this heave continues for many years after structural completion due to the low permeability of these clays. This process is known as long-term heave. One notable case study is the Horseferry Road basement in London, where engineers monitored the heave movement of an empty basement for 21 years and showed that the development of heave with time agrees with the swelling aspects of one-dimensional consolidation theory (Figure 1; Chan et al, 2018).

Engineers must predict and accommodate these future changes before constructing the basement. Unfortunately, there is scarce data available to calibrate the predictions. Instances of extensive monitoring like the Horseferry Road basement are the exception rather than the norm. There is thus much conservatism in the design of deep basements in over-consolidated clay, and great desire for further physical data to calibrate the design guidance (Chan & Madabhushi, 2017). Several previous researchers have used geotechnical centrifuge experiments to model the phenomenon of long-term heave, but these experiments generally focused on specific methods of heave mitigation such as tension piles (McNamara & Taylor, 2004) and soil reinforcement (Ohishi et al, 2000).

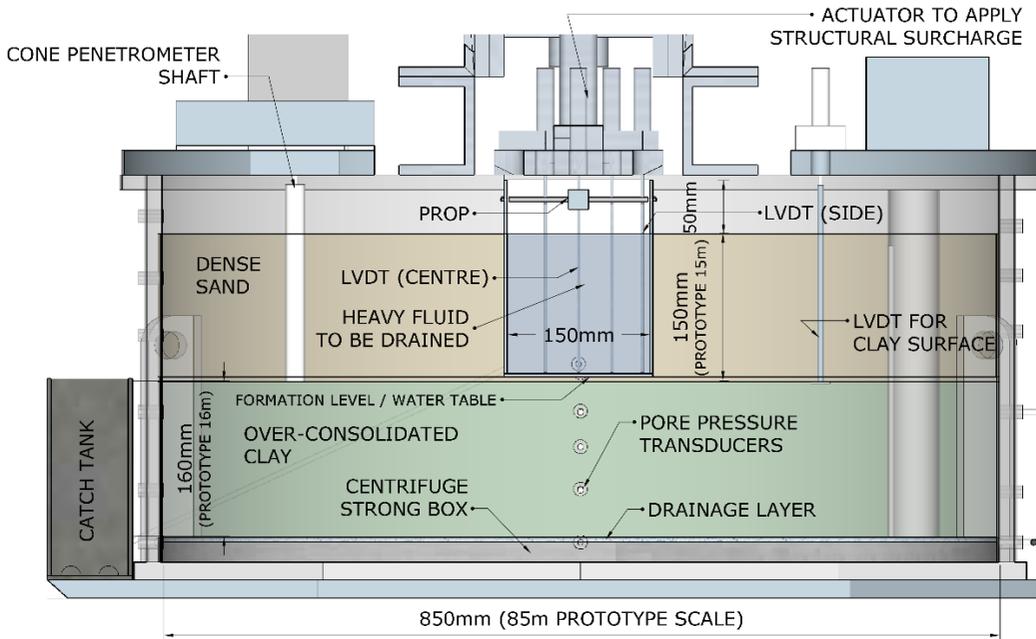


Figure 2: Cross-section of centrifuge model

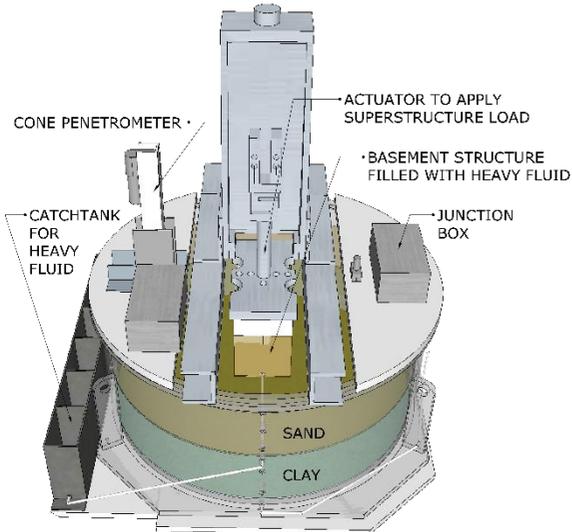


Figure 3: Three-dimensional drawing of centrifuge package



Figure 4: Photograph of centrifuge package loaded onto the Cambridge Geotechnical Beam Centrifuge

In contrast, there has been little investigation of the effects of basement slab stiffness and superstructure loading on long-term heave behaviour. This paper describes an ongoing research project at Schofield Centre, University of Cambridge which addresses this research gap.

2 EXPERIMENTAL SET-UP

The centrifuge package incorporates a metal basement model of footprint 150 mm × 300 mm (prototype 15 m × 30 m) underlain by a layer of over-consolidated Speswhite kaolin 160 mm

thick (prototype 16 m). The basement model is buried 150 mm deep (prototype 15 m) in a bed of dry Hostun sand. A thin layer of sand between the base slab and the clay layer ensures adequate drainage at formation level, reflecting the increasingly common practice of under-slab drainage for basements founded upon stiff clay (Figure 2). The water table is set at the formation level of the basement. Chan & Madabhushi (2018) provides further details about the model preparation process of this centrifuge package.

The basement model is initially filled with a heavy fluid solution (sodium polytungstate) of the same density as the sand around the basement (Table 1). Excavation is simulated by opening a set of valves during centrifuge flight, to drain the heavy fluid by centrifuge gravity from the basement model to a catch-tank. Subsequently, a one-dimensional electrical actuator applies vertical load onto the top of the basement walls, simulating the effect of building a superstructure (Figure 3; Figure 4).

The centrifuge package uses five types of instrumentation to monitor the behaviour of the clay and the basement structure:

- Linear variable differential transformers (LVDTs) measure the vertical displacements of various points on the base slab, the travel

of the actuator, and the settlement of the clay outside the basement;

- Strain gauges measure the change in bending curvature at various points on the wall and the slab of the basement;
- Two 6 mm-diameter aluminium alloy props provide excavation lateral support at ground level and each prop includes a load cell to measure the prop force;
- Pore pressure transducers monitor the progress of clay consolidation and pore pressure response to excavation and construction;
- A Tekscan tactile sensing mat measures the distribution of slab-soil contact pressure at formation level.

3 RESULTS AND DISCUSSION

The remainder of this paper will focus on two centrifuge tests, each involving a flexible basement structure. The main difference between the two tests is that one test simulated the case of a heavy superstructure, whereas the other test simulated a light superstructure. The superstructure weight of the light superstructure test was chosen to match the weight per unit area of the Horseferry Road basement (50 kN/m²).

Table 1: Specifications of centrifuge tests

Test identifier	DYC-03 (heavy superstructure)	DYC-04 (light superstructure)
Swelling index of clay from consolidometer (κ , Schmidt method)	0.0694	0.0720
Clay pre-consolidation stress	800 kPa	800 kPa
Density of dry sand	1617 kg/m ³	1614 kg/m ³
Centrifuge acceleration	100 g	100 g
Basement footprint	150 mm × 300 mm (model) 15 m × 30 m (prototype)	150 mm × 300 mm (model) 15 m × 30 m (prototype)
Basement slab and wall specification	1.22 mm-thick brass plate (Prototype: 300 mm-thick reinforced concrete slab & walls)	1.22 mm-thick brass plate
Superstructure weight	10 kN (model) (prototype: 10-storey building)	2.2 kN (model) (prototype: 2-storey building)

3.1 Vertical movement

Figure 5 shows the evolution of settlement and heave with time through each centrifuge test. In both tests, sufficient time had elapsed following spin-up for consolidation to reach equilibrium before commencing excavation. The basement slab settled more than the far-field clay surface (outside the influence zone of the basement) due to the dead weight of the basement structure. During excavation, both tests recorded short-term

heave of over 100 mm (prototype) at the centre of the base slab.

In both tests, the construction of the superstructure caused the centre of the base slab to settle by about 50 mm in the short term. Both structures continued to heave gradually after superstructure construction and the centrifuge tests continued until equilibrium was re-established. The light superstructure test showed more long-term heave than the heavy superstructure (Figure 6).

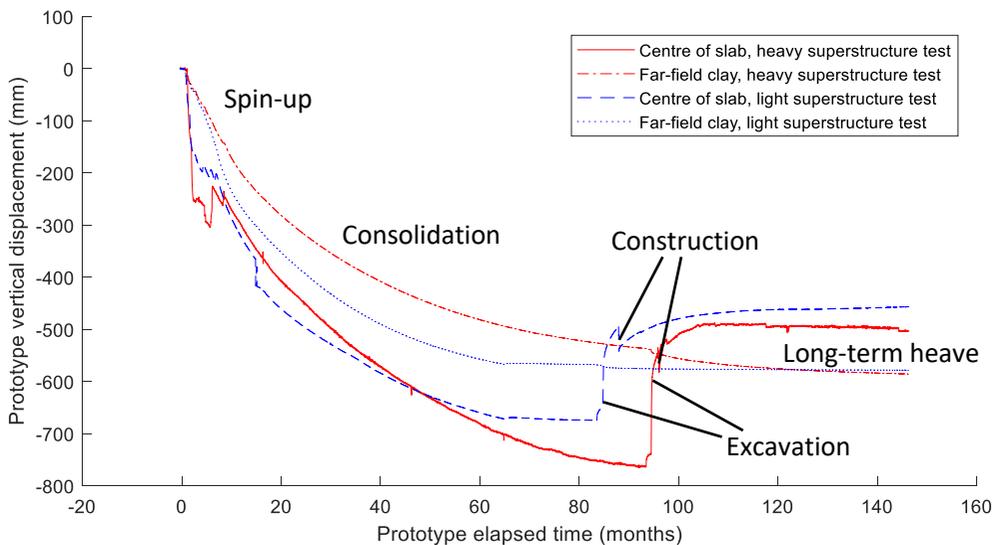


Figure 5: Graph of vertical movement of basement slab and clay surface throughout two centrifuge tests

3.2 Slab-soil contact behaviour

In both centrifuge tests, the sides of the slab showed little movement while the centres of the slab heaved significantly, showing differential heave (Figure 6).

The magnitudes of heave of the two basements were similar, suggesting that long-term heave after construction may be primarily caused by the

re-establishment of vertical effective stress at the slab-soil surface due to consolidation. Furthermore, Figure 7 only shows that the contact pressures of the two tests after superstructure construction only differ by about 20 kPa, or 10% of the difference in superstructure load. It appears that the weight of the superstructure is mainly transmitted through the toes of the structural walls and its effect on the magnitude of long-term differential heave is small.

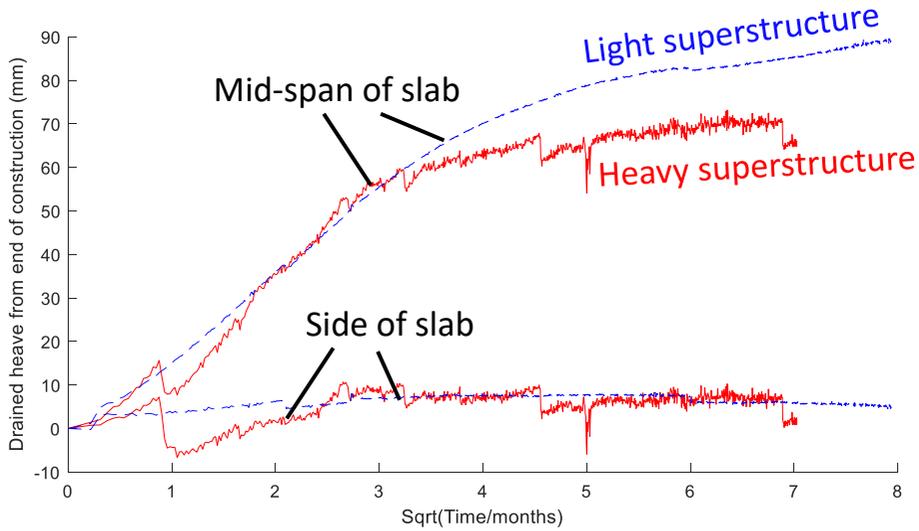


Figure 6: Development of heave displacement after construction in centrifuge tests

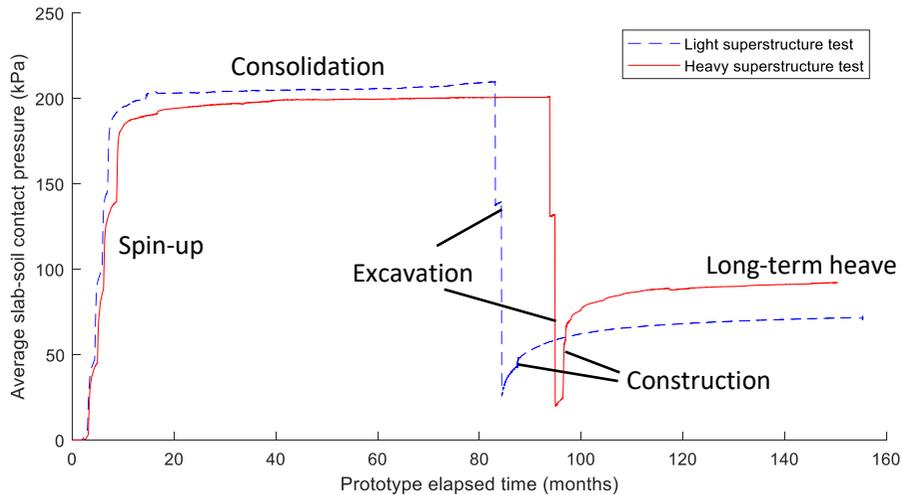


Figure 7: Development of slab-soil contact pressure

3.3 Comparison with site data

Figure 8 compares the results of the light superstructure experiment with heave monitoring data from the Horseferry Road basement. The magnitude of heave of the model basement is

plotted in prototype scale to allow direct comparison with the site data. The time factor is calculated as:

$$\text{Time factor} = \sqrt{T_v} = \sqrt{\frac{t}{t_{\text{ref}}}} = \sqrt{\frac{t c_v}{D^2}} \quad (1)$$

Where t (months) is the elapsed time since superstructure construction, c_v ($m^2/month$) is the coefficient of consolidation, and D (m) is the drainage distance. The value of $t_{ref} = \frac{D^2}{c_v}$ (months) for the site data is taken from the dataset of Chan et al (2018), and the value of t_{ref} for the experimental data is taken from the consolidation readings obtained during the preparation of the clay sample used in the centrifuge test.

There is good agreement between the site data and the experimental data, confirming that the centrifuge package is able to reproduce the phenomenon of long-term basement heave. The trends on Figure 8 also show that the evolution of long-term heave with time agrees with the swelling aspects of one-dimensional consolidation theory, whereby displacement initially scales with the square-root of time after superstructure construction, then exponentially decays towards the equilibrium values.

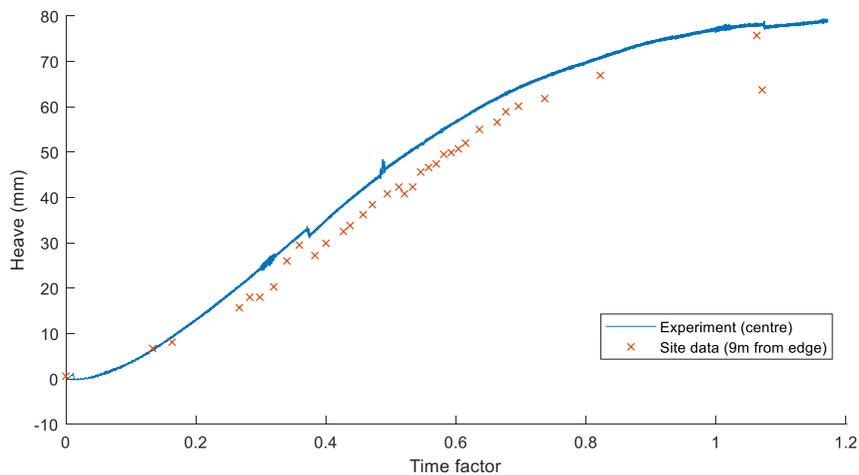


Figure 8: Comparison of light superstructure experiment and Horseferry Road basement data

4 FUTURE WORK

Both centrifuge tests discussed in this paper used a flexible basement structure, in order to generate large heave movements to aid identification of the mechanisms of deformation. Future centrifuge tests will investigate the influence of basement slab stiffness on the magnitudes of heave pressure and deformation.

Another variation in forthcoming centrifuge tests is the embedment condition of the basement toe. In both centrifuge tests presented in this paper, the basement structure was a rectangular box that sat entirely above the clay layer, with a drainage layer separating the base slab and the

clay. Two future experiments will investigate different embedment conditions: one basement model will be embedded into the clay and another model will include tension embedment that extend below slab level.

Future work in this research project will also involve comparing the experimental results with design guidance. One of the most prevalent methods used in the design of basements subject to long-term heave is the simplified non-linear method, also known as relaxation ratio method (O'Brien et al, 2001; Simpson, 2017). This method provides estimations heave pressure and heave displacement for design purposes. As this series of centrifuge tests provides measurements of both displacement and heave pressure, the experimental data will provide direct comparison

with the simplified non-linear method with a view towards refinement of the method.

5 CONCLUSIONS

- The centrifuge tests presented in this paper were able to reproduce the effects of long-term heave of deep basements in over-consolidated clay.
- The magnitude and time-dependency of heave observed in the centrifuge test agree with field data from the Horseferry Road basement.
- Regardless of the weight of the superstructure, a flexible base slab allows relaxation of heave loads. Most of the structural load appears to be carried through the toes of the structural walls.
- Future investigations will vary the structural stiffness and the embedment details of the basement, with a view to quantitative refinement of existing design guidance on deep basement slabs subject to long-term heave.

6 ACKNOWLEDGEMENTS

The authors would like to thank John Chandler, Kristian Pether, Mark Smith, and Chris McGinnie for facilitating the experiments; and Mélanie Jans-Singh for the French translations in this paper. The authors would also like to acknowledge the EPSRC Centre for Doctoral Training in Future Infrastructure and Built Environment at the University of Cambridge (EPSRC grant reference number EP/L016095/1) and Mott MacDonald Geotechnics for supporting this research project.

7 REFERENCES

Burland, J. B., Simpson, B., St John, H. D. 1979. Movements around excavations in London

clay. *Design Parameters in Geotechnical Engineering: Proceedings, 7th European Conference on Soil Mechanics and Foundation Engineering*, Vol. 1, 13–29. British Geotechnical Society, London.

Chan, D. Y. K., Madabhushi, S. P. G. 2017. Designing urban deep basements in South East England for future ground movement: Progress and opportunities for experimental simulation of long-term heave. *Proceedings: International Symposia for Next Generation Infrastructure*, London.

Chan, D. Y. K., Madabhushi, S. P. G. 2018. Centrifuge simulation of heave behaviour of deep basement slabs in over-consolidated clay. *Proceedings: International Conference on Physical Modelling in Geotechnics*. Taylor & Francis, London.

Chan, D. Y. K., Madabhushi, S. P. G., Nicholson, D. P., Chapman, T. J. P., Solera, S. A. 2018. Twenty-one years of heave monitoring in London Clay at Horseferry Road basement. *Ground Engineering*, **51**(11), 28-33.

McNamara, A. M., Taylor, R. N. 2004. The influence of enhanced excavation base stiffness on prop loads and ground movements during basement construction. *Structural Engineer*, **82**(4), 30–36.

O'Brien, A. S., Sharp, P., MacDonald, M. 2001. Settlement and heave of overconsolidated clays - A simplified non-linear method of calculation. *Ground Engineering*, **34**(10), 28–32.

Ohishi, K., Azuma, K., Katagiri, M., Saitoh, K. 2000. Deformation behaviour and heaving analysis of deep excavation. *Geotechnical Aspects of Underground Construction in Soft Ground*, Tokyo.

Simpson, B. 2017. Effective heave pressures beneath restrained basement slabs. *Proceedings of the Institution of Civil Engineers - Geotechnical Engineering*, **171**(1), 28–36.