Centrifuge and numerical modelling of the influence of structural stiffness on basement heave in over-consolidated clay

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ABSTRACT: Long-term basement heave is a pertinent problem in the construction of underground spaces in over-consolidated clay strata, notably the clays of southeastern England. When a basement is constructed, the permanent removal of soil above formation level inevitably causes upward movement of the remaining soil, or heave pressures on the base slab. In over-consolidated clay strata such as London Clay, this process of heave continues over many years after the basements structural completion. The designer must predict these future heave pressures and movements when designing the basement structure. However, there has been much conservatism in the methods of design due to the scarcity of site monitoring data to calibrate the methods of heave prediction. There is a need for further physical data to improve the methods of design.

This paper presents a research project that seeks to fill this research gap through the technique of geotechnical centrifuge modelling. The model simulates the construction and long-term heave of a 15 m deep basement underlain by stiff clay. The model basement is fitted with extensive instrumentation and this is the first research project to provide simultaneous measurements of the vertical movement of the base slab and the distribution of slab-soil contact pressure in a centrifuge model of basement heave. The experimental results are validated against finite element simulations of the same prototypes. The results show that the prediction of high heave pressures is a self-fulfilling prophecy: the assumption of high heave pressures by the engineer leads to the specification of strong structures to sustain the load, and the stiffness of these structures in turn restrain the soil, generating high heave pressures. This paper advocates an alternative design approach so that leaner basement structures can be specified, and thus urban underground spaces can be provided more economically.

1 INTRODUCTION

When a basement structure is excavated, the permanent removal of soil overburden leads to a reduction in vertical effective stress, causing the remaining soil to swell. In over-consolidated clay strata, such as London Clay and Gault Clay, this process of swelling continues after the completion of the basement structure, generating upward displacement and heave pressures on the base slab as the clay re-consolidates.

This process is known as "long-term heave" and engineers must design the base slab to restrain or allow for these gradual movements and pressure changes that often continue for over a decade beyond structural completion (Chan et al. 2018). One recent example of this issue was the Liverpool Street Crossrail site in London (Figure 1), where uncertainties in predictions of long-term heave effects on the station concourse basement had necessitated much conservatism in the substructure design.

Figure 1: Photograph of Liverpool Street Crossrail construction site

Some designers seek to model the effect of long-

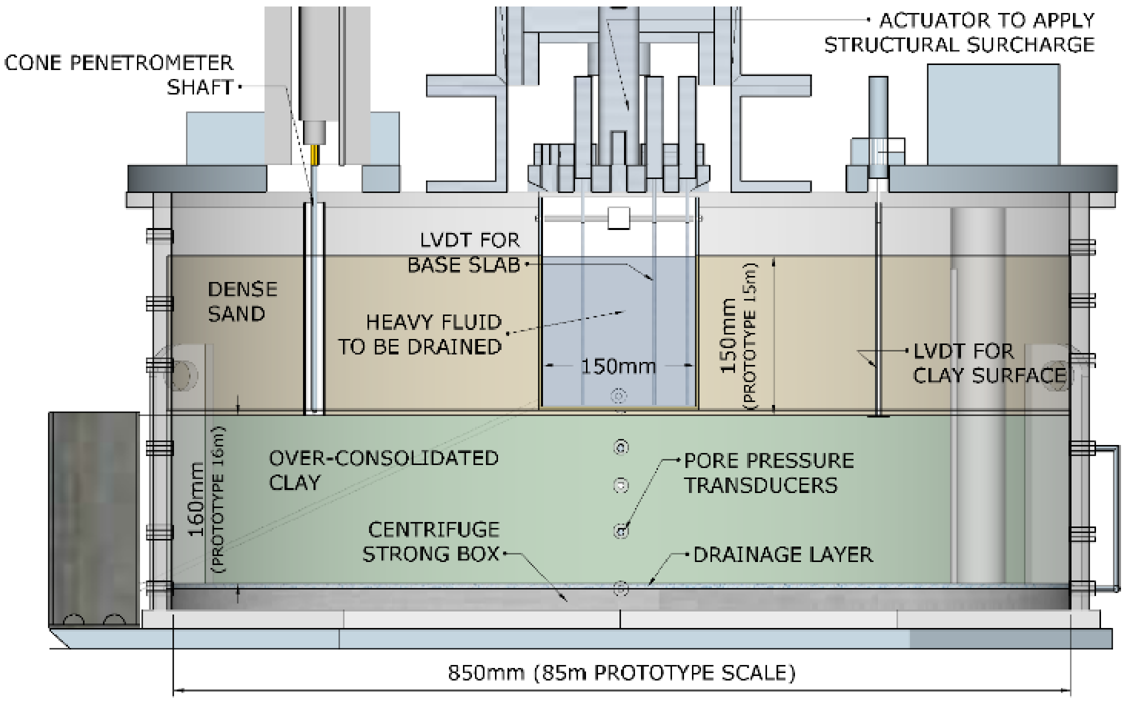

Figure 2: Cross-section drawing of centrifuge model

term heave as an upward load at formation level, typically quoting heave pressures of 50% to 65% of the pre-existing effective overburden. There is much uncertainty surrounding these estimates and the soil-structure interaction that generates the heave pressures and movements, so there is a desire for further research to fill this gap.

This paper presents a research project that investigates the phenomenon of long-term heave, using both geotechnical centrifuge modelling and finite element simulations to quantify the effects of long-term heave on a rectangular basement underlain by over-consolidated clay.

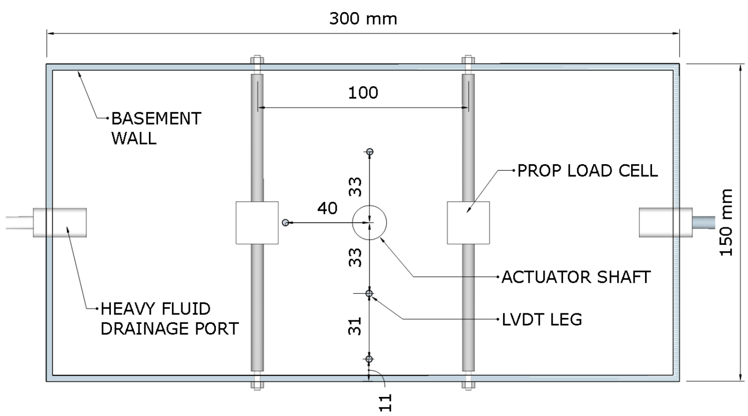

Figure 3: Plan view of basement model, showing locations of instrumentation

2 CENTRIFUGE MODEL

A 100 *g* geotechnical centrifuge model was used to simulate a 15 m deep basement (model scale: 150 mm) with plan area 30 m × 15 m (model: 300 mm × 150 mm). Each centrifuge test involved two layers of soil: a 16 m (model: 160 mm) layer of Speswhite kaolin at the bottom, and a 15 m (model: 150 mm) layer of dry Hostun sand on top (Figure 2). The water table of the centrifuge package was set at the level of the sand-clay interface and a thin layer of sand separated the base slab and the clay to ensure adequate drainage at formation level. The use of these sand layers reduced the amount of time it took for the clay to consolidate to equilibrium during an experiment and models the common construction practice of using an under-slab drainage layer to minimise buoyancy loads.

The clay was pre-consolidated to a maximum vertical stress of 800 kPa. In-flight cone penetrometer tests established that the undrained shear strength of the clay was about 100 kPa, consistent with Vardanega et al. (2012). The Hostun sand was poured into the centrifuge model using an automatic sand pourer, at a dry density of 1600 kg/m^3. The properties of the model soils are given in Table 1 and their representative stiffness parameters are given in Table 4.

Two different basement models were used in the experiments to investigate the influence of basement slab and wall stiffness on heave behaviour. The stiff basement model was made from 3.25 mm thick stainless steel plates, which matched the bending stiffness of 1 m thick reinforced concrete retaining walls and base slabs (Table 2). The flexible basement used 1.22 mm thick brass plates to create an arbitrarily flexible structure which would allow large heave movements (Table 3).

Before spin-up, the basement cavity was filled with a heavy fluid (sodium polytungstate solution) of the

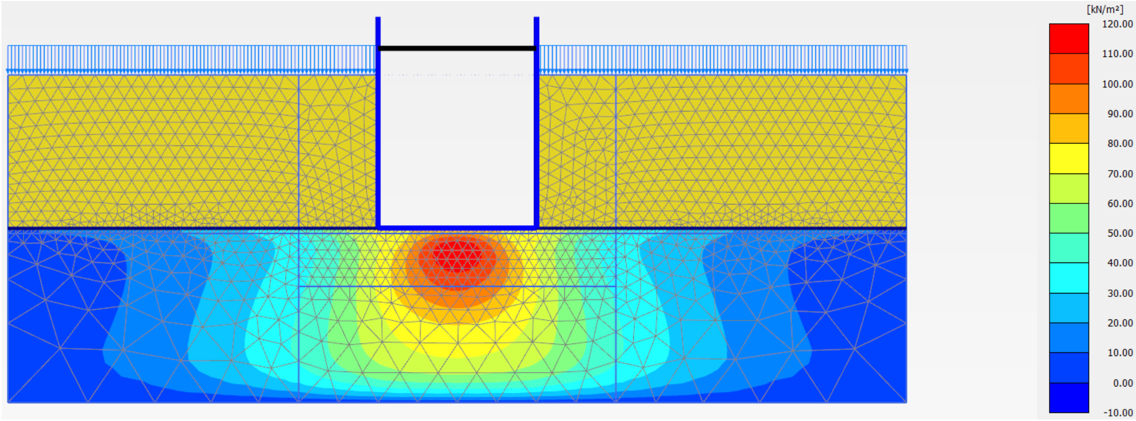

Figure 4: Finite element model of stiff basement, showing excess pore pressures immediately after excavation

same density as the dry sand outside the basement. This heavy fluid was removed from the basement cavity during centrifuge flight by draining it through a network of pipes and valves, to model the effect of excavation. Subsequently, an electrical actuator would apply a vertical load onto the top of the basement walls to model the construction of a three-storey underground building. The centrifuge model included instrumentation to record pore pressures, vertical displacements, structural bending curvatures, prop forces, and slab-soil contact pressures. In particular, the use of a Tekscan tactile sensing mat to measure the profile of slab-soil contact pressure (Figure 3) meant that this research project is the first centrifuge modelling study to provide simultaneous measurements of the profiles of heave displacement and swell pressures.

Further details about the preparation and the operation of the centrifuge model, and the validation of experimental results against site data, can be found in Chan and Madabhushi (2018) and Chan et al. (2019).

Table 1: Properties of soils used in centrifuge model

Dry density of sand	1600 kg/m^3
Saturated density of clay	1750 kg/m^3
Swelling index of clay (C_S)	0.1155
Pre-consolidation stress of clay	800 kPa

Table 2: Properties of stiff basement model

Basement footprint (model scale)	150 mm × 300 mm
Basement footprint (prototype)	15 m × 30 m
Wall and slab stiffness (model)	533 Nm^2/m
Wall and slab stiffness (prototype)	533 MNm^2/m

Table 3: Properties of flexible basement model

Basement footprint (model scale)	150 mm × 300 mm
Basement footprint (prototype)	15 m × 30 m
Wall and slab stiffness (model)	14 Nm^2/m
Wall and slab stiffness (prototype)	14 MNm^2/m

3 FINITE ELEMENTS MODEL

The finite element models in this research project were performed using PLAXIS 2D 2017-01. The plane of symmetry of the basement was taken as the representative cross-section, giving plane-strain models of 85 m overall width with a 15 m wide, 15 m deep basement cavity. The over-consolidated clay was represented by a small-strain hardening (HSS) model (Obrzud & Truty 2011) to capture the non-linear stiffness of the clay, and the constitutive parameters were calibrated using triaxial test data from Vardanega et al. (2012) and one-dimensional compression data from the preparation process of the clay samples used in the experiments reported in this paper. The sand was represented by a Mohr-Coulomb model with parameters obtained from the experiments reported in Heron (2013) and Deng & Haigh (2018). Table 4 summarises the constitutive parameters used in the finite element simulations. The software package and soil constitutive models were chosen to match current practices in industry where finite element models of basement heave in over-consolidated clays are needed.

To match the conditions in the centrifuge experiments, the left and right boundaries of each finite elements model were normally fixed and impermeable, while the bottom boundary was vertically fixed and fully permeable. Each basement model was represented by linear-elastic plate elements whose stiffness matched the prototype of the corresponding centrifuge test (Tables 2 and 3). Fully coupled consolidation analyses were performed, with undrained behaviour derived from effective stress parameters and excess pore pressures. Figure 4 shows the finite elements model for the stiff basement excavation, with contours of excess pore pressures caused by excavation.

Each simulation was initialised with greenfield conditions. Then, the basement model was added and the soil inside the basement cavity was replaced by line loads representing the hydrostatic loads of the heavy fluid in the centrifuge experiments. Excess pore pressures were then allowed to dissipate and displacements were zeroed after the simulation had reached equilibrium.

The hydrostatic loads were turned off to simulate excavation, and then point loads were imposed onto

Table 4: Properties of soils used in finite elements model

Model	Hostun sand Mohr-Coulomb	Speswhite kaolin HSS
Dry density	1600 kg/m^3	-
Saturated density	2000 kg/m^3	1750 kg/m^3
e_{init}	0.64	1.00
Permeability (m/s)	1×10^{-7}	5×10^{-10}
Poisson ratio ν	0.20	0.12
E (kPa)	47500	-
G_0 (kPa)	-	45000
γ_{ref}	-	2.5×10^{-4}
E_{ur} (kPa)	-	16800
E_{50} (kPa)	-	5600
E_{oed} (kPa)	-	4800
p_{ref} (kPa)	-	250
m	-	0.65
ϕ'	33°	20°
ψ	20°	0°
c'_{ref} (kPa)	1	0
R_f	0.9	0.8

the top of the walls to simulate construction. The same prototype lengths of time were used for the finite element models as the centrifuge models, to capture the concurrent effects of construction and consolidation.

4 RESULTS AND DISCUSSION

The aim of the centrifuge and numerical models presented in this paper is to measure the magnitude of heave displacement and swell pressures caused by long-term heave, so Figures 5 and 6 will focus on the equilibrium slab-soil contact pressures and the total displacements caused by excavation, construction, and consolidation. The differences in behaviour between the flexible basement models and the stiff basement models will be highlighted, and the goodness of fit between numerical data and experimental data will be discussed.

The profiles of equilibrium slab-soil contact pressures along the centre-line of the base slab are shown on Figure 5. There was good agreement between the experimental results and finite element results in terms of the profiles of pressure, giving confidence to the validity of the numerical model.

The pressure profiles of the both the stiff basement slab and the flexible basement slab showed concentrations of pressure near the toes of the walls and relaxations of pressure towards the centre of the slab, compared to the pressures observed before excavation (about 240 kPa). However, the effect of relaxation was much more profound in the case of the flexible slab, with almost complete relaxation of pressure at the centre. In contrast, the centre of the stiff slab attracted about 150 kPa of swell pressure, which agrees with the oft-quoted design rule of thumb that 50 - 65% of the pre-existing effective overburden would manifest itself as a long-term heave load after the construction of a basement of typical stiffness in over-consolidated clay.

The difference between the stiff basement and the flexible basement's behaviours can be explained by soil-structure interaction. This is best illustrated using a plot of vertical displacement versus slab-soil contact pressure for various positions along the centre-lines of the basement slabs (Figure 6).

The low stiffness of the flexible base slab allowed it to undergo some 200 mm of differential heave, letting the underlying clay expand and relax. In contrast, the high stiffness of the stiff base slab restrained the clay, permitting little upward movement and therefore attracting large swell pressures.

For the stiff basement, the finite elements model appeared to over-predict the magnitude of heave by about 30 mm compared to the experimental results. On closer inspection, this discrepancy arose from an over-estimation of the undrained stiffness of the clay when the building load was imposed onto the basement structure. Otherwise, there was good agreement between experimental and numerical data in terms of the changes in vertical displacement between short-term and long-term conditions. Further research will be needed to refine the constitutive model so that the short-term interactions between stiff slabs and over-consolidated clays can be modelled more accurately.

5 IMPLICATIONS FOR BASE SLAB DESIGN

The two basement structures presented in this paper had the same overall dimensions and were subject to the same soil conditions and construction sequence. They only differed in terms of structural stiffness and self-weight. Nevertheless, they exhibited very different heave pressures and movements. The stiff basement suppressed post-construction heave movement at the expense of generating high heave pressures. The flexible basement allowed drastic relaxation of swell pressures at the expense of permitting large heave movements. The magnitudes of swell pressures and heave displacements depend strongly on the stiffness of the basement slab.

The practical implication of this finding is that the prediction of high heave pressures is a self-fulfilling prophecy that should be avoided in design. If a design engineer attempted to predict heave pressures before specifying the sub-structure, the assumption of high heave pressures would lead to the specification of stiff and heavy slabs to carry the assumed loads (Figure 7). The high stiffness of such slabs would then constrain the vertical movement of the clay and generate high swell pressures. It would be preferable to specify a permissible movement limit based on serviceability requirements, then design a slab using soil-structure interaction methods to provide the appropriate flexibility to accommodate the specified displacement at the expected swell pressures (Figure 8).

One common used soil-structure interaction method is the "non-FE method", sometimes known as the "relaxation ratio method" (Chan & Madabhushi 2017; Simpson 2018). The procedure for

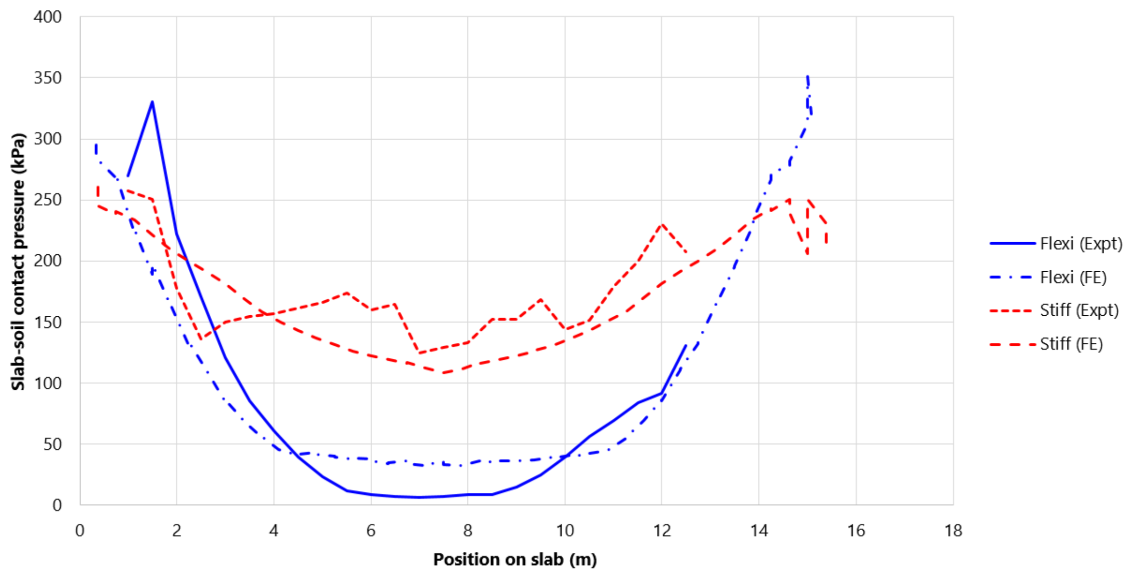

Figure 5: Graph of slab-soil contact pressures in long-term equilibrium after excavation and construction

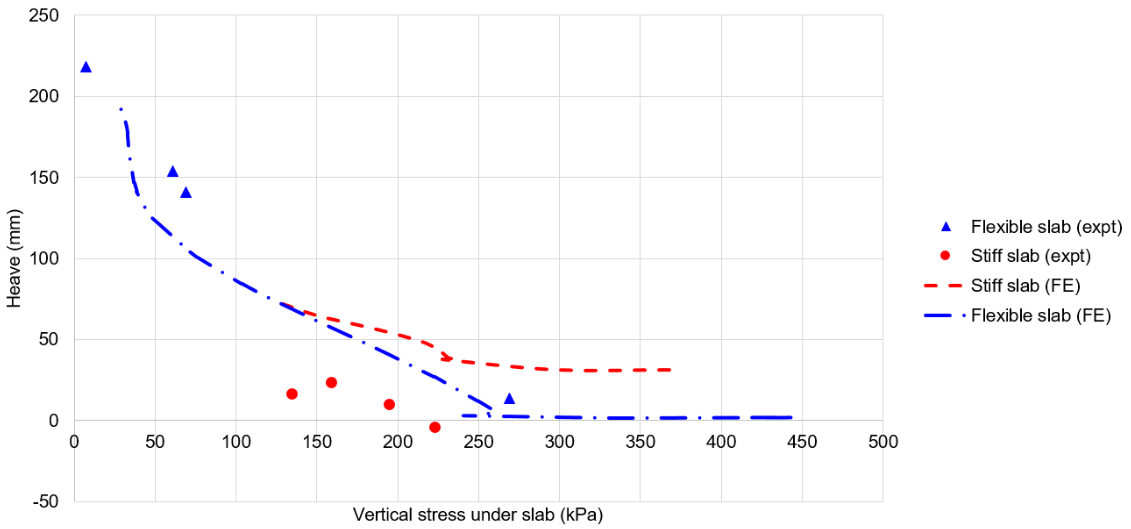

Figure 6: Graph of heave displacement against swell pressure in long-term equilibrium after excavation and construction

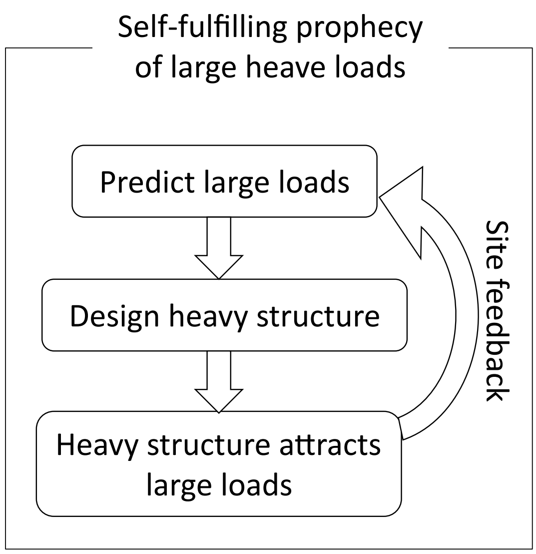

Figure 7: Flowchart showing the "self-fulfilling prophecy" of large heave load predictions in design

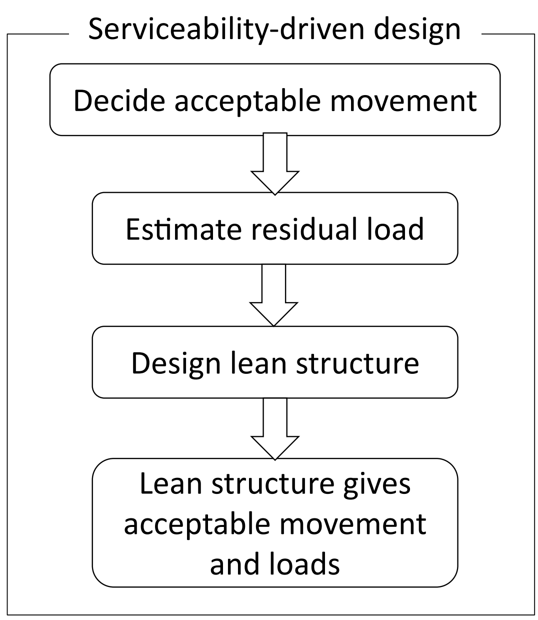

Figure 8: Flowchart showing the preferable, serviceability-driven approach of design

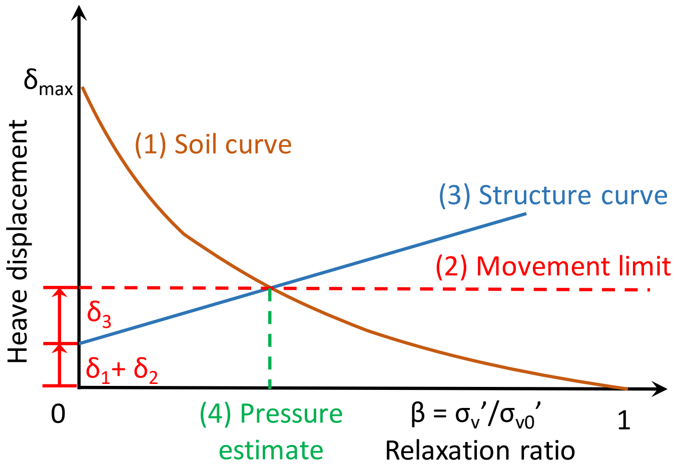

Figure 9: Illustration of serviceability-based heave design using relaxation ratio method

serviceability design with the relaxation ratio method is illustrated in Figure 9:

1. Plot a soil curve to represent the non-linear stiffness of the clay stratum;

2. Set a movement limit based on serviceability requirements ($\delta_1 + \delta_2 + \delta_3$) and mark the amount of heave that is predicted to occur before the construction of the slab (δ_1) and that due to buoyancy (δ_2);

3. From the intersection between the movement limit line and the soil curve, draw a straight line that represents the stiffness of the structure. The gradient of this line is the required structural stiffness. Design a slab with this stiffness.

4. Verify that the slab can carry the estimated heave pressure that is associated with the chosen movement limit.

Simpson (2018) demonstrated that, as long as there is a net reduction of soil stiffness due to clay swelling, the actual heave pressure and movement will not exceed this methods predictions. Furthermore, it will be greatly beneficial for the calibration of soil-structure interaction design methods if more basement construction sites in over-consolidated clay can be monitored to obtain data of actual heave pressure.

6 CONCLUSIONS

This research project used both centrifuge modelling and numerical modelling to shed light on the influence of basement slab stiffness on the phenomenon of long-term heave. It is the first published study to provide simultaneous measurements of the vertical movement of the base slab and the distribution of slab-soil contact pressure in a centrifuge model of basement heave.

For both the stiff basement and the flexible basement, there was good agreement between the two methods of investigation in terms of their estimations of slab-soil contact pressure. Further research is required to refine the finite element model's predictions of short-term displacements.

The results show that designers should avoid making guesses of the heave pressure before designing the sub-structure, because the heave pressure is strongly dependent on the basement slab's stiffness. It would be preferable to decide on a serviceability limit first and then use soil-structure interaction methods to design a suitable sub-structure. Site monitoring data of actual heave pressure will be beneficial for the calibration of these design methods.

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