Minimising base heave from deep excavations in soft soil conditions using underwater construction methods.

Minimiser pilonnement base à partir de profondes excavations dans des conditions de sol souples en utilisant des méthodes de construction sous-marine.

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ABSTRACT: There is a desire to be able construct very deep basements in soft soils without damaging adjacent buildings. Minimising the magnitude of ground movements arising from such excavations can be achieved by increasing the base stability. This paper will investigate the effectiveness of underwater excavation practices to maintain base stability of deep excavations and minimise surface settlements. Centrifuge modelling at 160*g* was used to observe the soil response to excavations to determine whether a raised water level on the excavation side of the retaining wall significantly reduces base heave. The model used a ‘rigid wall’ which eliminates lateral displacements associated with wall bending, thus focussing on the success of this method of construction. The results show that long term movements appear negligible within a year at prototype scale and surcharging the formation limits movements to 50% at distance *H* behind the wall.

RÉSUMÉ : Il y a un désir de construirer les sous-sols très profound dans les zones avec des sols mous sans endommager les bâtiments adjacents. Par minimiser l'ampleur des mouvements du sol résultant de fouilles peut être obtenu par augmenter la stabilité de la base. Ce document examinera l'efficacité des pratiques de fouilles sous-marines pour maintenir la stabilité de base des excavations profondes et minimiser les tassements de surface. La modélisation de la centrifugeuse à 160*g* a été utilisé d'observer la réponse du sol à l'excavation afin de determiner si un niveau d'eau soulevée sur le côté d'excavation la mur du retenue réduit de manière significative le soulèvement de base. Le modèle utilisé une ‘paroi rigide’ qui élimine les déplacements latéraux associés à le ploiment de pliage, concentrant ainsi sur le succès de cette méthode de construction. Les résultats montrent que mouvements à long terme semblent négligeables dan un délai d’un an à l’échelle du prototype et surcharger la formation limite les mouvements de jusqu’à 50% à la distance *H* derrière le mur.

KEYWORDS: centrifuge modelling, deep excavations, soft soils, ground movements, underwater excavation, basal heave

1 BACKGROUND

With a rise in demand for the development of urban areas comes the constraint of a lack of space above ground. Thus developers are increasingly constructing deep useable spaces underground. Controlling ground movements outside an excavation has always been a primary concern, particularly for sites underlain by soft soils, as there is significant risk of damage to neighbouring structures and services.

Ground movements associated with any excavation are largely associated with lateral wall displacements, wall bending and ground heave. Extensive research has previously been conducted with the aim of identifying methods of controlling horizontal wall movements to acceptable levels. Some of the methods suggested and generally used include stiff concrete diaphragm retaining walls; top down construction; installing props immediately after a layer of soil has been excavated and ensuring good workmanship. Regardless of these measures, contractors still find that surface settlements are excessive behind the wall. Peck (1969) explains that this is because of basal heave occurring at the formation level, arising from the relief of vertical stress during excavation. To reduce the degree of this soil movement, Peck recommended using air pressure or a fluid to reduce the magnitude of the change in vertical stress relief. Thus, by increasing the base stability of an excavation and controlling wall movements above final excavation level, it is thought that that the magnitude and extent of surface settlements can be restricted.

2 INTRODUCTION

Ground conditions in areas countries as Malaysia and Singapore typically consist of considerably deep deposits of soft clay and are overlain by a relatively shallow layer of over-consolidated clay. Therefore, constructing deep basements involves an appreciation of the expected magnitude and extent of ground movements and the implementation of a suitable excavation sequence to reduce movements to acceptable levels.

2 .1 *Marina Bay Station Box, Singapore*

Clark and Prebaharan (1987) discussed the Marina Bay project which comprised 900m long cut and cover twin tunnels on reclaimed land adjacent the East Coast Parkway Expressway. In order to complete the works with minimal disruption to neighbouring services it was decided that an underwater construction sequence be implemented.

Thus, the construction sequence, outlined by Denman *et al.* (1987), involved driving sheet piles into the stiff intermediate clay bands between the Upper and Lower Marine Clay layers and the piles protruded 2-3m above ground level. Soil was excavated to a depth of 7m and two levels of props installed. As the excavation progressed to depths of 15-18m below ground, water was pumped into the excavation 2m above ground level to surcharge the formation level, reducing lateral and vertical movements. Upon reaching the final excavation level, a tremie was used to cast a 1.5m thick concrete slab above a layer of compressible void formers before dewatering the excavation.

Clark and Prebaharan (1987) summarised that the lateral wall movements were negligible owing to the horizontal support offered by flooding the excavation. However, if the excavation had not been dewatered immediately, little is known about how the ground movements would continue to develop whilst the formation level is underwater.

3 OBJECTIVES

The aim of this study was to conduct an experiment at 160*g* using a geotechnical centrifuge to observe the soil settlement profile from an excavation in soft ground. Following this, the experiment aimed to model the effects of soil softening, following an excavation that had been flooded with water to record long term ground movements arising from such a construction technique.

4 PRINCIPALS OF CENTRIFUGE MODELLING

Centrifuge modelling allows engineers to simplify and physically simulate complex geotechnical problems using geotechnical materials. Typically physical modelling involves replicating real life events of a prototype at a reduced scale (Taylor, 1995). Similarity between the prototype and model must be achieved by applying the correct scaling laws and ensuring the correct stress profile throughout the soil model. The acceleration of the centrifuge induces an inertial radial acceleration field (N) on the model, which can be related to a gravitational acceleration field. The basic law of centrifuge modelling is that the height of the prototype h_p, is equal to the model height, h_m multiplied by the inertial acceleration field, N. Thus, the in situ vertical stresses within the soil model can be compared to the prototype.

5 SOIL MODEL

The test was conducted in a rectangular aluminium strongbox, with internal dimensions 550 x 200mm in plan and 375mm deep. The walls of the strongbox and extension were lubricated with waterpump grease.

The soil model comprised Speswhite kaolin clay, mixed to a water content of 120%. This was sandwiched between sheets of porous plastic and filter paper to halve the drainage path and increase the rate of consolidation. A 300mm high extension is bolted to the strongbox to produce a consolidated sample of sufficient height. The clay slurry was carefully placed in the strongbox to avoid the entrapment of air bubbles. The sample was then transferred to a hydraulic press and a pressure of 100kPa was applied until the sample had fully consolidated providing a 290mm deep sample.

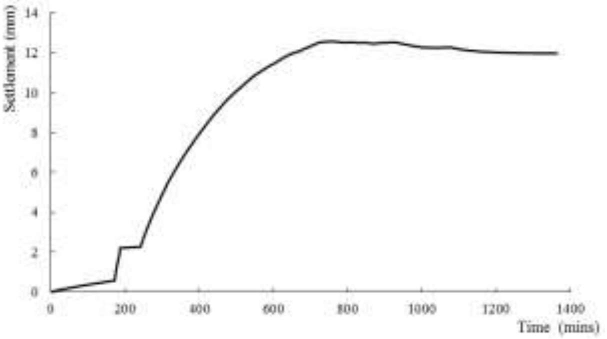

Figure 1. Settlement profile of soil model during initial in-flight consolidation process

The sample preparation process produced a very soft soil and it was necessary to further consolidate it on the centrifuge at 160*g* with a water table set 10mm above the soil surface to ensure it remained saturated whilst in flight. A lid was fitted to the strongbox and an LVDT was clamped to measure the settlement of the sample during consolidation. Once the rate of settlement plateaued the sample was removed from the centrifuge and the model making phase commenced. The sample was typically placed on the swing and left to consolidate for 11 hours. The settlement profile of the model during the initial consolidation phase is given in Figure 1.

6 APPARATUS

The apparatus set up for this experiment is illustrated in Figure 2. It consists of a ribbed retaining wall which was adopted as it allowed the modeller to insert it prior to excavating any material, thus minimising the risk of wall movements during model making. The wall was deliberately very stiff, with a prototype stiffness equivalent to a 2.1m thick reinforced concrete wall. This was designed such that the magnitude of soil movements due to wall bending were minimised. Bespoke moulds were fabricated to create concave silicone seals along the edge of the wall as these prevented the seepage of water around the wall.

A Perspex guide was machined to be bolted to the strongbox and allowed the ribbed wall to be installed in the soil sample whilst maintaining verticality and accurate positioning of the wall.

This experiment was designed such that the excavation process would be simulated by draining air pressure out from a latex bag. Thus, there was a requirement to protect the latex bag from the ribbed wall to avoid puncture whilst under pressure. Thus an aluminium plate and solid channels were attached to fit within the wall ribs and a silicone seal cast between them to prevent seepage of water.

An aluminium stiffener, designed by McNamara *et al.* (2009), was bolted to the side wall of the strongbox. The purpose of this was to support the top of the bag as well as laterally support the exposed length of the wall, thus representing an excavation of high support stiffness. Therefore, the ground movements occurring during the test could be directly correlated to basal heave and wall movements below the formation level.

Two standpipes were arranged such that one would provide a water table 5mm below the surface of the clay, whilst the other was controlled by an air actuator arrangement to supply water to the formation level, simulating the effects of soil softening during underwater excavations.

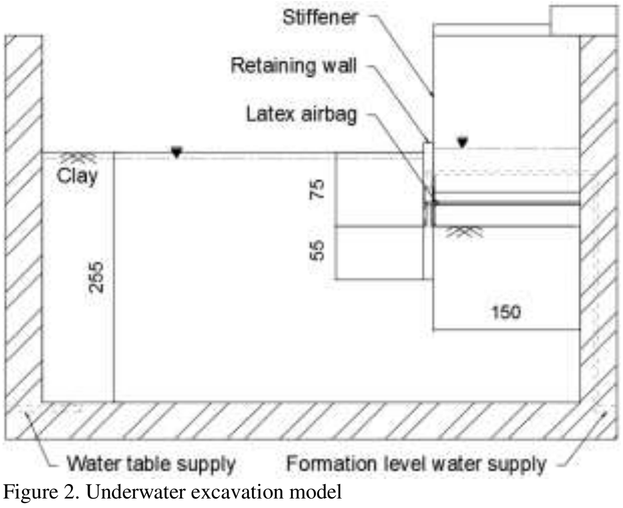

Figure 2. Underwater excavation model

7 TESTING PROCEDURE

Upon removing the model from the swing, the top surface of the sample was scraped to give a sample height of 255mm. PlastiDip, a proprietary aerosol applied impermeable membrane, was used to seal the top of the sample before the front face of the strongbox was removed. The Perspex guide was supported by the back wall of the strongbox and a front face aluminium shelf. Thin walled circular and square tubes were used to form voids in the soil along the front and back of the sample to cater for the seals at either edge of the wall. The wall was then pushed through the Perspex guide to the correct embedment. Stainless steel plates were used to scrape the soil away from the excavation area, giving a 75mm deep and 150mm wide excavation at model scale. Care was taken to ensure that the wall was not disturbed during this process.

Following the excavation, a sheet of filter paper and a 0.75mm thick porous plastic sheet were placed on the formation level, upon which a 25mm deep latex rubber bag was placed. An air feed and pressure transducer were connected to the bag, which was used to surcharge the formation level during reconsolidation, and was subsequently drained to simulate the excavation process. Over this another sheet of porous plastic was placed to provide an interface between the bag and the aluminium stiffener.

Three PPTs were installed during the model making phase and were backfilled with clay slurry mixed to a water content of 120%. In addition to this, LVDTs were used to measure vertical soil movements immediately behind the wall and at $^{H}/_{2}$ intervals from the wall. Details of the locations of the instrumentation are given in Figure 3.

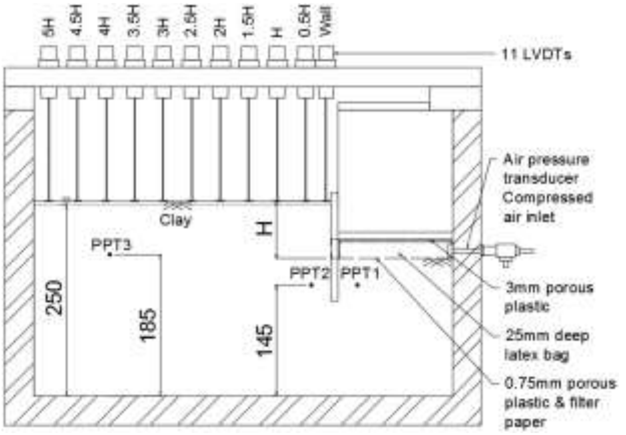

Figure 3. Model geometry and arrangement of instrumentation

Black glass ballotini balls, 1mm in diameter were randomly scattered across the front surface of the clay to create a suitable texture on the plain strain surface of the sample. In addition to this, 3mm diameter bullet shaped acetal targets were inserted in a 10mm grid. Subsurface movements were recorded by means of on board digital and analogue cameras. GeoPIV (particle image velocimetry) was used to track subsurface movements of the ballotini, whilst VisiMet analysed movements of the targets. A Perspex window was bolted to the front of the strongbox to allow the modeller to observe the excavation sequence.

Following the model making process, the strongbox was weighed before being transferred to the centrifuge and the counterweight adjusted. The model was gradually accelerated to 160*g* and the surcharge afforded to the excavation by the latex bag was increased to 202kPa. The model was left to re-consolidate under this air pressure until the PPTs indicated that the sample had come into equilibrium. The excavation was then simulated by releasing the air pressure at a rate of 1kPa/sec. Once the excavation was completed, the actuator connected to the second standpipe was activated and water was supplied to the base of the excavation. In addition to this a separate water feed was provided above the latex bag to flood the excavation 5mm above the ground level. The surcharge of the water level afforded the formation level 125kPa. The sample was left to consolidate for a further 30mins to observe long term movements which relate to 18 months at prototype scale.

8 TEST RESULTS

To date, one centrifuge test at 160*g* has been carried out and results presented below. In the experiment the model comprised half an excavation, 150mm wide and 75mm deep, representing 24m and 12m at prototype scale respectively. The toe of the retaining wall had been embedded 55mm into the clay, equating to 8.8m at prototype scale.

The stress change caused by the excavation process was simulated by draining air pressure from a latex bag over a 2 month period at prototype scale. The excavation was then flooded and the sample was further consolidated to observe the long term pore pressure response and ground movements.

Images were captured throughout the excavation process and during long term movements after the excavation had been flooded. Image analysis revealed that ground movements are concentrated around the wall and the magnitude of heave increases with distance from the wall, as illustrated in Figure 4. Table 1 summarises the surface settlements recorded by LVDTs and the percentage increase in movements in the long term.

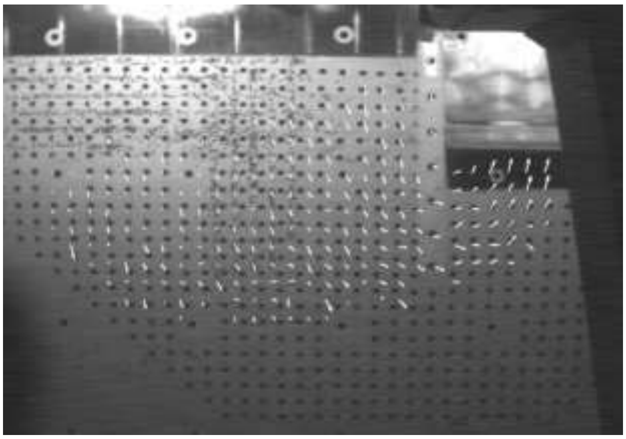

Figure 4. Mechanism of ground movements during excavation and long term consolidation

Table 1. Surface settlements behind retaining wall in the short term and the percentage increase in movements in the long term

Distance from wall	*Short term settlement (μm)*	*Long term settlement (μm)*	*Increase in settlement*
0*H*	392	649	65.7%
1.5*H*	598	859	43.5%
H	694	941	35.6%
1.5*H*	510	693	35.9%
2*H*	382	538	40.9%
2.5*H*	141	499	254.5%
3*H*	109	219	101.1%
3.5*H*	97	200	107.1%
4*H*	46	144	215.2%
4.5*H*	50	138	178.8%

9 ANALYSIS AND DISCUSSION

The primary concern arising from deep excavations is often related to the extent and magnitude of ground movements behind the wall. Predicting surface settlements have previously been investigated by Peck (1969), Clough and O'Rourke (1990) and more recently by Hsieh and Ou (1998).

These methods of predicting surface settlements were largely produced from case histories. Figure 5 illustrates the predicted surface settlement profiles for a propped retaining wall. Vertical settlement normalised against the maximum vertical settlements are plotted against distance from the wall against the final excavation depth (*H*). The movements immediately after the excavation from the centrifuge test were also plotted on Figure 5 and show that the centrifuge surface settlement profile for the propped wall in this test best follows the trend and magnitudes outlined by Hsieh and Ou (1998).

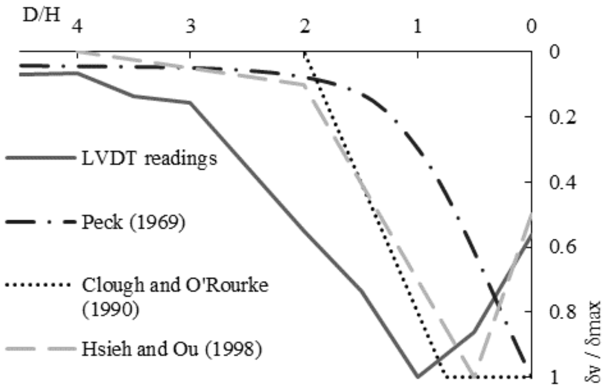

Figure 5. Comparison of surface settlement profile from LVDT measurements immediately after excavation against published profiles (Hsieh & Ou, 1993; Clough & O'Rourke, 1990)

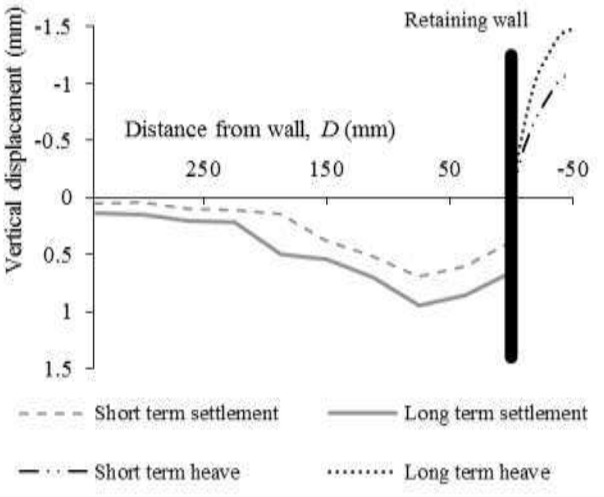

Figure 6. Immediate and long term settlement and heave profiles arising from unloading and soil softening

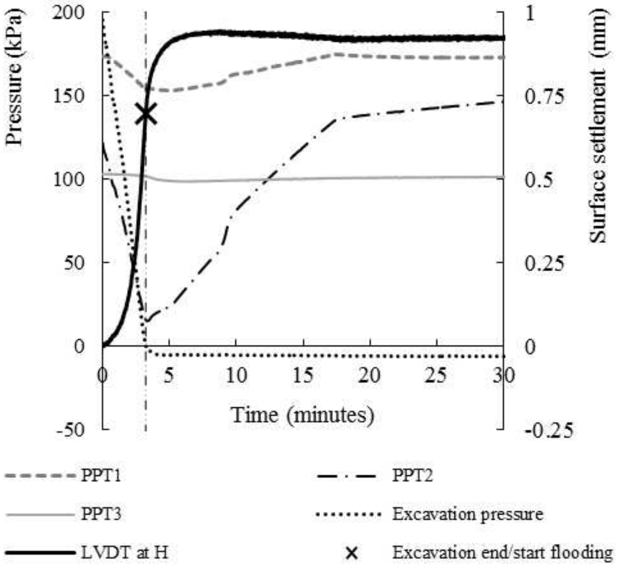

Figure 7. Short and long term response of LVDT at distance H behind the wall and pressure transducers during the test

LVDT measurements and image analysis throughout the test were plotted in Figure 6 and show the change in vertical ground movements during the excavation.

Figure 7 illustrate changes in pore pressure and vertical movements whilst the excavation is undertaken and significant surface settlements occurred immediately. The surface continued to settle at a similar rate during the initial stages of flooding and began plateauing 6 minutes into the test.

Considering the PPT responses, it can be noted that there is a corresponding fall in pore pressure recorded by PPT1 and PPT2 as the excavation proceeds. Fluctuations in pore pressure readings at 3, 9 and 18 minutes show further decreases in surface settlement readings at *H*. Post excavation, the area was flooded and pore pressures dissipated within 20 minutes.

10 CONCLUSION

One centrifuge test at 160*g* was carried out to investigate the magnitude of additional ground movements arising from an underwater excavation sequence. A high stiffness wall and support system were used to minimise movements arising from wall bending.

The test involved reducing air pressure in a latex bag to simulate the excavation process over a period of approximately 3 minutes. Subsequently, a direct water feed above the bag and a valve controlling the flow to the formation level were activated. Logging of measurements and images were captured for a further 30 minutes after the excavation had been simulated to observe long term ground responses.

The results were consistent with the expected mechanism of ground movements and the surface settlement profile behind a propped wall appear to relate to the settlement trend outlined by Hsieh and Ou (1993), whereby the movements adjacent the wall are approximately 50% of the maximum settlement, which occurs distance *H* behind the wall. The extent of ground movements arising immediately after the excavation concur with the findings of Peck (1969) who stated that movements in soft soils can extend up to 4 times the retained height of soil.

The additional surface settlements occurring after the excavation has been completed were seen to be negligible 20 minutes after the event at model scale. The long term changes in the settlements can be seen to increase by 36% at a distance of *H* from the wall as a result of pore pressure dissipation as illustrated in Figure 7.

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