The London Geotechnical Centrifuge Centre at City University London

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Abstract: The London Geotechnical Centrifuge Centre located at City University, London is one of four currently active centrifuges in the UK. The centrifuge is well used and much of the geotechnical research at City University employs physical modelling but supported by a large element testing facility and numerical modelling capability. The centre was established in 1990 and the facility was extensively upgraded to provide more space for sample preparation and model making in 2004. In 2012 the centre is supporting 4 doctoral research projects in addition to visitors from China, Italy and UK. The focus of research is urban construction processes with an underlying theme of sustainability. Over the last 10 years the group has established a capability for tackling complex modelling problems and is currently investigating the application of smart instrumentation and control at high g.

Keywords:
Centrifuge modelling, Reactive modelling, City University London,

1 INTRODUCTION

1.1 The facility

Schofield and Taylor (1988) describe the Acutronic 661 centrifuge at the London Geotechnical Centrifuge Centre, City University London. The swinging platform at one end of the rotor has overall dimensions of 500mm x 700mm with a usable height of 500mm. A package weight of 400kg at 100g can be accommodated and this capacity reduces linearly with acceleration to give a maximum 200kg at 200g; thus the centrifuge is a 40g/tonne machine. The package is balanced by a 1.45 tonne counterweight that can be moved radially along the centrifuge arm by a screw mechanism. The radius to the swinging platform is 1.8m giving a working radius of between 1.5m and 1.6m requiring an operating speed of approximately 340rpm to give 200g at 1.55m radius. Four strain gauged sensors are used in the base to detect out-of-balance operation of the centrifuge. The signals from these sensors are monitored continuously and the machine is shut down automatically if the out-of-balance exceeds the pre-set maximum of 15kN. Such a safety feature enables unmanned overnight running of the machine. A fibreglass clamshell around the centrifuge creates an aerodynamically smooth chamber and a fairing on the leading side of the swing improves performance. A sacrificial block wall surrounds the clamshell and is itself surrounded by a reinforced concrete structure to provide an effective and safe containment. Electrical and hydraulic connections are available at the swinging platform and are supplied through a stack of slip rings. 55 slip rings are electrical and 5 fluid with 15 bar capacity. Of the electrical slip rings 5 are used to transmit transducer signals, which are converted from analogue to digital by the on-board computer and may be amplified prior to transmission in bits. The remaining slip rings are used for communicating closed circuit television signals, supplying power for lights or operating solenoids or motors as necessary. The fluid slip rings may be used for water, oil, or compressed gas.

The centrifuge was designed to allow operation by a researcher assisted by a technician and its size permits use without heavy lifting equipment; a typical model with apparatus weighs about 200kg and is easy to manhandle. The need for few resources has proved to be a significant strength of the facility over the years and the limited sized models offer more advantages than obstacles. However, ingenuity is almost always a prerequisite in centrifuge testing with such compact models.

1.2 Centrifuge electronic upgrade works

The original data acquisition and motor control system comprised three separate systems:

A 64 channel data logger based on an industrial specification solid state PC
Video cameras coupled to a PC to acquire static images for digital image analysis
Servo motor drives controlled via another separate PC.

As these systems were completely separate a certain amount of manual logging of events was required when performing a test. Whilst reliable, they were becoming obsolete in terms of spares and support. In view of this it was decided that a single system should be developed that could perform all three functions and would provide the potential to perform 'reactive' modelling (i.e. to incorporate feedback between sensors and actuators). Additionally, all data and events could be time stamped thereby removing the need to manually record information.

A PXI system from National Instruments running LabView software was purchased. The PXI system is effectively a solid state PC within a custom chassis that allows modules of differing functionality to be installed. The modules purchased allow 64 channels of data to be acquired and two digital servo motors to be controlled. Image acquisition is catered for using 5 megapixel machine vision cameras connected via USB. The entire system is mounted on the arm and accessed via a wireless bridge and Windows remote desktop connection. The use of commercial hardware and software was felt to be advantageous in terms of future support and potential for expansion and upgrade.

Owing to the electrically noisy nature of the centrifuge when in operation each data channel is provided with a signal conditioning circuit external to the PXI system. This allows for the use of a filter as well as amplification for transducers with low voltage outputs.

2 CONSTRUCTION PROCESSES FOCUS

Research at the London Geotechnical Centrifuge Centre has focused for some while on processes relating to urban construction with a strong underlying theme of sustainability. Most of the activity has specific relevance to either tunneling or deep foundations and the group at City University have attracted significant interest and involvement from industry collaborators ranging from consulting engineers to specialist and general contracting organizations.

3 CURRENT AND RECENT RESEARCH PROJECTS

3.1 Mini pile groups as equivalent large diameter pile foundations – Alexis Rose, Neil Taylor

3.1.1 Background

Access for piling in urban sites is frequently a problem. Modern multi storey buildings with large column grids generate very high foundation loads. The piling industry has responded to the requirement for ever deeper and larger diameter bored piles by manufacturing piling rigs that are capable of drilling massive 2m diameter plus holes to depths of around 60m in London. However, such rigs are themselves huge and they are often incapable of accessing constricted sites where headroom can also be severely limited.

A recently completed project in Cannon Street, London involved the redevelopment of Cannon Street station, a major commuter rail terminus in the City of London. The requirement to install high capacity foundations whilst maintaining an operational station for passenger and rail use meant that headroom for piling was reduced. It was impossible to use conventional piling methods and alternative foundation solutions were sought.

The construction of groups of mini piles is an effective and practical means of constructing high capacity foundations in confined spaces. Where the ratio of group diameter to length is low the inner piles within a group of uniformly spaced piles may make little contribution to the performance of the group and the capacity of the group is therefore dependent upon the geometry of the envelope rather than the capacity of the individual piles. Under these conditions the most efficient group may be one which comprises a ring or irregular line of piles around the periphery of the area defining the group (Figure 1). The behaviour of such rings of piles have been examined in the context of piles jacked into granular soils (Yetginer et al 2006) and limited testing has been reported on groups of bored mini piles as part of the RuFUS project (Fernie et al, 2006). A major centrifuge study relating to reuse of piles supplemented by rings of mini piles was also carried out by Begaj Qerimi (2009).

Figure 1. A pile group at Cannon Place

The aim of the recent research was to explore the strength and stiffness characteristics of contiguous mini pile groups that are equivalent in area to large hand dug caissons such as used at Embankment Place (Grose 1989). Such pile groups can be installed with relative ease but there was little experience of the performance that could be expected.

The vertical capacity of a line of piles, such as in a bored pile wall, is usually assumed to be based on the capacity of an envelope comprising the planes to the rear and front tangential to the wall and the base area between them. A similar approach may be taken to the design of mini pile groups. This needs to be compared with the capacity of the individual piles and the lower bound capacity used in the design. Such an approach requires an understanding of how the construction of piles in close proximity to each other affects the overall group capacity.

3.1.2 Centrifuge modeling

Extremely careful design of the apparatus and careful model making for the tests was vital to ensure that the model piles could be accurately installed within the model. The pile installation process was undertaken prior to the model being placed in the centrifuge. The clay was extracted using a thin walled stainless steel tube with an external diameter of 5 mm, which was pushed through a guide plate then through a pile cap located approximately 75 mm below. This process was adopted to maintain a good verticality. The cutting was repeated and the clay excavated in three sections for each pile prior to installation of the model piles which were 5 mm diameter and 270 mm long aluminium rods. These were placed into each hole and held down with a grub screw, which was tightened into the top of the pilecap. The toe of each pile was 250 mm below the surface of the clay model which meant that a positional tolerance of about 1mm was required to match prototype tolerances. Figure 2a shows the patterns of model pile layouts investigated whilst some results from the tests are presented in Figure 2b.

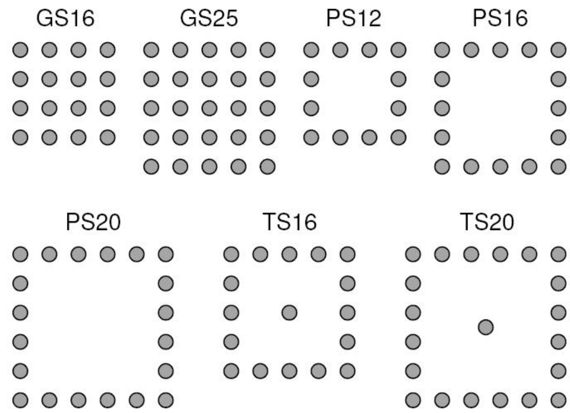

Figure 2a. Group arrangements

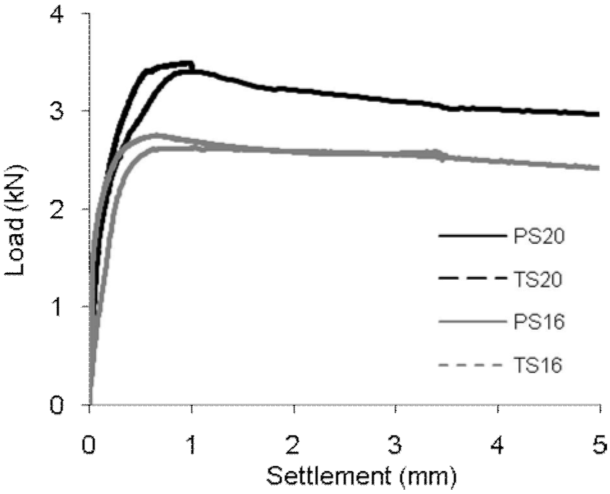

Figure 2b. Results from group tests

The pile spacing was 2.0d in each of the tests and was chosen so that the piles were sufficiently close to be considered ‘very closely spaced’ without being difficult to install. In addition the spacing was very similar to the spacing of the piles at Cannon Place. ‘Target’ groups (T) were the same as ‘Perimeter’ groups (P) but with the addition of a central pile, whilst ‘Grid’ groups (G) contain all central piles and were considered to be a more traditional pile group arrangement. The testing programme included both square and circular groups. For more information see Rose and Taylor, 2010

3.2 High capacity pile foundations – Rohit Gorasia, Andrew McNamara

3.2.1 Background

Conventional pile capacity is known to be sensitive to the construction process. ‘Over auguring’ during pile excavation appears to reduce pile capacity because the soil at concrete/soil interface is extensively disturbed and remoulded whilst pile test data have shown that subjecting concrete to extended vibration during placing can result in increased pile capacity in comparison to standard practice.

In 2002 Expanded Piling and Arup Geotechnics agreed to co operate and jointly fund a programme of research consisting of a limited number of full scale field trials which were undertaken by Expanded Piling and supported by numerical analyses carried out by Arup Geotechnics. The field trials involved construction of several ribbed piles which in turn required preliminary development work on a special tool used for profiling the shaft. The analyses and tests yielded promising results suggesting that pile capacity could be increased by 30% – 40% (‘Getting to Grips with Friction’ *Ground Engineering*, December 2003).

Whilst the technique of providing a mechanically rough pile/soil interface demonstrated increased shaft capacity in the field and was confirmed by numerical analyses, there was a need to test a wider range of geometries to establish how the additional capacity that such piles offer is derived. This was achieved by conducting a series of high quality centrifuge model tests in conjunction with numerical analyses and comparison with the full scale field trials. The main element of the project was the physical model testing that was designed to model important aspects of the pile construction to provide data to check and evaluate finite element calculations. The series of tests explored the load displacement characteristics of a range of profiles of ribbed piles in comparison with straight shafted piles for single piles. Some tests were aimed at understanding the influence that forming ribs in a continuous helix has compared to discrete ribs. In addition, the project included some experimental work to study the mechanism of load transfer at the pile/soil interface.

The commercial benefit of greater pile capacity is cheaper foundations. However, significant environmental benefits will also accrue from the use of efficient foundations that are able to carry higher load, leading to less excavation and spoil removal requiring disposal, and reduced concrete in construction. Moreover, redevelopment of urban sites often requires removal of existing deep foundations owing to clashes in position of old and new foundations. Removal of such obstructions is extremely costly in terms of plant and labour as well as time consuming. Higher capacity piles offer potential for greater flexibility in foundation layout owing to their reduced size, making them easier to install around existing piles. However, no information is currently available to allow rigorous design of ribbed piles and the aim of the project is to establish new design rules based on robust research into fundamental behaviour at the pile/soil interface.

3.2.2 Centrifuge modelling

Each centrifuge test consisted of three testing sites within a circular soil container; two of the sites were used for piles and the third for a T-bar penetrometer. Speswhite Kaolin clay consolidated to 500 kPa and swelled to 250 kPa was used. Since the soil container was a cylindrical tub, it was decided to locate each test site on a pitch circle diameter of 240mm. The straight shafted pile was bored using a hypodermic tube and stiff guide; this was also used for the initial boring of the ribbed pile. A custom made shaft profiling tool equipped with a retractable toothed plate was used to profile the piles shaft after the initial bore. Both piles were cut and cast at 1g prior to centrifuge spin up. The piles used were nominally 16mm in diameter by 180mm in length, at 50g this scales to an 800mm diameter by 9m long prototype pile. For the ribbed piles the shaft diameter remained constant at 16mm with the ribs protruding outwards, Figure 3.

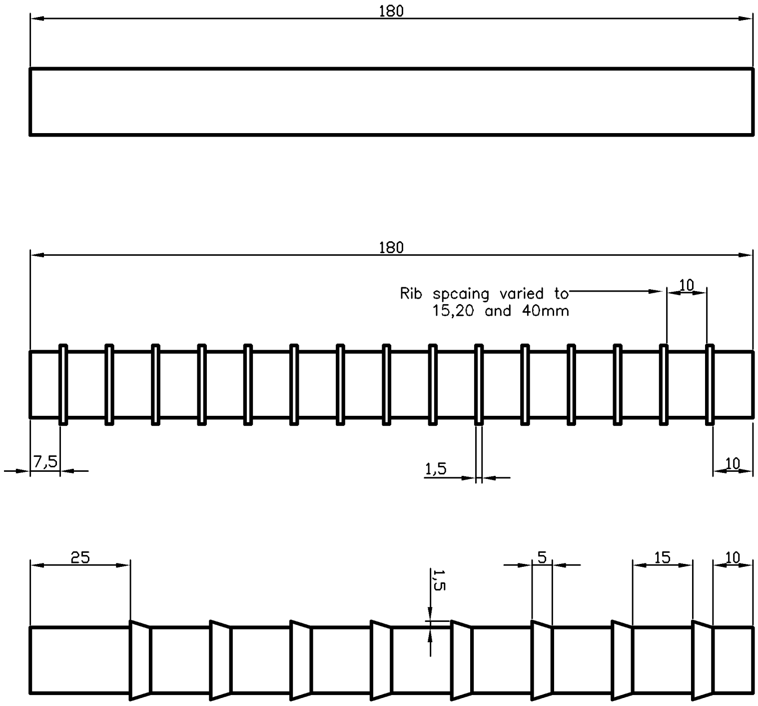

Figure 3. Range of pile test geometries.

Figure 4 shows normalised load/settlement curves for the main series of tests. In each test the pile rib height and outstand were kept constant, whilst the rib spacing was varied. The load data for each ribbed pile has been normalised against the straight pile in that test thus circumventing any inconsistencies within the soil sample.

The data shows that a 10mm rib spacing provided the greatest increase in capacity when compared to a plain pile. This increase in capacity is then shown to decrease as the rib spacing is increased to 15mm. With a rib spacing of 20mm the load at the lower displacement range was less than that of a plain pile, but this quickly recovered and at a displacement of 3mm the normalised load was some 20%

greater. A pile with rib spacing of 40mm was shown to mirror the behaviour of the 20mm spaced pile. The load at the lower displacements was higher than that of a plain pile, and at a displacement of 4mm the normalised load was 20% lower.

The test series also included a 19mm plain pile, which was bored in the same way as the ribbed piles to ensure a consistent pile/soil interface. The normalised load settlement data of this test is also shown in Figure 4. Surprisingly, the 10mm spaced ribs and to some extent the 15mm spaced ribs performed better than the pile with a diameter equivalent to the rib diameter.

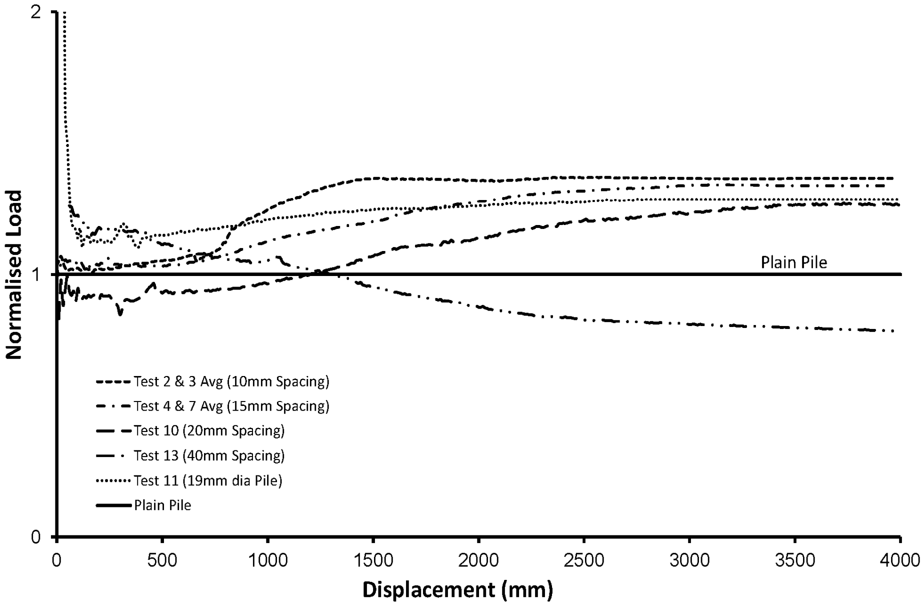

Figure 4. Normalised load settlement curves.

For more information see Gorasia and McNamara (2012).

3.3 Sequential twin-tunnelling in overconsolidated clay – Sam Divall, Richard Goodey

3.3.1 Background

Tunnelling is a widely used method for creating transport links, communication systems and for housing other services (water, cables etc). In urban regions, where available surface space is limited, tunnelling is used extensively. Owing to the relative ease with which tunnels are constructed through clay soils this method has grown in popularity. A Tunnel Boring Machine (TBM) is one of the most efficient construction methods for tunnelling through this medium, largely because of technological advances making the process highly automated with a high level of precise control. Irrespective of the method used, tunnel construction causes ground movements which have the potential to cause damage to existing structures. Modern tunnelling practice aims to reduce these movements to a minimum but there is still a requirement for accurate assessments.

The bored shape of a tunnel will always be larger than the final shape owing to the nature of the cutting process. The difference in these two volumes has been described by the term ‘ground lost’ or, the more frequently used, ‘volume loss’ and is usually expressed as a percentage of the excavated face area. This phenomenon manifests at the surface as a transverse settlement trough. Field observations and research have shown this to propagate throughout the soil mass causing possible damage to existing structures (Mair et al 1996). One accepted estimation of the settlement is a Gaussian curve in the plane perpendicular to the advancing tunnel face (Peck, 1969). Construction guidelines have been developed based, largely, on research from single tunnel arrangements e.g. Peck (1969), Mair (1979), Taylor (1984) and Attwell & Yeates (1984).

Mass transit tunnelling systems are often constructed in pairs (e.g. Jubilee Line Extension described by Burland et al., 2001). Pairs of tunnels constructed in quick succession in this way are known as ‘twin tunnels’. Superposition of single tunnel predictions is a common method of estimating movements around pairs of tunnels but implicit in this method is the assumption that construction of the second tunnel is unaffected by the presence of the first tunnel. Previous numerical studies have indicated that superposition may not necessarily be sufficient and this is reflected to some extent in field observations. Hunt (2005) explored the influence of constructing tunnels in close proximity using the finite element method and proposed some deviation from the superposition technique. In a number of major projects there has been extensive monitoring of ground movements and tunnel behaviour throughout the project life cycle. Examples of these projects are St James Park in UK (Nyren, 1998), Lafayette Park in USA (Cording & Hansmire, 1975), and The Heathrow Express in UK, (Cooper & Chapman, 1998). In all of these case studies observations of surface settlement data indicated asymmetry of the movements generated by each tunnel.

The aim of the research project is to explore the behaviour of the ground when constructing adjacent tunnels in overconsolidated clay.

3.3.2 Centrifuge modeling

Figure 5 shows a schematic representation of a typical model of the excavation of two adjacent tunnels in stiff clay (Divall and Goodey, 2012). The tunnel bores were both supported with water filled rubber membranes during spin up and consolidation. Sequential tunnel constructions were simulated by draining 3% of the total volume of the support fluid from each of the tunnels. A time period representing a construction delay was allowed between these events. The centrifuge was usually run for at least an hour post-test to allow any longer term movements to develop.

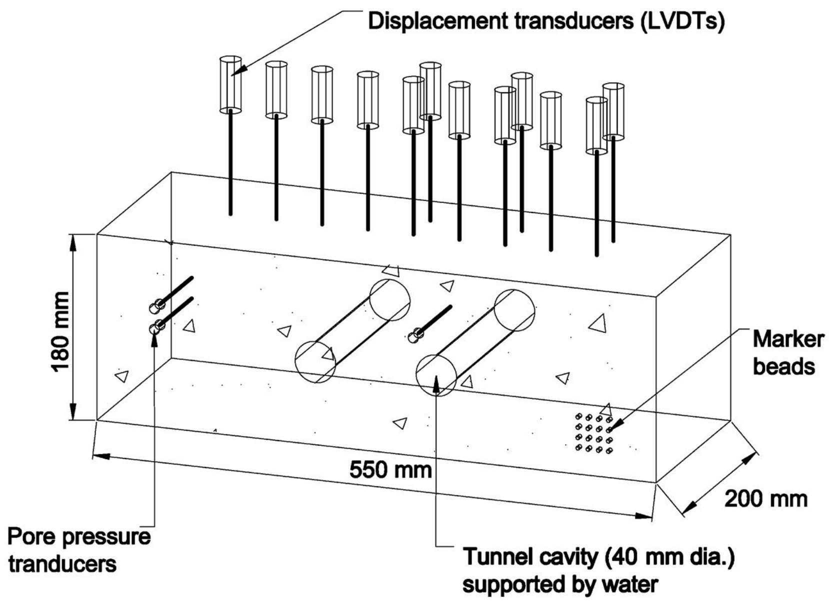

Figure 5: Schematic diagram of a typical plane strain centrifuge twin-tunnel model (not to scale), Divall and Goodey (2012)

The centrifuge model tests have provided useful data examining the small strain movements around twin-tunnels. The accepted practice of superposition of settlement predictions has been shown to have some shortcomings.

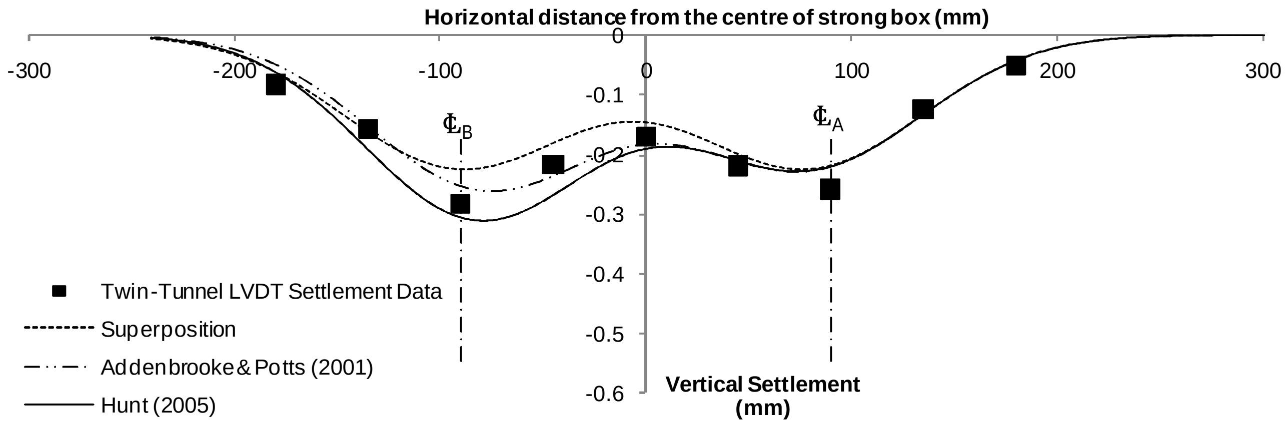

Figure 6: Twin-tunnel surface settlement measured by LVDTs

Typical test results are shown in Figure 6. The greenfield surface settlements for a single tunnel were well represented by a Gaussian distribution as might be expected, but this was not the case for the subsequent tunnel excavation. Taking the parameter i as a measurement of the distribution of settlements at the surface shows that the left and right-hand sides of the settlement troughs were not symmetrical. The extent to which the parameter i is affected is dependent on the position of the first bored tunnel with respect to the second. The closer the centres of the tunnels, the greater the added volume loss observed in the second bored tunnel. As the volume extracted from the tunnel is controlled, the reasons for this are unclear and are a topic for further investigation. For more information see Divall and Goodey (2012).

3.4 Grouting for ground movement control in open excavations - Hitesh Halai, Andrew McNamara

3.4.1 Background

Compensation grouting is a relatively new technique that was first used in the UK to control ground settlements during the construction of a 10m tunnel beneath Waterloo station, Mair and Harris (2001). The technique involves injecting cementitious grout into a zone between the excavation and the structure to be protected with the aim of minimising settlement. Its use in conjunction with tunnelling operations is now widespread after the technique was pioneered during construction of the Jubilee Line Extension where it was used to control the tilting of Big Ben during the construction of Westminster Station and tunnels. During this period a large amount of research activity into compensation grouting in controlling ground movement during tunnel excavation emerged and as a result there is a substantial volume of published material on the topic. In contrast the particular application of grouting behind a retaining wall around an open excavation remains unexplored. This leaves scope for new research to be conducted that will contribute to a better understanding of the effectiveness of the technique as well as its limitations.

The research aims to investigate the potential for the use of compensation grouting behind retaining walls used in deep excavations in order to remediate ground movement behind the retaining wall. There is an ever growing demand for more buildings and new mass transit systems, in cities that are already overcrowded and congested. Engineers are increasingly asked to seek solutions underground but face significant difficulties preventing the damage that can be caused by excavating large basements near to surrounding structures. As a consequence, most deep excavations are supported by very stiff retaining walls and heavy steel props to minimise the horizontal deflections which lead to settlement. A drawback to using such props is that they restrict access to the excavation and therefore slow down the construction process. They are also sensitive to temperature change which means that much of their capacity is used to resist temperature effects rather than provide stiff propping. The use of compensation grouting behind retaining walls may provide a solution to controlling ground movements without the need for extensive propping.

There are potential practical and commercial benefits in using compensation grouting techniques to control ground movements. A number of variables which could influence the magnitude and distribution of ground settlement may be studied and it is intended to use the research to generate an understanding of the limitations of using compensation grouting in this way such that guidelines can be established to aid in its future commercial implementation.

The key element of the project will be the use of physical model testing designed to investigate the influence of a range of variables on the effectiveness of the application. The use of compensation grouting to reduce ground movement beneath a particular structure during tunnel excavation has been shown to be sensitive to the positioning and location of the grout injection. However no work has been carried out to explore the influence these variables have on the behaviour of both the retaining solution and the surrounding ground when the technique is applied to large, deep excavations. Although in common practice cementitious based grouts of low viscosity and pressure are used in clay soils, Mair and Hight (1994), it is intended through this project to investigate the influence of using a clay slurry based material to control ground movement. This has the obvious environmental and commercial benefits of using what is essentially an inert, waste material from the excavation process which has no long term implications on the surrounding environment. For more information see Halai and McNamara (2012).

3.5 Plate bearing tests – Hitesh Halai, Andrew McNamara, Sarah Stallebrass

3.5.1 Background

Current guidance given on plate bearing testing in granular soils suggests that the plate should be at least five times the nominal size of the coarsest material. However this limiting ratio can have a huge influence on the reaction load required from plant and resources when conducted to confirm strength parameters used in the design of the sub grade and platform materials of working piling platforms. The aim of the research was to investigate the effect of particle to plate size to establish, if any correlation existed which would allow the use of a smaller plate size and plant on site to allow more economical plate testing of the platform for design purposes. Different sized model plate bearing tests were carried out in a centrifuge on a large, coarse grained Devonian Limestone. The results from the test series reported show a good similarity in the bearing stress against displacement behaviour between the different plate sizes.

Prior to 2004 several piling rig incidents resulting from improper design and maintenance of working platforms led to the Federation of Piling Specialists (FPS) instigating the preparation of a design guide in collaboration with the Building Research Establishment (BRE). The BRE Report 470, “Working Platforms for Tracked Plant” provides guidance on the design, installation and maintenance of piling platforms and specifically on the determination of the shear strength parameters from the granular fill required for the design of the platform. It is recommended that the characteristic value of ϕ' (critical state angle of friction) be established through the testing of the granular fill under conditions close to those experienced in the field, BRE 470 (2004). One of the testing methods available for determining the strength parameters is plate loading tests as described in BS1377: Part 9 (1990). The strength parameter can then be back calculated using the traditional bearing capacity equations (e.g. Terzaghi (1943); Hansen (1970); Vesic (1973); etc).

Owing to the limits placed on the recommended plate size that can be used by BS1377: Part 9 (1990), carrying out tests at prototype scale can often prove impractical and uneconomical. Whilst the British Standard requirement for plate diameter relates to size of the ‘nominal particle of the coarsest material’.the understanding of the definition of nominal particle size in plate bearing tests for determining the plate size is very vague within industry. A common misconception is that the size to which the standard refers concerns the maximum particle present in the material, Corke (2010a). The aim of the research presented was to investigate the effect of maximum particle on different plate sizes to improve the understanding and possibly allow small scale tests on the material to validate the strength parameters used in design and hence construct a more economical platform as highlighted by Corke (2010b).

3.5.2 Centrifuge modelling

The model plates were driven into prepared soil samples of crushed Devonian limestone from a quarry in Ashburton, Devon, UK, using the motor and screw jack assembly shown in Figure 7. A loading beam attached to the bottom of the screw jack allowed a force plate (consisting of three load cells sandwiched between two stiff plates) and model foundation plate to be attached. The foundation was driven into the soil at a constant rate of penetration of 1mm per minute until a minimum settlement of 0.1B (B = model plate diameter) was achieved. The force plate was used to measure the reaction force of the model foundations when being driven into the soil samples and the reaction force from the loading of the foundation was taken as the sum of the three load cells. The test tub shown in Figure 7 was selected to provide a container to model plate diameter ratio greater than 5 in order to minimise the constricting influence as suggested by Ovesen (1979).

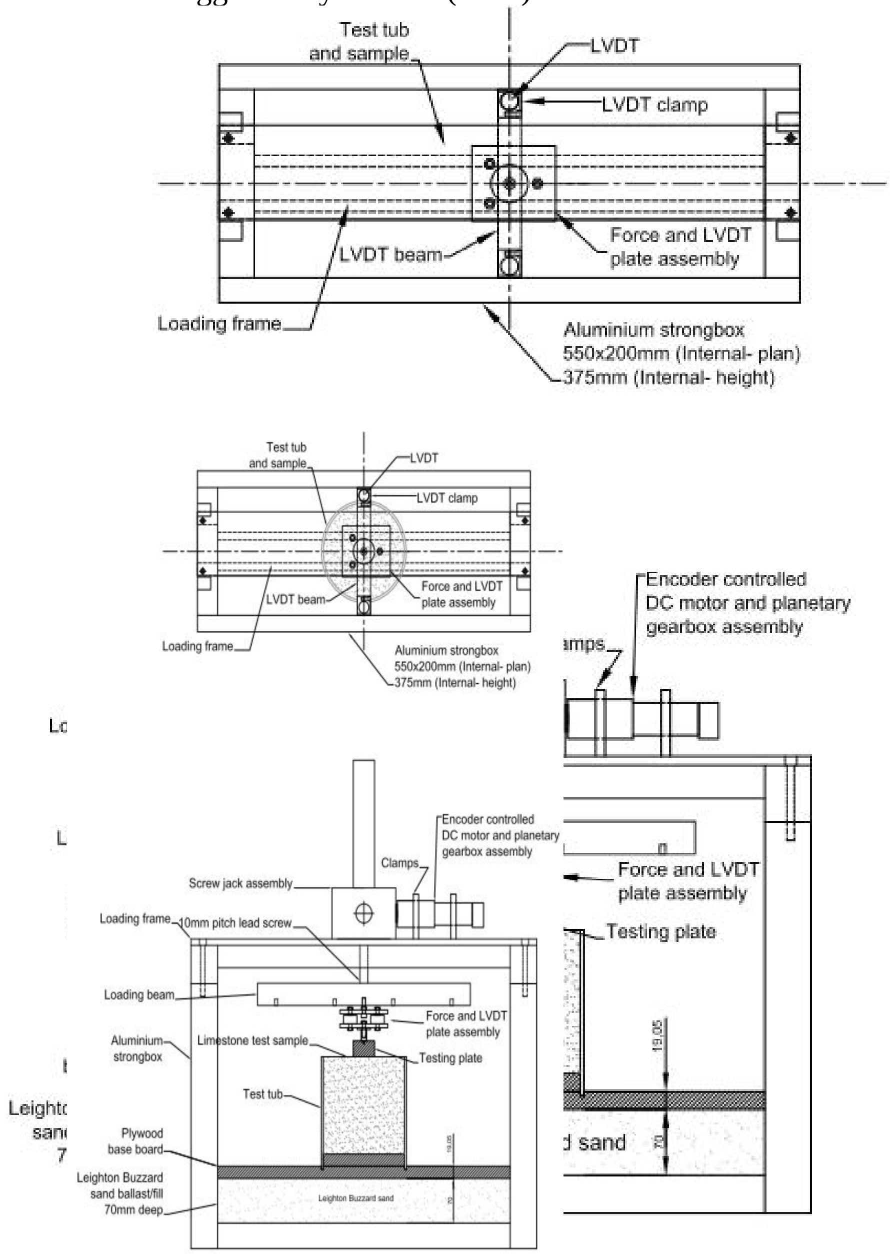

Figure 7. Assembled testing equipment and instrumentation.

It is possible to conclude from the short series of plate bearing tests carried out on a coarse grained single size material that over small strains/displacements there is very little influence of the scale effects between soil and foundation, as shown in Figure 8

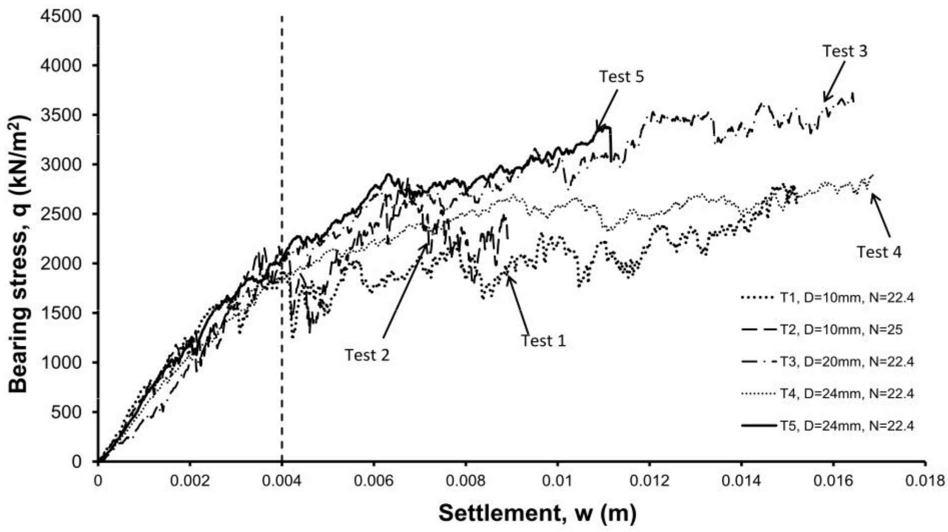

Figure 8. Bearing stress-settlement graph of tests using different plate sizes on the coarse single sized material.

There is currently a larger series of tests being carried out at City University London aimed at further investigation of the effect between maximum particle size and plate diameter. These tests will be conducted on a variety of different gradings including smaller single size gradings, a set of three identical gradings with each being scaled up or down from the other and also on a scaled down grading which closely resembles that of MOT Type 1 or 6F2 materials which are typically used in platform construction. For more information see Halai, McNamara and Stallebrass (2012).

3.6 Centrifuge modelling of tunnelling with embedded forepoles– Ming Xu, Neil Taylor

3.6.1 Background

Ground treatment is usually undertaken from within tunnels with open faces. Advances have been made in soil reinforcement ahead of the face to improve stability and to control ground movements. Improved techniques such as jet grouting (umbrella arches) and forepoling are used to form a pre-lining in difficult or uncertain ground conditions. Forepoling consists of installing longitudinal bars or steel plates at the periphery of the face, typically over the upper third or quarter of the excavated profile. In most cases, hollow pipes are used in lieu of bars, with grout being injected through the pipes.

3.6.2 Centrifuge modelling

Plane strain centrifuge model tests using front face image-processing techniques is an efficient method for investigating subsurface geotechnical scenarios. To determine how the installation of ground supports affects the plastic collapse mechanism surrounding a tunnel excavation the scenario has been simplified into a 2-dimensional plane strain model. This entailed installing a series of “forepoles” (slender resin overlapping pipes) around the periphery of the tunnel face. Unlike umbrella arch layouts, which are inclined during installation, this study’s inclusions spanned the entire plane strain width of the model. Therefore, the study only focused on a single plane of tunnel movement. This is a suitable approximation as all sources of ground movements described in Mair & Taylor (2000), with the exception of face loss, are in the plane perpendicular to the tunnel. The premise being tested is whether or not forepoles installed near the periphery of the face will be able to provide effective support to the tunnel cover, thus reducing the possible damage to nearby building foundations. Interest was focused on shallow circular tunnels, such as those which are often excavated for underground railways. Five different layouts of forepoles were investigated, including one reference test with no forepoles (Figure 9).

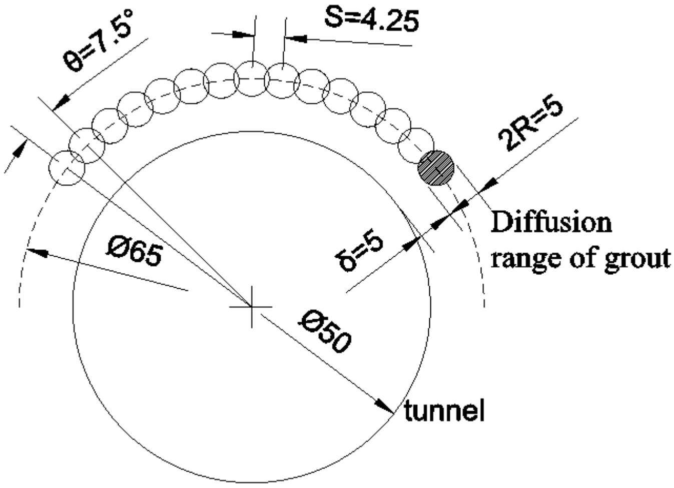

Figure 9: Example of typical reinforcement with all units given in mm (not to scale)

The tests were carried out using plane strain models of a circular model tunnel with D=50 mm and tested at 100g, so the model corresponded to a 5m diameter tunnel at prototype scale. Speswhite kaolin clay samples were used and the tunnel test was an essentially undrained event. Shallow tunnels with C/D (cover to depth ratio) equal to 2 were tested.

Various types of model forepoling arrangements were devised. in which diameter, overlap, distance from the tunnel circumference remained constant but the extent and quantity of the forepoles was varied. The displacement fields in the models were determined using standard displacement transducers at the ground surface and by digital image processing below ground level (Figure 10).

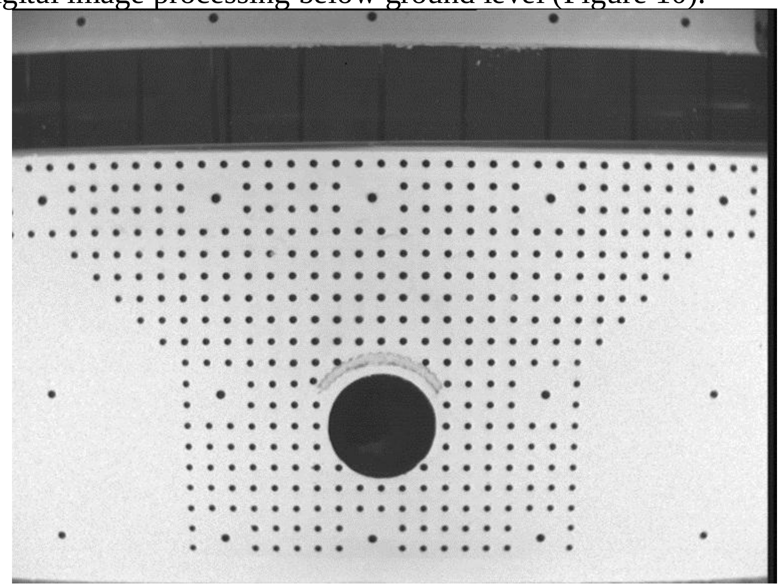

Figure 10 Typical digital image for analysis of plain strain displacements for a tunnel with forepoling.

When forepoling was introduced the proportion of horizontal to vertical displacement appears to decrease above the tunnel axis level whereas an increase was seen below the tunnel axis level compared with the reference test. The horizontal distance from the tunnel centre-line to the point of inflexion of the settlement trough appeared to increase, resulting in 'less severe' surface and subsurface settlement troughs with regard to building damage assessments. It would appear that forepoling changes the position of the failure plane, and spreads the overburden load so that the deep soil carries some of the external load. The presence of forepoling therefore makes the tunnel more ‘stable’. More information can be found in an internal report (City University London, 2012).

4 DATA ACQUISITION DEVELOPMENTS

The instruments that are currently available and capable of operating at high g levels are very limited but nonetheless adequate for simple plane strain events. With the exception of pore pressure transducers all are standard items that were developed for other applications and have been adopted for applications in the centrifuge.

Increasingly, there are opportunities to study problems where the construction process simulated is a truly three-dimensional event. An example of this is the simple case of construction of a foundation pile adjacent to an existing tunnel. Such a construction operation is a common occurrence in reality but it presents an extremely complex three dimensional numerical problem that can only be analysed with a limited degree of confidence. It is however an event that can be reproduced in the geotechnical centrifuge but not easily instrumented. This means that the trend towards modelling of increasingly complex problems is being stifled by the limitations of the available instrumentation. However, there are a number of new technologies that offer genuine and obvious opportunities for application to instrumentation for centrifuge modelling.

These include the use of optical fibres for strain measurement, wireless communication for data acquisition and MEMS (micro-electro-mechanical systems). The use of these technologies is becoming well established within other areas of research and there is now a pressing need to adapt and exploit these methods within geotechnical centrifuge modelling.

The group at City University London is currently adapting and miniaturising existing technologies for use in the extreme high g environment in parallel with the existing activities at the Geotechnical Engineering Research Centre. The design and development of the instruments requires technical expertise from within the group and this will play an important part in the success of the project as will collaboration with other leading research groups within the School of Engineering and Mathematical Sciences. The project therefore interacts with a number of other projects and will allow the instruments to be tested in a very wide range of applications.

The aim is to design and develop a new generation of centrifuge specific data capture, control, imaging and instrumentation that will support ongoing and future projects linked to industry. The instruments will be used in conjunction with the existing very limited instrumentation currently available and will dramatically improve current research outputs. Their use, even at an early stage, will have a major affect on the impact of the research itself as it will demonstrate a marked improvement in modelling capability.

5 THE FUTURE - REACTIVE CENTRIFUGE MODELLING

Some of the first geotechnical centrifuge tests were carried out in the UK in the 1970’s and these were simple tests on embankments. Over the years tests have become more ambitious and complex making use of advanced instrumentation for measurement including close range photogrammetry pioneered at City University London in the 1990’s and refined and developed to include Particle Image Velocimetry (White and Take, 2005). Some groups have also developed sophisticated robots to allow genuine in-flight excavation of soil whereas usual practice is to drain fluids to simulate the stress changes caused by excavation. A current project at the London Geotechnical Centrifuge Centre is likely to be the first to inject grout into a centrifuge model in flight.

Whilst models and techniques have become more complex over the years, they have thus far merely simulated events and observed collapse mechanisms and patterns of displacement. Experiments usually end when a single event has occurred. The aim now is to provide the ability for a new generation of experimental work that will allow the modeller to intervene and react to displacements during an experiment. This would mean that grout could be injected into a model to respond to ground movements resulting from, say, a tunnel excavation.

Amongst the difficulties that need to be overcome from the point of view of control are that events in the centrifuge occur extremely fast since time scales with g^2 when consolidation is the dominant mechanism or with g when dynamics determines the results. The scaling of consolidation with g^2 is often a useful phenomenon when simulating events in clay soils that can take many weeks, months or even years to take place at prototype scale but means that any control system must to be able to react very rapidly to non-linear model behaviour.

The City University London group is aiming to develop a control system to enable displacements to be monitored within our models resulting from some event, understand the magnitude and distribution of movements, and then initiate remedial measures to mitigate the effects.

6 CONCLUSIONS

Centrifuge modeling activity has been a feature of research at City University London for more than 20 years but over the last 10 years has become the main focus with a reduction in element testing and numerical modeling. The emphasis is on investigation of complex problems that cannot easily be investigated by other means and the research has a strong underlying theme of urban construction and sustainability.

The centrifuge is currently undergoing upgrade work to the data acquisition and control system such that it will soon be possible to attempt reactive modeling. If this is successful it will be possible to take centrifuge modeling to a new level.

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