Centrifuge modelling of bored piles in sands

Modélisation en centrifugeuse de pieux forés dans le sable

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ABSTRACT: As part of a series of experiments to investigate the effects of tunnelling on bored piles carried out at the Cambridge University Geotechnical Centrifuge, a new and novel model pile design is presented. The pile is semi-circular in cross section allowing the sub surface displacements around the pile toe to be monitored using particle image velocimetry (PIV). The new pile design, along with the loading mechanism, ensured the load was transmitted predominantly though the pile centroid, which reduced the bending effects which have previously caused significant errors in these types of problem. The pile load cells at the head and the base were also placed along the pile centroid to minimise the effects of bending on the load measurement. The paper presents the results of a centrifuge pile loading test, illustrating the excellent response of the load cells within their working range and the high quality PIV data which was obtained through this novel modelling approach.

RÉSUMÉ : Dans le cadre d'une série d'expériences réalisée dans centrifugeuse géotechnique de l'Université de Cambridge pour examiner les effets tunnels sur les pieux forés, un nouveau modèle de conception de pieu est présenté. Le pieu est semi-circulaire en coupe transversale permettant aux déplacements sous la surface autour de la pointe du pieu d'être surveillés par imagerie de la vélocimétrie des particules (PIV). La nouvelle conception du pieu et le mécanisme de chargement assurent que la charge soit transmise à dominante par le centroïde du pieu, ce qui a réduit les effets de flexion qui avaient précédemment causé des erreurs significatives dans ce type de problème. Les cellules de charge fixées en tête et en pointe des pieux étaient aussi placées le long du centroïde des pieux pour minimiser les effets de flexion sur la mesure de la charge. L'article présente les résultats d'un test de chargement de pieux en centrifugeuse, montrant une excellente réponse des cellules de charge dans la zone de travail et la grande qualité des données PIV obtenues par cette nouvelle approche de modélisation.

KEYWORDS: pile settlement centrifuge bored tunnelling base PIV modelling

1 INTRODUCTION

The ability to predict the effect of tunnelling on piles is increasingly important no only from a safety, but also economic point of view. To provide a better understanding of the mechanisms influencing the effects of tunnelling on bored piles in sands centrifuge modelling has been carried out at the Cambridge University Geotechnical Centrifuge (Schofield 1980).

A significant amount of research work at Cambridge and worldwide in recent years has been carried out using particle image velocimetry (PIV) developed at Cambridge (White et al. 2003) as a tool to understand subsurface mechanisms for soil-structure interaction problems. The ability of this method allows both 2D plane strain and 3D plane of symmetry problems to be modelled. The latter of these methods was used in this research using plane strain (2D) tunnelling movements and applying these to a non plane strain (3D) pile loading setup.

As part of this research work a novel pile and pile loading system were designed at Cambridge University to model bored pile behaviour in sands and it is the pile design aspect of the research which is described in detail within this paper.

1.1 *Background*

Accurate modelling of plane of symmetry pile behaviour in the centrifuge has been attempted by previous researchers (Marshall 2009 and Lu 2010) however a major drawback has been the difficulty in providing an accurate measurement of the axial pile load.

The cross section of a plane of symmetry pile is semi-circular; this creates a variation in the flexural stiffness of the pile in its two principal bending modes. This results in the piles having a propensity to bend towards or away from the plane of symmetry (its minor axis) rather than parallel to the plane of symmetry (its major axis), see Figure 1.

This bending can lead to significant errors when strain gauged load cells (Marshall 2009) are used to measure the axial load of the piles such that their accuracy cannot be relied upon.

Loading these piles has also proven to be difficult owing to their position within a centrifuge package (extremely close to the plane of symmetry). This has previously prevented researchers from loading these piles within their centroid accurately and hence led to greater bending problems. Loading along the centroid of the piles at the pile head and placement of the strain gauged load cells along the pile centroid would allow a significant proportion of this error to be mitigated through bending compensation within the strain gauge bridges.

Placement of strain gauges on the centroid of a plane of symmetry pile has been attempted previously (Lu 2010) however as the strain gauged bridges were only 'quarter' Wheatstone Bridges these still suffered from a lack of true bending and temperature compensation. However the results were shown to be a significant improvement on the attempts to position strain gauged load cells away from the pile centroid.

2 PILE SPECIFICATION

To produce a pile and pile loading system capable of high quality bored pile behavioural simulation a wholly new design was required of both the pile and the pile loading system.

2.1 *Pile Cross Section*

Researchers in the past have used a single wall to represent a series of piles to simplify the problem to 2D plane strain (White and Bolton 2004), while others have used square piles to simulate the behaviour of circular piles.

Such solutions are not suitable for the problem type given the inherent 3D nature of the problem and the significant edge effects when using a plane of symmetry respectively. As such a semi-circular design was deemed most appropriate to provide the correct 3D stress and strain field around the pile.

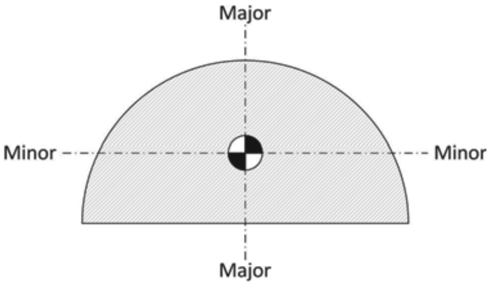

Figure 1. Schematic cross section of plane of symmetry pile.

2.2 *Axial Load Measurement*

Shaft friction piles in the centrifuge have previously been shown to produce inaccurate mechanisms for piles in sands. The effect of shear band dilatancy on lateral stresses conditions means that neither the load nor the mobilisation strain along the shaft can be replicated concurrently (Lehane et al 2005).

To remove this error and to investigate a worst case scenario of an end-bearing bored pile in sand, the shaft was sleeved against friction.

Following on from this it was therefore only necessary to measure the load at the pile head and base to ensure that the sleeving was working.

In an attempt to reduce the errors associated with pile bending on axial load measurement load cells situated along the pile centroid were considered a suitable option.

2.3 *Loading System*

The pile loading system was designed to ensure that loading remained through the centroid of the cross section and simulated a bored pile. (This system is described in detail in Williamson 2013).

2.4 *Final Specification*

The final specification was therefore set based on the requirements described:

- Pile to be semi-circular in cross section
- Axial load measurement at head/base
- Smooth face of shaft
- Pile must remain in contact with symmetry plane
- Loading through pile centroid
- Load measurement along pile centroid
- Loading to simulate bored pile behaviour

3 PILE DESIGN

The final pile design is shown in Figure 2.

3.1 *Pile Body*

The pile body was machined from 2014-T6 aluminium, with aluminium strain gauged load cells attached at the head and the base. The pile was 15 mm in diameter and had an overall length of 355 mm including the base and load cells.

3.2 *Load Cells*

The load cells were connected as full Wheatstone Bridges with 4 No 350 Ω strain gauges used, 2 active and 2 inactive.

These load cells are situated precisely on the centroid of the pile and connected securely between the pile shaft and base.

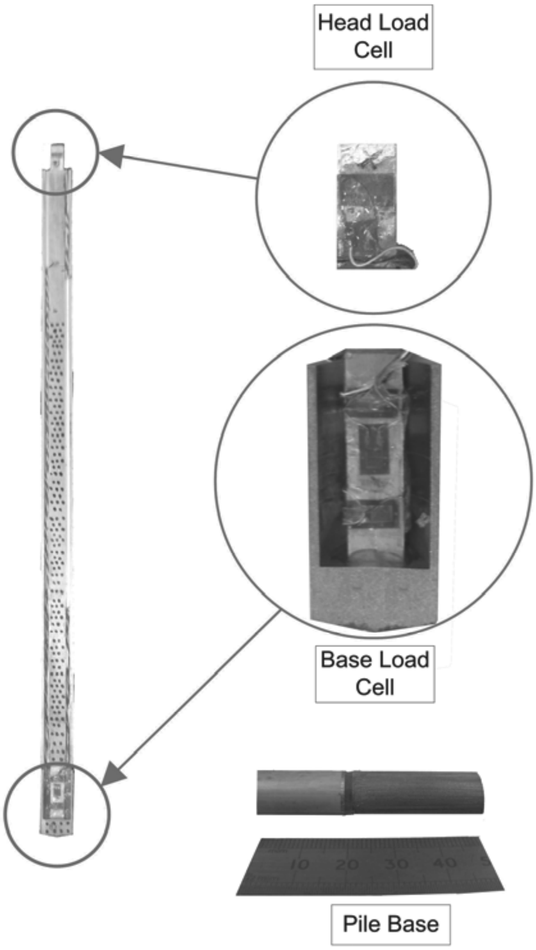

Figure 2. Final pile design.

3.3 *Calibration*

The pile load cells were calibrated before and after being affixed into the piles. This was to investigate the effect of bending during calibration resulting in the considerable free length of the pile which has previously found to be an issue (Marshall 2009).

A new calibration setup was designed to better replicate the effective lengths in the centrifuge (~75 mm), which were small in comparison with the overall free length of the pile (355 mm).

A comparison in the calibration factors between a load cell calibrated individually and the same load cell within the pile is shown in Figure 3. Clearly the agreement between the calibration factors was good, and hence the system was then taken forward to be used in the centrifuge where the effects of high acceleration loads could be tested on the pile.

4 CENTRIFUGE SETUP

4.1 *Centrifuge Package and Instrumentation*

The centrifuge setup consisted of a strongbox, with a loading frame/system and PIV cameras/lights (see Figure 4). The strongbox had a Perspex face against which the piles rested, a steel U-frame and an aluminium back, which provided very high stiffness boundaries around the soil.

The PIV markers were calibrated against known target positions. The pile displacements measured through PIV, were also monitored with linear variable differential transformers (LVDT's).

To verify the values provided by the head and base load cells, Novatech F259 Miniature Diaphragm 1 kN Loadcells were attached to the loading system so that the change in head load could be measured independently.

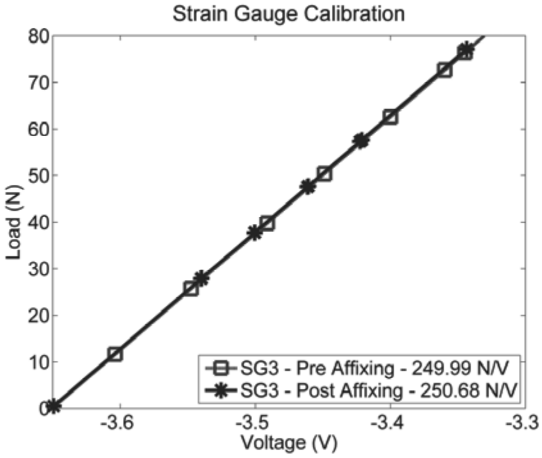

Figure 3. Pile calibration – before affixing to the pile body and after affixing to the pile body.

4.2 *Sand*

The piles were placed firmly against the Perspex face and the sand rained down over them. Fraction E Leighton Buzzard Sand was used in the experiments at a relative density of 76% ±2%.

4.3 *Experimental Procedure*

Piles A and B (see Figure 4) were used to provide data on the effects of tunnelling on bored piles, whereas Pile C was used to provide details of the pile capacity and load settlement response.

The centrifuge was accelerated slowly to the desired 75g, with photographs being taken from each of the PIV cameras at various stages. The pile loads were monitored during the acceleration phase after which loads were added to the pile heads using a specially designed loading system, which applies only the dead load of a pile cap for Piles A and B.

Pile C had a different loading system which also did not apply any load until the desired 75g had been reached. This pile also had a pile cap but with a loading pin capable of applying a head beyond that of the cap dead weight.

All the piles were sleeved to the base (for details see Williamson 2013) so that only the base component was a factor in the pile loading.

5 RESULTS

5.1 *Load Cell Response*

The response of the load cells to the changing head load for Pile C is shown in Figure 5.

Clearly the comparison between the commercially available Novatech head load cell and the response of the new strain gauged load cells is very good compared with the ideal 1 in 1 slope. No greater than 8% variation between the different types of load cell is found.

The variation between the head and base load cell response is relatively constant at around 80 N between 420 N and 1000N. It was found that the pile toe began to move away from the face slightly at 1000 N and hence the divergence is likely to be attributed to some high level bending to the base load cell.

Piles A and B operate at working loads of between 100 and 120 N depending upon the experiment. Within this range the variation between the change in head and base loads is small, but the incremental loading is shown to be linear. This would perhaps indicate slightly higher amounts of bending on the head load cell. The calibration factors for the head load cells though linear were slightly less consistent throughout the tests than the base load cells. It is thought that their shorter length and the slight inconsistency in the contact point between the pile cap and the load cell could have affected the calibration factor, though it was shown to vary by no more than 10 % throughout the test series.

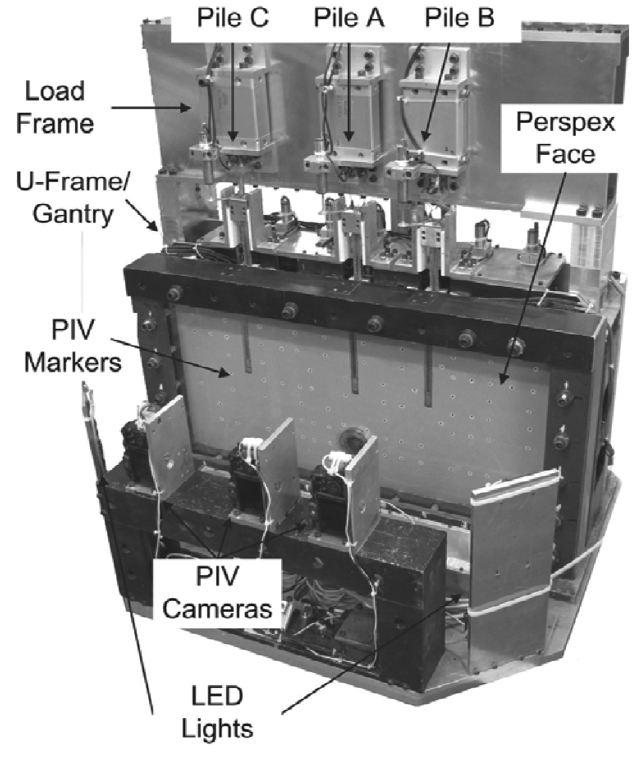

Figure 4. Centrifuge setup – illustrating the piles, loading system and PIV setup.

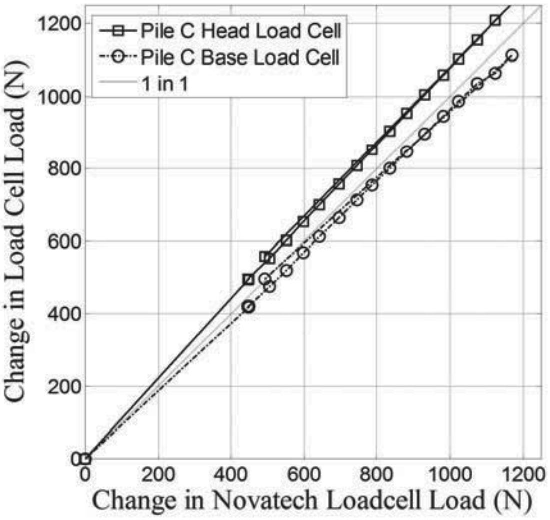

Figure 5. Pile C load cell response – comparison of novel load cells with commercially available Novatech head load cells.

5.2 *Load Settlement Response*

The PIV response of the pile toe and the surrounding soil is shown in Figure 6 for the load relating to 10% of the pile diameter or 520 N (2.8 MPa). The data around the pile toe is of exceptional quality, and it is possible to see the rigid cone beneath the pile toe with the emanating strain bulb centred beneath the pile toe.

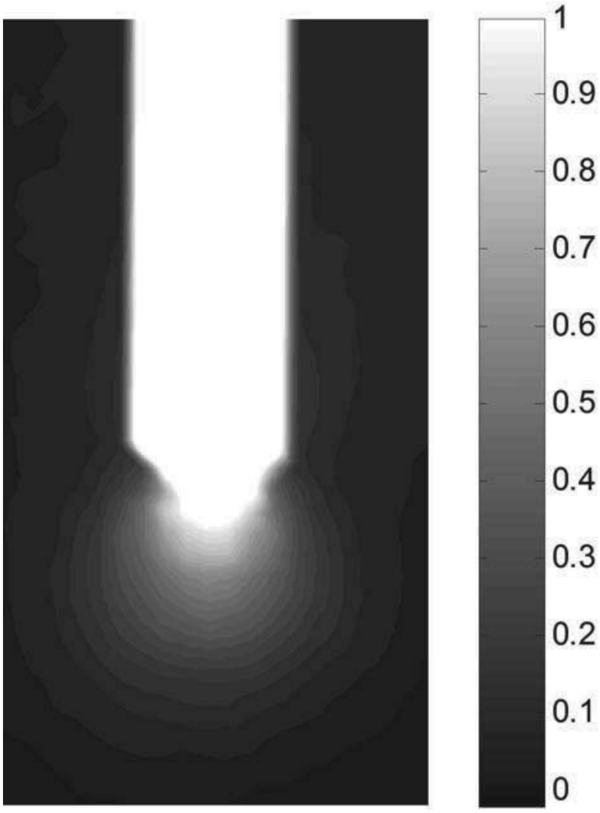

Figure 6. Vertical displacement contours (mm) at a pile displacement of 10% D_{Pile}.

6 CONCLUSIONS

The paper has presented and discussed the details of developing and testing a novel model pile loaded in the centrifuge using a novel pile loading setup. The new pile, which adopted a semi-circular cross-section and was sleeved along its shaft to minimise friction, enabled a test load from the loading setup to be predominantly transmitted axially along the pile with minimal bending effects, which have been traditionally difficult to deal with. Within the working load range, the variation between the change in head and base loads was found to be very small. The vertical displacement PIV data at the pile toe shows the importance of the modelling details in obtaining high quality data.

7 ACKNOWLEDGEMENTS

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