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The influence of tunnelling on piled foundations

L'influence de l'excavation des tunnels sur les fondations profondes

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ABSTRACT

A study of the influence of tunnelling on piled foundations was recently completed at the University of Cambridge. The study focussed on tunnelling near driven piles in dense sand and was carried out by means of centrifuge modelling. This paper presents a summary of the main findings, describing the mechanism controlling tunnelling-induced pile behaviour, a zone of influence around the tunnel where piles might be affected and recommendations for tunnelling near piles in practice. Both single piles and pile groups are considered.

RÉSUMÉ

L'influence de l'excavation de tunnels sur les pieux a été étudiée récemment à l'université de Cambridge. La recherche s'est concentrée sur l'excavation de tunnels à proximité de pieux foncés dans des sables denses et a été effectuée par modélisation en centrifugeuse. Cet article décrit un mécanisme de comportement des pieux influencés par l'excavation de tunnels et définit une zone d'influence autour du tunnel où les pieux peuvent être affectés. Des recommandations pratiques sont proposées. Les pieux isolés et les groupes de pieux sont considérés.

1 INTRODUCTION

Due to the congestion associated with urban centres, tunnel construction regularly encroaches on the foundations of nearby structures. This is especially applicable to piled foundations which often extend to the depths at which tunnels are constructed. In the design of a tunnelling project it may be important to evaluate the impact of the tunnelling activities on such foundations. Few case studies reporting on tunnel-pile interaction problems are available in the literature and considerable uncertainty exists regarding the effects of tunnelling near piled foundations. This could result in very conservative an hence costly solutions being adopted where this problem has to be confronted.

A study was undertaken at the University of Cambridge to examine the effects of tunnelling on piled foundations by means of centrifuge modelling. The study comprised a series of parametric studies in the centrifuge to model the interaction between tunnelling-induced ground movements and driven piles installed in dense dry sand. Of particular interest during this study was tunnelling-induced pile settlement as non-uniform foundation settlement is likely to result in the most critical tunnelling related impact on affected structures.

This paper presents a brief description of the centrifuge model, tunnelling-induced settlements and load changes on single piles and pile groups, as well as limited recommendations for the evaluation of tunnel-pile interaction problems.

2 CENTRIFUGE MODEL

The centrifuge model is described in detail by Jacobsz (2002) and Jacobsz *et al*. (2004) and only a concise description is presented here. Due to practical constraints the model was constructed at a scale of 1:75.

The model was assembled in an aluminium alloy strongbox measuring 750 x 400 x 470mm deep. This represents dimensions of 56 x 30 x 35m deep at the prototype scale.

The diameter of the model tunnel was 60mm, representing a prototype tunnel diameter of 4.5m. The centreline of the model tunnel was located at a depth of 286mm below the sand surface, i.e. 21.5m at the prototype scale. The model tunnel comprised a brass pipe with an outer diameter of 50mm surrounded by a 1mm thick latex rubber membrane. The 4mm thick annulus between the pipe and membrane was filled with water which could be extracted accurately to impose volume losses from 0% to approximately 20% on the surrounding sand. It was intended to use the model tunnel to impose relatively realistic plane-strain tunnelling-related ground movements on the surrounding ground, rather than model the progressive advance of a tunnel face.

A number of instrumented model piles were located at various offsets and to various depths during the centrifuge tests comprising the parametric study. During model preparation the piles were installed to 25mm from their final depths. The piles were jacked the remaining 25mm to their final depths during the centrifuge tests using pneumatic actuators which were subsequently retracted. The piles were kept loaded throughout the tests by means of brass weights sized to exert realistic service loads of approximately 50% of the ultimate pile capacity.

The aluminium alloy model piles had an outer diameter of 12mm, i.e. 900mm at the prototype scale and were installed to depths of 200mm (15m) and 250mm (18.75m) during the tests. The piles were instrumented with load cells along their shafts and at the base to enable volume loss-induced load changes to be monitored. One pile was equipped with stress cells to measure the normal stress acting on the pile shaft in addition to the axial load distribution.

The strongbox was filled by pluviating dry fine silica sand (Leighton Buzzard sand) from a hopper at a constant fall-height and flow rate parallel to the tunnel axis. The grading of the sand ranged from 90µm to 150µm. A relative density of approximately 75% was achieved.

During each centrifuge test, the centrifuge was accelerated to 75g. Once at 75g, the piles were jacked 25mm to their final depths after which the actuators were retracted. Volume loss was then imposed from 0% to 20% after which the centrifuge was stopped. During the tests the sand surface settlement and pile settlement were measured using LVDTs. The load distribution on the piles was measured using the load cells on the piles.

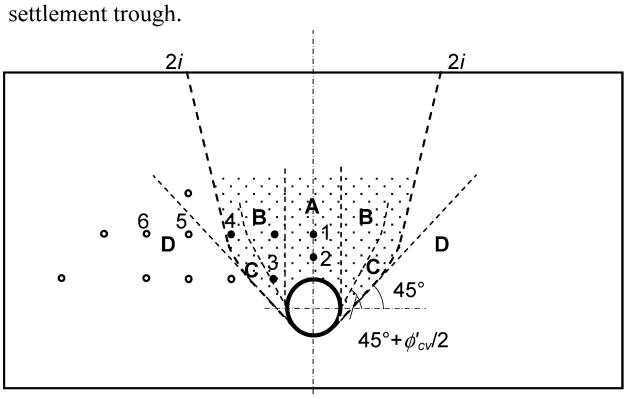
The internal tunnel pressure was measured as well as the tunnel wall displacements using miniature hinged extensometers.

3 TUNNELLING-INDUCED PILE SETTLEMENT

Single piles were tested, installed at various offsets from the tunnel centreline and to the depths mentioned above. Piles with their bases installed close to the tunnel were observed to initially settle by an amount similar to the sand surface, but the settlement soon accelerated, causing the piles fail rapidly once a certain volume loss was exceeded. The acceleration in pile settlement tended to occur between volume losses of 1% to 1.5%, values often encountered during tunnelling projects in practice. More detailed settlement records for the individual piles are given by Jacobsz *et al*. (2004).

The greater the distance between the piles and the tunnel, the more gradual the settlements were that took place. Beyond a certain distance piles did not exhibit an acceleration in settlement with increasing volume loss, but the settlement tended to stabilise as volume loss increased. The pile settlements observed during the parametric study are summarised in Figure 1, showing a shaded zone of influence around the tunnel in which a potential for large pile settlements exists. For the purposes of the investigation "large" refers to settlements in excess of 20mm at the prototype scale. The small circles in the figure represent the positions of pile bases tested during the parametric study.

The zone of influence appears to emanate from near the tunnel springlines, initially at an angle of approximately 45°, but soon narrowed towards the surface away from the tunnel. An upper boundary for the zone of influence was not investigated, but it appeared that for the geometry analysed in this study, the zone of influence intersects the surface at a distance of $2i$ from the tunnel centreline, where i refers to the distance from the tunnel centreline to the inflection point on the Gaussian surface settlement trough.



● Piles that underwent large settlements (in excess of 20mm at prototype scale).

o Piles that underwent small settlements (less than 20mm at prototype scale).

Area where "large" settlements might be expected .

Figure 1. Zone of influence around tunnel in which potential for large pile settlements exists.

The zone on influence can be further sub-divided based on the amount of settlement that the piles had undergone at a volume loss of 1.5% relative to that of the surface. Piles with their bases located within zones A and C settled by an amount very similar to that of the surface. However, piles with their bases located in zone B suffered larger settlement than at the surface, while piles with bases located outside the zone of influence (zone D) always settled less than the surface.

4 TUNNELLING-INDUCED LOAD CHANGES ON PILES

Load cells located in the bases of the instrumented model piles enabled changes in the pile base loads to be monitored in response to tunnelling-induced volume loss. Normalised base load records are presented against volume loss in Figure 2. The locations at which the various base load records were obtained are indicated in Figure 1. Note that two curves are presented for pile positions 1 and 3 as these tests were repeated. The closeness of the curves illustrates the repeatability of the tests.

Figure 2 shows that the loads mobilised on the bases of piles within the zone of influence identified in Figure 1 reduced with volume loss. As a constant load was maintained by the brass weights on the pile heads, positive shaft friction had to be mobilised on the pile shafts to maintain the piles in equilibrium. Rapid pile settlements occurred once the maximum shaft capacity was mobilised.

The bases of the two piles tested at position 1 (Figure 1) were located 56mm or 0.93D above the tunnel crown. The base loads reduced rapidly between volume losses of 0% and 1.5%. Beyond 1.5% the base loads remained constant as the pile settlement accelerated rapidly with increasing volume loss.

The effect of having the pile base closer to the tunnel is illustrated by the result for a pile installed to 31mm or 0.52D above the tunnel crown (position 2 in Figure 1). This pile suffered a very rapid reduction in base load as volume loss commenced and settled very rapidly by a large amount at 0.5% volume loss.

The base load on piles installed at position 3 (Figure 1), i.e. at an offset of 0.83D from the tunnel centre-line and to a depth of just 0.1D above the tunnel crown, reduced at a similar rate to that of the piles at position 1, as shown by the results from two tests in Figure 2. Due to the greater depth of these piles, higher loads could be supported by the shafts, so that the amount of base load reduction that they could sustain before failure was larger. It should be noted that the base loads did not stabilise as in the case of piles in zone A, but continued to reduce with volume loss. This pile position falls within the zone relative to the tunnel where the most intense shearing occurs (see shear strain distributions around tunnels by e.g. Cording & Hansmire, 1975). The shearing is accompanied by dilation resulting in a continued gradual increase in stress levels with volume loss, enabling larger shaft loads to be supported as volume loss increases.

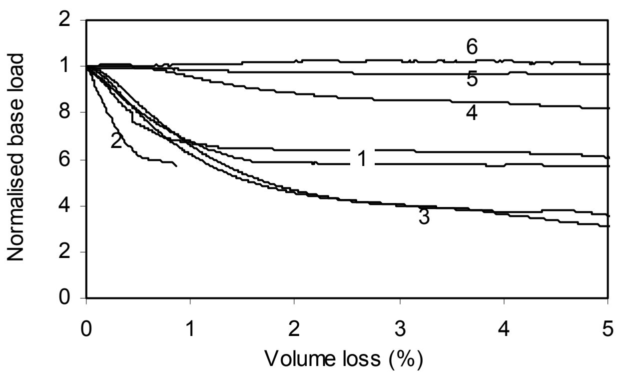


Figure 2. Normalised pile base loads against volume loss.

The base load of the pile installed to position 4 reduced more gradually than in zones A and B, so that the full shaft capacity was not mobilised even at a volume loss of 5%. The result is typical of the transition zone between the main zones of influence (zones A and B) and the zone where base load reduction did not occur (zone D). A small increase in base load was registered on the pile at position 6. This is probably the result of downward soil movements against the upper parts of the piles shaft while the pile base remained stationary outside the zone of influence.

5 SUBSURFACE SETTLEMENT AROUND SINGLE PILES

Tunnelling-induced ground movements in soft ground usually manifests at the surface as a Gaussian shaped settlement trough (Peck, 1969). Several methods are available for the calculation of tunnelling-induced subsurface ground movements under Greenfield conditions (Mair *et al.*, 1993, New & Bowers, 1994 and Loganathan & Poulos, 1998). These methods all predict an increase in subsurface settlement from the surface towards the tunnel, accompanied by a narrowing of the subsurface settlement trough. The question arises how these tunnelling-induced ground movements would influence the stress distribution along the shaft of a pile installed above the tunnel.

In the centrifuge tests, piles installed above the tunnel settled by an amount equal to that of the surface even up to volume losses of 1.5%. These piles also underwent a large reduction in mobilised base loads as volume loss occurred, resulting in the mobilisation of positive friction against the pile shaft. If the piles were to settle by an amount equal to the surface and subsurface settlements were to increase with depth as predicted by the Greenfield models, negative shaft friction would be expected against the pile shaft. This did however not occur, illustrating that the presence of piles alters the Greenfield subsurface settlement profile. In addition to the shear load that piles impose on the soil surrounding their shafts, significant normal stresses are also exerted. This increases the stress level and hence stiffness of the soils surrounding the pile shaft, resulting in an altered subsurface settlement profile in the vicinity of the pile.

6 PILE GROUPS

In addition to the tests on single piles, tests were also carried out on groups of respectively two and three piles at various locations relative to the tunnel. The service weights on the pile caps were bolted together to simulate rigid pile caps.

The basic behaviour of pile groups were similar to that of single piles, i.e. the base load on piles near the tunnel reduced, resulting on the mobilisation of positive friction against the pile shaft. The base load reduction however occurred somewhat more gradually than in the case of single piles, probably due to the stiffening of the ground by the larger number of loaded piles. In addition to base load reduction, another mechanism possible within a group of piles is the transfer of load within the group from one pile to another as the load carrying capacity on certain piles reduces. The behaviour observed within a pile group is well illustrated by a group of three piles with the first pile located at position 1 in Figure 1 (pile a), the third pile at position 4 (pile c) and the second pile in between (pile b).

Figure 3 illustrates the pile settlement and rotation of the group. As volume loss progressed little settlement initially occurred. By around 1.5% volume loss, the settlement of the pile closest to the tunnel (pile a) exceeded 20mm at the prototype scale and pile group rotation became significant. At 2.5% volume loss the settlement of piles a and b accelerated, causing the pile group to rotate rapidly towards the tunnel. During this time pile c appeared to heave upwards. At 3.5% volume loss all piles began to settle at roughly the same rate so that the pile group did not rotate further as it settled.

Changes in the mobilised shaft loads on the individual piles during the volume loss process explain the pile behaviour. Figure 4 illustrates the head, base and shaft loads on the piles comprising the group.

As volume loss increased, the base loads on piles a and b (Figure 4(b)), located in zones A and B of the zone of influence, began to reduce, mobilising the individual pile shaft capacities (Figure 4(c)). At around 1.5% volume loss the mobilised shaft load on pile a began to level off, suggesting that its shaft capacity was being approached. At this point the rotation of the pile group became noticeable as this pile could not support further base load reduction without suffering significant settlement. Examination of the head loads shows that load was gradually being transferred to piles b and c (Figure 4(a)).

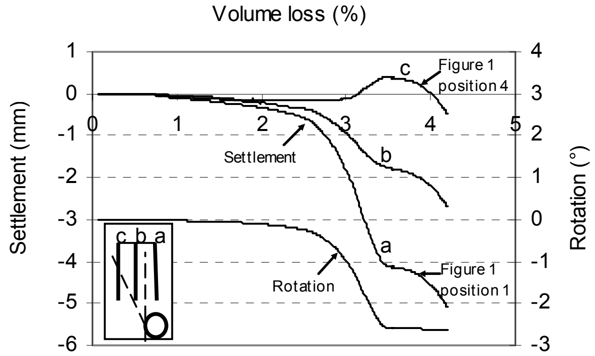


Figure 3. Settlement and rotation of triple pile group.

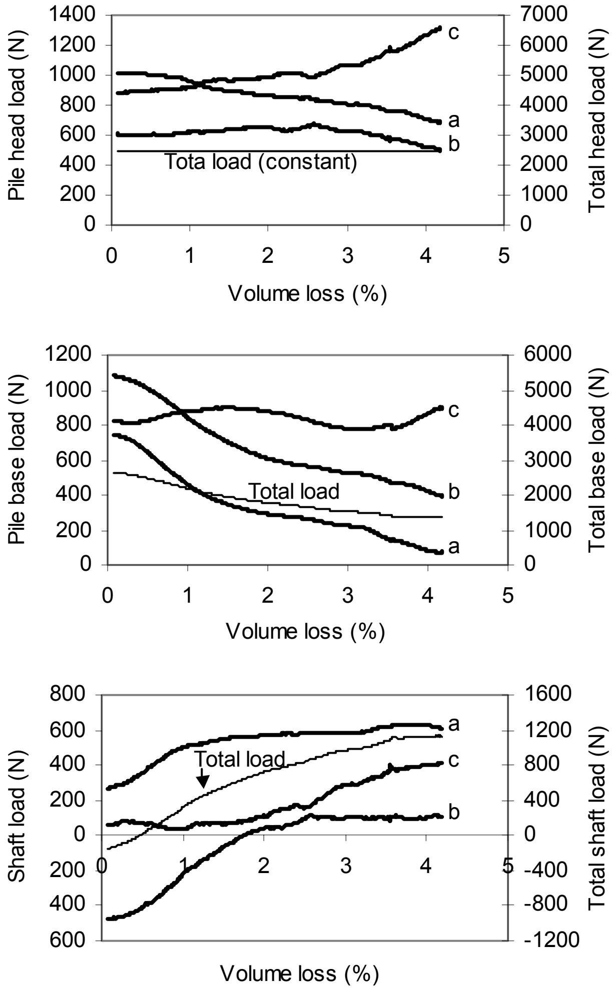


Figure 4. Load distribution on triple pile group.

At around 2.5% the shaft capacity of pile b had also been mobilised so that its settlement also accelerated (Figure 3). By now piles a and b could not support further base load reduction and the pile group began to rotate rapidly towards the tunnel, pivoting around pile c and transferring a considerable amount of load to it (see pile head loads, Figure 4(a)). This soon resulted in the mobilisation of the full shaft capacity of pile c. Once the shaft capacity of pile c had been reached, no further base load reduction was possible without further settlement. All three piles began to sink into the sand at the same rate, so that further rotation stopped. During this interval, base load reduction on piles a and b was compensated for by a base load increase on pile c as it penetrated deeper into the sand outside the zone of influence (Figure 4(b)), while the mobilised shaft loads on all three piles remained constant (Figure 4(c)).

Differences in the maximum shaft capacities of the three piles are probably related to the distribution of volume loss-induced soil movements around their shafts and also pile group effects.

The trends exhibited by triple pile groups at greater offsets from the tunnel than described here were similar, but as these groups had fewer piles in the zone of influence, they suffered smaller settlements and rotations. Load transfer between piles was more noticeable in the group discussed than in groups at a greater offset as load was transferred from two piles in the influence zone to one outside it. Significant load transfer only occurred at large volume losses (i.e. above 5%) in other pile groups investigated. More information on pile groups is presented by Jacobsz *et al*. (2004b).

7 CONCLUSIONS AND RECOMMENDATIONS

Tunnel construction results in stress relief in the ground, resulting in a reduction in the magnitude of the loads that can be sustained on pile bases. As the base loads reduce more load has to be mobilised on the pile shafts to ensure equilibrium. This is accompanied by a small amount of differential settlement between the pile and the surrounding ground (typically less than 3mm at the prototype scale). Once the maximum shaft capacity has been fully mobilised rapid pile settlement follows.

A zone of influence around a tunnel was presented in which significant base load reduction, accompanied by large pile settlements, are possible should a certain volume loss be exceeded. It is therefore essential to carefully control volume losses where pile bases carrying significant base load occur within the zone of influence. Piles with their bases outside the zone of influence did not suffer large settlements even at volume losses up to 10%.

The stresses exerted by piles on the surrounding ground result in a subsurface settlement profile differing from the Greenfield situation. Pile settlements can however be approximated by the Greenfield surface settlement should the pile shaft capacity not be exceeded due to volume loss.

The piles in the centrifuge study possessed significant reserve (unmobilised) shaft capacity. Should piles not have reserve shaft capacity, e.g. where piles are end-bearing in sand with the shafts surrounded by soft clay, volume loss may cause more rapid settlement than presented here.

Pile groups behave in a similar fashion to volume loss than individual piles. Load transfer from one pile to another within a group only occurs once the shaft capacity of a given pile has been mobilised causing its settlement to become significant. In the pile groups investigated this usually occurred at large volume which are undesirable in practice.

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