5ICEGE
5th International Conference on Earthquake Geotechnical Engineering
January 2011, 10-13 | Santiago, Chile
Paper No. EOPHA

EFFECT OF PILE SPACING ON THE BEHAVIOUR OF A PILE GROUP IN LATERALLY SPREADING SOIL

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ABSTRACT

Despite significant recent progress, there are many aspects of the interaction between pile foundations and laterally spreading soil that are still not well understood, one of which is the influence of pile spacing on the response and performance of the foundation. The design and results of two dynamic centrifuge tests, conducted to directly investigate this relationship, are outlined here. In both tests, rigid rotation of the foundations occurred, apparently as a result of insufficient fixity provided to the piles by the dense base soil in which the pile tips were embedded. This suggests that pile tip fixity conditions must be carefully considered in the analysis and design of pile foundations in soils that may undergo lateral spreading.

Keywords: Lateral spreading, pile foundations, pile spacing, liquefaction, centrifuge modelling

INTRODUCTION

For most strong earthquakes, for as long as records have been kept, accounts of damage to pile foundations passing through liquefiable soils can be found, although the precise cause and full extent of the damage were not necessarily recognised at the time. In fact, it was only following the widespread liquefaction-induced failure of structures and services in the 1964 Niigata earthquake (many of which were supported by piles) that the engineering significance of seismic soil liquefaction was widely acknowledged. Engineering design codes were subsequently amended to allow for the potential for near-complete loss of stiffness and strength of saturated, fine granular soils accompanying any strong ground motion (Berrill and Yasuda, 2002). In spite of this apparent improvement of engineering practice, foundation failures have continued to occur (Finn and Fujita, 2002), emphasising the vulnerability of piles to liquefaction-induced damage and exposing the unaddressed inadequacies of seismic design methods. Furthermore, the extensive field evidence gathered following the 1995 Hyogoken-Nambu (Kobe) earthquake (Tokimatsu and Asaka, 1998; Finn and Fujita, 2002) made clear the potential for the liquefying soil to be a critical agent driving the deformation of the foundation (in contrast to the conventional scenario in which the soil acts to resist any foundation displacement).

The gross permanent soil displacement associated with the lateral spreading of liquefied soil and the severe kinematic demands this displacing soil can place on any foundation or buried structure are now widely acknowledged. However, many fundamental aspects of the interaction between pile foundations and laterally spreading soils are at present unknown, and there exists no generally accepted method for the design of such foundations. In particular, the influence of basic foundation properties, such as pile

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spacing and pile cap embedment, on the demands on the foundation and its subsequent performance are at present unclear.

Given that the mechanisms of interaction between pile groups and laterally spreading soils are only approximately understood, and the link between variations of the soil, pile, and demand characteristics, the mechanism of interaction, and the subsequent foundation performance are not well established, we have elected to explore this interaction using centrifuge model tests of simplified, idealised pile groups in laterally spreading soil. This paper focuses exclusively on the influence of pile spacing on the foundation behaviour as inferred from these centrifuge tests, the discussion starting from the already-established understanding of spacing effects on the behaviour of pile groups under static, active loading. Also touched on is the design of the model pile group used in the centrifuge tests, whose modular nature permits the straightforward reconfiguration and reuse of instrumented and non-instrumented piles and the interchanging of pile caps.

In recognition of the preliminary stage of this project and the considerable uncertainties to be addressed, we do not offer here definite conclusions regarding the influence of pile spacing on pile group performance, but rather suggestions and ideas for further investigation and discussion based on the findings to date. Particular effort is made to discern those aspects of the model behaviour truly capturing the behaviour of foundations in real life from those that are artefacts of the modelling process and test design.

PILE SPACING EFFECTS ON LATERAL PILE RESPONSE

It is helpful to review some of the established understanding of the lateral response of pile groups subjected to conventional static demands, before examining in more detail their response in liquefying and laterally spreading soil. The term ‘group effects’ refers to the influence of piles on the behaviour of other piles nearby. Group effects for laterally loaded piles can be broadly categorised as either structural, where the piles influence each other as a result of a direct structural connection, or soil-deformational, where the deformation of soil around a given pile is altered by nearby piles (the piles need not be directly connected for this sort of interaction to take place) (Cubrinovski and Ishihara, 2007). Depending on the fixity conditions of the piles and their relative spacing as compared to their (effective) length, more or less of the lateral demand is resisted by frame action of the pile-pile cap-pile structure. The lateral and axial resistance offered to the piles by the soil will, of course, also affect the response.

In studies of soil-deformational group interaction, the distinction between perpendicular (i.e. side-by-side) and parallel (i.e. front-to-back or ‘shadowing’) interaction effects is usually made, and particular attention is given to the influence of pile spacing (typically measured in pile diameters) on the extent of the interaction. Extending our understanding of the nature of soil deformation around single piles, the side-to-side interaction can be thought of as an overlapping of shear wedges (Figure 1) or zones of plastic flow. The nature of shadowing interaction is more intuitively obvious, the soil between the leading and trailing piles being displaced (in the case of active loading, Figure 2a) or ‘held-up’ (in the case of passive loading, Figure 2b) such that the relative soil-pile deformation between trailing piles and the intermediate soil is reduced (Brown et al., 1988) and the mobilised soil resistance is altered such that, for example, the typical shear wedge is unable to form.

As emphasised by Bransby (1996), the distinction between active and passive loading is also important when analysing pile interaction effects on the mobilisation of lateral resistance to pile displacement. On the basis that the deformation of the soil near the piles controls the mobilised lateral resistance, and that the closer the piles, the harder it is for the soil to 'squeeze' through the space, it is clear that the soil driving passive piles must mobilise greater stress to achieve the same pile displacement (as compared to more widely spaced piles). Correspondingly, the displacement of actively-loaded piles for a given applied force is greater, the closer the spacing, as the soil is less able to deform and mobilise resistance. Passive piles should thus experience stiffened force-displacement response and active piles a softened force-displacement response due to side-by-side pile-soil-pile interaction.

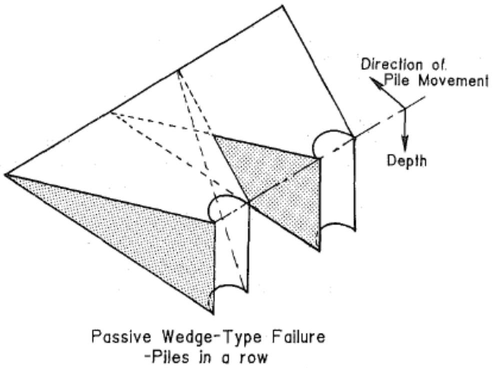


Figure 1. Overlapping shear wedges of piles in the same row (from Brown et al, 1988)

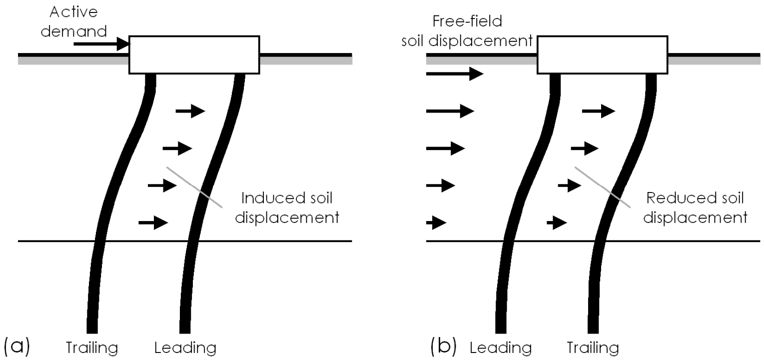


Figure 2. Relative soil-pile displacement and definition of leading and trailing piles for a) active, and b) passive loading of pile groups

In physical model and field tests it is typically found that the shadowing interaction between piles in a group is more significant than any side-by-side interaction (Brown et al., 1988, Rollins et al., 2006). The extent to which a given pile in a group is affected by its neighbours is expressed as an 'efficiency' using multiplying factors which relate (for active piles) the force driving the pile in the group to that required to displace a single pile an equal distance. Although there is no general consensus between various past studies regarding precise multiplier values, the following general trends can be identified:

1. Leading row piles carry greater force than rows behind, but less than equivalent single piles,
2. For a given row, outer piles carry a greater share of the load than inner piles, although for a given spacing this effect is less significant than the shadowing interaction between rows,
3. The closer the spacing, the lower the multiplier, indicating greater interaction and decreased efficiency.

Furthermore, the bending moment distributions of different piles in a group vary, with leading piles tending to exhibit more concentrated bending and higher peak moments, despite having the same pile head displacement as the piles behind (Rollins et al., 2006). They are thus more likely to suffer damage.

There are relatively few papers considering explicitly the passive loading of pile groups. Chen et al. (1997) focus on moment-based interaction factors rather than force multipliers in their 1g model study of capped and free-head pile groups in dry sands. They found a 20 to 30% reduction in peak bending moment for two piles spaced 2.5 pile diameters (2.5D) side-by-side, as compared to a single pile, and that some side-by-side interaction still occurs at spacings as large as 7.5D. The difference between capped and free-head piles arranged in a line parallel to the direction of soil displacement is understandably more significant, as the cap provides significant rotational restraint to the piles (which thus deform in double rather than single curvature). The cap also imposes an equal displacement condition at the heads of the piles, resulting in significant structural interaction, as well as soil-deformational interaction between the piles.

The bending moment distributions of Figure 3a illustrate not only the difference in magnitude of the negative (i.e. pile head) bending moment of the leading and trailing piles, but also the difference in its location. This can be explained by the interplay of soil-related and structural interaction (Figure 3b), the trailing pile being shielded by the pile in front and thus subjected to a reduced passive soil displacement demand, yet the rigid pile cap connection allowing the leading pile to drive the trailing pile at its head (the trailing pile having a corresponding restraining effect on the near pile, reducing the displacement it would otherwise experience).

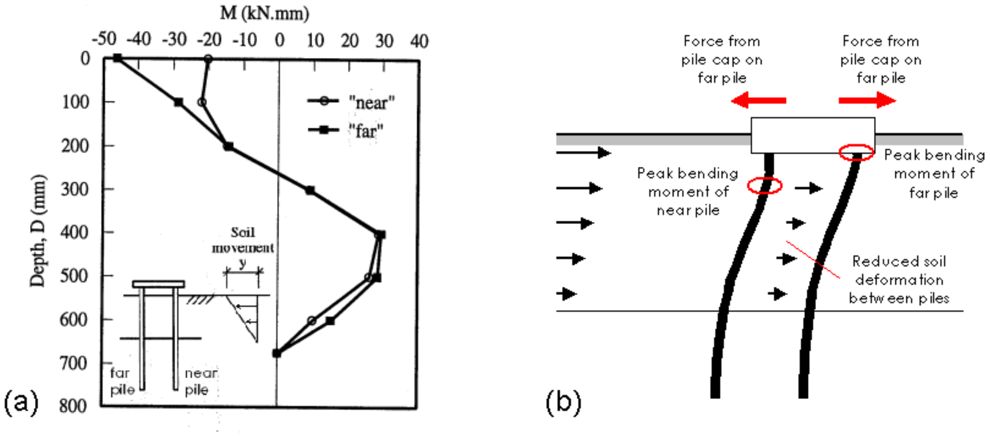


Figure 3. a) Bending moment distributions for near and far piles (Chen et al., 1997), and b) illustration of structural and soil pile group interaction effects

Earthquake-induced lateral spreading of soils is a complex phenomenon, and remains the subject of considerable research effort in its own right. The behaviour of pile foundations in laterally spreading soil is therefore additionally complex. As we've seen for piles and pile groups under more conventional loading, the essence of the problem is the nature of the interaction between the foundation and soil. However, the intense dynamic nature of the demand adds yet another layer of complexity, while rendering invalid several of the fundamental assumptions taken for granted in more straightforward scenarios – the response of pile foundations in laterally spreading soil is much less intuitively obvious.

Typically the demands on pile foundations in laterally spreading soil arise from two sources: inertial forces due to the dynamic response of the superstructure, transmitted to the foundation below, and kinematic forces acting on the piles and pile cap as the soil and foundation displace relative to one another. It is tempting to idealise these demands as examples of active and passive loading, respectively, however these demands are more subtle, and such a simplification cannot be justified. Furthermore, the simultaneous action of inertial superstructure and kinematic soil demands (which will certainly be the case if spreading occurs as a ratchetting movement during shaking) is not straightforward. In terms of pile group effects and the influence of pile spacing on the foundation response, significant differences between lateral spreading-related loading, as compared to conventional static active loading might be attributed to:

1. Significant changes to soil properties and behaviour (as compared to the conventional static case) due to liquefaction, resulting perhaps in changes to the pattern of soil deformation around/between the piles,
2. The interplay of inertial demands (due to the motion of the superstructure and pile cap), and kinematic demands from the displacing, laterally spreading soil on the piles and pile cap,
3. The variation of lateral spreading soil displacement across the extent of a single foundation (for example, piles nearer to a riverbank being subjected to larger soil displacements than those further away).

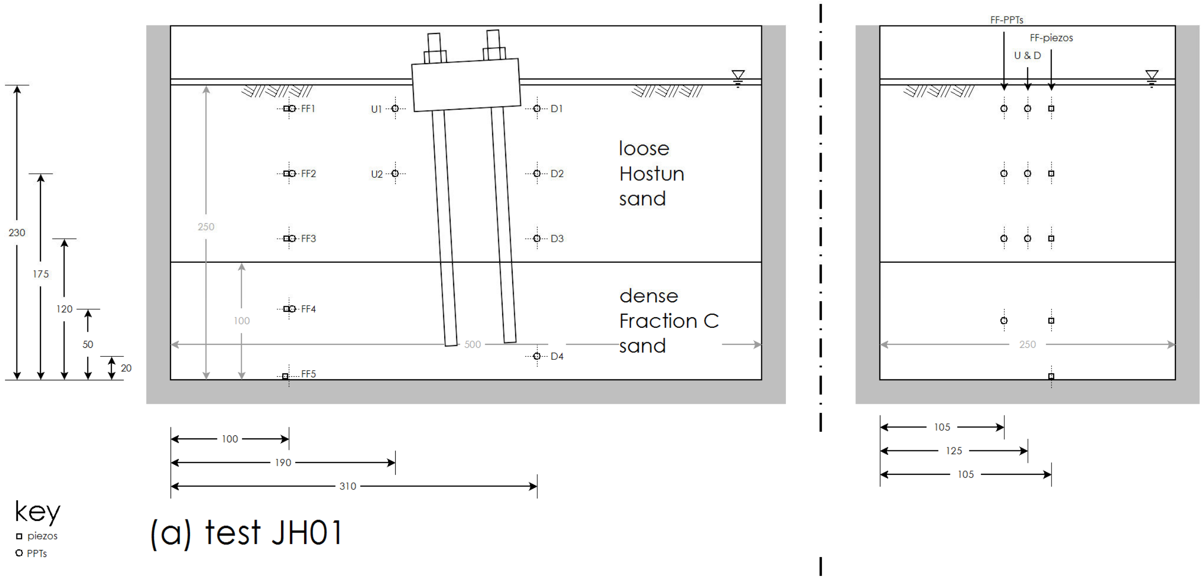
CENTRIFUGE TEST DETAILS

The philosophy that underpins the design of this study is that between the system characteristics and the foundation performance lie different mechanisms of soil-pile-demand interaction, the identification, unravelling, and (ultimately) the understanding of which are fundamental to the development of any global understanding of the response of pile foundations in laterally spreading soils. Essential then, is the correct replication of the nature of soil-pile interaction that occurs when lateral spreading takes place in real life.

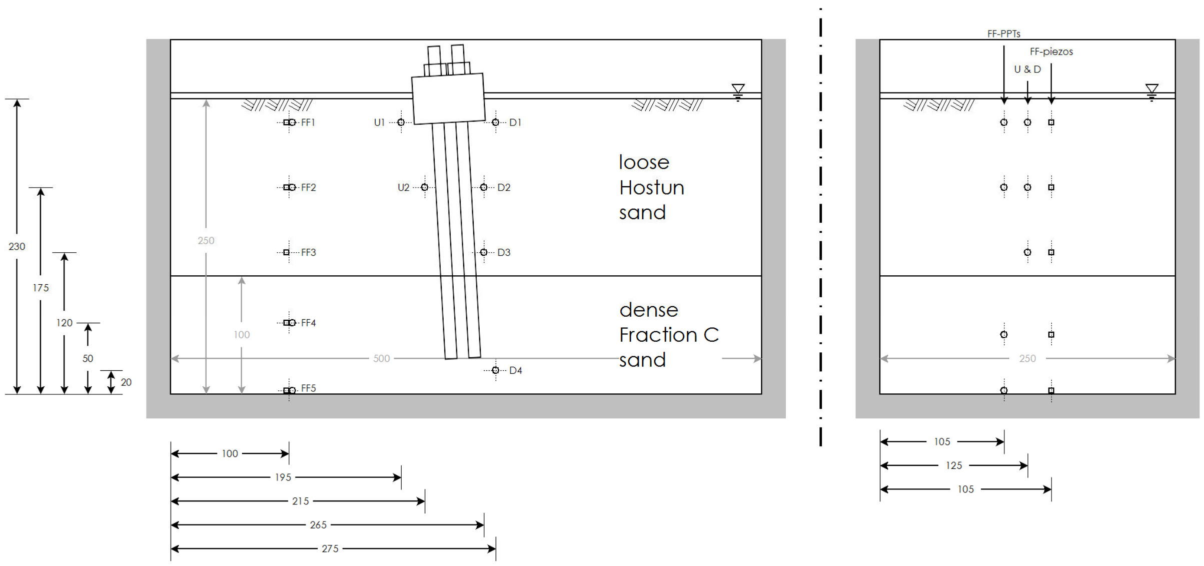
The centrifuge modelling of complete, idealised foundation-soil systems permits multiple soil-foundation configurations to be tested and the greater control of the soil, foundation, and demand afforded by reduced-scale testing, while still respecting the highly non-linear, time-varying and stress level-dependent behaviour of liquefying, laterally spreading soil. Nonetheless, the generation of meaningful results and valid conclusions requires careful consideration not only of the design of the testing programme, but also an appreciation of the unintended or uncontrollable aspects of the modelling process. In other words, care must be taken to ensure any observations are truly due to the phenomena to which they are attributed and not in fact artefacts of the modelling process used.

The two centrifuge tests considered in this paper were designed to isolate the influence of pile spacing on the foundation response, the tests being essentially identical except for the spacing of the piles of the model foundations, which were five pile diameters (5D) for test JH01 and two pile diameters (2D) for test JH02. Figure 4 shows the layout of each test including the instrumentation schemes designed to capture both near and free-field soil response, and the response of the foundation (using a combination of accelerometers, pore pressure transducers, displacement transducers, bending-strain gauges). The tests were conducted at a nominal centrifugal gravity of 50g (the true g-level of course varying with depth in the model, in this case ranging from about 42 to 44g). Both models comprise a loose (~D_R 38%) layer of Hostun sand 6.6 m {150 mm} thick (at prototype and model scales, respectively), overlying a denser layer (~D_R 60%) of Fraction C sand 4.4 m {100 mm} thick, both prepared by dry pluviation using the automatic sand pourer at the University of Cambridge. The models were saturated under vacuum with viscous (51 cSt.) methyl cellulose fluid such that the free water surface lay above the soil surface (i.e. no non-liquefied crust layer was able to form).

The design requirements for the model foundations span both scientific and practical considerations. Given the focus on relevant, directly applicable findings, the simultaneous effect of both side-by-side and shadowing interaction is of interest. The simplest suitable arrangement, namely a square, 2 by 2 pile layout, was used for this study. Practical requirements more or less constrain the size of the pile group to a certain range. The size of the piles themselves is limited at the lower end not only by the size of the soil particles, but also by the practical consideration of instrumentation. The upper limit for the size of the pile groups is essentially controlled by the size of the container. It is important in any physical model test that there is sufficient space between the model foundation and the sides of the container, so that the full and correct mechanisms of soil deformation are not altered or prevented from developing. Of course, the mechanisms of deformation for pile foundations in laterally spreading soils are not well understood at present, hence the upper limit for the dimensions of these first generation pile groups are based more on informed intuition than any more rigorous analysis of the predicted soil deformation. Here, the maximum width of the pile cap (the widest part of the model foundation) is 90 mm, slightly over one third of the width of the laminar box, thereby allowing a space of approximately one pile cap width either side of the foundation. Rather than create multiple pile groups corresponding to different spacings, a modular design approach has been developed, with individual piles (either instrumented or non-instrumented) free to be swapped to different positions or into another pile cap having a different spacing. Figure 5 shows the concept and key details of the modular design.



(a) test JH01



(b) test JH02

Figure 4. Layouts of centrifuge tests

In terms of the 'engineering' design requirements for the model pile groups, reasonable replication of the stiffness and strength of real foundations of a corresponding size is desirable, the intention being that the model groups reflect current best-practice for design to withstand lateral spreading demands. In saying this, the first generation piles have been intentionally over-designed somewhat, being significantly stronger than equivalent piles used in practice (although their flexural stiffness, 108×10^3 kNm^2, is of the correct order). This is to ensure that the model piles underwent only elastic deformation (i.e. did not suffer permanent plastic damage) in the first test, and thus could be immediately reused for the following test.

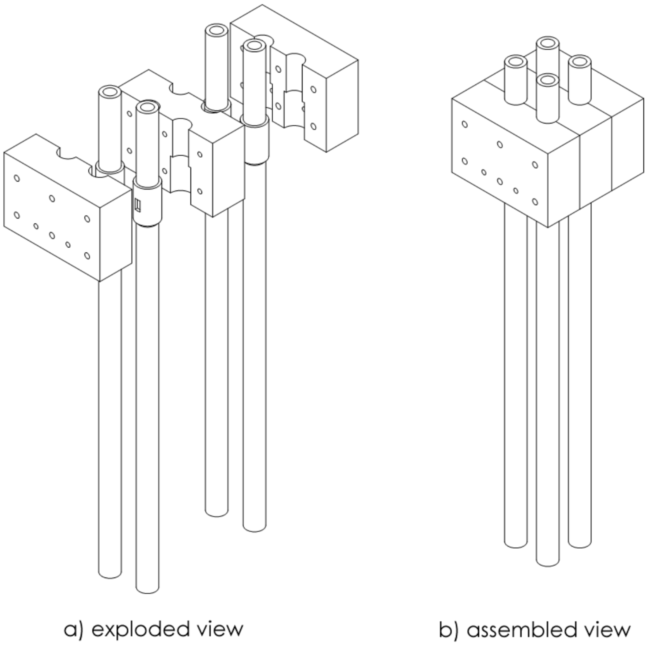

a) exploded view
b) assembled view

Figure 5. Modular pile group concept

The tests were conducted on the Turner Beam Centrifuge at the University of Cambridge. The model foundations were installed after the laminar box containing the prepared, saturated soil had been fixed (in its inclined position) onto the centrifuge swing. Earthquake demand was simulated via the shaking of the entire model using a stored angular momentum (SAM) actuator upon which the laminar container was fixed. These models were subjected to constant amplitude sinusoidal motion having a peak base acceleration of approx 0.25g, a frequency of 1.13 Hz., and a duration of 25-35 s (prototype scale).

CENTRIFUGE TEST FINDINGS

Considering first the 'free-field' response of the soil, as captured by the vertical array of pore pressure transducers and piezoelectric accelerometers with the prefix 'FF', located upslope of the foundation, it appears that the general nature of the free-field response is the same for the two tests (as intended). The dynamic acceleration time histories of Figure 6 (for test JH01 of the wider, 5D-spaced foundation) show the clear transition from approximately constant-amplitude symmetrical, sinusoidal (or perhaps saw tooth-like) motion at the laminar box base and within the dense Fraction C layer, to directionally-biased accelerations within the Hostun sand layer, comprising violent upslope acceleration spikes between much smaller, smoother, and longer duration downslope accelerations. Accelerations of this latter type are typical of the ratchetting mechanism of lateral spreading displacement commonly observed in lateral spreading centrifuge tests (for example Haigh, 2002), where the liquefied soil, particularly that at shallower depths, is abruptly halted during each shaking cycle as its shear strain reaches a peak in the downslope direction. The free-field soil accelerations from test JH02 (of the 2D-spaced group) are essentially the same, so are not shown here.

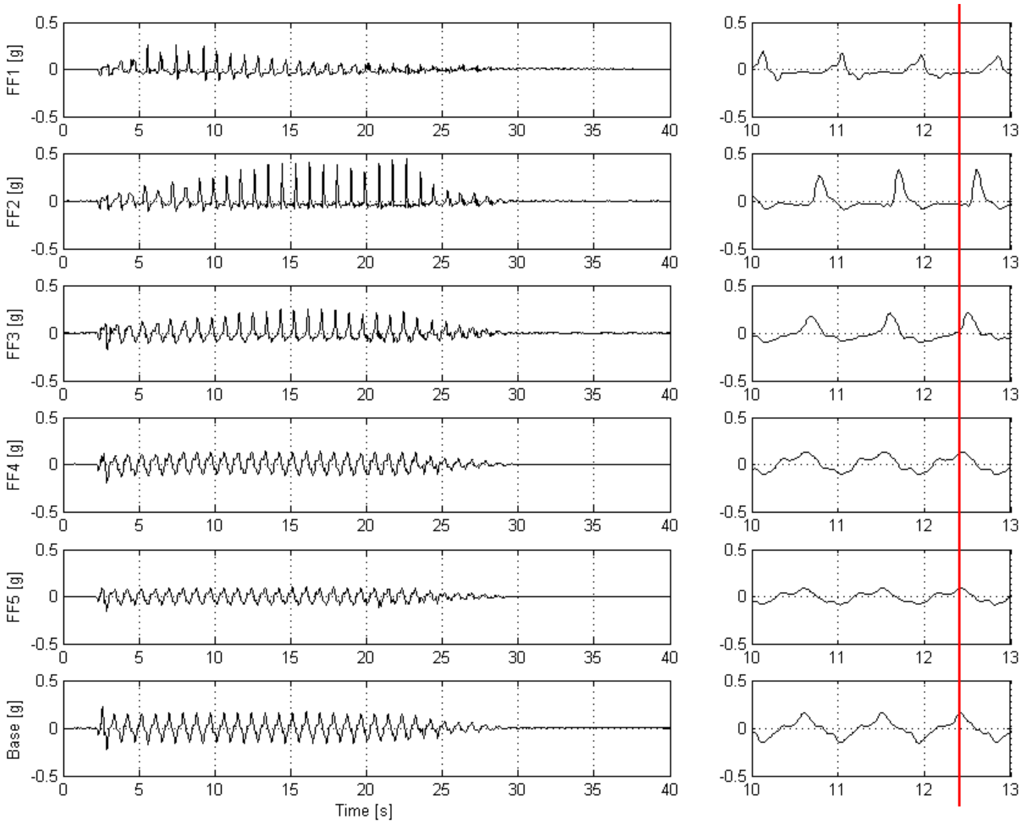


Figure 6. Soil acceleration time histories at different depths (test JH01-5D)

The vertical line superimposed on Figure 6 makes it clear that the upslope acceleration peaks at each depth lag slightly those of the soil below. Throughout the depth of the loose Hostun sand layer the lag versus depth is approximately 0.35 s moving up from instrument FF3 to FF1, near the ground surface. This corresponds to a time-averaged degraded shear wave velocity of the upper Hostun sand layer of approximately 14 ms-1 (of the order of values for liquefied soil suggested by Davis and Berrill (2001) from field studies and values quoted by Haigh (2002) from similar centrifuge tests).

Within the loose soil, the pore pressures (not shown) rise very rapidly as shaking begins, reaching or exceeding the nominal excess pore pressure limit for zero effective stress within the first few cycles. The nature of the dynamic pore pressure response changes somewhat with depth in this layer, with the pore pressures at greater depth tending to exhibit more uniform positive and negative cycles, as compared to the more ‘violent’ negative (or ‘suction’) spikes that punctuate the otherwise relatively constant high excess pore pressure developed in the loose layer nearer the ground surface. Positive excess pore pressure is also rapidly developed in the dense base layer, however the dynamic excess pore pressures tend to cycle about a value somewhat below that corresponding to the zero effective stress state. It appears that any tendency for the pore pressures in the base soil to continue to rise with each cycle is impeded by the rapid full liquefaction and loss of strength of the loose soil above, likely due to the reduction of shear demand on the base soil. Although no direct measurement of dynamic soil displacements was made in either test, it can be inferred from other measurements (for example the soil acceleration and pile bending moment time histories) that the lateral spreading soil displacement most likely accumulated reasonably steadily for the duration of shaking, and ceased as soon as the base shaking stopped. Figure 9 shows the residual soil displacement profiles for the two tests, the large displacement at the ground surface being largely due to the permanent strain accumulated throughout the loose soil (although permanent downslope deformation of the base soil also occurred).

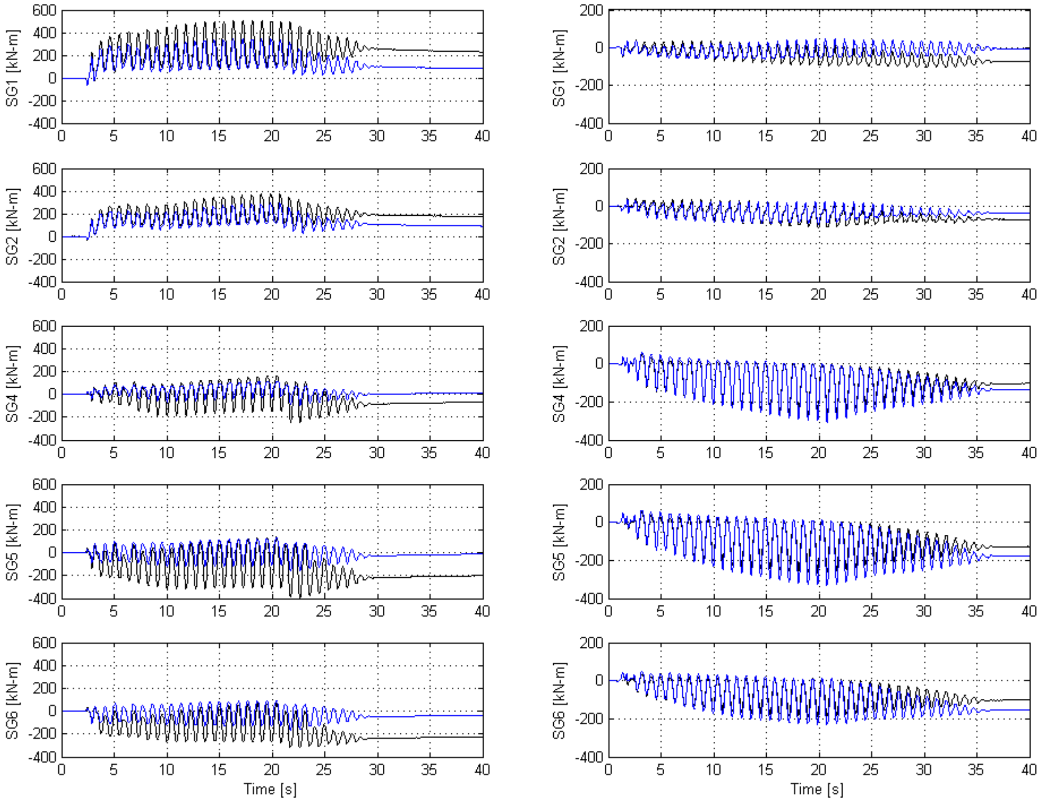


Figure 7. Upslope (blue) and downslope (black) bending moment time histories for tests JH01-5D (left and JH02-2D (right), from pile cap down to pile tip

Turning our attention to the response of the foundation itself, the lateral acceleration time histories of the pile cap from each test (not shown) both reveal similar non-symmetrical pile cap vibration at the driving frequency of the input motion, with larger, sharper upslope accelerations punctuating smaller magnitude downslope accelerations. In both tests the peak pile cap acceleration is of similar magnitude to the peak base acceleration. Displacement time histories for the pile caps (not shown) reveal a more or less steady accumulation of downslope foundation displacement for as long as shaking continues, the pile cap motion being well described by the term ‘ratchetting’. On this basis, the ultimate pile cap displacement (in tests such as these) would appear to fundamentally depend on the duration of shaking.

Despite this apparent similarity in pile cap motion, the bending deformations of the piles of the two groups are fundamentally different in nature, as revealed by the bending moment time histories of Figure 7 and the peak bending moment profiles of Figure 8. It would appear that the reduced rotational restraint afforded to the pile cap by the closely spaced piles (as compared to the more widely spaced piles) results in the transition from double-curvature pile bending to single-curvature bending. Careful interpretation is required at this point, as the fundamental difference in behaviour observed in these tests is almost certainly not due solely to a difference in soil deformation owing to the different spacing. Rather, the inherent sensitivity to pile spacing of the frame action of such a small (i.e. 2-by-2) pile group is the most likely reason for the contrasting pile group response.

For both groups, peak bending moments occur near the interface between the loose and dense soils, and the bending strains vary more or less linearly throughout the loose soil, implying minimal pressure on the piles themselves from the liquefying soil. For the 5D group (test JH01), a second peak moment (of the opposite sign) forms at the pile-pile cap connection. In both cases the bending moment demands on the downslope piles are greater than those on the upslope piles.

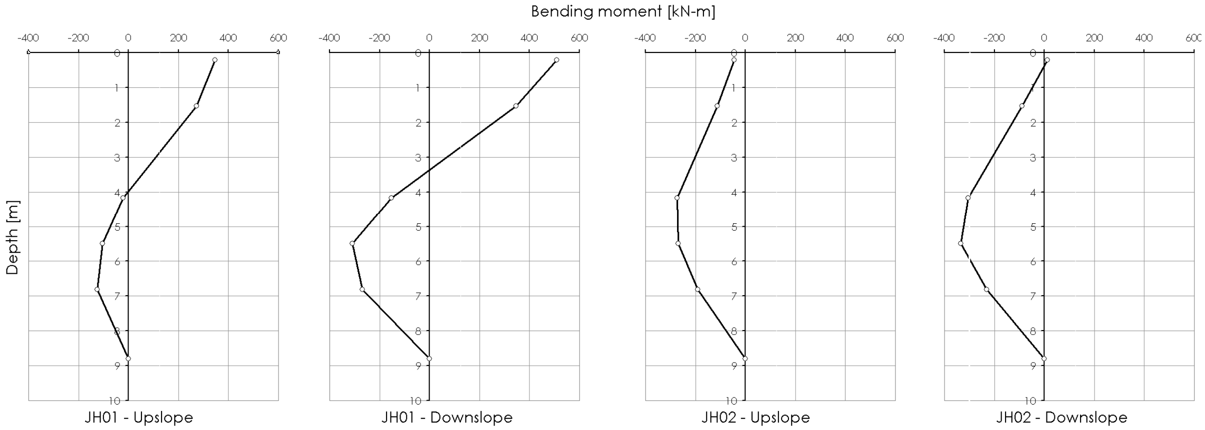


Figure 8. Peak bending moment profiles for piles of both groups

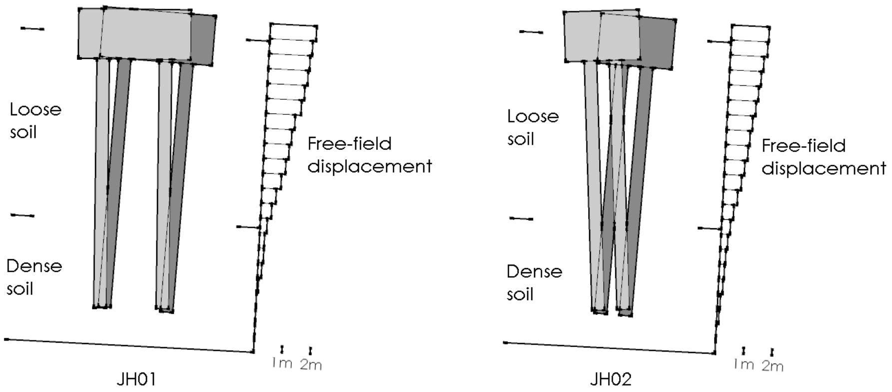


Figure 9. Initial and final foundation positions, and free-field soil displacement profiles

The residual bending moments for both foundations are notably less than the peak bending moments. This, together with the accumulated ratchetting of the foundation at the driving frequency of the input motion, suggests that the foundation motion and displacement are controlled by cyclic soil demands and inertial pile cap response. Interestingly, the residual head-to-tip bending deflections of the piles are of the order of fractions mm at model scale, significantly less than the overall pile cap displacement measured. At prototype scale, the 5D pile cap displaces approximately 0.88 m downslope (at prototype scale), the cap rotating downslope by approximately 4°, while the 2D cap displaces 1.3 m and rotates by 6°. Clearly significant rigid translation and/or rotation of the foundations have occurred. Acknowledging that this rigid nature of foundation displacement has been noted in few, if any, post-earthquake reconnaissance reports (and that further investigation of the influence of axial pile fixity on the rotational fixity of the pile cap via numerical modelling is still being undertaken), careful interpretation of the results is again required, keeping in mind the need to discern artifacts of the modeling process and design from behaviour truly reflecting that of real foundations. To this end, Figure 9 provides some clues as to the nature and cause of this rigid motion (the final foundation position shown in dark grey). It appears that the large lateral pile cap displacement is, in both tests, due primarily to the rigid rotation of the group about some point near the pile tips, and that the foundations largely followed the soil displacement, although apparently not due to any significant flexural deformation of the piles themselves.

DISCUSISON AND EVALUATION OF CENTRIFUGE TEST FINDINGS

On the basis of the available records and measurements from these preliminary tests we have identified several features of the tests thought to contribute (to some degree, at least) to the dominance of the rigid rotation mode of foundation response. In recognition of the stage of this project and the caution required when attributing observed behaviour to a particular cause, we outline our inferences here as tentative hypotheses rather than firm and certain statements regarding the cause of this response, with the intention that they serve as starting points for further investigation and discussion:

1. It would appear that inadequate lateral fixity is afforded to the foundations by the dense base soil, in spite of the embedment length of the piles in this layer being approximately 5 pile diameters, and the excess pore pressures in this layer (in the free-field, at least) never rising so much that complete loss of effective stress occurs. One likely reason for this loss of fixity is the cyclic and permanent deformation of the base soil which, although much less than that of the loose soil above, permits large movements of the pile cap via the rotation of the entire foundation about a point near the pile tips without significant relative soil-pile deformation (or mobilization of lateral soil resistance) within the base soil. The method of installation (driving of the pile groups prior to starting of the centrifuge) may also have contributed to the loss of fixity, due to the dilation of the base soil around the pile tips (aided by the low confining stress at the time of driving), which would tend to undergo greater softening and have lower stiffness than the free-field soil at the same depth.
2. During shaking, it is possible that there is a significant axial component of the foundation motion (Knappett and Madabhushi (2006) and Stringer and Madabhushi (2010) for example suggesting that pile groups in liquefying soil exhibit an alternating ‘stamping’ motion during shaking). Given the smooth aluminium surface of the model piles and the rapid and full liquefaction of the upper soil layer, it may be that inadequate shaft friction capacity could be developed to prevent uplift of the upslope piles relative to the soil as the foundations began to rotate.
3. Another contributing factor, almost certainly an artifact of the model design, is the absence of any damage (and subsequent change in deformation mode) of the model piles, owing to their unrealistically large strength (as compared to real pile of similar prototype size). Of course, this only becomes relevant at later stages of foundation failure i.e. once the bending moment demand exceeds the capacity of these equivalent real-life piles, by which time significant rigid rotation-induced displacement of the pile cap will likely have accumulated.
4. One final suggestion for a factor contributing to the overall response mechanism observed, is the nature of the input motion, namely its constant frequency and (relatively large) amplitude, as it appears that the inertial pile cap motion and cyclic soil displacements have been exaggerated in these tests compared to many real-life lateral spreading scenarios. Again, this is largely an artifact of the test design.

CONCLUSIONS

The design of pile foundations in laterally spreading soil is at present burdened by many uncertainties regarding the nature of the interaction between the foundation and the soil. There remains a significant lack of guidance for fundamental design decisions, such as the influence of pile spacing on the behavior of and demand placed on the foundation. Centrifuge modelling of pile groups in laterally spreading soil slopes has revealed that the pile spacing can fundamentally affect the nature of the flexural deformation of the piles owing to the reduction of rotational restraint of the pile cap as the spacing is reduced. When spaced at 5D, the piles deform in double curvature, whereas when the spacing is 2D, they deform in single curvature. In spite of this, the overall displacements of the foundations in these tests are similar, regardless of the pile spacing, due to the dominance of a rigid rotation mode of foundation displacement. It would seem, at this preliminary stage, that this rigid rotation occurs as a result of insufficient fixity provided to the piles by the dense base soil in which the pile tips are embedded, suggesting that tip fixity conditions must be carefully considered in the design of pile foundations in soils that may undergo lateral spreading.

AKNOWLEDGEMENTS

We thank the Woolf Fisher Trust, the New Zealand Earthquake Commission (EQC), and the Cambridge Commonwealth Trust for their ongoing support of this research.

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