



# Tests on Model Piled Rafts in Sand: Measured Settlements Compared with Finite Element Predictions

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**Abstract** Laboratory tests were carried out on non-piled rafts, single piles, surface contacting and non surface-contacting piled rafts which were made of aluminum and instrumented with strain gauges and deflection gauges. The foundations were installed in dry sand contained in a large metal tank to minimize boundary effects. Maintained loads were applied to each foundation until failure was closely approached. In parallel, analyses were performed using *PLAXIS<sup>TM</sup>* 3-D finite element program to compare the calculated and measured load-settlement trends hence assess the influence of soil stiffness on the foundation behaviour. The results confirmed that group efficiency of non-surface contacting piled increased with increasing pile–pile spacing and approached unity at a spacing equivalent to 8D (D = pile diameter). The data obtained from the strain gauges provided valuable insight into the load-transfer characteristics of different foundations and subsequently proved that the capacity of a surface contacting piled raft is significantly enhanced compared to that of either a non-piled raft or a non-surface contacting piled raft.

**Keywords** Model piled raft · Settlement · Finite element analysis

## 1 Introduction and Literature Review

Piled rafts are commonly installed to support heavy structures and are usually designed with the aid of computer software such as PLAXIS 3D, which overcomes limitations of simple older methods such as Poulos (2001). Of great importance are the interactions within piled rafts, which according to Lee and Chung (2005), are intertwined but are categorised as: (1) pile–soil–pile interaction and (2) cap–soil–pile interaction. These interactions govern the loaded behaviour of piled rafts and are strongly influenced by the installation technique, manner of loading, structural properties, dimensions and ground properties. Non consideration of the aforementioned interaction effects can lead to serious over-estimation of the raft stiffness, hence under-estimation of total and differential settlements.

Lee and Chung (2005) suggested that a piled raft is subject to two conflicting effects; the unfavorable settlement inducing effect and the favorable settlement reducing effect, which is due to increase in lateral stress in the surrounding soil as a consequence of driving a cluster of piles. The findings from the study showed that the favorable effect is governing for wider pile spacing, whilst the unfavorable effect prevails for narrower spacing of piles. For piles spacing of 5D, the bearing capacity of the raft was found to increase substantially, with pile driving effects increasing the raft capacity whereas applied

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vertical pile loads decreased the raft capacity. One might argue that the two opposite effects observed in the case study should nullify each other so that the piled raft has roughly the same capacity as the un-piled raft.

Conde de Freitas et al. (2015) used three dimensional finite element to analyse data from Lee and Chung's (2005) load tests on small-scale single piles and  $3 \times 3$  model sized piled rafts driven into sand of varying density. The piles were well instrumented and had different configurations, i.e. ground-contacting versus floating pile caps, various pile–pile spacing and overlap of cap from edge piles. They investigated the simultaneous effects of pile driving and group interaction on the densification of the sand, hence load capacity of the piled rafts. The findings from the numerical analysis agreed well with the experimental results and showed that the maximum improvement in sand density occurred for surface contacting piled rafts in which the pile spacing was 3D (where D = pile diameter). It was also found that densification was more pronounced for loose sand than dense sand and that, for pile spacing greater than 3D, differences in initial sand density did not affect the extent to which the pile installation enhanced the sand density.

Even prior to the works of Butterfield and Banerjee (1971), it was recognized that the cap–soil–pile interaction is a particularly influential mechanism controlling load capacity and that incorporating piles with a raft foundation can significantly increase the stiffness of the foundation, hence act as a settlement reducer. Among the simplest analytical methods of accounting for cap–soil–pile interaction is that of Randolph (1983), which defines an average interaction factor  $\alpha_{cp}$  between the pile and cap as follows:

$$\alpha_{cp} = \frac{\ln\left(\frac{r_m}{r_c}\right)}{\ln\left(\frac{r_m}{r_o}\right)} \quad (1)$$

in which  $r_m$  is the radius of influence of the piles,  $r_c$  is the effective radius of the element of pile cap associated with each pile and  $r_o$  is the pile radius. For a piled raft having  $n$  piles  $r_c$  is calculated such that  $n\pi r_c^2 =$  actual area of the pile cap. The overall stiffness  $k_f$  of the piled raft is then defined by:

$$k_f = \frac{k_p + k_c(1 - 2\alpha_{cp})}{1 - \alpha_{cp}^2 \frac{k_c}{k_p}} \quad (2)$$

where  $k_c$  and  $k_p$  are the stiffness of cap and piles respectively, both of which may be evaluated in a conventional way. The ratio of load  $P_c$  supported by cap to the total load ( $P_c + P_p$ ) carried by the piled raft is given by:

$$\frac{P_c}{(P_c + P_p)} = \frac{k_c(1 - \alpha_{cp})}{k_p + k_c(1 - 2\alpha_{cp})} \quad (3)$$

To assess the beneficial effects of incorporating piles beneath a raft foundation as opposed to raft only or piles with floating cap, an opportunity is taken in this paper to test small-scale piled rafts installed in sand with floating as well as surface-contacting caps. The piles are formed with different pile–pile spacing and tests are also conducted for cap-only (non-piled raft) cases. There are three research hypotheses to be tested or verified: (a) piled raft capacity increases with increasing pile–pile spacing and (b) a piled raft has an enhanced capacity compared to both a non piled raft and a single pile, (c) a piled raft with surface contacting cap has greater capacity and settlement resistance compared to all other cases. Along with the laboratory tests and finite element work, the above analytical methods (Eqs. 1–3) have been applied to ground-contacting piled rafts in order to assess the relative contribution of pile cap to total load resistance of piled rafts.

## 2 Materials and Experimental Arrangement

### 2.1 Soil Material

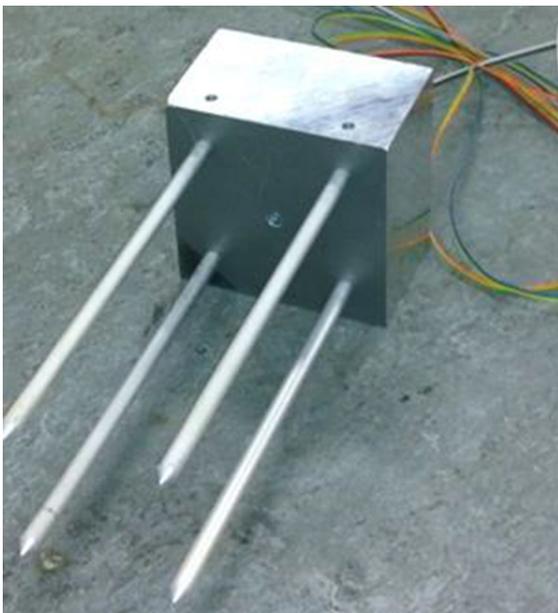
A sample of clean, well-graded sand was used as the founding medium for the model piled rafts. The basic characteristic properties of the sand, as measured in dry sieving and shear box tests, are shown in Table 1. The sand was poured into a stiff metal box container in three equal layers and vibrated with a jack hammer for 20 s. Due to the effects of pouring the weight density increased from 16 to 18 kN/m<sup>3</sup>. After compaction, a spirit level was placed on the soil to ensure that it was perfectly level.

**Table 1** Soil properties

Property of sand	Value
Angle of shearing resistance $\phi'$	35°
Coefficient of uniformity $C_u$	2.89
Coefficient of curvature $C_c$	0.96
$D_{60}$	0.52 mm
$D_{30}$	0.30 mm
$D_{10}$	0.18 mm
Average density index $I_D$	0.75
Minimum dry weight density $\gamma_{D,\min}$	14 kN/m <sup>3</sup>
Maximum dry weight density $\gamma_{D,\max}$	18 kN/m <sup>3</sup>

## 2.2 Pile and Raft Materials

The model piles were made of aluminum alloy tubes having an outer diameter of 8 mm, an internal diameter of 7 mm, and a modulus of elasticity of 70 GPa. The piles were instrumented with 6 × 3 mm strain gauges in a ¼ bridge configuration, the bases being closed with aluminum alloy caps of 60° conical shapes. The pile cap (raft) was constructed from a structural aluminum alloy (T6082) having a modulus of elasticity of 70 MPa. Its height of 62.5 mm relative to its breadth and length of 100 mm × 100 mm increased the stiffness of the raft and was thus

**Fig. 1** Piled raft model with wiring connecting to strain gauges

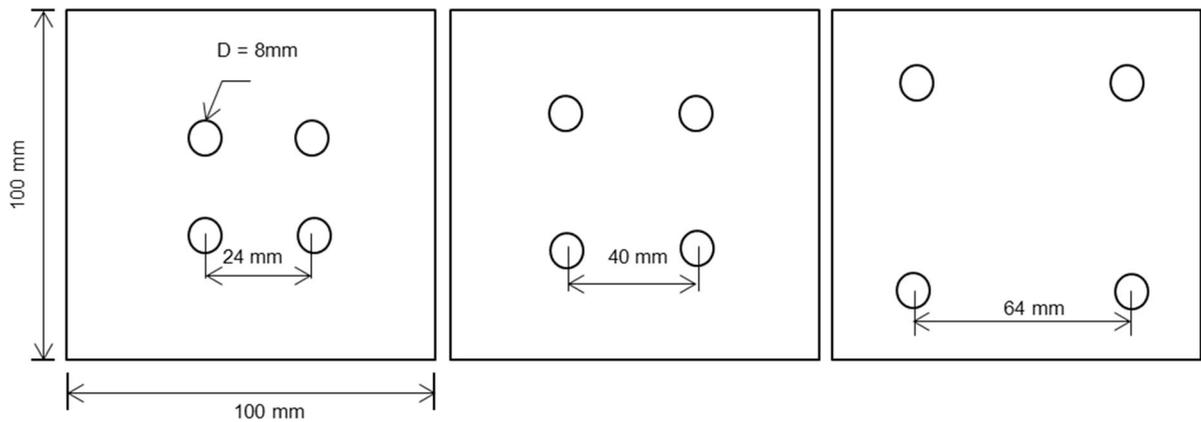
considered rigid. Figure 1 shows the completed model piled raft.

Three different cases of piled rafts were built by varying the pile–pile spacing as shown in Fig. 2 while keeping the raft dimensions constant. Finally, threads were machined 15 mm above the cap base on the side of each pile so that grub screws could be used to keep the piles firmly in place. Some of the 2 × 2 piled raft cases (see Fig. 2) were installed on the sand with the raft firmly in contact with the sand surface while in other cases a clear gap was left between the bottom of the raft and the sand surface. In other cases, a raft without pile attachment and a single isolated pile were installed and tested. The various test cases are depicted in Fig. 3 [C = raft only, S = single pile with floating cap, R = piled raft with surface contacting cap, F = pile group with floating cap].

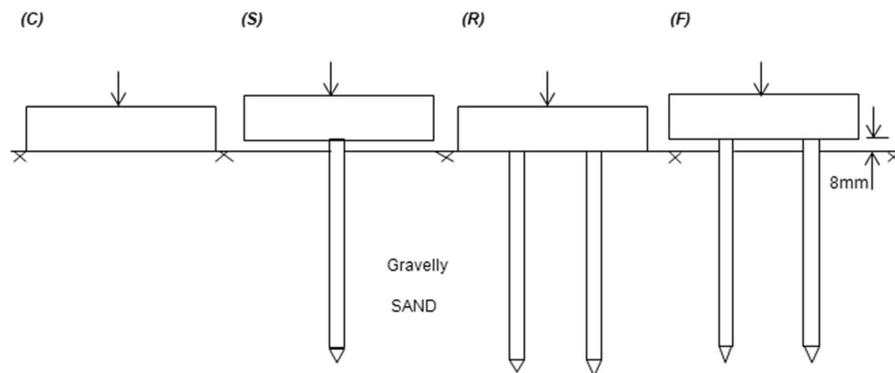
## 3 Load Test Program

Figure 4 illustrates the equipment used in the testing program; a linear variable differential transformer (LVDT) and strain gauges at the top and bottom of two diagonally positioned piles were connected to a data logger to measure settlement and calculate axial loads in the piles respectively. In addition, a manually pumped hydraulic jack applied the vertical loads to the pile cap against a rigid reaction beam, whilst a load cell measured the actual applied loads to a precision of 10 N displayed on a load transducer.

The testing program entailed incremental loading of: (1) pure cap (un-piled raft), (2) single pile, (3) piled raft with cap not in contact with the soil (free standing), (4) piled raft with surface contacting cap. The length to diameter ratio of the piles ( $L/D$ ) was 180/8 equating to 22.5; while the distance between the base of the piles and the rigid base of the container was considered sufficiently large to discount interaction between the two, following the guidelines in Nguyen et al. (2012). Model piles were fabricated with different spacing of piles in them (3D, 5D and 8D where  $D$  = pile diameter). The choice of 8D maximum spacing was based on the observation by Chen et al. (1997) that group interaction can still occur at spacing as large as 7.5D. Finally, the pile raft was placed on the soil and jacked to the predetermined level allowing 8 mm clearance between the cap and soil. Upon failure, the piled raft was jacked further until contact



**Fig. 2** Three piled raft configurations with pile spacing 3D, 5D and 8D



**Fig. 3** The various test cases [C = cap only (i.e. non-piled raft), S = single pile, R = surface-contacting piled raft, F = non-surface contacting piled raft (i.e. piled raft with floating cap)]

between the cap and soil was fully established. The load was then released; whilst the LVDT, strain gauges, and load transducer were reset to allow measurements for the surface contacting piled rafts. The loads were applied with the hand pump in a controlled and gradual manner until a reasonable decrement in settlement was reflected. Measurements were only recorded after the load and settlement stabilized. As the test progressed, the settlement for a given load also increased to a point where it was considered better to monitor load increments. Figure 5 shows the pile installation process.

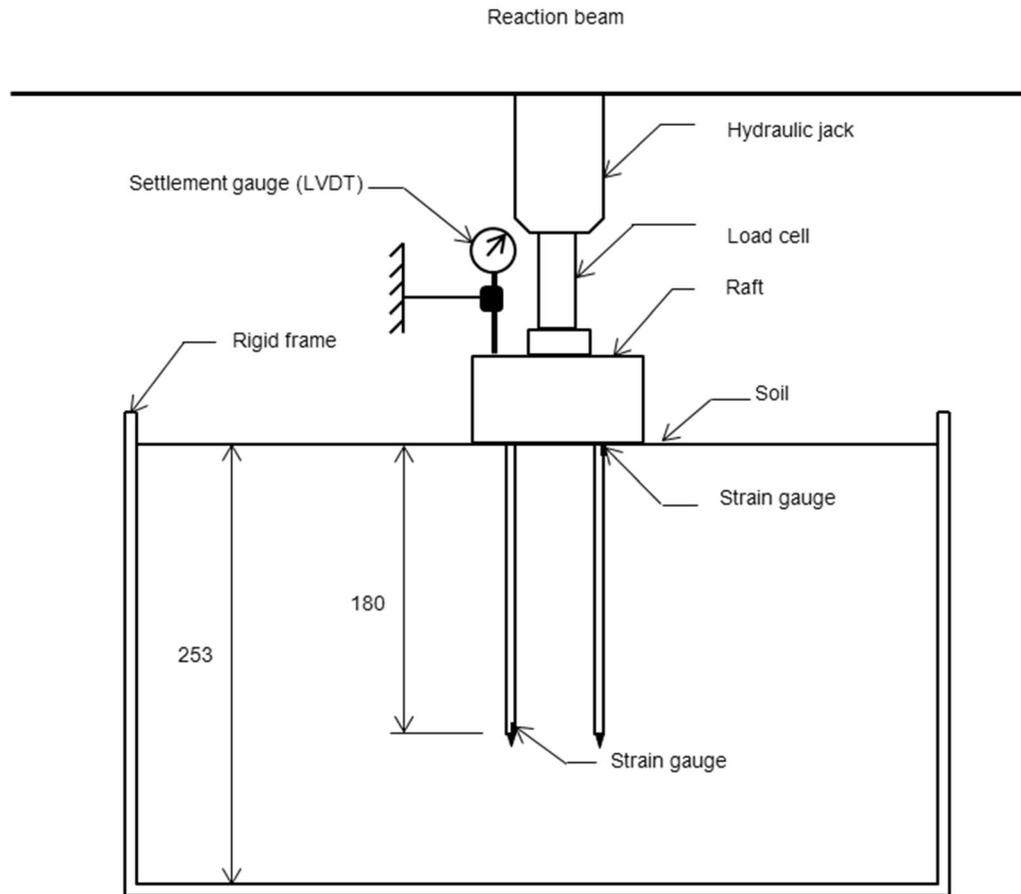
Strains monitored on the data logger were converted into equivalent forces and finally back into kilograms; the levels of accuracy ranged between 89 and 95%. Although these errors were recognized they were not expected to affect the primary function of the gauges which was to determine a percentage increase

in capacity of piles below a cap relative to that without cap contact rather than actual loads.

## 4 Experimental Results

### 4.1 Single Piles and Non-surface Contacting Piled Rafts

Figure 6 shows the measured load-settlement curves for single piles and non-surface contacting piled rafts comprising different pile–pile spacing: 3D, 5D and 8D. Two tests (test 1 and test 2) were performed for each spacing case. It is seen that the highest capacities were produced by the single piles whilst the capacities of the non-surface contacting piled rafts increased with increasing pile–pile spacing. This result conforms to the known phenomenon that pile–pile interaction effects decrease when piles are spaced



**Fig. 4** Load test arrangement for the model piled rafts installed in sand

out wider. Another reason for this, according to by Lee and Chung (2005), is that the soil densification benefits of driving closely spaced piles can negate the unfavorable interaction effects. The curves in Fig. 6 also show more rapid failure in the single piles compared to the non-surface contacting piled rafts and that the rapidity of failure generally increased with decreasing pile–pile spacing. This is consistent with theoretical load–settlement graphs derived from the group interaction factor method (Randolph 1994), in which the secant stiffness of the load–settlement graph of a pile group is represented by  $(1 + \alpha)^{-1}$  times the single pile stiffness, where the group interaction factor  $\alpha$  increases with decrease in pile–pile spacing.

#### 4.2 Non-piled Rafts and Surface-Contacting Piled Rafts

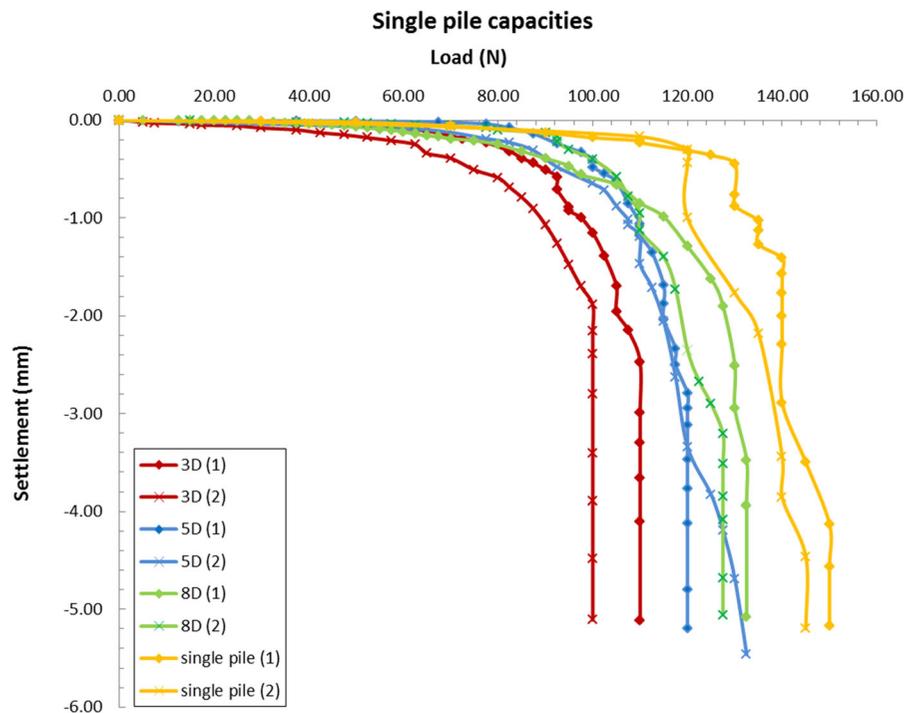
Figure 7 shows the measured load–settlement curves for the various cases of surface-contacting piled rafts and non-piled rafts. Generally, after 0.4 mm settlement point, the curves have reduced gradients, at which points the piles have yielded but not the cap. After this stage is a final non-linear portion representing yielding of both the cap and pile. Clearly the ultimate load capacities of all the piled rafts (despite the differing pile spacing 3D, 5D, 8D) are tens of times greater than that of the non-piled raft case. The average post-yield capacities from tests 1 and 2 are as follows:



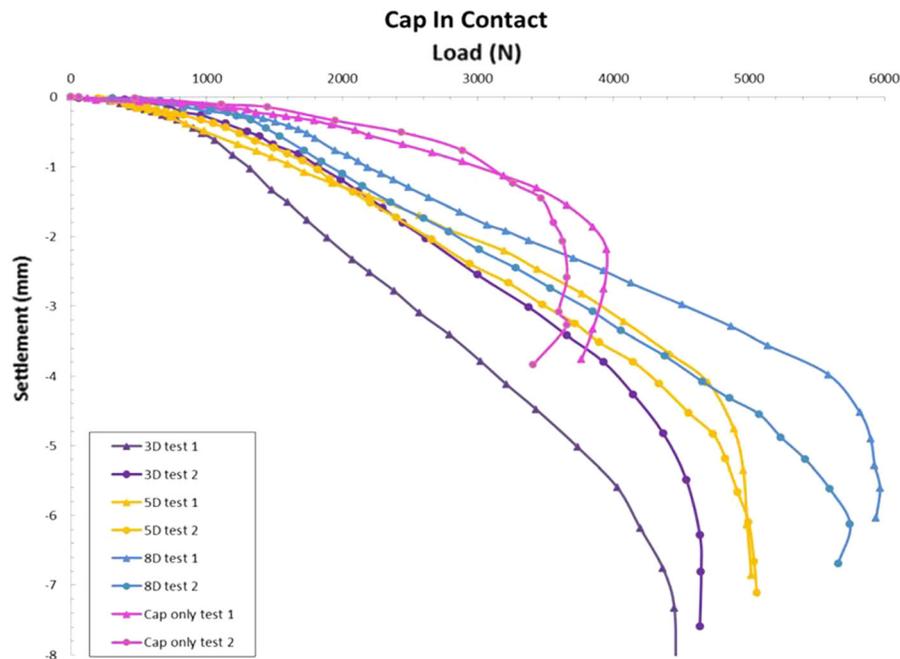
**Fig. 5** Jacking the piled raft into the sand

non-piled raft: 3700 N  
 surface-contacting piled raft with 3D pile–pile spacing: 4400 N (contrast with 104 N for non-surface contacting piled raft in Fig. 6)  
 surface-contacting piled raft with 5D pile–pile spacing: 4900 N (contrast with 24 N for non-surface contacting piled raft in Fig. 6)  
 surface-contacting piled raft with 8D pile–pile spacing: 5700 N (contrast with 128 N for non-surface contacting piled raft in Fig. 6)

However, of particular interest to engineers is the magnitude of settlement at design load. This requires consideration of the stiffness of the load-settlement curves. The results here show that the load-settlement graph for the non-piled raft has a higher initial stiffness than those of the surface-contacting piled rafts. Additionally, for the surface-contacting piled rafts, the initial stiffness of the curves decreases with decreasing pile–pile spacing. This can be explained by the fact that installation of a non-piled raft has less soil disturbance effects than in the case of a piled raft and also shorter pile spacing causes greater disturbance to soil than longer spacing does.



**Fig. 6** Measured load-settlement curves for single piles and for non-surface contacting piled rafts with various pile–pile spacing (two tests for each case)



**Fig. 7** Measured load-settlement curves for non-piled rafts (i.e. cap only) and for surface-contacting piled rafts having various pile spacing (2 tests in each case)

## 5 Finite Element Analysis

PLAXIS 3-D finite element (FE) software was used to model each of the piled rafts (at spacing of 3D, 5D and 8D) and the non-piled raft. The structure consisted of a plate element to model the raft and embedded piles (beam elements). Values of the material parameters assigned for the raft and pile structures are presented in Table 2.

Perhaps the most influential soil parameter for settlement analysis is the deformation modulus of the sand. Obviously sand stiffness and elastic modulus  $E_s$  depends on the state of consistency and packing (density). Obrzud and Truty (2012) catalogued values of  $E_s$  from several references. They recommended, for well graded sand, baseline values of  $E_s = 30\text{--}80$  MPa and  $E_s = 80\text{--}160$  MPa for loose and medium dense states respectively. For dense states  $E_s$  could be  $160\text{--}320$  MPa. Therefore, for the present research, allowing for the densification caused by the piles, it seems reasonable to adopt upper and lower limits of  $E_s$  as 100 and 200 MPa respectively. As for Poisson's ratio,  $\nu$ , typical values adopted for sand are 0.2–0.3 but generally variations in this parameter do not have a significant effect on calculated settlement. More

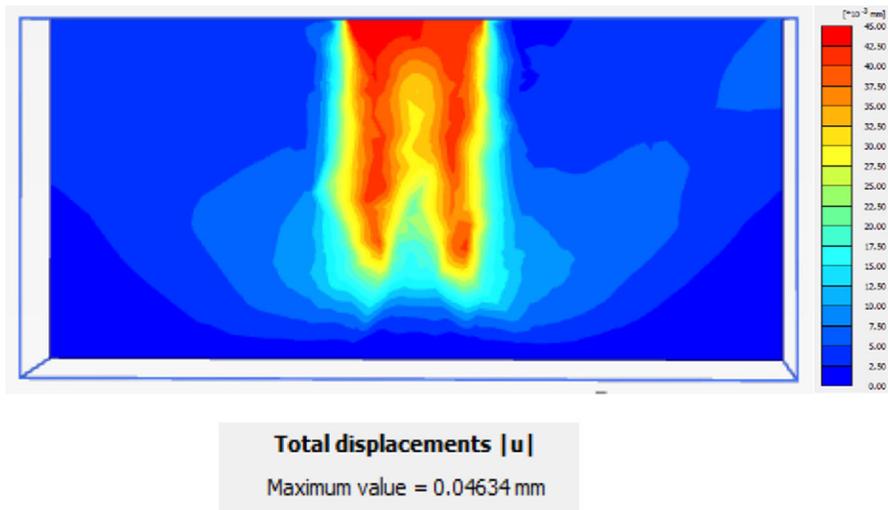
marked variations in the magnitude of  $\nu$  and effect on settlement occur in clays, where it can be proved from elasticity theory that for  $\nu = 0.5$  the elastic settlement takes place without volume change.

To account for positive installation effects the at-rest earth pressure coefficient  $K_0$  was increased by 50% to arrive at the operational lateral stress coefficient,  $K$ . This assumption is based on the recommendation by Fleming et al (2009) that  $K/K_0$  for displacement piles in sand is typically 1.5 for low stress levels and averages 1.2 over the range of stresses up to the limiting skin friction state.

Figure 8 typifies the PLAXIS output of vertical displacements, at 500 N load, for the surface contacting piled raft with 8D pile spacing when soil Young's modulus was  $E_s = 100$  MPa. The output is a cross-section that runs through the centre of two piles of the piled raft and reveals that no significant interaction occurred between the stressed soil and the sand box, hence removing concerns about possible boundary effects. Several other color-schemed outputs were produced, although excluded here for brevity. Some of them displayed the settlement of soil at approximately half way down the piles and immediately below the raft. In general it was indicated that maximum

**Table 2** Parameter values for PLAXIS 3D finite element analysis

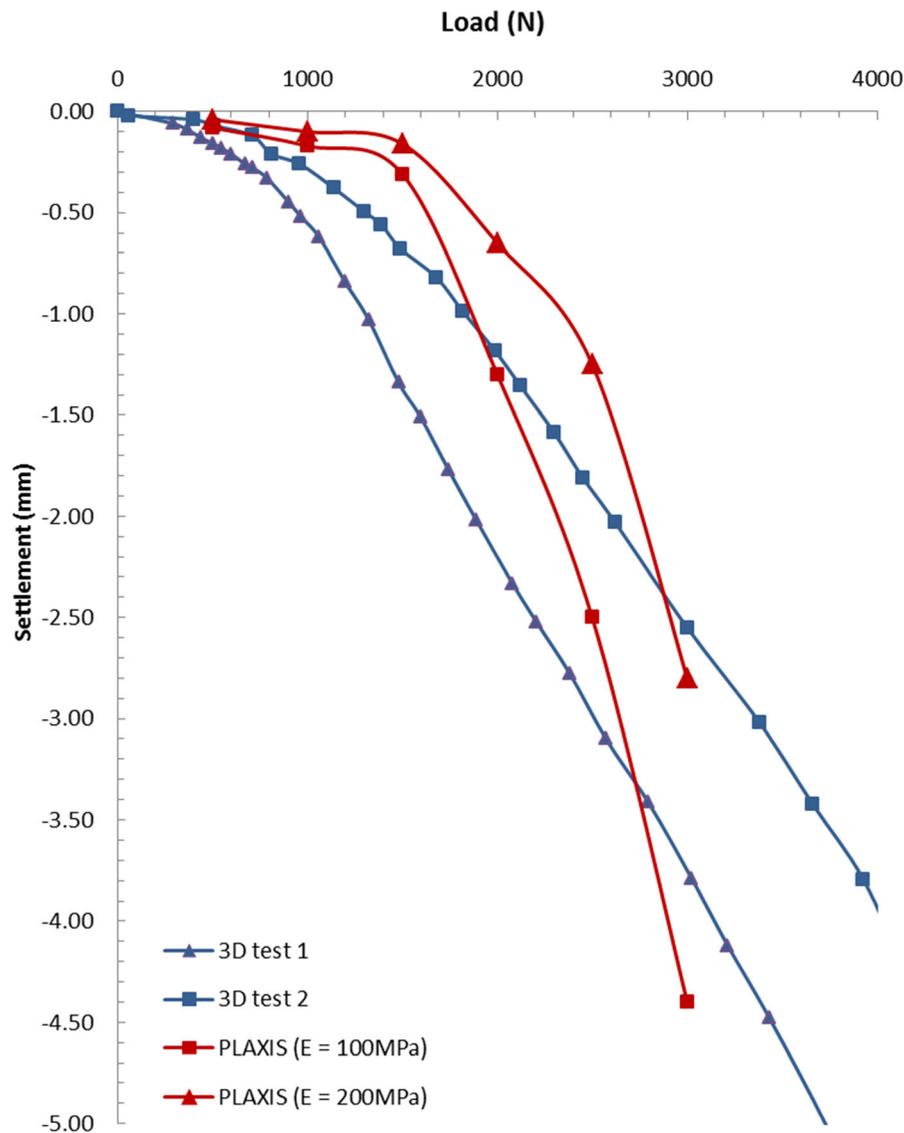
Parameter	Symbol	Value	Unit
<i>Soil material properties</i>			
Material model		Mohr–Coulomb	
Weight density	$\gamma$	18.10	kN/m <sup>3</sup>
Young's modulus	E	100–200	MPa
Poisson's ratio	$\nu$	0.30	–
Cohesion	c	0.00	kN/m <sup>2</sup>
Angle of friction	$\phi'$	35.00	degrees
Parameter	Symbol	Piles	Raft
<i>Structure material properties</i>			
Young's modulus	E	70	70
Weight density	$\gamma$	10	27
Diameter/width	D	8	100
Thickness	H	–	62.5
Poisson's ratio	$\nu$	0.3	0.3
Behavior type	–	Linear/isotropic	Linear/isotropic
Pile type	–	Massive circular	–

**Fig. 8** Computed vertical displacements (at 500 N load for surface-contacting piled raft at 8D pile spacing and  $E_s = 100$  MPa)

settlements occurred as the pile dragged soil downwards during loading. As seen in Fig. 8, the constant dark colored area immediately beneath the cap implies that, throughout the test, the zone just below the rigid pile cap was consistently the location of maximum settlement (Fig. 9).

Figures 10, 11 and 12 compare the PLAXIS predicted load-settlement curves for piled raft (for 3D, 5D and 8D spacing) and non-piled raft with experimental results. It is seen that PLAXIS

predictions have over-estimated the initial stiffness of the load-settlement curve and under-estimated the ultimate capacity. This is due to the possibility that the PLAXIS models have not taken full account of the additional settlement induced by the piles during installation and at working loads. However, PLAXIS has effectively accounted for the increase in bearing capacity with corresponding increases in pile spacing. The lower bound value of 100 MPa chosen for the Young's modulus was half that of the upper bound



**Fig. 9** Surface contacting-piled raft with 3D pile–pile spacing—measured and finite element predicted settlement curves

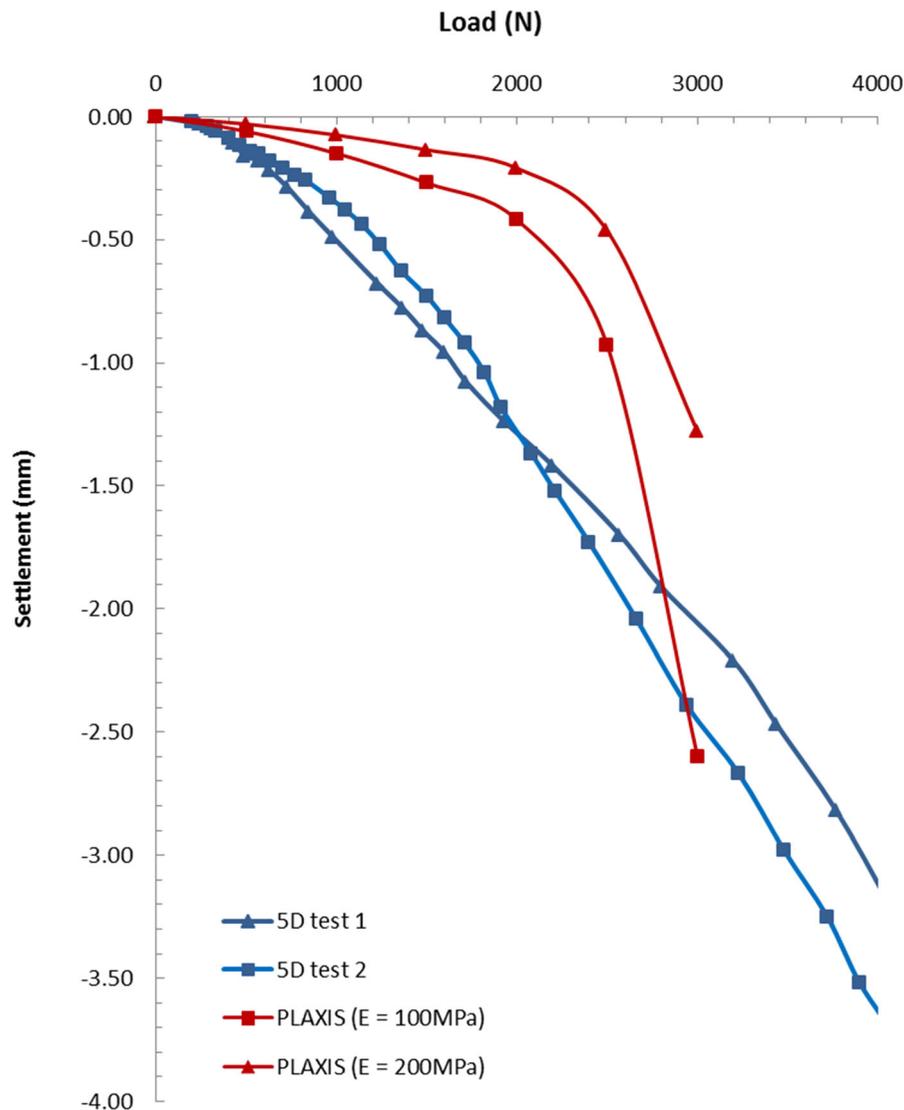
estimate of 200 MPa. For PLAXIS models using a Young's modulus of 100 MPa the settlement prediction was twice as great as that for corresponding loads pertaining to soil models of 200 MPa.

## 6 Discussions and Practical Implications

It can be seen from Fig. 12 that, in contrast to the piled rafts, the load capacity of the non-piled raft was grossly underestimated by the finite element method. Nevertheless, findings by Nguyen et al. (2012) also

reveal large variations in the PLAXIS 3-D output in comparison to experimental data from geotechnical centrifuge tests. This reinforces the need for pile testing, as a means of obtaining reliable design information for working piles, for large construction projects or where the ground conditions present special challenges.

Application of the Randolph's (1983) analytical Eqs. 1–3, discussed earlier, showed that the piled rafts tested here had a very high proportion (typically 55–85%) of total capacities contributed by the pile cap alone.

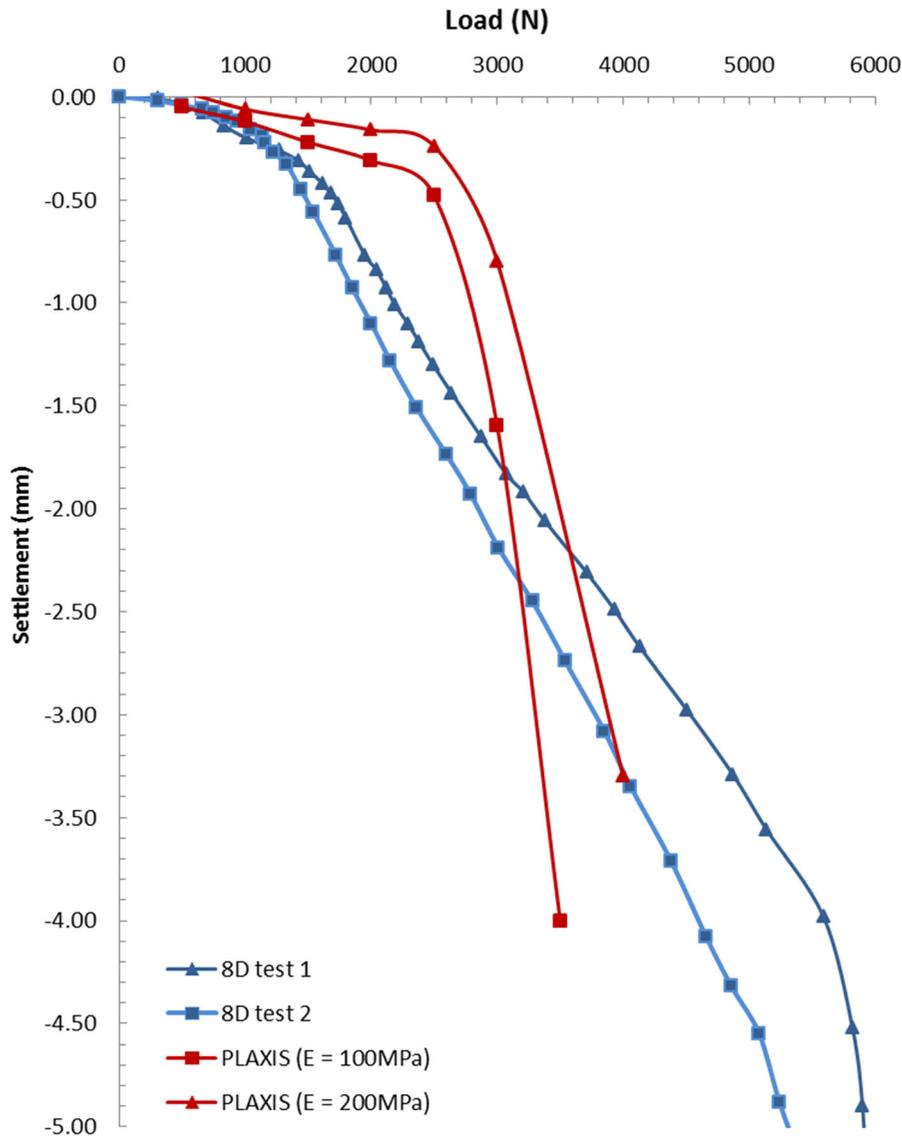


**Fig. 10** Surface contacting-piled raft with 5D pile–pile spacing—measured and finite element predicted settlement curves

It is seen that these percentages are well within the range of load sharing ratios covered by the normalized plots in charts published by Fleming et al. (2009). Therefore this gives confidence that the results from the lab tests and are reasonable, as are the finite element results albeit for low loading ranges. Although these findings are from model scale piles installed sand, the practical implications for design are as follows:

- (a) the results may be applicable to other soil types and in real ground. Evidence that this suggestion is valid can be found an example case record

reported by Cooke et al (1981), who analysed an instrumented piled raft comprising 351 piles of 450 mm diameter bored in clay at a site in London, UK. For a total load of 156 MN the mean settlement of the piled raft was 27 mm with the pile cap carrying approximately 50% of the total applied load, in the short term. This value is close to: (1) the lowest result 55% calculated from Eq. (3), and (2) 65% being the lowermost of the ratios 3700 N (cap-only capacity) divided by 5700 N (8D piled raft capacity) measured in the present research.



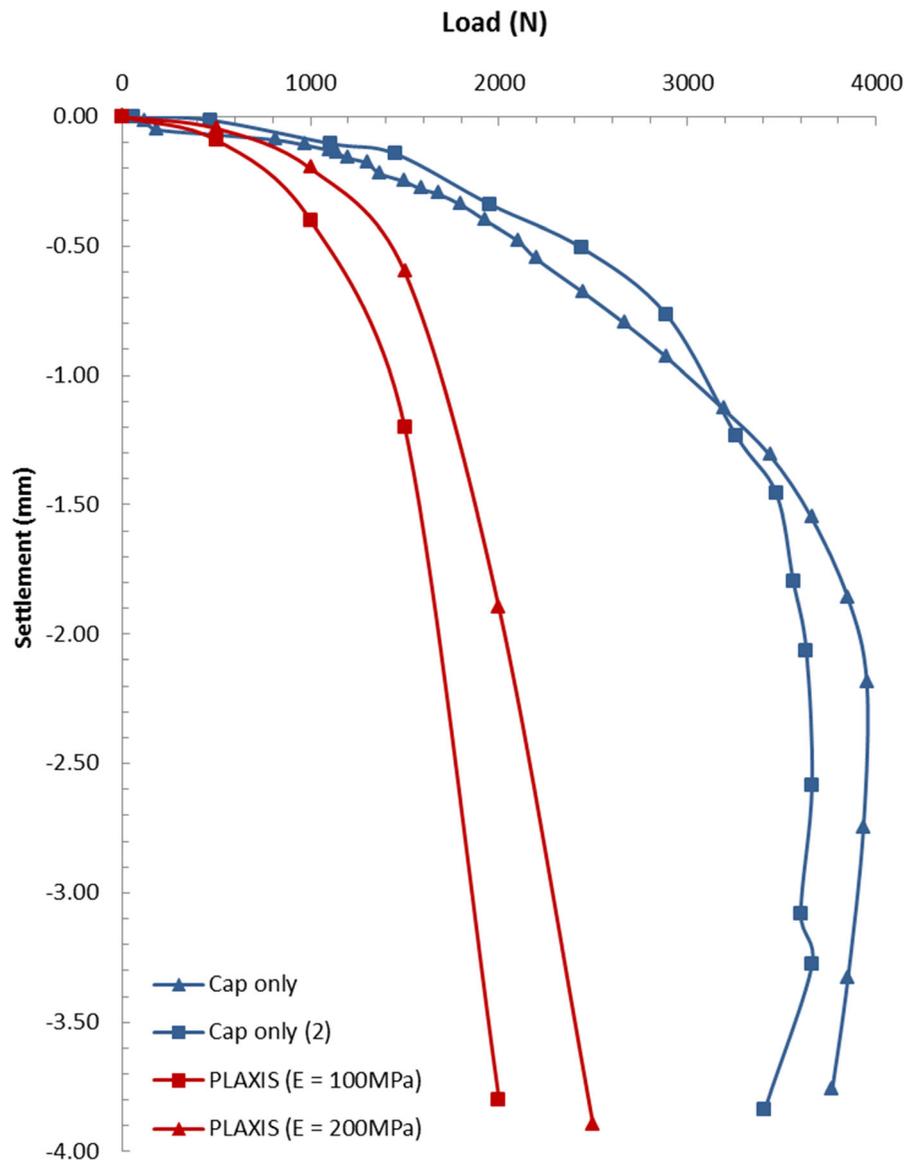
**Fig. 11** Surface contacting-piled raft with 8D pile–pile spacing—measured and finite element predicted settlement curves

- (b) the bearing capacity of a raft foundation is enhanced by the addition of piles but, even with a limited number of piles added, the settlement at working load is reduced significantly.
- (c) a piled raft is a complex problem with a large number of influencing parameters, which are not all accounted for even by sophisticated numerical methods. The factors govern load sharing between the individual piles as well as between the pile group and the cap, thereby impacting on the settlement response as well as the actions within and deformations of the cap.

**7 Conclusions**

Load tests were conducted on differently configured piled rafts, single piles and non-piled rafts installed in dry sand. In addition, the foundations were analyzed using the finite element program PLAXIS 3-D to predict the load-settlement response of the foundations. It was found that:

1. For the non-surface contacting piled rafts, unfavorable pile–pile interaction effects due to narrower pile–pile spacing outweighed favorable



**Fig. 12** Non-piled raft (cap only)—measured and finite element predicted settlement curves

installation effects, hence leading to reduced load bearing capacities.

2. The capacities of the piled rafts, whether surface contacting or not, were significantly larger than those of non-piled rafts.
3. The interaction of stiff raft bearing on the soil surface significantly increased the capacity of the piled raft as a whole.
4. Linear isotropic finite element analysis with PLAXIS 3-D over-estimated the initial stiffness of the load-settlement curve and under-estimated

the ultimate capacity, hence implying that there is need for more sophisticated and realistic non-linear models to produce accurate load-settlement predictions.

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