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The use of a bearing plate to enhance the lateral capacity of monopiles in sand

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The use of a bearing plate to enhance the lateral capacity of monopiles in sand.

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Abstract

Offshore foundation systems are constantly evolving to meet the needs of developments in the energy sector. These developments may be induced by the requirements of moving into ever deeper water for hydrocarbon recovery, or creating foundation systems from renewable energy sources such as offshore wind farms. One such approach is that foundation systems are developed which combine several foundation elements to create a 'hybrid' system. In this way it may be possible to develop a foundation system which is more efficient for the combination of vertical and lateral loads associated with the offshore environment, and in particular wind powered generators. This paper will present the results from a physical and numerical modelling programme undertaken to investigate the performance of hybrid monopiled-footing foundations under combined monotonic loading conditions in sand.

Introduction

The monopile is a widely used foundation solution in both onshore and offshore applications. It has the advantage that the solution is generally suitable for a large range of ground conditions. Design methods for both static and cyclic loading have been extensively researched as part of the development of the offshore resource development industries. More recently the monopile has been the foundation of choice

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driving the expansion of both onshore and offshore wind energy, and wind farms have been successfully installed in relatively shallow water depths with monopile diameters in excess of 5m.

However the feasibility of using monopile foundations in deep water is compromised by (i) the cost of installing piles in significant water depths, and (ii) the compliant nature of the structure. With regard to the latter issue much promise had been shown by theoretical studies of a guyed monopile system (Bunce and Carey 2001a, and 2001b) however such an approach remains to be fully exploited. An alternative approach is to incorporate a bearing plate at the mudline such that a degree of restraint is added to resist lateral loads (Dixon 2005). This hybrid monopiled-footing concept is not dissimilar to that of a retaining wall with a stabilising base, see for example (Carder 1993, Carder et al. 1999 and Powrie and Daly 2007).

Single gravity tests (Stone et al. 2007) and centrifuge model tests (Stone et al. 2010a, 2011) of the hybrid system where the bearing plate was rigidly fixed to the pile reported that; (i) a vertical capacity of the hybrid system generally greater than the sum of the individual components (pile and footing), (ii) the lateral stiffness and load capacity of the hybrid foundation is significantly improved over that of the pile alone, and (iii) that the initial contact stress between the footing and the soil has a significant influence on the lateral stiffness of the system response. Similar findings are also reported for physical and numerical model studies on sand (Lehane et al. 2014, Arshi 2016) and some full scale testing and numerical analysis (Trojnar 2013).

Single gravity tests (Arshi 2011), and centrifuge and numerical model studies (Arshi 2015, 2016) have also investigated the influence of the footing size, and in particular the connection between the footing and the pile on the system response. As identified in the early studies (e.g. Stone et al. 2007, Stone et al. 2010) the requirement for the plate to exert a positive contact with the soil at the onset of loading significantly enhances the initial lateral response of the system. This can be achieved in one of two ways. In the first approach the plate and pile are fixed together and sufficient vertical load is applied such that the axial capacity of the pile is exceeded and the remaining applied vertical load provides a positive pre-stress bearing pressure with the soil. The other approach is to allow vertical movement of the plate to occur such that the footing may act independently from the pile. The positive contact between the footing and the soil underneath is solely controlled by the vertical load acting on the footing. The two configurations are referred to as 'coupled' and 'decoupled' hybrid systems respectively and are shown schematically in Figures 1a and 1b. .

In the coupled system all the vertical loading is shared between the pile and the bearing plate. In order to achieve a contact pre-stress between the plate and the underlying soil, the loads applied to the system must be such that the axial capacity of the pile is exceeded and settlement and contact of the plate with the underlying soil will be maintained. This arrangement would appear to offer significant savings in the size and/or length of the monopile and is essentially analogous to a piled raft with a single pile.

In the decoupled configuration vertical loads applied to pile are carried independently from the plate and vice versa, with the only vertical load carried by the pile occurring as the result of frictional contact at the plate/pile connection. The bearing plate is capable of supporting significant vertical loads, for example the entire superstructure weight of a wind turbine and tower may be supported by the bearing plate with little or no vertical load acting on the pile (Arshi 2012), as illustrated in Figure 1c.

Arshi (2013) presents the results of an extensive set of single gravity studies, of coupled and decoupled systems, for a range of combinations of pile and plate geometries, and skirts of varying lengths. From these studies the following general observations can be made. In the coupled arrangement the presence of the bearing plate provides a degree of both lateral and moment fixity at the mudline leading to enhanced lateral resistance from both the shear resistance and moment restraint provided by the plate. In the decoupled configuration the bearing plate is free to move relative to the pile, and as little or no moment is transferred between the pile and the plate, the enhanced lateral resistance is essentially provided by the shear resistance between the plate and the underlying soil. The lateral shear resistance is further enhanced if skirts are provided due to additional passive pressure acting on the skirt and the forcing of a lower plane of sliding. Numerical studies (Anastasopoulos and Theofilou 2015), and centrifuge studies (Arshi and Stone 2015, and Arshi 2016), demonstrate the potential of the decoupled hybrid arrangement.

Physical Model Testing

This paper will focus on the results of centrifuge model tests undertaken on coupled and decoupled un-skirted arrangements, carried out on a model piles at two different embedment depths using a range of bearing plate diameters. These tests were part of an extensive model testing programme comprising of both single gravity and centrifuge testing of coupled and decoupled, skirted and unskirted hybrid systems, with a range of pile and plate dimensions, embedment depths and loading arrangements. All the tests were carried out on dry sand under monotonic loading conditions, and a comprehensive presentation can be found in Arshi (2013) and Arshi (2016).

Materials and test procedures

All the centrifuge model tests reported here were performed in soil models made from a rounded to sub-rounded, uniformly graded fine silica sand with an average particle size of 0.25mm and a critical state angle of shearing resistance of 32 degrees as determined from direct shear tests. The maximum and minimum void ratios of the sand are 1.06 and 0.61 respectively. The models were formed through a combination of dry pluviation and vibration to achieve consistently dense samples with a relative density of 94%.

The interface friction angle between the sand and the aluminium used to fabricate the bearing plates was evaluated through a series of direct shear box tests. The results are summarised below in Table 1, from which an average value of 16 degrees is obtained over the applied stress range.

Centrifuge Test Procedure

The centrifuge tests were carried out on the University of Brighton's balanced beam geotechnical centrifuge manufactured by Thomas Broadbent & Sons. This machine has a working radius of 650mm and is capable of accelerating a 20kg model package to 300g. All the tests reported here were undertaken in dry sand at an acceleration level of 50g. The samples were prepared in a 320mm diameter, 180mm deep, circular tub which was then placed in an open sided rectangular strongbox and mounted on the centrifuge. The actuator and pulley arrangement required for loading the foundation system is mounted on the topside of the rectangular box, refer to Figure 2. The model piles were fabricated from 10mm diameter aluminium rod. Circular footings of 60 and 80mm diameter were formed from 5mm thick aluminium plate with an upstanding collar clamp. Grub screws within the collar allow the plate to be rigidly clamped to the pile shaft. A smaller 40mm footing was formed from 15mm solid aluminium with the grub screw passing through the plate. For the decoupled arrangement the grub screws are not tightened and the bearing plate is free to slide on the pile.

The test methodology followed that developed for a series of centrifuge tests reported by Stone et al. (2010). The model foundation system was installed at 1g by pushing the pile by hand to about 40% of its desired penetration depth, followed by light driving until contact between the bearing plate and the soil surface was achieved. During installation the bearing plate is clamped to the pile. The plate remains clamped or unclamped depending on whether a coupled or decoupled system is being tested. It is noted that the installation of the pile with the plate attached can lead to some disturbance of the underlying soil as the system is driven to a firm contact. Such disturbance cannot be quantified, but it is possible that a loosening of the soil immediately below the plate could result in a reduction of the effective interface friction between the plate and the soil and a reduction in the local bearing stiffness below the plate.

Vertical loading of the model foundation was provided by dead weights placed directly onto the bearing plate. Lateral loading was applied by a single degree of freedom actuator via a wire and pulley arrangement such that lateral loading is applied to the pile horizontally at a height of 80mm above the soil surface. The displacement of the pile was measured at the point of application of the load.

At a test acceleration of 50g the model dimensions are equivalent to a 0.5m diameter pile and the 40, 60 and 80mm diameter plates correspond to respective 2, 3 and 4m prototype diameters. In all cases it is assumed that the stiffness of the pile and plate is such that both components are considered to respond rigidly.

Results

Vertical load response

It is of interest to investigate the vertical response of the hybrid system and the component elements (i.e. the pile and bearing plate) to establish their relative contributions to the ultimate vertical capacity. In particular it is required to determine suitable values for initial vertical loading of the coupled and decoupled systems to ensure a degree of pre-stress of the underlying soil is achieved. For the coupled arrangement the vertical capacity of the pile is required to be exceeded before any pre-stress can be developed between the bearing plate and the soil. In these tests the bearing plate was clamped to the pile shaft and the pile embedded such that the plate was initially clear of the soil surface at the start of loading.

Plots of vertical load versus vertical displacement for a two coupled hybrid systems are shown in Figures 3 and 4. Figures 3a and 3b show data for a 40mm plate and 10mm diameter pile with an 80mm pile embedment depth for tests conducted at 20 and 40g respectively. Figure 4 shows data for a 40mm plate with a 5mm diameter pile and a 40mm embedment depth. Also shown on these plots is the vertical load response for the pile and 40mm bearing plate.

In all the tests it is observed that for the initial portion of the plot the vertical capacity for the hybrid system is coincident with that observed for the pile. As the pile penetrates the soil the bearing plate comes into contact with the soil surface and an increase in vertical load is recorded and the total vertical capacity of the hybrid system is increased due to the additional load carrying capacity provided by the plate. For the test conducted at 20g (10mm pile, 80mm embedment, 40mm plate) the ultimate capacity of the hybrid system is approximately 25% greater than the sum of the individual components, namely the pile and the plate. This can be attributed to (i) the increase in shaft resistance generated at the pile soil interface as a result of increased vertical effective stresses resulting from the plate surcharge loading, and (ii) the presence of the pile protruding below the footing which tends to stabilise the footing and reduce the effect of eccentric loading during the test. This latter element would imply that a punching shear mode of failure is being imposed on the system.

For test conducted at 50g for the hybrid system with a 10mm diameter pile, 80mm embedment depth and 40mm plate, the capacity of the loading actuator is exceeded before the ultimate vertical capacity of the hybrid system is reached. Extrapolation of the data by utilising a similar curve to that observed for the 20g data, would suggest that the total vertical capacity of the hybrid system is approximately 25-30% higher than the sum of the pile and plate capacities. This is consistent with the observations made above for the 20g test.

Figure 4 shows the results for the smaller 5mm pile with a reduced embedment depth of 40mm. It is apparent that the vertical capacity of the hybrid system is approximately equal to the sum of the respective pile and plate capacities. The vertical capacity of the plate is the dominant component, and the contribution of the pile is small and unable to significantly influence the response of the system.

Referring to Figures 3 and 4 it is also noted that the form of the load displacement plots for the pile and plate are significantly different. For the footing tests a relatively distinct ultimate capacity is observed, whereas for the pile tests no ultimate vertical capacity can be readily defined since the capacity continues to increase as the pile is driven deeper into the soil.

From Figure 3b the ultimate load supported by the footing at 50g is estimated at about 1000N. An average value for several similar tests of about 1050N was observed, from which an ultimate average bearing stress of 830kPa is derived. This value is used for benchmarking the amount of vertical pre-stress that is applied by the plate to the soil at the start of the lateral loading tests. For the coupled system, the pre-stress values are obtained by applying vertical load in excess of the axial capacity of the pile, however as discussed above, the axial capacity of the pile is not distinctly defined, and so a value taken at a vertical settlement of 25-30% of the pile diameter (2.5-3.0 mm) is used to define the axial pile capacity. Applied pre-stress values were selected at 5%, 10% and 25% of the ultimate bearing capacity for the 40mm diameter footing which correspond to values of 43 kPa, 85 kPa and 214 kPa. Since the ultimate bearing stress is directly proportional to the footing diameter, the selected pre-stress values represent less significant proportions of the ultimate bearing capacity for the larger diameter footings.

Lateral response

The centrifuge tests were conducted to investigate the behaviour of the coupled and decoupled systems in relation to (i) the influence of the vertical loading applied to the soil through the bearing plate, and (ii) the effect of the plate diameter for a given pile diameter and embedment depth. There are of course a significant number of possible combinations of plate diameter, pile diameter, pile embedment depth and vertical loading that can be applied to both the coupled and decoupled systems, and many combinations were included in the overall testing programme, including the use of skirted bearing plates. A more complete record of all the tests undertaken can be found in Arshi (2016).

A summary of the tests reported in this paper is presented in Table 2. For each plate diameter a series of four tests were carried out. One test considered vertical loading only from the self weight of the bearing plate, and for the three other tests, weights were placed on the bearing plate to develop the initial pre-stress. The assumed bearing stress generated by the self-weight of the plate is also presented in Table 2.

The actual contact stress developed between the soil and the plate was not directly determined. For the decoupled arrangement is seems reasonable to assume that the initial pre-stress is simply the load carried by the plate divided by the plate area in contact with the soil. For the coupled arrangement the estimation of the soil pre-stress is more complex, and since there is no direct measurement of the vertical load carried by the pile, the actual initial plate contact stress for the coupled system cannot be readily determined. For the study reported here it has been assumed that the portion of total load carried by the pile is that associated with a pile settlement of 2.5 - 3.0mm (25 - 30% of the pile diameter), and the remainder of the applied load is assumed to be carried by the bearing plate, and provides a vertical pre-stress with the soil. This assumption is tentatively based on the vertical load-displacement curves presented in Figures 3a and 3b where full shaft and end-bearing resistance is assumed to have been developed, and further capacity is essentially due to penetration of the pile. It is also noted that for both systems the vertical and lateral capacity of the pile will increase as a result of the pre-stress which increases the vertical effective stress locally around the pile. This is likely to be of negligible effect at low pre-stress levels but may become more significant at higher values, especially for the larger diameter bearing plates, and could have a significant influence on the response of the system.

The results of the centrifuge tests are best presented through plots of lateral load versus lateral displacement. Two test series are reported here. In the first Series 1 a pile embedment depth of 40mm is used together with 60 mm and 80 mm bearing plates. In the Series 2 tests the pile embedment length of 80mm is used, together with 40 mm, 60 mm and 80 mm diameter bearing plates. In all the tests the pile diameter was 10 mm.

An overview of the Series 1 tests is presented as follows. Figure 5 shows the lateral response of the coupled hybrid system with a 10mm diameter pile with 40mm embedment depth, and 60 and 80mm diameter bearing plates. Figure 6 shows the response for the corresponding decoupled arrangement.

For all the Series 1 tests performed it is generally observed that for both the coupled and decoupled systems, the increase in lateral resistance is generally proportional to the degree of pre-stress applied. The Series 1 tests are further presented in Figures 7 and 8 which plot the response of the hybrid system for each level of applied bearing stress (applied vertical load).

Referring to Figures 7a and 8a for the 40mm long pile (Series 1) with 60 and 80mm diameter bearing plates, for the case where the pre-stress is derived from the self-weight of the bearing plate, it is apparent that even at this low pre-stress the bearing plate enhances the lateral capacity of the monopile with a very similar response being observed for the coupled and decoupled systems. For the higher 43 kPa and 85 kPa pre-stress values the results of the coupled and decoupled systems are again broadly similar, refer to Figures 7b, 7c and 7d, and Figures 8b, 8c and 8d, however it is noted that the relative increase in the lateral capacity is much more significant.

The Series 2 results, with the 80mm long pile, are presented in Figures 9 and 10. Figures 9a and 10a show the results for the 40mm bearing plate. It is interesting to note that for the coupled system (refer to 9a), there is an increase in lateral resistance as the result of the presence of the plate with its nominal pre-stress due to self-weight, but on further addition of load, the lateral response at the higher pre-stress levels (43 kPa, 85 kPa and 214 kPa) does not appear to influence the lateral capacity of the system. To a certain extent a similar trend is observed for the 60mm diameter plate (Figure 9b). In this case there are significant increases in lateral capacity with the lower pre-stress levels associated with the plate self-weight and 43 kPa pre-stress case, but little variation in lateral capacity is observed for further increases in pre-stress. This observation is discussed later in detail.

Some general observations can be made regarding the form of the observed lateral load response curves for the two different pile lengths used in the series 1 and 2 tests. For example, the load displacement curves for the shorter 40 mm pile, for both the coupled and decoupled arrangements, demonstrate a strain softening response which becomes more distinct at larger plate diameters. This response is similar to that observed for footings loaded on dense sand, and in particular for eccentrically loaded footings. In contrast a strain hardening load response is observed for the series 2 tests with the longer pile embedment depth, which is similar in form to a load-displacement curve that would be exhibited by the pile alone. In broad terms it appears that the series 1 tests are influenced by the response of the bearing plate, whereas the series 2 tests are more influenced by the pile response. This illustrates the effect of pile embedment depth and the contribution and interaction of the two elements that form the hybrid system.

For the coupled arrangement some interesting observations can be made in relation to the effectiveness of the pre-stress loading. Of particular interest are the results of the 80mm embedded pile with the 40mm bearing plate. For this arrangement very similar lateral responses were observed for the 43 kPa, 85kPa and 214 kPa pre-stress loads, with a lower lateral resistance for the self-weight of the plate (25 kPa), refer to Figure 9a. These tests were repeated several times with the same result being observed. It is suggested that the reason for the similar response at higher bearing stresses is due to the maximum soil bearing pressure being mobilised at a similar stage. Once the ultimate bearing capacity of the soil beneath the plate is obtained then the value of pre-stress is no longer of significance. The response of the system will thus be similar since both the mudline moment and interface shear developed will be associated with the same ultimate bearing stress of the soil.

Comparison between coupled and decoupled systems is best achieved by plotting the lateral load versus displacement response for both systems together for each applied pre-stress. These plots are shown in Figures 11, 12 and 13 for the 40, 60 and 80mm diameter footings respectively. From these figures some interesting observations are made. For example, at low initial bearing stress the response of the coupled and decoupled arrangements are very similar (refer to Figures 11a, 12a and 13a), in fact for the 40 and

60mm bearing plates the lateral response is almost the same, with only a slightly increased ultimate lateral capacity shown for the coupled 80mm footing system over the decoupled system, refer to Figure 13a.

For all the 43 kPa and 85 kPa pre-stress values the ultimate lateral capacity of the coupled arrangement is significantly greater than that observed for the corresponding decoupled arrangement, refer to Figures 11b, 11c, 12b, 12c, 13b and 13c. However for the highest pre-stress loading the lateral response of the coupled and decoupled systems tend to converge, refer to Figures 11d, 12d and 13d. In particular the response for high 214 kPa pre-stress for the 40 and 60mm plates are very similar for the coupled and decoupled arrangement (refer to Figure 11d and 12d). This may be attributed to the mobilised stress in both arrangements being similar.

Comparison coupled and decoupled response

For the decoupled arrangement the increase in lateral capacity of the hybrid system is provided by

(i) friction between the soil and the underside of the plate,

(ii) increased lateral resistance of the pile due to applied pre-stress.

For the coupled arrangement, the following additional interaction contributes to the lateral capacity of the system, namely

(iii) the development of a resisting moment at the mudline from soil reaction on the bearing plate.

It is significant to note that for the decoupled arrangement, since the pre-stress remains essentially unchanged during load application, then both the interface resistance and lateral pile capacity will remain essentially constant. However, for the coupled arrangement the actual contact stress developed between the bearing plate and the soil is a complex interaction analogous to a rotating piled-raft. The contact stress will be a function of the net vertical load carried by the plate which is related to vertical capacity of the pile. This in turn is related to the vertical effective stress which is a function of the pre-stress. The vertical effective stress developed around the pile is determined by a combination of the initial pre-stress and the soil reaction stress as the plate rotates.

As an initial analysis it is of interest to examine the effect of interface friction developed between the bearing plate and the underlying soil. This is best achieved by considering the increase in lateral resistance of the hybrid system over that observed for the corresponding pile. It is also of interest to present the displacement information of the system through the lateral displacement of the bearing plate at the soil surface, rather than the displacement at the point of loading (80mm above the soil surface).

Figures 14a to 14f show plots of the development in increased lateral resistance of the decoupled hybrid systems over the lateral resistance of the pile alone, plotted against the initial pre-stress, for the 10mm diameter 80mm long piles. The plots are derived for selected values of lateral displacement (at the mudline) of 2.5mm, 5mm and 10mm. Figures 15a to 15d show corresponding plots for the decoupled hybrid system with the 40mm long pile and at mudline displacements of 2.5mm, 5.0mm and corresponding to the peak lateral capacity (refer to Figures 5 to 6). Theoretical values of frictional force developed at the plate soil-interface ('Plate Friction' in Figures 14 and 15) are derived from the product of the pre-stress load and the tangent of the interface friction angle.

Referring to Figures 14a to 14c and 15a to 15b, it is apparent from these data that there is generally good agreement between the theoretical value of the frictional shear force developed at the plate-soil interface, and the increase in the lateral capacity of the decoupled hybrid system. The exception being that for the 40mm pile and 60mm plate combination (Figure 15a) where the use of mobilised interface friction value derived from the data presented in Table 1 (16°) over-predict the observed system response. In this instance an interface friction of 10° produces a very close match to the experimental results. This may be an illustration of (i) the sensitivity of the system to the mobilised interface friction which can be influenced by sample preparation, initial bedding of the plate and other factors, and (ii) the use of an assumed average contact stress to represent the non-uniform stress distribution between the plate and the soil.

It is also apparent for the decoupled system that the relationship between the increased lateral capacity and pre-stress is linear. This is consistent with the majority of the increased capacity being derived by the interface friction generated between the bearing plate and the underlying soil; the frictional shear stress being directly proportional to the applied normal stress, which in this case is the applied pre-stress.

Corresponding plots of increased lateral capacity against initial pre-stress for the coupled system are shown in Figures 14d to 14f and 15c to 15d for the 80mm (Series 1) and 40mm (Series 2) piles respectively. It is apparent that in this case the analysis presented above is unable to adequately capture the response of the system. The increase in the lateral capacity of the coupled hybrid is more complex, and as discussed earlier, the contribution of the other interactions must be considered since the system behaviour is significantly affected by the fixed connection between the plate and the pile.

In the decoupled system little moment can be transferred between the plate and the pile since the plate is free to slide, and it is also the case that the pre-stress applied at the start of the test will remain unchanged as the system is loaded. This is assuming that as the system rotates under the action of a lateral load, the bearing plate will tend to slide up the pile rather than develop a greater contact stress, although it is also noted that due to the eccentric soil reaction on the plate it is also possible that plate may 'lock-up' on the pile shaft rather than slide freely, and this would result in a degree of moment restraint at the pile-plate connection giving a similar response between decoupled and coupled arrangements. This 'locking-up' is a possible explanation for the similar load-displacement response of the coupled and decoupled systems reported earlier for the high pre-stress cases for the 40mm and 60mm plates with 80mm pile, refer to Figures 11d and 12d. However, it is noted that this convergence between coupled and decoupled responses at high pre-stress is not observed for the 40mm long pile (see Figures 7d and 8d) and it therefore may be related to the geometry of the system.

The convergence of the load displacement plots for the low pre-stress values is also observed for both the 40mm and 80mm pile lengths (refer to Figures 7a, 8a, and Figures 11a and 12a). In this case it is suggested that the similar responses are due to interface friction dominating the increased lateral capacity for both systems, with the additional mudline restoring moment of the coupled system being less significant.

For the coupled arrangement, as the system rotates bearing stresses increase on the underside of the plate and resisting moments can be developed at the plate-pile connection which introduces a degree of rotational fixity at the mudline. This results in a further increase in the lateral resistance of the system. Furthermore, the increased bearing stress developed between the plate and the soil will result in an increased frictional resistance further increasing the lateral capacity of the system. However, the higher vertical effective stresses below the bearing plate would increase the vertical (and lateral) capacity of the pile and a classic interaction develops between the axial pile capacity and the plate bearing pressure, and the whole process is further complicated by the changing contact area between the plate and the soil as the system rotates. It is however suggested that both the magnitude of the mudline moment and the interface friction would be limited by the ultimate bearing capacity of the soil (i.e. a maximum contact stress can develop). This limitation is perhaps illustrated, as discussed earlier, by the response of the 80mm pile with the 40mm bearing plate (L80 F40 C) shown in Figure 14d (see also Figure 9a). In these tests the increase in lateral resistance appears to be relatively constant for initial pre-stress values greater than about 50kPa.

The complex interactions described above are best modelled using numerical methods, and the following section presents an initial study in an attempt to gain further insights of the response of the hybrid systems.

Numerical modelling

The hybrid foundation system is relatively well suited to numerical analysis since it involves a complex soil-structure interaction. This is particularly true for the coupled hybrid system which is essentially analogous to a piled-raft foundation, albeit with a single pile. The decoupled system is perhaps more readily analysed through a simple addition of the contributions of the constituent elements but is also suitable for numerical analysis. In order to carry out a realistic analysis the programme must have as a minimum the following capabilities together with an appropriate model for the soil response;

i. 3-D geometry modelling,
ii. the ability to model separation (or zero tension) between the footing and the soil,
iii. the ability to model the interface properties between structural and soil elements,
iv. allow full decoupling and the ability for slippage between the plate and pile.

The 3D finite element analysis reported here was carried out using the Imperial College Finite Element Program (ICFEP), (Potts and Zdravkovic 1999). The analysis considered the equivalent prototype of the scaled up centrifuge model resulting in a 4m pile embedment of a 0.5m diameter pile with a 4m diameter bearing plate. The aim was to replicate the centrifuge tests in prototype dimensions and compare the load versus deflection response of the 3D FE results with the corresponding centrifuge tests. The analysis involved a 'wished in place' pile installation followed by the application of a uniform load over the bearing plate. Lateral loading was then applied incrementally in order to generate plots of lateral load against displacement for comparison with the centrifuge model tests.

The soil was modelled as a nonlinear elasto-plastic Mohr-Coulomb material fully described by Potts & Zdravkovic (1999), with the small strain stiffness formulation of Jardine et al. 1986 employed to cater for non-linearity below yield. This model takes into account the variation of normalised shear and bulk stiffness with deviatroic and volumetric strains. The input parameters including the small strain stiffness model parameters were those presented by Zdravkovic et al. (2005) for Thanet Sand, which was deemed to be similar in characteristics to the uniformly graded Fraction C sand used in the centrifuge tests.

A critical state friction value of 32 degrees was adopted for the soil model with a maximum dilation value of 20° which is associated with the relatively low stress level and unconfined surface boundary in the centrifuge model. Similar high dilation values have been reported by Stone (1988) and Stone and Wood (1992).

The main findings of the finite element results are presented at prototype scale through selected plots, and where applicable the centrifuge model test data is also presented for comparison.

Figure 16 shows a summary of the pile displacement profiles. It is apparent that the displacement profiles are very similar for the pile only and the coupled hybrid system. The presence of the bearing plate does not appear to influence the point of rotation of the pile which appears to be at a depth of approximately 2.75m below ground level which is about 70% of the embedment depth. However for the decoupled arrangement the point of rotation is seen to be at a depth of about 2.2m below ground level or at about 50-55% of the embedment depth. The interaction of the plate with the underlying soil is evaluated more closely by considering the settlement profile and development of plate bearing stress throughout the loading process. Figures 17a shows the plate centerline rotation plotted either side of the pile for the coupled hybrid system. It is evident from this plot that the dominant movement of the bearing plate is one of rigid body rotation centred on the pile axis. The rotation is symmetric with the leading edge penetrating some 70mm into the soil and a corresponding uplift to the trailing edge. Figure 17b shows the distribution of normal stress at the plate soil interface.

For the decoupled system the plate rotation and the bearing stress are shown in Figures 18a and 18b respectively.

Comparison of Figures 17a and 17b and 18a and 18b clearly illustrate that the behaviour of the coupled and decoupled arrangements are fundamentally different through the way the plate interacts with the underlying soil. For the coupled system the rigid body plate rotation develops bearing stresses up to twice those observed for the decoupled system. But this is to be expected because the decoupled plate will tend to slide up the pile. This observation is in agreement with experimental observations where the plate was observed to have slid up the pile during some tests. Although as already noted there is a tendency for the plate to lock-up under the action of non-uniform bearing pressure which would not be captured in the numerical simulation.

Ultimately it is of interest to develop full load-displacement curves for the hybrid systems to demonstrate an applicable method for design and further analysis. Figure 19 presents a comparison between the 3D-FE analysis and the corresponding centrifuge model test data, plotted at prototype scale, for the 80mm pile and 80mm bearing plate. From this Figure it is apparent that, for both pile only and hybrid cases, the numerical results show a very good match between the centrifuge and 3D-FE analysis. The match is not so satisfactory for the coupled system where the experimental results are seen to present a stiffer response and an overestimate of the ultimate capacity of the system. However, it is apparent that the numerical approach is able to capture the significantly different behaviour demonstrated by the coupled and decoupled arrangements.

Discussion

The experimental study has demonstrated that the use of a bearing plate can significantly enhance the lateral capacity of a monopile installed in dense sand under monotonic loading conditions. The hybrid foundation arrangement was investigated where the bearing plate was either fully fixed to the pile (coupled) or free to slide vertically on the pile shaft (decoupled).

In the coupled arrangement the lateral capacity of the system is derived from (i) the lateral resistance of the pile, (ii) the lateral shear resistance on the underside of the bearing plate, and (iii) the resisting moment developed at the mudline as the plate rotates. For a particular combination of pile and plate geometry, the development of each of these elements of resistance are associated with degrees of mobilisation, either of rotation, which is associated with changing contact stress between the plate and the soil, or displacement. The interactions that develop in the coupled system can be qualitatively summarised as follows:

i. The effect of the initial pre-stress on the pile capacity is a soil-structure interaction problem analogous to a piled raft. The vertical and lateral capacity of the pile increases as the vertical effective stress around the pile increases. An initial equilibrium between vertical pile capacity and the plate bearing stress (pre-stress) will develop.
ii. The development of the resisting moment at the mudline occurs as rotational embedment of the plate develops a non-symmetric contact stress.
iii. The vertical and lateral pile resistance increases as a result of the local increase in vertical effective stress under uniform pre-stress.
iv. The increase in the contact stress from rotational embedment of the plate results in a higher frictional resistance at the plate-soil interface.
v. Both the mudline moment and increased interface friction can only develop to a maximum value associated with the ultimate bearing stress of the underlying soil.

In the decoupled arrangement the interaction is much simpler since is assumed that the connection between the pile and bearing plate is unable to apply a resisting moment at the mudline. Since the plate is free to move vertically on the pile shaft with negligible frictional resistance, the initial pre-stress applied by the bearing plate can be readily determined. Since it can be assumed that the load applied to the plate remains relatively constant throughout the loading process, then the interface friction would also remain constant throughout the test. The analysis of the decoupled arrangement is thus relatively straightforward where the lateral capacity is derived from the following components:

i. the lateral capacity of the pile, including any effect of the plate surcharge, and
ii. the shear stress developed between the bearing plate and the underlying soil.

The results presented here indicate that this latter component dominates the response for the geometry of the decoupled systems tested, such that the increase in lateral resistance is essentially due to lateral shear force developed at the soil-plate interface.

In the experimental studies the development of the lateral capacity of the hybrid systems is influenced by the scale effect associated with the grain size of the sand used in the tests. Such scale effects are well reported elsewhere (Stone 1988, Stone and Wood 1992) and are associated with the absolute relative displacement required for the soil to achieve its peak and critical state values of mobilised friction. For a uniformly graded sand these relative displacements are a function of the relative density, stress level, and the particle size of the material. It is noted that some relative lateral displacement is required to fully mobilise the interface friction, the mudline moment, and the pile lateral capacity. All these components may have different mobilisation displacements which are likely to be an inherent scale effect of the model which is difficult to quantify, but is likely to overestimate the lateral movement required to develop ultimate lateral capacities for the hybrid systems with respect to a corresponding prototype.

For both arrangements it is also possible that some small increase in lateral capacity occurs from passive pressure against the edge of the bearing plate. This component is not considered to offer a significant contribution to the lateral resistance for the tests reported. However, for skirted system, see for example Arshi (2011), Haiderali and Madabhushi (2016), both high passive resistance and greater shear resistance can develop since the plane of sliding is not confined to the soil-plate interface.

The numerical analysis presented was able to capture the general response and mechanisms of both coupled and decoupled systems and provide reasonable agreement to the experimental results. In particular the analysis was able to demonstrate the development of high bearing stresses beneath the rotating plate of the coupled system, and the relatively constant bearing stress and plate uplifting mechanism of the decoupled arrangement.

Conclusions

From the studies reported herein the following conclusions can be made.

1. A hybrid foundation system can be formed from the combination of a pile and a bearing plate. The bearing plate can be fixed (coupled) to the pile or free (decoupled) from the pile and although apparently similar in concept, the different systems have fundamental differences in their response and development of lateral capacity.
2. Both hybrid systems demonstrate a higher lateral stiffness and ultimate lateral capacity over that of the pile or the bearing plate alone.
3. The lateral response of the hybrid system is a function of the plate and pile geometry and stress developed between the bearing plate and the underlying soil.
4. The initial lateral stiffness is influenced by the initial bearing stress between the plate and the soil at the onset of loading.
5. For the decoupled system the initial bearing stress is provided by dead load supported by the plate and is readily determined
6. For the coupled system the initial pre-stress is provided by the applied loads being in excess of the vertical capacity of the pile, and are not readily determined if the axial pile capacity is not well defined.
7. For the coupled system, lateral capacity is derived through pile resistance, the interface friction between the plate and underlying soil and the restoring moment generated at the mudline by the rotating bearing plate.
8. For the decoupled system the lateral capacity is derived through the pile lateral resistance and the bearing plate interface friction.
9. Numerical modelling is able to capture the behaviour of both the coupled and decoupled hybrid systems.

As a final remark, it is worth noting that this study has demonstrated some advantages of both coupled and decoupled systems. To best exploit the attributes of both arrangements it is proposed that a hybrid system is developed where the bearing plate is able to translate vertically down the pile shaft but not upwards. Such an arrangement has (i) the advantage of the decoupled arrangement where the bearing plate is able to maintain and develop sliding resistance through contact with the soil surface with a pre-set contact stress, and (ii) the ability to develop a resisting moment at the plate-pile connection as is the case for the coupled arrangement. The full scale practicalities of such a system remain to be developed. However, it is clear there are significant advantages to be gained in terms of the development monopile-bearing plate hybrid foundation systems for practical application.

References

Arshi HS (2016) Physical and numerical modelling of hybrid monopile-footing foundation systems. PhD dissertation, University of Brighton.

Arshi H.S and KJL Stone (2015) Improving the lateral resistance of offshore pile foundations for deep water application. Proceedings of the 3rd International Symposium on Frontiers in Offshore Geotechnics (Mayer ed.), Norway, ISBN:978-1-138-02848-7.

Arshi HS, Stone KJL, Vaziri M, Newson T, El-Marasi M, Taylor RN and Goodey R. (2013). Physical model testing of hybrid monopile-footing foundation system in sand for offshore structures. *In: Proceeding of the 19th International Conference on Soil Mechanics and Geotechnical Engineering*, Paris, Sep 2nd 2013. Pp. 2307-2310. ISBN 9782859784744

Arshi HS (2013) Unpublished Report, University of Brighton.

Arshi HS, Stone KJL and Vaziri M (2012) Decoupled Hybrid Monopile-Footing Foundation System. 10th Annual British Geotechnical Association Conference (Poster presentation).

Arshi HS. (2011). Structural behaviour and performance of skirted hybrid monopile-footing foundations for offshore oil and gas facilities. *Proceedings of the Institution of Structural Engineers: Young Researchers Conference '11*. London: IStructE Publications, 8.

Anastasopoulos I and Theofilou M (2015) On the development of a hybrid foundation for offshore wind turbines. Proceedings of the 3rd International Symposium on Frontiers in Offshore Geotechnics (Mayer ed.), Norway, ISBN:978-1-138-02848-7.

Bunce J.W and Carey J.M (2001) A guyed support structure design for large megawatt offshore wind turbines in deep waters, EWEA Special Topic Conference on Offshore Wind Energy, Brussels, 10-12 December 2001

Bunce J.W and Carey J.M (2001) A guyed OWEC support structure design, Proc. European Wind Energy Conference (EWEC 2001), Copenhagen, 2nd - 6th July 2001.

Carder, D.R., Watson, G.V.R., Chandler R.J & Powrie W (1999) Long term performance of an embedded retaining wall with a stabilizing base. Proc. Instn. Civ. Engrs Geotech. Engng 137, No. 2, 63-74.

Carder, D.R & Brookes N.J (1993). Discussion. In Retaining Structures (ed. C.R.I Clayton), London, Thomas Telford, 498-501.

Dixon RK (2005) Marine Foundations. WO (Patent application) 2005/038146.

Haiderali A and Madabhushi G (2016) Improving the lateral capacity of monopiles in submarine clay. Proc. Instititution of Civil Engineers, Ground Improvement, Vol. 169, Issue GI4,239-252.

Jardine RJ, Potts DM and Fourie AB. (1986). Studies of the influence of non-linear stress-strain charactersitics in soil-structure interaction. Geotechnique. 36(3). 377-396.

Lehane BM, Pedram B, Doherty JA and Powrie W (2014) Improved performance of monopiles when combined with footings for tower foundations in sand. Journal of Geotechnical and Geoenvironmental Engineering 140(7):04014027

Potts DM and Zdravkovic L. (1999). Finite element analysis in geotechnical engineering: theory. London, Thomas Telford.

Powrie W, and Daly MP. (2007). Centrifuge modelling of embedded retaining walls with stabilising bases. *Geotechnique*. 57(6), 485-497.

Stone KJL, Newson TA and Sandon J. (2007). An investigation of the performance of a ‘hybrid’ monopole-footing foundation for offshore structures. Proceedings of 6th International on Offshore Site Investigation and Geotechnics. London: SUT, 391-396.

Stone KJL, Newson TA and El Marassi, M. (2010). An investigation of a monopiled-footing foundation. International Conference on Physical Modelling in Geotechnics, ICPMG2010. Rotterdam: Balkema, 829-833.

Stone KJL, Newson TA, El Marassi M, El Naggar H, Taylor RN and Goodey RA. (2011). An investigation of the use of a bearing plate to enhance the bearing capacity of monopile foundations. International Conference on Frontiers in Offshore Geotechnics II, ISFOG. London. Taylor and Francis Group, 623-628.

Stone KJL 1988 Modelling of rupture Development in soils, PhD University of Cambridge.

Stone KJL and D.M Wood (1992) "Effects of Dilatancy and Particle Size Observed in Model Tests on Sand", Soils and Foundations, Vol 32, No. 4, 43-57.

Trojnar K (2013) Lateral stiffness of hybrid foundations: field investigations and 3D FEM analysis. Geotechnique 63, No. 5, 355-367.

Zdravkovic L, Potts DM and St. John HD. (2005). Modelling of a 3D excavation in finite element analysis. Gotechnique. Vol. 55(7), 497-513.

Table 1. Interface friction from direct shear box tests

Normal stress (kPA)	**Peak shear stress (kPA)**	**Interface friction (degrees)**	**Mobilisation displacement (mm)**
49	15	17.0	~1.75
98	28	15.9	~1
147	41	15.4	~1

Table 2. Summary of tests

Test ID C - coupled D - decoupled	**Pile embed-ment (mm)**	**Plate diameter (mm)**	**Total load on system (N)**	**Load carried by pile (N)**	**Load carried by plate (N)**	**Initial plate bearing pressure (kPa)**	**Percentage of ultimate bearing pressure (%)**
Series 1: Coupled Hybrid Tests (**L** (pile length) **F** (plate diameter) C (coupled) XX (pre-stress)							
L40 F60 C9	40	60	276	250	26	9	0.7
L40 F60 C43	40	60	371	250	121	43	3.5
L40 F60 C85	40	60	492	250	242	85	7
L40 F60 C214	40	60	854	250	604	214	17
L40 F80 C8	40	80	291	250	41	8	0.5
L40 F80 C43	40	80	465	250	215	43	2.6
L40 F80 C85	40	80	679	250	429	85	5
L40 F80 C214	40	80	1323	250	1073	214	13
Series 1: Decoupled Hybrid Tests (**L** (pile length) **F** (plate diameter) D (decoupled) XX (pre-stress)							
L40 F60 D9	40	60	276	250	26	9	0.7
L40 F60 D43	40	60	371	250	121	43	3.5
L40 F60 D85	40	60	492	250	242	85	7
L40 F60 D214	40	60	854	250	604	214	17
L40 F80 D8	40	80	291	250	41	8	0.5
L40 F80 D43	40	80	465	250	215	43	2.5
L40 F80 D83	40	80	655	250	415	83	5
L40 F80 D214	40	80	1323	250	1073	214	13
Series 2: Coupled Hybrid Tests (**L** (pile length) **F** (plate diameter) C (coupled) XX (pre-stress)							
L80 F40 C25	80	40	566	535	31	25	3
L80 F40 C43	80	40	589	535	54	43	5
L80 F40 C85	80	40	642	535	107	85	10
L80 F40 C214	80	40	803	535	268	214	25
L80 F60 C9	80	60	561	535	26	9	0.7
L80 F60 C43	80	60	656	535	121	43	3.5
L80 F60 C85	80	60	777	535	242	85	7
L80 F60 C214	80	60	1139	535	604	214	17
L80 F80 C8	80	80	576	535	41	8	0.5
L80 F80 C43	80	80	750	535	215	43	2.6
L80 F80 C85	80	80	964	535	429	85	5
L80 F80 C214	80	80	1608	535	1073	214	13
Series 2: Decoupled Hybrid Tests (**L** (pile length) **F** (plate diameter) D (decoupled) XX (pre-stress)							
L80 F40 D25	80	40	31	535	31	25	3
L80 F40 D43	80	40	54	535	54	43	5
L80 F40 D85	80	40	107	535	107	85	10
L80 F40 D25	80	40	268	535	268	214	25
L80 F60 D9	80	60	26	535	26	9	0.7
L80 F60 D43	80	60	121	535	121	43	3.5
L80 F60 D85	80	60	242	535	242	85	7
L80 F60 D214	80	60	604	535	604	214	17
L80 F80 D8	80	80	41	535	41	8	0.5
L80 F60 D43	80	80	215	535	215	43	2.6
L80 F80 D85	80	80	415	535	415	83	5
L80 F80 D214	80	80	1073	535	1073	214	13

Figure 1

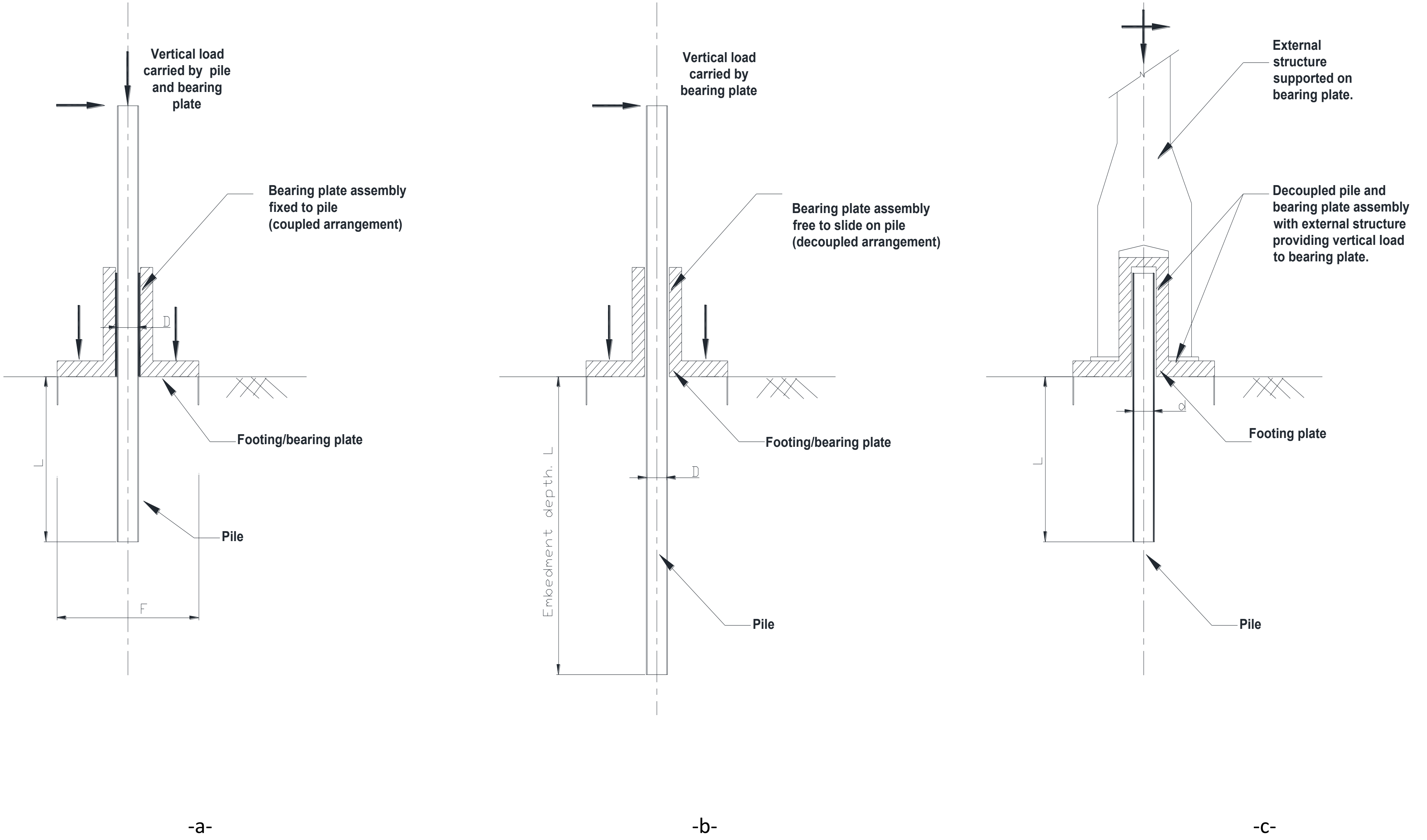


Figure 1.(a) Typical arrangement for coupled system, (b) a decoupled system with loading applied to bearing plate and, (c) a decoupled arrangement with superstructure loads carried by the bearing plate.

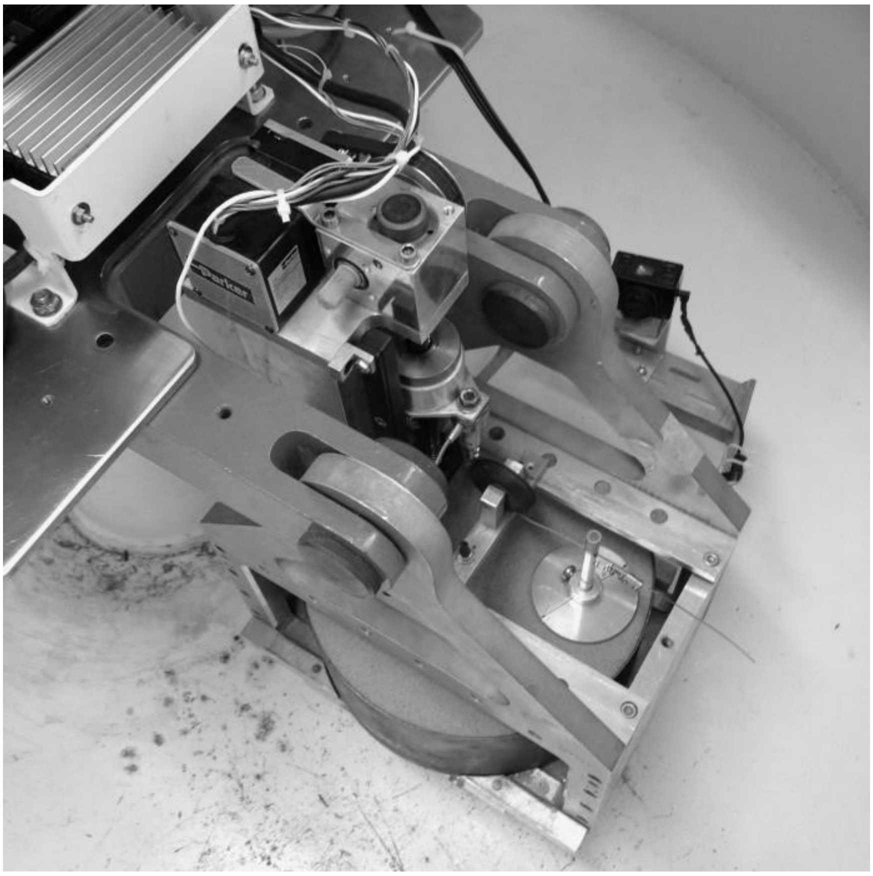
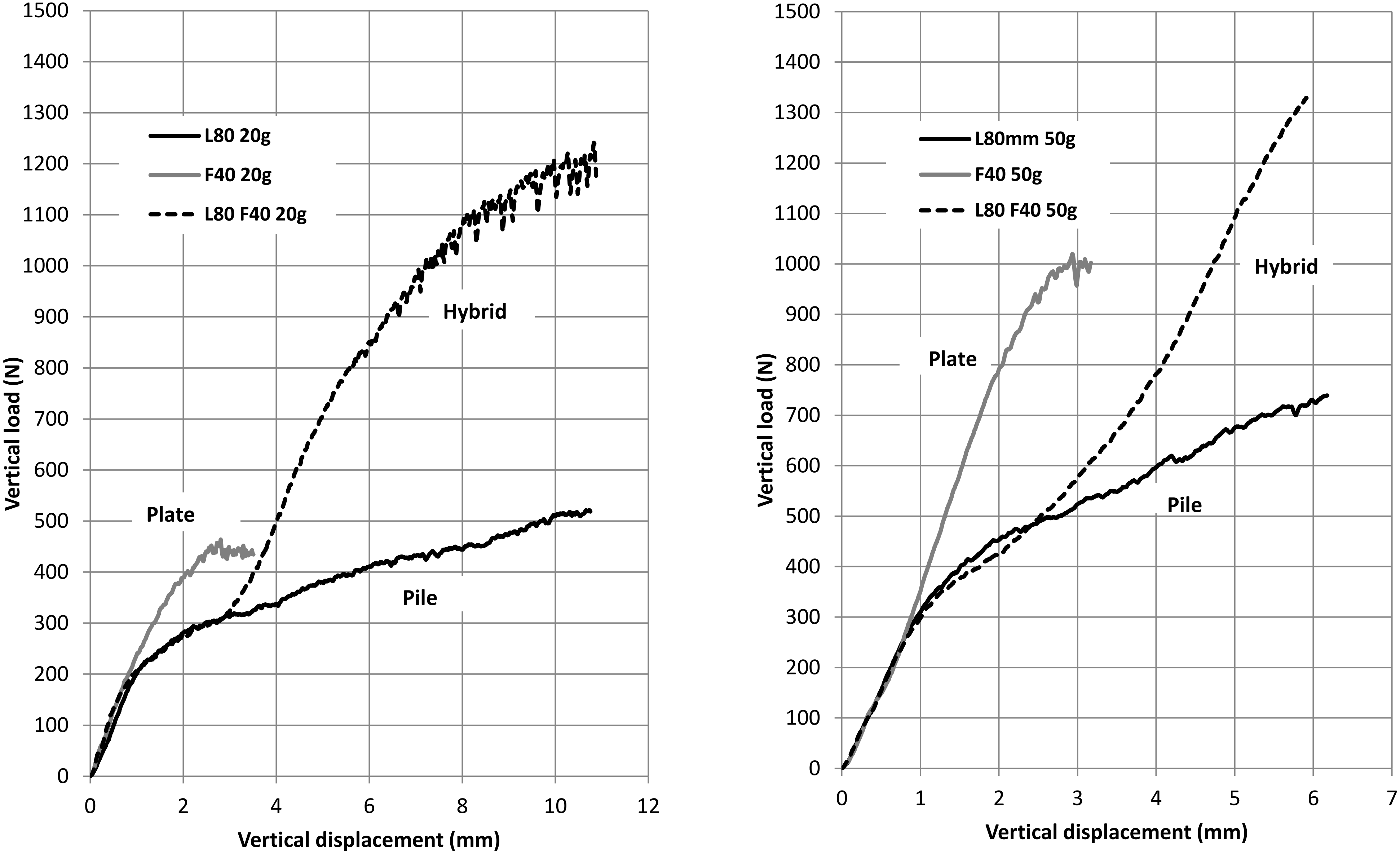


Figure 2. Centrifuge model test arrangement.



-a-

-b-

Figure 3.(a) Response of coupled hybrid system of 40mm plate and 10mm diameter pile with 80mm embedment (C10 L80 F40) under axial load at 20g and, (b) at 50g.

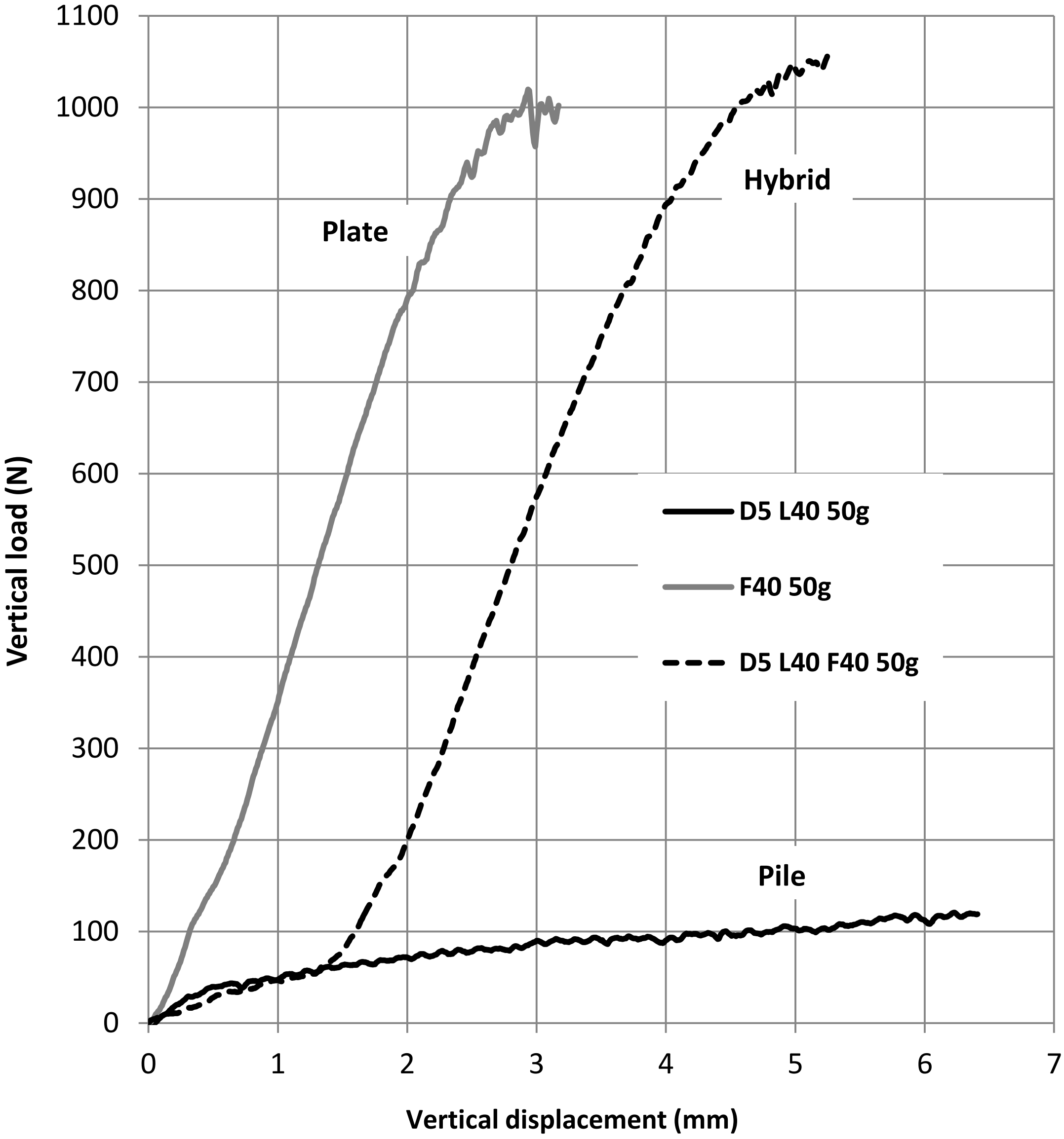


Figure 4. Response of coupled hybrid system of 40mm plate and 5mm diameter pile with 40mm embedment depth (C5 L40 F40 C) at 50g.

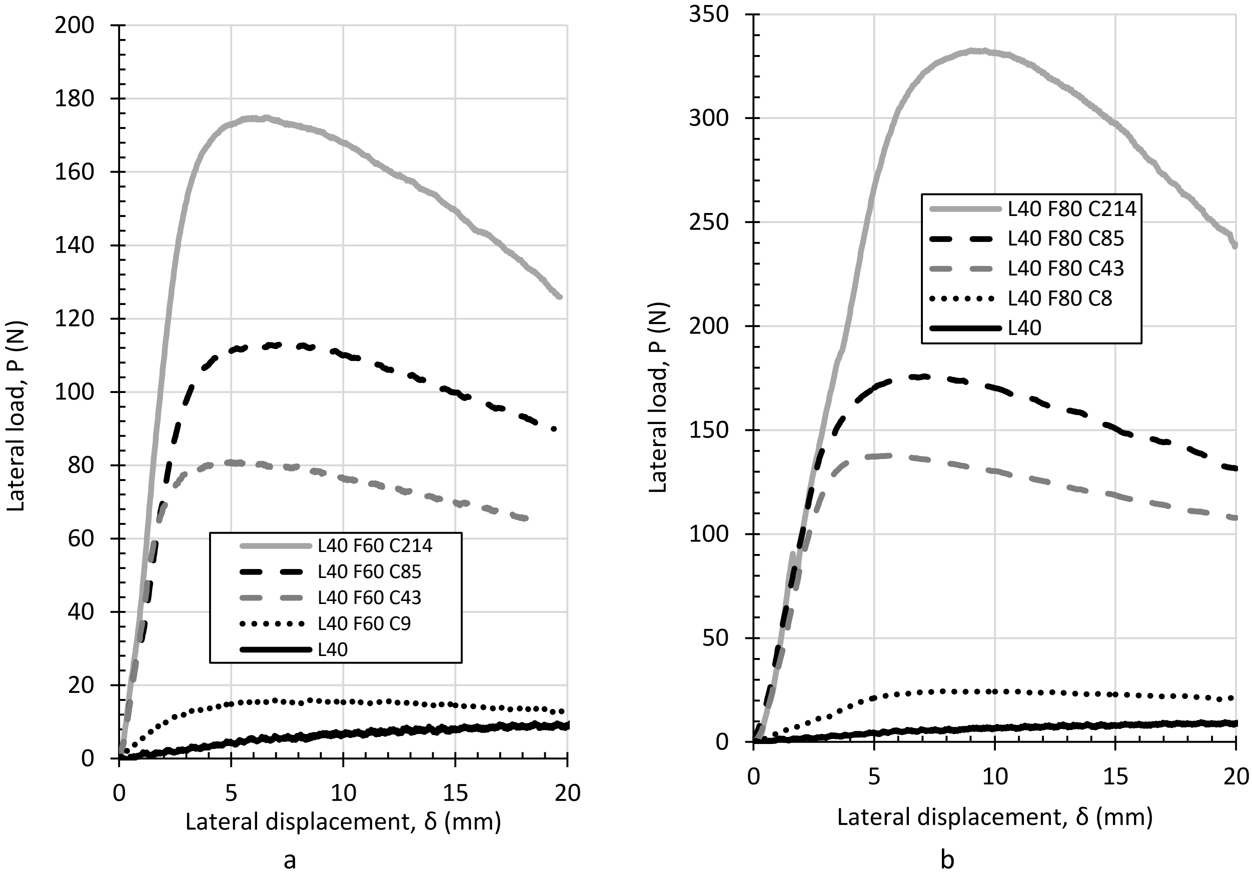
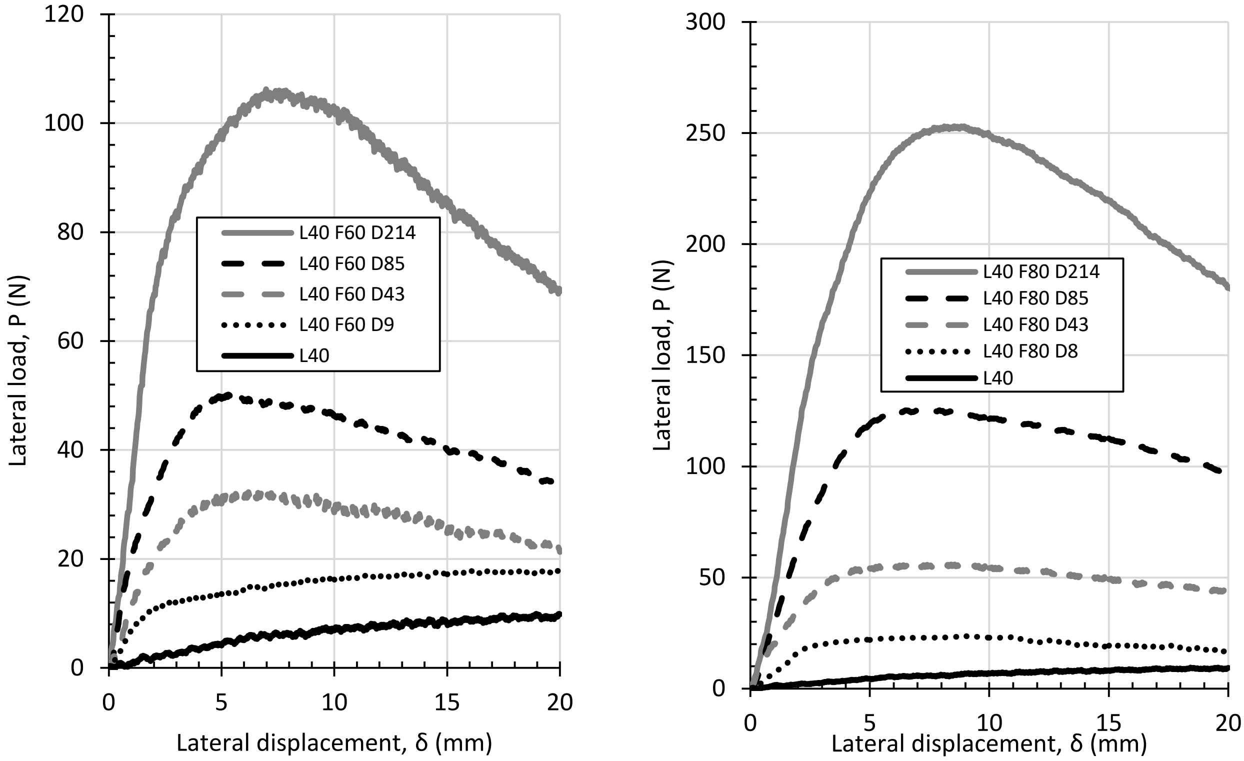


Figure 5.(a) Overview of coupled hybrid system; 10mm diameter pile, 40mm embedment depth (L40); 60mm bearing plate (F60) and (b) 80mm diameter bearing plate (F80) for all pre-stress levels.



b

a

Figure 6.(a) Overview of decoupled hybrid system; 10mm diameter pile, 40mm embedment depth (L40); 60mm bearing plate (F60) and (b) 80mm diameter bearing plate (F80) for all pre-stress levels.

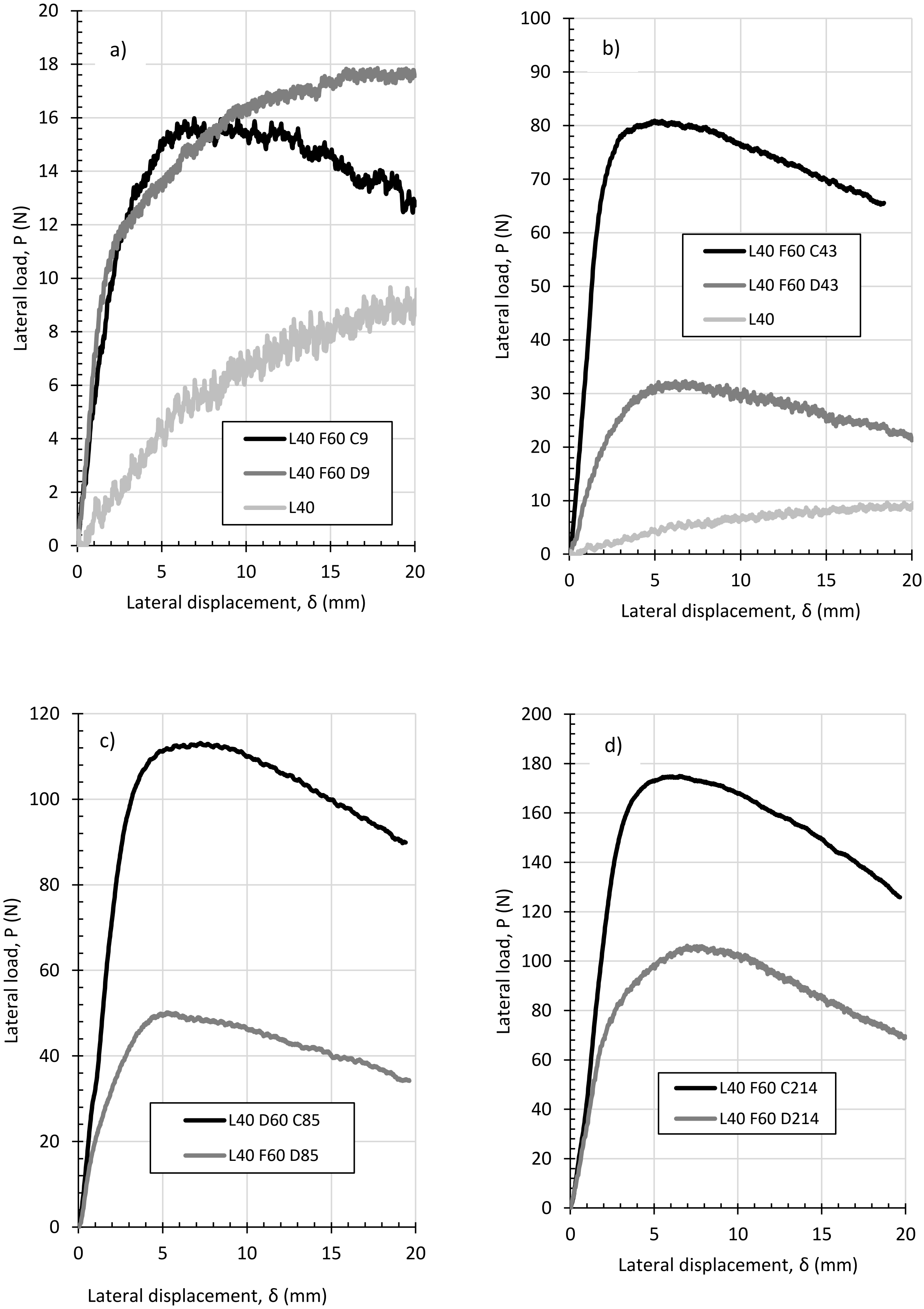


Figure 7. Comparison of coupled (C) and decoupled (D) lateral response for 10mm pile; 40mm embedment depth and 60mm diameter bearing plate for initial bearing stresses of (a) 9kPa; (b) 43kPa; (c) 85kPa and (d) 214kPa.

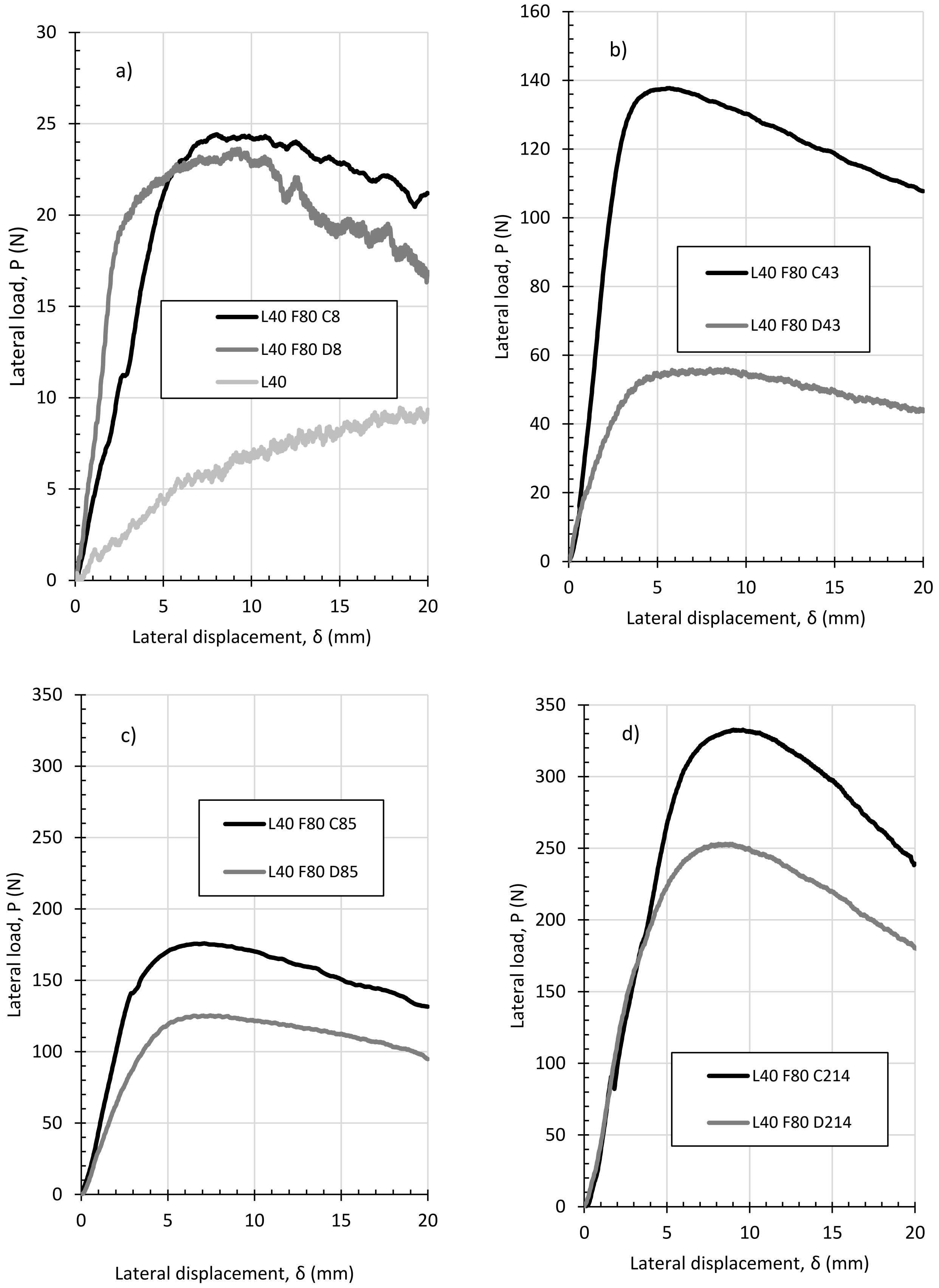


Figure 8. Comparison of coupled (C) and decoupled (D) lateral response for 10mm diameter pile; 40mm embedment depth and 80mm diameter bearing plate for initial bearing stresses of (a) 8kPa; (b) 43kPa; (c) 85kPa and (d) 214kPa.

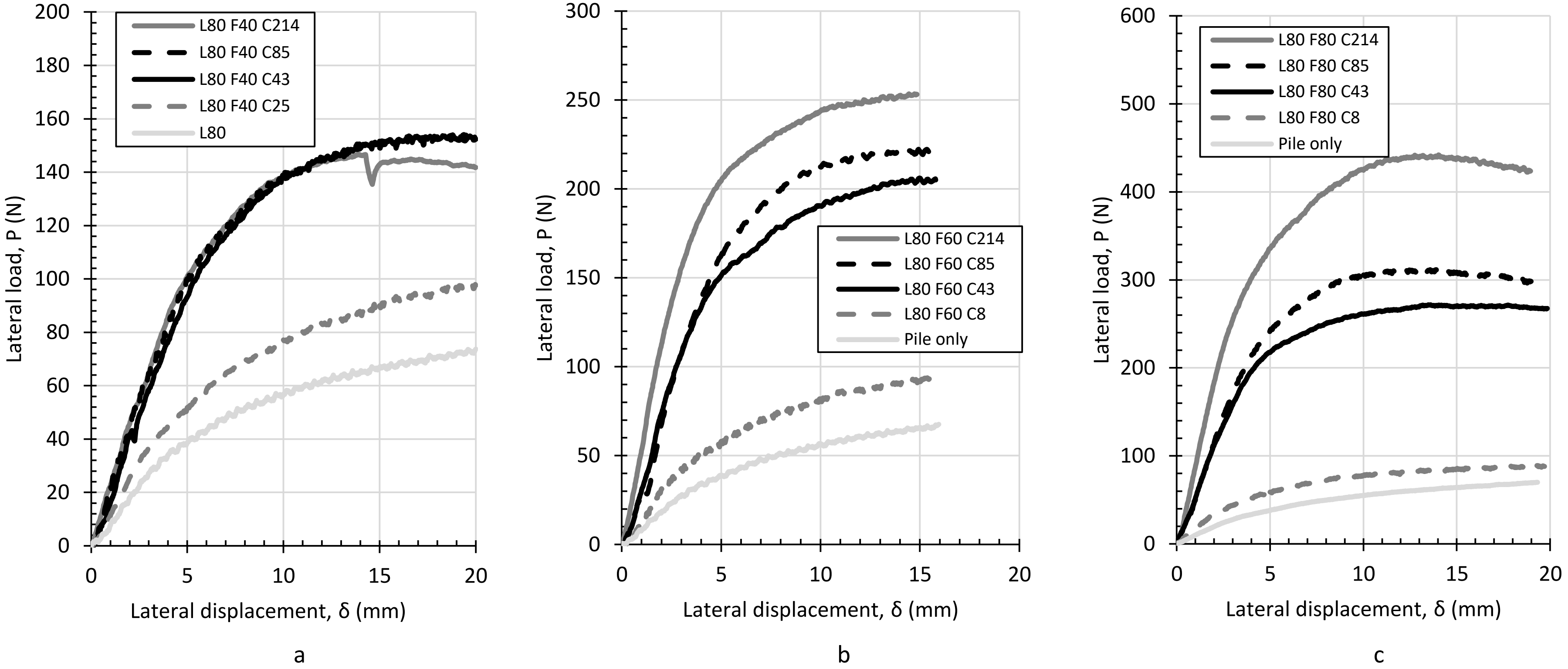
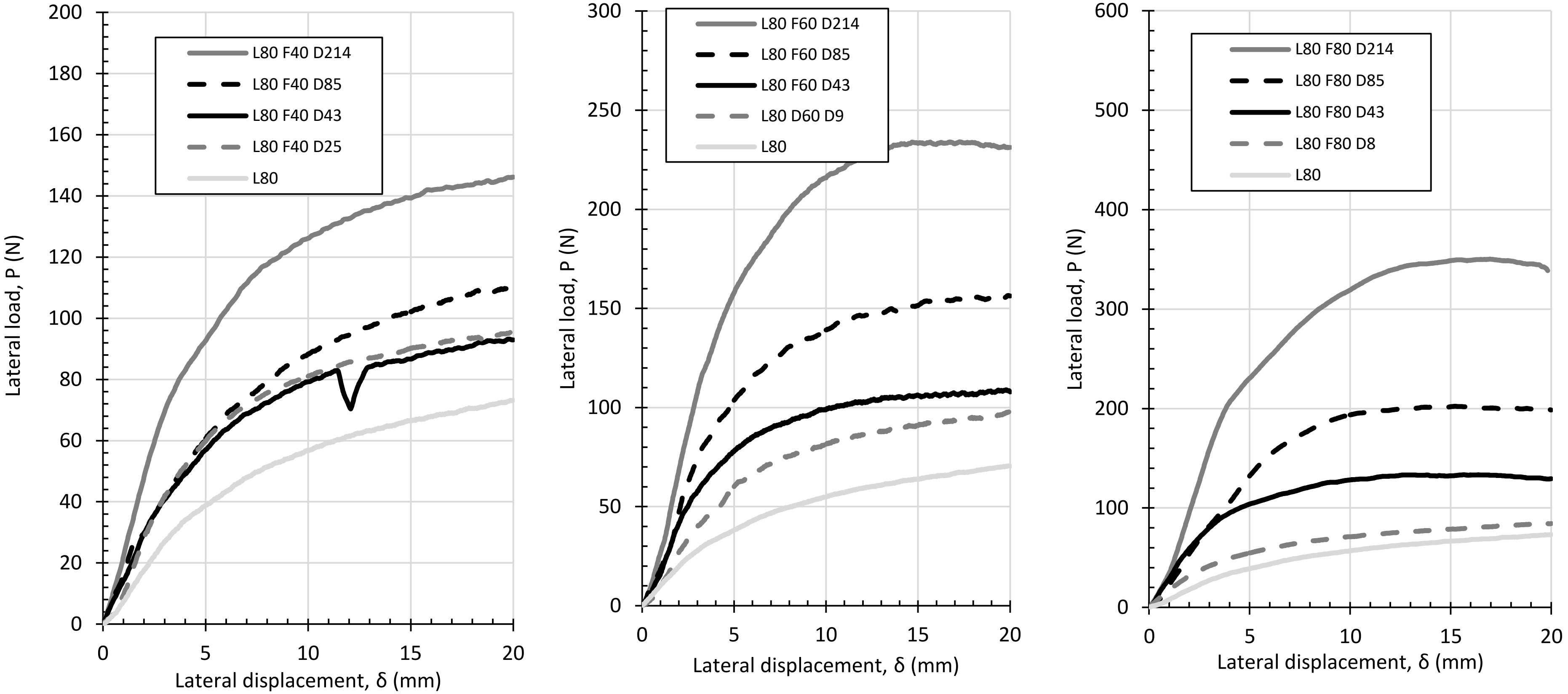


Figure 9.(a) Overview of coupled hybrid system with 10mm diameter pile, 80mm embedment depth (L80), with 40mm diameter bearing plate (F40), (b) 60mm diameter bearing plate (F60) and (c) 80mm diameter bearing plate (F80).

Figure 10



a

b

c

Figure 10.(a) Overview of decoupled hybrid system with 10mm diameter pile, 80mm embedment depth (L80), with 40mm diameter bearing plate (F40), (b) 60mm diameter bearing plate (F60) and (c) 80mm diameter bearing plate (F80).

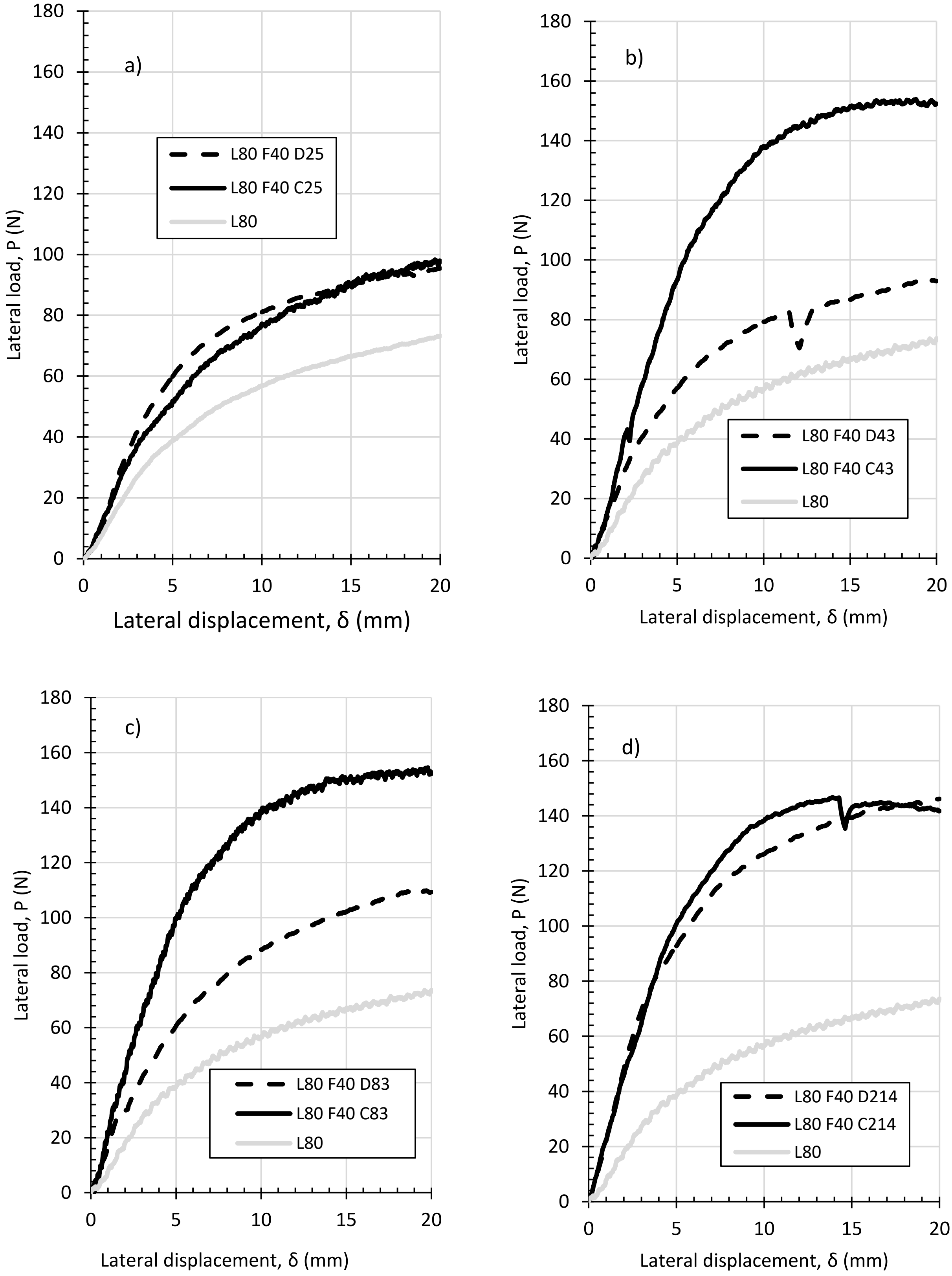


Figure 11. Comparison of coupled and decoupled lateral response for 10mm diameter pile with 80mm embedment depth and 40mm diameter bearing plate.

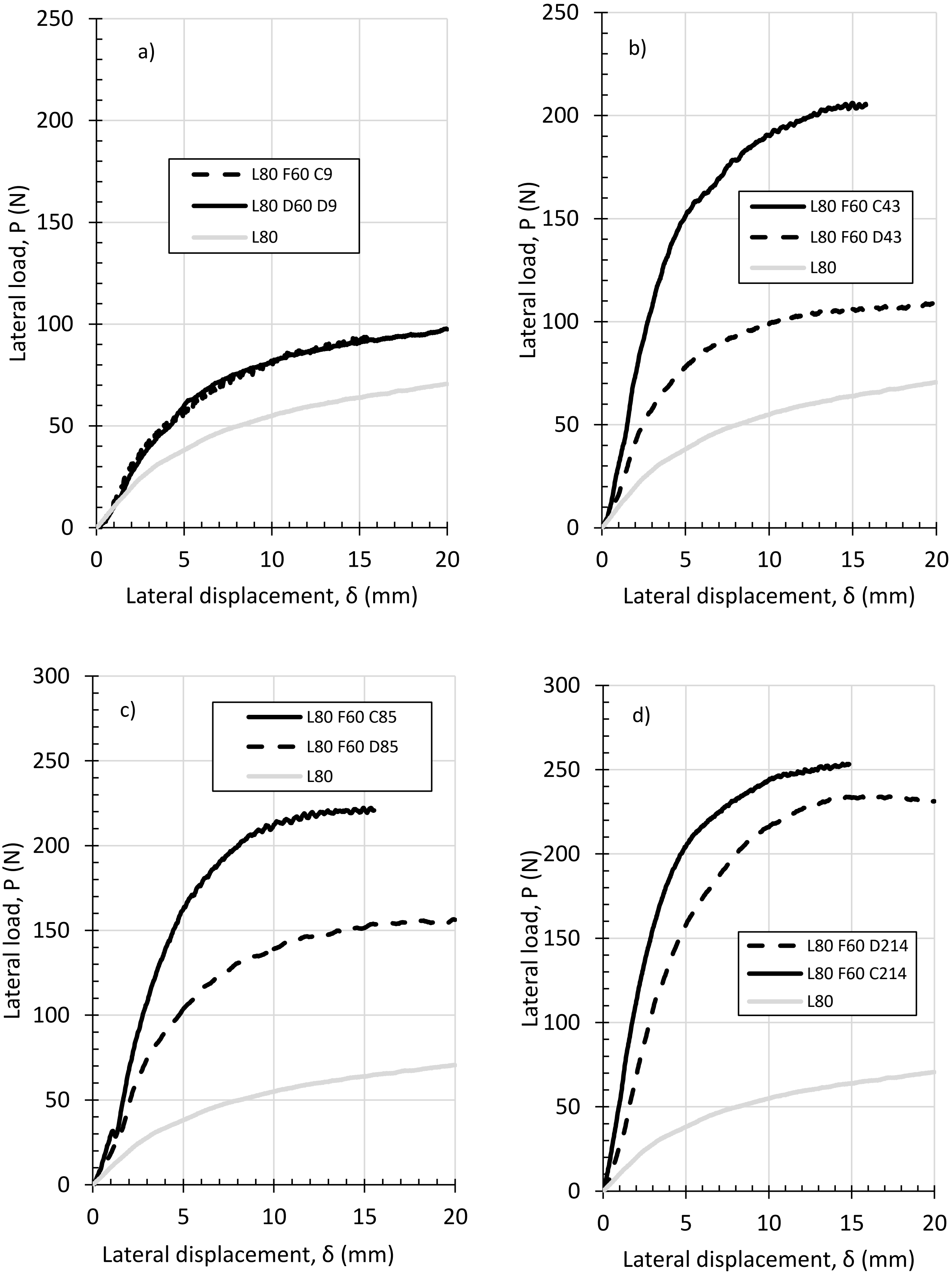


Figure 12. Comparison of coupled and decoupled lateral response for 10mm diameter pile with 60mm embedment depth and 80mm diameter bearing plate.

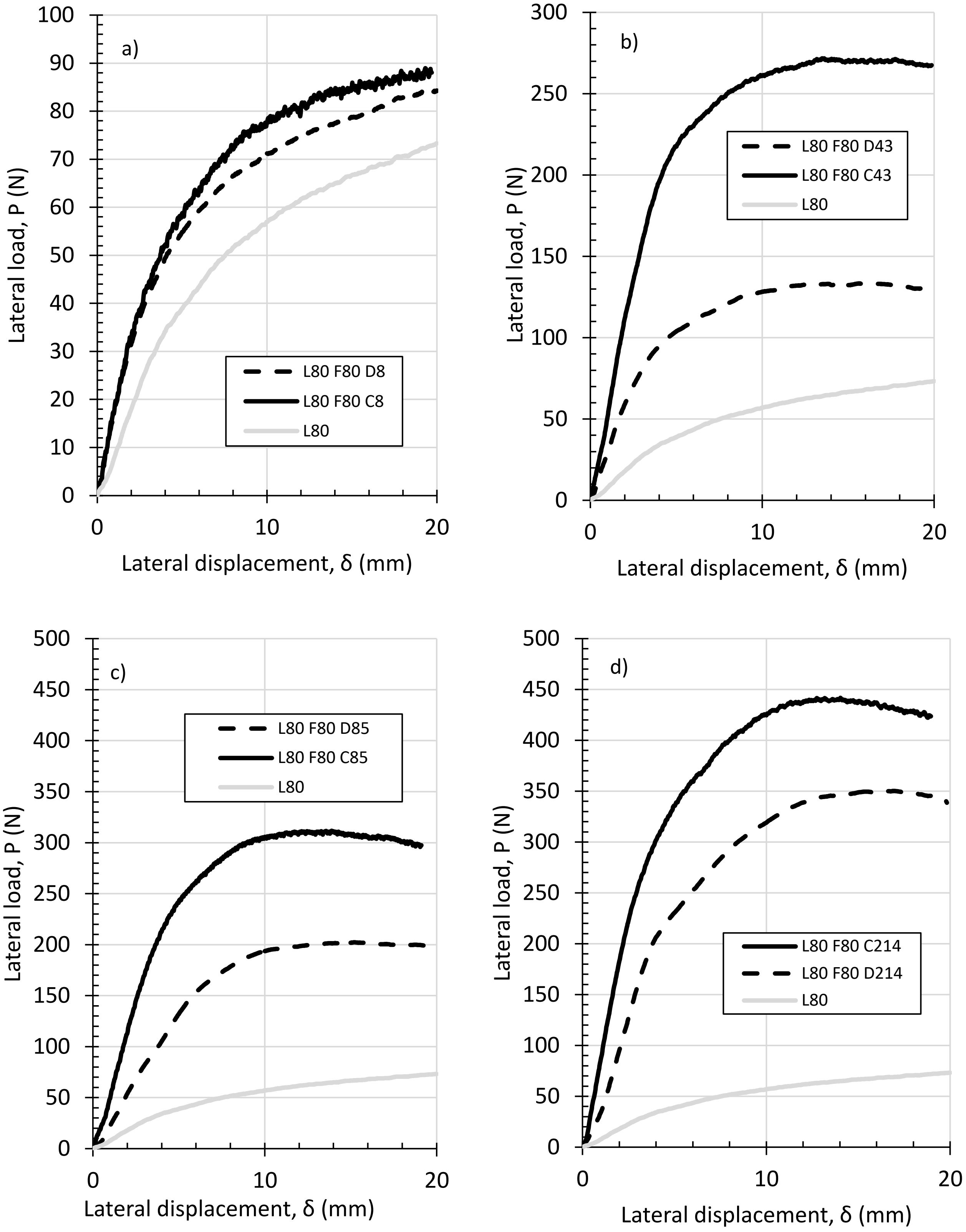


Figure 13. Comparison of coupled and decoupled lateral response for 10mm diameter pile with 80mm embedment depth and 80mm diameter bearing plate.

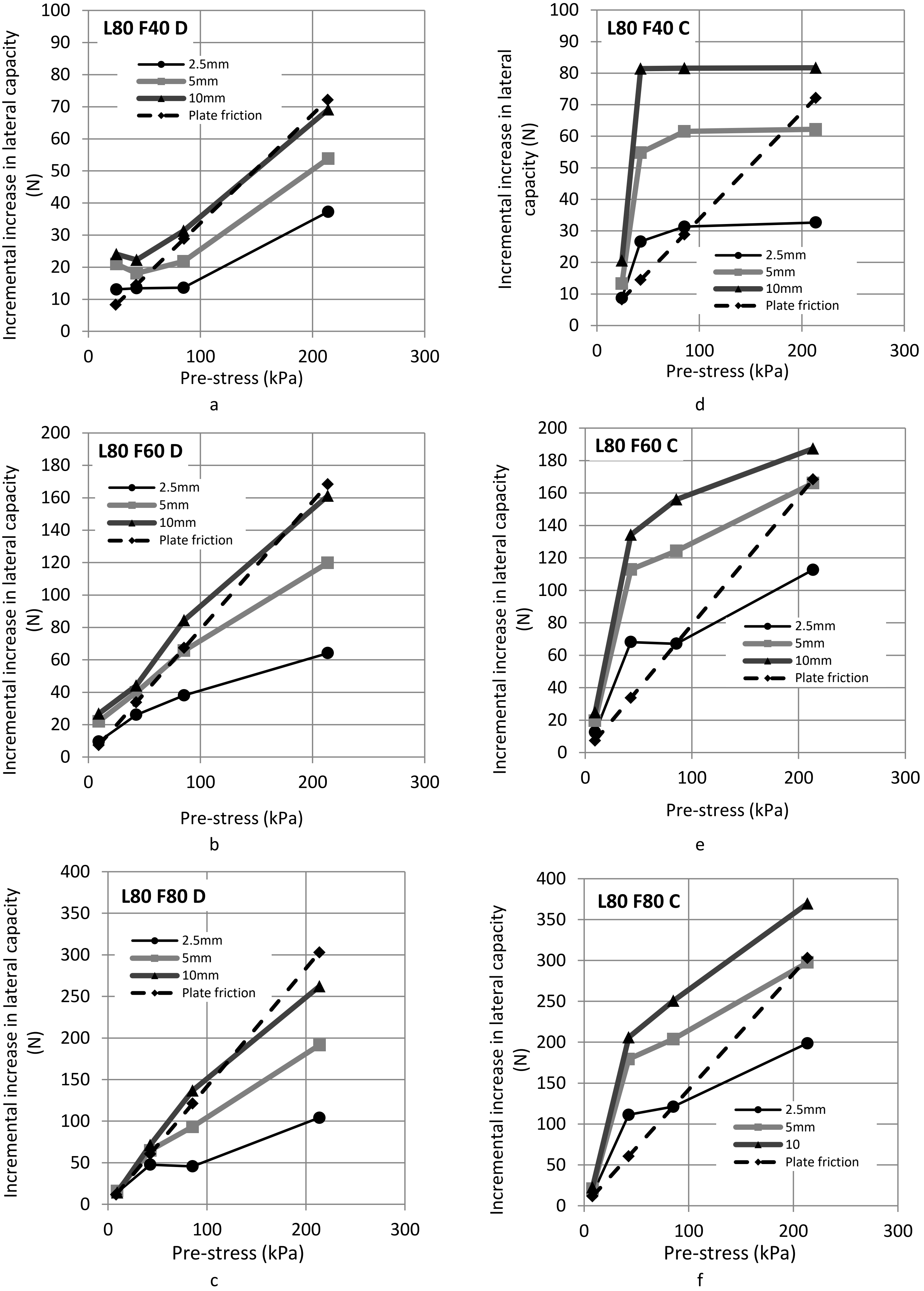


Figure 14. Plots of incremental increase in lateral resistance at discrete lateral displacements (refer to legend) for 80mm long pile with 40, 60 and 80mm bearing plates for coupled (C) and decoupled (D) systems.

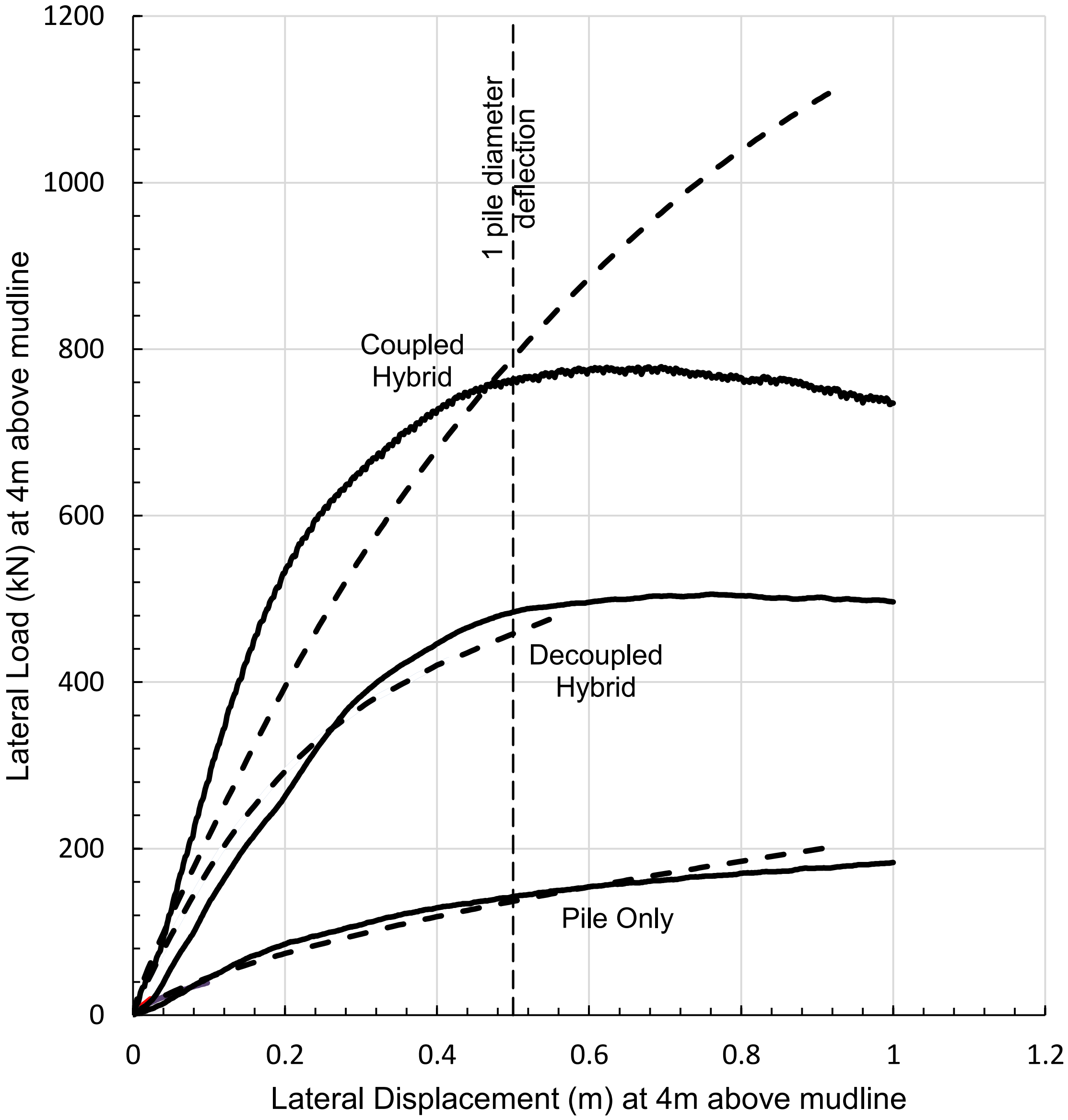
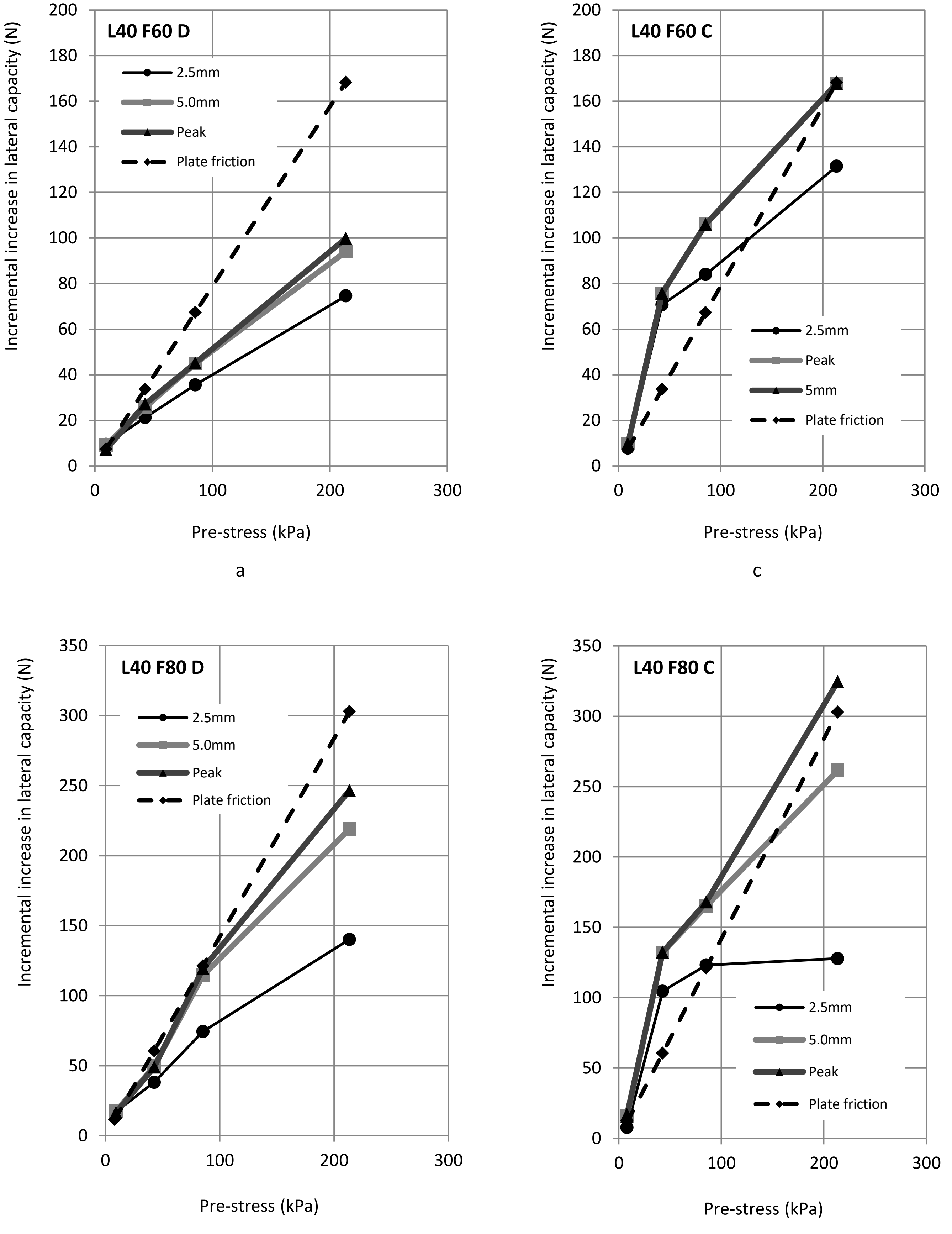


Figure 19. Comparison of numerical (dashed) and centrifuge model tests (solid) plotted at prototype scale for 80mm pile and 80mm bearing plate



a

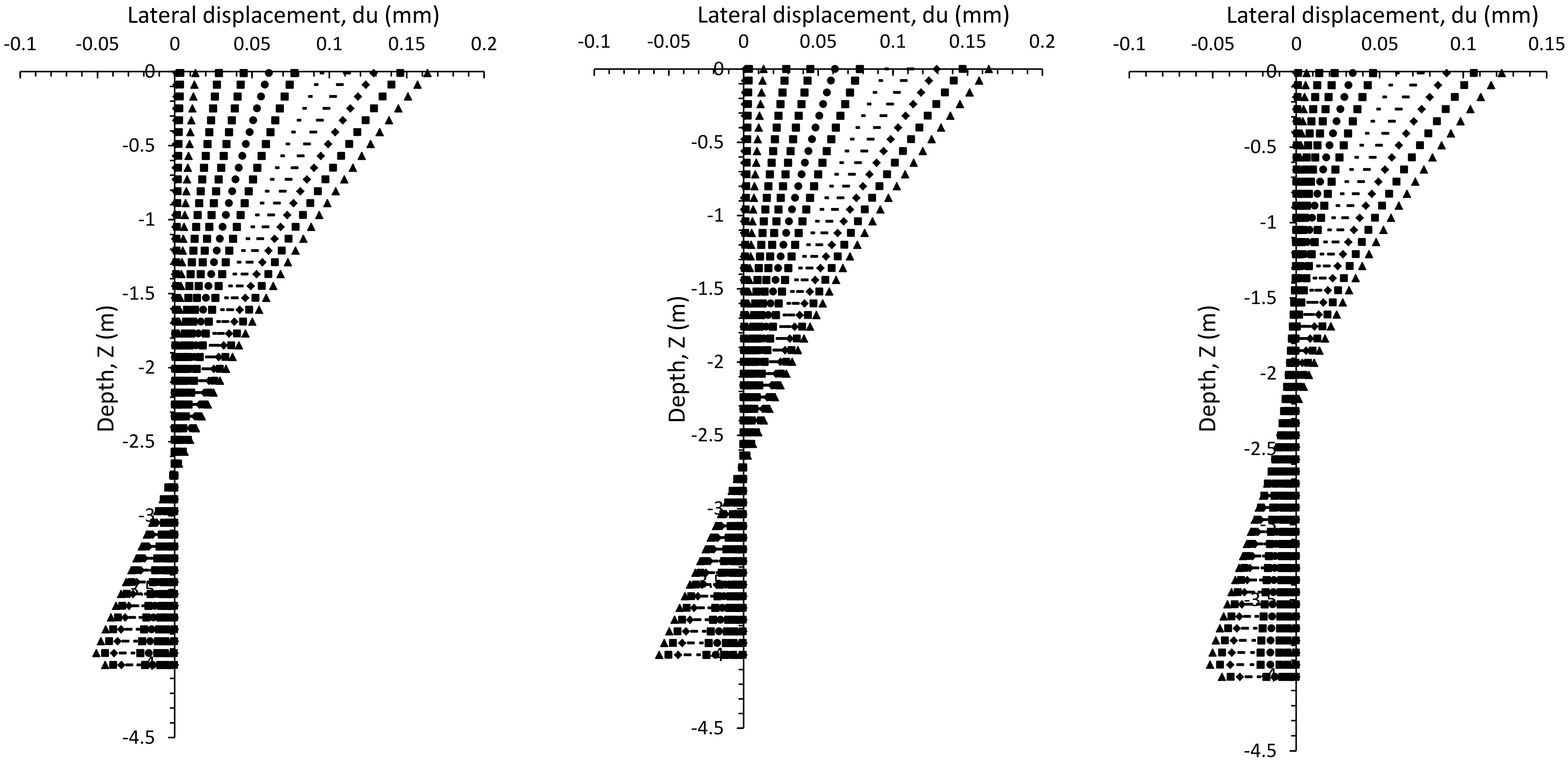
c

b

d

Figure 15. Plots of incremental increase in lateral resistance at discrete lateral displacements (refer to legend) for 80mm long pile with 40, 60 and 80mm bearing plates for coupled (C) and decoupled (D) systems.

Figure 16



-a-

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Figure 16. Lateral displacement profiles for (a) pile only, (b) pile and coupled bearing plate and (c) pile and decoupled bearing plate.

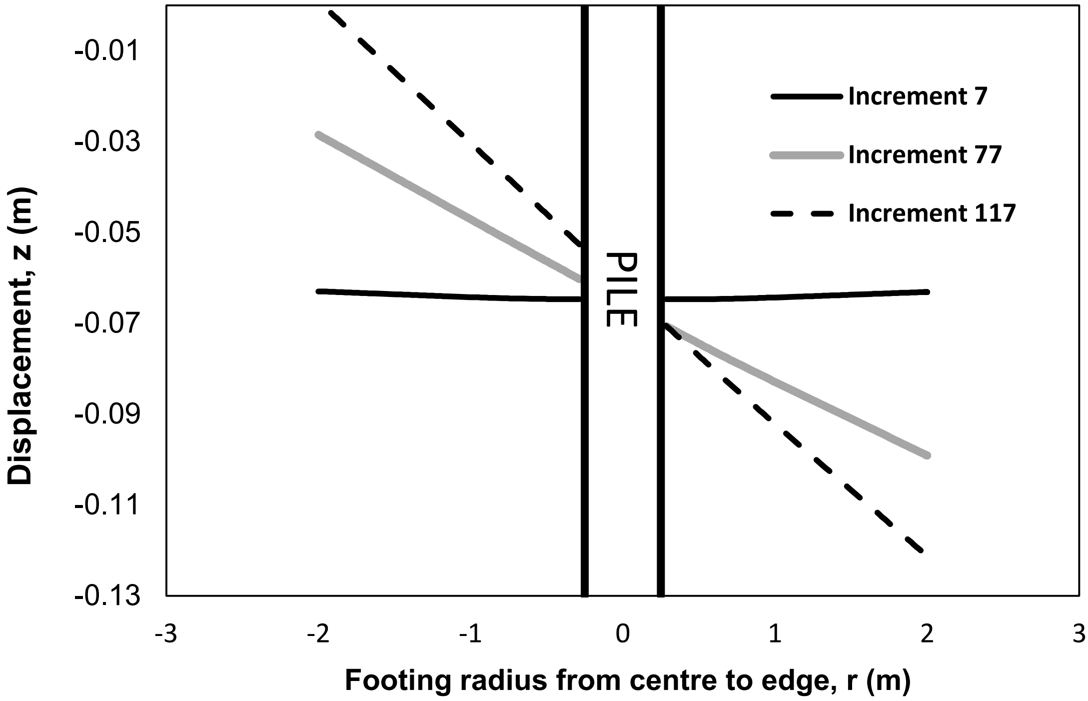

Figure 17a. Bearing plate rotation during loading for coupled hybrid.

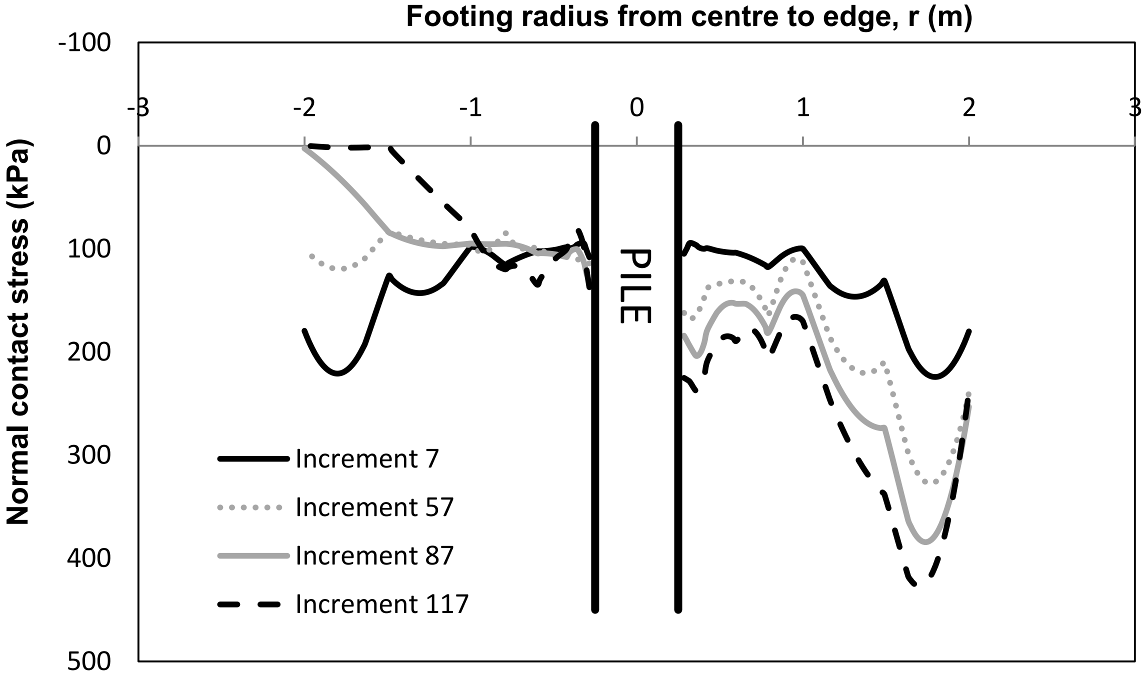

Figure 17b. Shows the distribution of normal stress at the plate soil interface for coupled hybrid system.

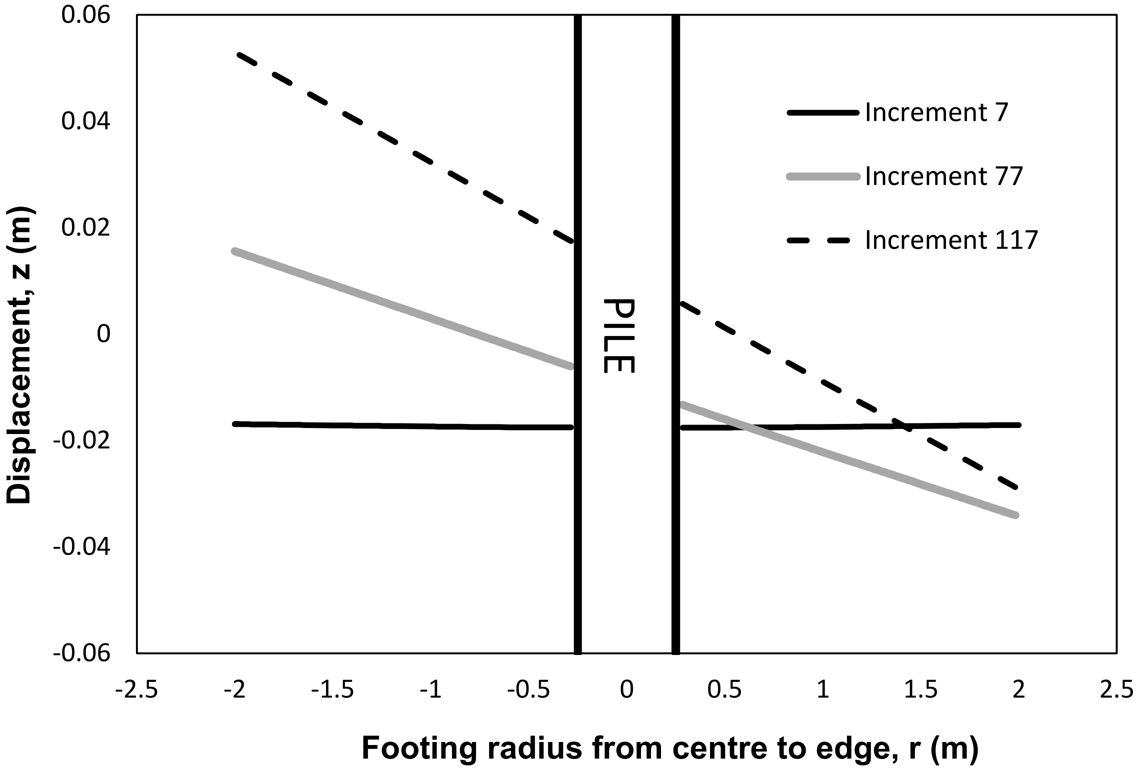

Figure 18a. Bearing plate rotation during loading for decoupled hybrid system.

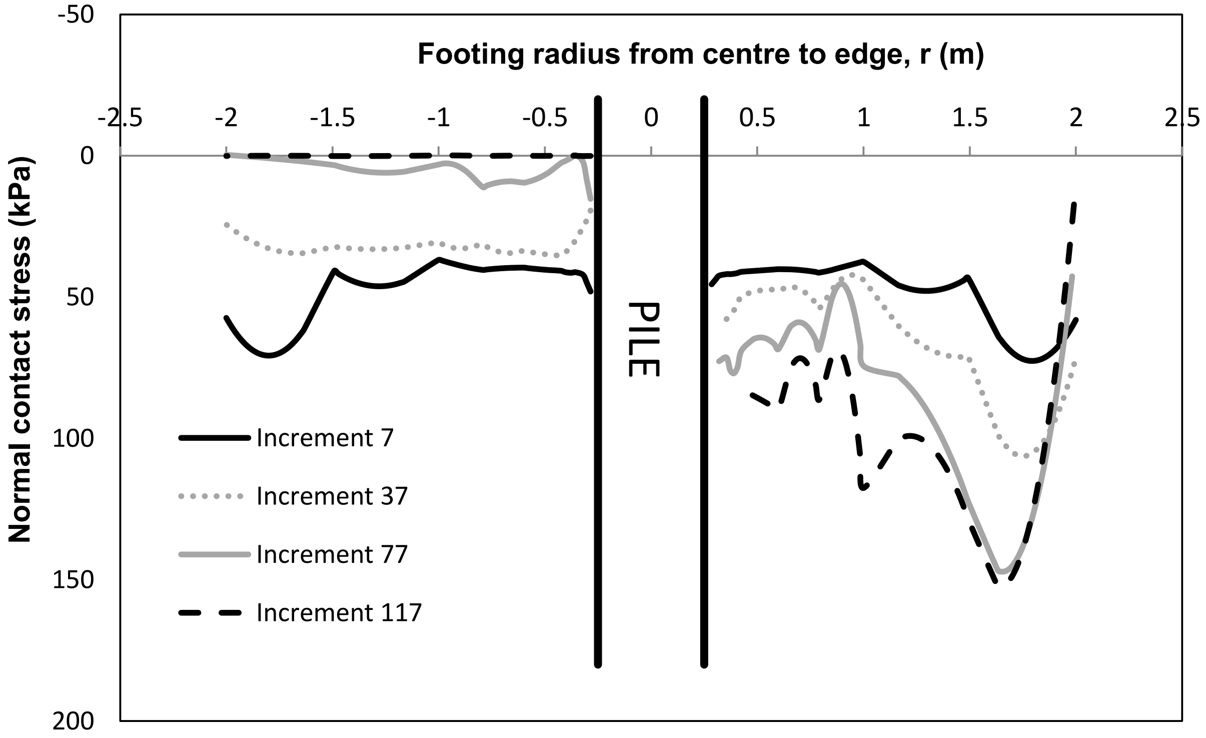

Figure 18b. Distribution of normal stress at the plate soil interface for decoupled hybrid system.

Figure Caption List

Figure 1.(a) Typical arrangement for coupled system, (b) a decoupled system with loading applied to bearing plate and, (c) a decoupled arrangement with superstructure loads carried by the bearing plate.

Figure 2. Centrifuge model test arrangement.

Figure 3.(a). Response of coupled hybrid system of 40mm plate and 10mm diameter pile with 80mm embedment (C10 L80 F40) under axial load at 20g and, (b) at 50g.

Figure 4. Response of coupled hybrid system of 40mm plate and 5mm diameter pile with 40mm embedment depth (C5 L40 F40 C) at 50g.

Figure 5.(a) Overview of coupled hybrid system; 10mm diameter pile, 40mm embedment depth (L40); 60mm bearing plate (F60) and, b) 80mm diameter bearing plate (F80) for all pre-stress levels

Figure 6.(a) Overview of decoupled hybrid system; 10mm diameter pile, 40mm embedment depth (L40); 60mm bearing plate (F60) and (b) 80mm diameter bearing plate (F80) for all pre-stress levels.

Figure 7. Comparison of coupled (C) and decoupled (D) lateral response for 10mm pile; 40mm embedment depth and 60mm diameter bearing plate for initial bearing stresses of (a) 9kPa; (b) 43kPa; (c) 85kPa and (d) 214kPa.

Figure 8. Comparison of coupled (C) and decoupled (D) lateral response for 10mm diameter pile; 40mm embedment depth and 80mm diameter bearing plate for initial bearing stresses of (a) 8kPa; (b) 43kPa; (c) 85kPa and (d) 214kPa.

Figure 9.(a) Overview of coupled hybrid system with 10mm diameter pile, 80mm embedment depth (L80), with 40mm diameter bearing plate (F40), (b) 60mm diameter bearing plate (F60) and (c) 80mm diameter bearing plate (F80).

Figure 10. (a) Overview of decoupled hybrid system with 10mm diameter pile, 80mm embedment depth (L80), with 40mm diameter bearing plate (F40), (b) 60mm diameter bearing plate (F60) and (c) 80mm diameter bearing plate (F80).

Figure 11. Comparison of coupled and decoupled lateral response for 10mm diameter pile with 80mm embedment depth and 40mm diameter bearing plate.

Figure 12. Comparison of coupled and decoupled lateral response for 10mm diameter pile with 60mm embedment depth and 80mm diameter bearing plate.

Figure 13. Comparison of coupled and decoupled lateral response for 10mm diameter pile with 80mm embedment depth and 80mm diameter bearing plate.

Figure 14. Plots of incremental increase in lateral resistance at discrete lateral displacements (refer to legend) for 80mm long pile with 40, 60 and 80mm bearing plates for coupled (C) and decoupled (D) systems.

Figure 15. Plots of incremental increase in lateral resistance at discrete lateral displacements (refer to legend) for 80mm long pile with 40, 60 and 80mm bearing plates for coupled (C) and decoupled (D) systems.

Figure 16. Lateral displacement profiles for (a) pile only, (b) pile and decoupled bearing plate and (c) pile and coupled bearing plate.

Figure 17a. Bearing plate rotation during loading for coupled hybrid

Figure 17b. shows the distribution of normal stress at the plate soil interface for coupled hybrid system

Figure 18a. Bearing plate rotation during loading for decoupled hybrid

Figure 18b. shows the distribution of normal stress at the plate soil interface for decoupled hybrid system

Figure 19. Comparison of numerical (red solid) and centrifuge model tests (black solid) plotted at prototype scale for 80mm pile and 80mm bearing plate

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Publication Title: Journal of Geotechnical and Geoenvironmental Engineering

Manuscript Title: The use of a bearing plate to enhance the lateral capacity of monopiles in sand

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Response to reviewer's comments

Manuscript title	The use of a bearing plate to enhance the lateral capacity of monopiles in sand
Manuscript #	#GTENG-6473

The authors wish to thank the editors and reviewers for their time in effort in reviewing our manuscript. We hope the changes listed have made the manuscript suitable for publication and we look forward to your response.

Editors Comments.	**Author's Response**
This paper presents a novel approach for enhancing the capacity and efficiency of monopiles by adding bearing plates. The researchers investigated their proposed system using finite element analyses and both single gravity and centrifuge model tests. Overall, the work appears to be original, it utilizes state of the art research methodology, and has significant potential to make a positive impact on the development of offshore wind power. The review comments are generally positive in regard to both the technical content and presentation of the research findings. However, both reviewers had a number of editorial comments which the authors should address. Additionally, Reviewer 1 raised some concerns in regard to the reported friction angles and their dependency on stress level. Some additional discussion on this point by the authors is warranted.	We have addressed the reviewer comments in our itemised response below. In particular we have revised our treatment of the interface friction angles in accordance with the concerns of Reviewer 1.
Reviewer #1: Comments	**Author's Response**
This is an interesting paper investigating a novel foundation technique for offshore foundation systems. The paper is generally well written and well structures. I have the following minor recommendations for improvements:	All the recommendations implemented as itemised below
Lines 70-72: sentence unclear, I believe the word "are" is missing after skirts.	Corrected in text

Line 78: I would clarify that skirted systems are not considered in this study.	added to text (L76-77)
Line 83: is a silica sand been used? Please add details.	Added to L85
Table 1: I am a bit surprised by the variation of interface friction angle with stress level. It appears reasonable that friction angle can increase for very low stress levels, but these stresses should be much lower in the order of few kPa (i.e below 10-15 kPa). Also, the authors suggested a variation of 5º which seems enormous. I think the authors should provide more justification for such choices or review the selected values.	We have reviewed the direct shear box tests and provide an average interface friction for use in the analysis. Table 1 has been expanded to include the shear stress developed for each normal stress.
Line 149: Can the authors clarify how the data have been extrapolated? Which assumptions have they made?	Text enhanced in line 150-151
Line 161: should 1050N read 1000N?	Text revised, 1000N for Figure 3a, but 1050N is average over several tests.
Line 188-189: can the author justify the assumption that "the portion of load carried by the pile is associated with a pile settlement of 2.5-3.0mm"?	Text enhanced and reference to Figure 3a and 3b
Line 258-259. Are the responses at high stress converging because the stress mobilised in the coupled and decoupled configuration now coincide? If so, I would add a comment on the manuscript.	Comment added in L260-261.
Figs. 14 -15. Describe in the text how the friction lines have been derived.	Added in lines 288-289
Line 290-291. I understand that a friction angle of 10º would produce a good match but such variation of friction angel appears rather improbable. I have the impression that vertical stress under the plate are not uniform and using an average stress leads to some inaccuracy in the prediction.	Comment added 298-299
Lines 382.Should the text refer to figs 17 and 18 instead?	Yes and corrected

I would attempt to use a uniform scale (as much as possible) on the y-axis of the figures. At least for subplot belonging to the same figure. This would ease direct comparison between plots.	We have revised the scale of the plots where this is helpful to ease comparison.
The reference style should be improved and all references should be checked. For example: parentheses are missing in line 40 [Trojnar (2013)]; line 41 (Arshi, 2011); line 41 Arshi 2015 should be Arshi and Stone, 2015?. Can the reference to Arshi 2013 be made to a published report? Please check the entire paper.	Reference styles are now consistent in accordance with the author guidelines. The Arshi 2013 document is an MPhil to PhD Transfer Report. The authors will investigate if this report can be published in one form or another.
Reviewer #2: Comments	**Author's Response**
This paper presents the results from a physical and numerical modelling testing programme to investigate the performance of hybrid monopiled-footing foundations under combined monotonic loading conditions in sand. It provides very good and useful insights for practitioners. Only minor changes are needed to be made before the full acceptance of the paper:	Changes to comments itemised below
1. On line 33, there is a reference missing (Stone et al. 2010b?)	Should have been Stone et al. 2011, now corrected and reference added
2. On line 72, add the reference by "Anastasopoulos and Thefilou (2015)	Reference added
3. On line 142, add the letter " in" in the sentence " This can be attributed to (i) the increase in shaft resistance ...	corrected
4. On line 178, is it " Arshi (2016) or " Ashri (2016)	corrected
5. On line 197, Table 2, there is a "*" in the table header, however, there is no associated note.	corrected
6. On line 272, " this is in turn is..." , delete " is" after " in turn".	Corrected

7. On line 336, " section presents and initial study".. change "and" to "an" .	corrected
8. On line 363, " unconfined surface boundary in of the centrifuge model", delete " of ".	corrected
9. On line 372, it discussed the depth of about 1.7 m below ground level for the coupled arrangement, the point of rotation. However, on Figure 16, it seems that the point of rotation is similar for pile only and pile and coupled bearing plate, around 2.75 m below ground level. And for the pile and decoupled bearing plate type (Figure 16 c), the point of rotation is about 2.2 m below ground level ?. Please clarify.	Text revised to match data presented in figure 16.
10. On line 448, is it "Ashri HS (2011) or "Arshi HS (2011)"?	corrected
11. On line 437, the reference "Wood and Stone (1992)" should be " Stone and Wood (1992)".	corrected
12. On line 462, the sentence "ultimate lateral capacity over that of the pile alone" should be "ultimate lateral capacity over that of the pile and the bearing plate alone".	Corrected to read pile OR bearing plate alone.
13. On figure 14, not quite clear about the case "plate friction". Can you please clarify and add an explanation in the main text.	Text enhanced
14. On figure 15b, the label "L40 F80" should be "L40 F80 D".	Corrected
15. On figure 15d, the label "L40 f80" should be "L40F80C".	Corrected

Response to Reviewers comments

Reviewer #2: The authors have satisfactorily addressed all the minor comments from the previous review.	
Reviewer #3: There were only two very minor comments:	
On page 9, line 194, there is a redundant "be" in the sentence "where full shaft and end-bearing resistance is assumed to be have been"...Remove the wording "be".	‘ be ’ removed from text
On page 20, line 483, missing a "." after the sentence "bearing plate interface friction".	‘ . ’ Added to text