Physical Modelling in Geotechnics

Behaviour of connected and disconnected piles in clayey soils under earthquake loading

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ABSTRACT: Vertical rigid pile inclusions are used as supports for the foundations built on soft soils. They function as load transferring elements onto stronger and more competent soils. In this case, the rigid pile inclusions are seen as a form of ground improvement method. However, their performance in transferring loads from the structure under dynamic conditions is not well studied. For piles that act as ground improvement devices, the foundation models have vertical, rigid inclusions that are disconnected from the pile cap via a load transfer platform placed as a cushion layer between pile heads and the foundation plate. In this paper, connected and disconnected pile systems are investigated under earthquake loading by comparing the results from centrifuge tests that were performed at 60g. The soil profile consists of soft clay and an underlying thin, dense sand layer into which the pile tips penetrate. The results show that the lateral displacements occurring during the earthquake in both systems are similar. However disconnected pile system showed greater vertical deformations.

Keywords: disconnected piles, connected piles, earthquakes, soft clay.

1 INTRODUCTION

While the utilisation of deep foundation systems and use of soil improvement methods are considered common practices for geotechnical engineering problems that involve soil conditions that are considered poor in terms of safely bearing against structural and dynamic loads, foundation support systems that revolve around pile-like rigid inclusions in the soil that are not structurally connected to the foundation plate is a relatively new solution to the problem at hand.

In such systems, any physical connection that links the piles to the foundation plate is severed as a design choice. Instead, a granular or concrete-based cushion layer—commonly referred to as a load transfer platform in the literature—is placed between the pile heads and the pile cap. Through the load transfer platform, structural loads are transmitted into the soil and rigid inclusion that are placed in the soil. Some of the examples that use such system can be given as Rion-Antirion bridge in Greece, Osman Gazi Bridge in Turkey, and 1915 Çanakkale bridge that is still under construction. In all cases, poor soil conditions pose a challenge to the engineers regarding designing a safe foundation support system. All the while adding an additional challenge of establishing a rigid connection between the piles and the foundation plate. (Pecker, 2004; Steenfelt et al., 2015).

In this study, lateral behaviour of disconnected pile foundation systems is investigated. Centrifuge tests are performed to study and observe the behaviour of the system when lateral forces are inflicted on the model. The model that represents the disconnected pile foundation system in the laboratory tests has a scale of one to sixty.

The rigidity of the system in seismic conditions tends to be a common concern in the absence of a direct physical connection between the piles and the pile cap. In this paper, the focus of the study remains on the lateral and vertical displacements that are measured upon the introduction of the lateral forces. In tests, both connected and disconnected systems are used to compare the apparent behavioural differences between the respective foundation support systems. The soil profile consists of a normally consolidated soft clay layer (speswhite kaolin), and a dense sand layer (Hostun sand) that lies at the bottom of the sample box, which acts as the load-bearing stratum in which the pile ends are driven into. In the model with the disconnected pile elements, another relatively coarser-grained sand layer (Fraction-B) is used to establish the cushion layer that separates the foundation plate from the vertical elements placed underneath it.

2 DISCONNECTED PILE FOUNDATION SYSTEMS

When piles are accepted as settlement reducer, the ultimate bearing capacity of piles could be mobilized or piles can be designed with lower factor of safety against bearing capacity (Eslami and Malekshah, 2011). However, high axial stress could occur in the piles when piles are structurally connected to the raft. Moreover, high horizontal shear forces and bending moments could develop along the pile heads in seismically active zones. Resulting from these negative effects, disconnecting piles from raft with a cushion layer have been used as a reinforcement to subsoil rather than as structural members (Wong et al., 2000).

Park et al. (2020) used centrifuge test to study settlement and load sharing mechanism of piled raft foundations; bearing capacity, load distribution and bending moment of piles. They prepared disconnected (DPR), connected piled raft (CPR) and raft foundation models in the same model box in order to evaluate efficiency of DPR directly. The study pointed out that DPR foundation system shows better performance than CPR by means of reducing axial load and bending moment of pile.

Ha et al. (2018) performed a series of centrifuge tests to investigate dynamic behaviour of disconnected piled raft foundation and assess the impacts of cushion layer and various pile tips on the efficiency of DPR. Ko et al. (2019) carried out experimental study to evaluate seismic behaviour of DPR and CPR foundations by using a centrifuge test. Two different materials: aluminum and stainless steel used as pile material to investigate effect of pile rigidity on bending moment of pile. The results indicate that when the PGA at the cushion layer increased, the seismic response of DPR decreased due to kinematic effect of soil-foundation-structure interactions.

In the context of the study, disconnected pile foundation systems refer to the foundation support systems, in which the rigid, direct structural connection of the pile heads are removed in favor of a granular load transfer platform. Similar to piled raft foundations, it allows the utilization of the soil's shear strength, as some of the load, depending on factors such as the thickness of the load transfer platform, is transferred into the soil in addition to the load carried by the piles. Accordingly, the structural forces developed in piles are reduced, in addition to the elimination of the bending moments at the pile heads.

Along the upper portion of the piles, the soil surrounding the piles undergo larger settlements than the piles. Thus, creating negative skin friction above the neutral plane. Such phenomena is demonstrated in Figure 1 on an axis-symmetrical numerical model for varying load transfer platform thicknesses. Vertical deformation is plotted.

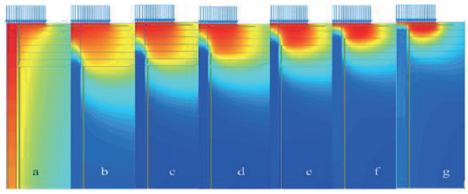


Fig. 1. Development of negative skin friction for varying cushion layer thicknesses: a) No cushion, b) 3m, c) 2.5m, d) 2m, e) 1.5m, f) 1m, g) 0.5m. (Ayraçma et al, 2019).

Omitting a rigid connection at the pile heads also affects the angular deformation of the foundation by increasing the rotational flexibility of the system. However, under seismic loads, given the maximum and residual deformations are below the limits, allowing some level of rocking in the system may help reduce the risk of plastic hinges along the structural elements by transmitting the bending moments into the soil instead of over-stressing the structural elements. (Gazetas, 2015).

3 TEST MODEL

Centrifuge tests are performed in the University of Cambridge at Schofield Centre. The 10m beam centrifuge unit is used to carry out the tests. To match the scale of the sample, all tests are performed at 60g. The scaling law that was applied was based on Madabhushi (2014). Model box used in the tests is an ESB box. In Figure 2, the model box used in the centrifuge is shown.

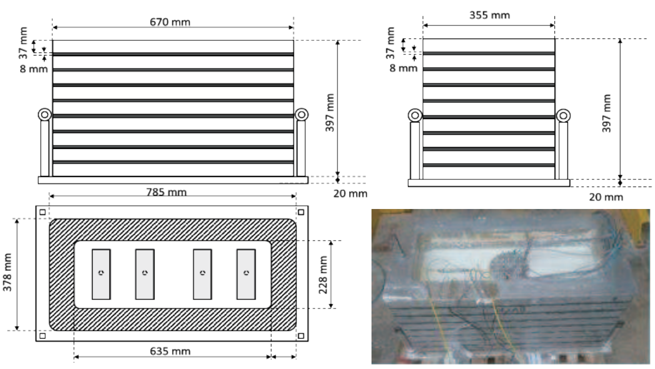


Fig. 2. Equivalent shear beam model box.

Soil profile of the test model consists of a dense sand layer and the overlying soft clay layer. The piles penetrate the bearing stratum 10 mm, which correlates to 60 cm in the prototype scale. For the disconnected case, the load transfer platform that separates the piles from the foundation plate has a thickness of 10 mm (0.60 m). The sand was compacted manually and the weight of the material placed gives a relative density of the Fraction B sand that is used to form the load transfer platform about 90%.

Outside the centrifuge, the clay layer is saturated with water as during the test undrained loading conditions are expected. The clay is consolidated before the experiment. Within the centrifuge, following the achievement of 60g centrifugal acceleration, the additional consolidation settlements are completed prior to the application of earthquake loading. The test model can be seen in Figure 3.

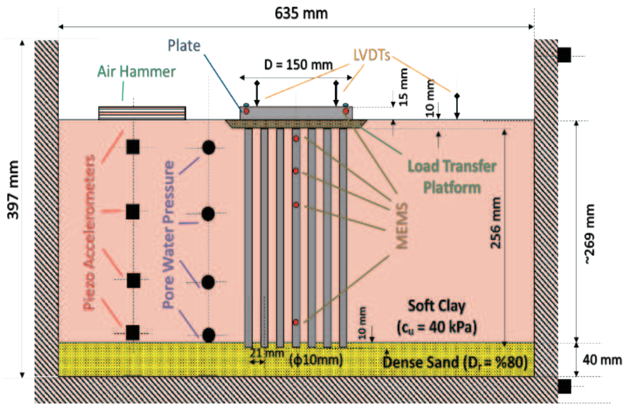


Fig. 3. Test model.

4 EXPERIMENTAL STUDIES

During the tests, a total of six earthquake loadings are inflicted on the model in centrifuge, four of which are in the form of harmonic motions, while the rest consist of earthquake records. In addition to the centrifugal acceleration, a separate hydraulic system allows the shaking of the model box. Compared to a mechanical contraption, the use of hydraulics provides the users with the ability of realising complicated motions such as time-history functions (Madabhushi, 2014). The motions used to shake the model box by at base are summarized in Table 1.

Table 1. Lateral motions used in the tests.

	Description	PGA
Motion-1	60 Hz, 10 Cycles	0.03g
Motion-2	60 Hz, 10 Cycles	0.12g
Motion-3	0-60 Hz Sine Sweep	0.05g
Motion-4	Kobe Earthquake	0.24g
Motion-5	Imperial Valley Earthquake	0.11g
Motion-6	60 Hz, 10 Cycles	0.33g

For both connected and disconnected systems, the response spectrums observed on the foundation plate is given in Figure 4. No significant difference is observed among the response spectrums. The peak values occur at 1Hz.

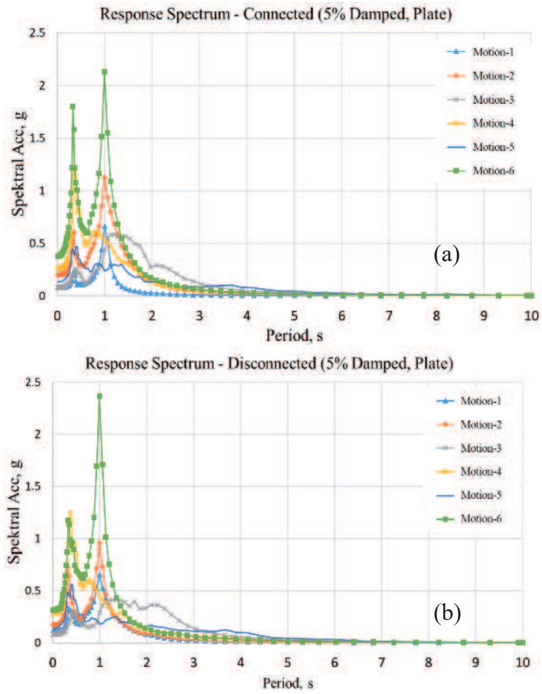
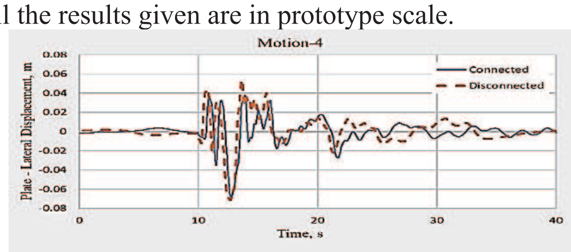


Fig. 4. Response spectrums plotted for the plate: a) connected system, b) disconnected system.

Acceleration and displacement values are measured through a web of sensitive instruments that include MEMS, LVDTs, and piezo accelerometers. While the vertical displacement of the foundation plate is directly measured by LVDTs, because of the technical difficulty of placing LVDTs on the foundation plate in horizontal direction, lateral displacements of the plate are calculated by the double integration of the acceleration readings.

Time-history plots of the lateral displacements that belongs to Motion-4 (Kobe earthquake record) and Motion-5 (the Imperial Valley earthquake record) are shown in Figure 5. In terms of lateral displacements that are observed on the foundation plate, for each lateral motion imposed on the system, the displacements yield similar values, with the disconnected system hinting at slightly larger values. All the results given are in prototype scale.



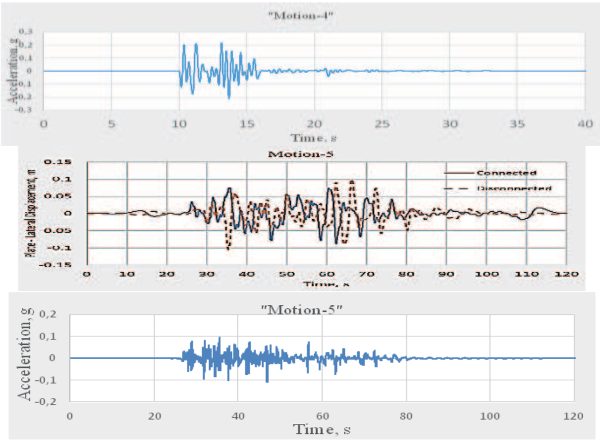


Fig. 5 Lateral displacement of the plate for connected and disconnected systems and the input motions.

When the settlements are investigated, the results indicate that the disconnected system undergoes relatively larger vertical displacements, albeit still remaining within tolerable levels. As an example, settlement values recorded during Motion-2 and Motion-3 are shown in Figure 6. Settlement values are close to 40 mm.

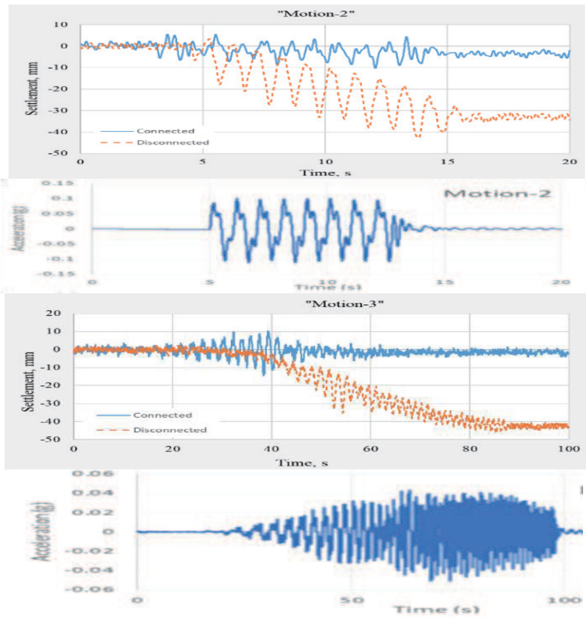


Fig. 6. Vertical displacement of the plate for connected and disconnected systems and the input motions.

It should also be noted that the disconnected system displays higher degrees of permanent settlements compared to the connected case, as the deformations are not restrained in vertical direction.

5 CONCLUSIONS

Separating the pile heads from the pile cap and replacing the physical structural connection with a load transfer platform improves the workability of the design, may offer economical benefits, and reduce the stress and internal forces developed in piles. Load transfer mechanism of the system is rather complex. Especially considering the seismic behavior of the system, it is still a relatively new practice that demands further research. In the study, lateral deformations and settlements of disconnected pile foundation systems are investigated.

Response spectrums plotted at the top of the plate display similar plots. Likewise, the lateral deformations observed on both connected and disconnected foundation systems during imposed seismic loads also show similar values, with disconnected foundation system showing relatively large displacements.

Regarding settlements, disconnecting the pile-elements results in larger vertical displacement for the foundation plate. With the compression of the load transfer platform, permanent settlements are also observed during the experiments.

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