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Numerical modeling of connected and disconnected piled raft foundation under seismic loading in clayey soil

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Abstract. The disconnected piled raft foundation (DCPRF) is one of the newly introduced type of foundations in geotechnical engineering, which greatly reduces the moment and stress on the pile head. In addition, this type of foundation is an ideal choice in areas with seismic activity due to the presence of cushion material between the raft and the piles. This paper aims to present a numerical model in PLAXIS-3D software to simulate the behavior of the connected piled raft foundations (CPRFs) and DCPRFs with the same number and pattern of the piles, under the influence of seismic loading in clayey soil. The study will depend on the earthquake that struck Iraq in November 2017 in the Halabja region of strength 7.3 on Richter scale with PGA (0.1 g). To verify the results of the proposed numerical model, the settlement calculated from numerical is compared with field measurement for the Messe-Torhaus building in Frankfurt and the difference was 2 %. The horizontal displacement of the raft in the CPRF is less than the horizontal displacement of the raft in the DCPRF during seismic loading by 15 %. The vertical displacement in the DCPRF decreased by 7 % in comparison with the CPRF. For the DCPRF, the bending moment value is approximately equal to zero at the head of the piles, and the maximum bending moment value was in the middle of the pile.

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1. *Introduction*

When the raft foundation bearing capacity is sufficient to sustain the superstructure, but the raft's total and differential settlements exceed the allowable limit, a small number of piles can be used to control the settlements [1–3]. The pile heads are usually structurally connected to the raft to make a rigid connection. These piles should have sufficient bearing capacity and sufficient safety factor to avoid structural failure. Because high axial stress can develop in the piles and lateral forces from wind and earthquakes can destroy connections, even though structural failure can be prevented by using high-strength materials with a high factor of safety, this technique may be uneconomical. A new solution for solving such concerns has recently been presented, which involves isolating the raft from the pile with soil material that is strong enough to sustain the stresses imposed on it while also preventing or reducing the load seismic waves or shear forces on the pile's head. This void may be filled with suitable materials, which can be selected depending on the circumstances, such as types of loading and availability of materials [4]. Since the piles are not structurally attached to the raft, a smaller factor of safety may be utilized to protect the pile materials and prevent structural damage (as low as 1.3) [4–6]. As a result of the previous works, the disconnected piled raft foundation (DCPRF) that contains a cushion between the pile and the raft will increase the carrying load capacity of the foundation more than the connected piles group foundation. At the same time, it may be greater in carrying the loads compared with the connected piled raft foundation (CPRF), and this method leads to more economical results than others. Also, disconnected piles can be used in buildings subjected to high horizontal loads, such as earthquakes or winds, especially in buildings containing basements and in buildings with weak soil that need to be strengthened, such as river sidewalks and ports.

Many researchers have studied the behavior of disconnected piles using the finite element method. Several characteristics (parametric study) of the parameters of this method were studied, such as pile stiffness, raft stiffness, cushion thickness, raft thickness, the behavior of the disconnected piled raft, and the distribution of axial loads on it. Wong et al. [4] are the first who proposed the DCPRF method. Cao et al. [7] studied the special properties of this method and the advantages and disadvantages of such a technique. According to Liang et al. [8] and Lee et al. [9], the cushion placed between the pile and the raft is either a sandy or a gravel soil material of high density to reduce the settlement that occurs in it. This cushion is considered a layer that transfers the loads to the soil and the piles below the mat and contributes to a certain amount of bearing the loads and the way of distributing the loads on the piles.

This research presents verification of the related connected piled raft with data measured in the field concerning the behavior of the connected piled raft under a building in Frankfurt subjected to static loading. After that, a numerical model is proposed to simulate the behavior of such a building under seismic loading and supported by DCPRFs. Then, a parametric study was presented for a DCPRF on the possibility of adding a cushion between the raft and the piles and studying the effect of the seismic loading on the proposed foundation.

2. Methods

In various geotechnical applications, numerical modeling is commonly utilized to simulate foundation behavior. The preponderance of finite element programs only captures the structure's linear behavior (i.e., up to the yielding of the design). These programs fail to capture post-peak behavior (e.g., ultimate load-displacement responses, failure modes, and fracture patterns). The interaction between the pile shaft and the surrounding soil, on the other hand, is nonlinear. In addition to nonlinearity, the program should be able to capture the structure's post-peak reaction. As a result, choosing a program that can accommodate this behavior is essential. PLAXIS is a 3D nonlinear finite element software package that includes commonly used constitutive models to represent soil behavior, pile behavior, and the interface between pile and soil, unlike other programs. PLAXIS can capture various pile structural loading conditions (e.g., static and seismic loads on the pile). Calculating the relationships between stress and strain in different soil models is one of the advantages of the PLAXIS 3D software, which allows loading and unloading behavior [10–12]. The most often used model for determining material plasticity is the Mohr–Coulomb model. It is a model that is linearly elastic, and perfectly plastic. Hooke's law describes the linear elastic element. At the same time, the Mohr–Coulomb failure criterion represents the completely plastic part whenever plastic deformations occur, irreversible strains, or permanent deformations, appear in the material yield function, which is introduced as a function that describes whether or not deformations occur. The material will stiffen or soften under plastic straining if the yield surface varies with plastic strain. As a result, a perfectly plastic model with a set yield surface is a constitutive model [13].

Interface elements are used to simulate the soil-structure interaction. The adjacent structural and soil elements may have to slide together if interface components are not present. Between them, there is no relative movement (slipping or gapping). An interface can be created next to a plate, between two soil volumes, or between two geogrids. Interfaces in PLAXIS 3D are made up of 12-node interface elements after meshing. Node pairs make up interface elements. One node in a node pair is related to the structure, while the other is associated with the soil. The interaction between these two nodes defines the soil-structure interaction. It is made up of two perfectly elastic-plastic springs. The strength reduction factor (R_{inter}) is used to define the strength of the interface. An elastic-plastic model describes the behavior of the interface. The following relationship can be used to compute the interface strength parameters [14]: Mohr–Coulomb is the most common and easy to use and does not require many parameters and is available compared with hardening soft soil model (HSS).

$$c_{inter} = R_{inter}.C' ; \tag{1}$$

$$tan\,\varphi_{inter} = R_{inter}.\,tan\,\varphi' ; \tag{2}$$

$$\psi_{inter} = 0.0 \;\; for \; R_{inter} < 1; otherwise \; \psi_{inter} = \psi_{soil} . \tag{3}$$

Rinter is a program parameter that is either automatically determined by the software or manually selected by the user. When the first option is chosen, there will be no drop in interface strength compared to surrounding soil; strength and all other characteristics will remain unchanged, except the Poisson's ratio. Rinter has a value = 1, this option is activated by default. The amount of Rinter is manually entered in the second option. In a real soil-structure interaction, the interface will be weaker and more flexible than soil, where R_{inter} has a value less than unity. The appropriate R_{inter} value for interaction could be chosen based on the type of soil. The strength reduction is greater in cohesive soil than for cohesionless soil, implying that the R_{inter} value for cohesionless soil is larger. Whenever the interface strength reaches its limit value as described by Rinter, it reduces to a residual strength described by R_{inter} residual strength. When the third option is chosen, the R_{inter} residual is enabled as shown in Figure 1.

When the geometry model is complete, it must be divided into a mesh of finite elements. To obtain accurate results in the calculations that are carried out within the PLAXIS 3D software, accurate meshes of soil and structure are used. However, they are not used with high accuracy, which leads to spending a long time in the calculation. The dimension of model is 250×250×100 m, X, Y, Z respectively. The same dimensions, properties, number of piles, and thickness. The program divided the model into 11867 elements and 19858 nodes and the types of mesh is medium as shown in Figure 2.

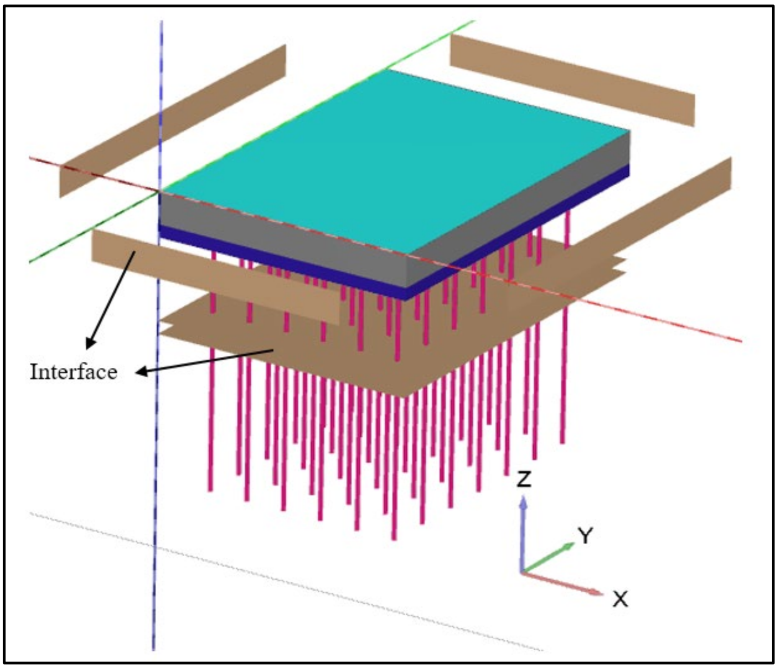

Figure 1. Modeling of interfaces.

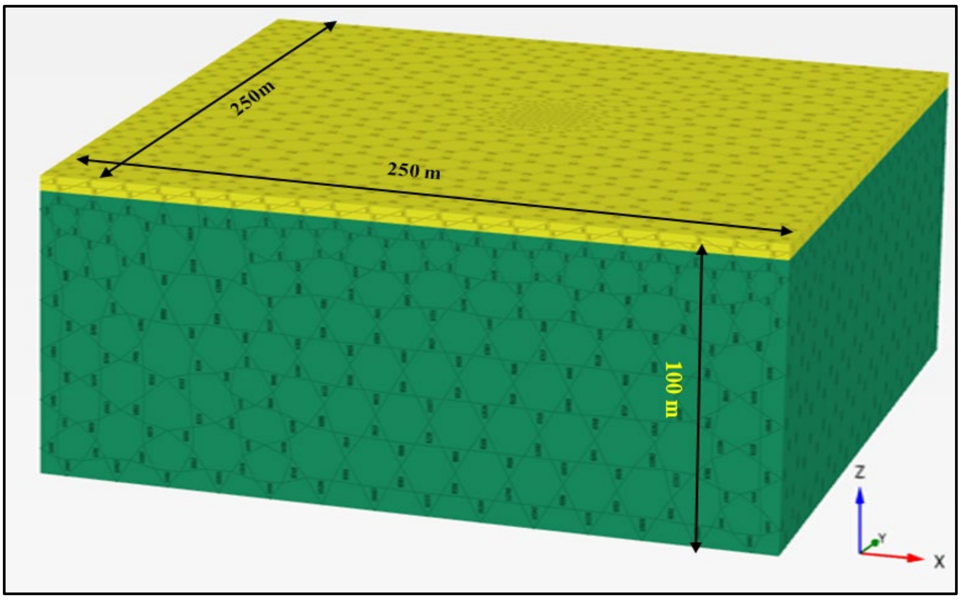

Figure 2. The mesh of finite element model used in this study.

2.1. Verification of Numerical Model

To verify the proposed numerical model, the foundation of the Messe-Torhaus building, Frankfurt, 1983–1985, under static loading was analyzed as an example of piled raft foundation [15]. The project is considered one of the first actual applications of piled raft foundation supporting a high-rise structure in

Germany. The proposed numerical model was formulated using PLAXIS 3D software. As a result, during the building phase, a monitoring program was rigorously implemented to watch the behavior of the piled raft foundation. This structure consists of 30 stories, split into two rafts 10 m apart. The rafts are constructed 3 m underneath the ground surface and have dimensions of 17.5×24.5 m. The structural load is 200,000 kN distributed evenly over the rafts to produce a stress of 466 kPa. The raft 2.5 m thick was attached to 42 drilled piles with a diameter of 0.9 m and a length of 20 m the groundwater level is 3 m below ground level as shown in Figure 3 [15]. The piles beneath each raft are evenly spaced with 3D to 3.5D spacing, where D is the pile diameter. Figure 4 shows the subsurface profile, consisting of 5 m of quaternary gravel and sand covering Frankfurt clay to a significant depth.

The properties of soil, cushion layer (sub-base), and geogrid used in the reinforcement of the cushion layer required in the proposed numerical model are listed in Tables 1 to 3 respectively. Figure 5 shows the piled raft foundation used in PLAXIS 3D. Reul and Randolph [16] presented an empirical equation to obtain the modulus of elasticity for the clay soils of the city of Frankfurt:

$$E = 45 + \left(tanh\left(z - 3015\right) + 1\right) \times 0.7z, \tag{4}$$

where E is modulus of elasticity (MPa) and z is depth below the surface (m).

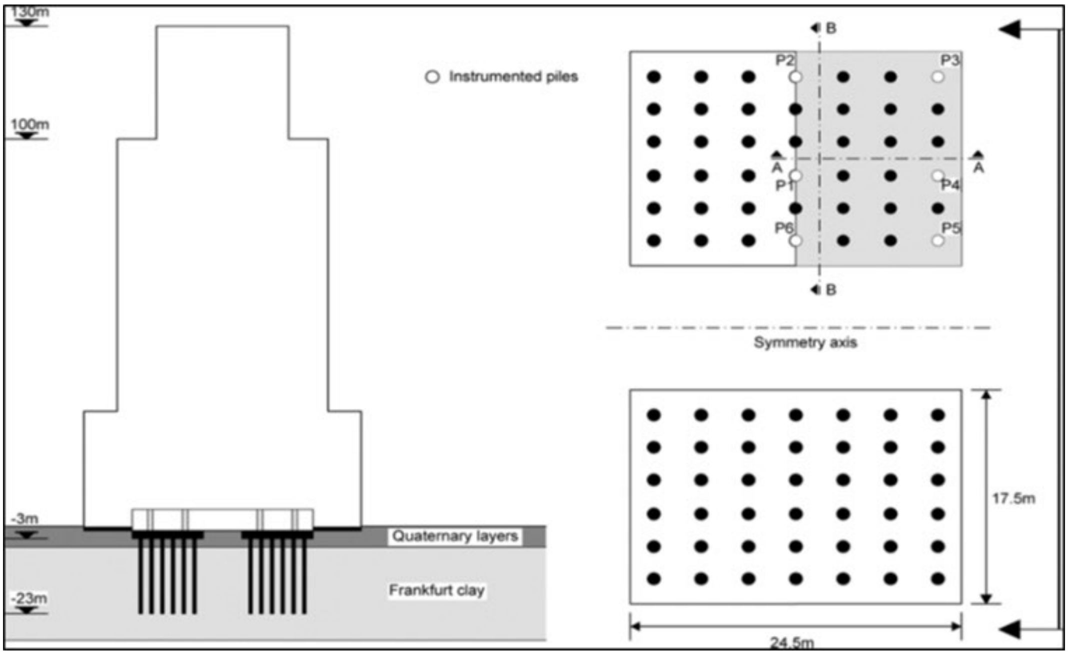

Figure 3. The piled raft system of the Messe-Torhaus building in Frankfurt [15].

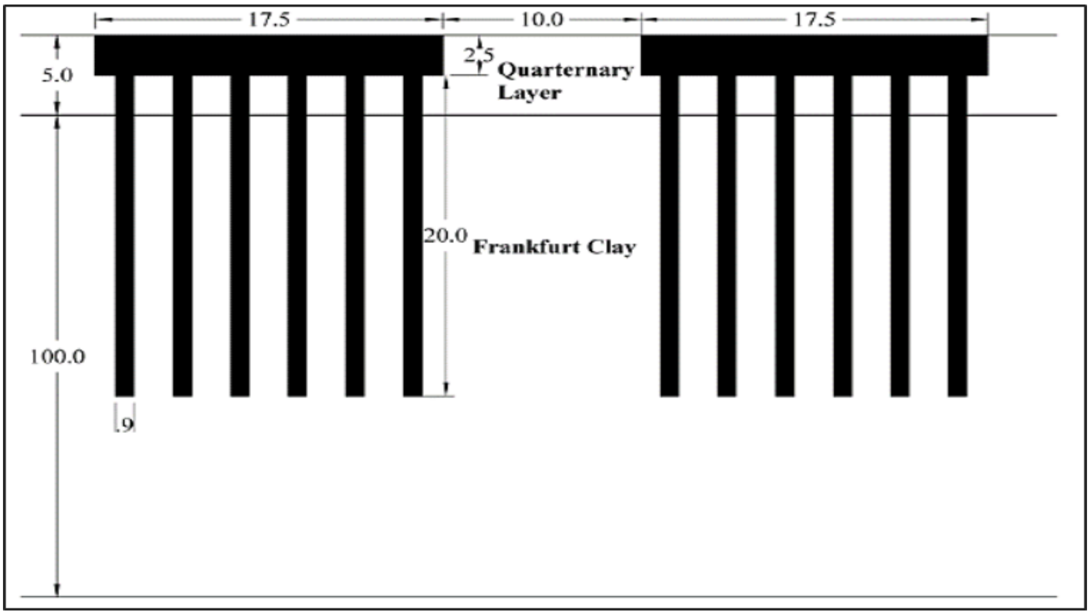

Figure 4. Soil layers support the foundation of the Messe-Torhaus building [15].

Table 1. Important parameters of the soil and piled raft for the Messe-Torhaus building [15].

Parameter	Quaternary gravel and sand	Frankfurt clay	Raft	Piles
Young's modulus, E (MPa)	75	50	34000	23500
Poisson ratio, v	0.25	0.35	0.2	0.2
Total unit weight (kN/m3)	18	19	25	25
Submerged unit weight (kN/m3)	–	9	–	–
Coefficient of lateral earth pressure at rest, k_o	0.72	0.46	–	–
The angle of internal friction, ∅′, degree	32.5	20	–	–
Cohesion, c (kPa)	0.1	20	–	–

Table 2. Properties of cushion layer used in the current study [17].

Property	Cushion layer
Modulus of elasticity, E (MPa)	60
The angle of friction, ∅ (degree)	19.4
Cohesion, c (kPa)	40
Dry unit weight (kN/m^3)	18.65

Table 3. Properties of geogrid used in the current study [18].

Parameters	Unit	Description or value
Material type	–	Elastic
Material behavior	–	Isotropic
Axial elastic stiffness (EA)	kN/m	110

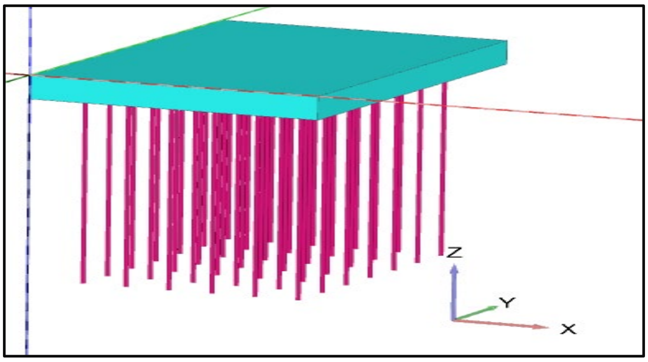

Figure 5. Modeling of Messe-Torhaus building in PLAXIS-3D software.

The maximum settlement recorded in the field due to the building's self-weight was 154 mm. For the same structural configuration and foundation characteristics (i.e., number of piles and raft dimensions), the numerical model predicted a settlement of 157 mm, demonstrating excellent agreement with the experimental observation (Figure 6). The deviation between the measured and simulated settlements is approximately 2%, indicating the reliability of the numerical model. In the foundation system of the Messe-Torhaus building, a 1 m-thick sand cushion layer (depicted in blue in Figure 7) was introduced to separate the piles from the raft. The influence of geogrid reinforcement within this cushion layer was also evaluated using the finite element software PLAXIS 3D. The geotechnical properties of the cushion layer are summarized in Table 2, where the elastic modulus of the sand layer was taken as 60 MPa [15].

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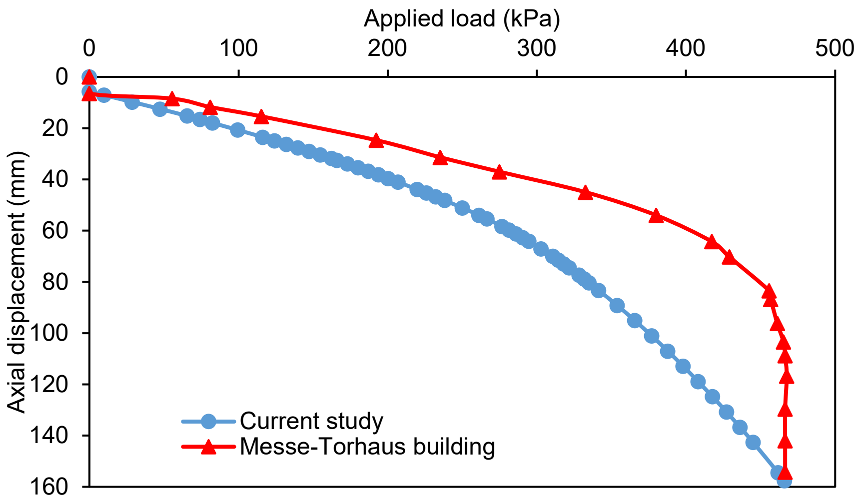

Figure 6. Verification of the settlement between the Messe-Torhaus building and the current study.

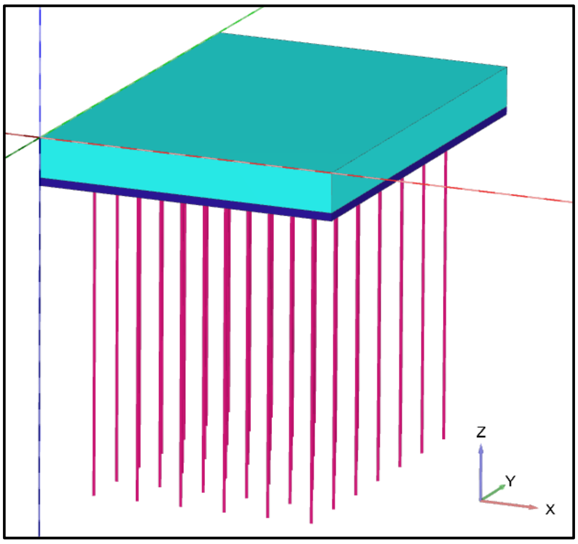

Figure 7. Disconnected piled raft model in PLAXIS 3D.

2.2. Seismic Loading

One of the most important and hazardous problems faced the geotechnical engineering is the presence of earthquakes that lead to damage or destruction of infrastructure as they affect the stability of facilities and foundations directly. Therefore, it is necessary to design the foundations in a strong manner that resists or limits the effect of earthquakes to preserve the safety of people from death. Recently, there has been an increasing interest in studying and understanding earthquake phenomena and trying to predict the time of their occurrence. Despite many studies having been conducted in this field, there was no accurate information on determining the time of earthquakes. Because Iraq is located within the earthquake-prone areas, where many earthquakes had hit Iraq over the past few years, where the eastern and northeastern regions witnessed many earthquakes, while the regions are stable in the south and southwest. This study will depend on the recorded data of an earthquake that struck Iraq in November 2017, in Halabja region, which killed many people and destroyed many structures. Halabja earthquake has a strength of 7.3 on the Richter scale (Peak ground acceleration, PGA = 1 m/sec^2) and its effect reached Baghdad city as shown in Figure 8 [19–25]. The behavior of the CPRFs and DCPRFs will be investigated under static and seismic loading.

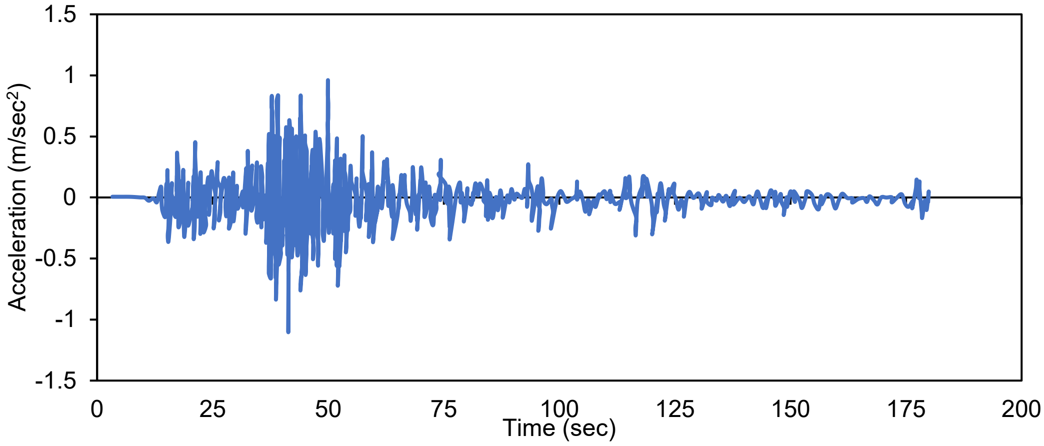

Figure 8. Acceleration–time history recorded in Baghdad for Halabjah earthquake.

3. Results and Discussion

The primary objective of this study is to evaluate the performance of the Disconnected Piled Raft Foundation (DCPRF) beneath the Messe-Torhaus building when subjected to seismic loading. This objective was achieved by analyzing the horizontal and vertical displacements of the foundation system and comparing the results with those obtained for a Connected Piled Raft Foundation (CPRF) under identical seismic conditions. The comparison aims to assess the effectiveness and seismic resistance behavior of the DCPRF.

3.1. Effect of Seismic Loading on Horizontal Displacement

To clarify the effect of the seismic load on the horizontal displacement during the static loads applied on the CPRFs and DCPRFs has been studied. Figure 9 shows the horizontal displacement of the raft caused by seismic loading in the CPRFs and DCPRFs.

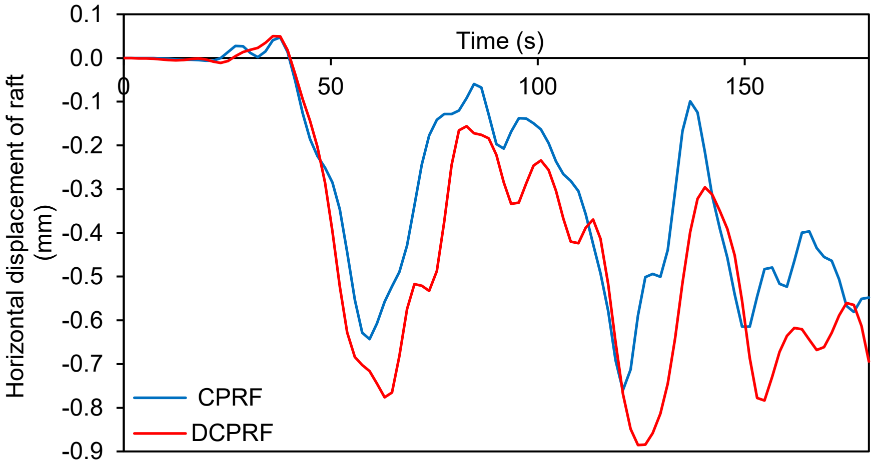

Figure 9. Horizontal displacement of the raft of the CPRF and DCPRF under seismic loading.

The horizontal displacement of the DCPRF is larger than the horizontal displacement of the CPRF by 15 %. This increase resulted from the lack of connection between the raft and piles or the piles behave as free head piles. When applying the Kobe earthquake with PGA (0.3 g), the horizontal displacement of the raft in the DCPRF increased by 45 % greater than the horizontal displacement in the CPRF as shown in Figure 10 due to increasing PGA from 0.1 g to 0.3 g.

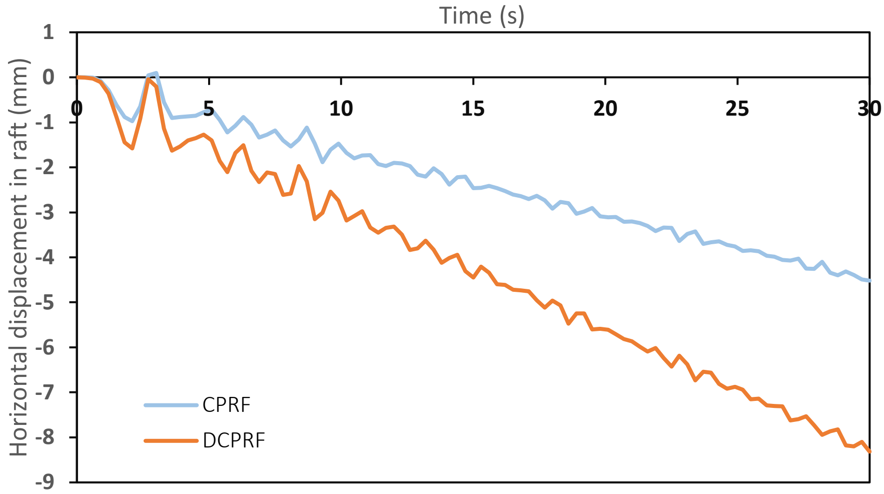

Figure 10. Horizontal displacement of the CPRF and DCPRF under seismic loading of Kobe.

3.2. Effect of Seismic Loading on Vertical Displacement

Figure 11 shows the effect of the seismic loading (Halabja earthquake) on the vertical displacement of the raft in the CPRF and DCPRF. The vertical displacement of the raft in the case of the CPRF is less than the vertical displacement of CPRF. The vertical displacement in the DCPRF decreased by 7 % from the CPRF because of the presence of the cushion layer, which plays an important role in the distribution of load between the soil and piles. Figure 12 shows the distribution of vertical settlement of the DCPRF under seismic loading obtained from PLAXIS 3D software. Applying the Kobe earthquake with PGA (0.3 g), the vertical displacement of the center of the raft in the CPRF increased by 38 % more than the displacement in the DCPRF as shown in Figure 13. Generally, increasing the intensity of the earthquake will increase the vertical displacement of the CPRF in comparison with the DCPRF.

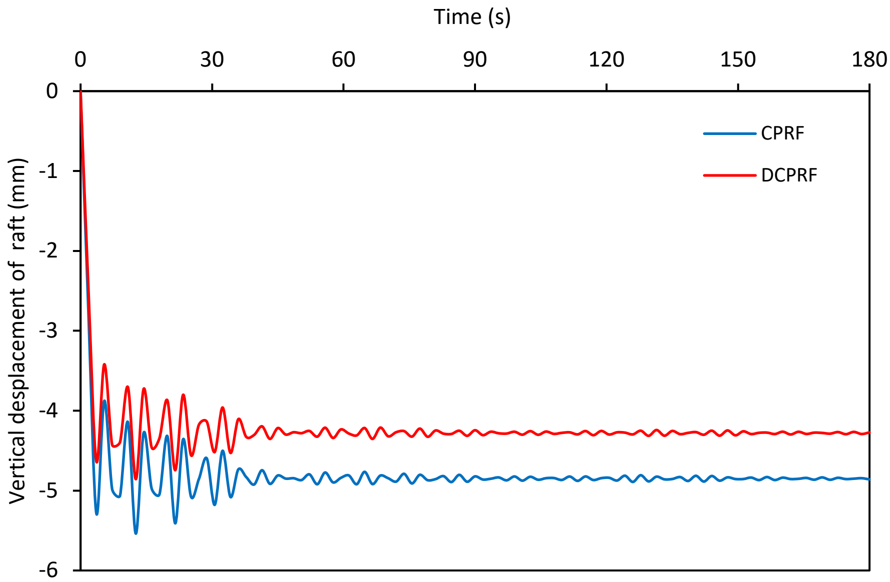

Figure 11. Vertical displacement at the center of the raft of the CPRF and DCPRF under seismic loading of Halabja earthquake.

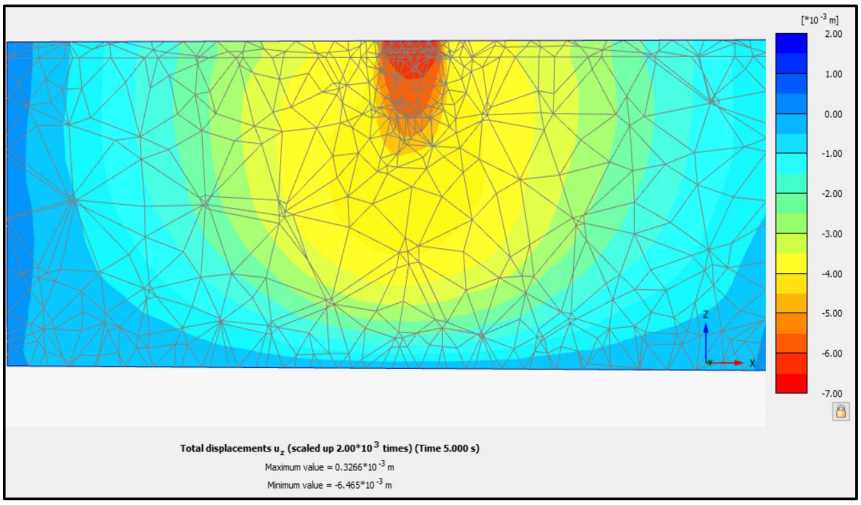

Figure 12. Distribution of vertical settlement of the DCPRF under seismic loading.

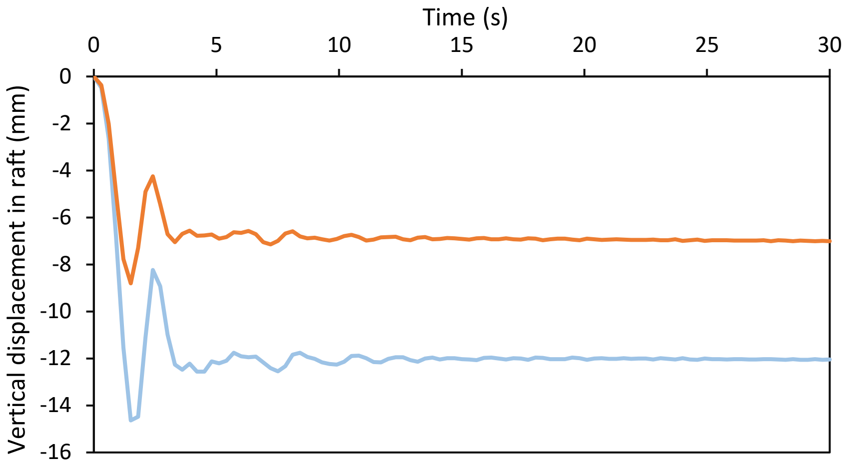

Figure 13. Vertical displacement at the center of the raft for the CPRF and DCPRF under seismic loading of Kobe earthquake.

Figure 14 shows the variation of the maximum vertical displacement under the raft foundation in both centerlines in long and short directions. The vertical displacement in the short direction at the edges is higher than that measured at the edges of the long direction of the raft. This decrease in vertical displacement is due to the difference in the dimensions of the raft foundation. While the vertical displacement at the center lines of long and short directions are almost the same.

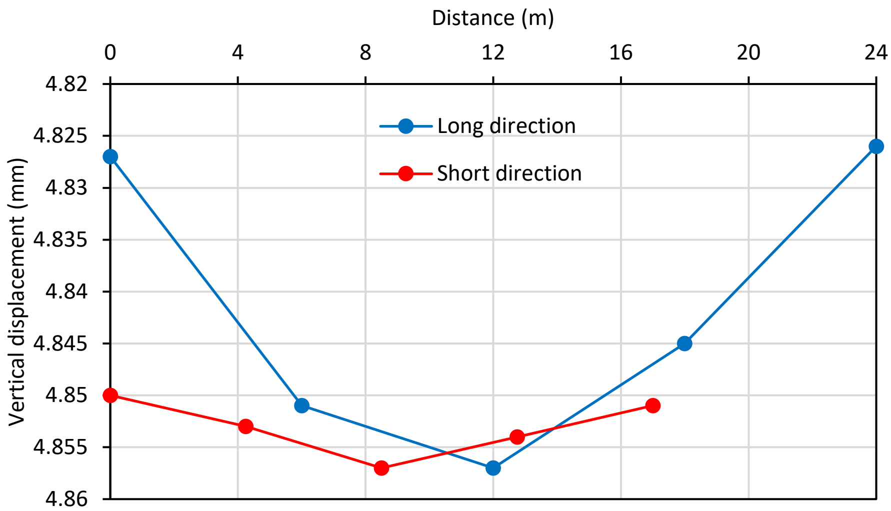

Figure 14. Vertical displacement of the raft foundation in the long and short directions under seismic loading.

The variation of axial load along the piles resulting from the seismic loading on the CPRF and the DCPRF is shown in Figure 15. In the case of the DCPRF, the axial force is less on the pile head compared to the CPRF by 44 %. In the case of the CPRF, the maximum axial load appears at the pile heal, and for DCPRF appears at the upper 1/5 of the pile length. The cushion layer will help to reduce the magnitude of axial load at the pile head, but the development of negative skin friction will increase the magnitude of axial load at the first quarter of the pile length.

The variation of shear force along the piles resulting from the effect of the seismic load on the DCPRF and CPRF is shown in Figure 16. At the pile head, the shear force is approximately equal to zero for the DCPRF, unlike the CPRF. The vanish in shear strength value results from the separation of piles from the raft by cushion layer, which change the situation of the pile head from fix pile head for the DCPRF to a free pile head. The DCPRF showed high variation in the shear force value along the pile length compared to the CPRF. From Figure 11, the shear force along the pile in the case of contact with the raft is less than it is in the pile disconnected from the raft. This decrease in shear force can be explained by the contact of the pile with the raft. At the pile tip, the shear force in the CPRF is higher than that in the pile head and higher than that in the DCPRF. The CPRF sustains low oscillation in the shear strength values which reflect the stability of such type of foundation.

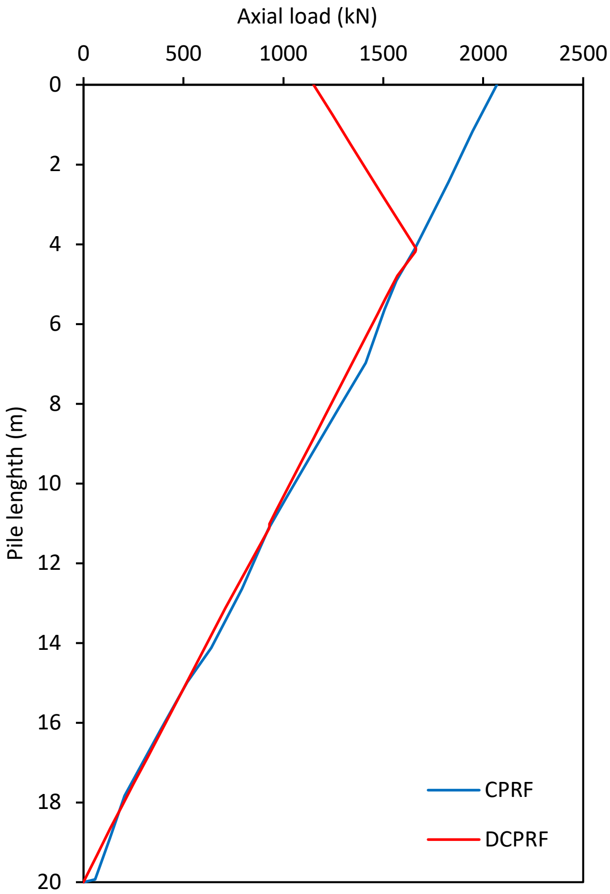

Figure 15. Variation of axial load along pile length of the DCPRF and CPRF system under seismic loading.

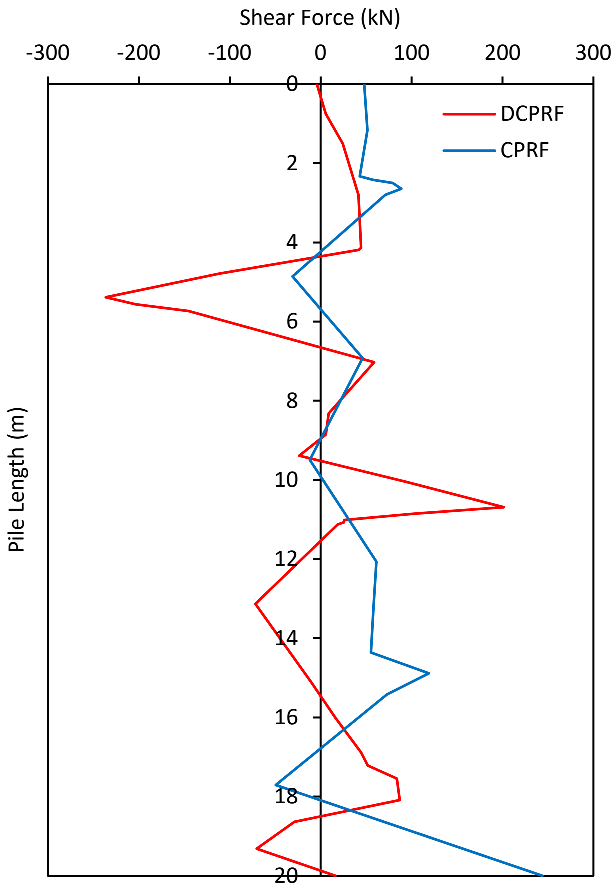

Figure 16. Variation of shear force of the DCPRF and CPRF system under seismic load at 180 sec.

Figure 17 shows the variation of the maximum bending moment along the pile under the influence of the seismic load in the connected and disconnected piled raft systems. In the connected piled raft system, the maximum bending moment value occurred at the head of the pile and then decreases with the depth. For the DCPRF, the bending moment value is approximately equal to zero at the head of the pile and the maximum value of the bending moment occurred in the upper quarter and middle of the pile. It is noticed from Figure 16 that the effect of the seismic load on the foundation compared to the vertical static load is small. While when use the DCPRF can solve the problems that damage the structural connections between the raft and the piles when an earthquake occurs.

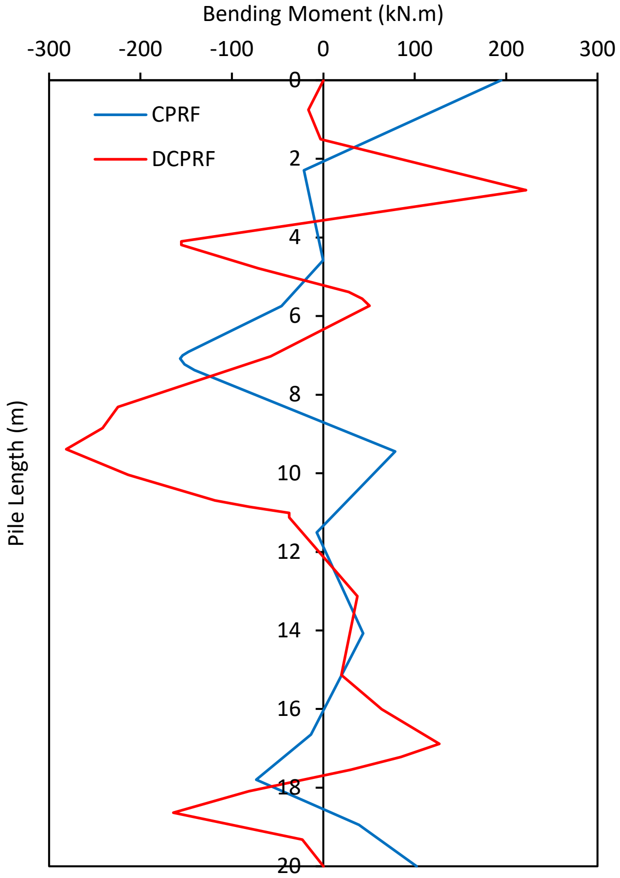

Figure 17. Bending moment of the DCPRF and CPRF system under seismic load at 180 sec.

4. Conclusions

The behavior of the proposed DCPRF is compared with the CPRF under the Messe-Torhaus building. Based on the results of the proposed numerical model simulating the behavior of the DCPRFs under seismic loading, the following points can be drawn out:

The verification of the proposed numerical model showed that the difference between the settlement calculated from numerical and field measurements for the Messe-Torhaus building in Frankfurt was 2 %.

The horizontal displacement of the raft in the CPRF is less than the horizontal displacement of the raft in the DCPRF during seismic loading by 15 %.

The vertical displacement in the DCPRF decreased by 7 % in comparison with the CPRF.

For the DCPRF, the bending moment value is approximately equal to zero at the pile head, and the maximum bending moment value occurred at the upper quarter and the middle of the pile.

The axial force at the pile head in the DCPRF is less on the pile head of the CPRF by 44 %.

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