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Study on Using Disconnected Piled Raft Foundations in Active Seismic Zones

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ABSTRACT

Choosing the suitable infrastructure system is becoming more challenging with the increase in demand for heavier structures contemporarily. This is the case where piled raft foundations have been widely used around the world to support heavy structures without extensive settlement. In the latter system, piles are rigidly connected to the raft, and part of the load goes to the soil layer on which the piles are bearing. In spite of that, when soil profiles contain thicker soft clay layers near the surface, or at relatively shallow depths, it is unfavorable to use the rigid piled raft foundation system. Consequently, the disconnected piled raft system was introduced as an alternative approach for the rigidly connected system. In this system, piles are disconnected from the raft using a cushion of soil, mostly of a granular interlayer. The cushion is used to redistribute the stresses among the piles and the subsoil. Piles are also used to stiffen the subsoil, and by this way reduce the settlement without being rigidly connected to the raft. However, the seismic loading effect on such disconnected foundation systems remains a problem, since the soil profiles may include thick clay layers which raise risks of amplification of the dynamic earthquake loads. In this paper, the effects of seismic behavior on the connected and disconnected piled raft systems are studied through a numerical model using Midas GTS NX software. The study concerns the soil-structure interaction and the expected behavior of the systems. Advantages and disadvantages of each foundation approach are studied and a comparison between the results are presented to show the effects of using disconnected piled raft systems in highly seismic zones. This was done by showing the excitation amplification in each of the foundation systems.
Keywords: Soil-Structure Interaction, Disconnected Piled Raft, Risks, Seismic Zones.

INTRODUCTION

In traditional foundation design, it is firstly expected to use shallow foundations (such as a raft foundations), where the load of the structure is expected to be transferred to the shallow subsoil from the raft. If it is found insufficient, deep foundations are used instead (such as a fully piled foundation), where piles are expected to carry the loads and transfer it to the soil further down the surface. Another alternative to both types, is called piled raft foundation or settlement reducing piles foundation, had been introduced by Davis and Poulos in 1972 [1], since then it has been popular in practical use. Raft and pile foundations are integrated together to achieve both an increase in the total bearing capacity and a reduction in the settlements induced by service loads.

Most of the cases this type is used in, the aim of adding piles is not to carry the entire load but to control the settlement [2].

Disconnected Piled Raft (DPR) system was being introduced to optimize the usage of piles. In this system, piles are designed as a settlement reducing piles only, not as a structural system which carries the entire loads of the super structures. The DPR system adapted a cushion of replacement soil between the raft and the piles as shown in Fig. 1. This cushion is used to redistribute the loads from the raft among the piles and the soil underneath, and disconnect the piles structurally from the piled raft system.

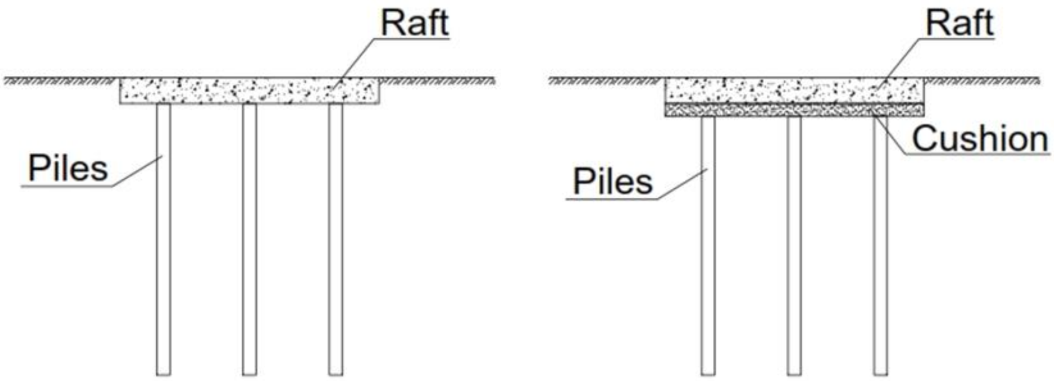

Fig. 1: Connected vs Disconnected Piled Rafts

This latter system prevents the pressure coming from the superstructure to be directly enforced on the piles as the cushion is used to redistribute the loads among the pile-soil system. From the design point of view, the embracement of DPRs allows lower safety factors for the piles. According to Abd Alaah [3] the DPRs provides an economical alternative for the Connected Piled Raft (CPR) system subjected to vertical loads using the same number and length of piles with a 57.8% reduction in material costs. DPRs have been commonly used in high rise building foundations due to its large bearing capacity, acceptable values of settlement, relatively low cost and suitable construction. The cushion plays a main role in making full use of the bearing capacity of soil between piles.

There have already been several studies of the behavior of DPR foundation under static load, which considered the behavior through numerical and experimental studies [4]; [5]; [6]; [7]; [8]. From these studies it was concluded that under the static loading the axial load carried by the piles in the case of the DPR is reduced, as the cushion redistributes the load among the soil and the piles. This directs to a conclusion that the piles in case of the DPR may be used as plain concrete piles. However, the studies on the load bearing mechanism of the DPR system under horizontal loading or during earthquakes is very limited [9]; [10].

As engineers, if a huge load coming from a high-rise building or from strategic structures such as bridges, the CPRs foundation is an option for this system, and as introduced before the DPRs foundations may also be an option for these loads.

This paper aims to study the two systems discussed later to carry a static load which is simulated to be a bridge pier. The two systems are designed to carry the static load with an acceptable settlement values for bridges. Then, the responses of the two systems due to the effect of horizontal dynamics force is analyzed. The responses of different systems are studied to inspect the effect of the connection state between the raft and the piles based on the finite element analysis.

METHODOLOGY

A 3-D finite element model was made using GTS-NX [11]. The main challenge was to build a numerical model that can obtain satisfactory results under both horizontal and vertical loads. The model was verified through comparing the results with field results from Huang [11] on a single pile under lateral and vertical loading. GTS NX software results was found very satisfactory when compared with the field results published in the latter paper. Fig. 2 shows the lateral displacement comparison which had a maximum error of 1.6%. Fig. 3 compares the maximum bending moment between GTS NX model and the field study, the results were found conforming with the filed study which had an increase of 9.2%. The axial load comparison results are shown in Fig. 4 and showed a good agreement with the experimental results.

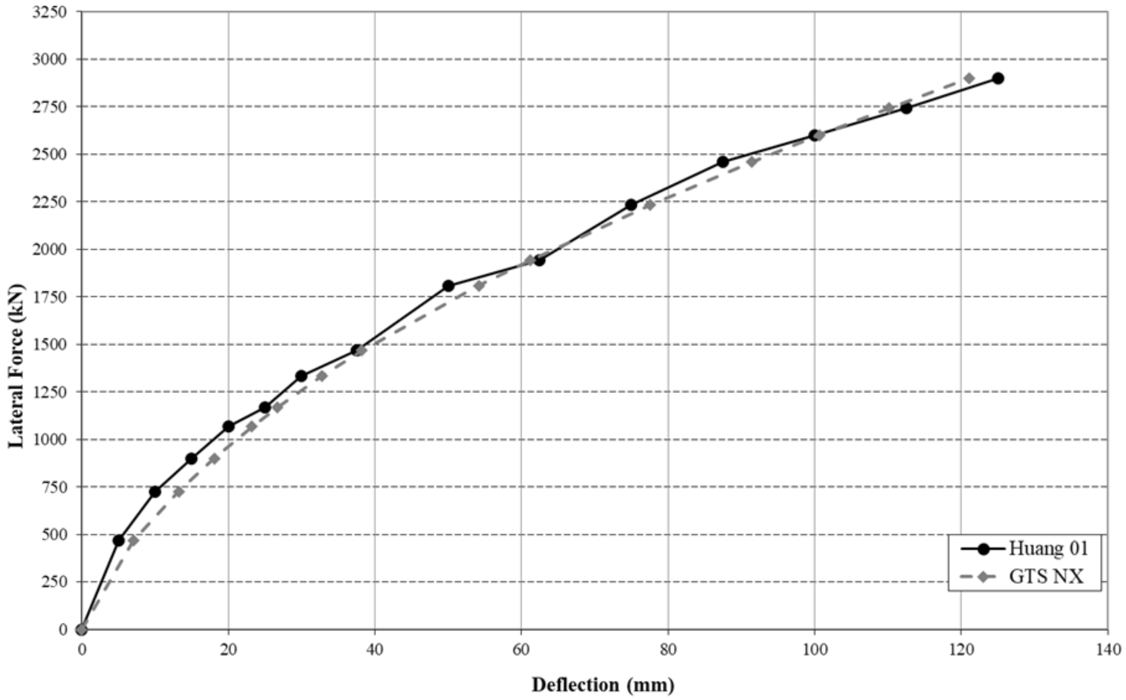

Fig. 2: Lateral Load Comparison

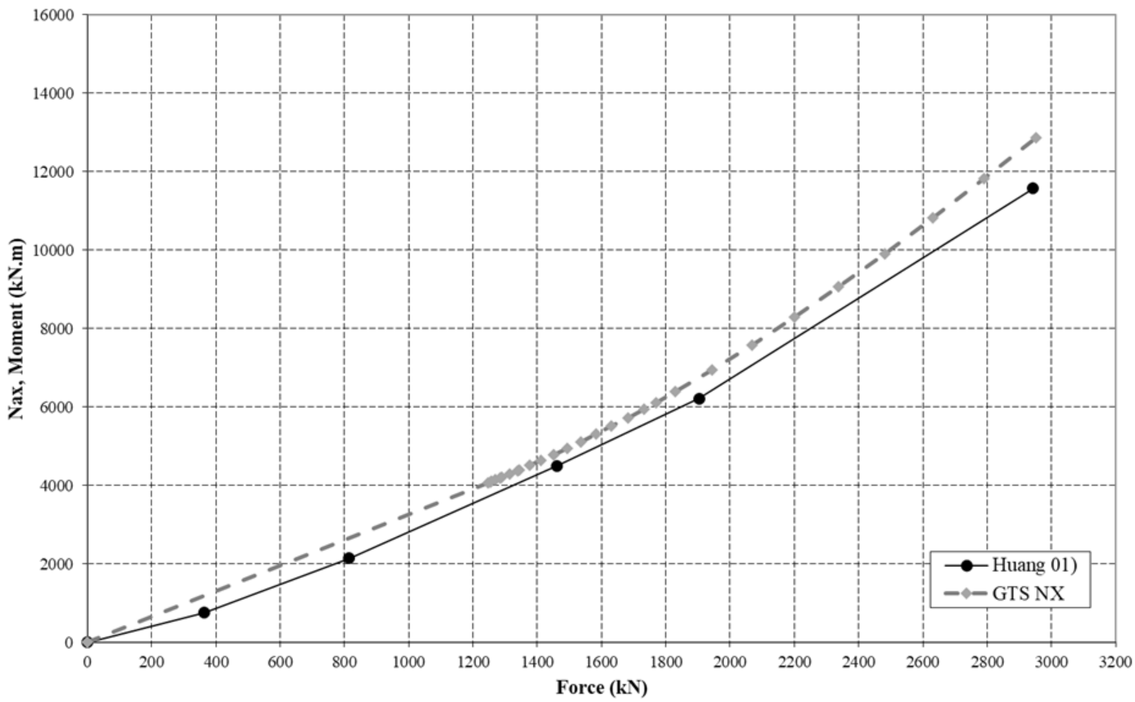

Fig. 3: Max. Moment Comparison

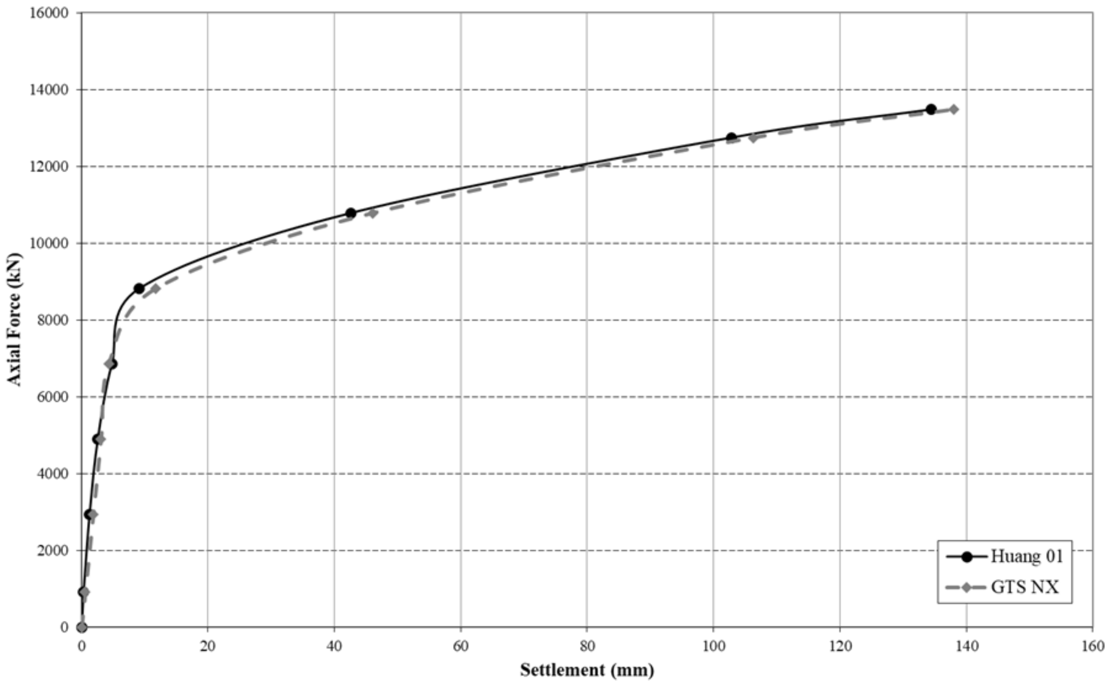

Fig. 4: Axial Load Comparison

Material Modelling:

In this paper, Drucker-Prager model was used. Drucker-Prager model was developed by Drucker and Prager [12] to solve the numerical problems that occur on the corners of the yield shape of the Mohr-Coulomb model. The internal algorithm is the same as the Mohr-Coulomb model, and the material constant can be related to the existing cohesion (c) and friction angle (Ø) of the Mohr-Coulomb model.

In the built models, interface is used between the raft and the soil, and between the piles and the surrounding soil in order to simulate the soil-structure interaction. The interface consists of normal and shear interface. The interface express nonlinear behavior through default stiffness as well as ultimate strength. The normal stiffness modulus (K_n) and the shear stiffness modulus (K_t) are calculated from the following equations:

$$K_n = \frac{E_{oed,i}}{tv} \tag{1}$$

$$K_t = \frac{G_i}{tv} \tag{2}$$

$$E_{oed,i} = 2 \times G_i \times \frac{(1-vi)}{(1-2\times vi)} \tag{3}$$

Where,

$E_{oed,i}$ ≡ Modulus of Elasticity from oedometer test

vi ≡ Interface Poisson's ratio

tv ≡ Virtual thickness

$$G_i = R \times G_{soil} \tag{4}$$

$$G_{soil} = \frac{E}{2(1+v_{soil})} \tag{5}$$

Where,

G_{soil} ≡ Shear Modulus for Soil

R≡ Strength Reduction Factor

E≡ Modulus of Elasticity

ν_{soil} ≡ Poisson Ratio of Soil

Modal Analysis:

Before applying the non-linear time history analysis, modal analysis was performed to analyze the inherent dynamic properties of the ground and structure. For sufficiently accurate analysis number of modes were studied to make sure that the sum of the mass participation factor is larger than 90%. The frequency of the two modes with the highest mass participation factor are computed to calculate the damping coefficients for the used materials.

Computing the damping constant for mass proportional attenuation and stiffness proportional attenuation. The proportional coefficient is automatically calculated from the mode attenuation by GTS NX software, for checked items on the attenuation type.

The damping effects in non-linear time history analysis are applied to the damping matrix C in the following form mentioned by Chopra [13]:

$$\mathrm{C} = \alpha_j M_j + \beta_j K_j + B \tag{6}$$

Where,

C ≡ Damping matrix

α_j ≡ Mass proportional damping coefficient for jth element

β_j ≡ Stiffness proportional damping coefficient for jth element

M_j ≡ Mass matrix of jth element

K_j ≡ Stiffness matrix of jth element

B ≡ Damping matrix due to damping element

The Rayleigh damping coefficients, α and β, are determined from the relationships given below:

$$\alpha = \zeta \frac{2\omega_i\omega_j}{\omega_j+\omega_j} \tag{7}$$

$$\beta = \zeta \frac{2}{\omega_j+\omega_j} \tag{8}$$

Where, ζ is the damping ratio of the material, and the (ω_i and ω_j) are the frequencies corresponding for the two higher mass modal participation factor.

The attenuation for each material, when calculating the mass & stiffness coefficients from the modal damping, can be reflected in the analysis. The damping ratio of each material and the damping coefficient (α, β), of the damping matrix, are calculated.

CASE STUDY

Two possibilities were put for the design of a foundation system carrying a load of 15,000 kN, which is proposed to be a bridge pier load. The design used two different systems, CPR and DPR. The design of the CPR system was developed from the allowable pile capacity. The main criterion for designing the DPR system was the allowable settlement as the two models are proposed to be a settlement reducing systems. The allowable settlement for the model was 2.54 cm as mentioned according to the Washington standards [14] for the maximum settlement for a bridge.

Geometrical Configuration:

The design for the CPR model resulted that 16 piles will be sufficient to sustain the proposed load. The raft was designed to be square with dimensions of 8 m x 8 m and with a thickness of 1m. The DPR model is designed using Plaxis 3D (V 8.6) [16]. It was found out to use 25 piles and a cushion thickness of 1 m under a 10 m x 10 m raft to be able to withstand the load. The two systems are sketched in Fig. 5.

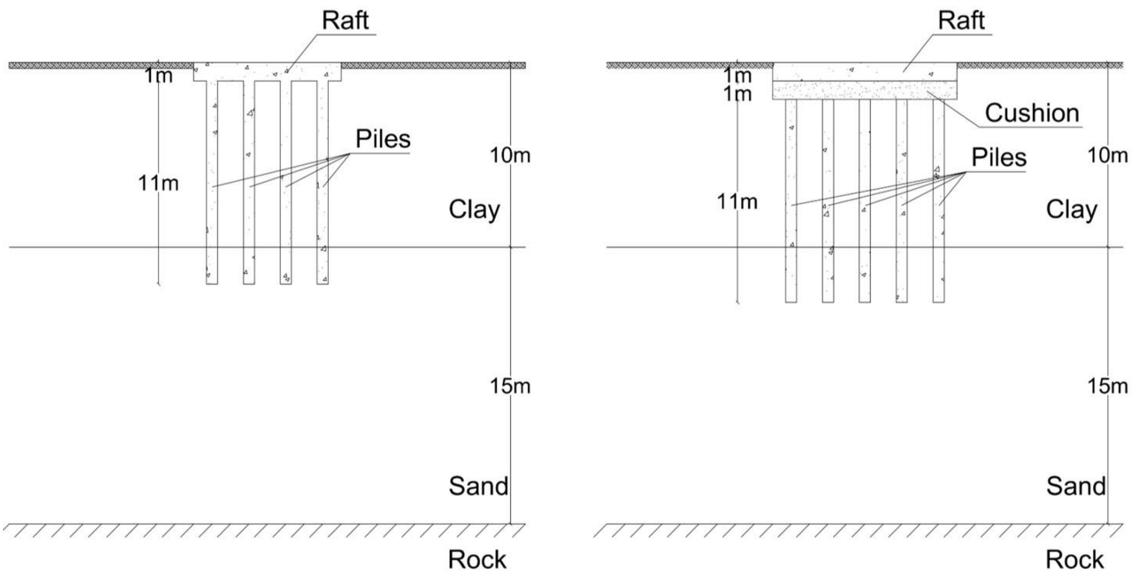

Fig. 5: CPR vs DPR's Geometry Configuration

The raft in the CPR model is based on 16 piles, connected to the raft, with a diameter of 0.6 m, embedded inside a clay layer, which has a thickness of 10 m from the ground surface, and rests 2 meters inside a layer of sand, which extends 15 m. DPR model has 25 piles, and also with the same length as the CPR system. Fig. 6 shows the finite element mesh for the disconnected system, which is consists of the raft, cushion, piles and soil.

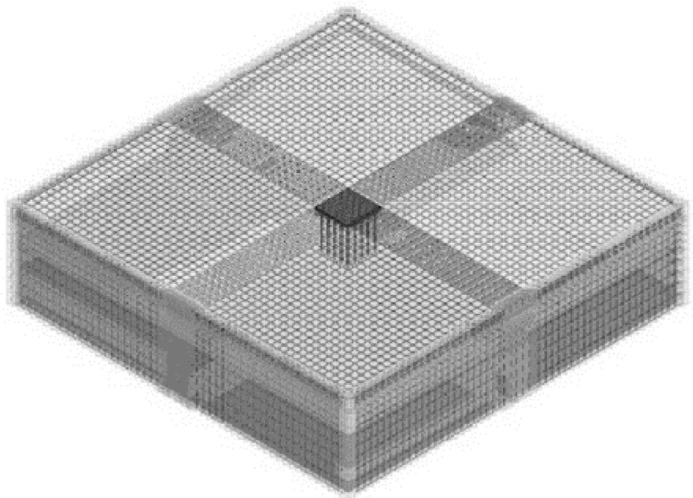

Fig. 6: 3D Finite Element Model

***Material Configuration*:**

Material parameters for the model was assumed homogenous and isotropic. The mechanical behavior of piles and raft has been assumed to be linear elastic, in order to allow the relative displacements, frictional elasto-plastic interface elements for soil–structure which were used between the soil and the structural elements.

According to Nakai [9] results which show the validity of using the Drucker-Prager material modelling, the materials properties of the sand, clay and the cushion were used as Drucker-Prager model. The mechanical properties of the cushion are simulated as mentioned according to [15].The material parameters for raft, piles, cushion, stone columns and soil are mentioned in Table 1.

Table 1: Material Parameters

Material Parameters	Unit	Raft	Piles	Cushion	Clay	Sand
Elastic Modulus "E"	kN/m^2	3.4E+7	2.1E+7	40,000	7,000	40,000
Poisson Ratio "υ"	-	0.2	0.2	0.3	0.45	0.3
Unit Weight "γ"	kN/m^2	25	25	18	16	18
Angle of Internal Friction "Ø"	°	-	-	30	-	30
Cohesion "Cu"	kN/m^2	-	-	-	43	-
Dilatancy Angle "Ψ"	°	-	-	15	-	30
Initial Stress Parameters "K_o"	-	-	-	0.5	1	0.5

***Boundary Conditions and Loading*:**

The static load on the raft is assumed 15,000 kN. This load replicates loads that may occur on a typical bridge support. For seismic analysis, the boundaries were modeled as infinite ground to eliminate the reflection of waves at the boundaries of the model. GTS NX software was used. GTS NX software provides the infinite ground through the Free Field Element. The model was fixed from the bottom to simulate the rock bottom where the ground acceleration initiates.

The usage of an earthquake acceleration for the seismic analysis will be unfair as every earthquake have only some frequencies that it will contain the maximum power, which will be favorable for a model more than another. Since, the white noise wave contains the same power for all frequencies, it was used as the ground acceleration. Time history of a white Gaussian noise was applied on the model with scale factor of 1 along X-axis. The white noise was produced by the use of MATLAB® [18]. The acceleration peak of the white noise is 0.2g and a duration of 30 seconds. The normalized acceleration for the white noise is plotted in Fig. 7.

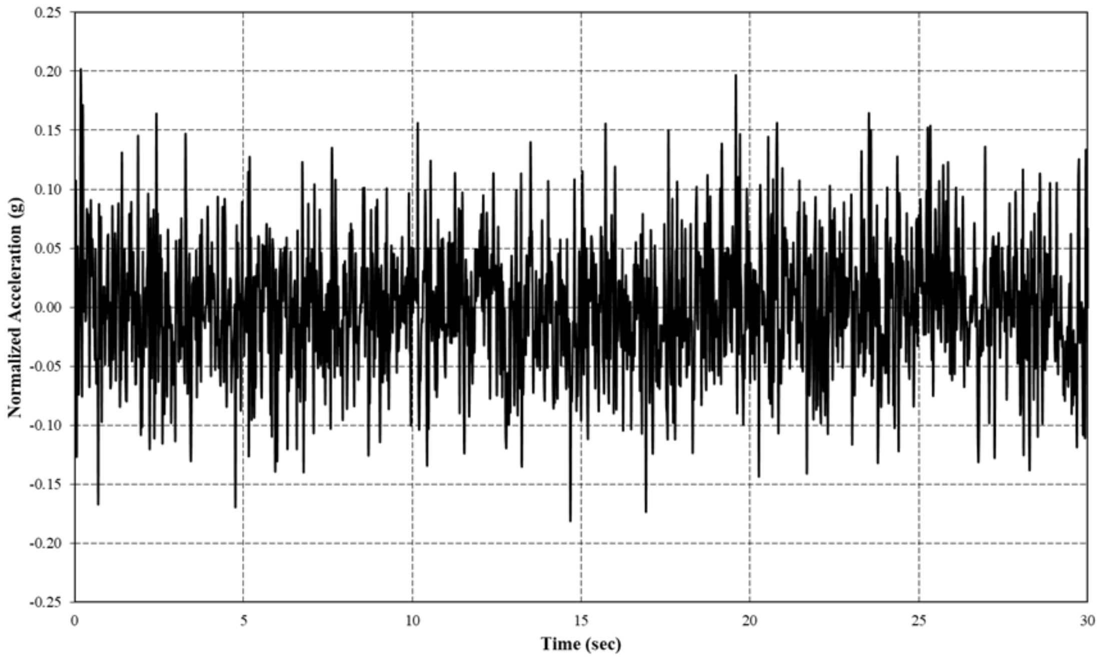

Fig. 7: White Noise Excitation

ANALYSIS OF RESULTS

On studying the static and dynamic responses of the CPR and the DPR systems under white noise (North-South direction), as shown in FIG. 7.

Lateral Response:

The lateral displacement responses of the model at the top of the raft, which will be transmitted to the structure above, are spotted for 30 seconds. As shown in Fig. 8, it is clear that the displacements in the two cases (CPR, and DPR) didn't vary a lot for the first 14 seconds. However, there were an increase in the disconnected model than the connected model in the last part of the excitation with a maximum variation of 27% in the case of the DPR. This amplification may be due to the effect of the release of energy in the DPR system as a strain energy in soil. As the soil in the disconnected system is carrying more share from the loads under the static and dynamic loading.

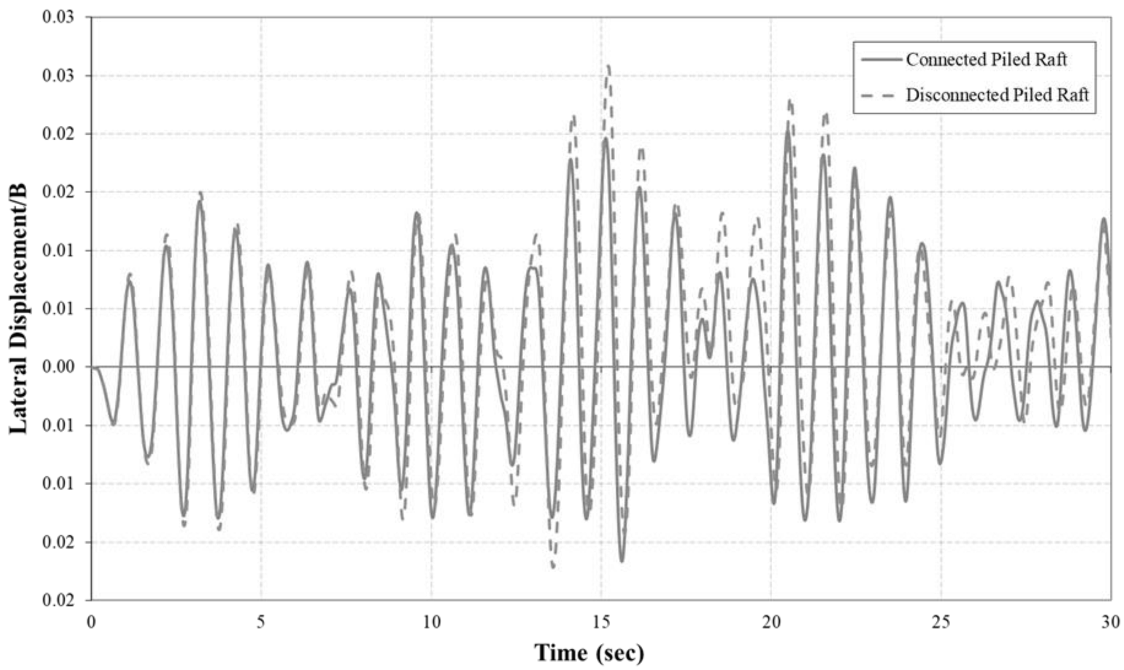

Fig. 8: Lateral Displacement Time History for Connected and Disconnected Systems

Moreover, the lateral acceleration responses at the top of the raft illustrate that the CPR system gives slightly lower acceleration values than that of the DPR, as shown in Fig. 9, with a maximum difference of 2%. As shown in Fig. 10, the acceleration of the CPR and DPR systems were transformed in the frequency domain using MATLAB®, the frequency of the peak values at the two models are the same at the first mode and have slightly different frequencies in the second mode. However, the CPR model gave to some extent lower values of power.

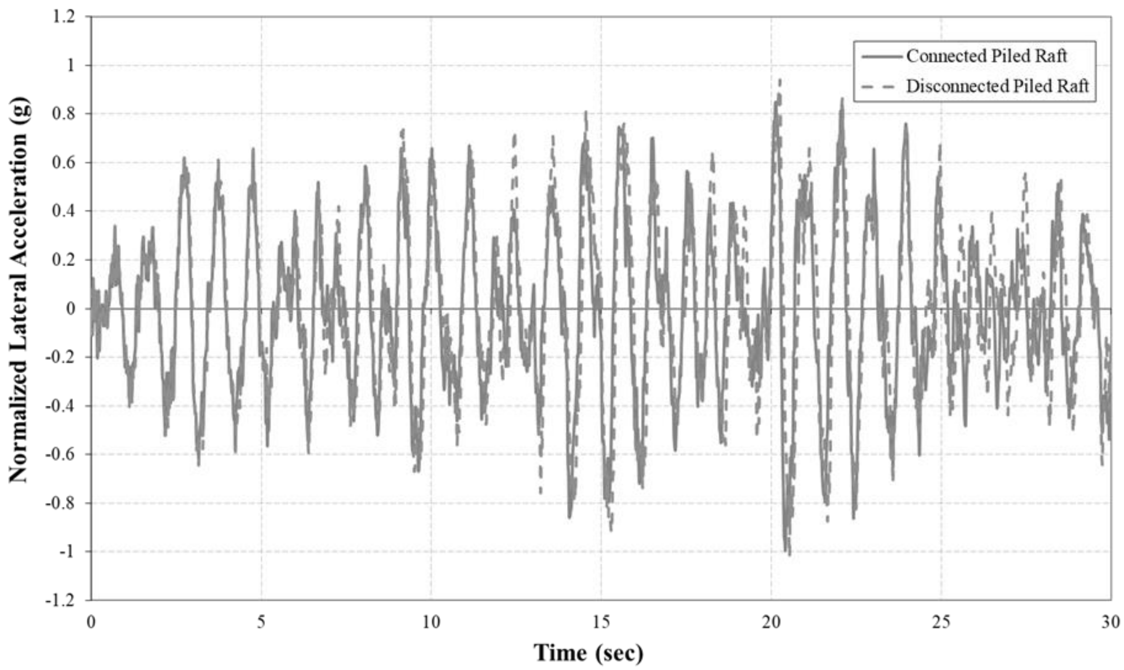

Fig. 9: Normalized Lateral Acceleration Time History for Connected and Disconnected Systems

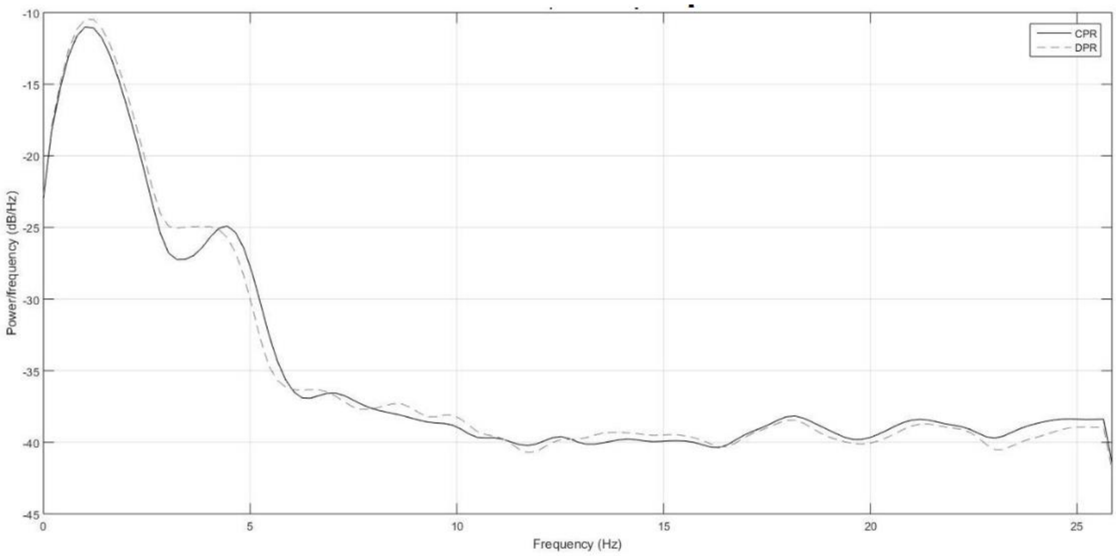

Fig. 10: Power Spectral Density for the Acceleration at the Top of the Raft

Vertical Response:

As shown in Fig. 11, settlement of the raft was monitored and showed huge differences between the two models. The difference in the settlement values for the first 9 seconds was almost constant. However, the settlement for the DPR model till the last of the excitation was almost five times more than that of the CPR model. Though, the CPR values are almost constant with a small drop after the first 14 seconds.

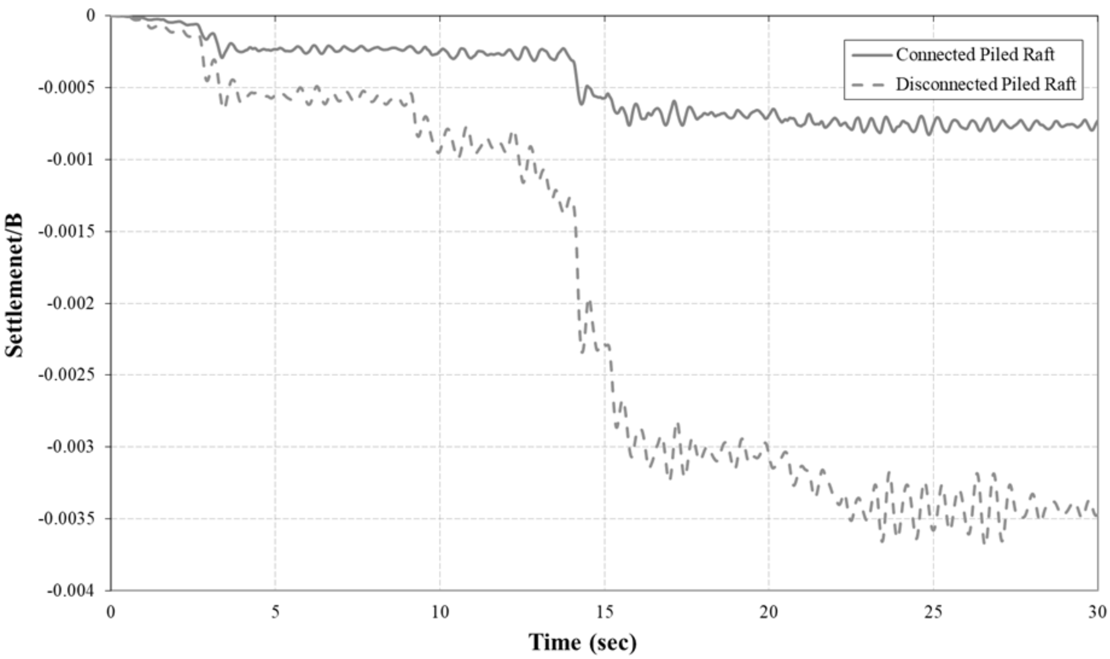

Fig. 11: Vertical Displacement Time History for Connected and Disconnected Systems

Axial Load Response:

Fig. 12 shows the axial load for corner piles under static load, as can be concluded the static axial load in the case of the DPR model is much smaller than the values of the CPR model and the maximum values in the DPR model is shifted towards the center of the pile, while the maximum value for the CPR model is at the top of the pile. This conclusion leads to the suggestion of reducing the strength of the pile by using plain concrete piles as suggested by (Ata, et al., 2014).

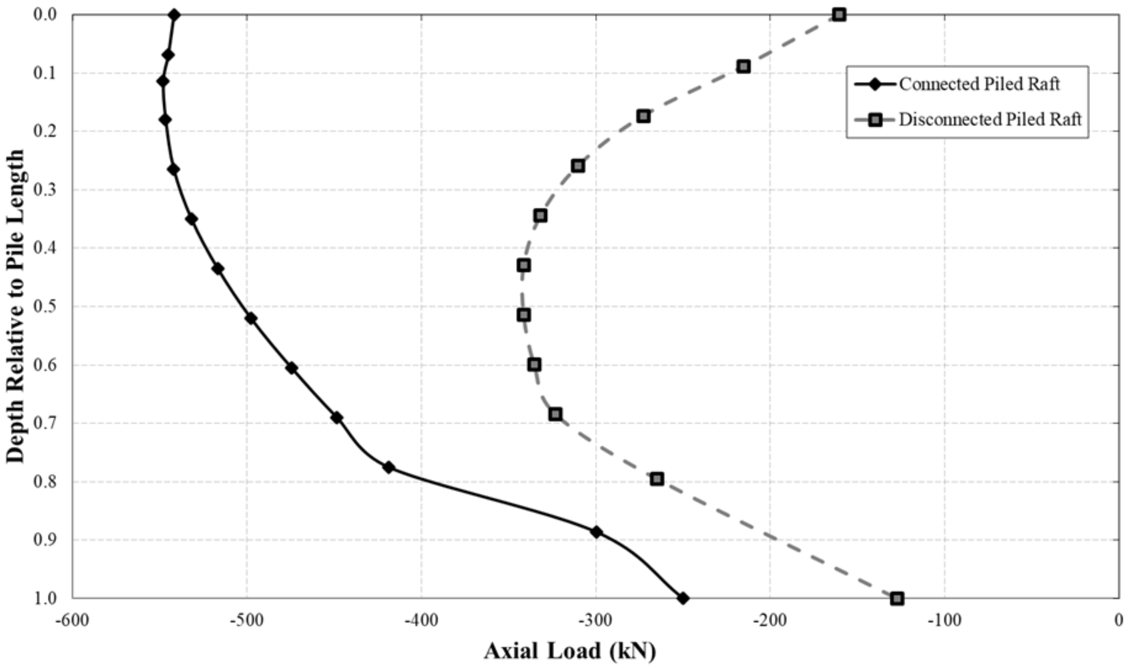

Fig. 12: Total Settlement of Raft, Connected Piled Raft, and Disconnected Piled Raft Systems under Static Loading

Fig. 13 and Fig. 14 show the axial load time history at the top of the pile and at the center of the pile respectively. The axial loads are normalized by dividing among the ultimate pile capacity for CPR and DPR models. From these figures it can be deduced that, the axial load in case of DPR model was lower than that for the CPR system under static loading due to the presence of the cushion. The trend of the values of the DPR model was to increase until it almost was equal to that of the CPR model. However, the CPR axial load trend was almost constant under the excitation. Even though, both models didn't reach the ultimate capacity of the piles.

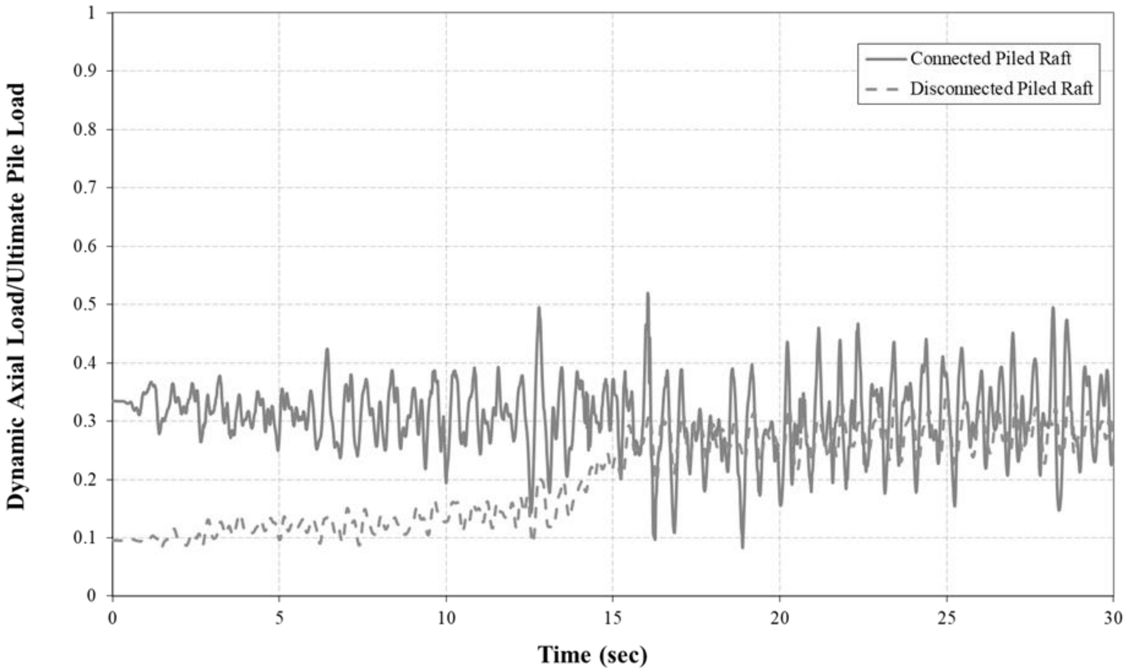

Fig. 13: Dynamic Axial Load/ Ultimate Pile Load at the Top of the Corner Pile for Connected and Disconnected Systems

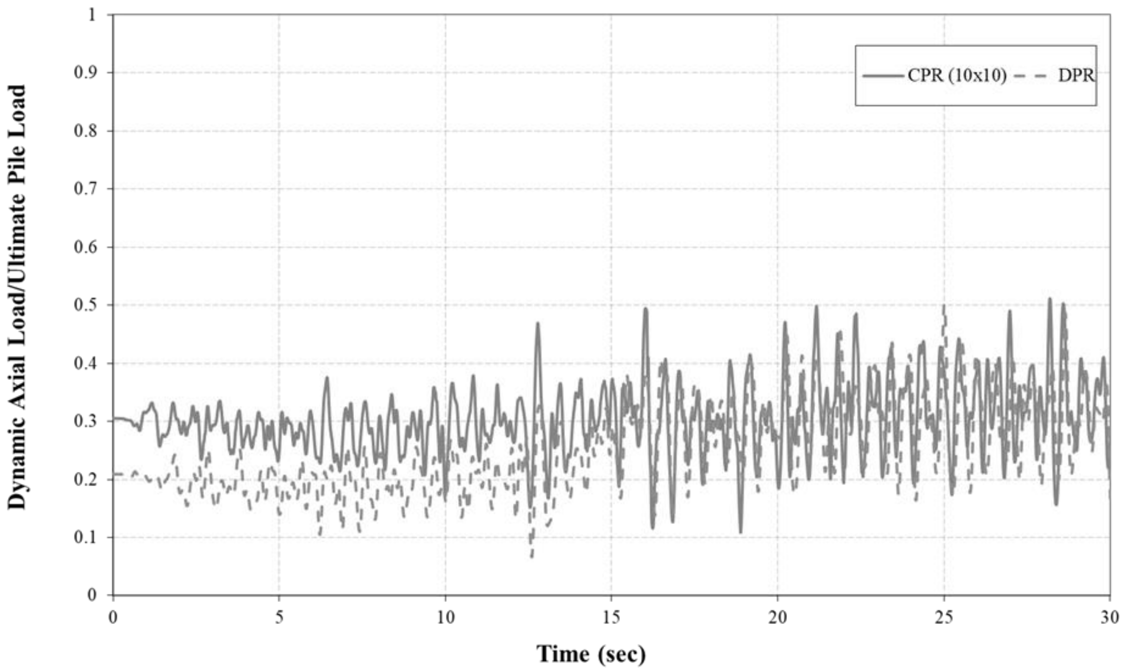

Fig. 14: Dynamic Axial Load/ Ultimate Pile Load at the Mid. Height of the Corner Pile for Connected and Disconnected Systems

At the top of the pile, the CPR model reached 52% of the ultimate capacity, while the DPR reached 35% of the ultimate capacity. However, at the center of the pile, the CPR model reached 51% of the ultimate capacity, while the DPR reached 50% of the ultimate capacity. This also demonstrates that the maximum value for the DPR model under dynamic loading was also at the center of the piles.

CONCLUSIONS

Connected and Disconnected Piled Rafts models' behavior under white noise excitation were studied. Numerical models were made using GTS NX software. This paper introduced a dynamic model for CPR and DPR systems that sustained safely a vertical static load which reflects a load reaction coming from a bridge support. White noise was used as the main excitation. Based on the numerical models results, the following main conclusions were drawn:

1. The inclusion of the cushion between the raft and the piles didn't have much effect on the lateral displacements under dynamic loads as both models almost gave the same results.
2. The values of the raft lateral acceleration in the frequency domain were the same even though the DPR had slightly higher values. The same applies to the values of energy when observed in the frequency domain.
3. DPR system gave higher values for the settlement than the CPR, which reached almost five times more, which may be unacceptable in cases of strategic structures projects.
4. The existence of the cushion had a great effect on the axial loads for the piles, as the DPR system had much less values than that of the CPR system under the static loads. However, the axial load for the DPR have reached the same values as the CPR in the dynamic loading, which may infer that the advantages of using DPR for less steel pile reinforcement or even reducing the number of piles is lost.
5. The existence of the cushion caused the maximum axial load of the piles to shift towards the center of the pile instead of the top of the pile in the connected model.
6. In an active seismic zone, connecting the piles to the raft will have much better effect on the raft responses for the lateral displacement and soil settlements.

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