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Performance Analysis of Disconnected Piled Raft System in Soft Clay under Static Load

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***Abstract* -** The use of piled raft foundation is preferred in soils having low bearing capacity and susceptible to undergo greater settlement. However, the piles and raft behave as structural elements in transferring the vertically imposed load to the subsoil which in turn resulting into transfer of high shear force and moments through the connection point of pile head and raft. This may instigate the structural collapse of pile before it mobilizes the full geotechnical capacity. To overcome this, a new type of foundation called Disconnected Piled Raft (DPR) with a layer of granular cushion between raft and piles which acts as soil stiffeners is suggested by sever-al studies. The present study aims at understanding the load sharing and settle-ment behavior of DPR under the application static vertical loading using PLAXIS 3D by varying cushion stiffness and piles stiffness. Piles and raft are considered to be linearly elastic, whereas Mohr-Coulomb model for granular cushion layer and Modified Cam Clay model for subsoil are chosen. DPR helps in improving the percentage of load resisted by raft and also prevents direct moment transfer from raft to pile head. Results show that the load sharing ratio between raft and piles, axial force distribution along the length of piles, bending moment and settlement behaviour of piled raft system was substantially modified by the presence of cushion.

***Keywords*:** Disconnected pile raft; Granular Cushion; Axial force; Bending moment; Settlement; Soft clay.

1. Introduction

Deep foundations are generally preferred when the foundation soil is very weak to carry the superstructure load and also undergoes larger settlement. Several types of deep foundation methods are in practice such as the use of single pile, group of piles with cap, piled raft foundation, etc., to overcome the shortcomings of weak subsoil. The use of granular cushion layer between pile and raft was further developed to enhance the performance of piled raft system in terms of distribution of overburden pressure [1]. Hence, the piles can be used as settlement reducers and not a load carrying structural member [2]. Relatively stronger long piles and flexible cushion was used in disconnected piled raft (DPR) system to reduce settlement and redistribute the stress-ration of piles to subsoil [3]. Several numerical and experimental studies were performed on DPR system by varying the pile length, pile diameter, number of piles, pile material, cushion thickness and cushion stiffness to understand the performance of DPR system in terms of settlement [2, 4, 5]. Few comparative studies on performance of connected and disconnected piled raft system with cushion were also analysed numerically and experimentally under vertical and eccentric loading conditions which concluded that the use of piles behaved as soil reinforcement in presence of cushion [6, 7]. Few centrifuge model tests and triaxial tests were conducted on disconnected piled raft to understand the incompatibility between raft and piles which led to the development of negative skin friction at the upper part of piles [4, 7, 8]. Parametric studies were done on several case studies of disconnected piled raft system by varying piles spacing, embedment length, piling configuration and raft thickness to get the optimized design [9]. Mechanical models were proposed to calculate the pile-soil stress ratio with the assumption of stress-deformation coordination in pile-cushion system [10]. Experimental and numerical studies on model piled rafts to study the effect of pile diameter, pile length, thickness of cushion, etc., on performance of DPR system were explored and comparison with unpiled and connected piled raft system to understand the soil-structure interaction mechanisms among raft-cushion-pile system [11, 12, 13]. Centrifuge model testing on performance of DPR system under lateral loads and bending moments were explored to some extent [14, 15]. Few investigations were performed on geogrid reinforced DPR system in enhancing the cushion behavior [16]. Dynamic behaviour of DPR system was further explored to some extent through numerical and centrifuge tests [17]. The present study is attempted to investigate the influence of pile stiffness and cushion stiffness along with their optimal combination on axial force, shear stress, raft settlement and pore pressure generation in sub soil. Further the study was extended to determine the variation of axial force distribution along the depth of piles at center and corner of the raft to understand the soil-structure interaction mechanism.

2. Numerical Modelling

In the present study, the term 'disconnected' is used to represent the separation of piles and raft by the presence of granular cushion layer and the term 'disconnected piled raft (DPR) system' represents the raft and piles system which are disconnected by a layer of cushion.

2.1. Finite Element Modelling

The present three-dimensional finite element analyses of disconnected piled raft (DPR) were done using PLAXIS 3D software. The geometry of the DPR system used in the present study is shown in the Figure 1. All the soil and structural elements are modelled by means of 10-node tetrahedral volume elements. The mesh size was taken as medium in the PLAXIS 3D analysis considering the requirement of accuracy in results as well as the time consumption for completing the numerical simulation after conducting several trial-and-error methods of varying mesh size. The structural elements of raft, cushion and piles were taken as volume elements to determine the variation in maximum deformation, shear stress distribution, pore pressure generation, bending moments, shear force and axial force distribution along with the length of the piles. The frictional elasto-plastic interface elements were also considered in order to incorporate the soil-structure interaction effects.

2.2. Geometric Configuration

The objective of the current study is to analyse the Disconnected Piled Raft (DPR) system of varying cushion stiffness and pile stiffness for a given geometric configuration. The base line model was taken typically for a sixteen-storey floor building on DPR system. The vertical loading imparted by the sixteen-storey building was assumed to be approximately as 300 kPa vertical stress acting on the raft. The area of soil medium is taken as ten times the area of piles being taken for the analysis with depth of soil layer as 23.5m and a bed rock layer of 2m below the soft soil layer. The dimension of the raft is taken as 3.5m*3.5m having thickness of 1.2m.

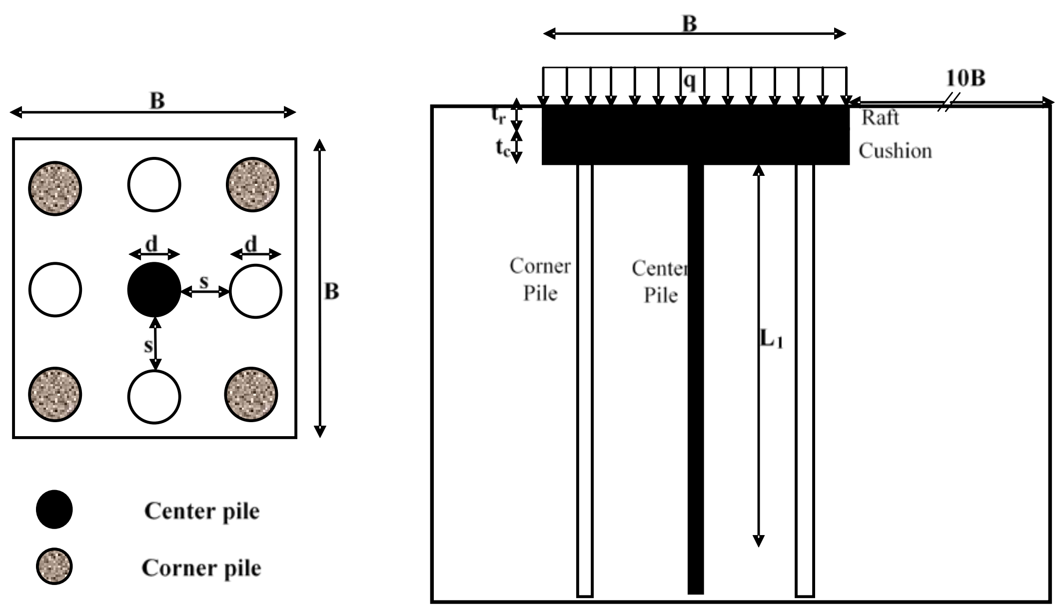

Fig. 1: Schematic Representation of the DPR system model

The baseline model for the 3D finite element analysis was taken from Kamash et al [18] while the dimension of the raft was reduced from 13.5*13.5m to 3.5*3.5m by utilizing the symmetry of the system taking only 9 piles (3*3) of square pattern. This helps in reducing the duration of numerical simulation as well as in eliminating the influence of rigid boundary elements. The cushion layer of thickness 3m is taken with varying stiffnesses having the same dimension as that of raft. The length of the pile is taken as 20m with 0.4m diameter and 1.12m spacing between the piles. A system of 9 piles (3*3) is arranged as square pattern with the assumed diameter and spacing. The schematic representation of the PLAXIS 3D model taken for the analysis is shown in figure 1. It was taken as whole configuration in 3D FEM model in spite of having symmetry and not the quarter symmetric portion.

2.3. Material Properties

The raft and the piles are assumed to be made of reinforced concrete which makes them rigid. The cushion layer is considered to be made of sand and hence relatively flexible as compared to that of piles. This helps in mobilizing the bearing capacity of subsoil and varies the pile load capacity due to alteration in load-transfer mechanism. The sub soil is considered to be soft clay of ridge embankment constructed on deep mixed (DM) columns beside the Sipoo River at Hertsby, Finland as per Kamash et al [18] and is listed in Table 1. The subsoil layer is underlain by bedrock having unit weight of 25 kN/m^3, Poisson's ratio of 0.3 and young's modulus of 100MPa. The bedrock layer is assumed to be linearly elastic in order to simulate its rigid behaviour.

Table 1: Material Properties of Sub soil

Soil model	MCC*
Slope of elastic swelling line, λ	0.22
Slope of the normal consolidation line, κ	0.03
Frictional constant, M	0.98
Specific volume at reference pressure (1 Pa), e_Γ	4.327
Poisson ratio, ν	0.20
Maximum elastic bulk modulus ($\times 10^6$ Pa), K_{max}	15.82
Preconsolidation pressure (kPa), P_c	173.00
Total unit density (kN/m^3), γ	14.8
Permeability ($\times 10^{-12}$ m/sec), k_w	0.06342

2.4. Material Modelling

The behaviour of the structural elements such as raft and piles are similar to reinforced concrete and hence it is modelled as linearly elastic material. The intermediate cushion layer was modelled as non-associated Mohr Coulomb elasto plastic model while the soft soil is defined using Modified Cam Clay model in order to incorporate the real compressibility behaviour of soft clay material. In order to consider the confinement effect and improved stiffness for cushion layer, a linear variation of the elastic modulus along depth, E(z)= E0+ Ez(z) was considered, where z is the vertical depth, E0 is the initial elastic modulus at z=0 and Ez is the spatial gradient. Table 2 shows the required properties of materials being used in the analyses of disconnected piled raft (DPR) system.

Table 2: Material properties of Disconnected Composite Piled Raft system

Properties	Raft	Cushion	Pile
γ (kN/m^3)	24	20	22
E (MPa)	$3*10^4$	10, 60, 120, 240	200, 2000, 20000
ν	0.2	0.3	0.21
c' (kPa)	-	0	-
Φ' (degree)	-	30	-
Ψ (degree)	-	1	-
R_{int}	1	1	0.8
Material model	Linear elastic	Mohr Coulomb	Linear Elastic

The major modelling parameters include: unit weight (γ), elastic modulus (E), Poisson's ratio (ν), shear strength parameters such as effective cohesion (c'), effective angle of internal friction (Φ'), dilatancy angle (Ψ), and the suitable constitutive material models.

3. Parametric Study

The current parametric study considered the variation in parameters such as cushion stiffness and pile stiffness under uniform vertical pressure. Table 3 shows the parameters considered in the study to understand the behaviour of disconnected piled raft (DPR) system during loading.

Table 3: Parameters and their values considered in the present study

Parameters	**Values**
Young's modulus of Cushion, E (MPa)	10, 60, 120, 240
Young's modulus of Pile, E (MPa)	200, 2000, 20000
Vertical stress from superstructure, (kPa)	300

The variation in the performance of the disconnected piled raft (DPR) system with varying cushion stiffness were compared with the DPR system of varying pile stiffness. The various stages used in the 3D FEM analysis are: Initial phase of K0 condition, Excavation for Raft and Cushion, Installation of piles, Placing of granular cushion layer, Placement of raft and application of uniform vertical stress (plastic loading). The preliminary results with base parameters were validated with the results of Kamash et al [18] and further the parametric study was extended by varying the above-mentioned variations.

4. Results and Discussions

4.1. Variation in maximum deformation of raft

The variation in maximum deformation/settlement at the centre of the raft of DPR system due to change in cushion and pile stiffness is shown in figure 2. When the stiffness of the pile was equivalent to the stiffness of the raft, the settlement of the raft was lowest irrespective of cushion stiffness. On the other hand, the settlement was higher for piles having stiffness much lesser than that of raft. The increase in cushion stiffness reduced the deformation of raft even at lower stiffness of pile. The increment of cushion stiffness did not show considerable reduction in the raft settlement beyond 60MPa. The settlement was almost same at larger cushion stiffness of greater than 60MPa.

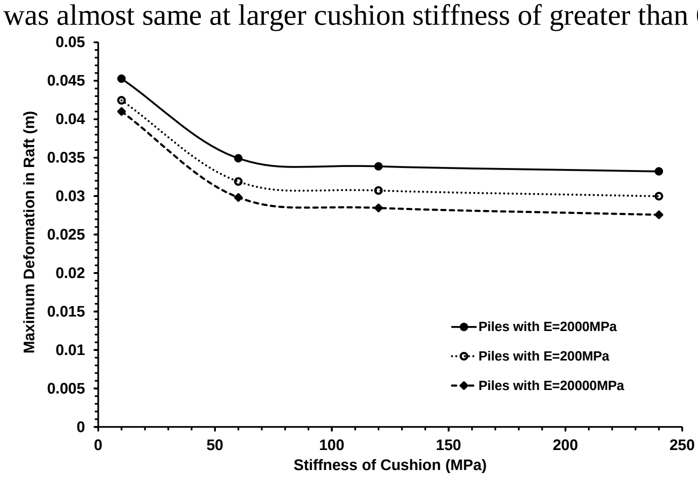

Figure 2: Variation in maximum deformation/settlement at the centre of the raft of DPR system due to change in cushion and pile stiffness

4.2. Maximum shear stress in Cushion layer

The variation in maximum shear stress in the cushion layer of DPR system due to change in cushion and pile stiffness stiffness is shown in figure 3. When the stiffness of the pile was the highest (20000MPa), the shear stress developed in the the cushion was also huge due to the high rigidity which in turn imparted maximum shear stress in the cushion. When the the pile stiffness was reduced to 2000MPa, the shear stress created in the cushion was lowest which could be due to the best best compatibility created between relatively flexible pile and cushion material. However, when the pile stiffness was reduced further (200MPa), which became comparable with that of the cushion, there was further increment of shear stress in the cushion due to low capability of pile in terms of rigidity to alter the load-transfer mechanism between pile and sub-soil. Hence, the stiffness of pile should be selected in such a way that it should be relatively rigid as compared to cushion so that the load transfer mechanism would be distributed from raft to subsoil through cushion and pile. Otherwise, it would lead to the improper accumulation of stress and deformation in cushion. In addition to that, it was observed that the role of cushion stiffness became least when it was greater than 60 MPa in affecting the shear stress distribution when the pile is relatively less rigid (2000MPa).

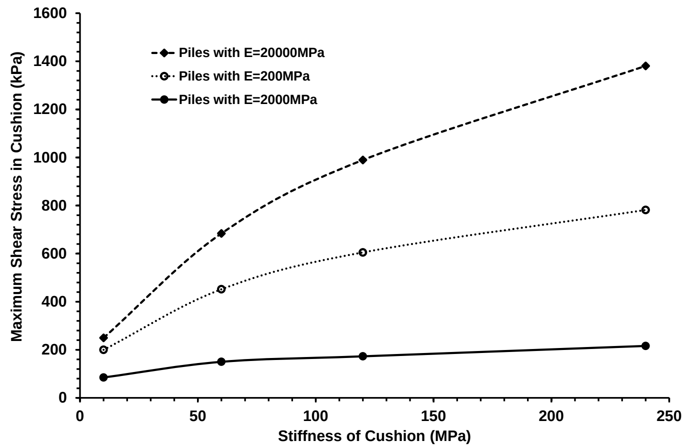

Figure 3: Variation in maximum shear stress in the cushion layer of DPR system due to change in cushion and pile stiffness

4.3. Variation in maximum pore pressure generation in soft soil

The variation in maximum pore pressure generation in the soft soil layer of DPR system due to change in cushion and pile stiffness is shown in figure 4.

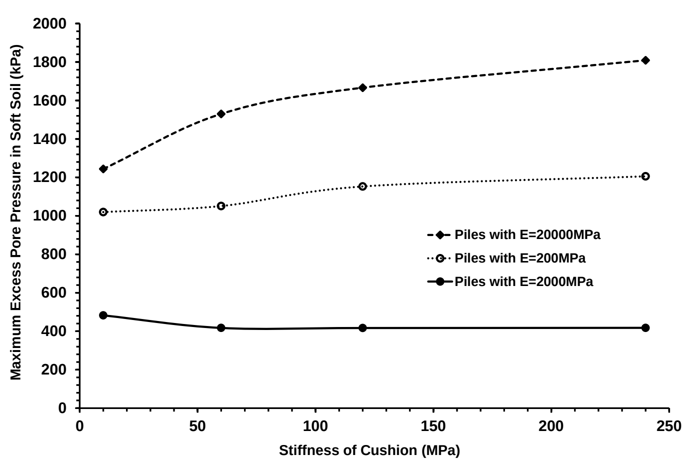

Figure 4: Variation in maximum pore pressure generation in the soft soil layer of DPR system due to change in cushion and pile stiffness

As observed in the maximum shear stress development, the pore pressure generation in subsoil was also maximum the pile stiffness is very high (20000MPa). The pile might not undergo larger deformation under the load transferred cushion due to high rigidity which in turn created major stress in subsoil. This resulted in the development of maximum pressure in sub soil along with maximum shear stress in cushion. On the other hand, when the pile stiffness was which was higher than that of cushion, the excess pore pressure developed in the subsoil was also very least. This could be further due to the compatibility between pile and cushion in order to evenly alter the load-transfer mechanism.

4.4. Variation in maximum bending moment of piles

The variation in maximum bending moment developed in the system of piles considered in the DPR system due to change in cushion and pile stiffness is shown in figure 5. The changes in the maximum bending moment of piles were compared among corner and centre piles also to understand the distribution of loads. The center piles were subjected to very lower bending moment as compared to that of corner piles. This would be due to the even sharing/distribution of loads in both dimensions to the nearby piles whereas the corner piles were subjected to stress concentrations that led to larger bending moment. The results were again in accordance with that of shear stress and pore pressure distribution. The piles of stiffness (2000MPa) underwent the least bending moment in case of both corner and center piles as compared to that of highly rigid (20000MPa) and least rigid (200MPa) piles. This would further be justified that the compatibility between cushion and pile worked well only when the pile stiffness is slightly higher than that of cushion. And also, the variation of cushion stiffness increased the developed maximum bending moment for highly rigid (20000MPa) and least rigid (200MPa) piles whereas for the piles of intermediate stiffness (2000MPa), the variation in cushion stiffness did not affect the bending moment beyond 60MPa.

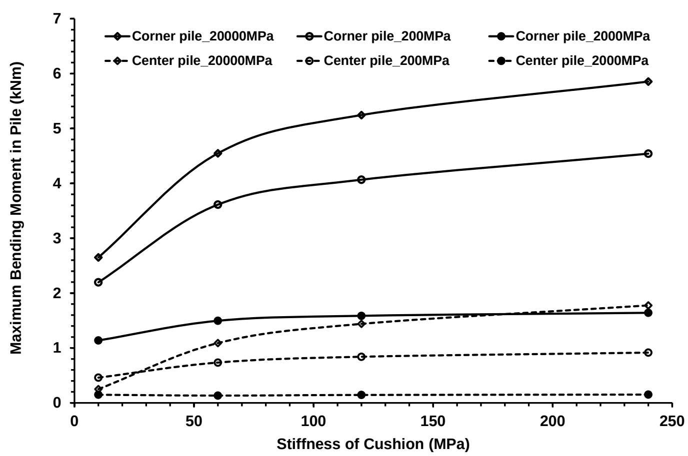

Figure 5: Variation in maximum bending moment in the system of piles in the DPR system due to change in cushion and pile stiffness

4.5. Variation in maximum axial force of piles

The variation in maximum axial force developed in the system of piles considered in the DPR system due to change in cushion and pile stiffness is shown in figure 6. The changes in the maximum axial force of piles were compared among corner and centre piles also to understand the distribution of loads. Similar to bending moment, axial forces were also higher for corner piles as compared to center piles. Also, the effect of cushion stiffness was almost negligible in all the cases considered. It was observed a higher axial force for piles with larger stiffness as expected due to the tendency of attracting greater loads on piles and very least distribution onto subsoil. In accordance with the above results, axial force was also minimum for piles of intermediate stiffness (2000MPa) in both center and corner piles. The axial force was increased 5 times when the pile stiffness was increased to 20000MPa and similarly, it was 3 times higher when the stiffness was reduced to 200MPa. The highly compatible pile stiffness of 2000MPa with varying cushion stiffness showed the least development of maximum axial force in piles due to even distribution of loads among raft, pile and subsoil.

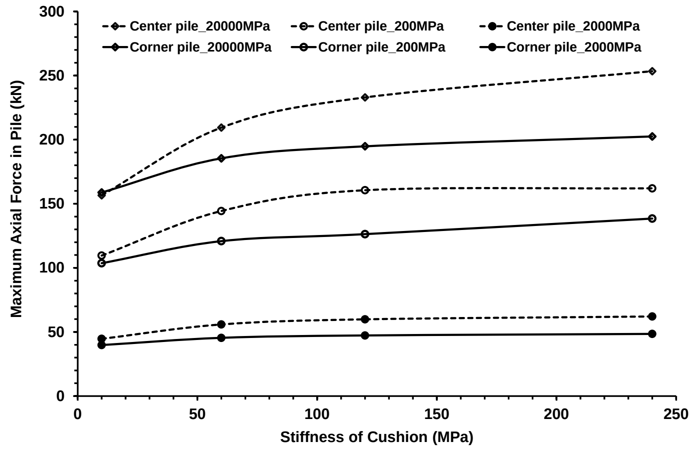

Figure 6: Variation in maximum axial force in the system of piles in the DPR system due to change in cushion and pile stiffness

4.6. Variation in maximum shear force of piles

The variation in maximum shear force developed in the system of piles considered in the DPR system due to change in cushion and pile stiffness is shown in figure 7. The results of maximum shear force developed was also in accordance with the maximum axial force development in piles of varying stiffness. The influence of cushion stiffness was observed to be higher only from 10 to 60 MPa and became negligible at larger stiffness of cushion on maximum shear force. Higher the stiffness of pile, larger was the shear force development and it was further greater for corner piles as compared to that of center piles.

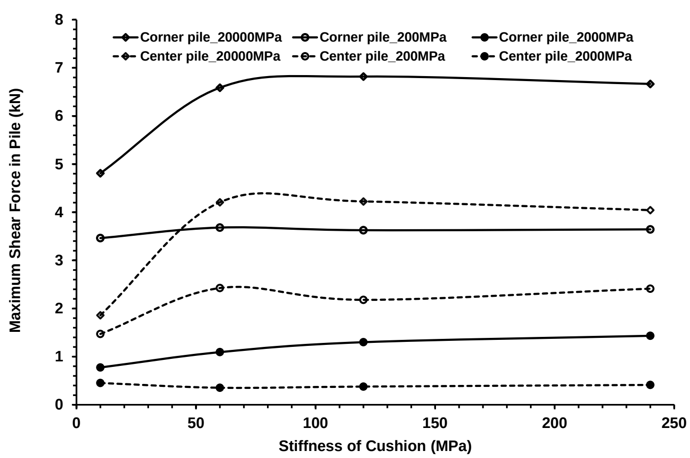

Figure 7: Variation in maximum shear force in the system of piles in the DPR system due to change in cushion and pile stiffness

4.7. Variation in Axial force distribution of piles

As there was no substantial change in the performance of DPR system with increased cushion stiffness, it was taken as 60MPa and the axial force distribution along the length of piles were analysed. The variation in axial force distribution along the length of the center piles considered in the DPR system due to change in pile stiffness is shown in figure 8. The maximum axial force occurred at a certain depth below the pile head in all three cases due to the presence of cushion. The distribution showed that the piles with low stiffness was effective for shorter length as the axial force distribution was uniform over larger depth with minimal load transfer to the pile and maximum load transfer to the weak subsoil. When the stiffness of the pile increased to highest value, the axial force distribution was varying over large depth with greatest load transfer to the pile and negligible load transfer to the weak subsoil. This did not serve the purpose of utilizing the cushion layer for optimal distribution of load between the pile and subsoil. The pile with intermediate stiffness showed a gradual axial force distribution with considerable load transfer to the pile as well as to the subsoil and also, the full pile length was utilized in load transfer mechanism.

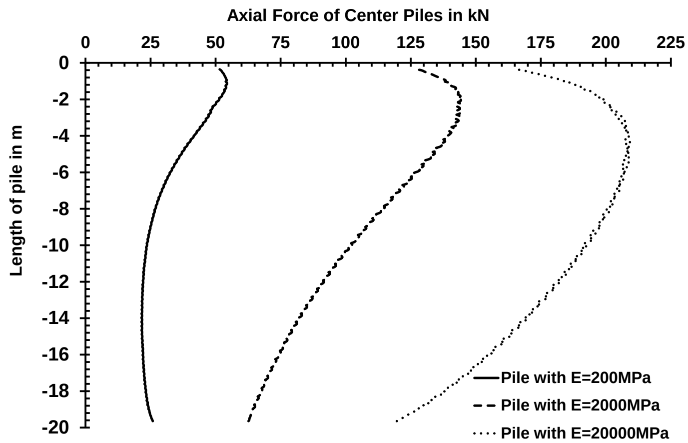

Figure 8: Variation in axial force distribution along the length of piles in the DPR system due to change in pile stiffness

5. Conclusion

The present study on performance evaluation of disconnected piled raft system by varying cushion stiffness and pile stiffness showed the following major conclusions.

- The variation in cushion stiffness did not impose any substantial improvement in the performance of DPR system beyond 60MPa
- The influence of pile stiffness on behavior of DPR system was large in terms of deformation and maximum shear stress of raft, axial and shear force distribution in piles, pore pressure generation in subsoil, etc.
- The piles with intermediate stiffness (2000MPa) showed the best performance unlike the highly stiffened piles
- The selection of pile stiffness should be decided along with the consideration of raft and cushion stiffness such that it helps in achieving the desirable performance of DPR system through appropriate load-transfer mechanism.

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