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Load Sharing Mechanism of Piled Raft System under Vertical and Lateral Loading

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Abstract. Piled raft foundations are now the most desirable foundation system in comparison to the alternative foundation system because of its load sharing mechanism, where the total structural load is partly carried by the piles and partly by the raft. However, due to the complication involved in computing the load sharing mechanism, the research in this field is lagging behind. The complex soil structure interactions which are dependent on various components such as geometry of the pile and raft, sub-soil condition, pile spacing, normalized settlement etc. may raise the complex load sharing mechanism of PRF. The main intention of this paper is to investigate the load sharing mechanism of PRF subjected to the vertical and lateral load, and to develop a prediction model for estimating the load sharing ratio (LSR). Three dimensional finite element analysis through ABAQUS 3D software are accomplished to develop a prediction model for assessing the LSR. The results of vertical load response reveals that the vertical LSR continuously decreases with the increase in the normalized settlement whereas, in the lateral loading case, the lateral LSR continues to increase with the increment in the normalized lateral displacement. The results of numerical analysis also reveal that the LSR is a function of normalized settlement. Therefore, a prediction model is established for estimating the load sharing ratio w.r.t the normalized settlement and this prediction model would be helpful to improve the conventional design of PRF.

Keywords: Piled raft, Finite element analysis, Load sharing ratio, Normalized settlement.

1 Introduction

The design of PRF is based on the concept that the total structural load is shared by piles and raft, and piles below the raft act as settlement reducers. This innovative approach was proposed by several researchers [1-7]. The basic concept of load sharing behaviour among the piled raft components is that the total imposed load from the superstructure is partially carried by raft and partly by the piles in the piled raft. This load sharing behaviour allows to develop an optimized design technique of PRF and significantly minimizes the number of settlement reducing piles as compared to the conventional design approach. Various researchers observed a significant impact of number of piles and pile spacing to pile diameter ratio on load sharing mechanism [8-10]. Horikoshi et al. [11] performed an experimental work on PRF subjected to static vertical and horizontal loading and observed that at initial horizontal displacement, the raft share (i.e., the proportion of horizontal load shared by the raft) is higher than the pile share (i.e., the proportion of horizontal load shared by the pile) and as the horizontal displacement increases the raft share is decreases.

From the previous researches it can be comprehended that the load sharing mechanism is a complex phenomenon and it is dependent on various parameter such as geometry of the pile and raft, sub-soil condition, pile spacing etc. and the widespread research works on the behaviour PRF under vertical loading enhances the performance of the piled raft foundation. However, this type of foundation has also provision to support the lateral loads. But the research work related to the piled raft under lateral loading is very limited. As considerably high amount of lateral loads are generated in coastline and offshore areas, it is now essential to study performance of PRF under vertical and lateral loading condition. Therefore, the major objective of this study is to assess the load sharing mechanism of PRF subjected to vertical and lateral loading condition and to study the impact of relative density of sand on the load sharing mechanism.

2 Numerical Modelling

To study the load sharing mechanism of the piled raft under vertical and lateral loading, the 3-D finite element analysis is executed with the help of finite element based software package ABAQUS. Full 3-D geometric models can be represented for the analysis of load sharing mechanism of the piled raft. However, considering the advantage of taking symmetry, the half portion of the full 3-D model are utilized to assess the load sharing mechanism of the piled raft under vertical and lateral loading and thus the computational time is significantly reduced. Fig. 1 represents the half portion of the full 3-D model and the general model layout. Total width of the soil continuum is selected as $6B_R$, where B_R is the width of the raft and the thickness of the soil continuum is considered as $(3L + B_R/3)$, where L is the length of pile. In case of mesh refinement, the raft and soil continuum is considered as hexahedral brick element (C3D20R) and pile is represented by triangular prism element. For the simulation of numerical model of soil-piled raft system various assumptions are made such as: (a) soil medium is considered as single phase medium in place of multiphase medium, (b) the material behaviour of piles and raft are assumed as linear elastic, (c) the pile and raft connection is considered as a rigid connection with no slip at interface, and (d) pore pressure change is neglected as relatively quick load is applied on the piled raft system [12]. The interaction among the soil, piles and raft interfaces are modelled through master-slave concept. The non-linear stress-strain characteristic of soil is simulated by using modified Drucker-Prager (D-P) cap plasticity model. The expression of Drucker-Prager yield surface is given as

$$F = \alpha J_1 + \sqrt{J_{2d}} - k \tag{1}$$

where, J_1 is the 1st invariant of stress tensor, J_{2d} is the 2nd invariant of deviator stress tensor and α and k is the material constants. A further detail of modified D-P model is found in Deb and Pal [13]. The soil and piled raft properties used in the FE modelling are presented in Table 1.

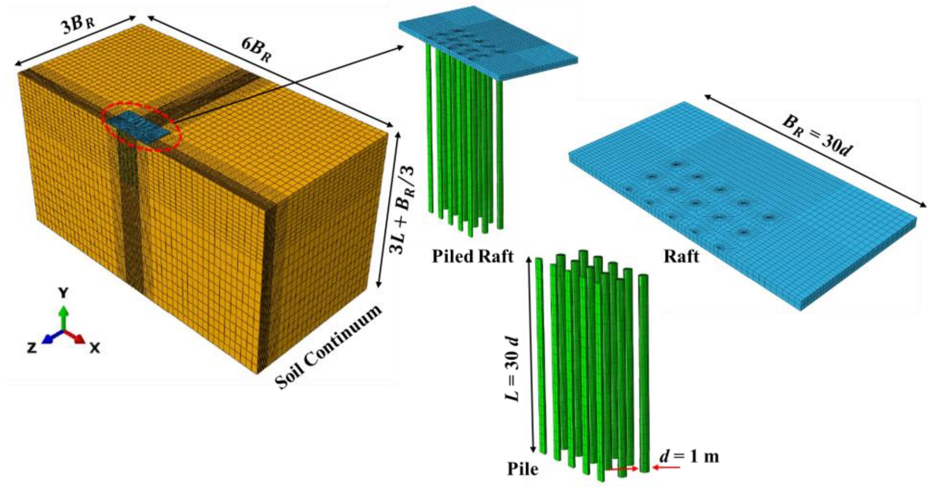

Fig.1. 3-D model layout of soil continuum and piled raft components

Table 1. Material properties used in FE analysis

Materials	RD (%)	*e*	γ (kN/m^3)	*E* (MPa)	Ø (in degree)	μ	Model
Sand	30	0.7	14.6	27	31	0.32	D-P
	50	0.64	15.73	33	34	0.3	D-P
	80	0.55	16.81	40	39	0.27	D-P
Pile	-	-	25	30,000	-	0.2	L.E
Raft	-	-	35	33,000	-	0.2	L.E

Note: RD = Relative density, *e* = Void ratio, γ = Unit weight, *E* = Modulus of elasticity, Ø = Internal friction angle, μ = Poisson's ratio, D-P = Drucker-Prager and L.E = Linear elastic

According to Reul and Randolph [6], the mesh refinement can influence the results of the finite element analysis and therefore to account the influence of mesh refinement, relatively finer meshes are provided in the loading area and moderately coarser meshes are incorporated at the other places. Regarding the boundary for vertical load analysis, all the bottom nodes are restricted against any kind of translation and rotation, and for corner nodes *x* and *z* translation is restricted. The boundary condition regarding the lateral load analysis, the bottom boundary is also restricted against any kind of translation and rotation, however, the soil surface is allowed to move in all three directions. For all the nodes of *y-z* plane and *x-y* plane are constrained against *x* and *z* direction, respectively. Three different steps are involved to simulate the loading condition: in initial step geostatic stress is applied to the soil continuum before the installation of piled raft to simulate the soil continuum in equilibrium state, in second step the self-weight of the model piled raft is provided and in final step vertical/lateral load is applied in the raft.

3 Model Configuration and Loading Sequence

To understand the load sharing mechanism of piled raft components, 5×5 pile group configuration is used and to assess the influence of relative density of sandy soil, three different relative densities (*RD*) such as 30%, 50% and 80% are incorporated in this study, i.e., loose sand, medium dense sand and dense sand are used to simulate the soil continuum. Three different pile spacing to pile diameter (*s/d*) ratio such as 3, 5 and 7 are also introduced in this study to observe the impact of pile spacing on load sharing mechanism. In this study, two types of loading condition (such as vertical and lateral loading system) are considered. For vertical loading, the maximum vertical settlement is restricted to a settlement corresponding to 10% of the raft width and in case of lateral loading the maximum lateral displacement is limited to the displacement corresponding to 10% of pile diameter [13, 14].

4 Validation of Numerical Analysis

To check the accuracy of the numerical analysis, the results of numerical analysis is compared with another FE analysis performed by Park et al. [15]. A similar FE model as made by Park et al. [15] is developed in this study for comparison purpose. In this study, a square raft of 9 m width and 4×4 pile configuration with 15 m long pile and 0.6 m pile diameter is used. Sand with 74% relative density is considered for foundation soil. The foundation material and soil properties are taken from Park et al. [15]. The comparison of load-settlement curve for reference FE analysis [15] and the FE modeling performed in this study is shown in Fig. 2. It is seen from the figure that the results developed in FE analysis exhibits a good agreement with the reference FE analysis.

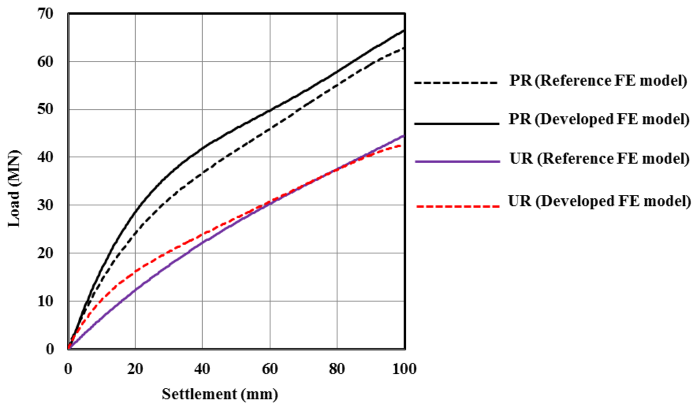

Fig.2. Validation of numerical analysis

5 Results and Analysis

5.1 Vertical load-settlement response of PRF

The vertical load (Q) obtained in the numerical analysis is normalized by dividing the maximum vertical load (Q_{max}) and the vertical settlement (w) is normalized by dividing the raft width (B_R). The normalized vertical settlement is symbolized as (∂_N). The normalized vertical load-settlement responses for different relative densities are plotted in Fig. 3. From the figure, it is observed that the normalized vertical load changes non-linearly with the normalized settlement and with the increase of relative density the normalized vertical load gradually increases. Increase of relative density indicates the increase of denseness of the sand and due to this, the vertical load capacity of PRF increases. When relative density of the sand increases from 30% to 50%, the vertical load capacity is improved by 17-19%, whereas the vertical load capacity is increased by 38-41% as the relative density of sand changes from 30% to 80%. After evaluating the vertical load-settlement profiles at different spacing, it is also observed that the normalized vertical load is enhanced due to the increase of the pile spacing. As the spacing between the piles increases, the overlapping stress zone among the pile group is considerably reduced and due to this the mobilization of pile-soil interface takes place at higher load level. Hence, the increase in spacing may enhance the piled raft vertical load capacity.

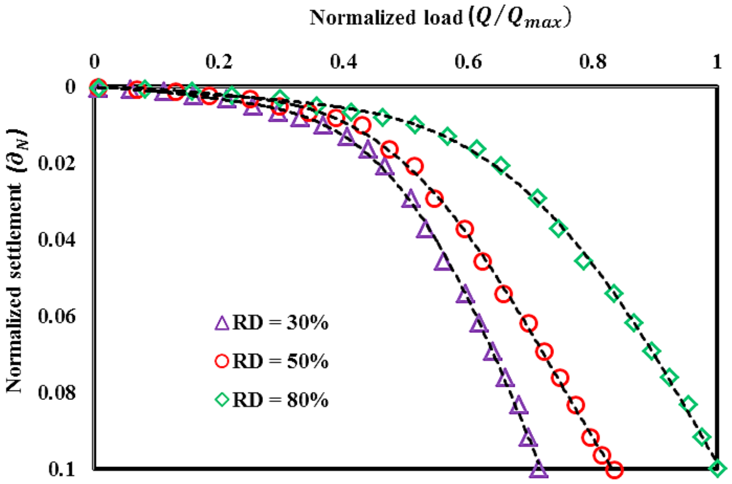

Fig.3. Vertical load-settlement response for s/d = 7

5.2 Vertical Load Sharing Ratio (*V-LSR*)

Load sharing ratio for vertically loaded piled raft can be defined as the ratio of vertical load taken by the pile to the total vertical load taken by the piled raft system. Therefore, vertical load sharing ratio (*V-LSR*) can be expressed as

$$V\text{-}LSR = Q_P/Q_{PR} \quad (2)$$

where, Q_P and Q_{PR} are the vertical load capacities of piles and piled raft system, respectively. To pretend the behaviour of *V-LSR* with respect to normalized settlement, all the results of *V-LSR* obtained from numerical analysis are summarized in a single graph (Fig. 4) and a power law is selected to idealized the general expression of *V-LSR* w.r.t. normalized settlement. This power law can be expressed as

$$V - LSR = 0.31\,\partial_N^{-0.13} \quad (3)$$

From the Fig. 4, it is observed that the vertical load sharing response follow a non-linear path w.r.t the normalized settlement and for all the cases, the value of *V-LSR* reduces gradually with the increase of vertical settlement. This indicate that at initial normalized settlement, the major portion of vertical load is taken by the piles.

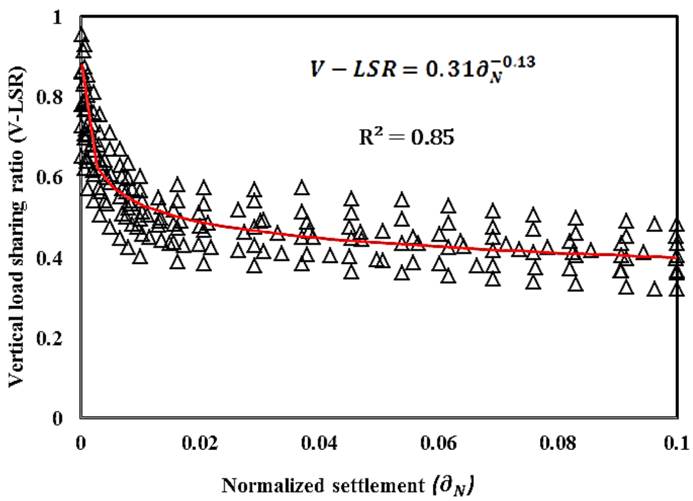

Fig.4. Generalized profile of vertical load sharing ratio

To observe the influence of relative density of sand *V-LSR* vs. normalized settlement profile is shown in Fig. 5. The figure (Fig. 5) reveals that the change in relative density of sand may have signaficant impact on *V-LSR*. As the relative density of sand increases from 30% to 50%, the value of *V-LSR* is improved by 10-12%, whereas the value of *V-LSR* is enhanced by 20-23% as the relative density changes from 30% to 80%. That means, the pile can share higher portion of vertical load in case of dense sand. The effect of spacing on *V-LSR* for defferent relative densities and vertical settlement is shown in Fig. 6. The figure indicate that at 2% settlement, the pile share is almost 38 to 57% of total imposed load, whereas at 10% settlement, pile share ranges from 32 to 48%. This is because, the higher raft-soil contact pressure is developed at larger settlement level and due to this, the raft share continuously increases at higher settlement. As the pile spacing ranges from 3 to 5, *V-LSR* is increased by 12 to 15%, however the value of pile share is improved by 22-25%, as the pile spacing increases from 3 to 7. This is due to the fact that as the pile spacing increases the pile-soil-pile interaction is gradually reduced and hence the pile share is increased.

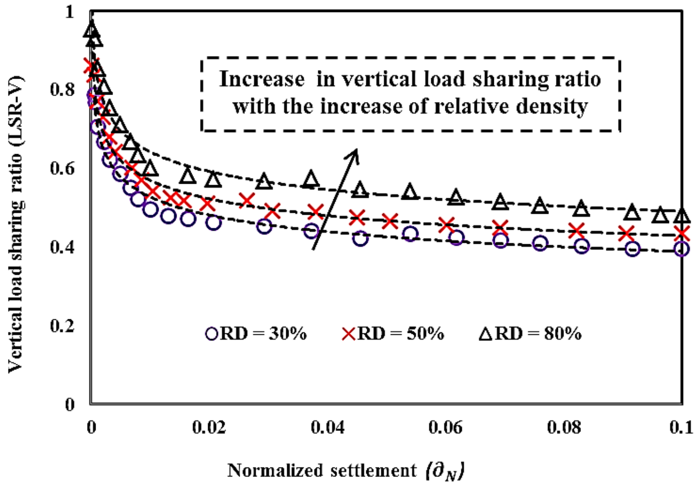

Fig.5. Variation *of V-LSR* w.r.t normalized settlement for different relative densities

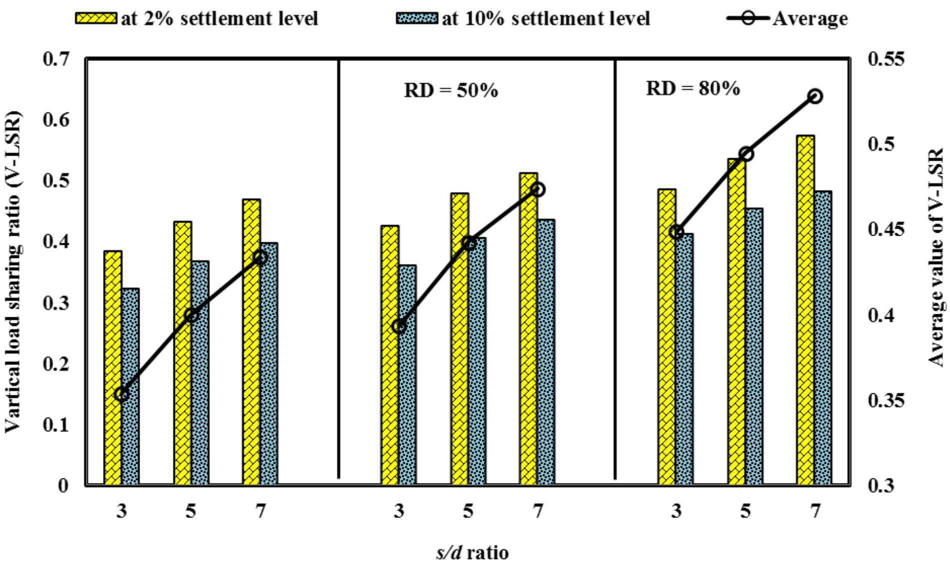

Fig.6. Variation of *V-LSR* with *s/d* ratio for different settlement level and relative densities

5.3 Lateral Response of PRF

The lateral load (L) obtained in the numerical analysis is normalized by dividing the maximum lateral load (L_{max}) and normalized lateral displacement (Δ_N) is achieved through dividing the each lateral displacement (y) by pile diameter (d). The normalized lateral load vs. displacement profiles for different relative densities are represented in Fig. 7. The figure indicates that the lateral load non-linearly varies with the lateral displacement and the lateral load capacity of PRF is enhanced by 33-35% as the relative density of the sand increases from 30% to 80%. Fig. 7 also reveals that the lateral load capacity increases continuously with the increase of lateral displacement level. After assessing the lateral response of PRF for different spacing, it is seen that the influence of pile spacing on the lateral response of PRF is significant and with the increase of pile spacing, the lateral load capacity is boosted up to a noticeable amount. The lateral load capacity is improved by 19-23% as the pile spacing increases from 3 to 7.

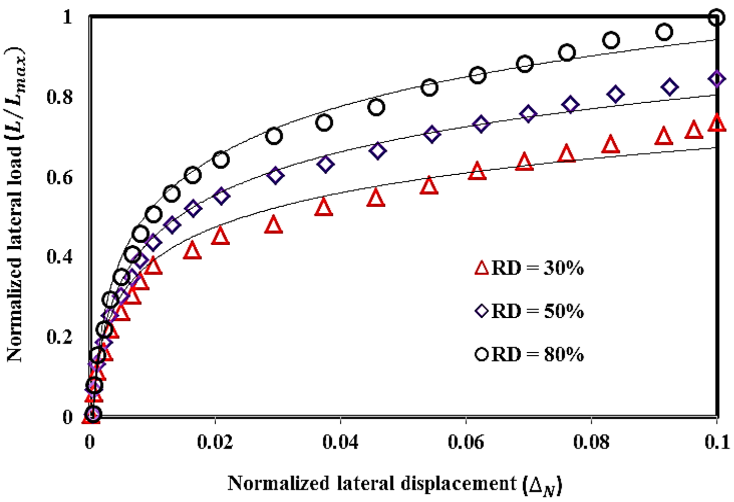

Fig.7. Lateral response of PRF for different relative densities

5.4 Lateral Load Sharing Ratio (*L-LSR*)

The lateral load sharing ratio (*L-LSR*) is a quite complex phenomenon in comparison with individual raft and pile. *L-LSR* can be obtained by using the expression

$$L\text{-}LSR = L_P/L_{PR} \tag{4}$$

where, L_P and L_{PR} are the lateral load capacity of piles and piled raft system, respectively. To predict the non-linear response of lateral load sharing ratio, a logarithmic law is idealized for formulating the generalize expression of *L-LSR* w.r.t normalized lateral displacement (Δ_N). The logarithmic law can be expressed as

$$L - LSR = 0.113 \ln \Delta_N + 0.92 \tag{5}$$

All the results obtained from the numerical analysis for *L-LSR* under lateral loading condition are collectively joined and represented in Fig. 8. The figure shows that the value of *L-LSR* continuously upsurges as the lateral displacement increases. For all the configuration, the value of *L-LSR* ranges from 56 to 75% at a lateral displacement of $0.1\Delta_N$.

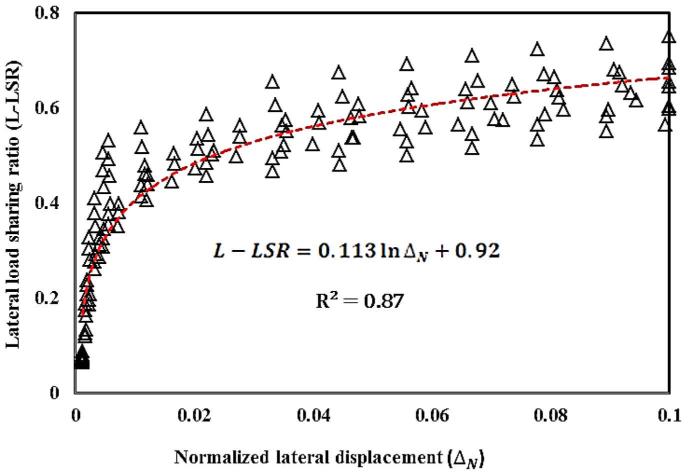

Fig.8. Generalized lateral load sharing response

The variation of *L-LSR* with normalized lateral displacement for different relative densities is shown in Fig. 9. From the figure, it is clear that the lateral load sharing ratio is enriched due to the increase of relative density of sand. As the relative density of sand rises from 30% to 80%, the sand provide higher resistance at the pile–soil interface in the direction opposite to the applied lateral load and due to this the pile lateral share is continuously increased with the increase of lateral displacement. When the relative density of sand increases from 30% to 50%, the value of *L-LSR* is boosted by 8-10%, whereas the value of *L-LSR* is improved by 16-19% as the relative density varies from 30% to 80%. The influence of pile spacing on *L-LSR* for different relative densities and different lateral displacement level is represented in Fig. 10. It can be perceived from the figure that at initial lateral displacement level the major portion of lateral load is sustained by the raft and this raft share is due to the action of frictional resistance between the raft and sand. With the progress of lateral displacement, the raft-soil interface friction gradually decreases and the lateral load is gradually transferred into the piles below the raft. Therefore, the value of *L-LSR* increases continuously with the increment of lateral displacement. The value of *L-LSR* is enhanced by 23-28% when the normalized lateral displacement rises from 2 to 10%. The Fig. 10 also reveals that as the pile spacing changes from 3 to 5, *L-LSR* is increased by 5 to 8%, and on the other hand the value of L-LSR is improved by 12-16%

as the pile spacing increases from 3 to 7. This indicates that the impact of spacing is more predominant in the case of vertical load sharing mechanism.

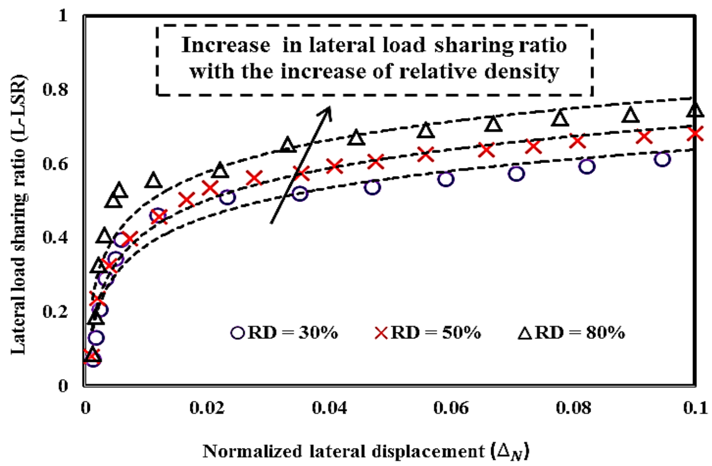

Fig.9. Variation of *L-LSR* with lateral displacement for different relative densities

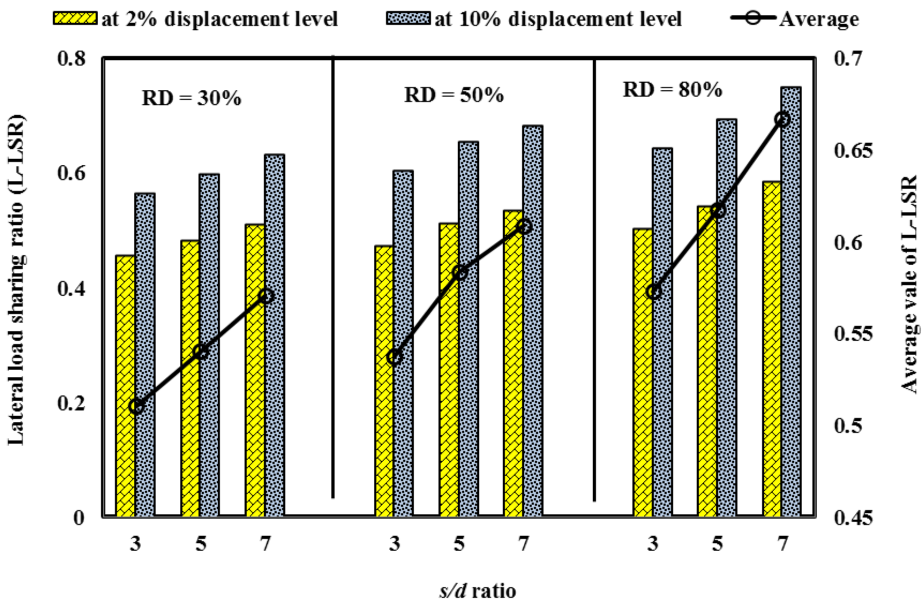

Fig.10. Variation of *L-LSR* with s/d ratio for different displacement leel and relative densities

6 Conclusions

The present study mainly deals with the vertical and lateral load sharing mechanism of PRF. A series of numerical analysis has been performed to comprehend the load sharing mechanism of PFR subjected to vertical and lateral loading. From several numerical analyses, following conclusions can be drawn.

1. From the vertical load-settlement response, it can be concluded that with the increment of vertical settlement the vertical load capacity increases nonlinearly, and with the increase of relative density of sand the normalized vertical load is gradually increased. The vertical load capacity is increased by about 38-41% as the relative density of sand changes from 30% to 80%.
2. The lateral response of PRF reveals that lateral load non-linearly varies with the lateral displacement and the lateral load capacity of PRF is enhanced by 33-35% as the relative density of the sand increases from 30% to 80%.
3. Vertical load sharing ratio (*V-LSR*) is directly related to the normalized settlement and this *V-LSR* can be associated with normalized settlement by power law. *V-LSR* reduces gradually with the increase of vertical settlement, whereas, the lateral load sharing ratio (*L-LSR*) is logarithmically correlated with the normalized lateral displacement and showing a gradual progress with the normalized lateral displacement.
4. The value of *V-LSR* is improved by 20-23% as the relative density of sand varies from 30% to 80%, whereas, the value of *L-LSR* is enhanced by 16-19% as the relative density changes from 30% to 80%.
5. As the pile spacing varies from 3 to 5, *V-LSR* is increased by 12 to 15%, and the value of *V-LSR* is boosted by 22-25% as the pile spacing increases from 3 to 7. In case of lateral response, as the pile spacing changes from 3 to 5, *L-LSR* is increased by 5 to 8% and the value of *L-LSR* is improved by 12-16% as the pile spacing changes from 3 to 7. This indicates that the impact of spacing is more predominant in the case of vertical load sharing mechanism.

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