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Distribution and Sharing of Load for Partially Strengthened Floating Granular Piled Raft

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Abstract . Ground stabilization using granular piles (GPs) or aggregate piers or stone column is most suitable method to upgrade soft soils for the foundation of embankments and structures. Ground improved with the granular pile partially strengthening from the top increases the bearing strength, stability of natural slopes, degree of consolidation and reduces the final settlement. Raft foundations are often preferred for high rise building constructed on soft soil for distribution of load on larger area. Partially strengthened piles under the raft are designed to decreases the settlements and differential settlement of soil. Raft, granular piles and soil are three components of partially strengthened piled-raft system through which the loads transfer to the subsoil. The present work deals with the study of partially strengthened floating granular pile or stone column with rigid raft depends on an elastic continuum approach. The parametric study has been worked out by considering the compatibility of settlement along the interface of partially strengthened granular pile & soil and raft & soil. Present study deals with the mathematical study of sharing of load between raft and granular pile with variation of relative strengthening of GP, relative size of raft, relative length of pile and strengthening parameters such as strengthening factor and relative length of strengthening from the top. The overall response of a partially strengthening granular pile with the rigid raft on top is evaluated in terms of standardize GP-soil interface shear stresses, fractional base load, fractional raft load, fractional pile load.

Keywords: Relative strengthening of granular pile, Fractional pile load, Fractional base load, Fractional raft load, Relative length of strengthening, Strengthening factor.

1 Introduction

Seeing the need of progressive modern construction, it has become necessary now that we have to do even bigger construction on loose coils. So now it is necessary to stabilize such soft soil areas and make them capable of construction. And one such useful way of foundation for construction on such sites is the Piled Raft Foundation. Piled Raft Foundation System is an appropriate foundation technique for construction of large structures like High Rise Buildings, Bridged, and Large Industrial Buildings. Conventional piled raft systems consist of piles of concrete, steel and timber, these piles are replaced with granular piles in this study so that make this foundation system economical. Granular piled raft can be used to construct foundations for larger area such as highways, railways embankment etc. using locally available granular material. Bulging failure is the most common failure criterion among the possible failure mechanisms – punching failure, shear failure and bulging failure. Granular piles generally fail in bulging in upper portion, overcome this problem of bulging in the present study the upper portion of granular pile is strengthen. Strengthening of granular pile is done by replacing the material of upper portion with the better strength and stiffness material.

The present study deals with the analysis of partially strengthened floating granular piled raft based on the elastic continuum approach. An attempt has been made to analyze the soil & partially strengthened GP interactions and raft & soil interaction concerning compute interfacial stresses of pile and raft, and eventually, the load distribution among the base of pile, granular pile and raft. Partial strengthening basically means that the material of the GP is restored partially in the top region of granular pile by the material, having better mechanical properties i.e. higher deformation modulus e.g. geo-grids, strengthened deep cement mixing, etc. Mathematical formulation and its numerical solution are developed to incorporate. The mathematical study of sharing of load between raft and granular pile with variation of relative/comparative strengthening of GP, comparative size of raft, comparative length of pile and strengthening parameters such as strengthening factor and comparative length of strengthening from the top. The overall response of a partially strengthening granular pile with the rigid raft on top is evaluated in terms of standardize GP-soil interface shear stresses, fractional base load, fractional raft load, fractional pile load.

Balaam and Booker (1985) and Pulko et al. (2011) were presented analytical solutions which provide the settlement of a unit cell and its evolution with time was presented by Castro and Sagaseta (2009). Watts et al. (2000) suggested that at low or moderate loading conditions stone columns have also been employed underneath small isolated footing or strip foundation. Influence of geometric and material properties, such as column length, friction angle, diameter, spacing and stiffness on the behavior of groups of floating stone columns using 2D and 3D finite element analyses have investigated by Killeen (2012) and Ng (2013). The effect of the column arrangement, number of column and length of stone column on the response of group of stone column under rigid footing has been numerically investigated by Castro J (2014).

2 Problem Definition

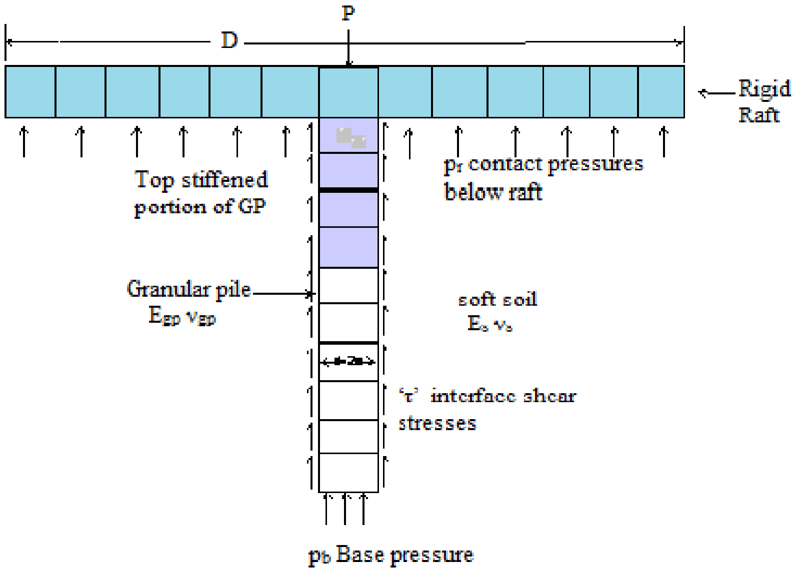

Fig. 1. Force and stresses on a partially strengthened Piled Raft Foundation

Partially strengthened floating granular piled raft foundation carrying a direct load P. The length of GP is L with radius 'a', and diameter, d_p=2a, is depicted in Fig. 1. The soil is characterized by it's the modulus of deformation, E_s, and Poisson's ratio, υ_s. The granular pile is compressible with the modulus of deformation, E_{gp} and Poisson's ratio, ν_{gp}. The comparative strengthening of GP is defined as $K_p= E_{gp}/E_s$, the ratio of deformation moduli of the GP to that of the soil. In this study, it is assumed that the top portion of length $L_s=\lambda L$ has been strengthened where λ is constant for comparative length of strengthening (RLS) of GP. The modulus of the deformation of the partially strengthened portion is E_{stgp}. Comparative strengthening (K_{stp}) of the partially strengthened portion of granular pile is μ times that of the unstrengthened portion, i.e., $K_{stp} = \mu K_p$, where μ is strengthening factor. It is assumed that the Poisson ratio ν_{gp} is the same throughout the GP.

To evaluate the vertical displacements due to point loads acting inside the soil mass Mindlin's expressions used to get vertical soil settlement of granular pile. The pile is discretized into 'n' cylindrical element (segments) and each segment is further subdivided vertically into 'nz' and circumferentially in to 'nt' segments. The displacements for cylindrical segments are evaluated at the nodes at the periphery of each segment on the granular pile - soil interface.

2.1 Soil Displacements

Soil Displacements at Granular Pile Nodes

Soil displacements along with GP-soil interface and along the raft-soft ground interface are evaluated at the mid-points on the side of each element by integrating Mindlin (1936) and Boussinesq's expressions correspondingly. The GP is divided in to 'n' elements of length, Δ L= (L_p / n). A displacement along GP-soil interface are evaluated at the mid-point on the side of each segment and at the center of the base by the integration of Mindlin & Boussinesq's expressions depends on the effect of the elemental stresses of GP and the raft stresses correspondingly in matrix form following Sharma and Madhav (1999).

$$\left\{\rho^{sp}\right\} = \left\{\frac{S^{sp}}{d}\right\} = \left[I_{pp}\right]\left\{\frac{\tau}{E_s}\right\} + \left[I_{pr}\right]\left\{\frac{p_r}{E_s}\right\} \tag{1}$$

where $\{S^{sp}\}$ and $\{\rho^{sp}\}$ are vertical and standardize vertical soil settlement vectors, $[I_{pp}]$=(n+1)×(n+1) and $[I_{pr}]$= (n+1)×kr, are displacement factor for the effect of GP shear stresses & base pressure and raft stresses on settlements of nodes of pile elements respectively. $\{\tau\}$and {pr} – column matrix, {n+1}and {kr} correspondingly.

Soil Displacements at Raft Nodes

The raft is divided in to 'kr' elements of equal area. Displacements along raft-soil interface are evaluated at the node of each element by the integration of Mindlin & Boussinesq's expressions depend on the effect of the elemental stresses of GP and the raft stresses. Corresponding soil displacement at raft node in matrix form is given by following equation:

$$\left\{\rho^{sr}\right\} = \left\{\frac{S^{sr}}{d}\right\} = \left[I_{rp}\right]\left\{\frac{\tau}{E_s}\right\} + \left[I_{rr}\right]\left\{\frac{p_r}{E_s}\right\} \tag{2}$$

where $\{S^{sr}\}$ and $\{\rho^{sr}\}$ are vertical and standardize vertical soil settlement vector, $[I_{rp}]$= kr×(n+1) and $[I_{rr}]$ = (kr×kr) displacement factor for shear stresses on settlement of raft nodes and raft stresses on the settlements of raft nodes respectively. $\{\tau\}$ and $\{p_r\}$ are column matrix of size {n+1} and {kr} correspondingly.

2.2 Displacements of pile

Displacements of node of GP are calculated depends on a relationship of stress-strain.

$$\varepsilon_v = \frac{\sigma_v}{E_{gp}} \tag{3}$$

Where ε_v & σ_v is the direct strain and stress on the segments of GP respectively and E_{gp} is the elasticity modulus of the GP.

Direct & Shear Stresses Relationship

Relation among shear and direct stresses on pile nodes is presented in matrix as:

$$\{\sigma_v\} = [A]\{\tau\} \tag{4}$$

where $\{\tau\}$ and $\{\sigma_v\}$ are consecutively columns matrix of shear and direct stresses on the pile nodes, size of both vectors is (n+1). [A] is a matrix of (n+1)×(n+1) size is formulated.

$$[A] = \begin{bmatrix} \frac{2(L_p/d_p)}{n} & \frac{4(L_p/d_p)}{n} & \frac{4(L_p/d_p)}{n} & \frac{4(L_p/d_p)}{n} & - & - & - & - & 1 \\ 0 & \frac{2(L_p/d_p)}{n} & \frac{4(L_p/d_p)}{n} & \frac{4(L_p/d_p)}{n} & - & - & - & - & 1 \\ 0 & 0 & \frac{2(L_p/d_p)}{n} & \frac{4(L_p/d_p)}{n} & - & - & - & - & 1 \\ - & - & - & - & - & - & - & - & - \\ - & - & - & - & - & - & - & - & - \\ - & - & - & - & - & - & - & - & - \\ - & - & - & - & - & 0 & \frac{2(L_p/d_p)}{n} & \frac{4(L_p/d_p)}{n} & 1 \\ - & - & - & - & - & - & 0 & \frac{2(L_p/d_p)}{n} & 1 \\ - & - & - & - & - & - & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

GP Displacements

Displacements of granular pile are evaluated depends on the method given by Garg and Sharma (2018). The vertical displacements at each node of granular pile are calculated starting from top settlement of the granular pile, ρ_t by progressing downwards considering the strain of each element successively. The vertical settlements of pile are

$$\{\rho^{ppv}\} = \rho_t\{1\} + [B]\left\{\frac{\sigma_v}{E_s}\right\} \tag{6}$$

where [B] is square matrix of sizes (n+1) and it is presented as

$$[B] = \frac{(L_p/d_p)}{nK_p}\begin{bmatrix} \frac{-0.5}{\mu} & 0 & 0 & 0 & - & - & - & - & 0 \\ \frac{-1}{\mu} & \frac{-0.5}{\mu} & 0 & 0 & - & - & - & - & 0 \\ \frac{-1}{\mu} & \frac{-1}{\mu} & \frac{-0.5}{\mu} & 0 & - & - & - & - & - \\ - & - & - & - & - & - & - & - & - \\ - & - & - & - & - & - & - & - & - \\ - & - & - & - & - & - & - & - & - \\ - & - & - & - & - & - & - & - & - \\ -1 & -1 & - & - & - & - & - & -0.5 & 0 \\ -1 & -1 & - & - & - & - & -\frac{34}{32} & -\frac{18}{32} & -\frac{6}{32} \end{bmatrix} \tag{7}$$

By replacing the direct stresses by shear stresses using (Eq. 4), the settlement of granular pile nodes in form of shear stresses is

$$\{\rho^{ppv}\} = \rho_t\{1\} + [C]\left\{\frac{\tau}{E_s}\right\} \tag{8}$$

where [C] =(n+1)×(n+1) matrix and given by = [B] [A].

2.3 Displacements of Raft

Raft is supposed to be rigid and henceforth settlements of raft nodes are all equal. The settlement of the top of the GP (ρt) is equal to raft displacement and expressed as

$$\{\rho^{r}\} = \rho_t\{1\} \tag{9}$$

where $\{\rho^{r}\}$ is the raft displacement vector of size 'kr'.

2.4 Condition of Compatibility

- Using compatibility of settlement of the GP and the soil,

$$\{\rho^{sp}\} = \{\rho^{ppv}\}$$

Or

$$[AA]\left\{\frac{\tau}{E_s}\right\} + [I_{pr}]\left\{\frac{p_r}{E_s}\right\} = \rho_t\{1\} \tag{10}$$

- Using compatibility of settlement of the raft and the soil,

$$\{\rho^{sr}\} = \{\rho^{r}\}$$

Or

$$[I_{rp}]\left\{\frac{\tau}{E_s}\right\} + [I_{rr}]\left\{\frac{p_r}{E_s}\right\} = \rho_t\{1\} \tag{11}$$

By solving the equations (10) & (11) standardize raft stresses and normalised interfacial shear stresses are evaluated. Using the shear stresses the load distribution among the raft and pile are evaluated.
Fractional load transferred on pile = $(P_p/P)*100$
Fractional load transferred on base of pile = $(P_b/P)*100$
Fractional load transferred on raft = $(P_r/P)*100$

3 Results

Results are deduced for comparative strengthening, K_p of GP = 10-1000, comparative size, D/d_p of GP = 2-10, strengthening factor μ =1-10 and comparative length of strengthening from top of GP, λ = 0.1-0.4. Even though the normal range of, K_p, for GP are 10-100, results are obtained for K_p= 1000.
Fig. 2 depict the influence of comparative raft of size, D/d_p, on the variation of shear stresses along GP normalised with total load, P, for K_p = 50 & 100. The shear stresses decrease by raising the comparative size of raft due to reduction in the load taken by GP. However, increments in the values of τ are observed near the top portions of GP with increasing comparative size of raft.

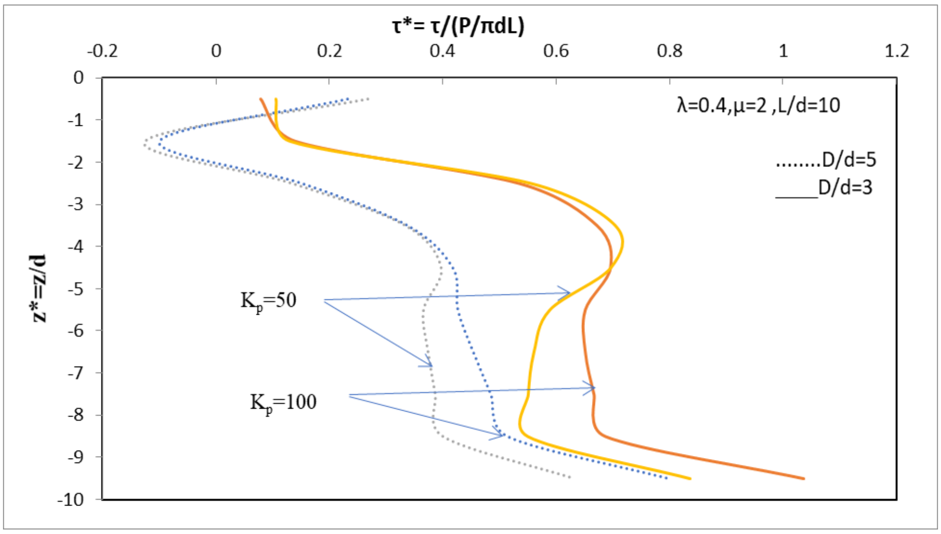

Fig. 2. Plot of standardized shear stresses, $\tau^* = \tau(\pi dL)/P$, with the normalized depth, $z^*=z/d_p$ – effect of comparative raft of size, D/d_p and comparative strengthening, K_p, of GP, on a partially strengthened GP-raft foundation (L_p/d_p =10, λ=0.4, μ=2)

Fig. 3 reveals the effect of comparative strengthening, K_p on fractional pile load, P_p/P, with strengthening factor, μ. As comparative strengthening, K_p, of GP and strengthening factor, μ, increases the fractional GP load enhances. At upper range of comparative strengthening, K_p = 100, 1000 the change in the fractional pile load is negligible. The value of fractional pile load for L_p/d_p = 10, λ = 0.4, D/d_p = 3 and K_p = 10, 100 and 1000 are 24.46, 58.95 and 70.61 respectively implying that there is significant improvement in load share by GP, with the increase in strengthening of the granular pile. The decreasing trends in the graph with respect to the increasing comparative strengthening parameters are due to increase in the comparative diameter of raft with the strengthened GP.

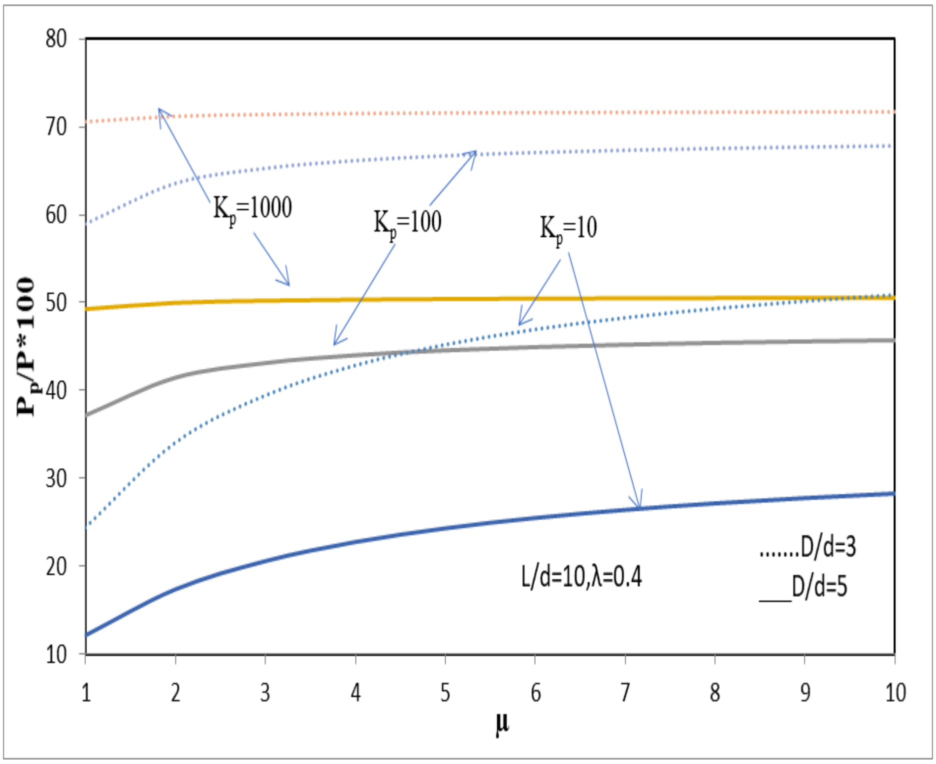

Fig. 3. Plot of fractional pile load, $(P_p/P)*100$, with the strengthening factor, μ – effect of comparative strengthening, K_p, and comparative raft of size, D/d_p, on partially strengthened GP-raft foundation (L_p/d_p =10, λ=0.4)

Fig. 4 depicted the variation of fractional load transferred to the raft, (P_r/P) x100, with strengthening factor, μ, with the effect of comparative strengthening of GP, K_p, on a strengthened GP. The fractional raft load decreases with increase in comparative strengthening, K_p, of GP and strengthening factor, μ. At higher value of comparative strengthening, K_p= 100, 1000 the change in the fractional raft load, (P_r / P) is negligible. The value of fractional raft load for $L_p/d_p = 10$, $\lambda = 0.2$, $D/d_p = 3$ and $K_p = 10$, 100 and 1000 are 75.53, 41.04 and 29.39 correspondingly imply that there is noteworthy decrease in values of, (P_r/ P) x 100, through the increase in comparative strengthening of the GP, K_p.

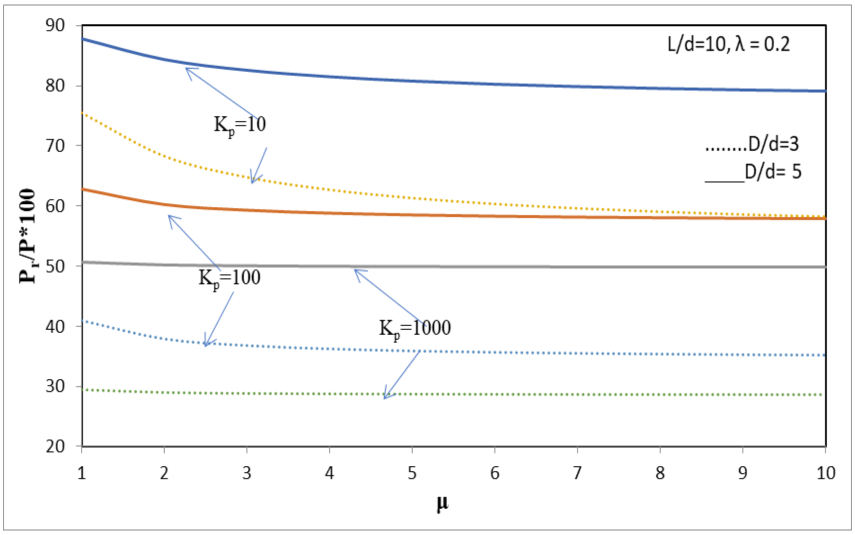

Fig. 4. Plot of fractional load transferred to raft, (P_r/P) x100, with strengthening factor, μ, –effect of comparative strengthening, K_p and comparative raft of size, D/d_p on partially strengthened GP-raft foundation (L_p/d_p =10, λ=0.2)

The deviation of fractional load transmitted to the pile, (P_p/P) x100, with comparative strengthening of GP, K_p, with the effect of comparative raft of size, D/d_p, and comparative length of stiffening, λ, on a strengthened GP raft is represented in Fig. 5 for, L_p/d_p = 10, and μ = 2. It is observed that with the increment in comparative size of raft the fractional pile load is decreased. It is also well noted that with the increase in the length of strengthening, λ the load carrying capacity of pile is enhanced. Graph shows that as the strengthening length of pile increased load bearing capacity of pile is improved.

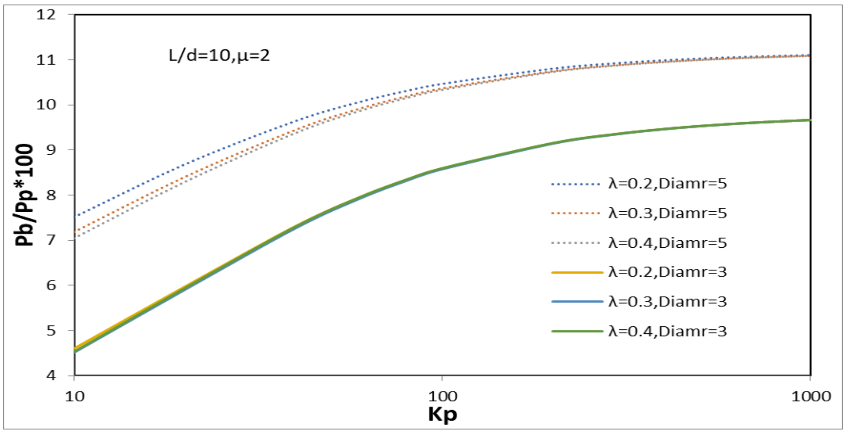

Fig. 5. Plot of fractional load transferred to pile, (P_p/P) x100, with comparative strengthening of GP, K_p, –effect of strengthening factor, μ and comparative raft of size, D/d_p on partially strengthened GP-raft foundation (L_p/d_p =10, μ = 2)

Fig. 6 reveals the effect of comparative strengthening of GP, K_p on fractional pile load, with strengthening factor, μ. As comparative strengthening, K_p, of GP and strengthening factor, μ, improved the load bearing capacity pile is improved. There is more load transferred to the pile for shorter piles initially for K_p = 10 but as the comparative strengthening of GP increases the fractional pile load taken by longer pile is more. At higher value of comparative strengthening of GP, K_p = 1000 the change in the fractional pile load, (P_p/ P) is negligible.

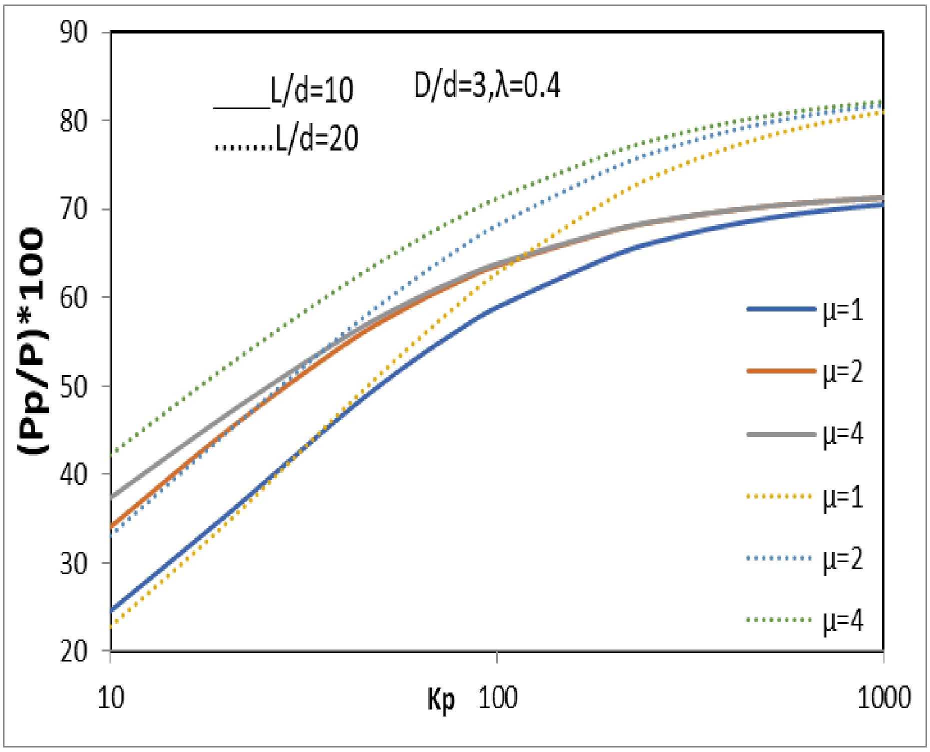

Fig. 6. Plot of fractional load transferred to pile, (P_p/P) x100, with comparative strengthening of GP, K_p, –effect of strengthening factor, μ and comparative length of pile, L_p/d_p on partially strengthened GP-raft foundation (D/d_p =3, λ =0.4)

Fig. 7 reveals the effect of comparative strengthening of GP, K_p on fractional pile load, P_b/P, with strengthening factor, μ. As comparative strengthening, K_p, of GP and strengthening factor, μ, increase the value of fractional base load. As the comparative length of GP is increases the value of fractional base load decreases because the base of pile farther from the top. The effect of strengthening at the top is clearly seen in the figure as strengthening factor increases the more load is transmitted to the base of pile.

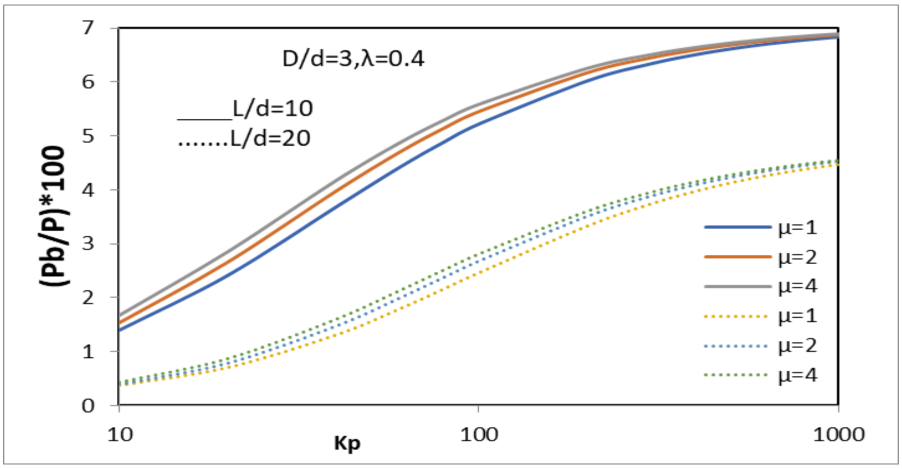

Fig. 7. Plot of fractional load transferred to pile, (P_b/P) x100, with comparative strengthening of GP, K_p, –effect of strengthening factor, μ and comparative length of pile, L_p/d_p on partially strengthened GP-raft foundation D/d_p =3, λ = 2)

Fig. 8 depicted the variation of fractional load transferred to the raft, (P_r/P) x100, with comparative strengthening of GP, K_p, with the effect of comparative raft of size, D/d_p. As the comparative raft size enhances the load transferred to the raft increases, it is revealing the role of comparative size of raft.

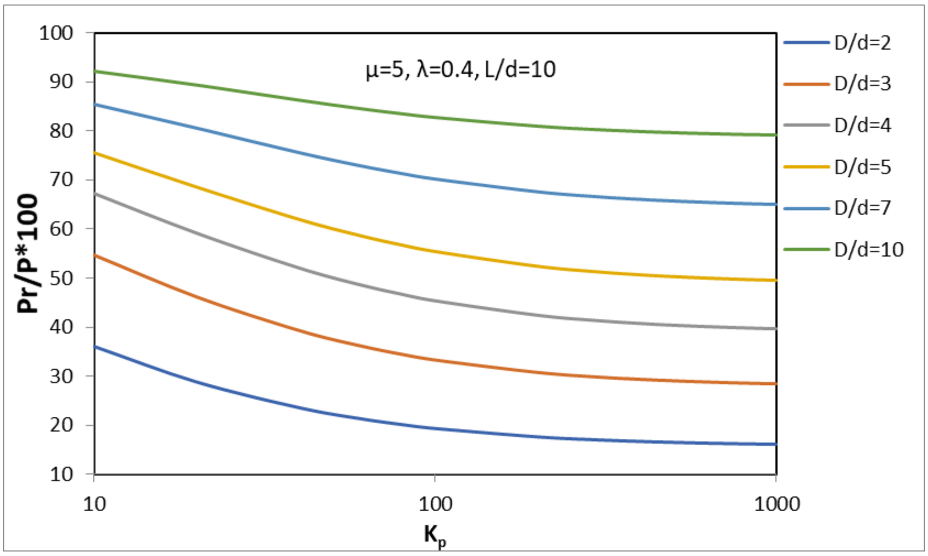

Fig. 8. Plot of fractional load transferred to pile, (P_r/P) x100, with comparative strengthening of GP, K_p, – effect of comparative raft of size, D/d_p on partially strengthened GP-raft foundation (L_p/d_p =10, μ=5, λ = 0.4)

4 Conclusions:

Pile settlement matrix is formulated by using finite difference technique and elastic continuum approach in the present analysis. Following are the outcomes of the study as:

1. The shear stresses decrease with the increase of comparative size of raft due to reduction in the load shared by GP.
2. The fractional load transmitted to the GP base increases with the improvement in the strengthening factor and comparative length of strengthening from top of GP and decrease with the increase comparative size of raft.
3. The load bearing capacity of granular pile is enhanced with the improvement in strengthening parameters and comparative strengthening of GP, K_p.
4. With the increase in comparative strengthening of GP, K_p the fractional pile load taken by longer pile is improved.
5. There is significant decrease in values of, (P_r/ P) x 100, with the increase in strengthening parameters, strengthening factor, μ and length of stiffening from the top, λ.

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