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BEHAVIOR OF STRIP FOOTING RESTING ON SOFT GROUND STIFFENED BY GRANULAR PILES

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ABSTRACT

This paper presents a method to analyze strip footing resting on granular layer over soft ground improved by granular piles (i.e., end bearing or floating). The granular layer beneath the strip footing is idealized as incompressible shear layer. The natural weak soil layer is idealized by soft Winkler springs and the granular piles is idealized as stiff Winkler springs. These springs is connected at their heads by a thin membrane under uniform tension to overcome the drawbacks of Winkler model related to the continuum nature of the soil. The finite element method is used to solve the problem under consideration. The granular piles of different lengths, diameters and stiffness can be modeled by the present analysis method. Validation of the proposed analysis method through comparisons with field measurements, predicted results by other analysis method and results of PLAXIS program are investigated.

INTRODUCTION

Use of granular piles, GP, in weak soils (e.g., soft clay and loose sand) is now a well known ground improvement technique. In case of loose granular soil, the provision of granular pile enhances the bearing capacity of foundation and reduces its total and differential settlements. However, in case of soft cohesive soil, it has an additional advantage of providing a drainage path, which accelerates consolidation. Granular piles may be fully penetrated and resting on strong soil layer (i.e., end bearing granular piles, EBGP) or partially penetrated (i.e., floating granular piles, FGP). The floating granular piles are considered an economic alternative system to fully penetrated granular piles in case of deep weak soil layer or in case of lightly loaded structures.

Several literature pertaining to the behavior of strip footings resting on fully penetrated granular piles are found (e.g., Deb et al. 2007; Maheshwari and Khatri 2010; Maheshwari and Khatri 2011;

Maheshwari and Khatri 2012). But, a little number of literature concerning the behavior of footings resting on floating granular piles are found (e.g., Kirsch 2006; Sivakumar et al. 2007; Kirsch 2009; Zahmatkesh and Choobbasti 2010). For space limitations, only review the technical literature pertaining to the analysis of strip footing resting on weak soil improved by granular piles is presented in this section.

Deb et al. (2007) proposed a mechanical model to predict the behavior of a Geosynthetic reinforced granular fill over soft soil improved with end bearing granular piles. The granular layer, surrounding soil, and stone columns were idealized by Pasternak shear layer, Kelvin-Voight model, and stiffer Winkler spring, respectively. The plane strain condition was considered in the analysis and the finite difference scheme is used to solve the governing differential equations. Nonlinear behaviors of soft soil and the granular fill were considered. For a uniformly loaded strip footing, the presence of granular layer helps to transfer stress from soil to granular piles and reduce maximum and differential settlements (Deb et al. 2007).

Maheshwari and Shukla (2010, 2011) proposed a nonlinear mechanical model for analysis of strip footing resting on granular layer over end bearing stone column reinforced earth beds. The granular layer, weak soil and stone columns were idealized by Pasternak shear layer, Kelvin-Voight model, and stiffer Winkler spring respectively. The flexural rigidity of strip footing and the nonlinearity of granular layer, stone column and soft soil were taken into consideration. The effect of different parameters on the behavior of soil-strip footing system was investigated. Maheshwari and Khatri (2012) proposed a generalized model for analysis of strip footing on Geosynthetic-reinforced granular fill over stone columns improved soft soil system. The granular layer, Geosynthetic layer, weak soil and stone columns were idealized by Pasternak shear layer, elastic membrane, Kelvin-Voight model, and stiffer Winkler spring respectively. The nonlinearity of granular layer, stone column and soft soil were taken into consideration.

Strip footings have finite flexural rigidity are usually analyzed as beams on elastic foundation. Many studies for the analysis of beams on elastic foundation were presented in the literature (e.g., Vallabhan and Das, 1988; Morfidis 2007). In these studies, the two-parameter model or three-parameter model used to idealize the soil.

In all the studies pertaining to the analysis of strip footing resting on weak soil improved by granular piles, the weak soil and the granular piles were idealized as a series of independent vertical soft and stiff Winkler springs and neglect the shear interaction between springs or the continuity of granular piles-weak soil composite. In addition, these studies do not incorporate the effect of granular piles length (i.e., floating granular piles), granular piles arrangement and granular piles of different diameters on the strip footing behavior.

In this paper, a method is developed to analyze the strip footing resting on granular layer over weak soil improved by end bearing or floating granular piles. The nonlinear behavior of weak soil and granular piles are taken into consideration. Comparisons between the results of the present analysis with the field measurements, results of other existing analysis method and results of PLAXIS program are presented and discussed.

THE PROBLEM UNDER CONSIDERATION

Figure 1 shows the definition sketch of a strip footing resting on a granular layer over top of granular piles improved weak soil. The strip footing is of width B and length L and subjected to a number of concentrated loads (i.e., Q_1, Q_2,.....,Q_n). The thickness of granular layer is H_{gl} and its shear modulus is G_{gl}. Diameter and spacing of granular piles are D_{gp} and S, respectively.

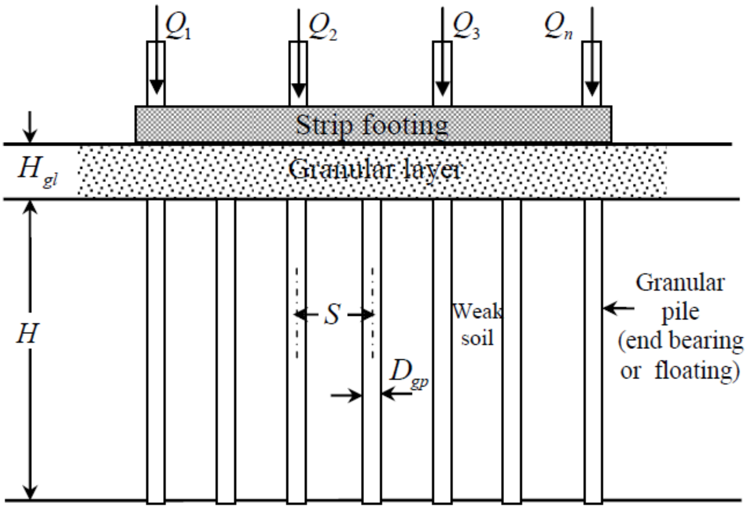

Figure 1 The problem to be analyzed

Figure 2 shows the proposed model for the soil-strip footing system under consideration. The strip footing is modeled as a finite beam of flexural rigidity, EI. The granular layer is idealized as Pasternak shear layer. The weak soil and the granular piles are idealized as soft and stiff Winkler springs respectively. These springs are connected at their ends by a thin membrane under uniform tension to take into account the shear interaction between the Winkler springs (Horvath 2002 and Worku 2013). The Length of the granular piles is assumed equal to the thickness of natural weak soil stratum (i.e., case of end bearing granular piles) or less than the thickness of weak soil stratum (i.e., case of floating granular piles). While installing the granular piles in weak soils, the original stiffness of ground will increase (Kirsch 2009). However, this effect is not considered in the present analysis.

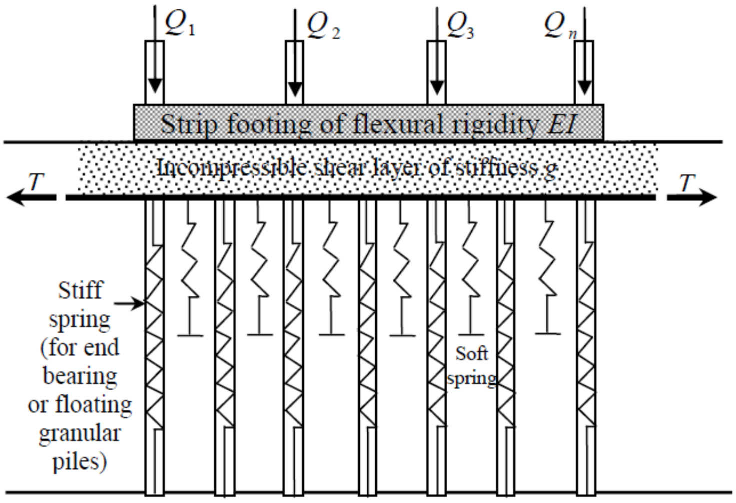

Figure 2 The problem modeling

MATERIAL METHOD

METHOD OF ANALYSIS

In the literature, a number of two-parameter models are presented to overcome the weakness of Winkler model (i.e., the assumption that there is no interaction between adjacent springs) in modeling the behavior of elastic foundation. In these models, the first parameter represents the stiffness of vertical springs, as in the Winkler model, and the second parameter was introduced to account for the coupling effect between vertical springs. These two-parameter models were presented and discussed by a number of researchers (e.g., Horvath 2002; Worku 2013).

The problem of a dense coarse grained soil layer laying on a compressible soil can be idealized as an incompressible shear layer (i.e., Pasternak shear layer) of stiffness g over a weak soil reinforced by granular piles idealized as soft and stiff Winkler springs of modulus of subgrade reaction coefficients k_s and k_{gp} respectively. The soft and stiff Winkler springs are connected at their ends by a thin membrane under uniform tension force per unit length, T, to overcome the drawbacks of Winkler model related to the shear effects or the continuity of the soil mass. The governing equation of such a mechanical subgrade model is as follows (Horvath 2002, Colasanti and Horvath 2010).

$$p = kw - (T+g)\frac{d^2w}{dx^2} \tag{1}$$

Where p is the subgrade reaction, k is the modulus of subgrade reaction (i.e., $k = k_s$ over weak soil and $k = k_{gp}$ over granular piles) and w is the vertical displacement. The differential equation of a beam is obtained by considering the bending of an elemental segment.

The differential equation of the beam with uniform cross section in the absence of any external uniformly distributed load can be written as follows.

$$EI\frac{d^4w}{dx^4} + p = q \tag{2}$$

Combining equations (1) and (2), the following differential equation is obtained.

$$EI\frac{d^4w}{dx^4} + kw - (T+g)\frac{d^2w}{dx^2} = q \tag{3}$$

Where E is the modulus of elasticity of strip footing, I is the moment of inertia of strip footing and q is the applied transverse load on strip footing. The nonlinear behavior of weak soil and granular piles are expressed by hyperbolic stress-strain relationships as suggested by Maheshwari and Khatri (2011).

$$k_s = k_{so}\left(1 - \frac{R_{fs}\sigma_s}{q_{su}}\right) \tag{4}$$

$$k_{gp} = k_{gpo}\left(1 - \frac{R_{fgp}\sigma_{gp}}{q_{gpu}}\right) \tag{5}$$

Where k_{so} and k_{gpo} are the initial values of modulus of subgrade reactions of weak soil and granular pile, σ_s and σ_{gp} are the stresses on weak soil and granular pile, q_{su} and q_{gpu} are the ultimate bearing capacities of weak soil and granular pile, R_{fs} and R_{fgp} are the hyperbolic curve fitting constants for weak soil and granular pile respectively. In the present analysis the length of the granular pile is generally greater than 6 times its diameter (i.e., long granular piles) and therefore, the value of q_{gpu} is calculated based on the bulging deformation of the granular pile (Ambily and Gandhi 2007, Black et al. 2007, Razeghi et al. 2011).

The initial modulus of subgrade reaction of weak soil can be calculated by one of the methods presented in the literature (Sadrekarimi and Akbarzad 2009). Here, the initial modulus of subgrade reaction is calculated from the following equation (Worku 2013).

$$k_{so} = \frac{E_s(1-\nu_s)}{H(1-\nu_s - 2\nu_s^2)} \tag{6}$$

Where E_s and ν_s are the modulus of elasticity and Poisson's ratio of weak soil layer and H is the depth of influence. The depth of influence is the smaller depth of either the depth of weak soil below foundation level to the rigid base or the depth below foundation level at which the settlement caused by foundation pressure equal to zero (Colasanti and Horvath 2010). The value of H is dependent on beam dimensions, relative rigidity of the beam with the soil and load pattern acting on the beam and can be taken in the range of 2 to 4 times beam width (Colasanti and Horvath 2010, Worku 2013).

For simplicity, the value of the second parameter, T, is calculated based on the assumption that the granular piles-soil composite behaves like a uniform soil mass with composite modulus of elasticity and Poisson's ratio, E_{comp} and ν_{comp}, as follows (Worku 2013). Such simplification used by Priebe (1995) to calculate the shear values of the improved ground.

$$E_{comp} = A_r E_{gp} + (1 - A_r)E_s \tag{7}$$

$$\nu_{comp} = A_r \nu_{gp} + (1 - A_r)\nu_s \tag{8}$$

$$A_r = \frac{BL}{N_{gp}A_{gp}} \tag{9}$$

$$T = \frac{E_{comp}H}{3(1+\nu_{comp})} \tag{10}$$

Where E_{gp} and ν_{gp} are the modulus of elasticity and Poisson's ratio of granular piles, A_r is the area replacement ratio, N_{gp} is the number of granular piles, A_{gp} is the cross sectional area of granular pile, and B, L are the width and the length of the strip footing.

The stiffness of incompressible shear layer (i.e., granular layer) can be calculated from the following equation (Horvath 2002 and Worku 2013).

$$g = \frac{G_{gl} H_{gl}}{2} = \frac{H_{gl}}{2}\left(\frac{E_{gl}}{2(1+\nu_{gl})}\right) \tag{11}$$

Where H_{gl} and G_{gl} are the thickness and shear modulus of granular layer. E_{gl} and ν_{gl} are the modulus of elasticity and Poisson's ratio, ν_{gl}, of the granular layer.

For end bearing granular piles, the coefficient k_{gpo} can be calculated as the calculation of the coefficient k_{so} as follows:

$$k_{gpo} = \frac{E_{gp}(1-\nu_{gp})}{H(1-\nu_{gp} - 2\nu_{gp}^2)} \tag{12}$$

Where the parameters of Eq. (12) as defined above.

Partially improved ground with granular piles and the underlying compressible weak soil create a double-layered compressible foundation. So far, no reasonable solution is available to estimate the modulus of subgrade reaction of such a double-layered foundation. In the present study, the initial modulus of subgrade reaction of floating granular pile, k_{fgpo}, is calculated from the following equation:

$$k_{fgpo} = \frac{E_{eq}(1-\nu_{eq})}{H(1-\nu_{eq} - 2\nu_{eq}^2)} \tag{13}$$

Where E_{eq} and ν_{eq} are the equivalent modulus of elasticity and equivalent Poisson's ratio for a double-layered compressible foundation. The equivalent homogeneous, isotropic value of E_{eq} and ν_{eq} are determined using the weighted average approach.

Finite Element Formulation

The strip footing is divided into a number of elements (i.e., 4 d.o.f. beam element) taking into account the locations of granular piles to be at the elements nodes. Using the standard procedures in the finite element method for the assemblage of elements, the global stiffness matrix is constructed as a half banded matrix. In matrix formulation, the differential equation, Eq. (3), can be expressed as follows:

$$[K]\{W\} = \{F\} \tag{14}$$

$$[K] = \sum_{i=1}^{N_e} \left[(K_b) + (K_s) + (K_T) + (K_g) \right] \tag{15}$$

Where $[K]$ is the global coefficient matrix, $\{W\}$ is the global nodal displacements; and $\{F\}$ is the global nodal external load vector of the system, (K_b) is the stiffness matrix of the flexure beam element, (K_s) is the first foundation stiffness matrix to account the effect of k_s, (K_T) is the second foundation stiffness matrix to account the effect of T and (K_g) is the stiffness matrix of incompressible shear layer to account the effect of g.

The stiffness matrix of the beam element, the subgrade parameters (k_s, T) and incompressible shear layer parameter, g, were presented in the literature (e.g., Horvath 2002; Teodoru and Musat 2010). The spring stiffness of the granular piles added to the corresponding places on the diagonal of the global stiffness matrix. Applying the proper boundary conditions, we get the solution of the deformations (i.e., vertical displacements and rotations) in the strip footing. These deformations are used to determine the internal forces in the strip footing (i.e., shear forces and bending moments), contact pressure and the nodes reactions.

At the edge of the beam, special boundary condition is required to replace the subgrade effects beyond the edge of the beam. Colasanti and Horvath (2010) suggested an additional independent axial spring under the edge of the beam (i.e., at the level of weak soil springs). The stiffness of these additional boundary condition springs can be calculated from the following equation (Colasanti and Horvath 2010).

$$k_{bc} = \sqrt{k_s T} \tag{16}$$

RESULTS AND DISCUSSION

A computer program is developed based on the finite element method to analyze the soil-strip footing system under consideration using the above methodology. The developed program is able to calculate vertical displacements, rotations, shear forces, bending moments, contact pressure, nodes reactions. The analysis procedure is general enough to take into account different lengths, diameters, and stiffness of granular piles, any arrangements of granular piles and any types of external loads acting on the strip footing (i.e., concentrated loads, uniformly and non-uniformly distributed loads and moment loads).

Validation

For the purpose of validation, comparison between the predicted values by the present method with the field measurements, the results of other existing analysis method and the results of PLAXIS program are presented and discussed in the following sections.

Comparison with field measurement

Watts et al. (2000) carried out a full-scale instrumented load tests to study the performance of end bearing stone columns supporting a strip footing in a variable fill and the performance of a similar strip footing on untreated ground. Watts et al. (2000) presented soil profile, results of various in situ and laboratory tests and instrumentation. The dimensions of treated and untreated strip footings were 9 m length, 0.75 m width and 0.25 m thickness and subjected to three different uniformly distributed loads. Here, only comparison with the uniformly distributed load of 123 kPa is considered. The number, diameter and spacing of stone columns were 9, 0.6 m and 1.8 m, respectively. Thickness of the treated soil below the foundation level varies from 3.15 m at left edge to 4.35 m at right edge with an average thickness of 3.75 m. Lengths of stone columns varied with the thickness of the treated soil. The modulus of elasticity of untreated soil and stone columns were 5 MPa and 30 MPa, respectively (Watts et al. 2000). Poisson's ratio of the soil and the granular piles are taken equal to 0.35. The modulus of subgrade reaction of the soil and the second parameter, T, are calculated from Eq. (6) and Eq. (10) respectively. The modulus of subgrade reaction of stone column is taken 6 times the modulus of subgrade reaction of the soil (where 6 is the ratio between E_{gp} and E_s). Linear analysis is considered. Figure 3 shows comparisons between measured and predicted vertical displacements for treated and untreated strip footings.

For untreated strip footing, the best match between measured and predicted vertical displacements is obtained at the value of the depth of influence equal to 1.65 times width of the strip footing as shown in Figure 3. The difference between the present results and the measured values at the left part of the strip footing is because in the present analysis a constant soil layer is considered, whereas in the field the soil thickness is varied along the beam length. However, for treated strip footing, the predicted values by the present analysis are compared well with the measured vertical displacements at the edges and slightly smaller than the measured values at the middle part of the strip footing as shown in Figure 3. One of the drawbacks of Winkler model is that a strip footing subjected to a uniformly distributed load will undergo rigid body displacements without any shear forces or bending moments in the strip footing. The results obtained by the present analysis for case of untreated strip footing reveals that the importance of using two-parameter model to represent the soil instead of using one-parameter model (i.e., Winkler model).

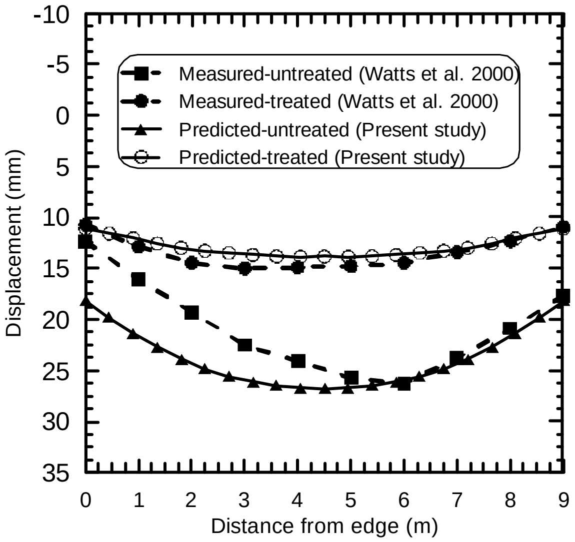

Figure 3 Comparison between measured and predicted settlements for untreated and treated strip footings

Comparison with other existing analysis method

Maheshwari and Khatri (2011) developed a method for the analysis of strip footing resting on granular layer over weak soil reinforced by granular piles. The present method is validated by comparing its results with the results from Maheshwari and Khatri (2011). The strip footing is of flexural rigidity $EI = 115500$ kN.m^2 and subjected to five equal concentrated loads. The granular piles diameters are 0.5 m and its spacing is 1.5 m. The stiffness, g, of the granular layer is 272.35 kN/m. The coefficients of subgrade reaction of weak soil and granular piles are 10000 kN/m^3 and 100000 kN/m^3, respectively (Maheshwari and Khatri 2011). Linear analysis is considered.

Figure 4 shows comparison between vertical displacements obtained by the present analysis with those obtained by Maheshwari and Khatri (2011).

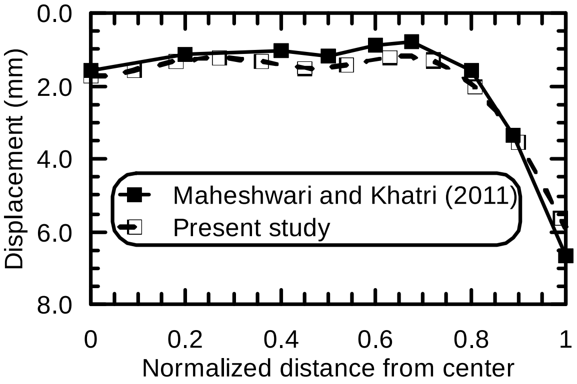

Figure 4 Comparison between vertical displacements obtained by the present method and Maheshwari and Khatri (2011) method

At the center of the strip footing, the displacement value obtained by the present method is 11.7% greater than that obtained by Maheshwari and Khatri (2011). While at the edge of the strip footing, the predicted displacement by the present method is 11.7% smaller than that obtained by Maheshwari and Khatri (2011) as shown in Figure 4. The difference between the present results and the results presented by Maheshwari and Khatri (2011) is due to the fact that in the present study the stiffness of granular layer $g = H_{gl} G_{gl} / 2$, whereas Maheshwari and Khatri (2011) considered the stiffness of granular layer $g = H_{gl} G_{gl}$.

Comparison with PLAXIS program

The present method is validated by comparing its results with the results from PLAXIS program. The strip footing is of length 20 m, width 1.0 m and flexural rigidity EI = 281300 kN.m^2 and subjected to uniformly distributed load of 100 kN/m^2. The thickness of the weak soil layer is 10 m. The thickness of the granular layer and its modulus of elasticity are 0.3 m and 20000 kN/m^2 respectively. The end bearing granular piles diameters are 0.5 m and its spacing is 1.5 m. The modulus of elasticity of weak soil and granular piles are 6000 kN/m^2 and 50000 kN/m^2, respectively. The Poisson's ratio of weak soil, granular layer and granular piles is 0.25. Linear analysis is considered. Triangular elements of 15 nodes are used in the finite element analysis by PLAXIS program as shown in Figure 5. The mesh has 364 elements and 3037 nodes. The linear elastic model under drained conditions, which is available in PLAXIS program library, used to model the weak soil, the stone column and the granular layer.

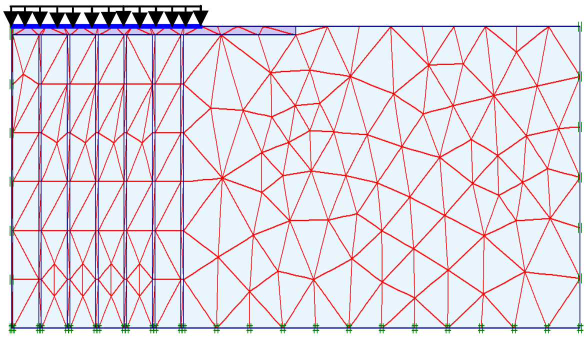

Figure 5 Finite element mesh of PLAXIS program

Figure 6 shows comparisons between the results of PLAXIS program and present program for untreated treated cases. For untreated case, the results of the present method approximately equal to the results of PLAXIS program at the center of the beam while, at the edge of the beam the results of the present method smaller than that of PLAXIS program by 6.6% as shown in Figure 6. For treated case, the results of the present program smaller than the results of PLAXIS program by approximately 11.1% and 10.1 at the center and the edge of the beam respectively.

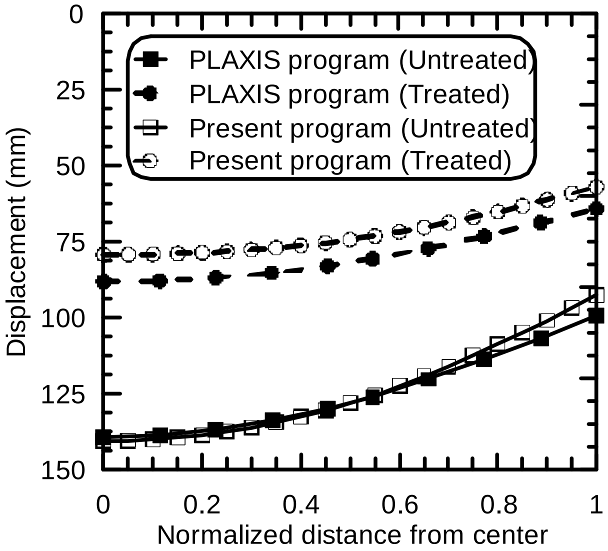

Figure 6 Comparisons between the results of PLAXIS program and present program for untreated treated cases

CONCLUSION

This paper presents a method for analysis of strip footing resting on granular layer over weak soil reinforced by end bearing or floating granular piles. The method of analysis taking into account the shear effect or the continuity of the granular piles-weak soil composite and the nonlinear behavior of weak soil and granular piles. Comparisons between the results of the present analysis with the field measurements, the results of other existing analysis method and the results of PLAXIS program show good agreement in case of linear analysis.

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