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Nonlinear Subgrade Modelling of Granular Fill Soft Soil

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Introduction

A relatively thin compacted granular base helps in distributing the applied load over a larger area so that the underlying soft soil experiences less settlement. Few reliable theoretical approaches are available for the analysis of two layer foundation. Extensive use of the theory of elasticity has been made for the calculation of stresses and displacements in soil media (Poulos and Davis, 1974). Although problems in the theory of elasticity are restricted to the consideration of ideal materials and ideal boundary conditions, they have been found to be of practical use in studies of imperfectly elastic and somewhat nonhomogeneous materials, such as soils. On the other hand limit equilibrium method has been widely accepted for the analysis of stability problems. Most of the problems of bearing capacity treat the foundations supported by soil deposits extending to great depths. In many circumstances soil deposits encountered are multi-layered or foundations are made to rest on prepared soil bed. Bearing capacity factors for two layer clayey soil considering various combinations of upper and lower soil layer properties have been attempted by many, e.g. averaging the strength parameter (cf. Bowles, 1988), using limit equilibrium considerations (Reddy and Srinivasan 1967, Meyerhof 1974, Meyerhof and Hanna 1978, Hanna and Meyerhof 1980) and limit analysis approaches (Chen and Davidson 1973, Florkiewicz 1989, Michalowski and Lei Shi 1995). Nonlinear behavior of soil in nature cannot be easily understood with the help of limit equilibrium methods. However, a good deal of exercise can be made in mathematical

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modeling by incorporating feasible nonlinear function to the representative model parameter. In this paper a parametric study has been done with two parameter Pasternak type model (Pasternak, 1954) by incorporating hyperbolic nonlinear responses to the model parameters.

Stress-Strain Relations for Soil

With the advent of powerful numerical tools such as finite element method, the nonlinearity of the soil behavior is being incorporated in quantitative terms by various mathematical functions, such as bilinear (D'appolonia. and Lambe, 1970), hyperbolic (Kondner, 1963), parabolic (Hansen, 1963), spline (Desai, 1971) and more recently with logarithmic (Puzrin and Burland, 1996) expression. A comprehensive review of the nonlinear stress-strain response of soil mass are available in the. literatures (Duncan and Chang, 1970; Maximovic, 1989; Boscardin, 1990). However, the main shortcoming of these mathematical functions as well as empirical strength criteria lies in the validity within limited stress range and their evaluations on physical basis. Among the various nonlinear stress-strain models for the soils, the hyperbolic function is found simple and reasonably approximates the nonlinear behavior of soils within the widest possible range of stresses, from zero to practically infinity. This paper incorporates hyperbolic nonlinearity to the model parameters.

Load-Settlement Response Models

The deformation characteristics of the soil have been idealized in terms of various foundation models. These idealizations are carried out in two directions, viz.

i) modelling the soil mass as a whole [e.g. mathematical or mechanical spring models such as the Winkler model, the two parameter Pasternak type model, modified Pasternak model (Kerr, 1965; Horvath, 1983; Rhines, *1969*; Selvadurai, *1979*; *Poorooshasb et al., 1985*)] and

ii) idealizing the behaviour of the soil itself (e.g. continuum behaviour of the soil medium such as isotropic elastic half space).

This paper is related to the first kind of idealization. In this case, the parameters do not necessarily represent the intrinsic material properties of the soil. This concept arises from the elimination of the discontinuities of the Winkler model by providing a shear layer (Pasternak, 1954) over the springs. The shear layer consists of incompressible vertical elements deforming in transverse shear only. The other forms of spring interactions consist of smooth membrane (Filonenko-Borodich, 1940) and elastic beam (Hetenyi, 1946).

Formulations

Plane Strain Case

This model consists of incompressible vertical elements deforming in transverse shear only. The forces acting on a shear layer element maintain vertical equilibrium of forces in z direction. The vertical deformation w, at the surface is continuous along x axis (Fig. 1). Assuming that the shear layer parameter, GH is isotropic in x-y plane and with shear moduli $G_x = G_y = G_p$, the expression for shear stress in the vertical direction will be,

$$\tau_{xz} = G_p \gamma_{xz} = G_p \frac{\partial w}{\partial x} \tag{1a}$$

$$\tau_{yz} = G_p \gamma_{yz} = G_p \frac{\partial w}{\partial y} \tag{1b}$$

Corresponding shear forces acting across the shear layer of thickness H are,

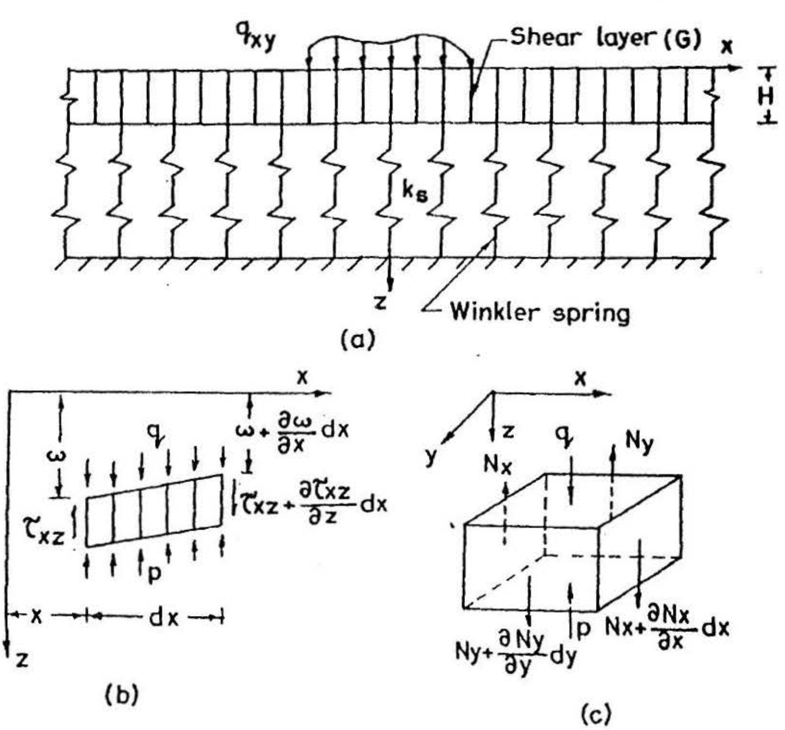

FIGURE 1 : The Pasternak Model-Definition Sketch (Plain Strain Case)

$$N_x = \int_0^x \tau_{xz} dz = G_p H \frac{\partial w}{\partial x} \tag{2a}$$

$$N_y = \int_0^H \tau_{yz} dz = G_p H \frac{\partial w}{\partial y} \tag{2b}$$

From the force equilibrium in z direction (Fig. 1c),

$$\frac{\partial N_x}{\partial x} + \frac{\partial N_y}{\partial y} + q - p = 0 \tag{3}$$

Since the shear layer is incompressible in the z direction, the vertical reaction at the bottom of the shear layer is

$$p = k_s w(x, y) \tag{4}$$

where k_s is the modulus of subgrade reaction for soft soil.

Introducing Eqns. 1 and 2 into Eqn. 3 one gets

$$q(x, y) = k_s w(x, y) - G_p H \nabla^2 w(x, y) \tag{5}$$

For the particular case of a strip footing of width 2B and uniform load intensity q, Eqn. 5 can be written for plane strain condition as,

$$q(x) = k_s w(x) - G_p H \frac{d^2 w}{dx^2} \tag{6}$$

The second term on the right hand side of the Eqn. 6, shows the effect of transverse shear interactions of the vertical elements.

The continuity and boundary conditions for solving Eqn.6 are,

$$\frac{dw}{dx} = 0 \text{ at } x = 0 \text{ and} \tag{7a}$$

$$w(x) = 0 \text{ at } x \rightarrow \infty \tag{7b}$$

Using Eqns. 7a and 7b, the analytical solution of Eqn. 6 for uniformly loaded strip footing becomes,

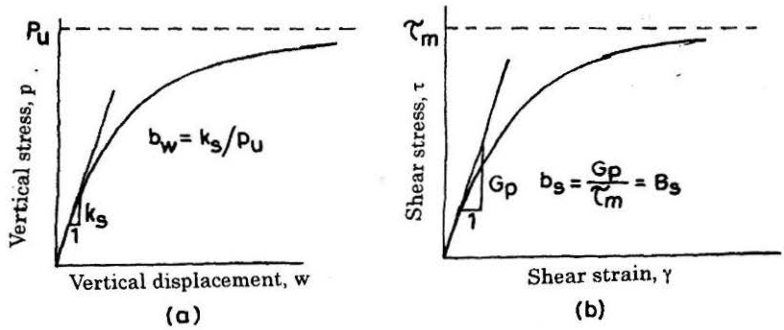

FIGURE 2 : Hyperbolic Response Model for (a) Soft Soil and (b) Granular Soil

$$w(x) = \frac{q}{k_s}\left[1-\exp(-\beta)\cosh\left(x\frac{\beta}{B}\right)\right] \quad \text{for } 0 \leq x \leq B \tag{8a}$$

and

$$w(x) = \frac{q}{k_s}\left[1-\exp(-\beta)\cosh(\beta)\right]\exp\left(1-\frac{x}{B}\right) \quad \text{for } B \leq x \leq \infty \tag{8b}$$

where $$\beta = \left(\frac{k_s B^2}{G_p H}\right)^{1/2}$$

For a rigid strip footing with vertical deflection w_0, the surface deformation profile outside the edge of the footing is obtained from Eqn. 6 and boundary condition 7b as

$$w(x) = w_0 \exp\left\{\beta\left(1-\frac{x}{B}\right)\right\} \quad \text{for } B \leq x \tag{9}$$

Expressions 8 and 9 give the surface deformations for a flexible and rigid strip footing respectively when soft soil and granular fill stress-strain responses are linear. Considering the load-settlement response of the soft soil in the form of hyperbolic function (Fig. 2a) as,

$$p = \frac{k_s w}{1 + b_w w} \tag{10}$$

where k_s = initial slope of the stress–settlement response curve of the soft soil (Winkler spring) and

b_w = k_s/p_u , a nonlinearity parameter where p_u is the ultimate stress of the soft soil.

Similarly, the nonlinear shear stress-shear strain relation for the granular fill (Pasternak shear layer) is expressed as (Fig. 2b),

$$\tau_{xz} = \frac{G_p \gamma_{xz}}{1 + b_s \gamma_{xz}} \tag{11}$$

where G_p = initial slope of the shear stress-shear strain response of the granular fill,

b_s = G_p/τ_m , a nonlinear shear parameter, where τ_m is the maximum shear stress taken by the shear layer and

γ_{xz} = shear strain.

Combining Eqns. 10 and 11 with Eqn. 6, for plane strain case,

$$q = \frac{k_s w}{1 + b_w w} - \left[\frac{G_p H}{1 + b_s\left(\frac{dw}{dx}\right)^2}\right]\frac{d^2 w}{dx^2} \tag{12}$$

The above equation is expressed in nondimensional finite difference form as,

$$q_i^* = \frac{W_i}{1 + B_w W_i} - \frac{G^*}{\left\{1 + B_s \left.\frac{dW}{dX}\right|_i\right\}^2}\left(\frac{W_{i+1} - 2W_i + W_{i-1}}{\Delta X^2}\right) \tag{13}$$

where $B_s = b_s = G/\gamma_m$

$B_w = B b_w = k_s B/p_u$

$X = x/B$

$W = w/B$

$G^* = G_p H/k_s B$

$q^* = q/k_sB$

B = is the half width of the strip footing and

ΔX = step length in the finite difference scheme.

Equation 13 is the governing expression for the modified Pasternak model (GH and k_s) which incorporates nonlinearity responses of the soft soil (B_w) and granular fill (B_s). This equation can not be solved by classical analytical methods. Iterative finite difference method has been used to obtain vertical displacement W_i from the above equation in which all other parameters are either known or supplied during the iterative solution process. For uniformly loaded footing, q_i^* and for rigid footing, W_0, are to be specified over the width of the strip footing. Finite difference discretisation with surface displacement boundary conditions along X-axis for plane strain case are shown in Fig. 4b. Results obtained for different parametric inputs have been compared with exact solutions (for linear response) given in Eqns. 8 and 9 and it was found that for step size in finite difference scheme shown in Fig. 4b, the error limit was within 2.5%.

Axi-symmetric Case

Axi-symmetric loading case occurs in many of the foundation engineering problems. Assuming that Pasternak shear layer consists of granular soil in the form of circular disc of thickness H and rests upon the Winkler spring, the vertical force equilibrium (Fig. 3) becomes,

$$q = p - \left(\frac{N_{rz}}{r} + \frac{\partial N_{rz}}{\partial r} \right) \tag{14}$$

where the transverse shear force along z-direction is expressed as,

$$N_{rz} = \int_0^H \tau_{rz}\, dz = \int_0^H G_p \frac{\partial w}{\partial r} dz = G_p H \frac{\partial w}{\partial r} \tag{15}$$

and

$$\frac{\partial N_{rz}}{\partial r} = \int_0^H \frac{\partial \tau_{rz}}{\partial r} dz = \int_0^H G_p \frac{\partial^2 w}{\partial^2 r} dz = G_p H \frac{\partial^2 w}{\partial^2 r} \tag{16}$$

Therefore, Eqn.14 can be rewritten in terms of vertical surface deformation as,

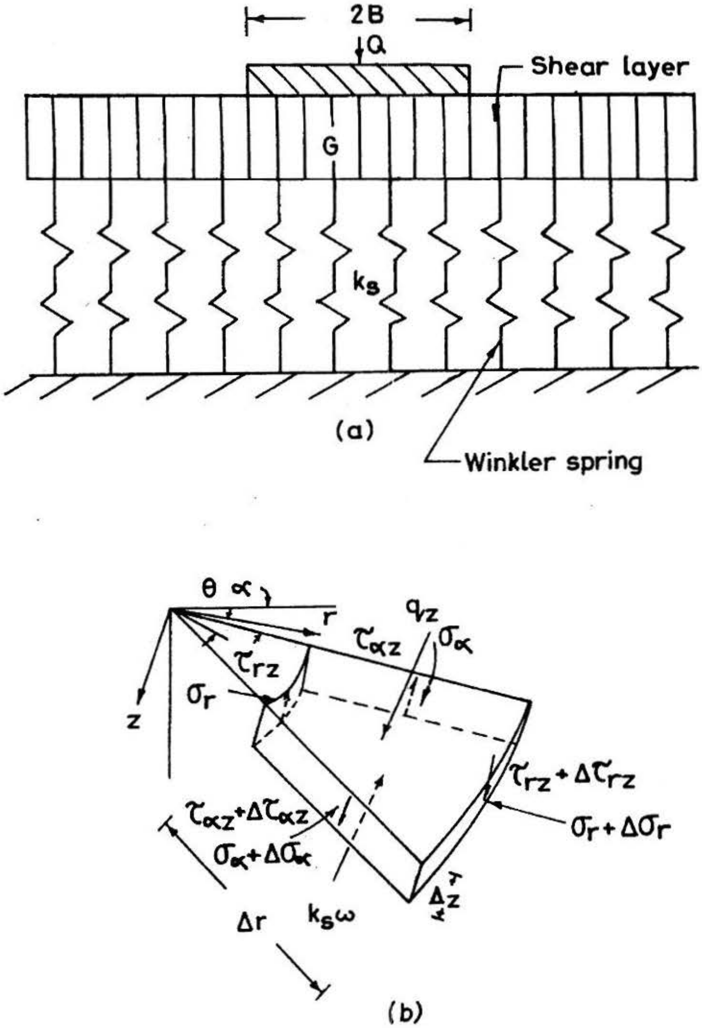

FIGURE 3 : The Pasternak Model-Definition Sketch (Axi-Symmetric Case)

$$q = k_s w - G_p H\left(\frac{1}{r}\frac{dw}{dr} + \frac{d^2w}{dr^2}\right) \tag{17}$$

In order to incorporate the nonlinear response of the soft soil and the granular fill, Eqn.17 is combined with Eqns.10 and 11 and expressing the same in nondimensional finite difference form as,

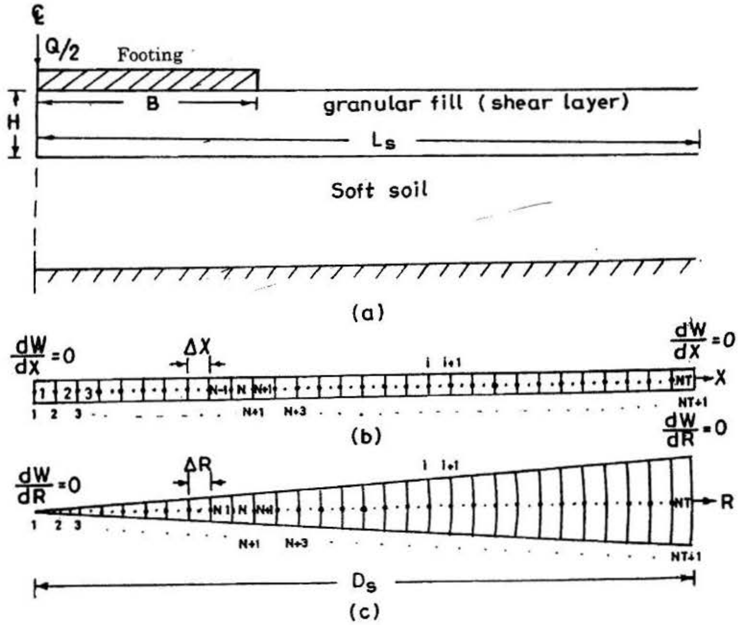

FIGURE 4 : Basic Foundation System and Finite Difference Scheme for (b) Plane Strain Case and (c) Axxi-Symmetric Case

$$q_i^* = \frac{W_i}{(1+B_w W_i)} - \frac{G^*}{\left(1+B_s \left.\frac{dW}{dR}\right|_i\right)^2} \left[\left\{ \frac{(W_{i+1}-W_{i-1})}{2\Delta R} \right\} \frac{\left(1+B_s \left.\frac{dW}{dR}\right|_i\right)}{R_i} + \left\{ \frac{W_{i-1}-2W_i+W_{i+1}}{\Delta R^2} \right\} \right] \qquad \text{........ (18)}$$

where $R = r/B$,

$G^* = G_p H / k_s B^2$,

$B_w = k_s B / p_u$,

p_u = ultimate stress taken by the soft soil at infinite settlement (Fig. 2a),

$B_s = G/\tau_m$,

τ_m = maximum shear stress of the granular fill (Fig. 2b), B = radius of the circular footing,

ΔR = step size and

i = node point in the finite difference scheme as shown in Fig. 4c.

The displacement and boundary loading conditions required for solving Eqn. 18 are,

$$\left.\frac{dW}{dR}\right|_i = 0 \quad \text{at } i = 1 \text{ and at } i = NT+1 \tag{19}$$

where NT is the total number of finite steps along the radius upto the extent of the shear layer (Fig. 4c) and

$$q_i^* = q^* \quad \text{for } 1 \leq i \leq N+1 \tag{20}$$

where N is the number of elements within the radius of the circular footing. At the node i = 1, numerical solution of the term $(dW_i/dR)/R_i$ is not possible. The same can be obtained either by subdividing the finite step length so that W_i can be solved at node point sufficiently closer to the centre or by the following limiting condition,

$$\lim_{R \to 0} \frac{1}{R}\frac{dW}{dR} = \frac{d^2W}{dR^2} \tag{21}$$

For rigid circular footing, a uniform vertical displacement, W_o, is specified and hence displacement boundary conditions for solving *Eqn. 18 are,*

$$W_i = W_o \quad \text{at } i = N+1 \tag{22a}$$

and

$$\left.\frac{dW}{dR}\right|_i = 0 \quad \text{at } i = NT+1 \tag{22b}$$

For convenience in the finite difference approximation, step size is taken as 0.1 and parametric results have been obtained for various extents of the granular layer. It has been found that for a granular layer extended upto three times the footing width and with step size of 0.1, error in the output remained

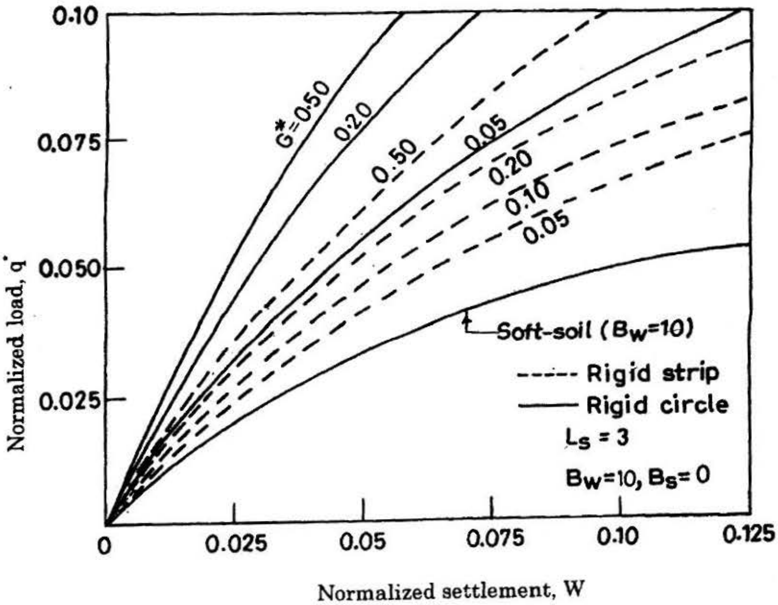

FIGURE 5 : Load – Settlement – Effect of Shear Parameter

within 2.5% of exact solution. In the following section discussions of the parametric results arising from numerical solution of Eqns.13 and 18 have been made. The various ranges of parameters used in the present study are given in the Appendix.

Parametric Study

The load-settlement responses of a rigid footing due to the shear resistance of a granular layer laid over a soft clay are depicted in Fig. 5, based on the analysis presented earlier. The ultimate resistance of the soft soil is characterised by the parameter B_w whose value is taken as 10. The shear layer response is linear i.e., $B_s = 0$. For a rigid strip footing the improvement with a granular fill with a small G^* (= 0.05), is significant. The initial slope is much steeper and the ultimate load of the granular layer–soft soil system is more than 150% of the soft soil alone. For stiffer granular layers, both initial stiffness and ultimate load are much more than those for $G^* = 0.05$. At a load intensity, q^* of 0.025, and the normalised settlements of soft soil, and soft soil with shear layer with $G^* = 0.05$ and 0.20, are 0.033, 0.026 and 0.019 respectively. At higher loads the reduction in settlement due to granular shear layer is much more. This improvement is possible because the shear layer distributes the applied load over a wider

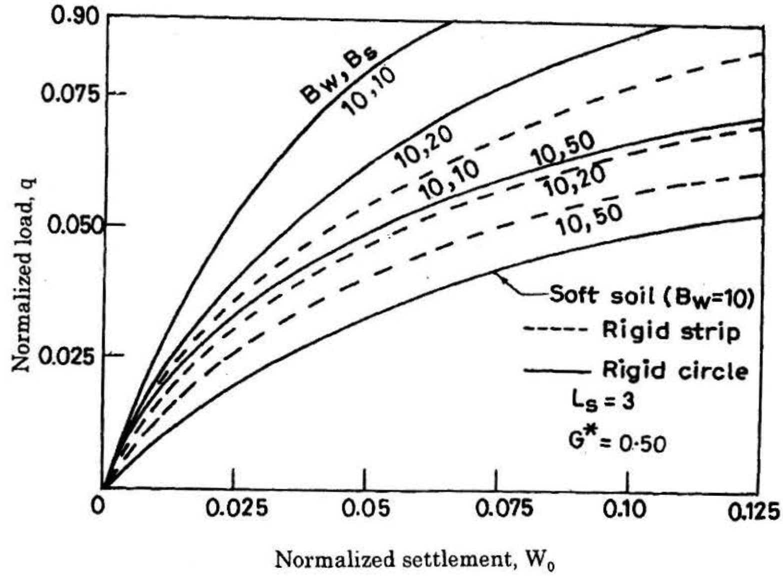

FIGURE 6 : Load – Settlement Response – Effect of B_w and B_s

area. The width of the load spread on the soft clay increases with the shear stiffness of the granular fill. In the limit, if the shear stiffness of the granular layer tends to infinity, the settlement of the footing is practically zero. The response of a rigid circular footing over a granular fill-soft soil system is much better than that of a strip footing due to axi-symmetric conditions compared to plane strain conditions. In the former case, the load spread occurs in all the directions in a horizontal plane while in the latter it takes place only sideways. For $G^* = 0.05$, the settlements of a rigid circular footing on soft soil alone, and on a granular fill-soft soil system with $G^* = 0.05$ and 0.20, are 0.033, 0.018 and 0.011 respectively. For a given stress level the settlements reduce to a fraction if a granular layer is interposed between the rigid circular footing and the soft soil. The ultimate loads of the footing also are high since the shear layer is considered to behave linearly. The footing response curves for the case where the shear layer also has a nonlinear finite strength response, are presented in Fig. 6. The parameter, B_s, characterises the ultimate shear resistance of the granular fin. Higher the value of B_s, lower is its ultimate shear resistance. The shear stiffness of the layer, G^*, is 0.05. In this instance, i.e. with $B_s > 0$ the improvements in load-settlement responses of both rigid strip and circular footings are significant but not as significant as in the case of shear layer with linear response. For rigid strip footing the settlements at a load intensity of $q^* = 0.025$, are 0.033, 0.025, 0.020, and 0.017 for soft soil, and soft soil-granular fill system with $B_s = 50$, 20 and 10 respectively. Stronger the shear layer, the smaller would

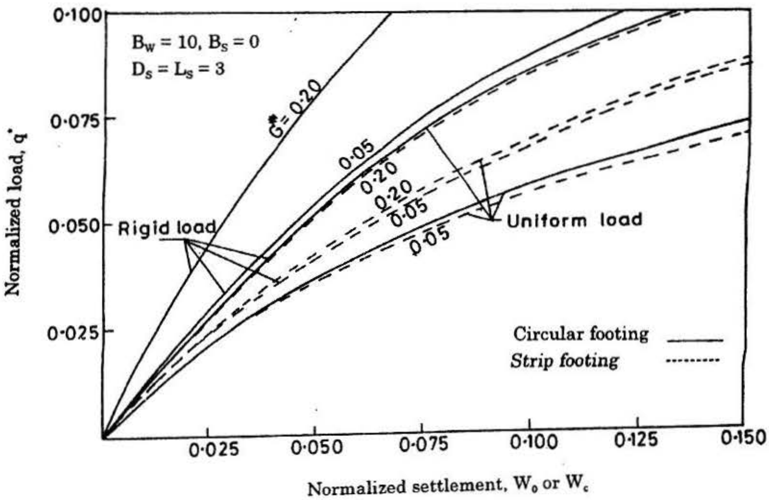

FIGURE 7 : Load – Settlement Response – Effect of Footing Shape and Rigidity

be the settlements under a given load. Similar but significantly smaller settlements are predicted in case of a rigid circular footing on granular fill-soft soil system. A stiff but not so strong a shear layer also improves the load-settlement response of footings.

The improvement in the load-settlement response of a granular fill-soft soil foundation system due to the shape and rigidity effects of both strip and circular footings are depicted in Fig. 7. The resistance parameter of soft soil, B_w is 10 and the granular fill behaves linearly i.e. $B_s = 0$. Shear layer under axi-symmetric (rigid footing) conditions mobilizes much higher shear resistance than under plane strain conditions. This observation is true for footings under uniform load also. For the same applied load, settlements below the rigid footing are much lower than the central settlements of uniformly loaded footings. This aspect is more pronounced in case of circular footings than in case of strip footings. For example, at an applied load intensity, q^* of 0.05 and for normalised granular fill shear stiffness $G^* = 0.05$, settlement at the centre below rigid and uniformly loaded strip footings are 0.064 and 0.084 respectively. The corresponding settlement for rigid and uniformly loaded circular footing are 0.047 and 0.078 respectively. Different ultimate resistance values for a granular fill with $G^* = 0.1$ and $B_s = 0$ are shown in Fig. 8. Larger the value of B_w, smaller is its ultimate resistance. The improvement in load-settlement response due to the granular fill in case the soil is weaker is much more than if it is stronger. The settlements of a rigid circular footing on a soft soil alone and on soft soil-granular fill system are 0.075 and 0.025, 0.051 and 0.020 and 0.03 and

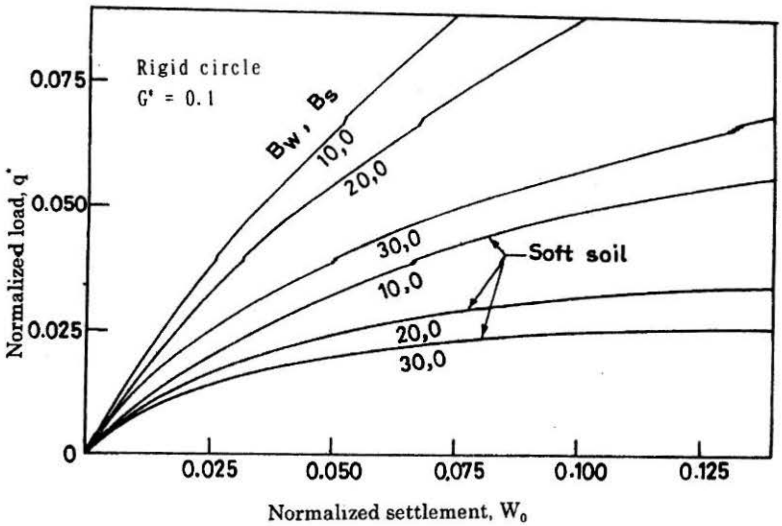

FIGURE 8 : Load – Settlement Response – Effect of B_w

0.015 respectively for B_w equal to 30, 20, and 10. The efficiency of the granular fill is much more if laid over a softer clay since the load spread reduces the stresses to a lower range and thus improves the over all response of the footings.

The settlement profiles of a strip footing over a granular fill (B_s = 0) on a soft soil with B_w = 10, for a load intensity of q^* = 0.05 can be seen in Fig. 9 for different values of shear stiffnesses. In the absence of a shear layer, the soft soil responds like a Winkler medium with a uniform settlement W equal to 0.1 beneath the footing and with no settlement outside the footing. With increasing values of G^* the settlements beneath the footing decrease while those outside the footing width, increase significantly. The central settlements are 0.1, 0.065, and 0.04 for soft soil alone, and granular fill-soft soil system with G^* equal to 0.2 and 1.0 respectively. The settlement at the edge of the footing in all the cases are nearly the same. The settlements at the edge of the shear layer increase with G^*. The phenomenon of load spread due to the stiffness of the granular fill discussed earlier is corroborated by the settlement profiles. The granular layer spreads the applied load more efficiently if its shear stiffness is larger.

The reduction in settlement in case of a uniformly loaded circular footing is much more than that of a strip footing (Fig. 10). The results for a soil with B_s = 0 the central settlements of the soft soil alone, and uniformly loaded strip and circular footing under a load intensity q^* equal to 0.05, are

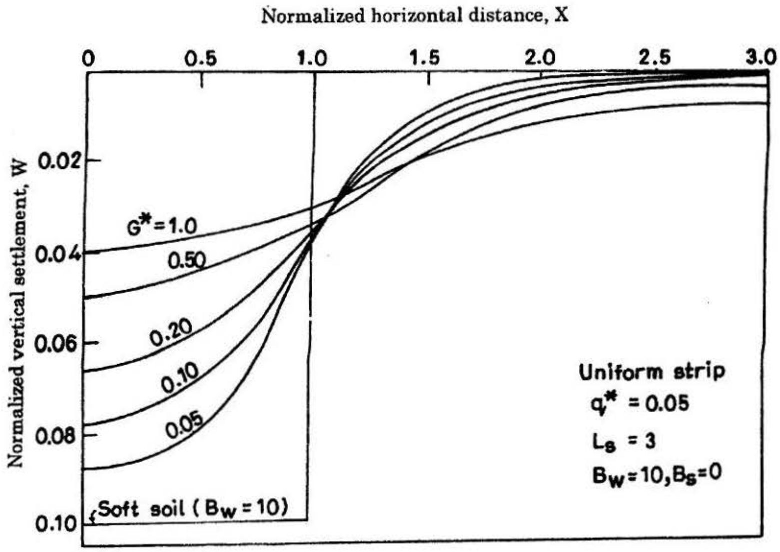

FIGURE 9 : Surface Deformation Profile – Effect of Shear Parameter G^*

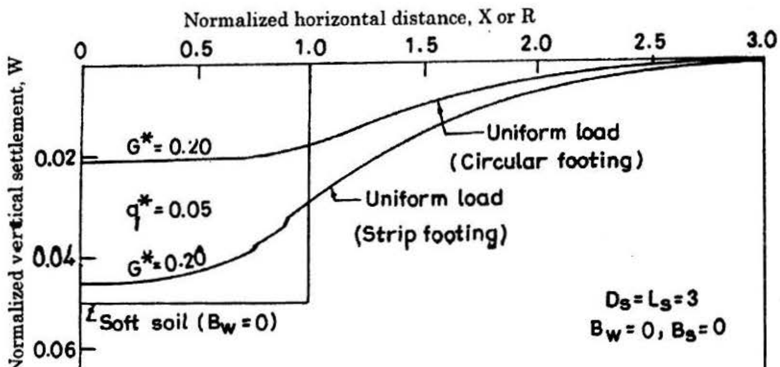

FIGURE 10 : Settlement – Distance Profile – Shape Effect of Footing

respectively 0.05, 0.046, and 0.021. Thus while for a strip footing, the settlement reduces by only 8% due to a granular fill with $G^* = 0.2$, the corresponding reduction is 58% for a circular footing. This result once again, is a consequence of the axi-symmetric conditions.

The settlement-distance profiles for a rigid strip on soft soil-granular fill system is shown in Fig. 11. In case of a rigid footing, the solution is obtained

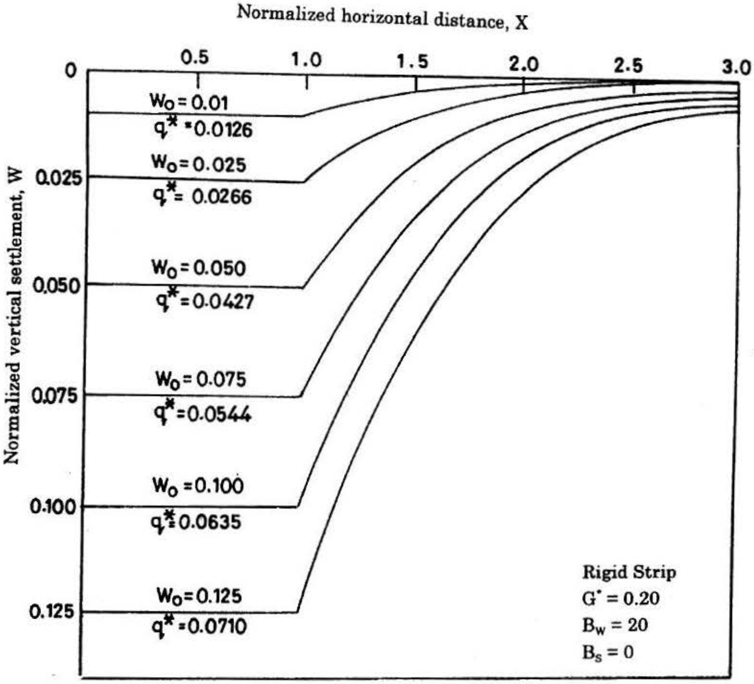

FIGURE 11 : Settlement – Distance Profile for Various Rigid Footing Displacements

for a given footing displacement. From the settlement profile so derived, the stresses on the soft soil are calculated from Eqn. 13, and integrated to obtain an equivalent uniform load corresponding to the given displacement. The curves in Fig. 11 are for $G^* = 0.2$ and depict wider spread of displacements with increasing footing displacements. At footing displacement of 0.025, 0.05, and 0.1, the corresponding settlements of the system at a normalized distance *of 2.0, are 0.0035, 0.0075 and 0.018 respectively.*

All the results presented earlier are for a shear layer of lateral extent equal to three times the width of the footing. The effect of the lateral extent of the shear layer on settlement profiles is presented in Fig. 12 for $G^* = 0.05$, $B_w = 10$ and $B_s = 20$. Extending the shear layer beyond three times the width of the footing has only a marginal effect on the overall response of the system. Settlements upto a distance of 2.4 times the footing width are unaffected for values of $L > 3.0$. The settlements at the edge of the granular fill decrease with increasing values of L. It can be surmised that for the usual values of shear stiffness ($G^* < 0.05$), the load spread does not extend beyond distances $X = 2.5$ to 3.0. Thus provision of wider granular fill i.e. $L > 3.0$ is not beneficial.

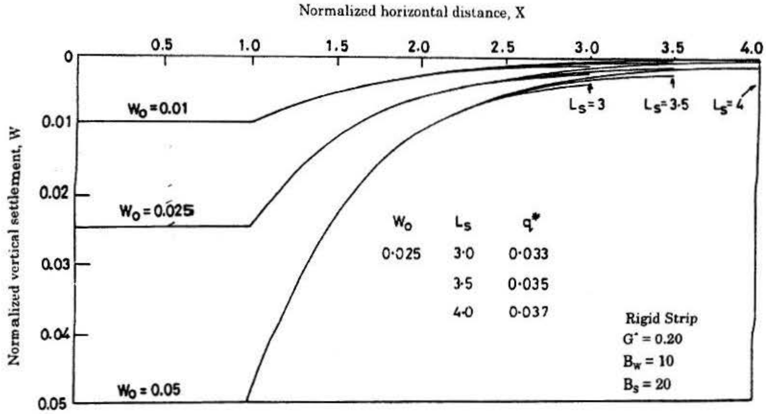

FIGURE 12 : Settlement – Distance Profile – Effect of Extent of Granular Fill

The shear stresses mobilized in the granular fill beneath a uniformly loaded circular footing for a load of intensity $q^* = 0.075$, and for $G^* = 0.10$, and $B_w = 0$, can be seen in Fig. 13. The shear stresses increase from zero at the centre to a maximum beneath the edge, and reduce with distance for points beyond the edge. For the granular fill with linear response the maximum normalized shear stress is nearly 0.01. This value decreases with increasing values of B_s i.e. for weaker granular fills.

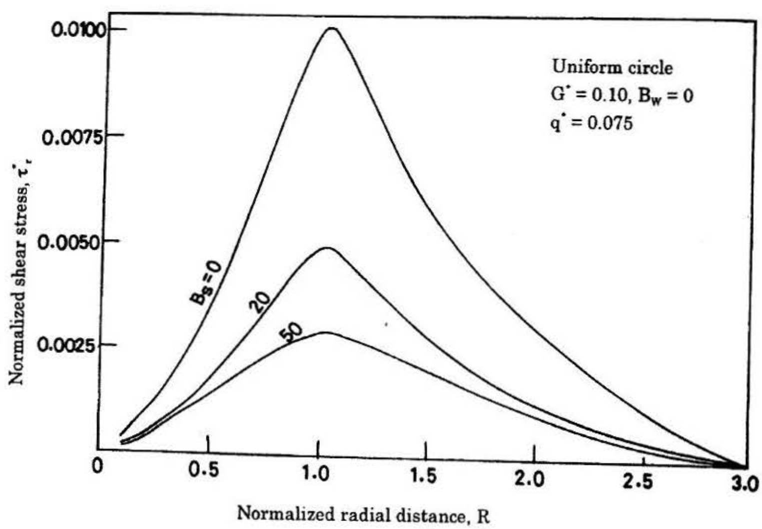

FIGURE 13 : Shear Stress – Distance Profile – Effect of B_s

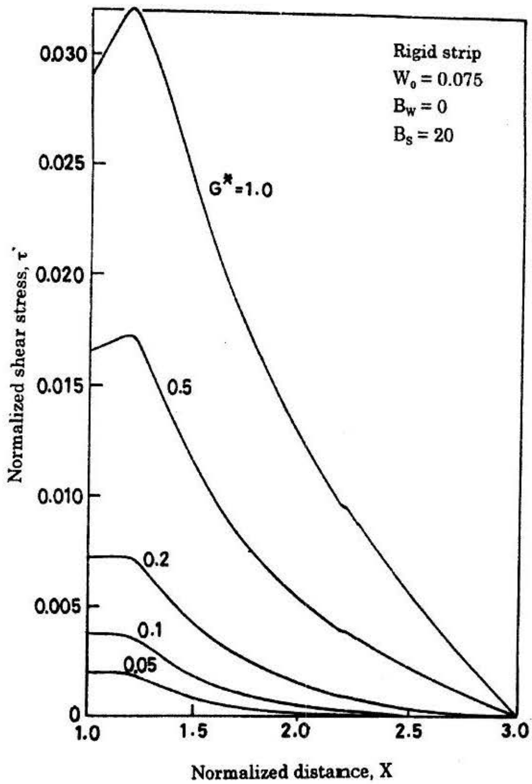

FIGURE 14 : Shear Stress – Distance Profile – Effect of G^*

For a rigid footing on a granular fill underlain by a soft soil with a linear load-settlement response, the shear stress-distance profile can be seen in Fig. 14. For $W_0 = 0.075$, the variation of shear stresses with distance as *influenced by shear stiffness* G^* *can be seen in this figure.* In case of low shear stiffness of the granular fill ($G^* = 0.2$), the shear stresses in the fill are uniform beneath the footing and decrease with distance beyond X (=1.2). The shear stresses attain peak values at this distance (X = 1.2) for $G^* \geq 0.2$. This type of response could be due to the effect of better load spread achieved in case of stiff granular fills.

This phenomenon of shear stress in the granular fill peaking just beyond the footing edge in case of rigid footings, is illustrated in Fig. 15 where the curves are drawn for a soft soil with $B_w = 10$ and B_s values of 10, 20 and 50. The maximum values of shear stresses are 0.024, 0.17 and 0.0088 for B_s values of 10, 20 and 50 respectively. It may also be noted that the shape of the shear stress distance curve flattens with decreasing strength of the shear

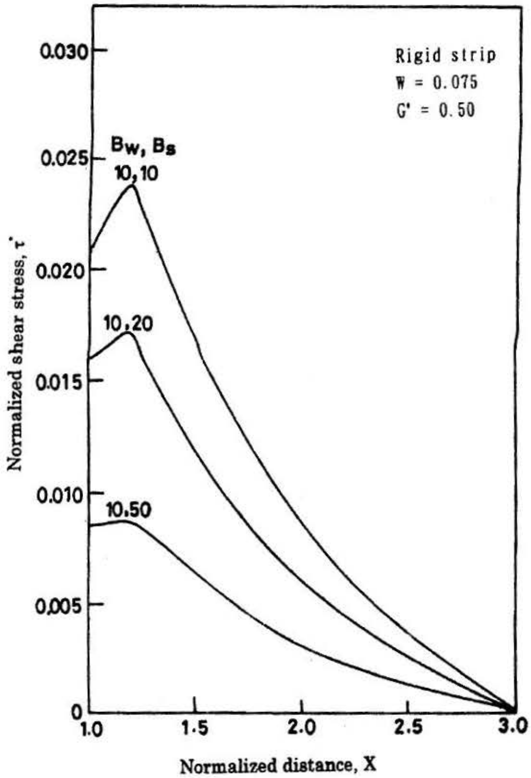

FIGURE 15 : Shear Stress – Distance Profile – Effect of B_w, B_s and G^*

layer, since the shear stress tends to its ultimate shear resistance.

Evaluation of Model Parameters

In order to evaluate the model parameters in realistic units, experimental findings of Kenny (1998, Fig. 2) are reproduced in Fig. 16. Only unreinforced sandy soil (with $H/B = 0.5$, 1.0 and 2) placed over soft clay ($H/B = 0.0$) are important in the present context. It is to be noted that while obtaining model parameters as per formulations presented in this paper, half width of the footing is taken as 0.06 m. From the load settlement plot for soft clay, the initial slope, herein considered as k_s (modulus of subgrade reaction) is obtained as 4286 kN/m^2 and q_{ult} for soft clay is estimated as 60 kN/m^2. The normalized soft soil nonlinear parameter, B_w ($= k_s B/q_{ult}$) is 4.29. From the present experimental data, the other two parameters, G^* and B_s cannot be easily evaluated. However, an attempt is being made to evaluate static (approximate) G^* from the load-settlement plot for $H/B = 2.0$. In this plot

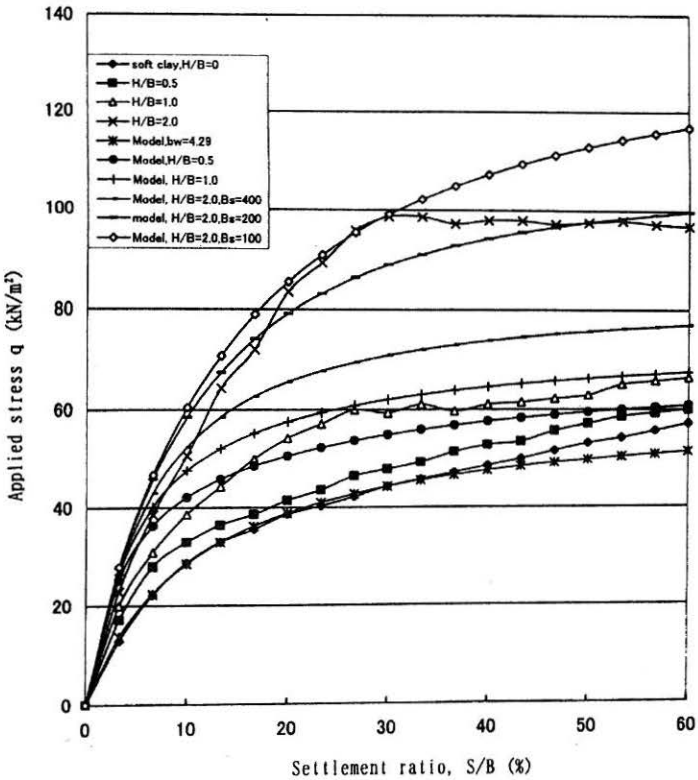

FIGURE 16 : Comparison of Predicted and Experimental Results (Kenny, 1988)

$k_{s\,(sand)}$ is obtained as 5000 kN/m^2 and elastic modulus of sand (cf. Bowels, 1988, page 322, 184) can be estimated as 423.12 kN/m^2 (where for rigid square footing, $I_w = 0.82$, $\nu = 0.4$, $B = 0.12\,m$). Consequently, the static shear modulus of sand, G is obtained as 151.11 kN/m^2. Therefore, normalized shear parameter G^* as per Eqn. 13 can be obtained as 0.587, 1.175, 2.35 respectively for H/B = 0.5, 1.0, 2.0 respectively. Now with the above input data, the computer program made for solving Eqn. 13, was run for various values of B_s. The normalized load (q^*) obtained was multiplied by $k_{s\,(clay)}B$ and results are presented in Fig. 16. It is observed that predicted and experimental values compared well for the soft soil alone. Due to the lack of proper experimental data, the evaluated G^*, is overly approximate. However, the present analysis can effectively demonstrate the feasible ranges of model parameters as depicted in Fig. 16.

Conclusions

A granular fill-soft soil system is represented by the two parameter Pasternak model. The model is modified to include the nonlinear load-settlement response of the soft soil and shear stress-shear strain response of the granular fill. Formulations have been presented for both rigid and flexible footings under plane strain and axi-symmetric loading conditions respectively. All model parameters are expressed in non dimensional terms. Parametric study reveals that a thin granular base ($H < B$) laid over the soft soil spreads the load over a wider area on the soft soil resulting in the reduction of the settlement. A granular fill of extent of three times the footing width is found sufficient to reduce the settlement by a significant amount. With the increase in B_w and B_s together, the response of the two layer foundation tends to that of the soft soil response. Compared to uniformly loaded footing, the response is significantly better for rigid footing. Rigidity effects are more pronounced at lower shear stiffness (G^*) of the granular fill. Evaluation of model parameters from laboratory model test corroborates the importance of present parametric study.

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