Landmarks in Earth Reinforcement, Ochiai et al. (eds),
 ISBN 90 2651 863 3

Multi-layered reinforced granular soil resting on soft soil – tension membrane effect

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ABSTRACT: The effect of applied surface loading on reinforced soil structures have been conveniently obtained in the form of increase in load bearing capacity/stability enhancement which are mainly expressed in terms of degree of improvement compared to the unreinforced ones. In this paper with the help of Pasternak's model, the granular fill have been modified to include the effect of no. of layers of reinforcement in plain strain loading situation. Nonlinear hyperbolic responses of the granular and soft soil are introduced into the formulation. Parametric results reveal that reinforcement action is significant at lower stiffness of the granular fill and tensile forces are maximized at the center of the foundation. Reinforcement layer of 3 times the footing width placed within significant depth below footing is sufficient for effective improvement.

1 INTRODUCTION

In order to build structures on soft soil granular fill are often spread out so that underlying soft soil experience less pressure. Else due to low load bearing capacity soft soil often requires replacement or modification of its nature by mechanical or chemical method. Use of planar reinforcement (e.g. woven and non-woven geosynthetics, geogrids, etc.) in granular soil helps the load spreading efficiency and thus ensures betterment in the load settlement behaviour. Usually 2 to 3 layers of such materials extending 2 to 3 times the footing width are placed within depth of 1 to 1.5 times the footing width. Quite extensive experimental investigations are reported in the literature but analytical treatise to this kind of reinforced soil system is very few. Moreover realistic analytical explanations are yet to be far from the behaviour traditionally obtained in the small-scale model tests. Efforts have been made by many to evaluate the nature of tensile forces both experimentally and numerically. Considerably umpteen numbers of analytical and mathematical models are available in the literature to recast above problems from the viewpoint of realistic quantification and prediction of the actual behaviour. The basic aim of all such approaches have been primarily to predict the amount of tensile force developed within the reinforcement so that a choice could be made for the design geosynthetic requirement. Almost same has been the approach for the stability requirement of the reinforced earth retaining wall system, reinforced slope or embankment structures. In none of these investigations, the effect of tensile reinforcement (extensible, e.g. planar geosynthetics or inextensible, eg. iron or aluminium metal strips) on the internal system modification could be accounted for. Some way of looking into such behaviour could be in the form of interaction shear transfer, soil-reinforcement interlock, and lateral bearing effect in case of grid reinforcement or adhesion effect in case of reinforced clay.

Pastemak type model has been found suitable to describe the mechanical response of such foundation system. This model has been modified to include the nonlinear response of the soft soil as well as granular fill (Ghosh and Madhav, 1999). An extension of the same for single layer reinforced granular fill has been presented by Ghosh and Madhav (1994a, 1994b). This paper presents "tension membrane" effect of multi-layer reinforced system for plain strain loading condition.

2 SOIL-REINFORCEMENT INTERACTIONS

Schematic of soil-reinforcement interactions in granular fill-soft soil foundation system are shown in Fig. 1. Interaction between granular soil and planar reinforcement layer has been represented in terms of "tension" and "confinement" effect, both separately and together, which is here in called "combined" effect. Ideally a reinforcement layer becomes effective in tension as well as confinement of the surrounding soil. Confinement of the soil mainly derives from the inward shear forces at the soil-reinforcement interface. In this paper "tension" effect of reinforcement has been formulated for plain strain loading.

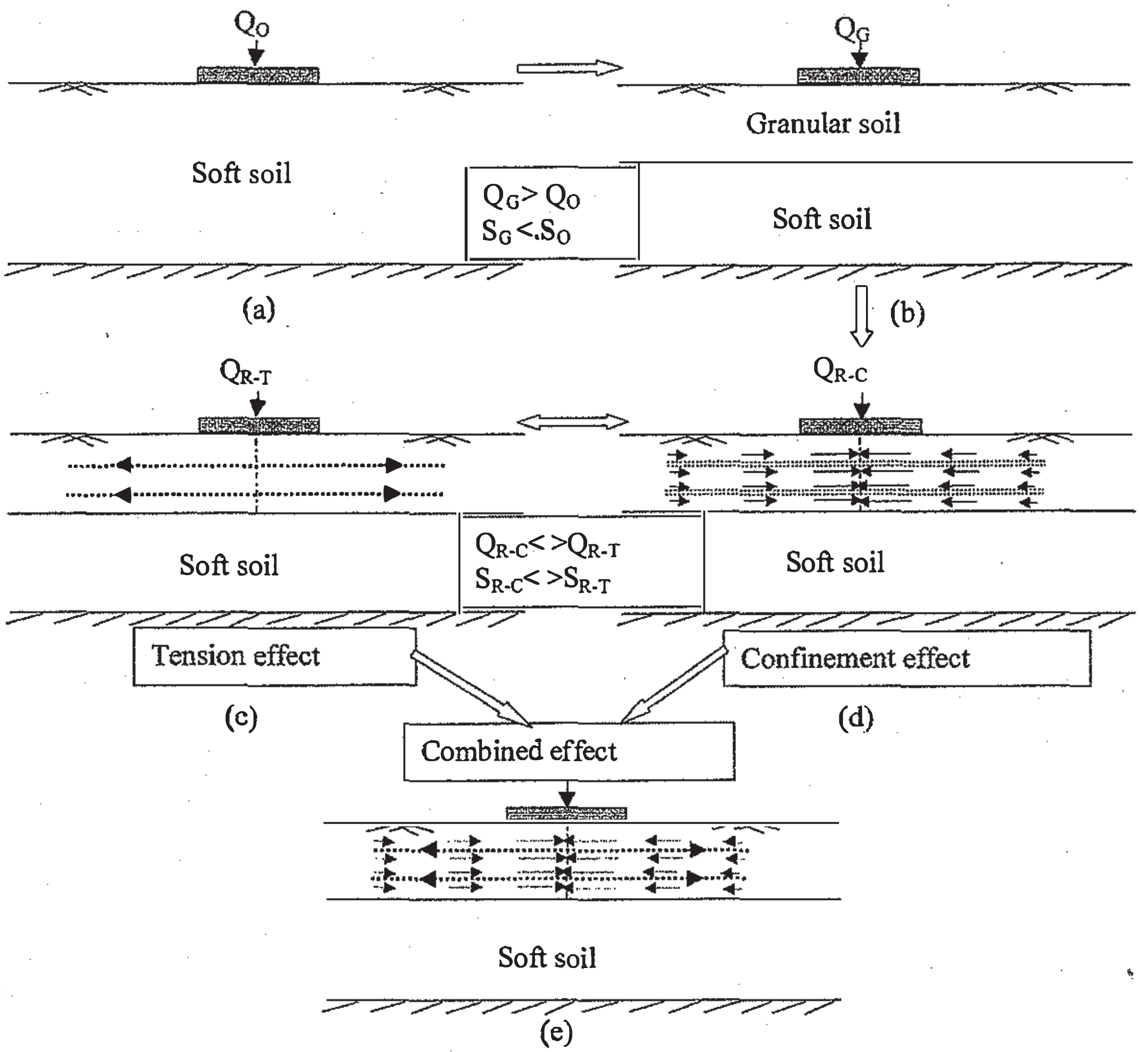

Figure 1. Shematic of soil-reinforcement interaction mechanisms in foundation beds.

3 TENSION EFFECT

In Fig. 2, schematic of granular bed and reinforcement are shown. Due to applied load (in case of uniformly loaded footing)/ displacement (in case of rigid footing), the foundation deforms. The granular soil is assumed as Pasternak shear layer in 1-Dimension. As a consequence same amount of deformation will be transmitted to the soft soil, which is conveniently idealized by Winkler spring. With increasing deformation, the reinforcement will develop tensile forces, which is due to frictional bond between granular soil and reinforcement. Below a formulation of the same is being presented for multi-layer reinforced foundation bed.

4 FORMULATIONS

Positions of reinforcement are shown in Fig.3a. In most of the design practice, 2 to 3 layers are commonly adopted. Herein 3 layers are being used for the analysis. Bottommost layer is placed at the interface of granular soil and soft soil. Position of each layer and granular soil are defined with shear modulus (G), thickness of soil (h) and interface friction (μ) at both faces of the reinforcement. As per Pasternak's concept granular soil is assumed incompressible in the vertical direction and hence all the reinforcement layers will remain parallel to each other, both before and after the load application. The reinforced soil element is discretised in Fig. 3b. The unknowns are, the surface deformation (w) and tensile forces in respective layers. The governing equations for plain strain loading conditions are as follows:

$$q = q_1 - G_1H_1 \frac{d^2w}{dx^2} \tag{1a}$$

$$q_1 = q_2 \frac{1-\mu_{12}\tan\theta}{1+\mu_{11}\tan\theta} - \frac{T_1\cos\theta}{1+\mu_{11}\tan\theta}\frac{d^2w}{dx^2} \tag{1b}$$

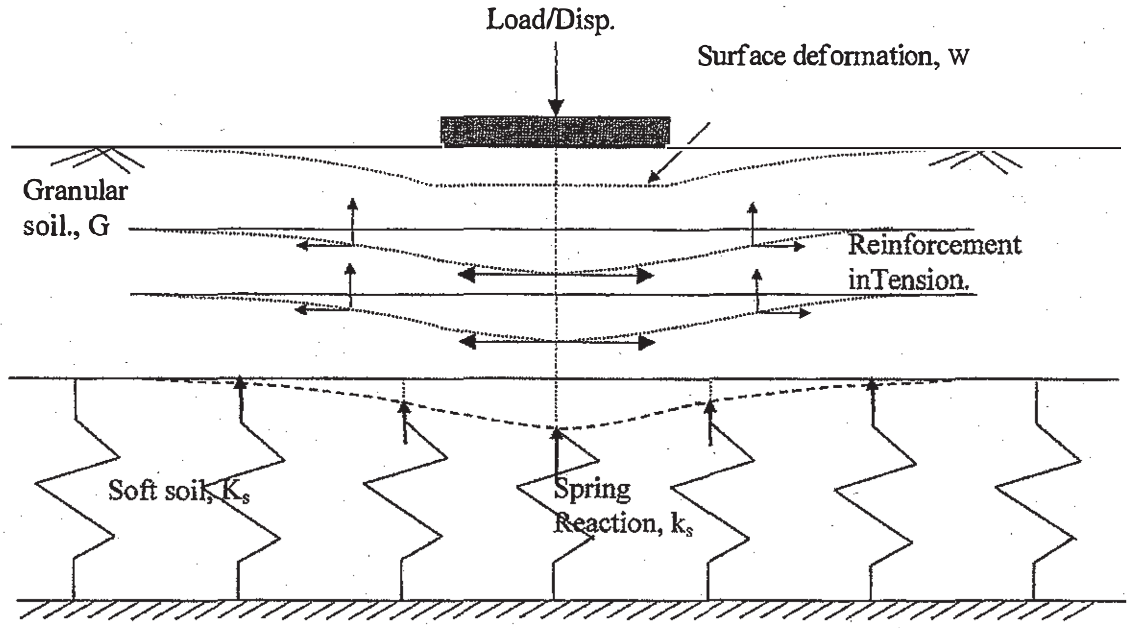

Figure 2. Tensile membrane mechanism – two layers reinforced foundation bed.

$$q_2 = q_3 - G_2H_2\frac{d^2w}{dx^2} \quad (1c)$$

$$q_3 = q_4\,\frac{1-\mu_{22}\tan\theta}{1+\mu_{21}\tan\theta} - \frac{T_1\cos\theta}{1+\mu_{21}\tan\theta}\,\frac{d^2w}{dx^2} \quad (1d)$$

$$q_4 = q_5 - G_3H_3\frac{d^2w}{dx^2} \quad (1e)$$

$$q_5 = q_6\,\frac{1-\mu_{32}\tan\theta}{1+\mu_{31}\tan\theta} - \frac{T_1\cos\theta}{1+\mu_{31}\tan\theta}\,\frac{d^2w}{dx^2} \quad (1f)$$

$$q_6 = k_s w \quad (1g)$$

$$\frac{dT_1}{dx} = -\,(\mu_{11}\cos\theta-\sin\theta)q_1 - (\mu_{12}\cos\theta-\sin\theta)q_2 \quad (1h)$$

$$\frac{dT_2}{dx} = -(\mu_{21}\cos\theta-\sin\theta)q_3 - (\mu_{22}\cos\theta-\sin\theta)q_4 \quad (1i)$$

$$\frac{dT_3}{dx} = -\,(\mu_{31}\cos\theta-\sin\theta)q_5 - (\mu_{32}\cos\theta-\sin\theta)q_6 \quad (1j)$$

The above equations are interdependent. They can be conveniently expressed into equations with four unknowns as w, T1, T2 and T3. Combining Eqns. 1, the final expression for applied load, q is,

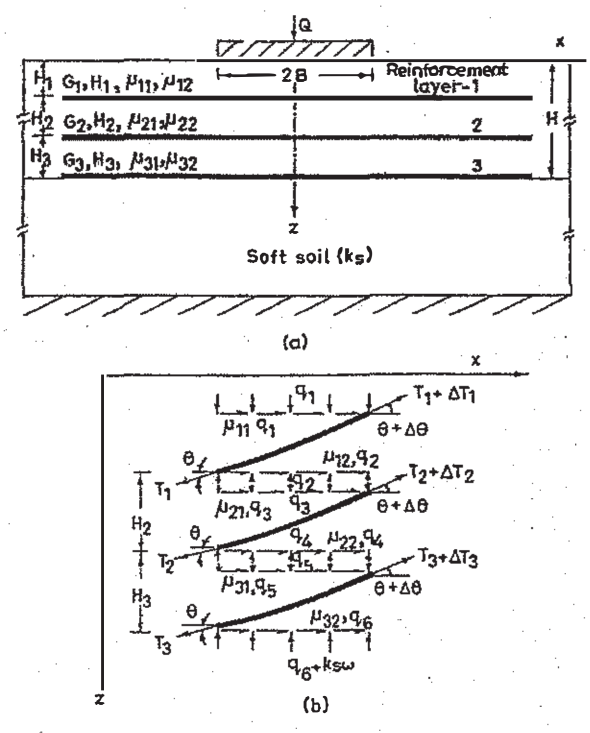

Figure 3. Definition sketch – (a) Reinforced granular fill overlying soft soil, (b) Reinforced soil element.

$$q = \left(\frac{1-\mu_{12}\tan\theta}{1+\mu_{11}\tan\theta}\right)\left(\frac{1-\mu_{22}\tan\theta}{1+\mu_{21}\tan\theta}\right)\left(\frac{1-\mu_{32}\tan\theta}{1+\mu_{31}\tan\theta}\right)$$

$$k_s w - [G_1H_1 + G_2H_2\left(\frac{1-\mu_{12}\tan\theta}{1+\mu_{11}\tan\theta}\right) + G_3H_3$$

$$\left(\frac{1-\mu_{12}\tan\theta}{1+\mu_{11}\tan\theta}\right)\left(\frac{1-\mu_{22}\tan\theta}{1+\mu_{21}\tan\theta}\right)+\frac{T_1\cos\theta}{1+\mu_{11}\tan\theta}+$$

$$\frac{T_2\cos\theta}{1+\mu_{21}\tan\theta}\left(\frac{1-\mu_{12}\tan\theta}{1+\mu_{11}\tan\theta}\right)+\frac{T_3\cos\theta}{1+\mu_{31}\tan\theta}$$

$$\left(\frac{1-\mu_{12}\tan\theta}{1+\mu_{11}\tan\theta}\right)\left(\frac{1-\mu_{22}\tan\theta}{1+\mu_{21}\tan\theta}\right)] \tag{2}$$

Now substituting Eqns. 1a and 1b into Eqn. 1h, we get for T_1 as,

$$\frac{dT_1}{dx}+T_1\left[\frac{(\mu_{12}\cos\theta+\sin\theta)\cos\theta}{1-\mu_{12}\tan\theta}\right]\frac{d^2w}{dx^2}=$$

$$-\{(\mu_{11}\cos\theta-\sin\theta)+(\mu_{12}\cos\theta+\sin\theta)$$

$$\left(\frac{1+\mu_{11}\tan\theta}{1-\mu_{12}\tan\theta}\right)\}(q+G_1H_1\frac{d^2w}{dx^2}) \tag{3}$$

From Eqn. 1j, we get for T_2 as,

$$\frac{dT_2}{dx}+T_2\ (\mu_{22}\cos\theta+\sin\theta)\ \frac{\cos\theta}{1+\mu_{22}\tan\theta}\ \frac{d^2w}{dx^2}=$$

$$\{(\mu_{21}\cos\theta-\sin\theta)+(\mu_{22}\cos\theta+\sin\theta)$$

$$\left(\frac{1-\mu_{21}\tan\theta}{1-\mu_{22}\tan\theta}\right)\}\{(q+G_1H_1\frac{d^2w}{dx^2})\left(\frac{1+\mu_{11}\tan\theta}{1-\mu_{12}\tan\theta}\right)+$$

$$G_2H_2\frac{d^2w}{dx^2}+\frac{T_1\cos\theta}{1+\mu_{11}\tan\theta}\frac{d^2w}{dx^2}\} \tag{4}$$

Similarly from Eqn. 1j,

$$\frac{dT_3}{dx}-\frac{T_3\cos\theta}{1+\mu_{31}\tan\theta}\frac{d^2w}{dx^2}=-\{(\mu_{31}\cos\theta-\sin\theta)$$

$$\left(\frac{1-\mu_{32}\tan\theta}{1+\mu_{31}\tan\theta}\right)+(\mu_{32}\cos\theta+\sin\theta)\}k_s w \tag{5}$$

Now introducing hyperbolic nonlinearity for the soft soil (b_w) as well as for the granular soil (b_s), all the four equations are expressed in non dimensional finite difference form. Gauss-Seidal iteration technique has been used to solve the equations. Minimum step size of 0.05 was found sufficient. Displacement boundary conditions were taken as that slope at the centre as well as at the far extent of the granular fill are zero. For uniformly loaded strip footing, applied load within the footing width is taken as uniform and zero at elsewhere. For rigid footing, displacement is taken as uniform within the footing zone. For the reinforcement, tensile forces at the ends are taken as zero or it can be specified if the effect of end anchorage is required.

5 RESULTS AND DISCUSSIONS

Load-settlement responses of the reinforced foundation are shown in Fig. 4. In this case only 'tension membrane' effect are depicted in qualitative terms for rigid strip footing. With increasing number of reinforcement layers, load carried by the footing also increased. This model cannot identify optimum no. of reinforcement layers required for the design. The nonlinear parameter (B_w = k_sB/p_u) for soft soil is taken as 20 and for granular fill B_s =0. Interface friction coefficients at both top and bottom faces are taken as 0.3. Lengths of all reinforcement layers, L are taken 3 times the footing width, B. Normalised load q^* (=q/k_sB) is plotted against settlement of the induced displacement, W_0 (=w/B). Effect of granular soil stiffness is presented in Fig. 4. For ten fold increase in shear stiffness (G^* (=GH/k_sB^2) = 0.05 to 0.5) load carried by footing also increased significantly. With stiffer granular soil effect of tensile reinforcement is small. However, reinforcement layers contribute significantly in the confinement enhancement of the granular soil (Ghosh and Madhav, 1994b).

Settlement-distance profiles of the rigid strip and uniformly loaded strip footing are shown in Fig. 5 and Fig. 6. Load carried by the rigid strip footing for given settlement are calculated from the integration of the surface deformation profile and they are shown in Fig. 5. With more reinforcing layers, the footing carries more load. This is being indicated as larger spreading of surface deformation profile outside the footing base. Load spread is more with higher W_0 which means membrane action is effective at larger displacement of the footing. Relative reduction in the settlement of uniformly loaded footing at the center is more at lower load intensity (Fig. 6). However, surface deformation is more or less limited within 2.5 times the footing width.

6 CONCLUSIONS

Various parametric studies reveal that with suitable selection of B_w and B_s model tests results can be compared with the present analysis. Model parameters, like k_s is usually evaluated as initial slope of the load-settlement plot of soft soil. Shear stiffness of the granular soil (G) are obtained from standard laboratory or field tests. Interface friction coefficients are obtained from the pullout or modified direct shear tests.

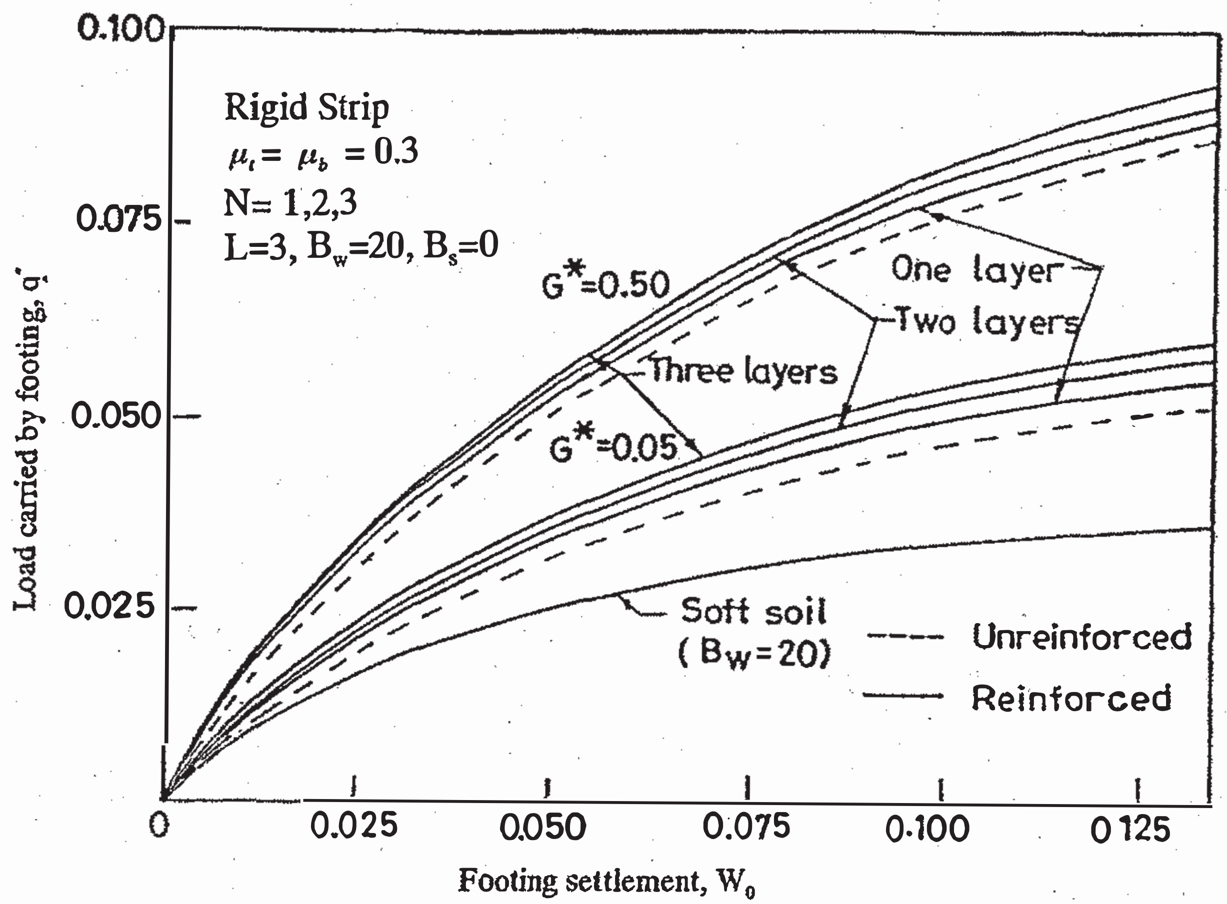

Figure 4. Load vs. settlement response – effect of number of reinforcing layers (N) and shear stiffness of granular soil (G).

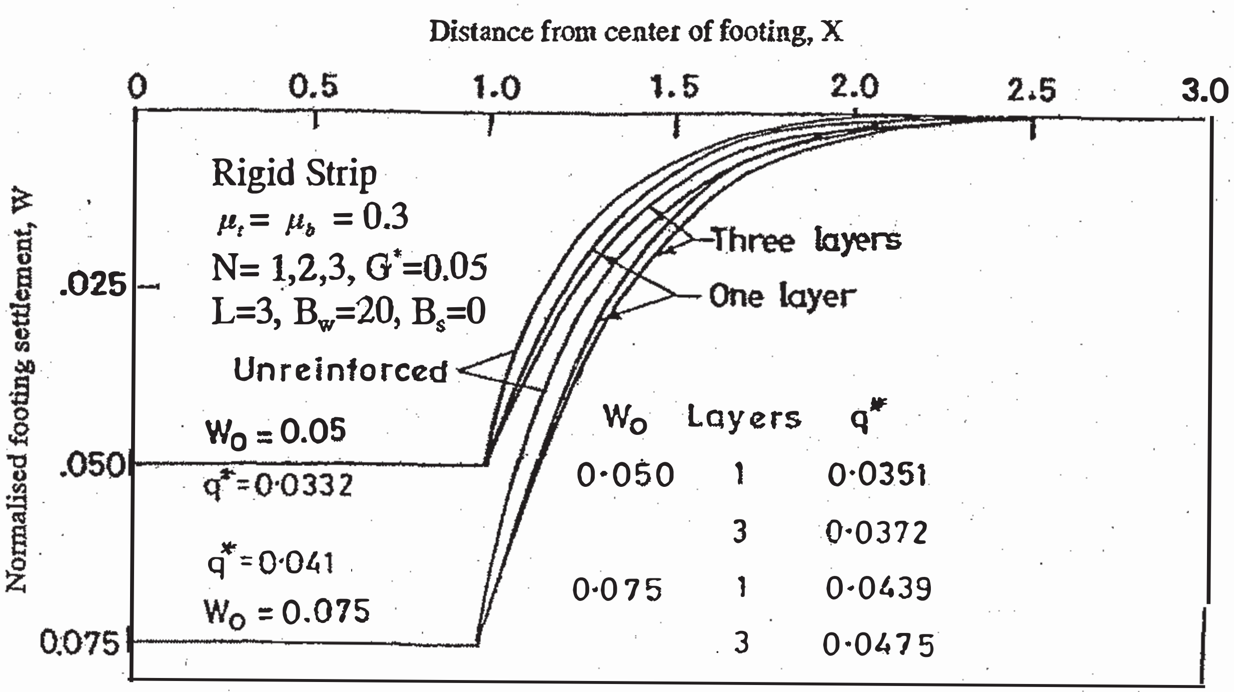

Figure 5. Surface deformation profile for rigid strip footing – effect of number of reinforcing layers (N).

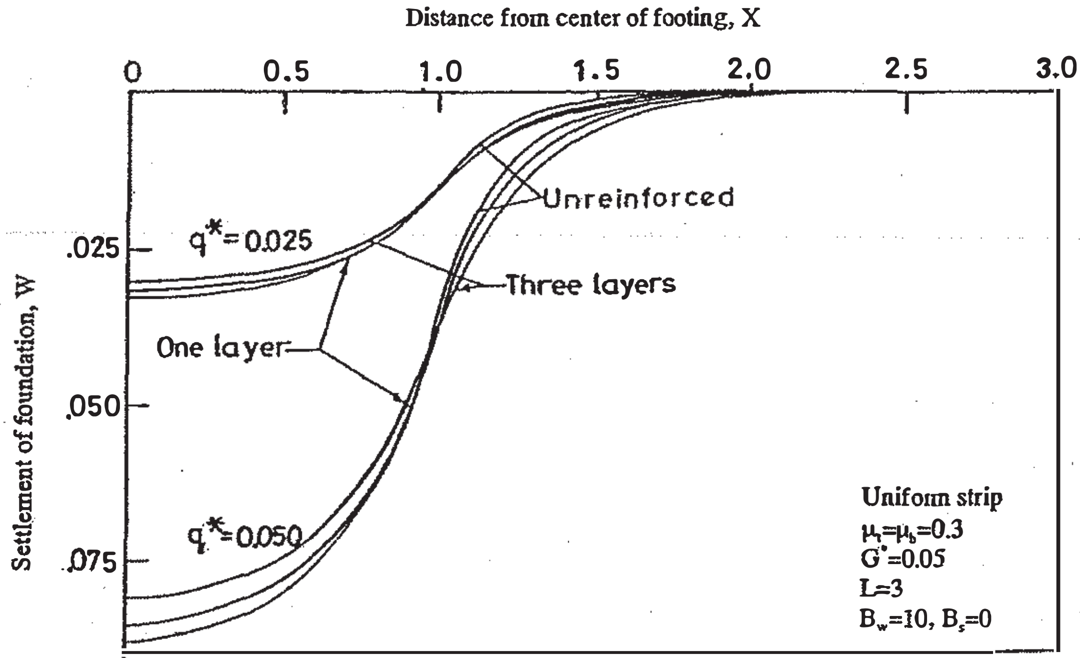

Figure 6. Surface deformation profile for uniformly loaded strip footing – effect of number of reinforcing layers (N).

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