An Approach to Predict Settlement of Embankments on Granular Fill – Soft Ground System

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ABSTRACT: This paper presents an approach to predict the settlement of embankments constructed on granular fill–soft ground system using Pasternak model, wherein, soft ground is modeled as a bed of Winkler springs with low subgrade stiffness while the granular fill is idealized akin to an incompressible Pasternak shear layer. Formulations are developed considering linear load-settlement behavior of soft ground and shear stress-strain response of granular fill. A parametric study quantifies the effects of various non-dimensional parameters on the deformation of the two-layered system. Results obtained indicate that, lower the relative stiffness index and stiffer the shear layer, the greater is the reduction in settlement, particularly at higher embankment loads. Predictions compare fairly well with measured settlement profiles of a full-scale embankment.

1 INTRODUCTION

Soft ground, encountered commonly along deltas and coastal regions throughout the world, possess poor geotechnical properties such as high natural moisture content (close to liquid limit), high compressibility, low undrained shear strength and hydraulic conductivity. Consequently, such deposits pose problems of stability and deformation to embankments constructed over them. A simple method to improve the load-settlement response of soft ground involves provision of a layer of compacted granular material over soft ground, followed by the construction of the structure on the granular fill. The granular base distributes the applied load over a wider area such that the structure endures relatively less settlement.

Poorooshasb et al. (1985), Madhav and Poorooshasb (1989), Yin (1997) and Faby Mole *et al*. (2014) proposed models to estimate the load-settlement response of unreinforced and geosynthetic-reinforced granular fills over soft ground subjected to rigid and uniformly distributed strip/circular loads. This paper presents an approach to analyse the load-settlement response of embankments constructed on a granular fill over soft ground. A parametric study quantifies the effects of various parameters on the deformation of the granular fill-soft ground system.

2 PROBLEM DEFINITION AND FORMULATION

An embankment with top width $2B$, height, h and side slopes 1 (vertical) to n (horizontal), rests on a granular fill of width, $2L$; shear modulus, G, and thickness, H, over soft ground whose modulus of subgrade reaction is k_s (Fig. 1). The width of the granular fill, $2L$, equals the base width of the embankment, $2(B+nh)$. The definition sketch of the model is shown in Fig. 2. The embankment rests on a Pasternak (1954) shear layer (granular fill) with shear stiffness, GH, over soft ground idealized by a series of Winkler springs with low subgrade stiffness, k_s.

The settlement profile of the granular fill-soft ground system from the centerline of the embankment is depicted in Fig. 3. The load from the embankment is transferred through the granular fill/shear layer onto underlying soft ground. The settlement of the embankment, w, decreases with increase in distance, x, from the centerline; from a maximum of w_0 at the center of the embankment to w_B at the shoulder and thereafter to a minimum of w_L at the toe of the embankment. Considering symmetry of the problem, the settlement profile is divided into two regions, Region 1 ($0 \leq x \leq B$) and Region 2 ($B \leq x \leq L$) as illustrated in Fig. 3.

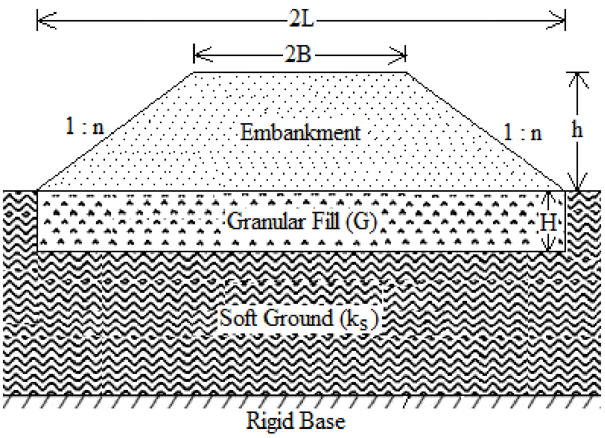

Fig. 1 Definition sketch of embankment on granular fill over soft ground.

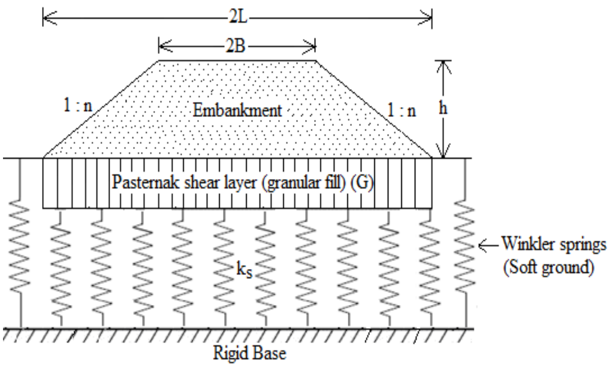

Fig. 2 Embankment on Pasternak shear layer over Winkler springs.

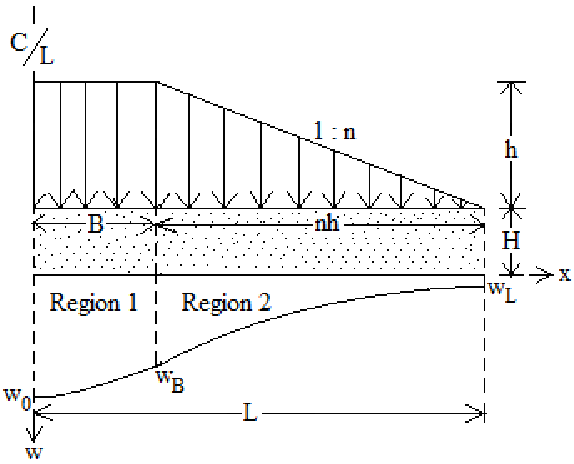

Fig. 3 Settlement profile of granular fill-soft ground system from embankment centerline.

Equations governing the response of the idealized model are derived by considering vertical force equilibrium of an infinitesimal element of the granular fill/shear layer as,

$$k_s w - GH\frac{d^2 w}{dx^2} = p \tag{1}$$

(for Region 1, $0 \le x \le B$)

$$k_s w - GH\frac{d^2 w}{dx^2} = p\left[1 - \frac{(x-B)}{(L-B)}\right] \tag{2}$$

(for Region 2, $B \le x \le L$)

where $p = \gamma h$ is the pressure transmitted by the top width region of the embankment onto the granular fill-soft ground system. The solutions of Eqs. (1) and (2) are,

$$w = c_1 e^{\lambda x} + c_2 e^{-\lambda x} + \frac{p}{k_s} \tag{3}$$

$$w = c_3 e^{\lambda x} + c_4 e^{-\lambda x} + \left(\frac{p}{k_s}\right)\left(\frac{L-x}{L-B}\right) \tag{4}$$

where λ is a parameter equal to $\sqrt{k_s / GH}$ with dimensions of L^{-1}; c_1, c_2, c_3 and c_4 are arbitrary constants evaluated from the following boundary and continuity conditions,

1. At $x = 0$ (center of embankment), shear strain, dw/dx, of Region 1 equals zero.
2. At $x = B$ (shoulder of embankment), settlement, w, of Region 1 equals that of Region 2.
3. At $x = B$ (shoulder of embankment), shear strain, dw/dx, of Region 1 equals that of Region 2.
4. At $x = L$ (toe of embankment), shear stress and hence shear strain, dw/dx, of Region 2 equals zero.

Applying the boundary and continuity conditions,

$$c_1 = c_2 = \frac{1}{\left(e^{\lambda B} + e^{-\lambda B}\right)}\left\{c_4\left[e^{\lambda(B-2L)} + e^{-\lambda B}\right] + \frac{pe^{\lambda(B-L)}}{\lambda k_s nh}\right\} \tag{5}$$

$$c_3 = c_4 e^{-2\lambda L} + \frac{pe^{-\lambda L}}{\lambda k_s nh} \tag{6}$$

$$c_4 = \frac{p\left(2e^{-\lambda L} - e^{\lambda B} - e^{-\lambda B}\right)}{2\lambda k_s nh\left(1 - e^{-2\lambda L}\right)} \tag{7}$$

Normalizing Eqs. (3) and (4) with half the top width of the embankment B,

$$W = c_1^* e^{\lambda' X} + c_2^* e^{-\lambda' X} + p^* \tag{8}$$

(for Region 1, $0 \le X \le 1$)

$$W = c_3^* e^{\lambda' X} + c_4^* e^{-\lambda' X} + p^*\left(\frac{L_s - X}{L_s - 1}\right) \tag{9}$$

(for Region 2, $1 \le X \le L_s$)

where

$$c_1^* = c_2^* = \frac{1}{\left(e^{\lambda'} + e^{-\lambda'}\right)}\left\{c_4^*\left[e^{\lambda'(1-2L_s)} + e^{-\lambda'}\right] + \frac{p^* e^{\lambda'(1-L_s)}}{\lambda' nh^*}\right\} \tag{10}$$

$$c_3^* = c_4^* e^{-2\lambda' L_s} + \frac{p^* e^{-\lambda' L_s}}{\lambda' nh^*} \tag{11}$$

$$c_4^* = \frac{p^*\left(2e^{-\lambda' L_s} - e^{\lambda'} - e^{-\lambda'}\right)}{2\lambda' n h^*\left(1 - e^{-2\lambda' L_s}\right)} \quad (12)$$

where $W = w/B$ and $h^* = h/B$ are the normalized settlement and height of the embankment respectively, $p^* = p/k_sB$ is the normalized pressure from the top width region of the embankment, $X = x/B$ is the normalized distance from the embankment centerline, $L_s = L/B = 1+nh^*$ is the normalized half width of the granular fill/shear layer and λ' is the relative stiffness index of the granular fill/shear layer defined by,

$$\lambda' = \sqrt{\frac{k_s B^2}{GH}} \quad (13)$$

3 RESULTS AND DISCUSSION

The settlement of the embankment on the granular fill-soft ground system depends on the stiffness of the granular fill/shear layer relative to that of soft ground, normalized width of the granular fill/shear layer, geometry and material properties of the embankment. A parametric study quantifies the effect of parameters λ' (a function of the modulus of subgrade reaction of soft ground, half the top width of the embankment and the shear stiffness of the shear layer) and L_s (a function of the side slope and height of the embankment). Results are obtained for λ' and L_s varying from 0.1 to 4.0 and 1.5 to 3.0 respectively. λ' equal to 0.1 corresponds to a relatively stiff shear layer while λ' of 4.0 represents a soft shear layer. Likewise, L_s equal to 1.5 corresponds to a relatively low to medium height embankment with steep side slope (of the order of 1:1) while L_s of 3.0 represents a relatively higher embankment with flatter slope (of the order of 1:2.5 to 1:3).

Figs. 4, 5 and 6 present the variations of the normalized settlement at the center, W_0, shoulder, W_B, and toe, W_L, of the embankment, respectively, with the relative stiffness index λ' for L_s of 1.5, 2.0, 2.5 and 3.0. For a given height and side slope of the embankment, W_0 and W_B increase non-linearly with λ', whereas, W_L decreases. As λ' increases, the shear stiffness, GH, of the shear layer decreases and the shear layer deforms progressively under the applied loading. The load transferred by the embankment onto the granular fill-soft ground system is maximum below the center and shoulder but minimum near the toe. The percentage reduction in settlement at the center of the embankment due to a stiff shear layer (λ' = 0.1) when compared to a relatively soft one (λ' = 4) is 16.0%, 24.5%, 29.5%, 32.8% corresponding to L_s values of 1.5, 2.0, 2.5, 3.0 while that at the shoulder is 2.4%, 14.7%, 23.6% and 28.7% respectively.

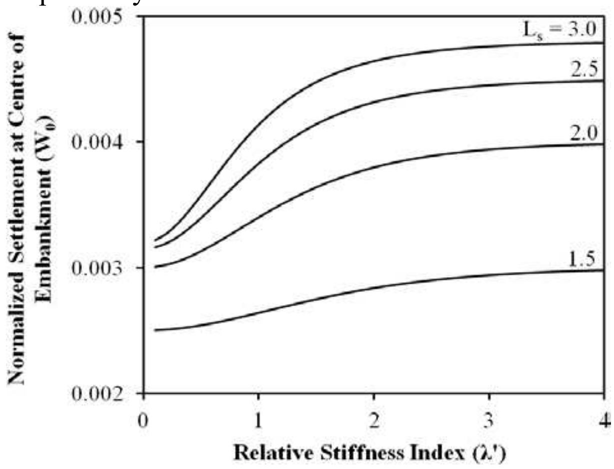

Fig. 4 Variation of normalized settlement at center of embankment W_0 with λ' – effect of L_s

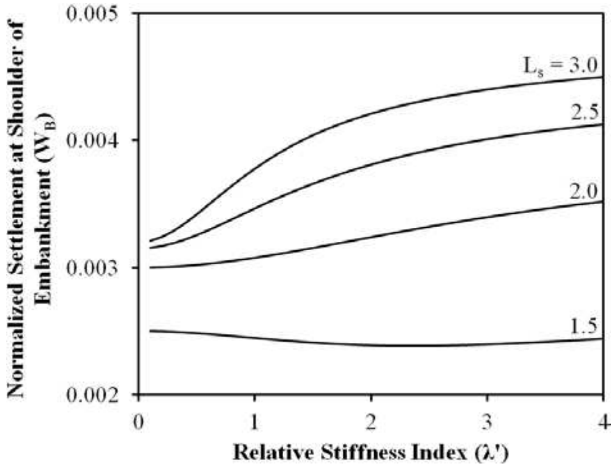

Fig. 5 Variation of normalized settlement at shoulder of embankment W_B with λ' – effect of L_s.

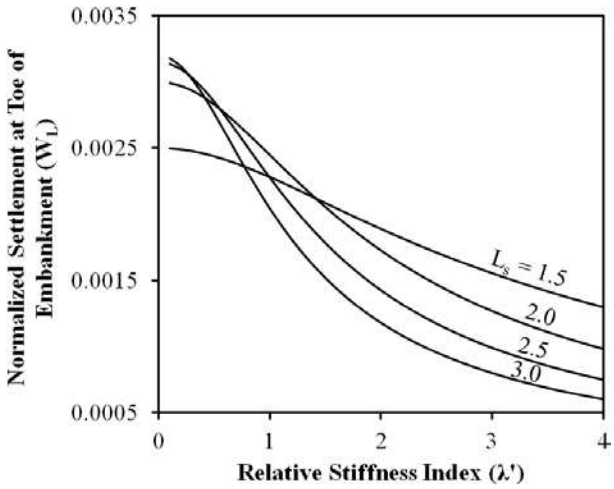

Fig. 6 Variation of normalized settlement at toe of embankment W_L with λ' – effect of L_s.

Fig. 7 illustrates the effect of the relative stiffness index λ' on the settlement profiles of an embankment with normalized height h^* of 0.5 and side slopes 1 (vertical) to 2 (horizontal), on a granular fill/shear layer over soft ground, for normalized pressure p^* of 0.003. The settlement profile of the embankment resting on a relatively stiff shear layer ($\lambda' = 0.1$) is uniform, as the shear layer distributes the load uniformly over a wider area onto soft ground. However, as λ' increases, the normalized settlements at the center ($X = 0$) and shoulder ($X = 1$) of the embankment increase while that at the toe ($X = 2$) decreases.

Fig. 8 compares the predictions with the measured surface settlement profiles of a full-scale trial embankment on soft Muar clay by Indraratna *et al*. (1992). The fill thicknesses of the embankment ranged from 2 to 5 m and consisted of lateritic fill compacted to a unit weight of 20.5 kN/m^3. The top width and side slopes of the embankment are 20 m and 1 (vertical) to 2 (horizontal) respectively. The subsoil profile at the site consisted of top 2.0 m thick weathered crust, idealized as a shear layer with modulus of elasticity, E_s, of 25500 kPa and Poisson's ratio, μ, of 0.3, overlying a 16.5 m thick layer of soft clay with average undrained shear strength of 12 kPa.

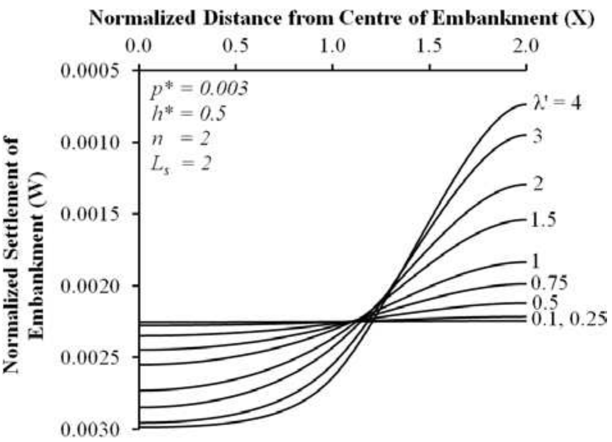

Fig. 7 Settlement profiles of embankment – effect of λ'

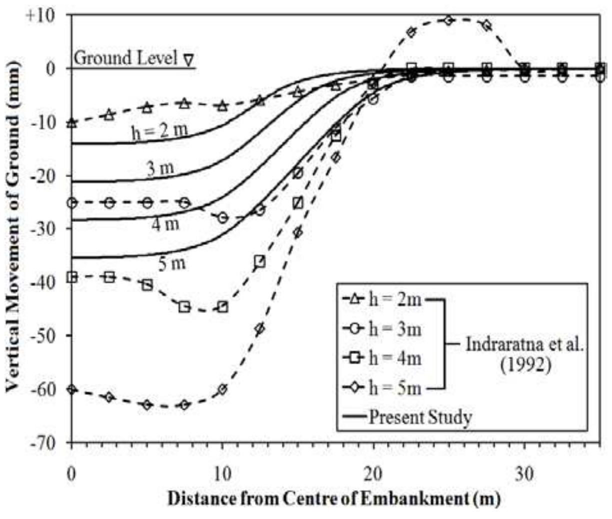

Fig. 8 Comparison with measured settlement profiles of Indraratna *et al*. (1992)

The shear modulus of crust, subgrade modulus of soft clay and relative stiffness index are computed to be 9808 kPa, 2880 kN/m^3 and 3.8 respectively. The predicted settlements compare reasonably well with the measured values for fill height of 2 m. However, for fill heights greater than 3 m, the pressure exerted by the embankment exceeds the pre-consolidation pressure of soft clay, resulting in notable contribution from consolidation settlements. Since this study considers linear load-settlement behavior and mechanical response of soft ground, the estimated settlements are lower than those measured. Nevertheless, it is reassuring to note that the predicted settlement profiles match closely the trend of the measured ones, except for the 5 m fill where ground heave of about 10 mm was observed beyond the embankment toe.

4 CONCLUSIONS

A preliminary approach to predict the load-settlement response of embankments constructed on a granular fill over soft ground is presented. Soft ground is modeled as a bed of Winkler springs with low subgrade stiffness while the granular fill is idealized akin to an incompressible Pasternak shear layer. Results show that lower the relative stiffness index and stiffer the shear layer, the greater is the reduction in settlement, particularly at higher embankment loads. The settlement profile of the embankment resting on a stiff shear layer is uniform, whereas, that on a relatively softer one is non-uniform with the deformations concentrated below the center of the embankment. The paper offers a framework for further numerical development of the model with nonlinear and time-dependent load-settlement responses of soft ground.

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