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Lateral Displacements of Soft Ground under Embankment Loading

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Abstract. Prediction of the settlements and the lateral deformations of the ground are essential for the design of embankments. Several techniques are available to control embankment deformations by different construction and ground improvement methods. One frequently used method of improving soft ground is to provide a stiff reinforced granular bed (RGB) over soft ground. This paper presents analysis of deformations of embankment over RGB treating the system as a two layer soil system consisting of stiff layer over homogeneous soft clay layer as foundation through incremental loading representing the staged construction of embankment. The settlements and lateral deformations of two layer system are obtained using PLAXIS software. The results indicate that the toe displacement at the end of construction of the embankment get reduced up to 60% of those without reinforced granular bed with placement of RGB over soft ground.

Keywords: Embankment, homogenous soil, two-layered soil, incremental load, modular ratio, toe displacements.

1 Introduction

Embankments were used in earlier times to impound and divert water. Construction of embankments is playing vital role in the development of communication networks such as highways and railways. Due to necessity embankments are often constructed even on soft soils. Hence the design and construction of embankments over soft soils has become a major issue due to low shear strength and high compressibility of soft ground. The estimation of settlements and lateral displacements of embankment for good serviceability is the main design concern for embankments on soft soil. Rapid construction of the embankment generates large horizontal stresses in soft ground, which in turn leads to lateral soil movement under the toe of embankment. Heaving of soil adjacent to the toe of the embankment may cause excessive deformations of the adjacent structures. It is essential to predict settlements and lateral displacements of the ground beneath an embankment and a reasonable criterion on the limits of lateral soil displacements incorporated in the design. Generally when soft ground is subjected to embankment loading plastic flow or squeezing of soil occurs near the top of the ground. During construction, due to fast rate of load application and low permeability of clays, an undrained response prevails which leads to the development of lateral displacements. The failure of soft ground under embankment is obviously related to the settlements and lateral displacements of the embankment. Matsuo (1977) proposed a plot (Fig.1) between the ratio of lateral displacement to vertical settlement and vertical settlement to predict the failure of an embankment. The rate of increase in settlements and lateral displacements (Tevanas et al., 1979) are functions of undrained shear parameters of the ground. Loganathan et al. (1998) study numerically the deformations of soft subsoil during embankment loading and consolidation stages using finite element and finite difference methods. The factors influencing lateral displacement induced by embankment loading are: (a) Magnitude and loading rate of the embankment loading; (b) Undrained shear strength (c_u) of the subsoil; (c) Deformation characteristics of the soft sub soil. Provision of stiff layer at the base embankment would minimize the deformations. Many experimental and numerical studies are available to estimate the effect of reinforcement on deformations of subsoil under the embankment. Chai et al. (2002) compared embankment behavior with and without reinforcement with respect to factor of safety (FOS) and concluded that the factor of safety increases and the lateral displacements reduce with the provision of reinforcement. Huang et al. (2006) suggested that the increase of embankment soil stiffness results to the reduction of lateral displacements at the toe of the embankment. Rankine et al. (2007) developed equations to determine lateral displacements at the toe and at a short distance from the toe of the embankment based on the results of numerical analysis. Safadoust et al. (2013) concluded that the increase of reinforcement stiffness does not lead to reduction in the settlement compared to the reduction in horizontal displacement. Various techniques are available to control deformations and for rapid construction of embankments by implementing different methods. Placing a stiff reinforced granular bed (RGB) over soft soil is one of the simplest technique of ground improvement to minimize the lateral deformations of soft soil.

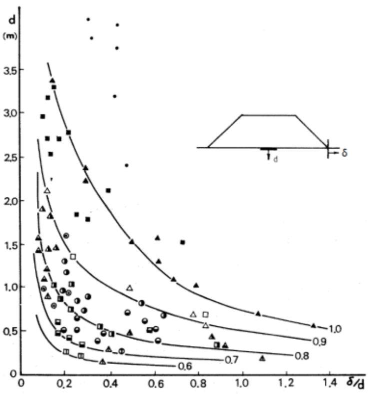

Fig.1. (δ/d - d) Diagram for prediction of failure

The present study is concentrated on the lateral displacements during construction of embankment on a reinforced granular bed treated as a two-layer system consisting of a stiff (upper) layer over soft ground. The objective of this paper is to estimate the effect of stiffness of reinforced granular bed (RGB) on the performance of embankment founded on soft soil through prediction of lateral displacements for different modular ratios.

2 Methodology

A finite element analysis is carried out to investigate the effect of reinforced granular bed on the deformations of subsoil due to incremental or stage-wise loading of embankment. PLAXIS 2D software is used and the model is setup in plane strain condition with 15-noded triangular 1551 number of elements. The mesh generated is medium to course refined to finer in the high stress regions. As the embankment is symmetric, only half-section of the embankment is considered in the analysis.

To eliminate possible boundary effects on the results, the foundation soil is extended to a distance more than ten times horizontally and five times the embankment width vertically. Mohr- Coulomb model is used to simulate soil behaviour. The soil parameters considered in the analysis are shown in Table 1.

Table 1. Soil parameters

Parameter	Embankment soil	Layer 1-RGB	Layer -2 (Soft clay)
Material Model	Mohr-Coulomb (MC)	Mohr-Coulomb (MC)	Mohr-Coulomb (MC)
γ_b (kN/m³)	17	20	15
Cohesion kPa	5	3	10
φ (°)	32	38	0
Deformation Modulus, EMPa	20.0	25.0 – 50.0	5.0
Poisson's ratio, ν	0.3	0.3	0.35

Embankment founded on homogeneous soft soil is analyzed first and then a two layer system with 2.0 m thick RGB over soft soil. The embankment is of 6.0 m height with base width of 31.0 m with side slopes of 2H: 1V.The sequence of construction is modeled by 0.5 m thick fill placed for each raise such that the total height of embankment is reached in 12 increments. RGB at the top of the soft ground is freely draining while the soft clay is treated as in undrained state. The geometry and PLAXIS model of embankment with homogeneous soil and of two layer system are shown in Figs. 2 (a) and (b) and Fig. 3.

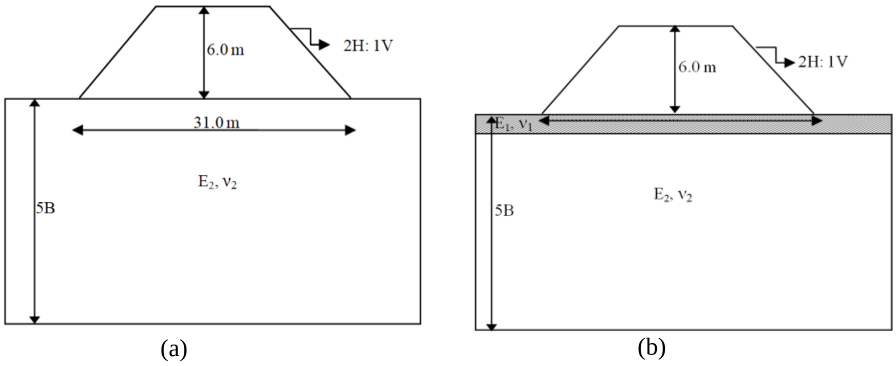

Fig. 2. Geometry of the embankment (a) homogeneous soil and (b) two-layer system

The settlements and lateral deformations are predicted for various deformation modular ratios, E_1/E_2, where E_1 and E_2 are the deformation moduli of the stiff RGB and soft layer respectively. Deformations are estimated for modular ratios of 1, 5, 20, 50 and 100 for homogeneous and two layer systems. The modular ratio, $E_1/E_2 = 1$ represents homogeneous soil and $E_1/E_2 > 1$ a stiff foundation bed over soft layer.

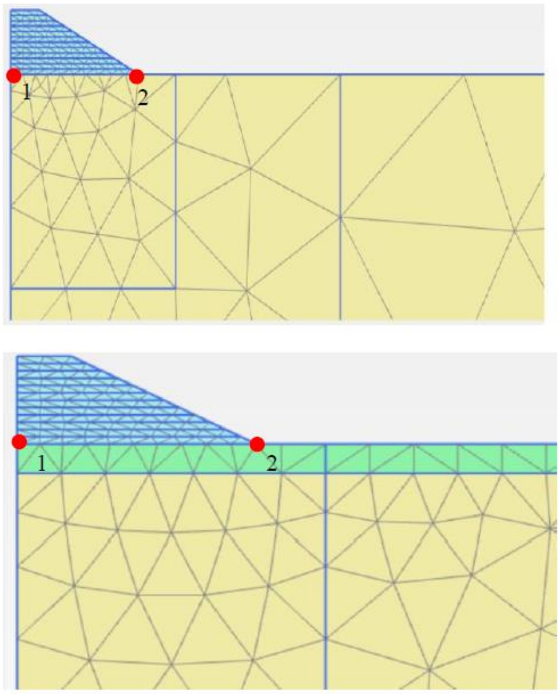

Fig. 3. PLAXIS model of embankment

3 Results and Discussion

3.1 Settlements

The variations of surface settlements beneath the center of embankment with increase in height of fill for homogeneous and two layer system of different modular ratio are shown in Fig.4. Near linear increase of settlements at the end of construction are observed for the thickness of embankment fill till about 4.0 m and non-linear increase for thickness greater than 4.0 m.Fig.5presents the surface settlement profiles beneath the embankment at the end of construction. The predicted surface settlements decrease marginally from 175 mm to 165 mm for modular ratio increasing from 1 to 100. The settlements of the two layer system are not much different compared to those of homogeneous layer.

3.2 Lateral displacements

The variation of lateral displacements at the toe of the embankment, at point 2(Fig. 3) with height of fill for homogeneous and two-layered soils cases are shown in Fig.6.For the modular ratio E_1/E_2= 1 (homogeneous soil), the lateral displacement at the ground surface at point 2 is 27 mm. and The displacements at the toe decrease from 14 mm to 11 mm with increase of modular ratio from 5 to 100. Fig.7presents the lateral displacement profile under the toe of embankment at the end of construction. With the provision of a stiff layer over the soft soil the lateral displacements reduce over the full depth of the soft layer. At a depth of 2 m that is at the top of soft clay layer the lateral displacements reduce marginally from 30 mm to 27 mm with the increase of modular ratio from 5 to 100.

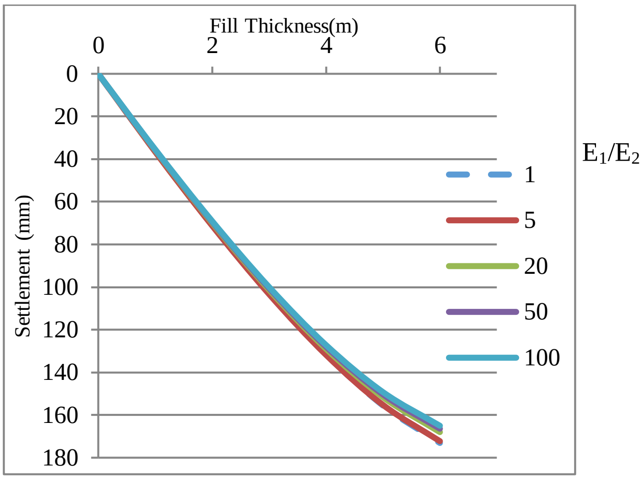

Fig.4. Variation of settlements with height of fill

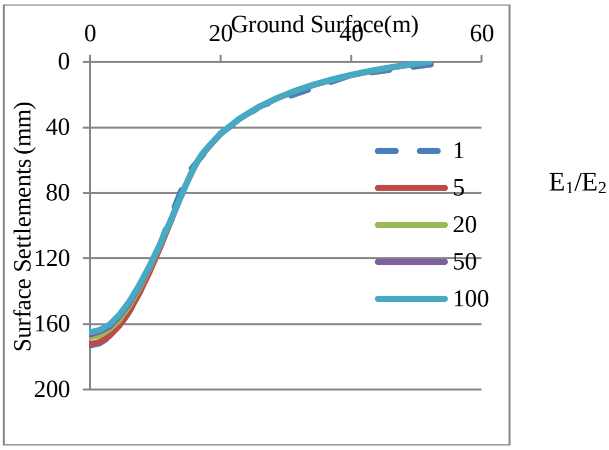

Fig.5. Surface settlement profiles at the end of construction

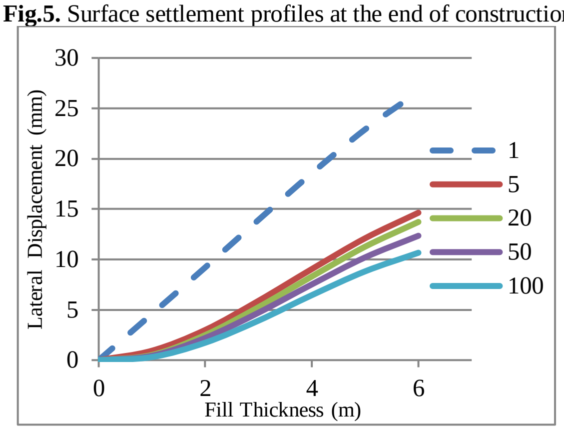

Fig.6. Lateral displacements at the toe of embankment with incremental load

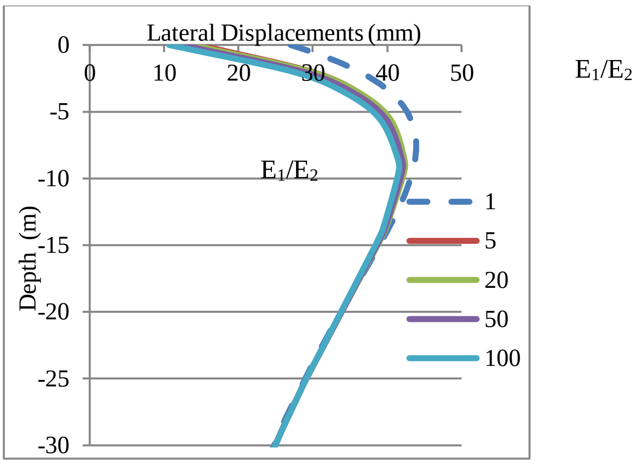

Fig.7. Lateral displacements under the toe of embankment

3.3 Construction control chart

Matsuo's stability chart plots ratio of lateral displacement by settlement at center as abscissa and settlement beneath the center of embankment as ordinate as in Fig.8. Failure is indicated by the points moving away from the center and towards the top. The converse is true, i.e., increased stability or factor of safety is indicated if the points move to the left and downwards from the numerical analysis Results from the numerical analysis reported here for the embankment indicate the displacements curves moving towards left in the Matsuo chart. The provision of reinforced granular bed over the soft clay decreases settlements marginally but lateral displacements by a larger amounts. Consequently the ratio of lateral displacement to settlement decreases with the increase of modular ratio (E_1/E_2) form 1 to 100. The curves shift towards to the left from right as shown in Fig.9. The embankment is on the safer side and the factor of safety more than1.67 as per the Matsuo plot.

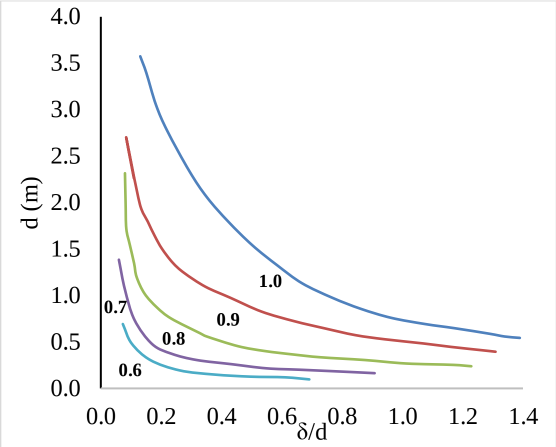

Fig. 8. Matsuo's stability

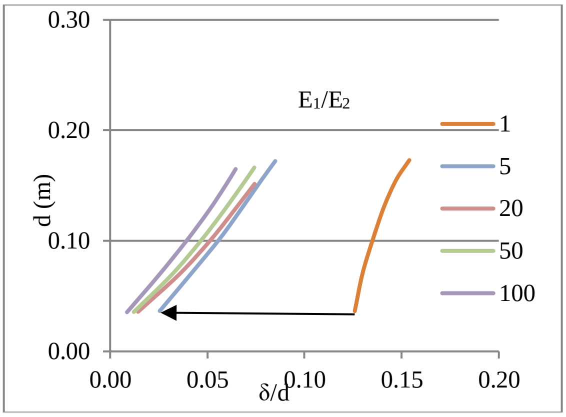

Fig. 9. Matsuo plot for proposed section

4 Conclusions

The influence of stiff granular layer over soft layer on deformations beneath an embankment is estimated for different modular ratios by finite element analysis using PLAXIS program. Conclusions that can be drawn from this study are:

1. Provision of reinforced granular bed over the soft clay does not contribute to reduction in settlements.

2. The lateral displacements at the toe of the embankment get reduced up to 60% with placement of stiff layer over soft layer compared to those without granular bed and lead to prediction of higher factor of safety.

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