Behavior of embankment supported by rigid inclusions under static loads-parametric study

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Abstract— **Rigid inclusions has been gained popularity to support embankments over soft soil layers. The goal of rigid inclusions is to decrease the settlement and to improve the bearing capacity. The system contains the rigid elements, the load transfer platform and the reinforcement. Complex soil-structure interaction is developed due to the effect of the soil arching and tensioned membrane. In this paper, a validated 3D model of an embankment supported by rigid inclusions and two layers of geogrid are introduced based on a full-scale model with field measurements. The results highlight the effect of number and position of the geogrid layers on the load efficiency, add to that, the increase of the cover ratio by enlarging the column cap increases the load efficiency while the increase by enlarging the column cross-section area decreases the load efficiency.**

Keywords— rigid inclusions; load efficiency; cover ratio.

I. INTRODUCTION

The demand of transportation grows in the last years, especially the high-speed railway lines. Sometimes, these lines need to be supported to fulfil the requirements of settlement and bearing capacity, essentially for the soft and weak soils. Sometimes, the piles can be overdesigned and the shallow foundations are not acceptable. In this case, the rigid inclusions technology is considered as a compromise solution [1].

The embankments over soft soils generally need to be supported by various technologies (rigid inclusions, stone columns, basal reinforcement with geosynthetics, prefabricated vertical drains) [2]. These technologies are used to enhance the shear resistance or to reduce the consolidation time of soft soils. Although the rigid inclusions outperform the other technologies to meet the aforementioned requirements, but this system is complex regarding the soil-structure interactions. The effects of soil arching, tensioned membrane and frictional interactions between the soil and geosynthetics represent the load transfer mechanism in this system. Due to the complexity and various interactions between the rigid inclusions' components, different researchers worked to clarify the behavior of rigid inclusions. a series of small-scale model tests performed by van Eekelen et al. [3] showed that the increase the internal friction angle improves the soil arching and using two layers of geogrid, on behalf of one, increases the load efficiency (defined as a ratio of vertical forces applied on the pile (column) to the total vertical forces in a unit cell) by a small amount. Girout et al. [4] performed thirty-three geotechnical centrifuge tests, and the findings were, increase the embankment height increases the load efficiency, using geogrid layers improves the load efficiency, and the position and stiffness of the geosynthetic plays a main role of the load efficiency. Jenck [5] found, based on a small-scale model, that the increase of cover ratio increases the load efficiency. Blanc et al. [6] conducted a series of centrifuge tests, these tests showed that when the load transfer platform is thicker, the load efficiency is larger. Xu et al. [7] performed a series of scaled model tests, they concluded that the use of a cohesive soil as an embankment fill enhances the soil arching and hence the load efficiency. Okyay and Dias [8] conducted numerous model tests using centrifuges and concluded that the cover ratio is an important factor affecting the load efficiency.

Han and Gabr [9] used Flac program to perform a numerical analysis for the purpose of investigating the interactions between piles, soils, and geosynthetic layers. The researchers found that the load efficiency increases when the height of the embankment and the elastic modulus of the pile increases. Le Hello et al. [10] observed that the geosynthetic layers contribute in increasing the load efficiency as the pile network, the embankment height, and the cover ratio do. Wijerathna et al. [11] performed a 3D numerical model of rigid inclusion-supported embankment, Wijerathna et al. found that the load efficiency is affected by a small amount by the geosynthetic stiffness and column material stiffness, while the column spacing, column diameter, and friction angle of the embankment fill have a large effect on the load efficiency. The 2D numerical analysis of a physical model by Boussetta et al. [12] showed that the load efficiency increases with the increase of the cover ratio. This result was confirmed by Lee et al. [13].

Different analytical methods are used to design the rigid inclusion-supported embankment. The analytical method proposed by Abusharae et al. [14] showed that the load efficiency increases as the soft soil layer thickness decreases. Zhuang et al. [15] developed a new analytical method of design and found that the load efficiency increases if the geosynthetic stiffness increases and the soft soil stiffness decreases. Pham [16] proposed a new design method, the parametrical analysis based on this method was conducted, the results indicated that the load efficiency increases when the cover ratio, internal friction angle of embankment soils and embankment height increase.

The paper discusses the effect of geosynthetic and the optimum positions of these reinforcement layers on the load efficiency, moreover, this paper investigates the differences between the changeable cover ratio by enlarging the column cap or the column cross-section area on the load efficiency and column behavior.

II. GEOMETRY OF THE SUPPORTED EMBANKMENT

A rigid inclusion-supported embankment located over different layers of soft soils was simulated by the finite element method (Plaxis 3D CONNECT Edition V20 program is adopted in the analysis). The soil profile is shown in *Fig. 1*. The levels of the soil layers are related to the NGF (French georeferenced level) [17].

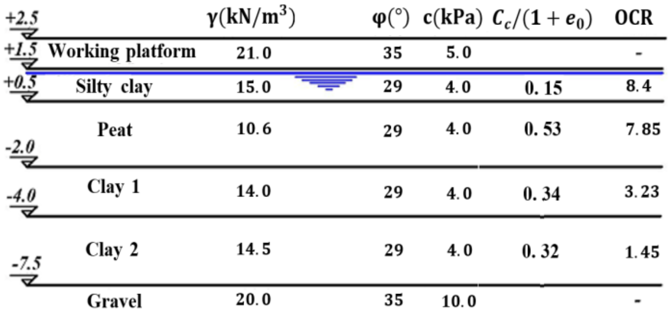

Fig. 1. The soil profile

A working platform was applied before the construction stages. The columns were driven to be anchored to a gravel layer. The column spacing and diameter are respectively (1.6m, 0.274m). two layers of a geogrid were inserted in the load transfer platform with a thickness equal to 0.7m. the position of these two layers are 0.2m and 0.4m over the column heads [17].

The height of the embankment is 3.8m, the width of the embankment at the crest is 7m and at the base is 12m as shown in *Fig. 2*. The properties of the embankment fill, platform working soil, and column material are tabulated in *Table 1*.

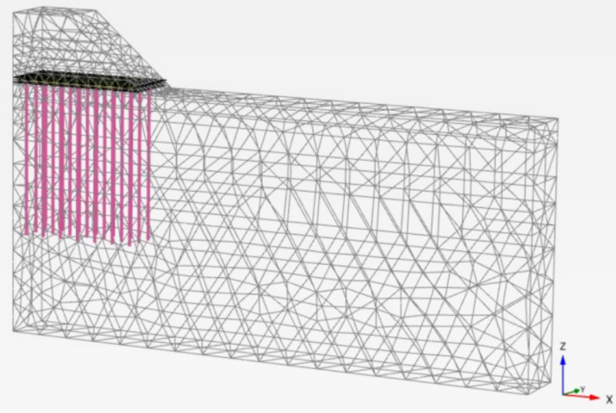

Fig. 2. Supported embankment by rigid inclusions and two layers of geogrid.

Soft Soil Creep (SSC) model was used to simulate the behavior of the soft soils. Hardening Soil (HS) model was used to simulate the behavior of the embankment fill, the working platform soil, and the gravel. The columns are modeled as embedded beam elements and the stiffness of the geogrid equal to 13000 kN/m.

TABLE I. PROPERTIS OF SOIL AND COLUMN MATERIAL.

Embankment fill			
γ = 21 kN/m^3	φ=35°	Ψ=5°	
c=5 kPa	E= 16000 kPa	k=0.864 m/day	
Working platform soil			
γ = 21 kN/m^3	φ=35°	Ψ=5°	
c=5 kPa	E= 12860 kPa	k=0.864 m/day	
Column			
γ= 24 kN/m^3	*E=20 GPa*	ν=0.2	*L=12.7 m*

III. RESULTS AND DISCUSSION

A. Effect of rigid inclusion on the embankment settlement

Due to the significant settlement problem of the embankments over soft soil layers, different technologies are used to reduce these settlements and increase the stability of the soil. *Fig. 3* shows the difference between the unsupported embankments, supported embankments by two layers of the geogrid located in the working platform, and supported embankments with rigid inclusions and two layers of geogrid. Rigid inclusion contributes to reduce the settlements at the embankment surface to reasonable values, especially for the high embankments.

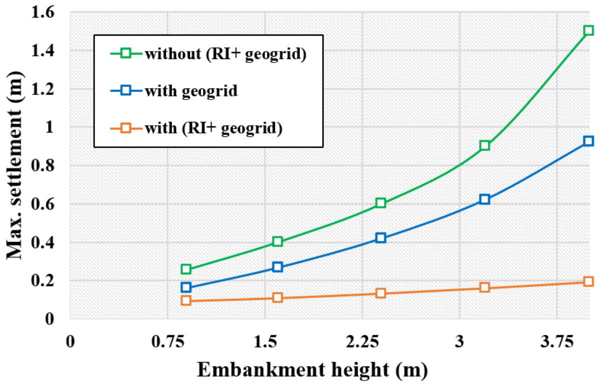

Fig. 3. Maximum settlements at the embankment surface for different heights

B. Effect of geogrid layers on the load efficiency

The soil arching phenomenon is noticeable in the supported embankments whether the geogrid reinforcement is used or not, while the tensioned membrane phenomenon is relating to the presence of the geogrid layers. The geogrid stretch and subsoil settlement occur simultaneously, these phenomena contribute to mobilize the tensile forces in the geogrid layers and as a result, increase the load efficiency. *Fig. 4* shows the effect of using the geogrid layers on the load efficiency during the construction stages and consolidation period. It is evident that the load efficiency increases by about (60%) when one layer of geogrid is used and by about (63%) when two layers are used. Generally, using one layer is considered an effective and economical solution.

The position of the geogrid layer plays an important role in transferring the load to the rigid columns. Different positions of the geogrid layer were investigated to find out the effects on the load efficiency, the hypothetical positions of this layer are

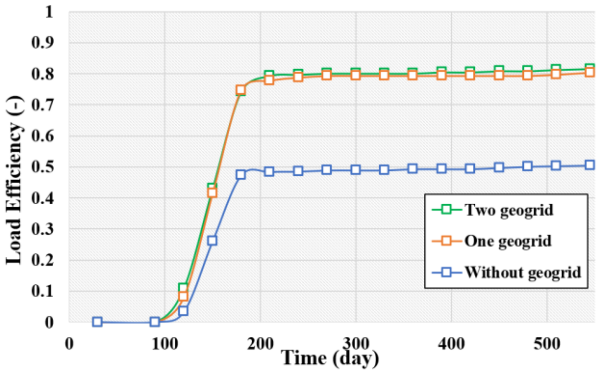

Fig. 4. Effect of geogrid on the load eeficiency.

(0, 0.2, 0.5) m above the column head. The load efficiency reaches its maximum (E=0.88) when the single geogrid layer located directly over the column head as shown in *Fig. 5*. The attribution of that, the lower the layer position, the higher the load applied on the geogrid layer. this load moves later to the column head.

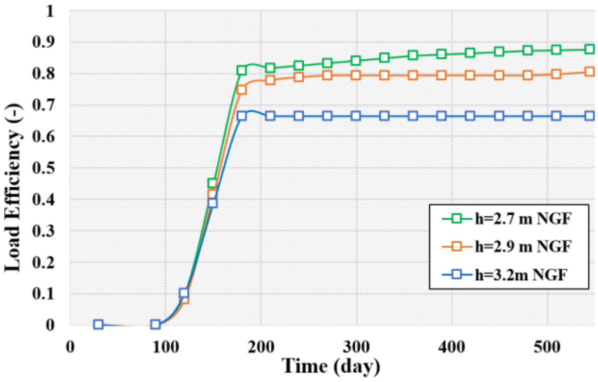

Fig. 5. Effect of the the first geogrid layer position on the load efficiency.

Next step after finding the optimum position of the first layer of geogrid is to find the position of the second layer (if any). The position of first layer is located directly over the column heads. Different positions of the second layer were investigated to find the effect on the load efficiency, the hypothetical positions of the second layer are (0, 0.2, 0.3, 1.02, 1.52) m over the column head. Insertion of this layer leads to decrease or increase the load efficiency between (2-5%). *Fig. 6* indicates that the effect of this layer cab be negligible. The results of the numerical analysis comply with those obtained from the experimental tests of van Eekelen et al. [3]. The researchers found that the behavior of the load distribution is approximately the same when one or two layers are placed in the embankment body.

C. *Effect of cover ratio on the load efficiency*

Based on the reference case, numerous numerical analyses were performed to determine the effects of cover ratio on the load efficiency and the behavior of axial forces along the column. The cover ratio ranges from (3%) to (27%) in the analysis, these percentages correspond to a range of column diameter (0.25-0.8) m suggested by ASIRI [1].

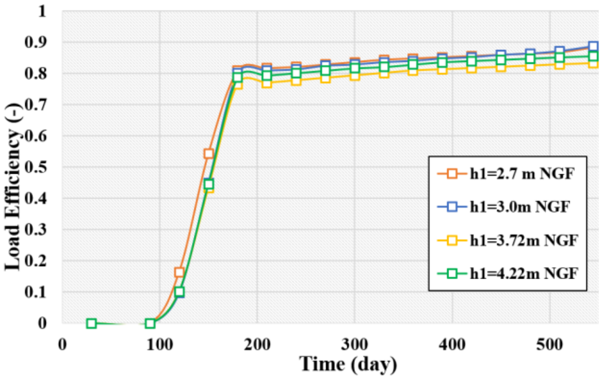

Fig. 6. Effect of the the second geogrid layer position on the load efficiency.

Two cases are discussed in this paper: Case A - increased cover ratio by enlarging the column cap; Case B – increased cover ratio by enlarging the cross- sectional area of the column.

Fig. 7 shows that the load efficiency increases as the cover ratio increases according to case (A), and decreases as the cover ratio increases according to case (B).

In case (B), the skin friction zone increases and the shear forces resulting from the negative skin friction increases while the applied load on the column head decreases. *Fig. 8* shows the distribution of the axial forces for both cases (A and B) for two values of cover ratio (α= 9%, α= 15%).

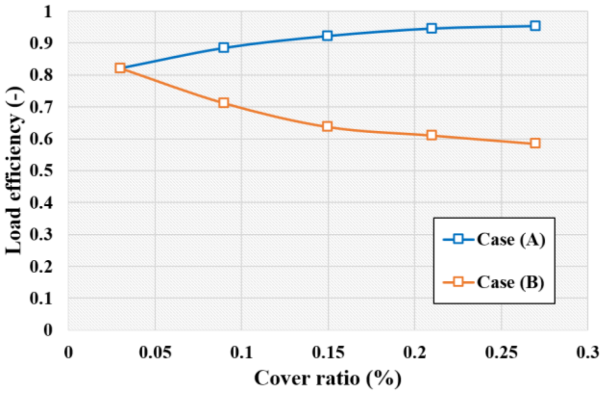

Fig. 7. Effect of cover ratio on the load efficiency in two cases (A),(B).

For the embankments supported by rigid inclusions and two layers of geogrid, the curves were plotted with different load efficiencies to be used for the preliminary design purpose as shown in Fig. 9. These curves comply relatively with several history cases [18] taking into consideration the effect of the possible differences (thickness of the load transfer platform, characteristics of the embankment fill, stiffness of the geogrid, stiffness and thickness of the soft soil layers, etc).

The cover ratios, for embankments with heights (H/(s-a) <1), is high in comparison with those, for embankments with heights (H/(s-a) >1) as shown in Fig. 9. On this basis, these curves provide a new criterion for classifying low and high embankments, where H is the embankment height, s is the column spacing, and a is the column diameter.

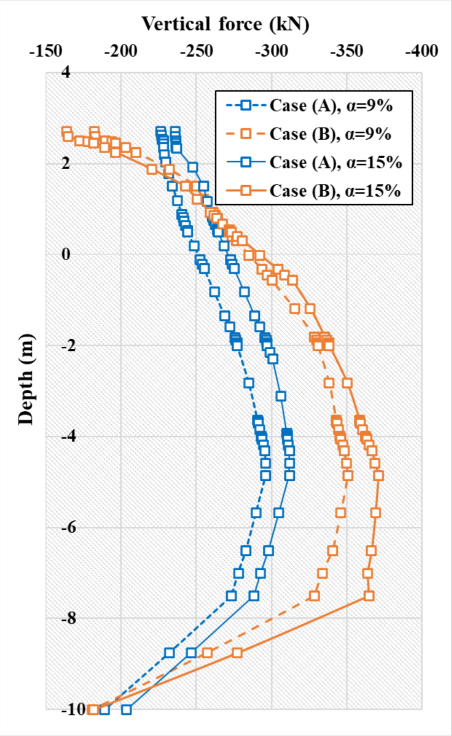

Fig. 8. Distribution of axial forces in the column in two cases (A),(B).

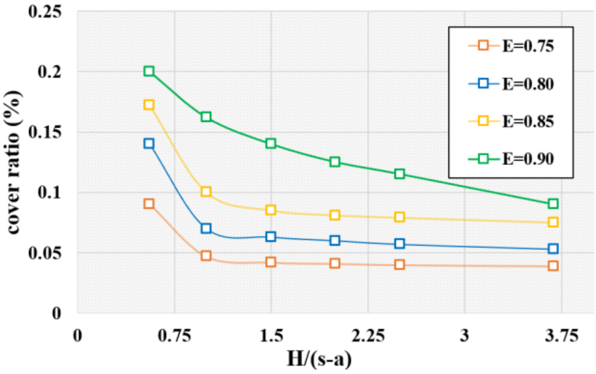

Fig. 9. Correlation between cover ratio of column cap and embankment height.

IV. CONCLOUSIONS

Based on the numerical model of the embankment supported by rigid inclusions and two layers of geogrids, a parametric study was carried out, which yielded the following results:

1. The rigid inclusions help to reduce the settlements of the embankment to a reasonable value.

2. Inserting the geogrid layers in the load transfer platform helps to increase the load effeciency due to the transfer a part of the load by these layers to the column head. The results show that the load efficiency increases by (60%) if one layer is used and (63%) if two layers are used. Therefore, the use of a single geogrid layer is considered an effective and economical.

3. The position of the single geogrid layer plays an important role in transferring the load to the rigid columns. The maximum load efficiency occurs when the geogrid layer is located directly over the column head.

4. The effect of using the second geogrid layer can be neglegable. The load efficiency increases or decreases between (2-5%), the optimal position can be directly above the first geogrid layer.

5. The increase of the cover ratio by enlarging the column cap leads to increase the load efficiency while the increase of the cover ratio by enlarging the column cross-sectional area leads to decrease the load efficiency.

6. In the case of enlarging the column cross-sectional area, the skin friction zone increases, and the shear forces resulting from the negative skin friction in the upper part of the colum increases while the applied load on the column head decreases.

7. The curves in *Fig. 8* with different load efficiencies can be used for preliminary design.

8. The cover ratio decreases as the embankment height increases, the limitation (H/(s-a) =1) can be accepted as a criterion to distinguish between low and high embankments.

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