Lateral spreading in basal reinforced embankments supported by pile-like elements

Propagation latérale dans des remblais renforcés aux bases soutenus par des éléments pieux

G.S. Fahmy

Dar Al-Handasah Consultants (Shair & Partners), Cairo, Egypt

H.-G. Kempfert & B. Gebreselassie

University of Kassel, Kassel, Germany

ABSTRACT

A series of three-dimensional well- instrumented model tests at a scale of 1:3 has been carried out to investigate spreading and shear stresses at the base of a reinforced embankment and the results were verified by FE-model. Furthermore, numerical parameter study on the prototype using 3D-FEM had been performed under different parameter variations. A modified analytical method to calculate the spreading force in reinforcement had been derived which takes into account different factors. Dimensionless factors are developed to include these factors in determining the spreading forces.

RÉSUMÉ

Une série d'essais sur un modèle physique tridimensionnel bien instrumenté, à l'échelle de 1:3, a été réalisé pour étudier la propagation des forces et les contraintes de cisaillement à la base de remblais renforcés et les résultats ont été vérifiés par des modèles numériques en éléments finis. En outre, des études de paramètres numériques du prototype, en utilisant les éléments finis à 3D, ont été réalisées avec variations de différents paramètres. Une modification de la méthode analytique pour le calcul de la propagation de force dans les renforcements pourrait être obtenue pour les différents paramètres effectifs. Des facteurs adimensionnels peuvent alors être déterminées et mises au point pour exprimer ces paramètres qui influent sur la propagation des forces.

Keywords : piled embankment, lateral spreading, geosynthetics reinforcement

1 INTRODUCTION

The construction of road/railroad embankments on weak or very soft soils such as peat is normally treated using a soil replacement method or by introducing pile-like-elements into the soft layer to partially support the embankment. In the slope zone of the embankment the underground is subjected to additional lateral stresses due to the spreading effect of the slope. In practice, the spreading stresses are assumed equal to the active earth pressure at a section through the crest of the embankment. The spreading stresses influence the stability of the bearing system and possibly may result a horizontal displacement of the pile-like-elements or a horizontal displacement of the toe of the embankment slope. Kempfert et al. (1997) pointed out that the horizontal forces must be transferred to reinforced elements, such as horizontally lied geosynthetics reinforcement. Figure 1 shows the structural system and the load transfer mechanism of the lateral spreading.

With increasing embankment heights, the spreading forces, and as a result, the tensile forces on the reinforcement will be dramatically increased and lead to higher deformations in the system. Both the membrane effect (arching effect) and the spreading effect influence the behaviour of the bearing system (such as pile elements) and the tensile forces on the reinforcement. Therefore, there is a high need to analyse and evaluate these effects for higher embankments. Moreover, the behaviour of soil-reinforcement interaction must be accurately described in order to attain the real stress-strain relations in such zones.

The determination of the shear stresses and the horizontal deformations at the embankment base, as well as the tensile forces in the geosynthetics reinforcement followed through a series of large-scale model tests under variation of underground conditions. Similarly, the horizontal force on head of pile element due to spreading effect has also been measured and analysed. The large-scale model test-results have been verified using a finite element method. The goal of the validation processes is to calibrate the soil parameters obtained from laboratory tests for further FE-parameter study.

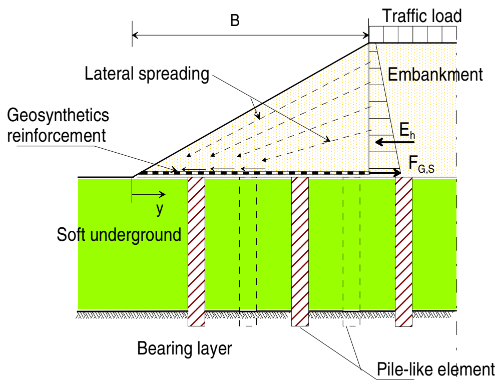

Figure 1. Lateral spreading of a reinforced embankment

An extensive parameter study has been carried out by means of keeping one or more parameters constant and varying the others. The parameter study gives a clear overview of all the factors that influence the tensile forces in the reinforcement.

A modified analytical method has been introduced to estimate analytically the spreading force sustained by the reinforcement. The modified method can be used for qualitative

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determination of the spreading forces in the reinforcement in the case of high and very high embankments, different underground conditions and embankment slopes.

2. LARGE-SCALE MODEL TESTS

A section of an embankment was simulated in a model test at a scale of 1:3. Thereby, three different underground conditions were considered. These are: underground material the same as embankment (sand), soft underground represented by foam material and soft underground with pile-like elements. Each case was tested with and without a base reinforcement (geogrids).

The first model test was carried out on homogeneous sand without a surcharge load and it is aimed at investigation of the effect of slope variations (1:3, 1:2 and 1:1.5) on the outward shear stresses at the embankment base. The shear stresses due to lateral spreading are derived from horizontal earth pressures measured at different sections in the slope zone taking equilibrium condition of an infinite vertical slice as follows:

$$\tau = \frac{\partial E_h}{\partial y} \tag{1}$$

Figure 2 shows the development of the shear stresses in the slope zone at the base of the embankment under different slope variations (B is the width of the slope, i.e at embankment shoulder y/B = 1). It can be seen from Figure 2 that the steeper the embankment the higher the shear stresses.

The rest four model tests were conducted on loaded embankment with a slope of 1:1.5; with and without base reinforcement, with and without pile-like elements. The pile-like elements were arranged in a square grid.

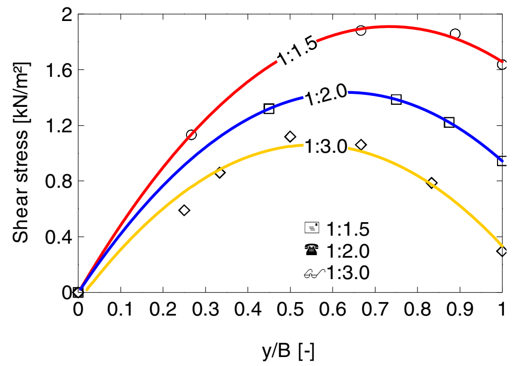

Figure 2. Shear stresses at embankment base under slope variations.

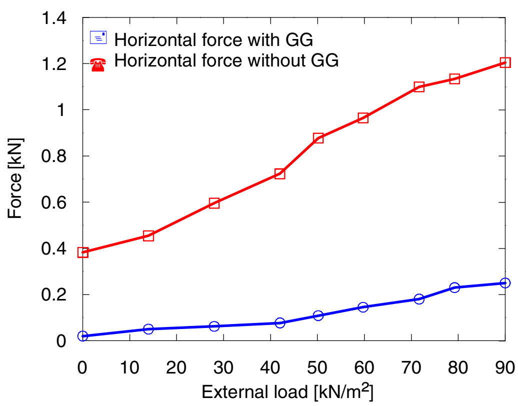

Figure 3. Measured horizontal force in the pile-like element

The effect of the geosynthetics reinforcement has also been evaluated by measuring the horizontal force on the top of the pile-like elements with and without basal reinforcement. It can be seen from Figure 3 that the geosynthetics reinforcement reduces the horizontal force on pile head. For details of model test results and interpretations, see Fahmy (2008).

3. VERIFICATION OF THE MODEL TEST RESULTS

The model tests are verified using FEM. The soil parameters are first calibrated on the homogeneous model test (sand underground without reinforcement and pile-like elements). Comparison of the measured and calculated deformations at different sections and earth pressures in the slope zone shows good agreement (see Fahmy 2008) without major adjustment of the soil parameter. The rest of the models are then analyzed using the calibrated soil parameters.

Plane strain FE-models were used to analyze the model tests of un/reinforced embankments on soft underground without pile- like elements, whereas three-dimensional FE- models had been employed in the case of a piled soft underground. Figure 4 shows selective results of the FE-computation and comparison with measured values. As it can be seen from Figure 4a, the calculated and measured strains in the geogrids agree very well in the case of underground without pile-like elements. Whereas, the calculated strains in the base reinforcement on top of a pile like elements shows a large difference (Figure 4b). This may be attributed to the simulation of the geogrids as a membrane. The geogrids seems to behave differently as a membrane, especially when it is laid on a point support system. This phenomenon has also been reported by Zaeske (2001), Bussert et al. (2004), Jenck et al. (2005) and Heitz (2006). Based on the authors own results, such as shown in Figure 4b, and back analysis of model test results from the literature (for e.g. Zaeske 2001, Heitz 2006) a factor of about 3.5 is derived between calculated and measured results.

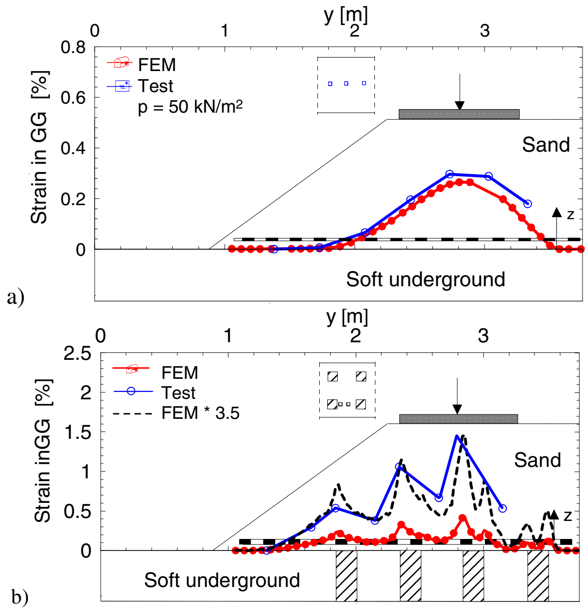

Figure 4. Tensile strain in reinforcement a) unpiled and b) piled embankment.

4. PARAMETER STUDY

A series of numerical parameter studies on the prototype using 3D-FEM are performed under different parameter variations such as embankment height, slope, underground stiffness, geogrids stiffness and number of layers, etc. It is obvious that the spreading and the membrane forces increase with increasing height (Figure 5). The result of the numerical study also confirms that under steeper slope the shear stress at the slope base is greater, and consequently the resulting spreading forces are greater. The effect of the slope is more noticeable by high embankments than the lower embankments.

Both the spreading and membrane forces in reinforcement are also observed to be smaller in the case of stiffer underground than soft underground. This is attributed to the small shear deformations of the stiffer underground.

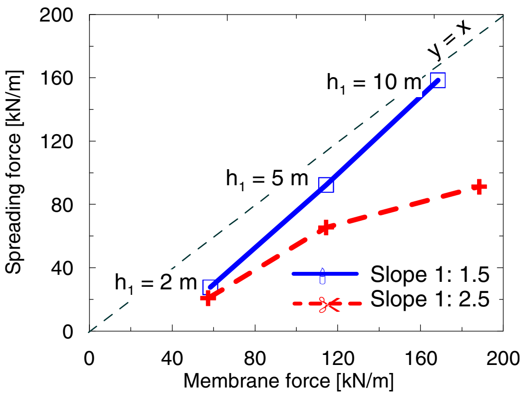

Figure 5. Spreading and membrane forces under different embankment heights and slopes.

5. COMPARISON OF FEM-RESULTS WITH THE ANALYTICAL APPROACH

EBGEO (2007) recommends two approaches (option 1 and 2) for the determination of the total tensile force in reinforcement analytically for embankments supported by pile-like elements. In option 1 the total tensile force in reinforcement is taken as the sum total of the membrane force ($F_{G,M}$) and the spreading force ($F_{G,S}$) (Equation 2). The spreading force is assumed equal to the horizontal earth pressure force at a section through the crest of the embankment. This approach is similar to that recommended by BS 8006 (1995).

$$F_G = F_{G,M} + F_{G,S} \tag{2}$$

Option 2 is similar to the approach by Love & Milligan (2003) and it is based on the concept that basal reinforcement can only have one tension in the transverse direction of embankment. The reinforcement in this case should be designed for whichever is the greater: the membrane force or spreading force (Equation 3), but not their sum. The same approach was also adopted by Klobe (2007).

$$F_G = \max\begin{cases} F_{G,M} \\ F_{G,S} \end{cases} \tag{3}$$

Option 2 however requires that the piles should not suffer from bending due to deflection of the pile heads.

Figure 6 shows a comparison between the analytical and the numerical results in case of stiffer underground with flatter embankment slope 1:2.5. It can be seen from Figure 6 that both options of EBGEO (2007) would lead to an overestimation of the tensile force in the reinforcement as compared to the FEM-results, especially in the case of high embankments. This is mainly attributed to the assumption that the spreading force is equal to the horizontal active earth pressure force at a section through the crest of the embankment and ignorance of the stiffness of the underground.

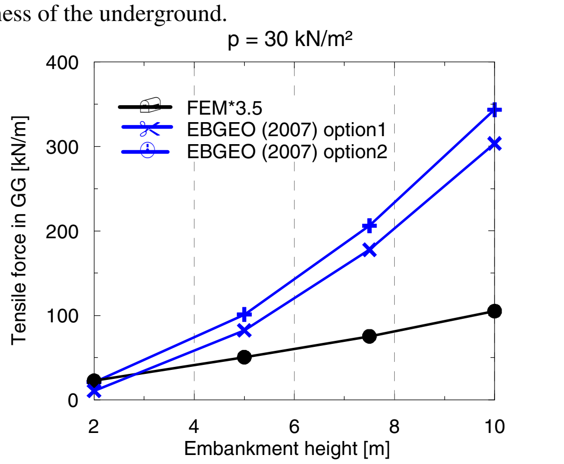

Figure 6. Comparison of tensile forces in reinforcement determined analytically (EBGEO 2007) and numerically (FEM)

6. MODIFIED ANALYTICAL METHOD

A modification of the analytical method to calculate the spreading force in reinforcement is carried out based on the assumption that the section through which the horizontal earth pressure force is determined is not always fixed at the embankment crest, rather it moves towards the toe depending on the height of the embankment as shown in Figure 7. The position and the height of the fictitious wall h_w depends mainly on a vertical angle θ from the slope crest. The critical angle θ can be determined by equating the so calculated spreading force with that obtained from FEM.

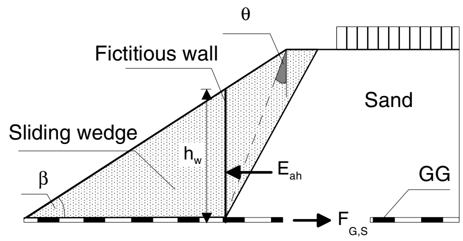

Figure 7. Sliding soil wedge to determine the spreading force

The earth pressure force E_{ah} on the fictitious wall which is assumed equal to the spreading force $F_{G,S}$ can be calculated using the earth pressure theory (see also Figure 8).

By comparing the tensile forces due to spreading determined analytically and numerically, the critical angles for different embankment heights are identified for the case of a peat underground (E_s = 0.8 MN/m²) and embankment slope of 1:1.5 (reference model). For embankment height up to *5 m*, the critical angle is found to be $\theta = 0°$ and for $h_1 = 10$ m $\theta = 30°$.

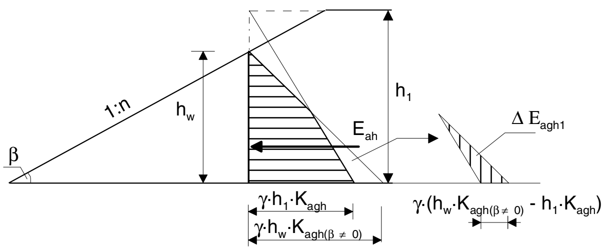

Figure 8. The horizontal earth pressure on the sliding soil wedge

For other underground condition and different embankment slope, adjustment factors are introduced to the tensile force due to spreading as shown in Equation 4.

$$F_{G,S} = E_{ah}(h = h_w) \cdot f_{E_s} \cdot f_\beta \tag{4}$$

where E_{ah} $(h = h_w)$ is the earth pressure force for the reference model, f_{Es} is dimensionless factor to account for the influence of the stiffness of the underground (f_{Es} = 1.0 in the case of peat underground), and f_β is a factor to account for the influence of the slope of the embankment (f_β = 1.0 in the case of slope 1:1.5). The factors f_{Es} and f_β can be formulated as functions of underground stiffness E_s and embankment slope β as:

$$f_{E_s} = \kappa_1 \cdot E_s^{(\kappa_2)} \quad \text{and} \quad f_\beta = k_3 \cdot \left(\frac{1}{\tan\beta}\right)^{k_4} \tag{5}$$

where κ_1, κ_2, κ_3 and κ_4 are variables that depend on embankment height h_1. Equation 4 can now be written in general form as:

$$F_{G,S} = E_{ah} \cdot (0.92 - 0.0085 \cdot h_1) \cdot E_s^{(-0.4768-0.0165 \cdot h_1)} \cdot (0.962 + 0.0504 \cdot h_1) \cdot \left(\frac{1}{\tan\beta}\right)^{(0.0334-0.099\cdot h_1)} \tag{6}$$

Figure 9 shows a comparison of the tensile forces in the reinforcement due to spreading according to the modified and the EBGEO (2007) approaches for different underground conditions and embankment slopes.

7 CONCLUSION

The existing analytical methods overestimate the spreading force, especially for high embankments, and ignore the effect of the embankment slope and the underground stiffness. On the other hand, the modified method based on model tests and intensive FE-parameter study takes into account all these effects and leads to a reasonable tensile force in reinforcement.

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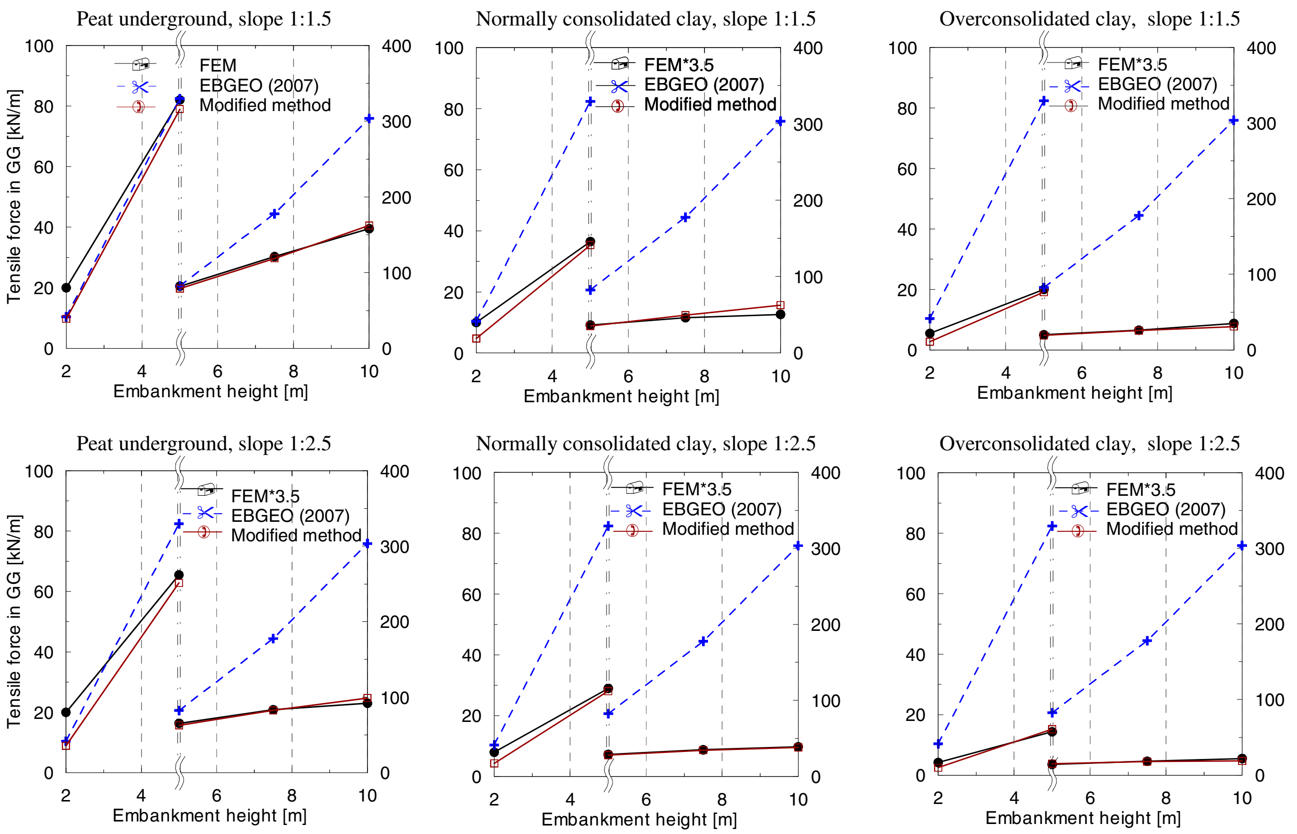

Figure 9. Comparison of tensile forces in reinforcement due to spreading according to the EBGEO (2007) and the modified approaches