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Laboratory small scale tests to study the behavior of reinforced soil wall

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ABSTRACT: A number of laboratory tests have been performed to observe the behavior of a steep reinforced soil wall in small scale model. In these tests the effect of the tensile strength of reinforcement layers and the effect of vertical interval spacing of reinforcement layers have been evaluated under the plane strain conditions. In computing the safety factor and interpreting the results, various values of the affecting parameters and different options of computing formulae have been examined for finding the best fitting quantities and to achieve the most reliable analytical interpretation. It was found that if the tensile strength of reinforcing elements and also the effect of side friction of the container are inserted into the modified Bishop's formula, then this formula reveals the most reliable analysis for the failure conditions. Because of the limited allowed pages, only very brief explanations can be presented in the present article.

1 INTRODUCTION

During the last decades many books and papers have been published regarding the various aspects of the subject of soil reinforcement and particularly about the topic of reinforcing by the geosynthetics. Therefore, at the moment we are aware that great strides have been so far made in the area of soil reinforcement, either theoretically, analytically, numerically or experimentally and also many experimental studies have been reported either in small laboratory scales in centrifuge apparatus or from the full scale models.

In the following, only a few examples of the recent relevant literatures are cited:

The laboratory study by Lee et al. (1973) may be considered as the first laboratory tests in small models (without the centrifuge apparatus) in which the reinforcement was made by some weak metal strip bands. Examples of some centrifuge model results have been reported by Porbaha and Kobayashi (1988) and Zornberg et al. (1998, a & b) regarding the shape of the failure surface.

Juran and Christopher(1989) described the results of a laboratory model study on the behavior of reinforced soil retaining walls using different reinforcing materials, i. e.: woven polyester, geotextile strips, plastic grids, and non-woven materials.

Zornberg and Arriaga(2000) reported a list of 13 experimental studies on real cases of reinforced slopes or embankments with the heights, mainly between 2.7 m to 7.6 m and one case with 27.4 m height.

2 SCOPES OF PRESENT EXPERIMENTS

The reinforced soil was modeled in a laboratory container with the dimensions of 120 cm (height), 100 cm (length), and 20 cm (width) with two sides of 6 mm thick glass walls as shown in Fig. 1.

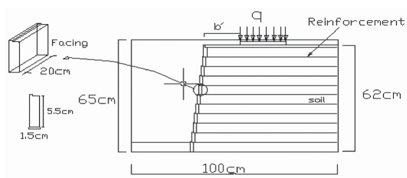

Figure 1. A simple view of vertical section of the test assembly and the pieces of facing.

The selected soil was a sand (SP in Unified Soil Classification) with grain size distribution between 0.1 and 2 mm. The sand was poured into the container through a hopper by raining method from a suitable and constant height to achieve the arbitrary (previously calibrated) density. The wall facing was made of pieces of wooden blocks with two different heights (5.5 and 11cm) and the reinforcement layers were the cotton papers of very low tensile strength values from 0.06 to 0.7 kN/m.

Because the main purpose of this study was to observe the behavior of a reinforced soil wall under the effect of the external surface loads and also to examine the reliability of the relevant formula for computing the safety factor, so it was necessary to assemble a suitable loading processes. In Figure 1, a simple view of the test assembly and the detail of facing blocks are shown.

The test program was planned as to be appropriate to: (1) observe the behavior of the layered reinforced soil wall; and (2) evaluate the effects of different factors on the stability and failure of this type of steep embankment under the external vertical loads similar to some actual cases of road embankments.

The density of soil in each test was measured by some cylindrical pots located inside the container at different levels during filling the container. This was necessary because the friction angle of used soil can only be evaluated by its relationship to its bulk density. This relationship was also determined primarily by means of some appropriate tests. The loading procedure was made by applying the dead weights in step-wised increments on a rigid plate at the top surface of the soil (as shown in Fig. 1). The vertical displacements of the soil body and the deformations along the failure path on the vertical plane of glass sides were measured by observations, and also by means of photography by a digital camera which was fixed at a constant distance from the model. A hand drawing mesh with 1 cm intervals was drawn on the inside the vertical surface of the glass side of ontainer wall to constitute a reference datum frame for observing and measuring the plane deformation on the vertical sections.

3 TESTS RESULTS AND DISCUSSIONS

Several tests have been performed in two main categories:

In some tests, without the applied surface load, the height of the model soil wall was increased towards the possible maximum height at which the failure could occurred under the weight (gravity) of the embankment, from which the final critical height (H_{cr}) was determined. The results of those tests are not discussed in the present article.

In other tests (which is the scope of the present article), the embankment models were built up to the fixed height of 60 cm and then the dead weights applied on the rigid plate on the soil surface gradually increased up to the stage of the failure, and the failure loads were determined accordingly.

The specifications of some of these tests and the results are shown in Table 1. The symbols of the variables in these tests (as indicated in Table) are:

a: distance from the edge of loading plate to the top edge of the wall, a = 10 or 15 cm.
b = the width of loading plate, mainly b = 15 cm
l = the length of loading plate, l = 22 cm
h_f = the height of a single part of facing = 5.5 or 11 cm
s_v = the vertical spacing of reinforcement layers, usually equals to h_f, but in some tests $2h_f$.
T_j = the tensile strength (kN/m) of reinforcing sheets.
FL = the failure load corresponding to the maximum tolerable external vertical load on the soil surface.

Table1. Measured failure loads for 10 tests with the parameters: a = 15 cm, h_f = 5.5 cm, H = 60 cm; b, as indicted in Table, and T_j = 0.32 kN/m for all, except for test EW in which T_j = 0.2 kN/m.

No.	symbol	b (cm)	failure load	$s_{v(cm)}$
1	E1	15	1.1 (kN)	5.5
2	E2	15	1.33 ”	”
3	E3	15	1.48 ”	”
4	E4	15	1.37 ”	”
5	E5	15	1.7 ”	”
6	E1-18	18.5	1.37 ”	”
7	E1-11r	11.5	1.25 ”	”
8	EW	115	0.85 (kN)	5.5
9	EW1-18	18.5	0.9(kN)	5.5
10	EW2-18	18.5	0.375(kN)	11

Photo 1. Failure of reinforced soil wall under the external surface load.

The photograph 1 is an example of the actual view of the final stage of tests in which the failure happened under the external load of 1.1 kN.

As we expect, the observations and measurements in these series of tests show that promoting the reinforcements (either by increasing the number of reinforcing layers or using the reinforcements of higher tensile strength or using double layers together) results in more stability (larger amount of safety factor). A brief explanation on these tests can be presented as follows:

In test E1 (Table 1), there are 10 single layers of reinforcements, the tensile strength of each layer was 0.32 kN/m, but in tests E2 to E4 in which three layers of reinforcements became doubled (near the toe in E2, at the mid height in E3 and at the top in E4). In test E5 the double layers were arranged alternatively between the single layers (five double layers of 0. 64 kN/m). Comparing the results of test E1 (with the failure load, FL = 1.1 kN) with any of tests E2 (FL = 1.33 kN), E3 (FL = 1.48 kN), E4 (FL =1.37 kN), and E5 (FL = 1.7 kN) clearly indicates the expecting proportional relationship between the amounts of the applied reinforcement and the failure load. The failure load in these tests is the maximum tolerable load which was applied on the loading plate of l = 22 cm and b = 15.5 cm; therefore for the conventional calculations for 1 m of length, this load must be multiplied by 1/0.22 = 4.55. Tests E1 and EW1 are identical in layer arrangements, but the tensile strength of reinforcement layers is 0.32 in E1 and 0.1 kN/m in EW1, accordingly the failure loads are 1.1 and 0.85 respectively. Comparing the results of tests EW1-18 (spacing of reinforcing = 5.5 cm) and EW2-18 (spacing of reinforcing layers = 11 cm) is an example to show the effect of vertical spacing of the reinforcement layers. In these tests, the tensile strength of layers is 0.2 kN/m and the failure load falls from 0.9 kN (in EW1-18, s_v = 5.5 cm) to 0.375 kN (in EW2-18, s_v = 11 cm).

Comparison between the tests E1 (b = 15 cm, FL = 1.1 kN) and E1-18 (b = 18.5 cm, FL = 1.37 kN), shows that increasing the width of loading plate results in ascending the failure load proportionally. As the ratio of 1.37/1.1 = 1.24 is about the same as the ratio 18.5/15, it means that both of them are still under plane strain conditions. Conversely, when the width of plate was decreased to 11.5 cm, not only the final load did not descend proportionally, but it became even larger. This effect can be attributed to the activation of arching phenomenon inside the sand medium, the discussion on this topic is beyond the length of the present article.

4 CALCULATIONS FOR SAFETY FACTOR

The cross section of failure zone in our tests were clearly two types, i.e.: circular (for strong reinforcement, as shown in Photo No. 1) and planar (for weak reinforcement). In addition, in tests without external loading the failure cross section seemed to be almost a logarithmic spiral.

As it is well known, the Fellenius's and Bishop's formulae are the most common formulae for evaluating the factor of safety of sloped embankments. Although these formulae were principally developed for the non-reinforced soils, but they can be logically modified to the more advanced form that become suitable for considering the reinforcement tensile strength. It is also worth mentioning that though the Bishop's method is known as more accurate than the Fellenius's, nevertheless, Zornberg et al. (1998 b) have used the modified form of Fellenius formula in which they considered the effect of tensile strength of reinforcement elements for analyzing the results of their centrifuge tests.

For the present study, both formulae were examined and based on the results many diagrams were drawn and compared, but because of the page limitation the complete results can not be presented here. The procedure for the analyses are summarized as follows:

In Fig. 2, the vertical section of the failure zone is divided into selected vertical slices in which the total applied external load (Q) is distributed on the top of slices to be Q_i for each single slice. The first step of modification of Fellenius's and Bishop's formulae is to take into account the effect of reinforcing tensile strength and the effect of external load, both of them have been so far used for the full scale project and also for the centrifuge tests. For these conditions, the modified formulae for computing the safety factor are as follows:

Modified Fellenius formula: (1)

$$FS_F = \frac{R \sum [(W_i + Q_i) \cdot \cos \alpha_i \cdot tg\varphi] + \sum T_j Y_j}{R \sum [(W_i + Q_i) \cdot \sin \alpha_i]}$$

or Modified Bishop formula: (2)

$$FS_B = \frac{R \sum \left[\frac{(W_i + Q_i) \cdot tg\varphi}{\cos \alpha_i + (\sin \alpha_i \cdot tg\varphi)/FS_B} \right] + \sum \frac{T_j \cdot Y_j}{FS_B}}{R \sum [(W_i + Q_i) \cdot \sin \alpha_i]}$$

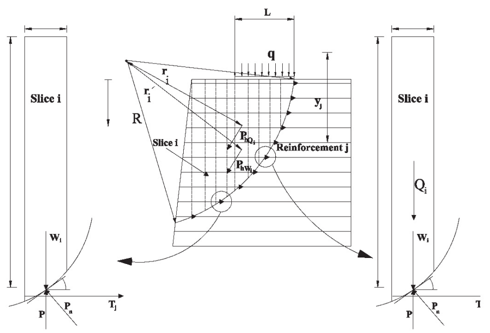

Figure 2. Characteristic of the sliding section and the relevant forces with corresponding distances.

The terms and the characteristics in the above formulae are defined as follows:

$R \cdot \sum [(W_i + Q_i) \cdot \cos \alpha_i \cdot \tan \phi] + M_T$: resisting moment

$M_T = \sum (T_j \cdot Y_j)$: total resistant moment due to the tensile strength of reinforcement

$R \cdot \Sigma (W_i + Q_i) \cdot \sin \alpha_i$ the sum of disturbing moment
W_i, = the weigth of each slice
α_i = the slope angle of the base of each slice
R = the radius of the failure circle
T_j = the tensile strength of the reinforcing layers acts at a vertical distance of Y_j from the circle center.
Q_i = the effect of vertical external load in each slice

The above formulae were modified further to be able to take into account the effect of side friction of the container in our tests. Then they were rearranged another time in term of tan ϕ for the FS = 1. Then, Fellenius formula in this case becomes:

$$tg\varphi = \frac{R\,\Sigma\,[(W_i + Q_i)\sin \alpha_i] - \Sigma\,T_j Y_j - \Sigma\,2F_{Wh_i} \cdot r_i - \Sigma\,2F_{Qh_i} \cdot r'}{R\,\Sigma\,[(W_i + Q_i) \cdot \cos \alpha_i]}$$

The symbols r_i and r_i' in Figure 2 and in the last formula are the defined distances for the resistant moments due to the effect of side friction.

Several computations carried out with different values of soil friction angle (the peak values) and various amounts of reinforcement tensile strength by the mentioned four formulae, and various graphs were also drawn, then these computational results were compared to the tests results. It was found finally that for an amount of 1 for the safety factor, i.e. at the failure, the best agreements occurred with the modified Bishop's formula. In these calculations, it was necessary to take into account the effect of side friction, because the calculations without the effect of side friction resulted in wrong results. As an representative example, the numerical values From the modified

Bishop's formula for FS = 1 corresponding to test E1 are: $\phi = 38°$ (related to $\gamma = 16.3$ kN/m), and T_j = 0.32 kN/m, which is quite reliable and in agreement with the measured values of ϕ and T_j. The coincident amounts of ϕ calculated from other formulae: i.e. modified Bishop's without side friction, and Fellenius's with or without side friction for the same amount of T_j are 44, to 58 degrees which are not acceptable for the tested sand.

The detailed results and discussions should be presented in a more lengthy text.

5 CONCLUSION

Laboratory models can reveal valuable results in showing the behavior of reinforced soils in plane strain conditions. For the thin laboratory model, if the movement of side walls of the container is practically restricted as $\varepsilon_x = 0$, and the effect of side friction is taken into account in the calculations, then the modified Bishop's formula with considering the effect of relevant factors (like side friction, external load, variations of friction angle, etc.) can be accepted as the best equation for analyzing the failure conditions of layer - wised reinforced soil, even for laboratory scale cases.

REFERENCES

Juran, I. and Christopher, B. (1988). "Laboratory Model Study on Geosynthtic Reinforced Soil Retaining Walls", ASCE, J. of Geotech. and Geoenv. Eng., Vol. 115, No. 5, pp. 905-926.

Lee, K.L., Adams, B.D. and Vagneron, J.M.J. (1973). "Reinforced Earth Retaining Walls", ASCE, Vol. 99, No. SM10, pp. 745-764.

Porbaha, A. and Kobayashi, M. (1998). "An Investigation of Hazard in Reinforced Embank-ments", Geotechnical Hazards, pp. 251-258.

Zornberg, J.G., Sitar, N. and Mitchell, J.K. (1998a). "Performance of Geosynthetic Reinforced Slopes at Failure", J of Geotech. & Geoenv. Eng., ASCE , Vol. 124, No. 8, pp. 670-683.

Zornberg, J.G. and Arriaga, F. (2000). "Reinforced Soil Design: Integration of Digital Image Analysis", Numerical Modeling and Limit Equilibrium, Technical Report, Colorado advanced Software Institute, USA, 135 pages.

Zornberg, J.G., Sitar, N. and Mitchell, J.K. (1998b). "Limit Equilibrium as Basis for Design of Geosynthetic Reinforced Slope", ASCE Journal of Geotechnical and Geoenvironmental Engineering, Vol. 124, No. 8, pp. 684-698.