Finite Element Analysis of Centrifuge Tests on Embankments on Soft and Stiff Grounds

Ali Sobhanmanesh[1], Ramli bin Nazir[2], and Nurly Gofar[3]

***Abstract*—** The behavior of unreinforced and reinforced embankments on soft and stiff grounds have been investigated using the centrifuge tests and verified by numerical finite element simulation modeling. Four different cases have been considered in this study based on various types of foundation materials and reinforcement situation. Soft kaolin and compacted dry sand were used as soft and stiff foundations respectively. A clayey-sand soil was used as fill material and a proper textile was considered as reinforcement. A commercial Finite element program "Plaxis" has been used to model and analyze the prototypes behavior provided by centrifuge tests. Deformation behavior, vertical settlements and effect of reinforcement have been studied in this paper. Verifications of the numerical model were taken by comparing the numerical results with the measurements obtained from the centrifugal tests and it was found that both were in good agreement.

***Keywords*—** Centrifuge test, Finite Element Analysis, Reinforced Embankment, Soft foundation

I. Introduction

MANY embankments constructed on soft grounds are susceptible to failure and large settlements. These stability problems of embankments on soft soils occur due to high compressibility and low shear strength of soil. Many of the ground improvement techniques, which have been used in the past to increase the shear strength of the soil, are time-consuming and uneconomical. Hence an alternative method such as soil reinforcing by geosynthetics is needed to solve this problem [1]. The emergence of geosynthetic reinforcement in recent times has revolutionized the concept of ground improvement. The idea behind this technique is to make use of the tensile strength of the reinforcement to limit the spreading of the embankment and lateral displacement of the soft foundation [2]. Although geosynthetics have been widely used in practice to improve the stability of various geotechnical projects, the reinforcement mechanisms are still far from clear [3], so designing an embankment on a soft soil Still raises several concerns related to the weak geotechnical properties of the soft soil.

In recent years, the behavior of geo-synthetically reinforced structures has been studied through field observation of full-scale physical model. However, the cost of constructing and monitoring full-scale reinforced test embankments is quite high and is time consuming. Hence, an alternative method such as scaled-down centrifuge test and numerical simulations can be used to study the deformation behavior of embankments on soft soil.

Numerical simulation by means of appropriate methods such as finite-element (FE) or finite-difference (FD) techniques is essentially required to better understanding of the mechanical response of reinforced soil embankments subjected to different loading conditions and to develop more advanced design methodologies compared to the current limit equilibrium-based or laboratory approaches.

The strategy is to performance of reinforced embankments on soft ground using numerical models validated against physical data gathered from field or laboratory model [4].

This paper deals with the finite element simulations of reinforced and unreinforced embankments subjected to accelerate gravity conditions in small beam centrifuge apparatus to study settlement and deformation behavior of embankment, effect of reinforcement and reinforcement mechanism.

II. Centrifuge Modeling

Reduced scale models are economical and timesaving alternatives to full scale tasting. Centrifuge model testing is an example of small-scale models and is a useful tool in the investigation of geotechnical problems because of its ability to reproduce the same stress levels in a small-scale model as those present in a full-scale prototype.

A. Description of Small Geotechnical Centrifuge Apparatus

Centrifuge tests were carry out in a small geotechnical centrifuge apparatus at department of geology, faculty of Science and technology FST, Universiti Kebangsaan Malaysia (UKM), under the supervision of associated professor Dr. Wan Zuhairi Wan Yaacob.

The apparatus is a small-size beam-type centrifuge, designed to allow centrifuge testing of soil package up to 6Kg with a maximum rotational speed of 500rpm and can accelerate up to 140 in units of times gravity at an effective radius of 0.5 m. The

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capacity of the small geotechnical centrifuge is 0.84 *g-ton* machine (140 *g* x 0.6 kg). For observing the performance of model during the test, the centrifuge apparatus is equipped with colored digital video camera and high-speed stroboscope. The recorded of moving images can be stored directly into the computer. Real time video images can also be observed on the LCD monitor installed in the operation room.

An overall view of small-size beam-type centrifuge apparatus and its equipment is shown in Fig. 1-2.

Fig. 1 Overall view of small centrifuge apparatus

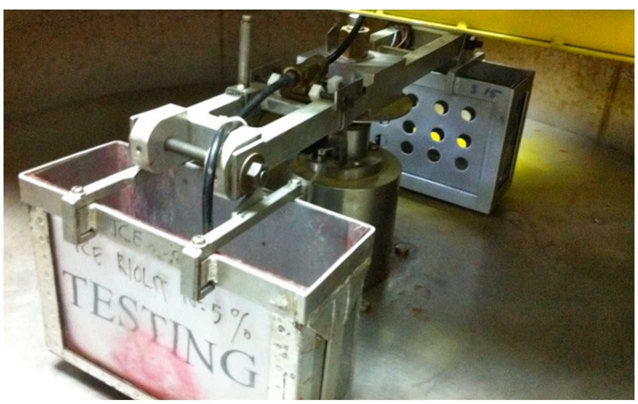

Fig. 2 Small size beam-type centrifuge

B. Test Box

The soil sample box with dimensions of 28cm (length) x 10cm (width) x 19.5cm (height) was placed in a strongbox that was fixed to the centrifuge arm. The strongbox constructed with aluminum walls and Perspex at the front to allow the sample to be seen during the test. To monitor the soil settlement during testing, a sketch of embankment and foundation layers were drawn on the front surface of the model specimens.

Details of the small geotechnical centrifuge are shown in Table I [5].

TABLE I
SPECIFICATION OF SMALL GEOTECHNICAL CENTRIFUGE

Parameter	**Value**
Package volume	290mm x 100mm x 195mm
Package mass	6 kg
Drive Power	600 W
Rotational speed	80 to 500 rpm
Radius at base package	0.5 m
Acceleration	3 to 140 g
Centrifuge capacity	0.84 g-ton

C. Centrifuge Models

In this study, four model cases are tested in centrifuge apparatus base on different conditions of foundation materials and reinforcement:

Case I: Unreinforced embankment on soft foundation
Case II: Unreinforced embankment on stiff foundation
Case III: Reinforced embankment on soft foundation
Case IV: Reinforced embankment on stiff foundation

The general condition of each case is listed in Table II. In all models clayey-sand was used as fill material. Compacted sand was modeled as stiff soil foundation while the consolidated kaolin was modeled as soft soil foundation. Models I & II are unreinforced and models III & IV are reinforced with textile.

The scaled-down centrifugal embankment has a height of 5cm, a crest width of 14cm and slope of 1V to 1H, underlain by a soft kaolin foundation of 7cm thickness. Due to inherent symmetry about the centerline, only one half of the model was considered. Sectional view of model is shown schematically in Fig. 3.

TABLE II
DIFFERENT CASES OF EMBANKMENT AND FOUNDATION MODELS

NO.	Foundation	Fill Material	Reinforcement
1	Sand	Clayey-Sand	-
2	Kaolin	Clayey-Sand	-
3	Sand	Clayey-Sand	Textile
4	Kaolin	Clayey-Sand	Textile

1. Geosynthetic Material

The properties of the textile that is used as a reinforcement were obtained from tensile strength test carried out at department of civil engineering, Universiti Teknologi Malaysia (UTM) and are given in Table III.

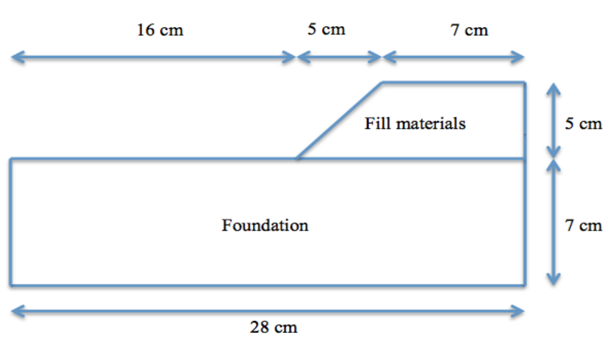

Fig. 3 Sectional view of embankment model at centrifuge test

TABLE III
PROPERTIES OF TEXTILE

Parameter	Value
Thickness (mm)	0.17
Tensile stress (kN/m)	6.1
Elasticity modulus (Mpa)	65.3
Tensile strain (%)	53.4

D. Centrifuge Test Methodology

After preparing the model in sample box, the model weighted and then the sample box was fixed to the centrifuge arm. To balance the system, a counterweight equal to weight of sample added to opposite side of the centrifuge arm.

The staged-construction processes of embankment were simulated in centrifugal tests by increasing the accelerations. The models were initially run at low acceleration and were subjected to a progressively increasing centrifugal acceleration limited to 50 g in about 60 minutes. At certain accelerations the test was maintained constant for certain times and then again the acceleration continued to increase. This process is shown in Table IV.

TABLE IV
GRAVITY ACCELERATION AND TIME MAINTAINED OF CENTRIFUGE TEST

Time Maintained (minute)	ω (rpm)	Gravity (g) $G=(1.18\times10^{-3})\times r^{*}\omega^{2}$
5	120	8.5
5	185	20
5	225	30
15	250	37
10	285	48
20	300	50

III. NUMERICAL ANALYZING

A. Finite Element Models

Finite element analyses of embankments on stiff and soft soil foundations were carried out using Plaxis 2D program. This finite element program allows for a realistic simulation of the construction sequences, the inclusion of reinforcement and the interface elements at any stage of the analysis. The FE model of reinforced embankment consisted of embankment fill material, foundation soil material, reinforcements, and soil-to-reinforcement interaction elements.

Because the problem is symmetric, only one half of the embankment was modeled. The model dimensions are N times (N=50g) of the centrifuge model dimensions to simulate full-scale prototype. Fig 4 shows the model developed by 2D finite element program.

A plain strain model with the 15-node triangular element was used in model simulation. The standard fixities were used to define the boundary conditions, i.e. full fixity was assumed along the bottom of the model and the vertical boundaries of the model were fixed in the horizontal direction The elastic perfectly plastic with Mohr–Coulomb failure criterion was used to model the behavior of the embankment fill material and soft clay foundation. The linear elastic material model was used to model the reinforcement.

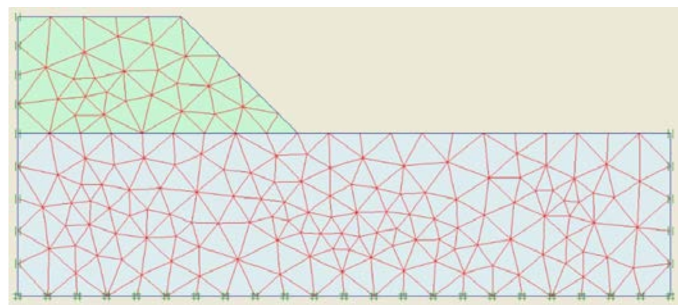

Fig. 4 Resulting mesh of finite element model

TABLE V
MATERIAL PROPERTIES OF EMBANKMENT FILL AND FOUNDATIONS

Parameters	Name	Kaolin	Sand	Clayey-Sand
Material Model	Model	MC	MC	MC
Type of Behavior	Type	Undrained	Drained	Drained
Soil unit weight above phreatic level (kN/m^3)	γ_{unsat}	15	18	17
Soil unit weight below phreatic level (kN/m^3)	γ_{sat}	17	20	19
Horizontal Permeability (m/day)	K_x	$1*10^{-4}$	1	0.5
Vertical Permeability (m/day)	K_y	$1*10^{-4}$	1	0.5
Young's Modulus (kN/m^2)	E	1200	4000	3500
Poison's ratio	ν	0.35	0.3	0.3
Cohesion (kN/m^2)	C	5	1	5
Friction angle	φ	15	31	30

1. Material Modeling

The properties of materials used in the models are shown in Table V, where ϕ = friction angle of foundation soil or fill; *c* =cohesion of foundation soil or fill; *E*=Young's modulus number; ν = Poisson ratio number; *kx* and *ky*= permeability coefficient of foundation soil or fill.

2. Soil-Reinforcement Interfaces

In Plaxis 2D, geogrid elements were specified to model soil reinforcement. Geogrids are composed of geogrid elements (line elements) with two translational degrees of freedom in each node (ux, uy). The only material property of a geogrid is an elastic normal (axial) stiffness EA [6]. EA can be determined from the curve of the elongation of the geogrid plotted against the applied force and is the ratio of the axial force per unit width to the axial strain [3].

The interface elements should be used to model the interaction between reinforcement and soil. The roughness of the interaction is modeled by choosing a suitable value for the strength reduction factor in the interface (R_{inter}).

Interface behavior of geosynthetic and soil are important for the performance of the geosynthetic-reinforced embankments system. Under a relatively small deformation, however, the influence of these interfaces on the system performance is expected to be less important [7]. In this study, the interfaces ratio between geosynthetics and soil are assumed as R_{inter} =95%.

B. Calculations

Four analyses were carried out based on aforementioned cases as used in centrifuge tests. The calculation consists of two phases. Firstly the initial stress field has to be calculated when the embankment and reinforcement have been deactivated. The second calculation phase is the staged construction of embankment and reinforcement. After the construction, consolidation analysis was used, allowed clay foundation to consolidate under the embankment loading to dissipate the excess pore water pressure (cases I & III). In order to simulate the settlement of the embankment on sand foundations, the plastic calculation was used (cases II & IV).

IV. RESULTS

Comparison between the maximum measured settlements of centrifuge tests and maximum calculated settlements of finite element simulations are shown in Table VI.

TABLE VI
MAXIMUM SETTLEMENTS OF CENTRIFUGE AND FINITE ELEMENT ANALYSIS FOR DIFFERENT CASES

Analysis Type	Case I	Case II	Case III	Case IV
Centrifuge maximum settlement (Cm)	21	5	10	4.5
Finite element maximum settlement (Cm)	19.8	4	11.1	4

From Table VI it can be seen that both measured and calculated results are in good agreement, so finite element simulation is a validated and powerful method to analyze the reinforced embankments on soft grounds.

A. Deformed Mesh

Fig. 5 to 8 show the deformed mesh of four cases models in Plaxis respectively.

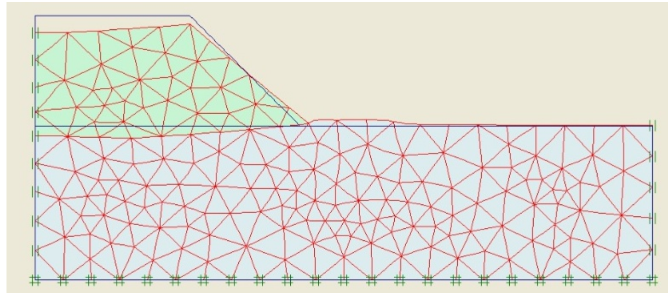

Fig. 5 Deformed mesh of case I

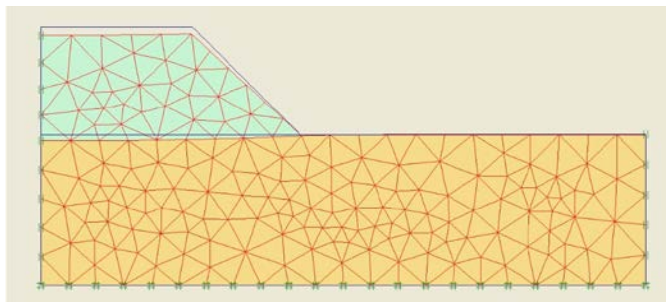

Fig. 6 Deformed mesh of case II

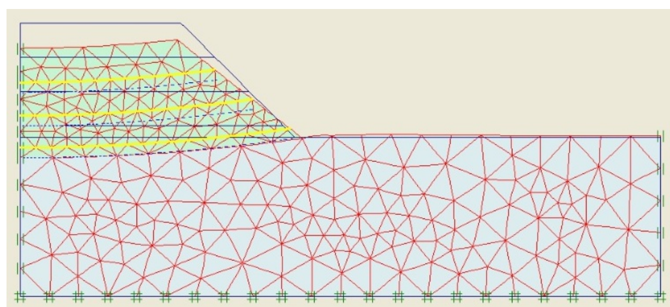

Fig. 7 Deformed mesh of case III

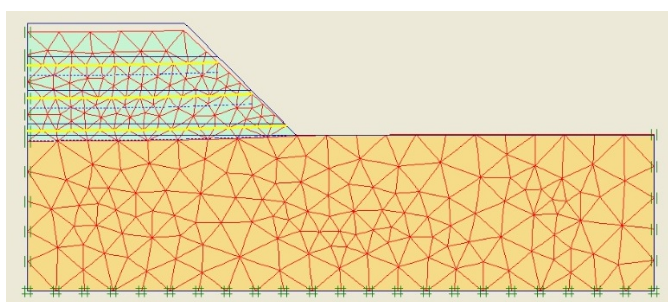

Fig. 8 Deformed mesh of case IV

From these figures it can be seen that for models with soft foundations (cases I & III) significant vertical and horizontal displacements occurred under the center and toe of the embankment, respectively, while slight heave occurred at the ground surface beyond the toe.

For models with stiff foundations the vertical and horizontal settlements are very low and soil heave did not occurred at the ground surface beyond the toe.

By comparing the reinforced and unreinforced models it can be seen that reinforcement has a significant effect on reduction of vertical and horizontal displacements on models with soft foundations (cases I & III), but low or no effects on cases with stiff foundations (cases II & IV).

B. Excess Pore Pressure in Kaolin

Fig. 9 shows the Excess Pore Water Pressure (E.P.W.P) in kaolin foundation (case I) at point B (1.14, -1.50). It can be seen that during the construction phases the excess pore pressure increases with a small increase in time while during the consolidation periods the excess pore pressure decreases with time. From the curve it can be seen that more than 300 days are needed to reach full consolidation.

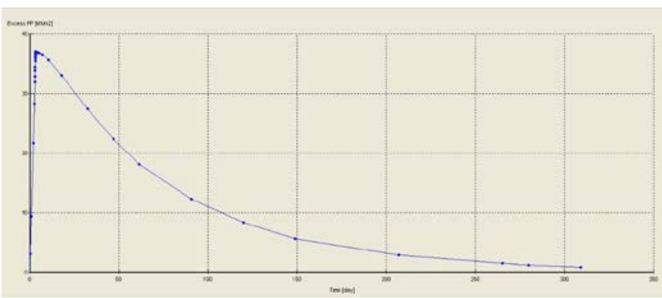

Fig. 9 E.P.W.P in kaolin foundation

C. Settlement of Embankment

Fig. 10 shows that the settlement of the embankment on stiff foundations (cases II & IV) increased slower and with seemingly no clear change in the rate of settlement, while the settlement of embankment on soft foundations (cases I & III) increases rapidly in the construction phase, indicating that the critical phase for the embankment was just after the completion of its construction.

After the construction of embankment, the settlement was continues considerably at constant rate during the consolidation phase. This is due to the dissipation of the excess pore pressures (= consolidation), which causes further settlement of the soil.

D. Tension in the Reinforcement

Fig. 11 shows the axial force along the first geogrid reinforcement (geogrid at the ground surface). The maximum axial force is 5.84 kN/m, 2.99 kN/m and 0.4 kN/m for first to last geogrids respectively (from ground surface to top of embankment). it was found that the axial forces and the tensile strain of the geogrid at the ground surface is much bigger than the upper geogrids . This indicates that the geogrid at the ground surface is more important than others and has the most effect on the reduction of displacements of embankment on soft soils.

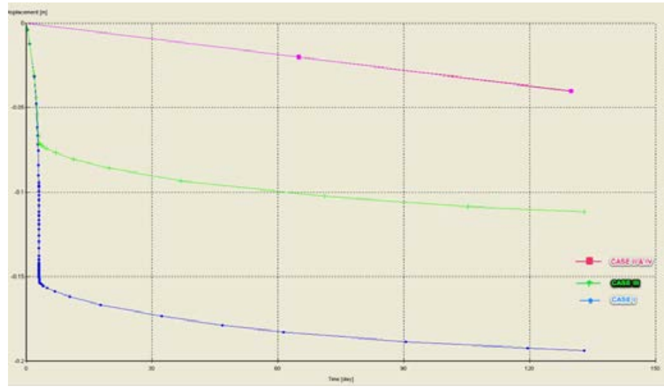

Fig. 10 Settlement of embankment for cases I to IV

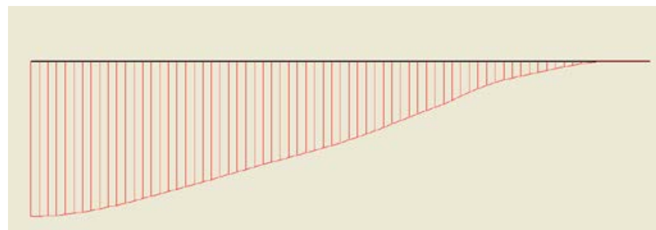

Fig. 11 Axial force of the geogrid at the ground surface

V. Conclusion

Finite element analyses of centrifuge tests were carried out based on different conditions of foundation strength and embankment reinforcement condition.

The mini-centrifuge equipment used in this study does not enable a comprehensive study of reinforced embankments due to the capacity of the centrifuge apparatus. However, this apparatus has enabled the qualitative behavior of the problem to be studied.

The finite element modeling of different cases were successful in predicting the overall behavior of unreinforced and reinforced embankments. Predictions of settlements were in good agreement with the measured values for all the analyses.

The tension mobilized in the reinforcement can be very effective in improving the short-term stability of the embankment.

The tension in the reinforcement is sensitive to the magnitude and distribution of shear strength of clay foundation.

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REFERENCES

[1] Bergado, D.T., Teerawattanasuk, C., "2D and 3D numerical simulations of reinforced embankments on soft ground." *Geotextiles and Geomembranes* 26:39-55, 2008.

[2] Sharma, J.S., Bolton, M.D. "Centrifuge modeling of an embankment on soft clay reinforced with geogrid." *Geotextile and Geomembranes*. 14 (1): 1-17, 1996.

[3] Chen, J. F., Yu, S.B. and Han, J., "Numerical modeling of a reinforced embankment based on centrifuge test dimensions." *ASCE GeoHunan International Conference*, 2009.

[4] Tanchaisawat, T., Bergado, D.T., Voottipruex, P., "Numerical simulation and sensitivity analyses of full-scale test embankment with reinforced lightweight geomaterials on soft Bangkok clay." *Geotextiles and Geomembranes* 26:498-511, 2008.

[5] Muhardi, "Pulverized fuel ash as structural fill for embankment construction." A PhD Dissertation Thesis, Universiti Teknologi Malaysia, 2011.

[6] Xin, JIANG. 2009. "A comparative study of various commercially available programs for numerical analysis of reinforced soil." *International Conference on Transportation Engineering 2009 (ICTE 2009)*: 753-758.

[7] ZHANG, J. H., ZHENG, J. L., HUANG. X. M., "Centrifuge Model Test and Numerical Analysis of Geosynthetic-Reinforced Embankments for a Road Widening." *Geotechnical Special Publication No. 213 © ASCE 2011*.