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NUMERICAL MODELING OF CENTRIFUGE TEST PROCEDURE FOR DIFFERENT EMBANKMENT CASES

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ABSTRACT: Physical modelling through full-scale and small-scale models is widely implemented in order to define specific aspects of the prototype behaviour. On the other hand, numerical modeling is essentially required to cope with the complex geotechnical problems due to the ability of considering and analyzing all aspects of the model and can afford more perception about the behavior of structures such as geosynthetic-reinforced embankments. In this study, four different cases of unreinforced and reinforced embankment models constructed on soft and stiff grounds were studied. Small-scale physical modelling by means of centrifuge tests and numerical modelling by means of finite element simulations were performed. As the small-scale model was rotated in different acceleration fields during the centrifuge test, the dimensions of the centrifugal model were different from the original state of the prototype in different stages of the test. This paper focused on developing a finite element simulation based on the dimensions of a centrifugal model in different incremental acceleration fields applied during the stages of the test. Comparing the results of finite element simulations with the measurements of the centrifuge tests showed a good agreement between the two methods, which verified the reasonableness of the finite element models in analysis of embankments based on small-scale centrifugal dimensions. Moreover, the results showed the different deformation behaviour for embankments on soft and stiff grounds and indicated the significant effect of the geosyntheic reinforcement on increasing the stability of the embankment on soft ground.

Keywords: Finite Element Simulation, Centrifuge Test, Reinforced Embankment, geosynthetics

1. INTRODUCTION

The behaviour of geosynthetically-reinforced structures has been studied through observation of full-scale physical models by many researchers. However, the cost of construction and monitoring the full-scale embankment model is quite high and is a time consuming procedure with some limitations. Hence, an alternative method such as scaled-down modelling can be used. Although a small-scale model is relatively economical, in terms of finance and time, it is not reliable in predicting the actual prototype behavior due to the differences in stress levels surrounding the model and prototype respectively. For this reason, the centrifugal modeling technique has become increasingly used as it has ability to reproduce the same stress levels in a small-scale dimension model as those present in a full-scale prototype. Centrifuge modeling also has some limitations, e.g. the prototype is under earth’s gravity field where the radius of the earth is infinite compared to the prototype size. Thus the earth's gravitational field will act parallel and be uniform in direction at all points in the prototype. However, in the centrifuge, since it has finite radius compared to the model size, the artificial gravitational field is radial, which is non-linear and non-uniform.

There are two methods of the staged-construction of a model in the centrifuge test: 1) constructing the model in flight using raining technique 2) applying incremental acceleration fields in different stages of construction on a pre-constructed model with constant dimensions. The first method gives more accurate results but requires more advanced fully equipped apparatus to perform. However, due to the limitations, second method is also used commonly in many centrifuge tests.

A number of these centrifuge tests have been modelled by numerical approaches. In numerical simulation of centrifugal models, most of researchers have only utilized the full-scale prototype dimensions. [1]-[11]. It should be mentioned that using the second method, a scaled-down model has same dimensions and stress levels only at the final stage (final acceleration field) of the test compare to the prototype, i.e. the centrifugal model has different dimensions and stress levels in different acceleration fields before reaching the final stage. Therefore, a numerical simulation, which can consider these differences of dimensions and stress levels in varying acceleration fields of the centrifuge test, is very important and can consequence in more accurate results. Nevertheless, such simulations are limited in number so far.

Therefore, the focus of this paper is to conduct a realistic numerical simulation of centrifugal models utilizing small-scale centrifugal model dimensions to consider exact procedure of a centrifuge test utilizing abovementioned factors, i.e. different dimensions and stress levels in different applying acceleration fields of the test. Comparing the results of these numerical simulations with measurements of centrifugal models validates this numerical modelling technique.

2. EMBANKMENT MODEL CASES

In this research, four embankment models with different foundation soil and reinforcement condition were considered in both centrifugal and numerical modelling. Details of these cases are shown in Table 1. It is shown that in all cases, clayey-sand was used as fill material. Kaolin and compacted sand were considered as soft and stiff soil foundation respectively and a specific textile was utilized as reinforcement material.

Table 1 Details of four embankment cases

Case	Foundation	Fill material	Reinforcement
I	Kaolin	Claye sand	-
II	Kaolin	Claye sand	Textile
III	Sand	Claye sand	-
IV	Sand	Claye sand	Textile

A plan view and cross section of embankment model used in both centrifuge and numerical modeling is shown in Fig. 1. The scaled-down embankment model has a height of 5 cm, a crest width of 14 cm and slope of 1V to 1H, underlain by 7 cm foundation soil. Due to inherent symmetry about the centerline, only one half of the model was considered.

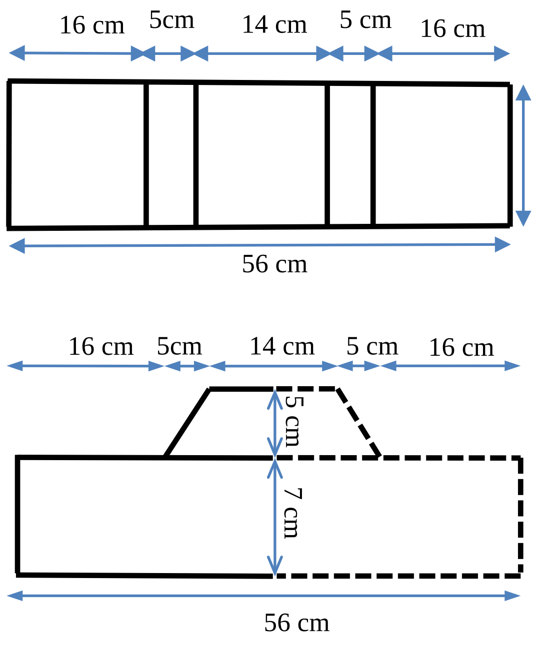


Fig. 1 Plan view and cross-section of embankment model

3. CENTRIFUGE TEST

Although a small-scale test is relatively economical in terms of finance and time (compared with a full-scale test), it is not reliable in predicting the actual prototype behavior due to the differences in stress levels of the model and prototype. For this reason, the centrifugal modeling technique has become increasingly used. Centrifuge test, which is an example of small-scale physical modeling, is a useful and applicable technic in geotechnical engineering. It has ability to reproduce the same stress levels in a reduced-scale model as those present in a full-scale prototype. In centrifuge modeling, inertial forces are utilized for a simulation of the gravitational forces. By raising centrifuge's rotational speed, model's inertial acceleration is raised, thus simulating the gravitational forces. According to (Taylor, 1995) a fundamental rule in centrifuge testing is determining geometric models of the particular prototype by a scale factor of *N* at inertial acceleration equivalent to *N* times the earth's gravity.

In this study, the centrifuge tests were carried out by mini centrifuge apparatus of Universiti Kebangsaan Malaysia (UKM). It is a beam-type centrifuge, designed to allow centrifuge testing of soil package up to 6 kg with a maximum rotational speed of 500 rpm and can accelerate up to 140 g at an effective radius of 0.5 m. The capacity of the small geotechnical centrifuge is 0.84 g-ton [12]. Section and inside view of small-size beam-type centrifuge apparatus and its equipment is shown in Fig. 2.

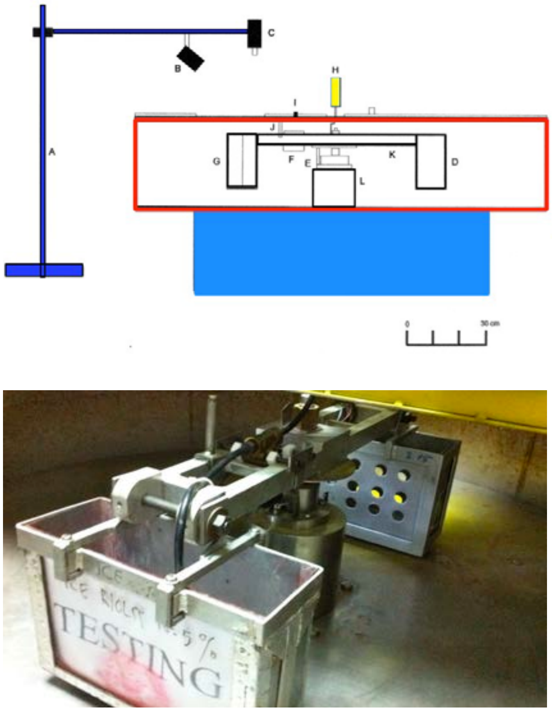


Fig.2 Section view and inside view of UKM mini centrifuge apparatus

3.1 Test Procedure

Because of limitations and technical difficulties of UKM mini-centrifuge apparatus in constructing a shaped embankment in flight, the centrifuge model was constructed before the test running and incremental accelerations was applied to simulate staged-construction of centrifugal modeling. In this method, the acceleration increased slowly to reach the predefined level. The rotation was maintained in this specific acceleration level for a certain time, and then the acceleration increased to reach the next level. Details of centrifuge test processes are depicted in Table 2.

Table 2 Centrifuge test procedures

ω (rpm)	Gravity (g) $g = (1.18\times10^{-3}) \times r^{*}\times(\omega)^{2}$	Maintained Time (minute)
130	10	5
184	20	5
225	30	5
260	40	15
291	50	30

4. FINITE ELEMENT MODELING

In this research, numerical modeling by means of finite element (FE) simulations were conducted using PLAXIS software, which is a powerful program in simulating and analyzing the geotechnical problems. Properties of materials used in the finite element analysis are shown in Table 3. These properties are adopted from laboratory tests. The undarined shear strength (Su) of kaolin considered as 8 kPa, which was defined by a mini-vane shear test.

Table 3 Properties of materials in FE modeling

Parameters	ClayeySand	Sand	Kaolin
Material Model	MC	MC	MC
Behavior	Drained	Drained	Undrained
Unit weight (kN/m^3)	18	19	16
Permeability $K_x = K_y$ (m/day)	0.5	1	3×10^{-4}
Young's Modulus (kN/m^2)	6000	10000	1000
Poison's ratio ν	0.3	0.3	0.35
Cohesion(kN/m^2)	5	1	8
Friction angle φ	30	31	0

The standard fixities were used to define the boundary conditions, i.e. full fixity (rough rigid boundary) was assumed along the bottom of the model and the vertical boundaries of the model were fixed in the horizontal direction (smooth rigid boundary). Geogrid reinforcement was modeled as line elements with two translational degrees of freedom in each node (ux, uy). The only material property of the geogrids in 2-D simulation is an elastic normal (axial) stiffness EA determined from the curve of the elongation of the geogrids plotted against the applied force and is the ratio of the axial force per unit width to the axial strain. The interface elements are considered 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}). Based on the direct shear tests carried on the interface of the soil and textile, the interfaces ratio between geotextile and soil was calculated as 0.95 for this study.

The key to successful displacement predictions with FE analyses is the selection of a suitable stress-strain relationship for the soil. Since FE is based on the deformations of a discretized elastic body, a numerical scheme must be incorporated to allow for the non-linear stress-strain behavior of the soil. This is most commonly achieved by means of step-wise loading, whereby the elastic parameters of the material are varied after each increment to account for the non-linear behavior. This is incorporated into the numerical process by adjusting the elastic matrix or the initial strain matrix. In this way, the stress-strain curve obtained from laboratory tests can be employed directly. Alternatively, an elastic-plastic model that employs a particular yield criterion such as Mohr-Coulomb model can be incorporated. The Mohr-Coulomb model is the most widely employed in geotechnical models and was considered in this analysis too [13].

4.1 Simulation Procedure

Construction stages by means of plastic analysis and post-construction stages by means of consolidation analysis were utilized as PLAXIS allows for undrained, drained and consolidation analyses of two-dimensional plane strain or axisymmetric problems. The elastic perfectly plastic materials with consideration of Mohr–Coulomb failure criterion were utilized to model the behavior of the embankment and foundation materials for all cases; the reinforcement element was modeled as linear-elastic material model. Due to symmetry, only one half of the embankment was considered. Fig. 3 shows the generated mesh and the considered plate at centerline of the embankment to simulate the interaction between soil and side-wall of strong box.

Different phases were considered in analysis of FE models. First, the initial stress field (initial phase) was calculated when the embankment and reinforcement were deactivated to consider the initial stresses of foundation body due to its own weight before the construction of embankment fill. The next calculation phase was the staged construction of embankment and reinforcement. The construction stages and processes were simulated by activation of the stiffness and weight of the fill elements one layer after the other. Since embankment construction on soft soil and high groundwater levels results in a rise in pore pressure, the effective stress remains small. In addition, the intermediary periods of consolidation (Consolidation Phase) need to be taken into consideration so that the extra pore pressure dissipates and the soil becomes able to acquire the shear strength that is required for the embankment construction process to go on safely. In order to simulate the settlement of the embankment on stiff sand foundations with high permeability, the plastic calculation was used to simulate the construction stage of embankment.

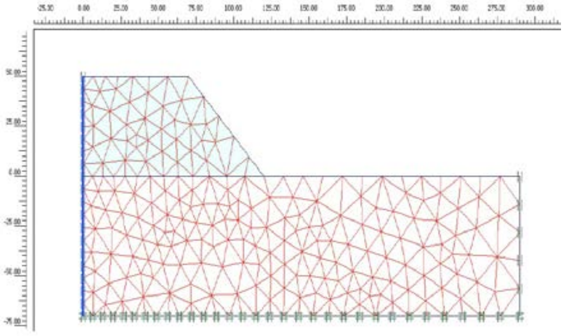


Fig. 3 generated mesh and boundary fixities

To consider varying dimensions of model due to the different acceleration fields of centrifugal tests, the FE modelling was performed based on the small-scale centrifugal model dimensions but under the accelerations more than earth gravitational acceleration (g).

In PLAXIS, the earth gravitational acceleration (g) can be simulated by considering the multiplier (Σ*Mweight)* equal to 1. Therefore, the process of varying incremental centrifugal accelerations was simulated in PLAXIS by considering different multiplier of Σ*Mweight* more than 1 related to different acceleration fields of centrifuge test (5 g, 10 g, 20 g, 30 g, 40 g, and 50 g) and also correspond to time period of rotation in that acceleration level as shown in Fig.4. Increasing the acceleration up to five levels of 10 g, 20 g, 30 g, 40 g, and 50 g simulated a five-staged construction of the embankment in centrifuge test.

The five level accelerations corresponded to the construction heights of 0.5 m, 1 m, 1.5 m, 2 m, and 2.5 m, respectively, according to the law of similarity. After each staged construction, a rest period was considered in the centrifuge model that is almost equal to the 10 hours for thickness of 0.5 m, 1.0 day for thickness of 1 m, 3 day for thickness of 1.5 m, 16.5 days for thickness of 2.0 m, and 52 days for thickness of 2.5 m.

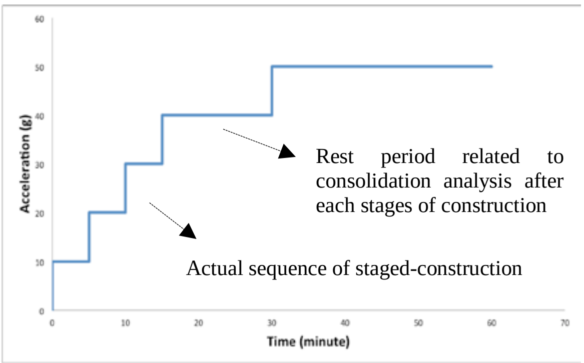


Fig. 4 Sequence staged-construction of model with varying acceleration fields

5. RESULTS AND DISCUSSION

The results of centrifuge tests and FE analyses for all cases are described in the following. A side-by side comparison between the FE results and centrifuge measurements are also depicted at the last section. Deformed mesh and shading of vertical displacements for different cases are shown in Figs. 5, 6 and 7.

It is clear that vertical and horizontal displacements occurred at the embankment fill, beneath the fill and at toe of the embankment. For cases constructed on soft ground i.e. cases I & II (refer to Table 1), slight heave and uplift occurred at the embankment toe and ground surface beyond the toe due to the undrained behaviour of subsoil layers. The extreme total displacements occurred at topside of the fill slope at embankment crest. The maximum displacement of case II at topside of fill slope of embankment computed as 3.1 mm, which reduced about 24.4% compare to the displacements of the unreinforced model (4.1 mm for case I). The uplift of the embankment toe was also decreased significantly compare to case I. This shows the effect of the geotextile reinforcement on increasing the stability and reducing the deformations of the embankment constructed on soft ground.

For cases constructed on stiff ground (cases III & IV), there was not any considerable difference in deformations and displacements of unreinforced and reinforced models. It indicated that the geosynthetic reinforcement have small influence on deformation behaviour of embankments on stiff ground because of small induced vertical displacements and lateral movements.

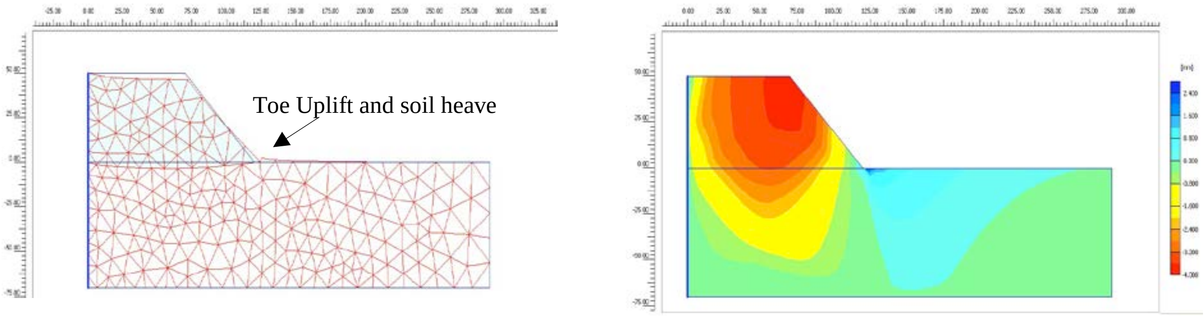


Fig. 5 (a) Deformed mesh (b) vertical displacements (case I)

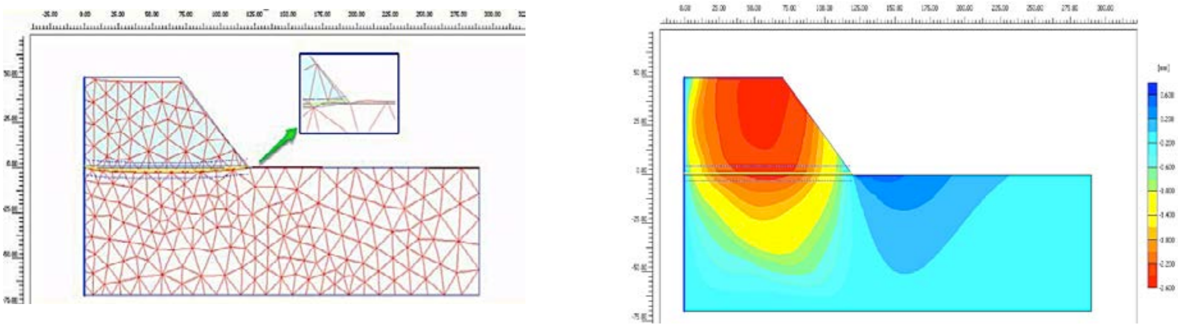


Fig. 6 Deformed mesh (b) vertical displacements (Case II)

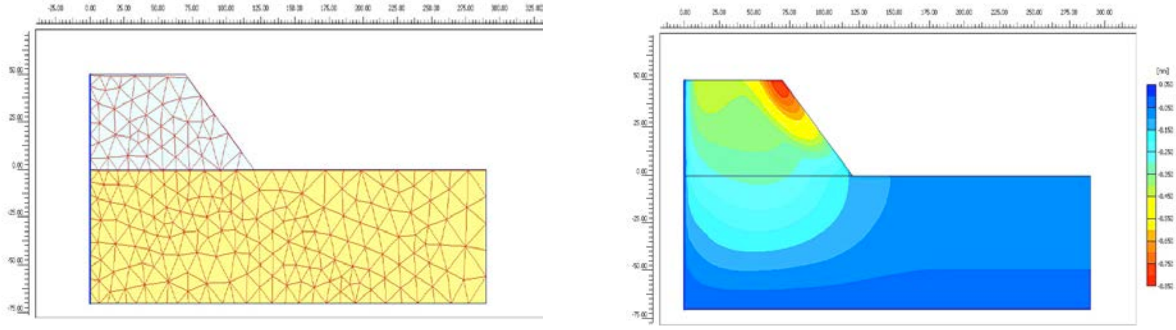


Fig. 7 Deformed mesh (b) vertical displacements (Case III)

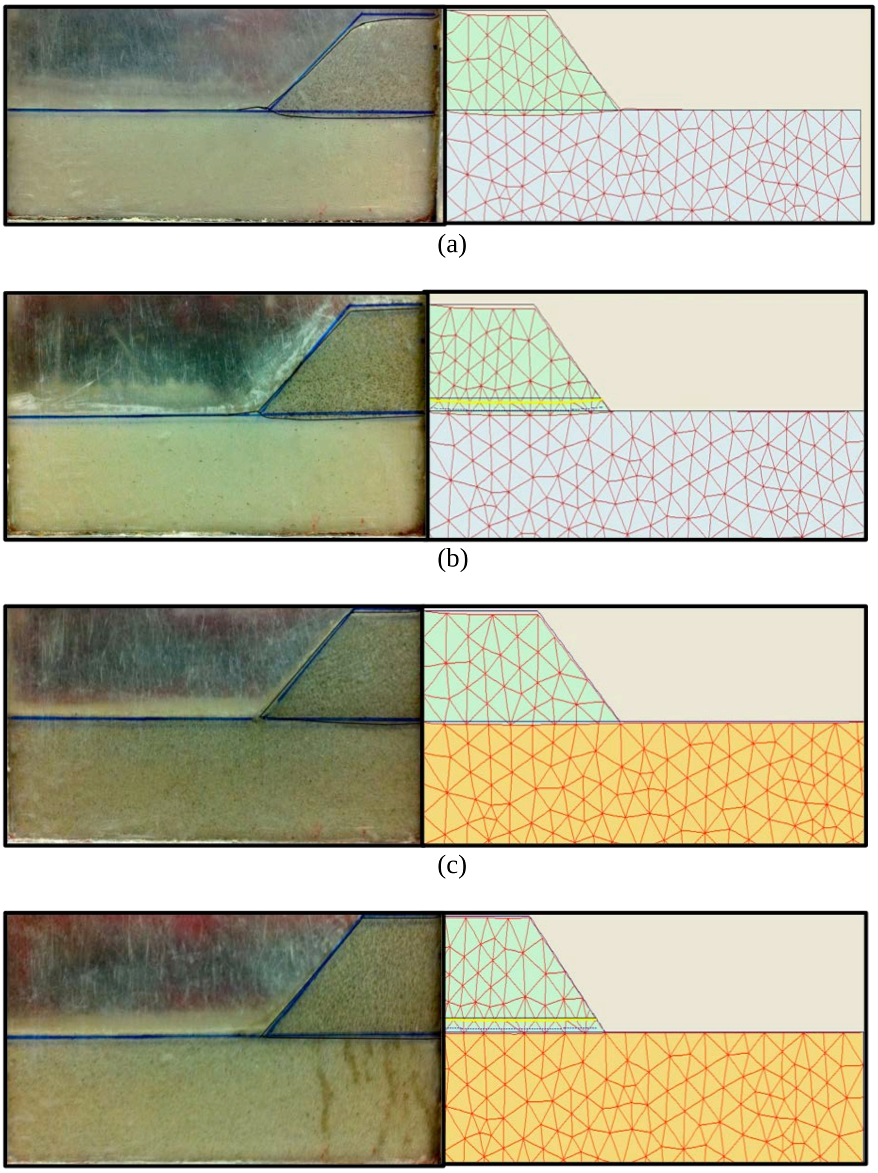
5.1 Comparison Between the Results of the Finite Element and Centrifuge Modelling

A side-by-side comparison between the deformation patterns resulted from the measurements of centrifuge tests and analysis of finite element simulations for four different cases are shown in Fig. 8. It is clear that the deformation patterns of the centrifugal model test and finite element simulation are almost similar for all cases, which validates the simulation of centrifugal model tests, using finite element simulation, based on small-scale modelling procedure.

A comparison between resulted vertical displacements of the centrifuge test and FE analysis for all cases are shown in Fig. 9. Moreover, the maximum vertical displacement obtained from centrifuge test and FE analysis is presented in Table 4. The coincidence of the lines correspond to centrifuge tests and FE analysis for each case in Fig. 9 and results of Table 4 indicates a good agreement between displacements obtained from these two methods of modelling.

Table 4 Maximum settlements resulted from centrifuge test and FE analysis

Cases	Centrifuge Test	FE analysis
Case I	4 mm	4.10 mm
Case II	3 mm	3.10 mm
Case III	1 mm	1.0 mm
Case IV	1 mm	1.0 mm



(a)

(b)

(c)

(d)

Fig. 8 Side-by side comparison of the deformation patterns resulted from centrifuge and FE models a) Case I, b) Case II, c) Case III, d) case IV

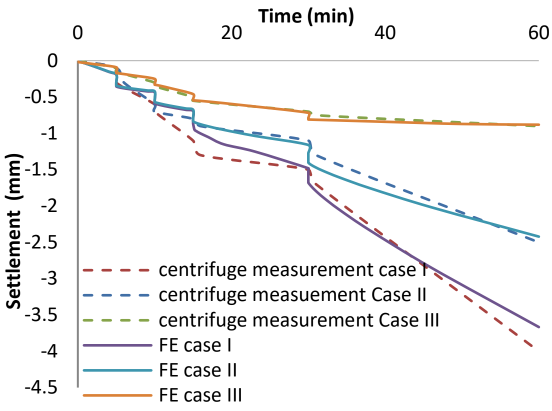


Fig. 9 Vertical displacement of different cases resulted in centrifuge test and FE analysis

6. CONCLUSIONS AND SUMMARY

Small-scale physical modeling and numerical analysis of different embankment cases have been carried out using centrifugal test and finite element simulations. Important effective factors have been studied to provide a better understanding and deeper insight of the embankment behavior under different conditions. In reinforced embankments, 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. Basal reinforcement of the embankment using geotextile resulted in reduction of the displacements up to 25% and leads to construction of higher fill embankment or steeper slope. Under a relatively small deformation, however, the influence of interfaces behaviour of geosynthetic reinforcement and soil on the system performance is expected to be less important as observed in cases on stiff ground (Cases III and IV).

Finite element simulations are successful in predicting the overall behavior of unreinforced and reinforced embankments. The results of FE simulation using full-scale prototype dimensions can have some differences with centrifuge measurements. However, FE modeling using small-scale centrifuge dimensions with simulation of actual conditions of the test with considering effective parameters (e.g. varying gravitational acceleration level, side-wall friction and small boundary condition of the test box), minimizes the differences between FE predictions and centrifugal measurements. It is shown a good agreement between results of these two methods, which validates the finite element simulation.

The effect of side friction between soil and sidewall on deformation behavior can be significant on the deformation pattern and behavior of models. Efforts should be made in the centrifuge work to minimize the effects of side friction by using some materials like silicon grease to reduce the friction.

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