

# **CHAPTER 7**

## **FINITE ELEMENT ANALYSIS OF EMBANKMENT**

### **MODEL TESTS**

#### **7.1 General**

In geotechnical engineering, the need for Finite Element Analysis (FEA) arises due to several key factors, such as non-linearity (stress-strain behavior), heterogeneity, and time-dependent behavior of soil. Since soil behavior is complex and highly variable, FEA is essential to geotechnical engineering modeling. In-depth knowledge of soil-structure interaction, stress distribution, and deformation mechanisms are necessary for geotechnical constructions such as retaining walls, embankments, and foundations. It is not always feasible to simulate field problems in the laboratory, and field testing can become quite expensive. Nonetheless, numerical analysis is a helpful tool for handling complex geotechnical engineering problems. In recent years, the most effective and adaptable numerical technique to perform numerical analysis is the Finite Element Method (FEM). Proper validation is required for the successful application of numerical analysis to any prototype. Therefore, the findings of the measured embankment model tests are validated using the finite element analysis and are presented in this chapter.

In the present study, three-dimensional finite element analyses of embankment model tests on soft ground improved with soil-geopolymer deep mix columns under static loading have been conducted to validate the measured embankment model test results. The analyses have been carried out by using a commercially available FEM software code, PLAXIS 3D Version 2023.1.0.136. have been used to carry out the numerical analysis.

## **7.2 PLAXIS 3D software**

FEM is not a new application; for more than 40 years, it has been a part of several engineering practices. Of the several finite element software solutions available, PLAXIS is the one that is most commonly employed for geotechnical applications. There are two versions of PLAXIS: PLAXIS 2D and PLAXIS 3D.

PLAXIS 3D is an advanced finite element analysis (FEA) software specifically designed for geotechnical engineering applications. It is essential for modeling infrastructure such as embankments, retaining walls, tunnels, foundations, and other infrastructures because it offers strong tools for simulating complex soil-structure interactions. With the software, precise three-dimensional modeling is possible, including several soil and material models, capturing the non-linear, time-dependent behavior of soils. This software has been widely used for the analysis of a variety of problems. Such problems include the estimation of stresses and deformations in underground excavations, embankments, and foundations, as well as the evaluation of the distribution of pore water pressure as a result of seepage and consolidation (Cook 1981; Reddy 2006; Zienkiewicz and Emeritus 2002). Non-homogenous and anisotropic materials with complex boundary structures and non-linear stress-strain behavior can easily be analyzed with PLAXIS 3D.

## **7.3 Finite element simulation of embankment model tests**

This study modeled the constitutive behavior of geopolymer stabilized soil column (GPSCs) supported embankment rested on the soft soil using PLAXIS 3D software. All the components in the model test, namely, embankment, soft clay, and GPSCs (DSM columns), are modeled using quadratic 10-node tetrahedral elements. The model test tank of 0.5 m X 0.2 m X 0.4 m used in the experimental work is numerically modeled. The lateral boundaries allowed for vertical displacement but restricted horizontal

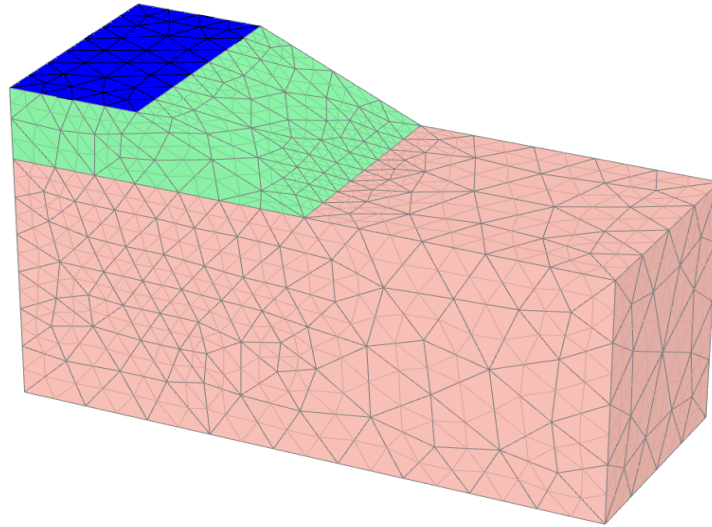
movement. Movement in both the vertical and horizontal directions is restricted on the bottom boundary. In the meantime, the model domain's top surface is free to move vertically in response to applied loads. Additionally, the slope surface of the embankment is not subject to any particular boundary conditions. The results obtained from the finite element analysis are compared with the results of model tests. The initial vertical stress due to gravity load has been considered in the analysis.

The Mohr-Coulomb elastic-perfectly plastic model was used as the yield criteria for the geopolymer stabilized soil column, soft clay, and embankment soil. A linear elastic model is used to model the footing plate. For both soft soil and the GPSC, the undrained behavior is assumed, whereas the embankment soil is modeled to have drained behavior. The consolidated undrained triaxial tests on the GPSC sample provided the model parameters that are mentioned in Table 7.1, such as the angle of internal friction, modulus of elasticity, and undrained shear strength. Very soft soils have a Poisson's ratio between 0.45 and 0.5, according to (Bowles 1996). Incompressible fluids and other similar materials often have a Poisson's ratio of 0.5. The water content of the soil bed used in this investigation was 38% (liquid limit = 41.2%), at which the undrained shear strength was 5 kPa. Under undrained (c) conditions, the linear-elastic perfectly plastic Mohr-Coulomb criteria were used to simulate the behavior of soft soil.

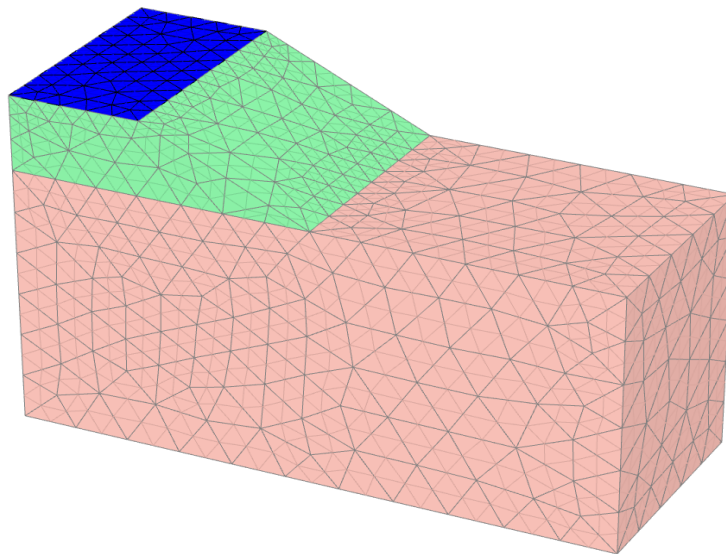
**Table 7.1** Material properties used for finite element analysis.

<b>Parameters</b>	<b>Soft soil</b>	<b>Geopolymer-stabilized soil column</b>	<b>Embankment soil</b>
Model used	MC	MC	MC
Material behavior	Undrained	Undrained	Drained
Modulus of elasticity, $E$ (kPa)	1110	88000	15000
Undrained shear strength, $c_u$ (kPa)	5	264	3.8
Angle of internal friction, $\varphi$	-	31.5	34
Poisson's ratio, $\nu$	0.49	0.3	0.3

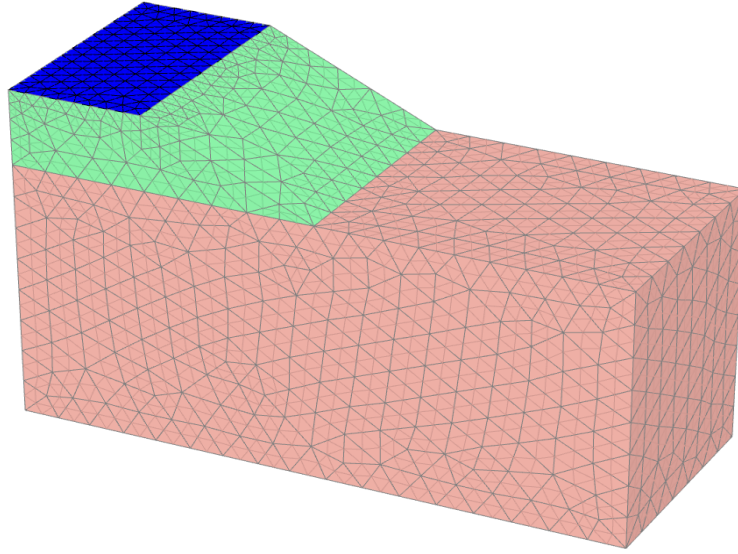
Mesh sensitivity analyses were carried out to check the convergence of the finite element results. Five meshing options, from ‘very coarse’ to ‘very fine’, are offered based on their mesh coarseness factor. The embankment model components were discretized using medium mesh discretization. Fig. 7.1 to 7.5 display the mesh discretization available in PLAXIS 3D for the embankment model, ranging from very coarse to very fine. Fig. 7.6 displays the mesh convergence study for all mesh discretization. It can be seen that medium meshing gave satisfactory results compared to fine and very fine mesh. Therefore, medium meshing was selected for embankment modeling as it gave acceptable accuracy with minimum computational cost.



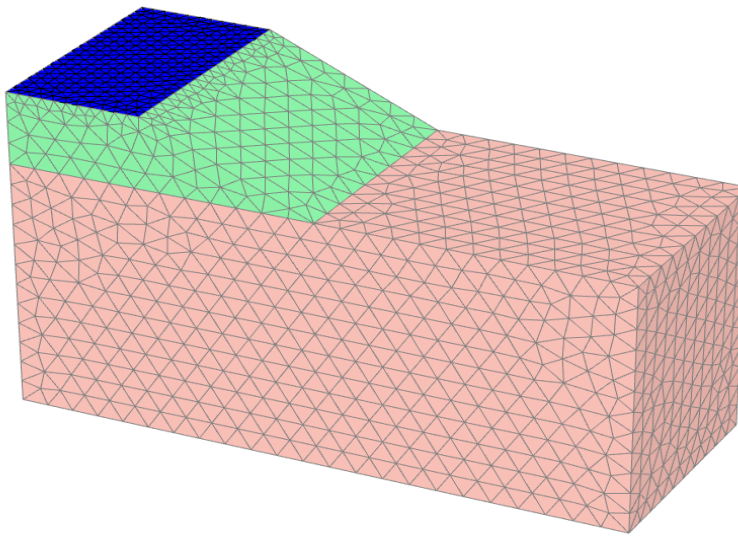
**Fig. 7.1** Very coarse meshing adopted for embankment over floating GPSCs improved soft soil ground.



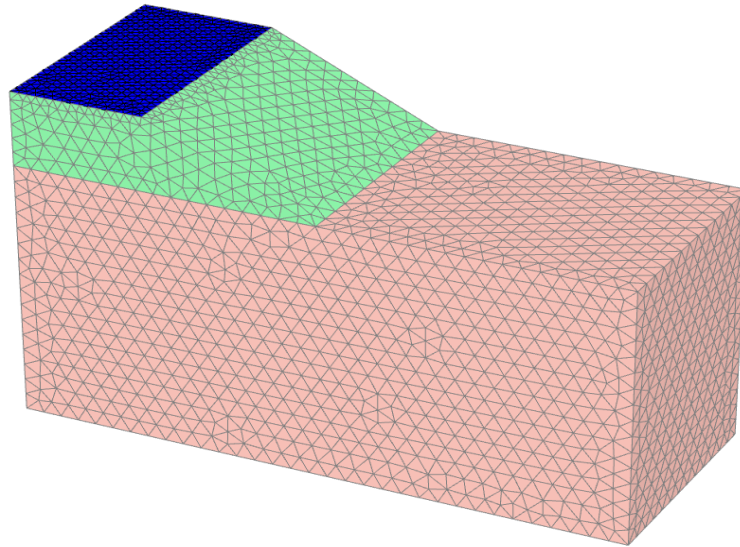
**Fig. 7.2** Coarse meshing adopted for embankment over floating GPSCs improved soft soil ground.



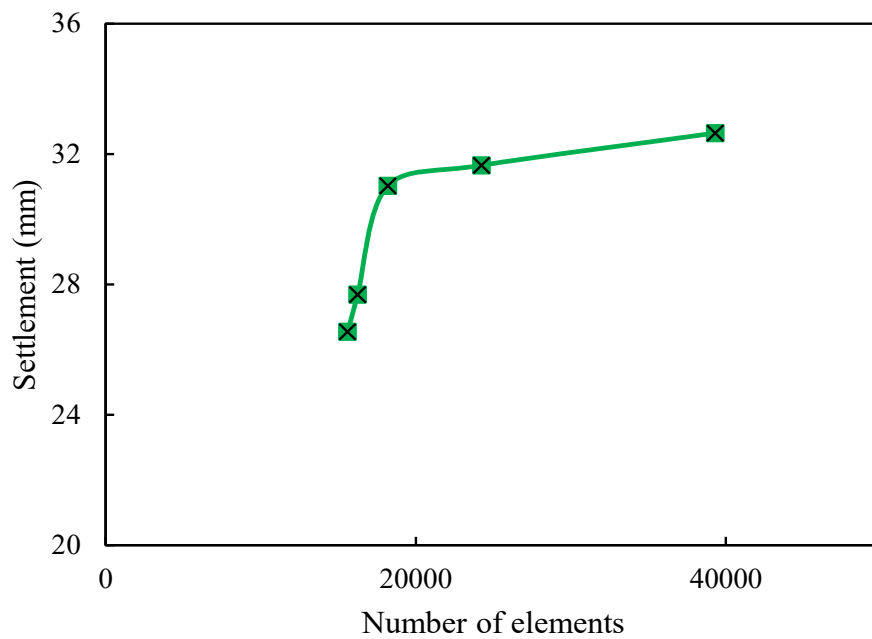
**Fig. 7.3** Medium meshing adopted for embankment over floating GPSCs improved soft soil ground.



**Fig. 7.4** Fine meshing adopted for embankment over floating GPSCs improved soft soil ground.



**Fig. 7.5** Very fine meshing adopted for embankment over floating GPSCs improved soft soil ground.



**Fig. 7.6** Mesh convergence analysis of FEM modeling in Plaxis 3D.

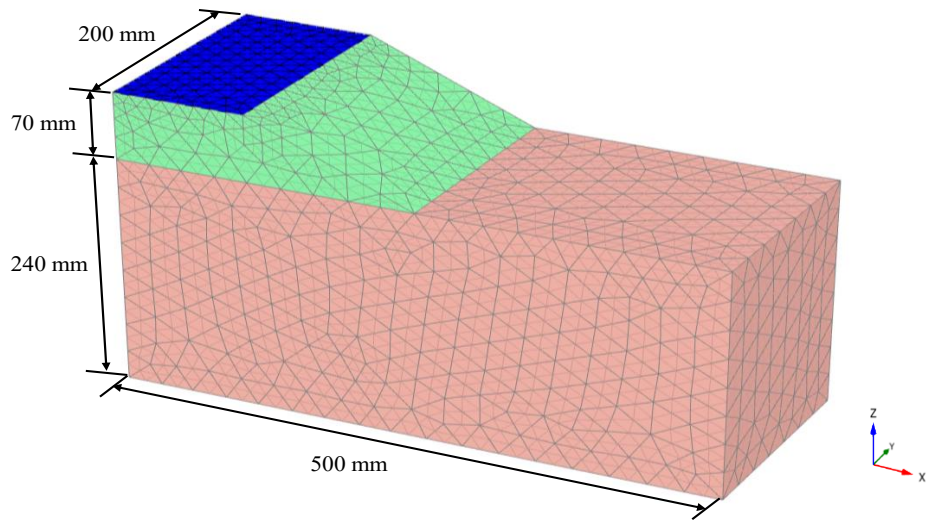
Table 7.2 provides information on the total number of elements and nodes utilized in discretizing various components of the selected finite element meshes for a GPSC-supported embankment on soft soil.

**Table 7.2** Details of mesh diagnostics in finite element analysis for all the components of floating GPSCs with an  $A_r$  of 21.2% stabilized soft soil embankment model.

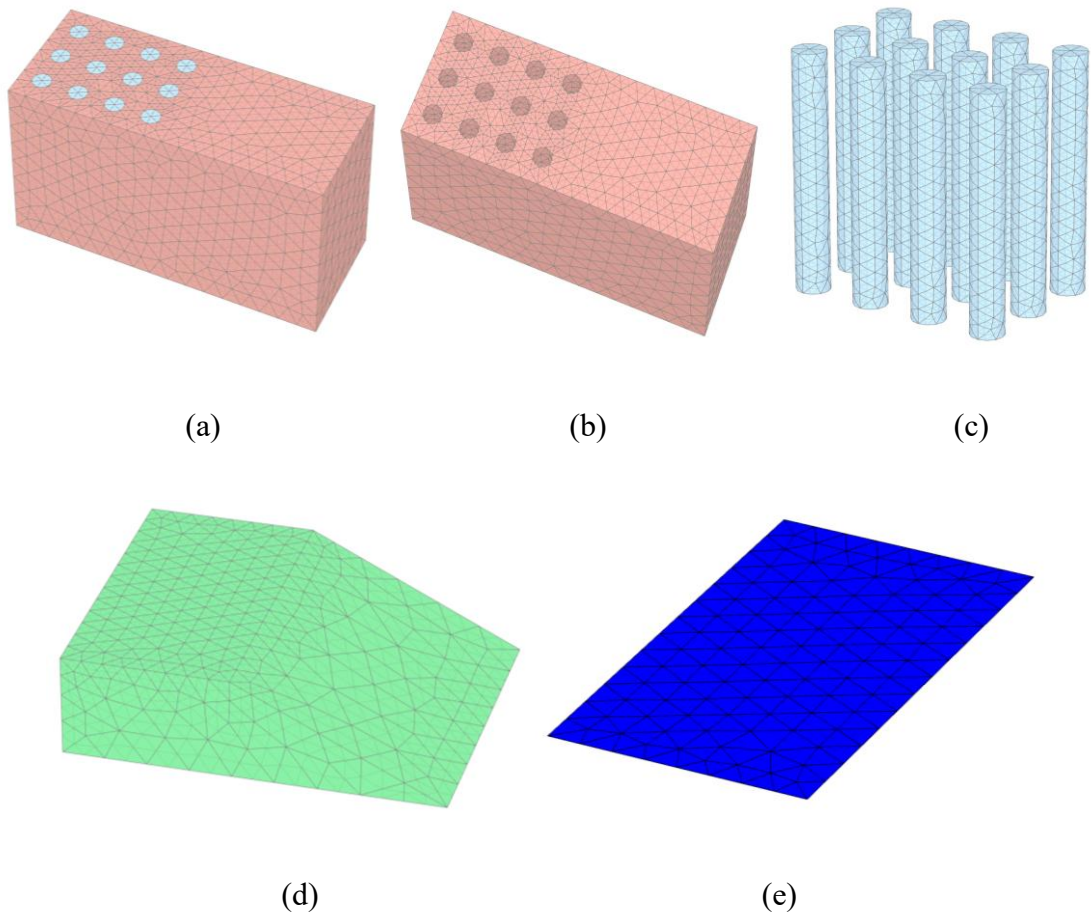
S. No	Meshing type	Number of elements	Number of nodes
1.	Very coarse mesh	15607	21883
2.	Coarse mesh	16241	23006
3.	Medium mesh	18192	26425
4.	Fine mesh	24244	36163
5.	Very fine mesh	39318	59339

#### 7.4 Model test results analysis

In this chapter, numerical modeling of laboratory-constructed embankment model over GPSCs improved soft soil bed was performed using PLAXIS 3D. The model construction and foundation components for the GPSCs-supported embankment over soft soil are shown in Fig. 7.7 and Fig. 7.8. In the present analysis, numerical validation of the embankment over untreated soil bed and a group of end-bearing ( $l/h=1$ ) and floating ( $l/h=0.75$ ) GPSCs with area replacement ratios of 12.7%, 17%, and 21.2% supported embankment is included. The comparisons of applied pressure vs. footing settlement responses measured during the model tests with those predicted by the finite element analyses using PLAXIS 3D under static loading are presented.



**Fig. 7.7** Model creation and mesh generation in Plaxis 3D.



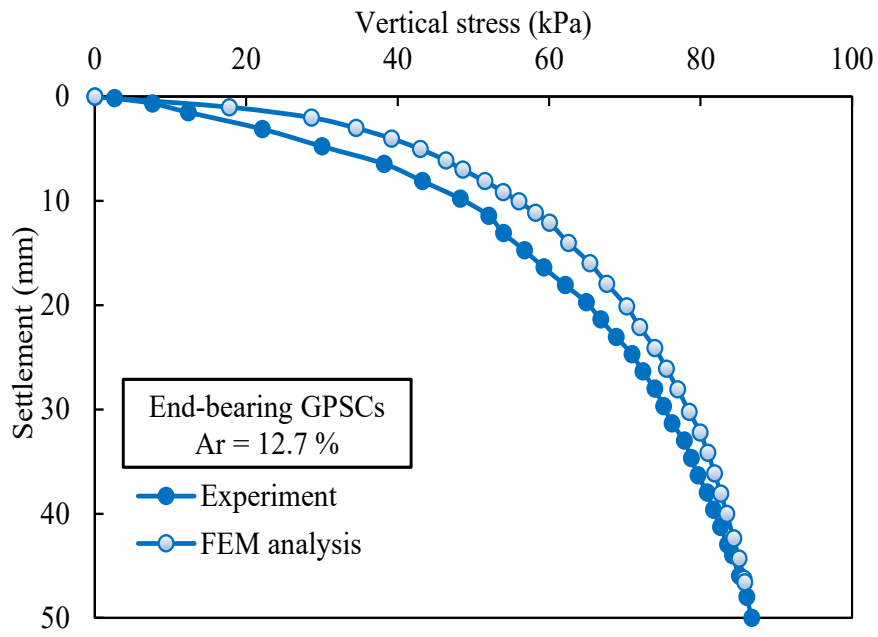
**Fig. 7.8** Components of GPSCs supported embankment on soft soil (a) Soft soil bed with a group of GPSCs, (b) Soft soil bed with excavated holes to install GPSCs, (c) Geopolymer stabilized soil column (GPSCs), (d) Embankment, and (e) Loading plate.

## 7.4.1 Embankment Supported on the Group of End-Bearing GPSCs

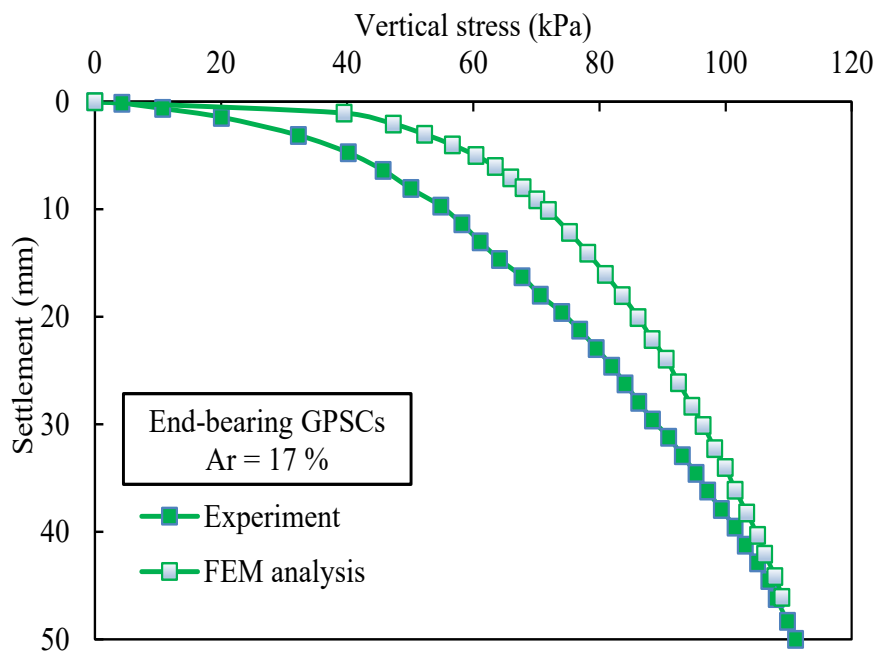
### Stabilized Soft Soil

The load intensity-settlement behavior of a group of end-bearing GPSCs supported embankment for  $A_r$  of 12.7%, 17%, and 21.2% obtained from laboratory model studies and Plaxis validations are shown in Fig. 7.9. A close agreement is obtained between finite element predictions and measured model test results in case of a group of end-bearing GPSCs under the embankment. The ultimate bearing capacity obtained from laboratory model tests for end-bearing GPSCs improved soft ground with  $A_r$  of 12.7%, 17%, and 21.2% is 86.73 kPa, 111.14 kPa, and 129.7 kPa, respectively, at 50 mm of settlement. Noticeably, the validation through Plaxis slightly overestimated the bearing capacity at lower settlements as compared to the laboratory model test results. While the load intensity curve gradually increases with settlement up to 50 mm in the experimental studies, the Plaxis validations yield an ultimate load intensity of 85.84 kPa (at settlement of 46.56 mm), 108.96 kPa (at settlement of 46.08 mm), and 122.64 kPa (at settlement of 41.16 mm) for  $A_r$  of 12.7%, 17%, and 21.2% respectively.

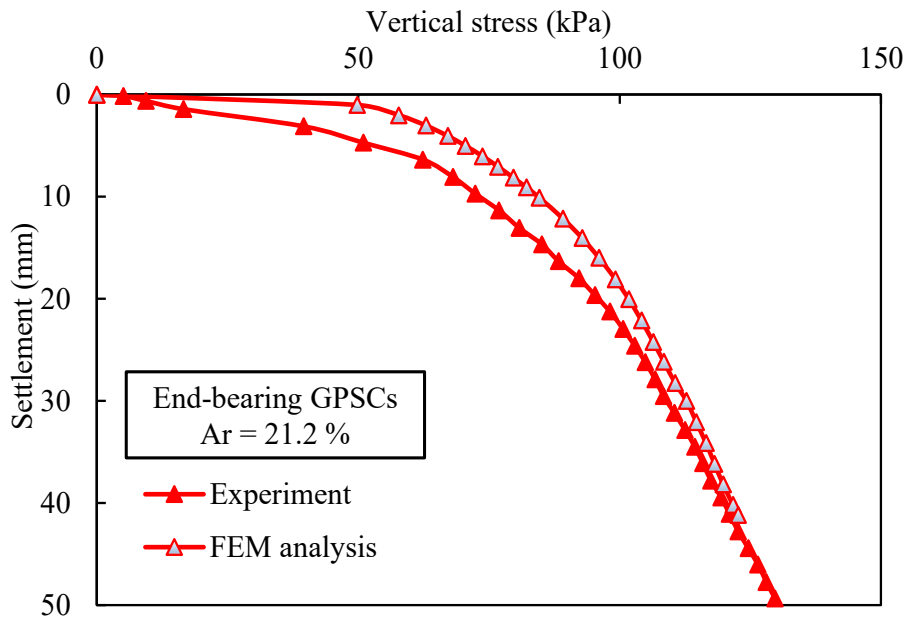
The vertical and horizontal displacement contours of different components of end-bearing GPSCs supported embankment on soft soil from finite element analysis at failure under static loading are shown in Fig. 7.10 and Fig. 7.11, respectively.



(a)

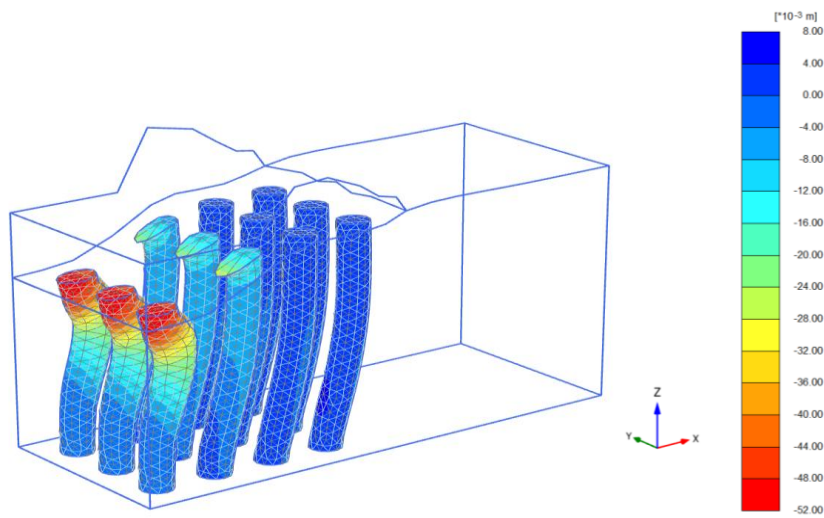


(b)

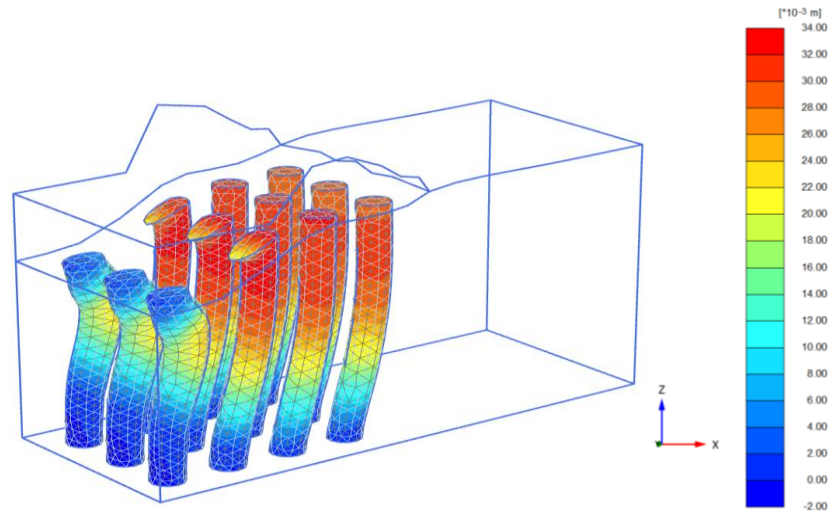


(c)

**Fig. 7.9** Comparison of measured laboratory model test results with finite element analysis prediction for embankment over end-bearing GPSCs improved ground with  $A_r$  of (a) 12.7%, (b) 17%, and (c) 21.2%.



**Fig. 7.10** Vertical displacement contours for different components of end-bearing GPSCs supported embankment model at 50 mm footing settlement ( $d = 30$  mm,  $l = 300$  mm,  $l/h = 1$ ,  $A_r = 17\%$ ).

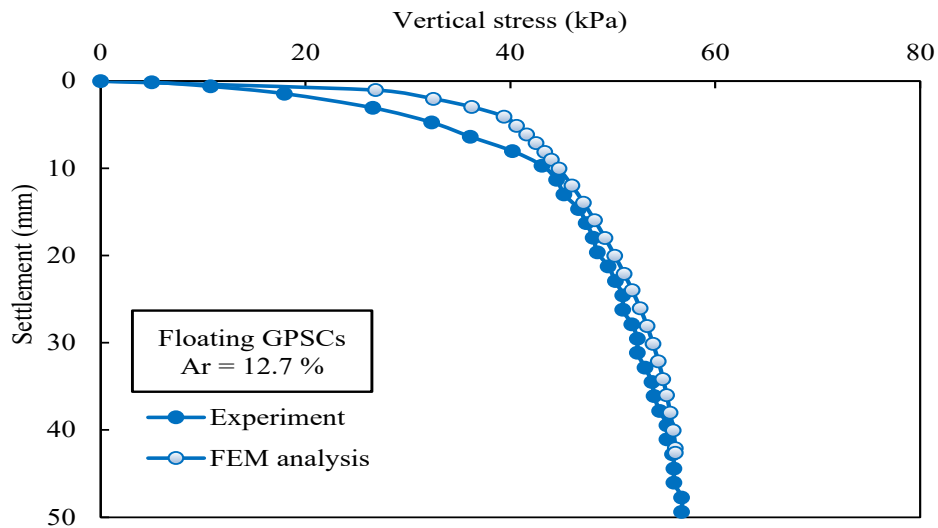


**Fig. 7.11** Horizontal displacement contours for different components of end-bearing GPSCs supported embankment model at 50 mm footing settlement ( $d = 30$  mm,  $l = 300$  mm,  $l/h = 1$ ,  $A_r = 17\%$ ).

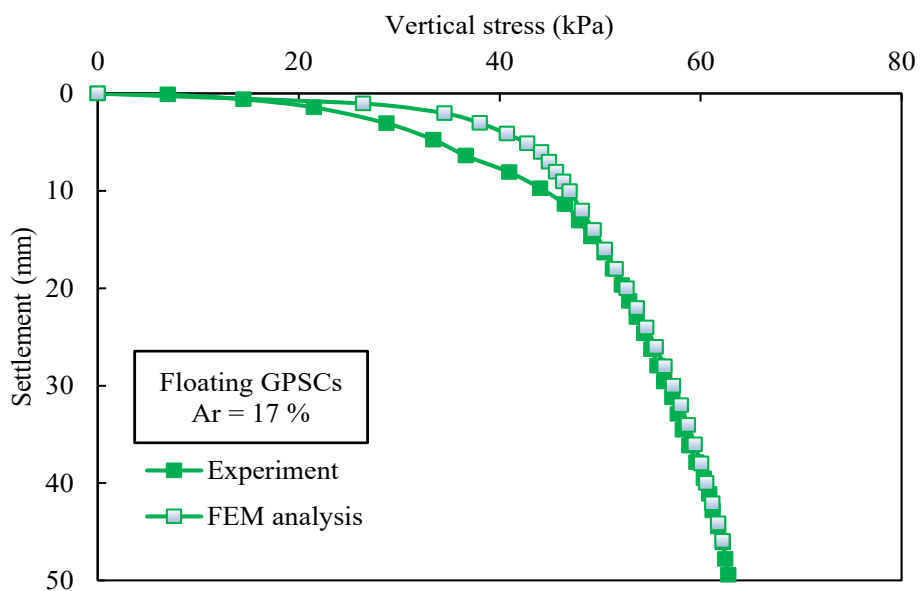
#### **7.4.2 Embankment Supported on the Group of Floating GPSCs Stabilized Soft Soil**

The load intensity-settlement behavior of the group of floating GPSCs supported embankment for  $A_r$  of 12.7%, 17%, and 21.2% obtained from laboratory model studies and Plaxis validations are shown in Fig. 7.12. Finite element analysis is also able to predict the results of the model test on floating GPSCs supported embankment on soft soil reasonably well. The ultimate bearing capacity obtained from laboratory model tests for floating GPSCs improved soft ground with  $A_r$  of 12.7%, 17%, and 21.2% is 56.73 kPa, 62.76 kPa, and 70.41 kPa, respectively, at 50 mm of settlement. While the load intensity curve gradually increases with settlement up to 50 mm in the experimental studies, the Plaxis validations yield an ultimate load intensity of 56.12 kPa (at settlement of 42.62 mm), 62.18 kPa (at settlement of 45.94 mm), and 69.57 kPa (at settlement of 42.69 mm) for  $A_r$  of 12.7%, 17%, and 21.2% respectively.

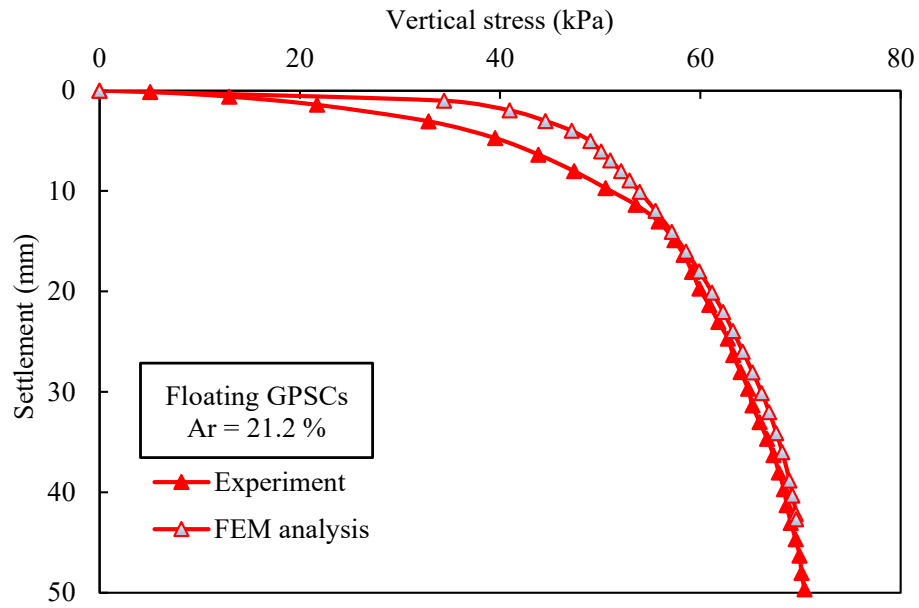
The vertical and horizontal displacement contours of different components of floating GPSCs supported embankment on soft soil from finite element analysis at failure under static loading are shown in Fig. 7.13 and Fig. 7.14, respectively. The failure mode obtained from finite element modeling matches well with the failure pattern obtained from laboratory model tests.



(a)

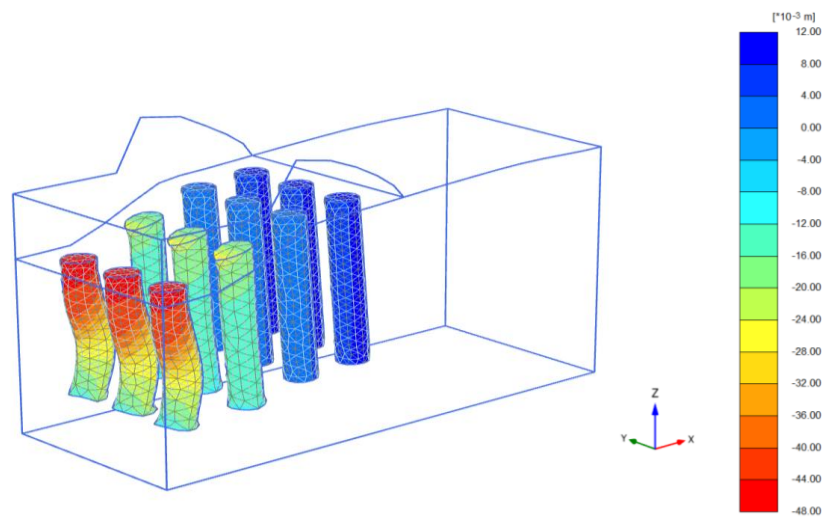


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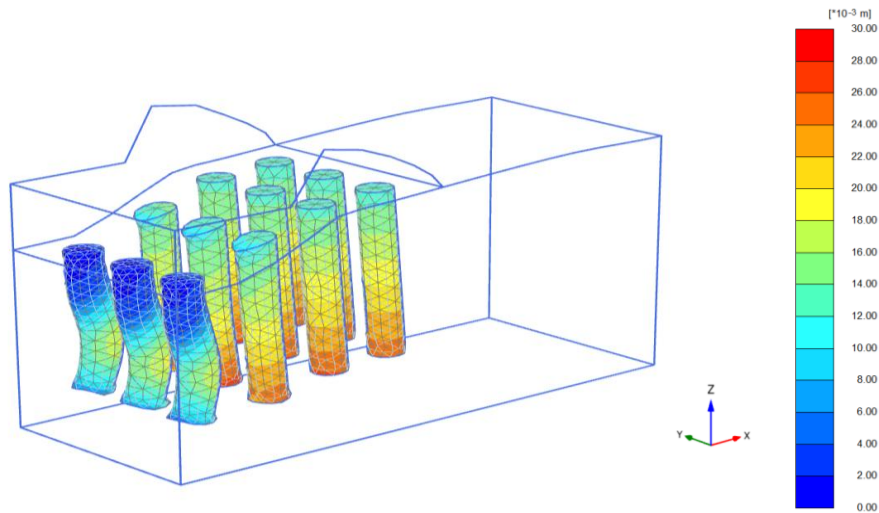


(c)

**Fig. 7.12** Comparison of measured laboratory model test results with finite element analysis prediction for embankment over floating GPSCs improved ground with  $A_r$  of (a) 12.7%, (b) 17%, and (c) 21.2%.



**Fig. 7.13** Vertical displacement contours for different components of floating GPSCs supported embankment model at 50 mm footing settlement ( $d = 30$  mm,  $l = 300$  mm,  $l/h = 1$ ,  $A_r = 17\%$ ).



**Fig. 7.14** Horizontal displacement contours for different components of floating GPSCs supported embankment model at 50 mm footing settlement ( $d = 30$  mm,  $l = 300$  mm,  $l/h = 1$ ,  $A_r = 17\%$ ).

## 7.5 Conclusion

This chapter discusses the numerical validations of the embankment over end-bearing and floating GPSCs improved soft soil under static loading conditions. The engineering properties of the soft soil bed, geopolymer stabilized soil column (GPSC), and embankment are determined from laboratory experiments. Three-dimensional, elastoplastic, finite element analyses of GPSCs-supported embankment over soft soil have been conducted using commercially available PLAXIS 3D software. The PLAXIS 3D results regarding vertical stress vs. footing settlement relationship were compared with laboratory model test results from Chapter 6. Both finite element predictions and measured model test results show that end-bearing columns give higher failure stress at lower settlement values compared to floating columns. Overall, the predicted results from the finite element analyses compare well with the laboratory model test results for the soft ground improved with groups of end-bearing and floating GPSCs subjected to static loading.