Numerical Modelling of Lateral Deformation of the Cantilever Retaining Wall in Expansive Clays

Santosh Sharma, N. Vinod Prabhu, Y. Naveen and S. Bhuvaneshwari

Abstract Retaining walls are relatively rigid walls used for supporting the soil mass laterally. The soil properties of the retained material exert lateral pressure on the wall. Thus, the important consideration in the design of retaining wall is to counter the lateral pressure generated by the backfill. The present study focuses on theoretical study on the retaining wall parameters such as the heel width, stem height, inclined backfill, with cohesive and expansive soil backfill. The lateral earth pressure is evaluated in each of these cases using the Rankine's lateral earth pressure theory. The numerical modelling of the cantilever retaining wall in cohesive backfill (expansive in nature) is carried out using the finite element software (PLAXIS 2D). Two soil models, Mohr–Coulomb model and the Hardening Soil model, are used for modelling the backfill. The expansive nature of the backfill is incorporated in terms of the positive volumetric strain of the backfill. To cater to the large lateral pressure induced by the expansive backfill, geofoam layer is introduced in between the backfill layer and the retaining wall and modelled using Mohr–Coulomb model. A comparative evaluation is made for the behaviour of the retaining wall in terms of the lateral deformation. The expansive soil with 12% volumetric strain caused nearly 900 mm lateral deformation, compared to 600 mm on inclusion of the 2 m thick geofoam layers. The hardening soil model used for modelling of the expansive soil depicts an reduction in deformation compared to the elasto-plastic, Mohr–Coulomb model.

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1 Introduction

Retaining walls are structures specifically constructed for retaining large amount of soil, intended for bridge abutments, embankments, elevated roadways, etc. They are designed to withstand high lateral earth pressures due to vertical backfills [1]. The properties of the retained material, angle of internal friction (phi) and the cohesive strength (c) create lateral pressure on the wall. Thus, the important consideration in the design of retaining wall is to counter the lateral earth pressure generated by the backfill [1]. Active lateral earth pressure is generated due to the movement of the soil towards the wall. Additional groundwater variation also causes a huge lateral earth pressure. If these factors are taken into account, there is a great possibility of overturning of the wall. The total thrust acts at one-third of the retaining wall from the lowest depth due to the triangular pressure variation. The lateral earth pressure on a retaining wall is determined using the Rankine's method or the Coulomb's method. The pressures acting on the wall cause movement of the wall due to the three differential pressures acting, at rest condition, active state and the passive state [2, 3].

In many of the practical situations, it becomes necessary to use the in situ soil present in the site for backfilling of the retaining wall. In many of the occasions, the in situ soil is cohesive in nature and could lead to excessive settlement or heaving of the backfill. Further, when the clay soil is expansive in nature, they induce additional pressure on the retaining wall. Expansive soils are typically clay soil that has a tendency to expand when it comes in contact with water and further shrinks when dries out. This volume change behaviour can cause adverse effects on the residential building, retaining walls and roads and pavements [4]. During expansion, these soils exert large uplift force against the concrete slabs and foundation footings which in turn causes a wide range of damage to buildings and surrounding areas. The costs associated with expansive soil damage, total to several billion rupees annually, more than all other natural calamities combined [4]. The damage of structures on expansive soil has been studied in various parts of the world specifically in Australia and United Nation (U.S) by various searches. Some of the problems have been studied by [4–6]. Retaining walls, buried structure like buried conduits, foundation piles are some of the structures subjected to large uplift pressures [4] and lateral swelling pressures. Hence, structures like retaining walls are subjected to additional lateral earth pressures if the backfill is expansive in nature causing further wall deformation and bending. The replacement of the expansive soil by non-expansive layer cannot be a viable option as it consumes large amount of resources and is usually expensive.

Few studies have been carried out to study the behaviour of the retaining walls in expansive soil. Tan [3] studied the behaviour of retaining walls in expansive soils. Experimental studies were carried out to determine the swell pressure on the retaining wall. Based on the laboratory tests, equations for the prediction of swell pressure due to expansive soils were developed. Limited studies have been carried out to understand the behaviour of retaining wall in expansive soil through numerical modelling in 2D as well as 3D. Goh [7] carried out theoretical and numerical studies to investigate the behaviour of concrete cantilever retaining walls. Al-Busoda et al. [8] carried out numerical studies on retaining wall resting on expansive soil. A 3-D model of the cantilever retaining wall was created in PLAXIS 3D with expansive foundation soil. The expansive soil was modelled as hardening soil model and the retaining wall as elastic plate elements. The additional lateral pressure due to the expansive soil was modelled as the positive volumetric strain. Helical piles were also introduced to counter the swelling behaviour of the soil.

The behaviour of the retaining wall depends on many geometric influencing parameters such as the wall friction, sloping backfills and fluctuating water table and also the backfill soil properties. The present study focuses on the evaluation of the critical influencing parameter of the retaining wall and the theoretical evaluation of the swell pressure on the retaining wall. Further, based on the literature review, numerical analysis is also carried out to understand the deformation behaviour of the retaining wall with expansive backfill. Finally, remedial solutions are recommended for the retaining wall to control the excessive lateral deformation.

2 Methodology

2.1 *Proportioning of Retaining Wall*

The cantilever retaining wall is designed based on proportions prescribed by Bowles [9]. The stem height is taken as 5.8 m, and the heel width is taken as 3 m. Figure 1 shows the details of the retaining wall proportions.

2.2 *Theoretical Analysis Using Rankine's Theory*

The theoretical analysis is carried out for the cantilever retaining wall based on the Rankine's theory. The various parameters considered for the analysis are given in Fig. 2. The lateral earth pressure is calculated for the various factors influencing the behaviour of the retaining wall with the cohesive backfill. The effect of inclined backfill and the water table on lateral earth pressure is evaluated. Finally, the effect of the swelling soil as backfill material, on the lateral earth pressure, is calculated based on the method suggested by Thomas [10]. The lateral earth pressure is compared in all these cases, and the most critical parameter is evaluated. The analysis is carried out for stem height of 5.8, 6.8, 7.8, 8.8 and 9.8 m and heel width of 3, 4, 5 and 6 m.

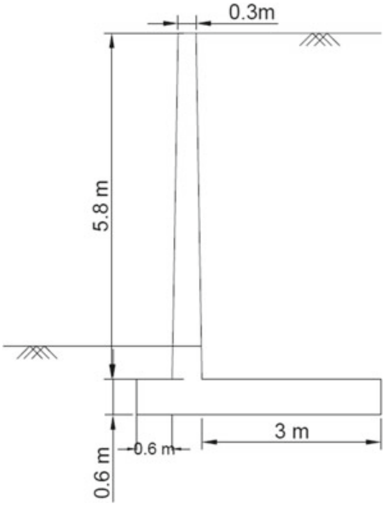

Fig. 1 Geometry of the cantilever retaining wall

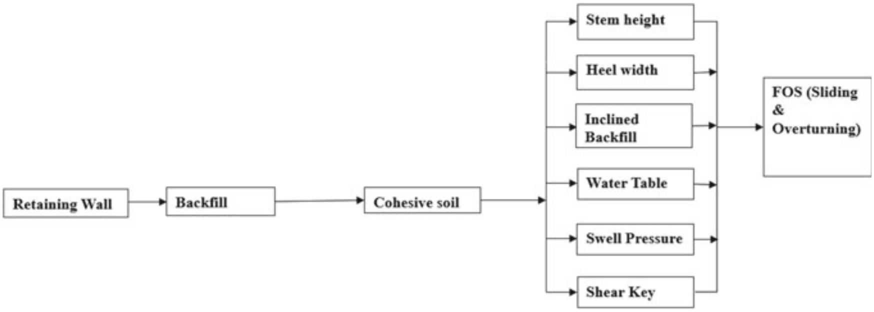

Fig. 2 Schematic of the theoretical analysis

2.3 Numerical Modelling Using PLAXIS 2D

The behaviour of the retaining wall with expansive backfill is studied through numerical modelling in PLAXIS 2D. The finite element software is adopted to understand the deformation of the retaining wall with cohesive backfill and also the effect due to the expansive backfill. PLAXIS 2D is a finite element software used for analysing practical geotechnical problems. The practical problems are modelled either as plane strain or axis symmetric depending on the geometry of the problem.

The behaviour of soil is highly nonlinear and time dependent, and advance models are required to predict the realistic behaviour. PLAXIS 2D provides many models for modelling of the real soil behaviour. For the present study, the backfill is modelled as the Mohr–Coulomb model and hardening soil model, and the elasto-plastic Mohr–Coulomb model involves five input parameters such as the Young's modulus (E), Poisson's ratio (ν), angle of internal friction (φ), undrained cohesion (C) and angle of dilatancy (ψ). Hardening soil model requires ten parameters. E_{50}^{ref}—triaxial compression, E_{ur}^{ref}—triaxial unloading and $E_{\mathrm{oed}}^{\mathrm{ref}}$—oedometer loading, P^{ref}—power, m_1—the stress-dependent stiffness formulation, Poisson's ratio for unloading and unloading. In the present study, both Mohr–Coulomb model and hardening soil model are adopted.

2.3.1 Geometric Modelling of the Retaining Wall in PLAXIS 2D

In the present study, the cantilever retaining wall adopted for the theoretical analysis is modelled as a plane strain model. The discretised geometric model of the retaining wall is created and depicted as shown in Fig. 3. The retaining wall is modelled as elastic material with concrete properties. The backfill is modelled using both Mohr–Coulomb model and hardening soil model. The details of the parameters adopted are given in Tables 1 and 2. The properties are based on the analysis by Al-Busoda et al. [8]. Table 3 gives the details of the parametric study carried out using PLAXIS 2D. The expansive backfill is modelled using the volumetric strain. The volumetric strain percentage is based on the swell potential of the expansive soil. The volumetric strain is varied from 2 to 12% with 12% indicating highly expansive soil. In order to counter the effect of the lateral earth pressure due to expansive backfill, geofoam, a synthetic polystyrene material, is proceeded at the interface between the soil and retaining wall. Table 4 gives the properties of the geofoam material adopted for the parametric study. The values are based on the study by Mandal [11]. The remedial measures

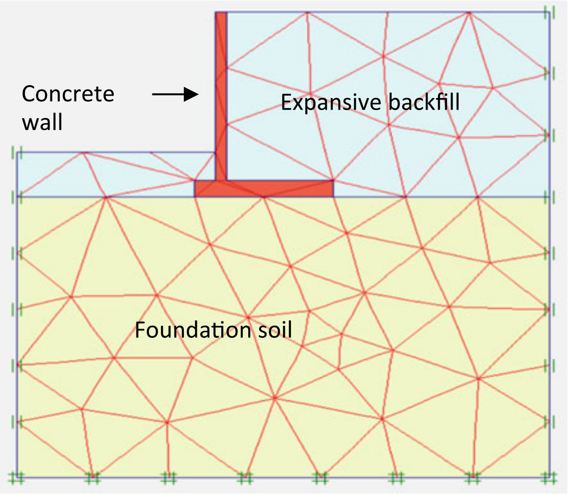

Fig. 3 Discretised geometric model in PLAXIS 2D

Table 1 Input parameters of Mohr–Coulomb model (based on Al-Busoda et al. [8])

Model parameters	Expansive soil	Sandy soil	Concrete
γ_{unsat} (kN/m^3)	16	16	24
γ_{sat} (kN/m^3)	18	19	–
E_{ref} (kPa)	20,000	180,000	30,000,000
v	0.3	0.25	0.3
c_{ref} (kPa)	20	0.1	–
φ (° deg)	24	37	–
R_{inter}	0.5	0.65	1.0

Table 2 Input parameters of hardening soil model Al-Busoda et al. [8]

Model parameters	Expansive soil	Sandy soil	Concrete
γ_{unsat} (kN/m^3)	16	16	24
γ_{sat} (kN/m^3)	18	19	–
$E^{\mathrm{ref}}{}_{50}$ (kPa)	5000	60,000	–
$E^{\mathrm{ref}}{}_{\mathrm{oed}}$ (kPa)	5000	60,000	–
$E^{\mathrm{ref}}{}_{\mathrm{ur}}$ (kPa)	30,000	180,000	30,000,000
Power (m)	1.0	–	1.0
c_{ref} (kPa)	20	0.1	–
φ (° deg)	24	37	–
R_{inter}	0.5	0.65	1.0
V_{ur}	0.5	0.2	–
K_{o}	0.4	0.6	–

Table 3 Details of the parametric study carried out

Sl. No	Parameter	Model used
1	Cantilever retaining wall	Mohr–Coulomb
2	Cantilever retaining wall	Hardening soil
3	Cantilever retaining wall + swelling backfill	Hardening soil
3 (i)	2% (volumetric strain)	Mohr–Coulomb, hardening Soil
3b (ii)	4%	Mohr–Coulomb, hardening soil
3 (iii)	6%	Mohr–Coulomb, hardening soil
3 (iv)	8%	Mohr–Coulomb, hardening soil
3 (v)	9%	Mohr–Coulomb, hardening soil
3 (vi)	12%	Mohr–Coulomb, hardening soil
4	Cantilever retaining wall + swelling backfill + geofoam	Mohr–Coulomb

Table 4 Properties of geofoam Mandal [11]

Density (ρ) (kg/m$^{3)}$	Cohesion c (kPa)	Angle of internal friction φ (° deg)	Young's modulus E (kPa)	Dry density γ (kN/m^3)
15	33.75	1.5	2400	0.10
20	38.75	2	4000	0.12
22	41.88	2	5500	0.125
30	62.00	2.5	7800	0.17

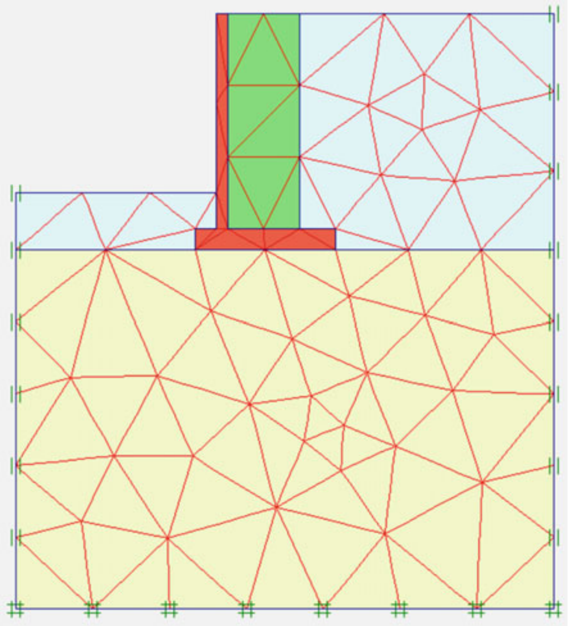

Fig. 4 Cantilever retaining wall with geofoam

using geofoam are also modelled using PLAXIS 2D. The discretised geometry of the retaining wall with geofoam is given in Fig. 4.

3 Results and Discussion

3.1 *Discussion on Theoretical Analysis*

Theoretical calculations based on Rankine's theory were adopted for the evaluation of the lateral earth pressure for the various influencing parameters under study (inclined backfill, water table, swell pressure and shear key). Shear key is provided as the remedial method to counter the lateral earth pressure and can increase the FoS. These geometrical variations increase the lateral earth pressure and thereby reduce the FoS. Table 5 gives the FoS for the various influencing factors considered for a stem height of 5.8 m and different heel width. The results indicate that water table and swell pressure highly reduce the FoS compared to the inclined backfill for the same geometrical condition. The FoS reduction is comparatively high for the swelling soil factor compared to non-swelling backfill. For the non-swelling backfill, FoS against overturning is round 8.0, for the stem height of 5.8 and 3 m heel width, whereas for the swelling backfill for the same geometry, the values reduce to 0.83 (Figs. 5 and 6). Provision of shear key increases the stability of the retaining wall by providing passive resistance. The FoS against sliding is increased to 1.12 for the same geometrical condition on the presence of shear key (Table 5).

Figure 7 depicts the effects of different factors on the lateral earth pressures of the retaining wall. The contribution by swelling soil to the magnitude of lateral earth pressure is higher compared to the other factors.

3.2 Results of Numerical Analysis

Numerical modelling of the cantilever retaining wall is carried out using PLAXIS 2D. Figure 3 depicts the plane strain model of the cantilever retaining wall, adopted for the study. The cantilever retaining wall is modelled using concrete properties and modelled as elastic model. The backfill is modelled using both Mohr–Coulomb model and hardening soil model. The Mohr–Coulomb is the basic elasto-plastic model, and hardening soil model is the advanced soil model which precisely describes the soil behaviour. In this study, the expansive soil is modelled using hardening soil model. The input properties for the backfill are given based on the studies by Al-Busoda et al. [8]. In this study, a preliminary analysis is carried out by comparing the deformation behaviour of the retaining wall with the backfill modelled as Mohr–Coulomb and hardening soil model. Figures 8 and 9 depict the deformed mesh of retaining wall for both the Mohr–Coulomb model and hardening soil model. Mohr–Coulomb model causes a lateral deformation of 785 mm compared to the hardening soil model depicting 697 mm.

3.3 Deformation Behaviour of Retaining Wall with Expansive Backfill

The expansive backfill is modelled as the positive volumetric strain of the backfill. The numerical analysis is carried out for different percentages of strain (2–12%). The volumetric strain indicates the swell potential of the swelling backfill. The deformation obtained for different percentages of volumetric strain for Mohr–Coulomb model

Table 5 Variation of the FoS for inclined backfill/water table/swell pressure/shear key

Parameters		Inclined backfill		Water table		Swell pressure		Shear key	
Stem height (m)	Heel width (m)	FoS sliding	FoS OT	FoS sliding	FoS OT	FoS sliding	FoS OT	FoS sliding	FoS OT
5.8	3	1.36	3.83	0.45	0.86	0.38	0.83	0.86	1.12
	4	1.63	5.56	0.57	1.33	0.48	1.29	1.00	1.74
	5	2.05	8.24	0.70	1.91	0.59	1.85	1.14	2.50
	6	2.41	11.07	0.82	2.60	0.70	2.51	1.29	3.38

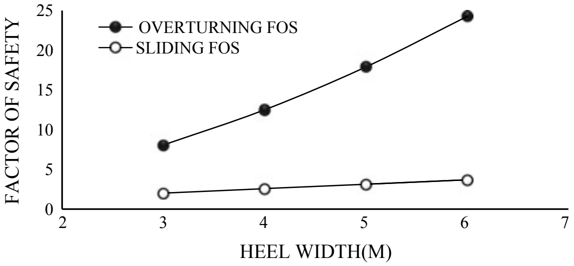

Fig. 5 Heel width versus FoS for 5.8 m stem height

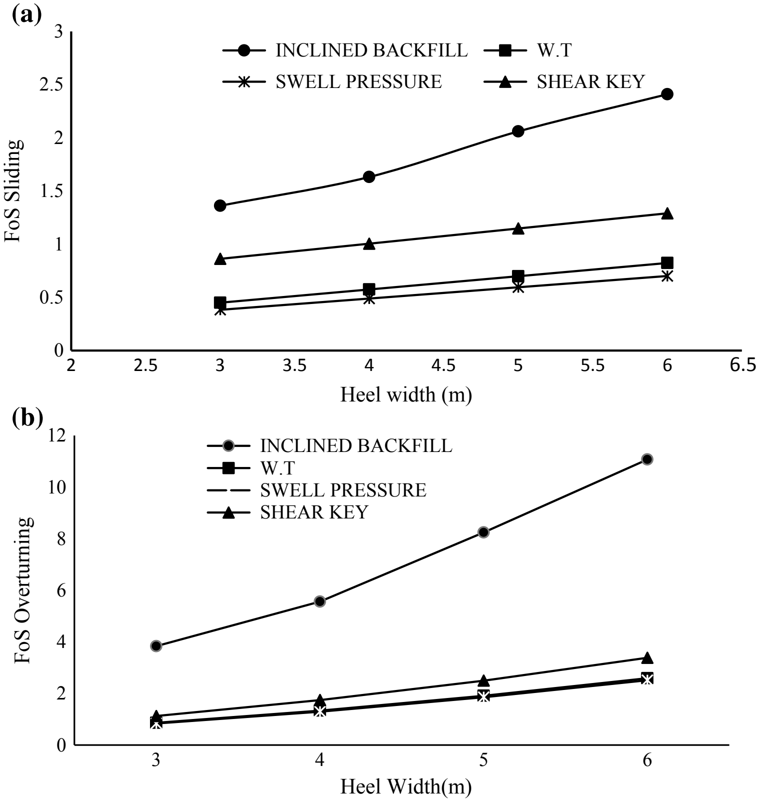

Fig. 6 **a** Variation of the FoS (sliding) for inclined backfill/water table/swell pressure/shear key. **b** Variation of the FoS (overturning) for inclined backfill/water table/swell pressure/shear key

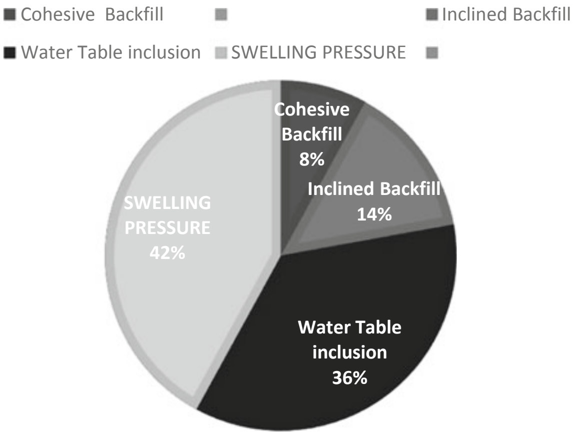

Fig. 7 Variation of lateral earth pressure for different factors

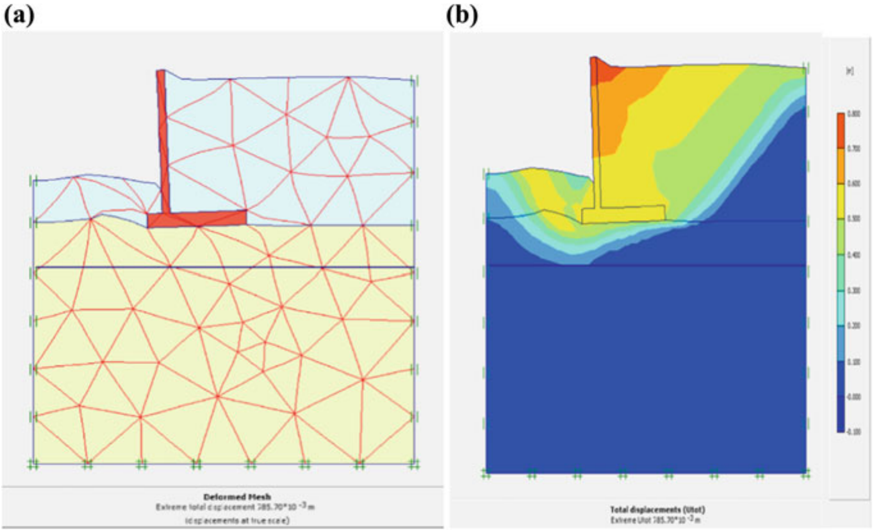

Fig. 8 **a** Deformed mesh of Mohr–Coulomb model with deformation of 785 mm **b** The deformation pattern for the retaining wall for the Mohr–Coulomb model

and hardening soil model is given in Table 6. As the expansive nature of the soil increases as indicated by the swell potential, the horizontal deformations increase 785 for (non-swelling soil) to 965 mm for 12% volumetric strain of the backfill. The hardening soil model also depicts a similar trend of increasing deformation with increase in volumetric strain; however, the deformation is lesser compared to Mohr–Coulomb model. For a volumetric strain of 12%, the deformation decreases

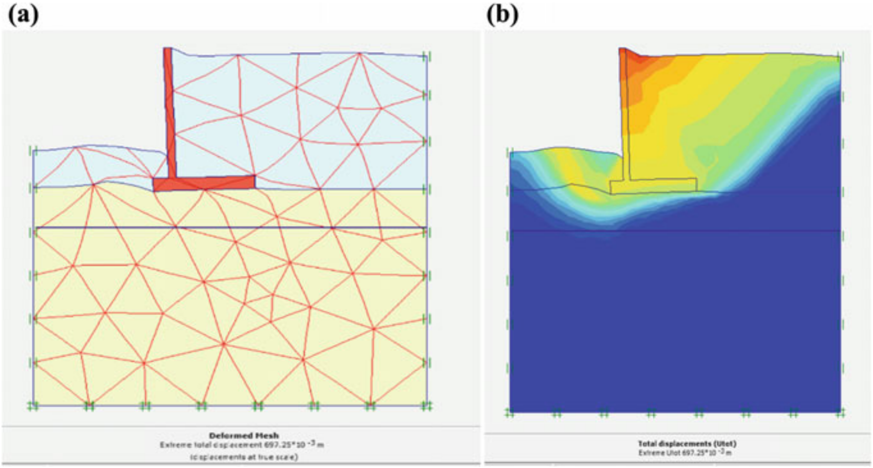

Fig. 9 **a** Deformed mesh for hardening soil model with deformation of 697 mm. **b** The deformation pattern for the retaining wall for the hardening soil model

Table 6 Mohr–Coulomb and hardening soil model results

Volumetric strain (%)	Deformation (mm) Mohr–Coulomb	Deformation (mm) hardening soil
0	785	697
2	610	542
4	551	648
6	738	733
8	762	799
12	965	901

from 965 mm for Mohr–Coulomb model to 901 mm for hardening soil model. The deformation pattern is depicted in Figs. 10 and 11 for 12% strain.

3.4 Numerical Model with Geofoam Layers

The geofoam layer is modelled as Mohr–Coulomb model. For the parametric study, geofoam thickness is varied as 0.5 m, 1.0 m and 2.0 m, respectively, and the corresponding change in the deformation is inferred. The deformation behaviour is observed for the various thickness of the geofoam material. As the thickness of the geofoam material increases, the lateral deformation is reduced. For a thickness of 2.0 m of the geofoam material, the deformation reduces to 636 mm from 965 mm. Figure 12 shows the deformation pattern of the retaining wall with the 2 m geofoam material. Table 7 depicts the variation of total deformation with different geofoam

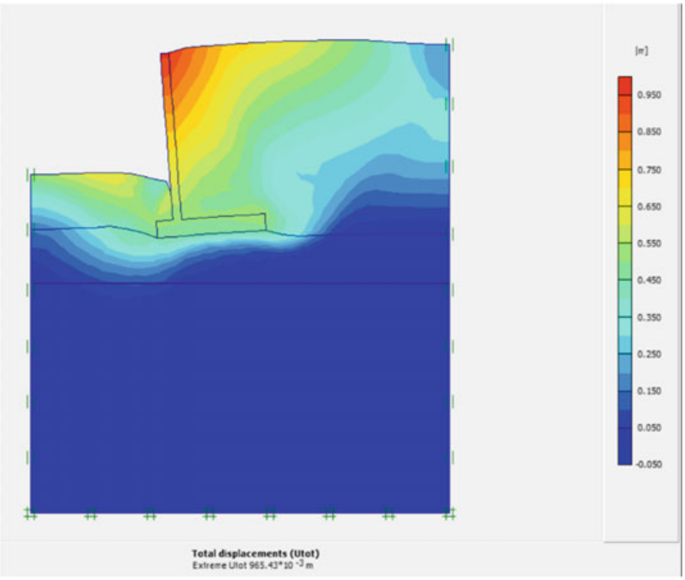

Fig. 10 Deformation of 965 mm for 12% volumetric strain (Mohr–Coulomb model)

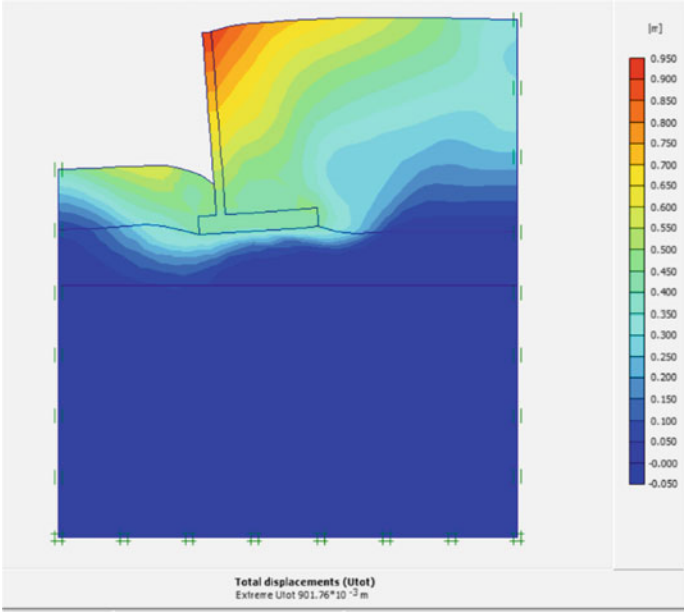

Fig. 11 Deformation of 901 mm for 12% volumetric strain (hardening soil model)

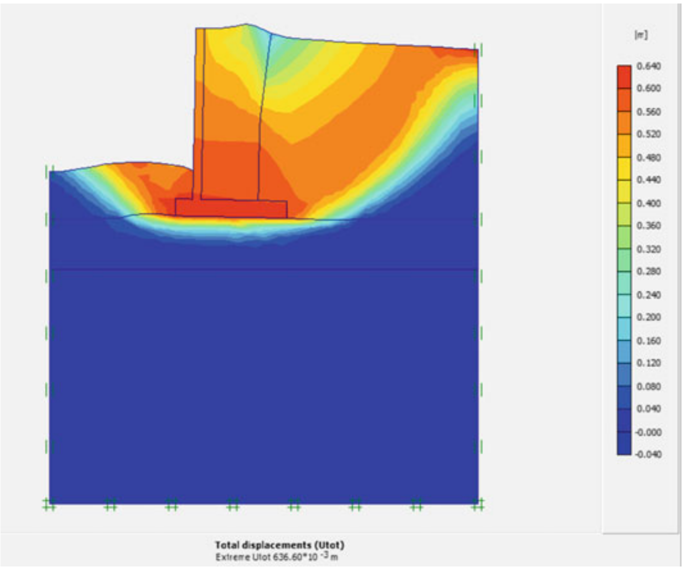

Fig. 12 Deformations in retaining wall with geofoam layer

Table 7 Comparison of lateral deformation with geofoam and without geofoam

Geofoam thickness (m)	Deformation (mm)	Deformation without geofoam (mm)
0.5	880	965
1.0	792	965
2.0	636	965

thickness. Limiting values of retaining wall displacements and impact to the adjacent structures the deformations of the retaining wall are within permissible limits (it can be greater than or less than 0.5% of total stem height), however not specific limit is applied as far the as the sufficient FoS is ensured [12].

4 Conclusion

The theoretical analysis is carried out for different influencing factors such as the inclined backfill, water table and swelling soil for the model cantilever retaining wall adopted in the study. Numerical analysis is carried out to predict the lateral deformation of the cantilever retaining wall under different soil conditions and different soil models in PLAXIS 2D. Based on the theoretical analysis, it is inferred that overall factor of safety (FOS) decreases with inclusion of cohesive inclined backfill, water table and swell pressure, respectively, with swell pressure parameter giving high lateral earth pressure. Provision of shear key with a swelling backfill could counter the lateral earth pressure to a reasonable extent. The Mohr–Coulomb model and hardening soil model predict the lateral movement of the retaining wall more appropriately. The lateral deformation predicted by HSM (697 mm) is lesser than MC (785 mm) for cantilever retaining wall with non-swelling backfill. The HSM could be a more appropriate model for expansive soil modelling, the swelling soil is modelled as equivalent volumetric strain equal to the swell potential, and the lateral deformations are higher than the non-swelling backfills. The lateral deformation increases for increase in the swell potential of the soil. For 12% volumetric strain, the deformation predicted by hardening soil model (901 mm) is 1.3 times more than deformation predicted by normal backfill without swell pressure (697 mm).

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