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Numerical Modelling of Shallow Foundations on Expansive Shale: A Case Study of Jamshoro, Pakistan

Muhammad Rehan Hakro, Aneel Kumar, Zaheer Ahmed Almani, Agha Faisal Habib, Muhammad Auchar Zardari*

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Abstract. This study analyzes expansive soil swelling under the shallow foundation using the Plaxis 2D FEM software. Under the impact of changing water conditions, expansive soil undergoes obvious volumetric changes, which often cause differential movements of the shallow foundations resting on it, which may lead to structural damage if no special precautions had been taken during the design process. In previous studies, the swelling of soil was simulated in Plaxis by applying the swelling potential with a positive volumetric strain, without considering water level changes, which proved to be not practical. This study demonstrates the time-dependent deformation (swelling) in expansive soil using the Plaxis 2D user-defined Swelling Rock Model in different soil and parametric conditions. The geotechnical properties of expansive shale were determined in the laboratory and by field testing, using parameters of the collected soil as input for the numerical model. Swelling of soil increased due to the increase of water level and decreased with the load. The heave was minimum in the center of the foundation (20 mm), attaining the maximum value at the corner (16 cm). The increase in the modulus of elasticity does not have much effect on soil swelling compared to soil settlement. The effect of matric suction-related changes on the swelling of soil due to the rise of the water table is not significant compared to the inherent soil swelling behaviour.

Keywords: *swelling; expansive soil; shale; Finite Element Method; PLAXIS 2D; swelling rock model*

Muhammad Rehan Hakro (rehan.hakro@faculty.muet.edu.pk), https://orcid.org/0000-0003-4740-6588, Aneel Kumar (aneel.kumar@faculty.muet.edu.pk), https://orcid.org/0000-0002-1579-5681, Zaheer Almani (zaheer.almani@faculty.muet.edu.pk), Agha Faisal Habib (dr.faisal@faculty.muet.edu.pk), Department of Civil Engineering Mehran University of Engineering and Technology, Pakistan; Muhammad Auchar Zardari (muhammad.auchar@quest.edu.pk), Department of Civil Engineering, Quaid-e-Awam University, Nawabshah, Pakistan*

**Corresponding author*

INTRODUCTION

It is important to predict the behaviour and performance of the foundation of the structure to be constructed on soil before constructing engineering structures on it. Soil is a complex natural material. The foundation is considered to be one of the basic and most significant parts of any structure. All structural loads are transmitted to soil by a foundation. A shallow foundation is provided as an economical and simple transfer mechanism of load to the ground beneath to support structures. In geotechnical engineering, stress distribution in the foundation soil is significant in the area and at the depth around the foundation. External load-induced stress depends on numerous factors such as soil properties, applied load, and dimensions of the loaded area (Desai, Moogi 2016). The expansive nature of clay is dominant near the ground surface where the profile is subjected to seasonal and environment changes. Expansive soils are usually in unsaturated condition, which means that when they absorb water, their volume increases, and they shrink or decrease in volume when moisture is lost and dries out. Fissures in soil can also develop. These fissures help water to penetrate into deeper layers when water is present, producing a cycle of shrinkage and swelling that causes the soil to undergo great volume changes. Structural damage may be significant in all types of structures ranging from light weight structures such as basement floor, pipelines, etc., to structures constructed on shallow foundations (Mokhtari, Dehghani 2012; Phuor *et al*. 2021, 2022).

Shale is a weak and swelling rock. It is mainly composed of the clay mineral montriomollite, which is highly expansive in conditions of increased moisture content. Shallow foundations constructed on the shale are subjected to swelling pressure due to expansion of shale. The high swelling pressure due to expansive soil creates differential heaving in structures, particularly in light structures placed on shallow foundations. The foundations, which play a vital role in transferring loads to the supporting soils, ensure soil-structure interaction. Hence, the mechanical behaviour of soil under the loads applied should be considered while assessing the foundation of a construction on expansive soils.

Closed-form analytical solutions for displacement calculation are difficult due to the complex behaviour of such expansive soils in the presence of moisture, with varying void ratios, and under building loads. To determine the effect of moisture ingress through unsaturated expansive soils, suction, and the resulting volume shifts, numerical methods such as Finite Difference Method (FDM) and Finite Element Method (FEM) were used. Therefore, the computer programs developed based on the finite element method as the powerful tool for solving complex cases have been receiving much attention over the recent decades (Mosadegh, Nikraz 2015).

Some researchers (Wray *et al*. 2005) used the FORTRAN computer programme SUCH to create a three-dimensional moisture diffusion and volume change model called Suction Heave. Mitchell's equation was used to describe water movement via unsaturated expansive soil, and FDM was used to calculate the vertical volume shift. Hamdhan and Schweiger (Hamdhan, Schweiger 2013) compared the results of pore water pressure obtained from FEM for 11 m high cut slopes in three regions of China with those calculated using tensiometers in the area. It was discovered that pore water pressures increased (i.e., suction decreased) until the end of the first rainfall cycle, and then decreased during the no-rain period.

In Texas, the impacts of rainfall and the dry-wet cycle were investigated on the shallow slope failure due to expansive clay (Khan *et al*. 2019). The results of the laboratory tests were used in PLAXIS 2D for Finite Element Analysis (FEA). The authors discovered that slope failure occurs a few years after construction due to the combination of reduced shear strength in completely softened conditions and excess pore water pressures caused by the formation of the perched-water zone near the crest.

Our study is focused on isolated shallow foundations such as rectangular footings, because their mechanical behaviour in expansive soils has been studied insufficiently. Furthermore, the majority of damaged structures with low stiffness are built on shallow foundations of this type.

Problem identification

Shallow foundation construction on top of expansive soil layers faces excessive heave/settlement problems. The problem of foundation movement may cause serious structural damage leading to failure and loss of serviceability of the structure. In Jamshoro, a large area of land is available, which is, however, underlain by expansive shale layers of varying depth. The past experience shows that buildings constructed in this area were seriously cracked and damaged due to the movement of shallow foundations caused by the expansive/shrinkage nature of shale layers. Investigations into shallow foundations of structures on shale layers in this region, which could provide insights into this problem, have not been carried out earlier. In the present study, the performance-based analysis of the shallow foundation of structure on the shale ground (expansive soil) will be carried out by investigating the movement of the shallow foundation using the Finite Element method, the commercially available software Plaxis 2D with a user-defined Swelling Rock Model.

METHODOLOGY

This section consists of two sub-sections. The first subsection presents the methodology employed for conducting laboratory experiments. The aspects of numerical modelling are discussed in the second subsection.

Laboratory work

In this study, soil at the MURC site located near the Department of Civil Engineering of the Mehran University Jamshoro, where shale layers are underlying the ground surface, was investigated by rotary drilling. The geotechnical properties of all soil layers were determined in the Geotechnical Engineering Laboratory from the collected samples.

The geotechnical index properties were determined for soil assessment and for the determination of numerical model parameters. The laboratory investigations performed employing the ASTM test methods are as follows: specific gravity (Gs) by the Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer (D854-10); (iv) liquid limit, plastic limit and plasticity index by the Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils (D4318-10); grain size distribution by the Standard Test Method for Particle-Size Analysis of Soils (D422-63(2007). ASTM D4546 – 21 for Standard Test Methods for One-Dimensional Swell.

Numerical modelling

Numerical models of the model structure and its shallow foundation on the shale ground of different lithology will be prepared and analyzed for settlement. This numerical model will simulate the real field conditions. Behavior of the expansive soil and that of limestone are simulated by the constitutive swelling rock model and the linear elastic model, respectively.

Swelling Rock Model. The numerical modelling in PLAXIS 2D will be carried out to investigate the behaviour of the shallow foundation constructed on shale layers using a new user-defined Swelling Rock Constitutive Model. The constitutive swelling rock model is based on the time-dependent swelling of rock. The model was developed by Professor Thomas Benz of NTNU, which was further updated and adapted to PLAXIS 2D by Bert Schädlich of University of Technology. The swelling rock model was developed based on the study by (Anagnostou 1993) and (Heidkamp, Katz 2002), which explains the dependence of swelling deformation on stress and time. The model is available in PLAXIS 2D as a Dynamic Link Library (DLL) and works only in PLAXIS 2D VIP version (Plaxis 2014). According to this model, rocks expand due to the osmotic swelling and the inner-crystalline swelling of clay minerals (Madsen, Müller-Vonmoos 1989). The osmotic swelling is caused by the difference between cation concentrations in clay and free pore water and occurs after the inner-crystalline swelling has been completed. This swelling is caused by an increase in the repulsive forces between the neighbouring negatively charged clay layers, which results in the increase of the distance between these layers. The inner-crystalline swelling occurs first, and in the case of montmorillonite, it may cause a 100 percent volume increase of clay particles. This swelling occurs as a result of the water molecules integration into clay mineral crystals when the already present cations hydrate in the presence of water. Swelling occurs when the energy released during cation hydration exceeds the anion–cation bond within the clay mineral.

It is well established that the swelling of clays at various stress levels follows the logarithmic relationship described by Grob's swelling law (Grob 1972). $\varepsilon_q^{(t=\infty)}$ is the final swelling strain at the current axial stress σ_a, kq is the swelling parameter (equal to the inclination of the swelling curve) and σ_{q0}, k_q is the maximum swelling stress.

$$\varepsilon_q^{(t=\infty)} = -k_q \cdot \log\left(\frac{\sigma_a}{\sigma_{q0}}\right) \quad (1)$$

The Swelling Rock Model in Plaxis will be calibrated by conducting a 1-D Consolidation test.

The parametric studies will be carried out for various soil and structure parameters such as soil models, thickness of layers, structural pressures and types of structures.

RESULTS AND DISCUSSION

Laboratory results

Undisturbed soil samples were collected by rotatory drilling. The engineering properties of the soil samples were determined according to ASTM standards. The grain size distribution curve is presented in Fig. 1. The soil was classified as A-7-5 according to AAHSTO standards, while CH (Clay of High Plasticity) was identified based on the Unified soil classification system. The liquid limit and the plasticity index of the analyzed soil samples were higher, the liquid limit values ranging from 42 to 112 and those of PI from 19 to 56 as shown in Fig. 2. According to (Sabtan 2005), soil swelling is linked to the plasticity index and clay content. The shear strength parameters (c and ϕ), which were determined from the shear box test in the laboratory, were 22 kN/m^2 and 11^0 respectively; however they did not affect swelling results (Hosseinzadeh 2012; Hosseinpour *et al*. 2017). The modulus of soil elasticity was determined from equation 2.

$$E\ (\mathrm{kN/m^2}) = 180\ c_u \quad (2)$$

$$E(\mathrm{kN/m^2}) = 68810 + 124\ (\mathrm{UCS,\ kN/\ m^2}) \quad (3)$$

The cu = qu/2, where cu is undrained cohesion and qu is unconfined compressive strength of clay soil. In this study, the critical (minimum) unconfined compressive strength of shale (Psudo-Rock) was determined to be 10 kg/cm^2, and after conversion into SI units, it was used to calculate the elastic modulus of shale applying Equation 3, which was found to be equal to 192,800 kN/m^2. The equation (4) for computing the swelling potential of soil using the plasticity index (PI) was proposed by (Puppala *et al*. 2013).

$$Vs = 0.05 \times (PI)^{1.415}\ (\%) \quad (4)$$

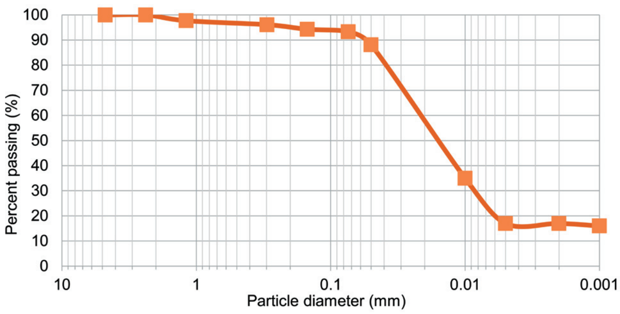

Fig. 1 Sieve analysis curve

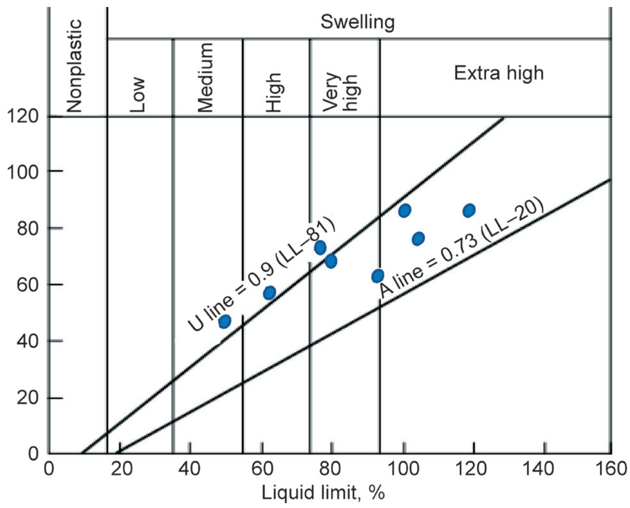

Fig. 2 Soil swelling potential based on plasticity index and liquid limit of study area

The main advantage of this model is that it requires a few parameters related to the swelling of expansive soil, which are relatively easy to determine in the laboratory or can be computed from the correlations available in the literature.

The swelling pressure ($\sigma q0p$, $\sigma q0t$) of soil, which was determined using the odometer constant volume method, was 200 kN/m^2. According to (Hosseinzadeh 2012), the value of tensile strength of 0.001 kN/m^2 should be inserted into the model. The value of Poisson's ratio was set at 0.25, which is commonly used for clay in High Plasticity (CH) soil. The value of A_0 was taken as 0.033, as the one which best corresponds to experimental results of the values determined from the calibration curve (Hosseinzadeh 2012; Hosseinpour *et al*. 2017).

Numerical modelling results

Soil swelling is influenced by several factors such as soil properties, loading, and water level conditions. In our case, the foundation was constructed on the surface of expansive soil and subjected to a vertical loading of 100 to 300 kPa.

The shallow foundation was built on a single layer of the homogeneous clayey soil. The depth of the foundation was 20 cm, the strip foundation was subjected to different levels of vertical stress. The modelling in Plaxis 2D was performed taking into consideration the plane strain condition.

Table 1 Input parameters for the model

Symbol	Description	Unit	Values
ϕ'	Mohr-Coulomb friction angle	°	11
c'	cohesion	kN/m^2	22
ψ	angle of dilatancy	°	0
σ_{tens}	tensile strength	kN/m^2	0.1 (assumed)
E_t	Young's modulus parallel to bedding plane	kN/m^2	25000
E_p	Young's modulus normal to bedding plane	kN/m^2	25000
ν_{pt}	Poisson's ratio out of bedding plane	--	0.25
ν_{tt}	Poisson's ratio within bedding plane	--	0.25
G_{pt}	independent shear modulus	kN/m^2	----
α	Rotation angle of bedding plane with respect to global Coordin ate system (counter-clockwise)	°	0
A_0	time swelling parameter (threshold)	1/day	0.033
A_{el}	time swelling parameter for elastic vol. strains	1/day	----
A_{pl}	time swelling parameter for plastic vol. strains	1/day	----
$\varepsilon_{pl,max}$	maximum plastic volumetric strain for A_{pl}	--	-----
k_{qp}	swelling potential normal to bedding plane	--	10%
k_{qt}	swelling potential tangential to bedding plane	--	10%
σ_{q0p}	maximum swelling stress normal to bedding plane (only used when *inicoupling* = 0)	kN/m^2	200
σ_{q0t}	maximum swelling stress tangential to bedding plane (only used when *inicoupling* = 0)	kN/m^2	200
Swell_ID	1: Wittke 2: Anagnostou 3: Mixed	--	3
Water	0: no coupling of swelling to presence of water 1: swelling only active if water is present	--	1

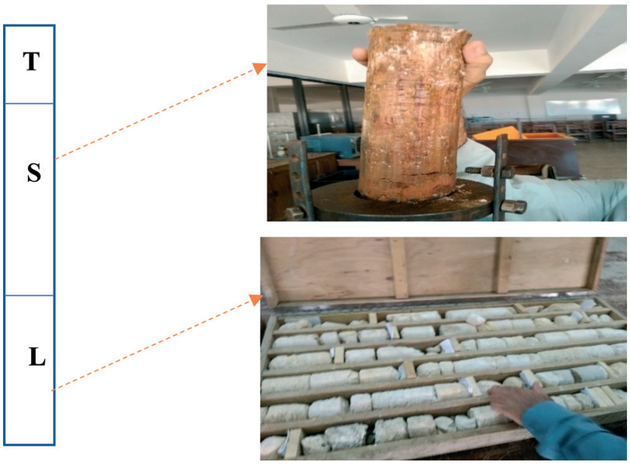

Fig. 3 Soil profile of study area (T = top soil, S = shale, L = limestone)

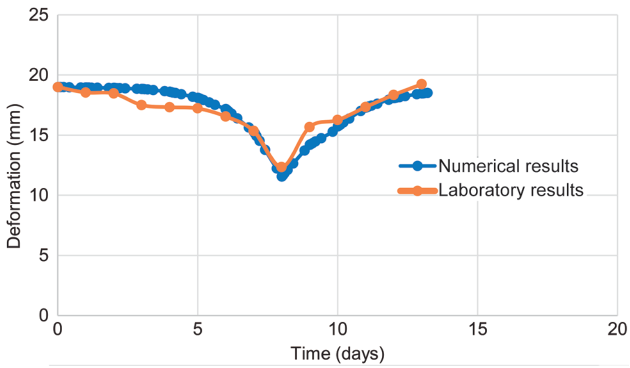

Fig. 4 Model calibration

The concrete foundation was modelled on the linear elastic model. The Young's modulus of concrete footing was taken as 30 GPa, Poisson's ratio ν = 0.2 and the unit weight γ = 25 kN/m^2. The undrained shear strength parameters of soil were determined in the shear box apparatus and presented in Table 1. The elasticity parameter of soil was calculated from equation [1] and [2].

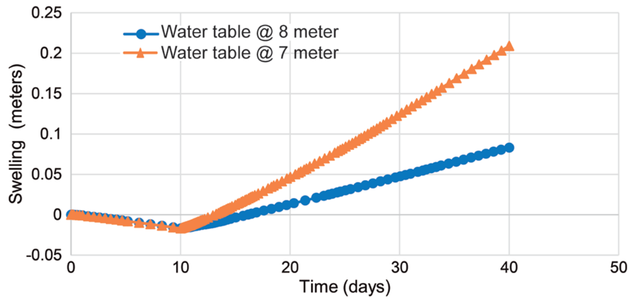

Fig. 5 Water table effect on swelling

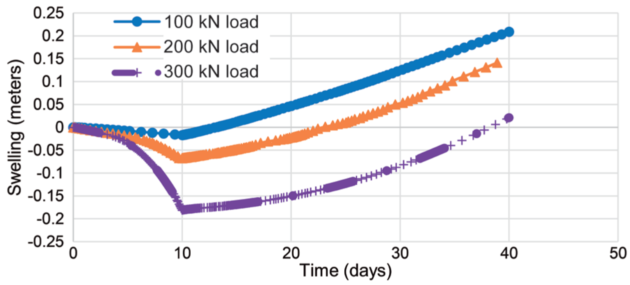

Fig. 6 Loading conditions effect on swelling

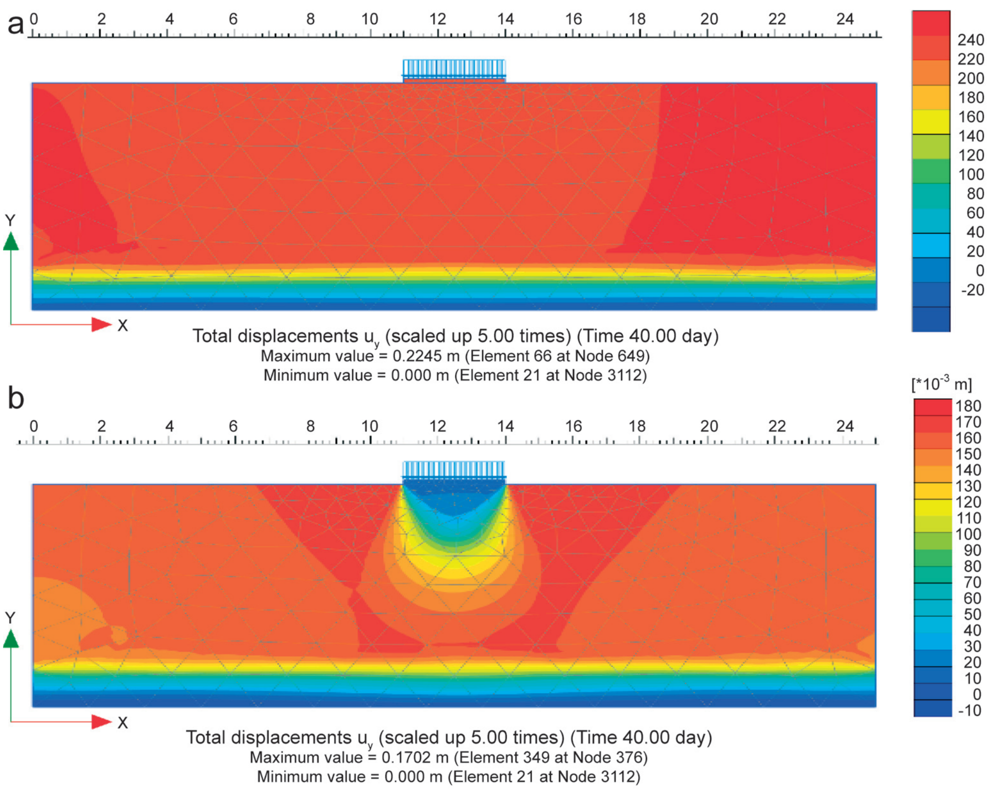

Fig. 7 Swelling at: a) 100 kN/m^2; b) 300 kN/m^2

The typical soil and rock profile was divided into three units based on the results of field and laboratory studies: (1) surficial top sandy soil, (2) residual clay soil (3), and limestone (Fig. 3).

The calibration of swelling rock model with laboratory consolidation test given in Fig. 4. The chosen depth of the model was 10 meters, and width 25 meters. The dimensions of the model were chosen so that boundary conditions would not disturb the efficacy of results. Several authors have recommended extending the limits of the model to a distance of 5–6 times greater than the foundation dimensions (Sheng *et al*. 2003). The building load was applied as a line load.

As the water level rose from 7 m to 8 m, the swelling increased from 83 mm to 20 cm as shown in Fig. 5. The settlement was higher for higher loading as shown in Fig. 6 and Fig. 7.

Also, the heave was minimum in the center of the foundation (20 mm), attaining the maximum value in the corner (16 cm) as shown in Fig. 8. This can be explained by the fact that the loading stress is the

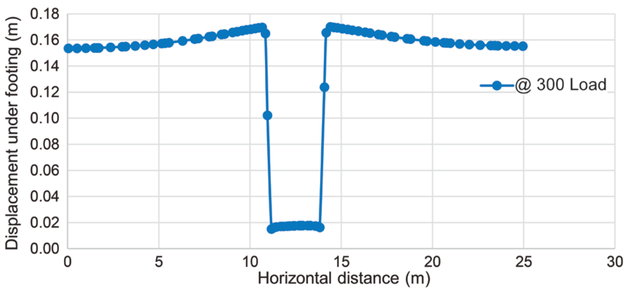

Fig. 8 Swelling below the footing

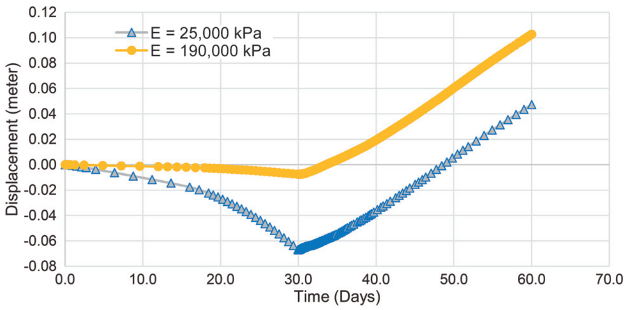

Fig. 10 Displacement variation in time with effect of modulus of elasticity

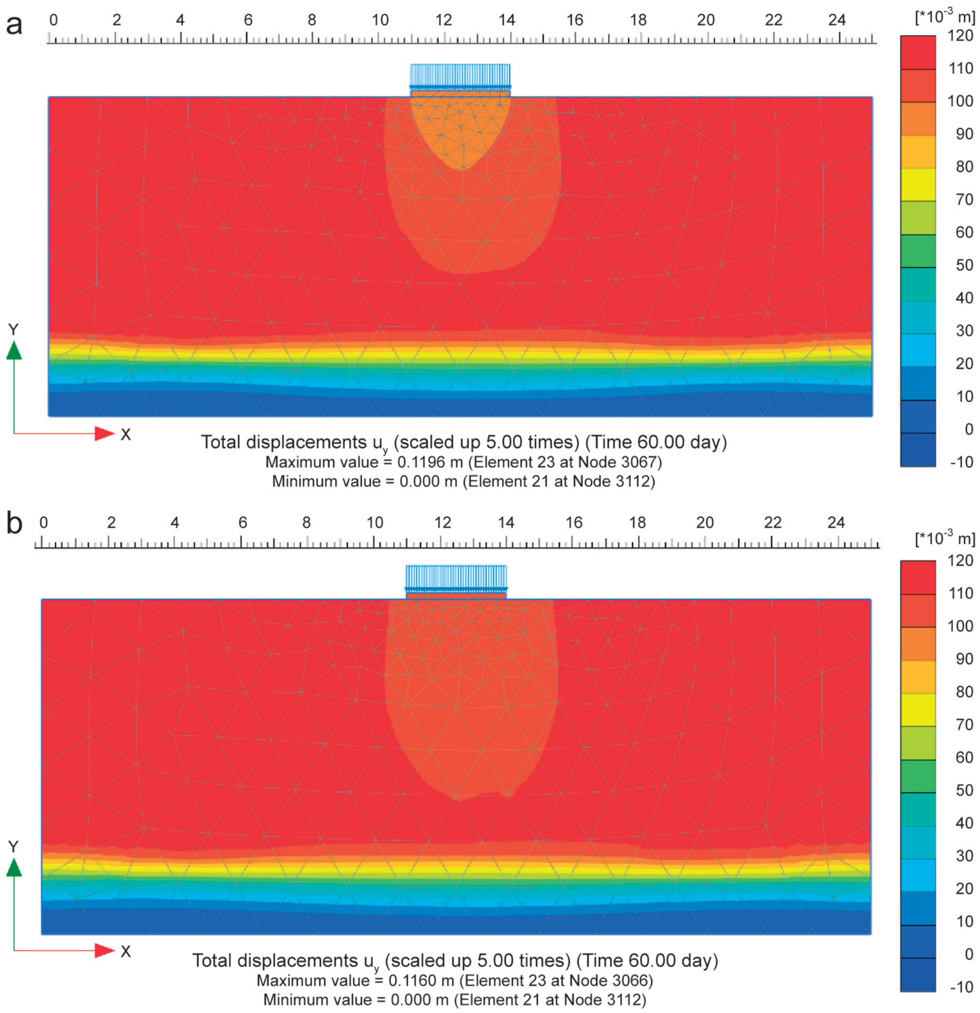

Fig. 9 Modulus of elasticity effect: a) E = 25000 kPa; b) 90000 kPa

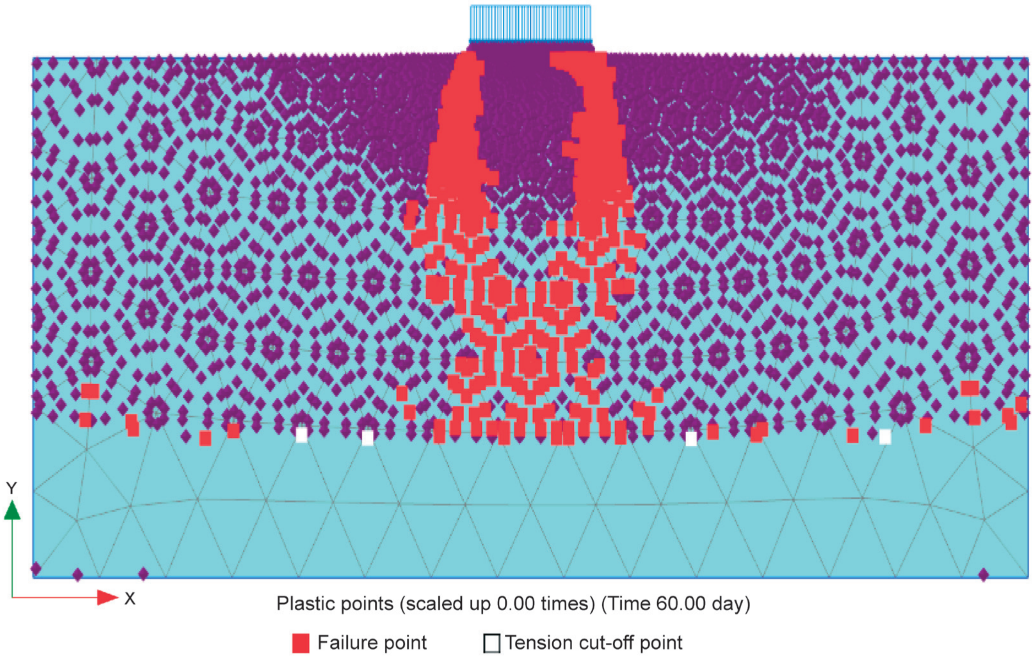

Fig. 11 Tension cut-off points and failure points

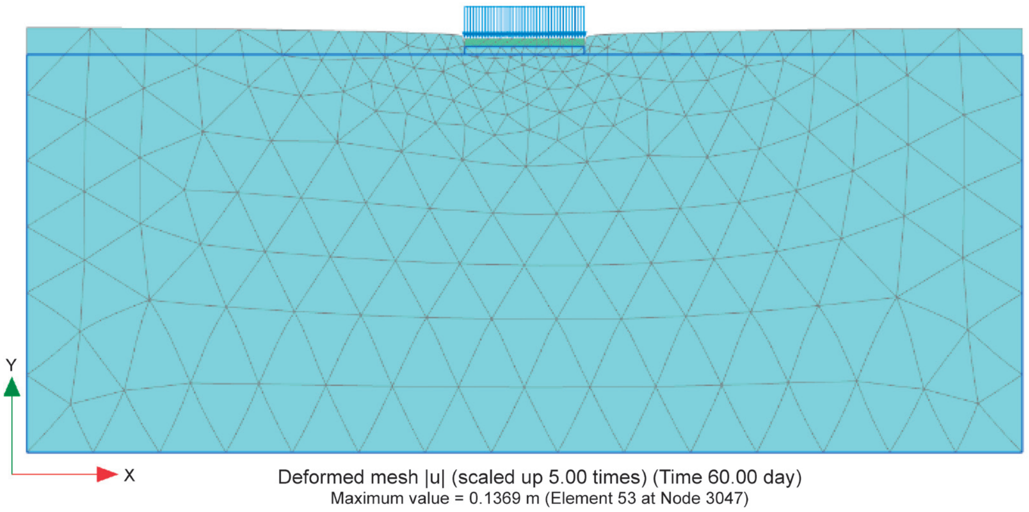

Fig. 12 Deformed mesh after swelling

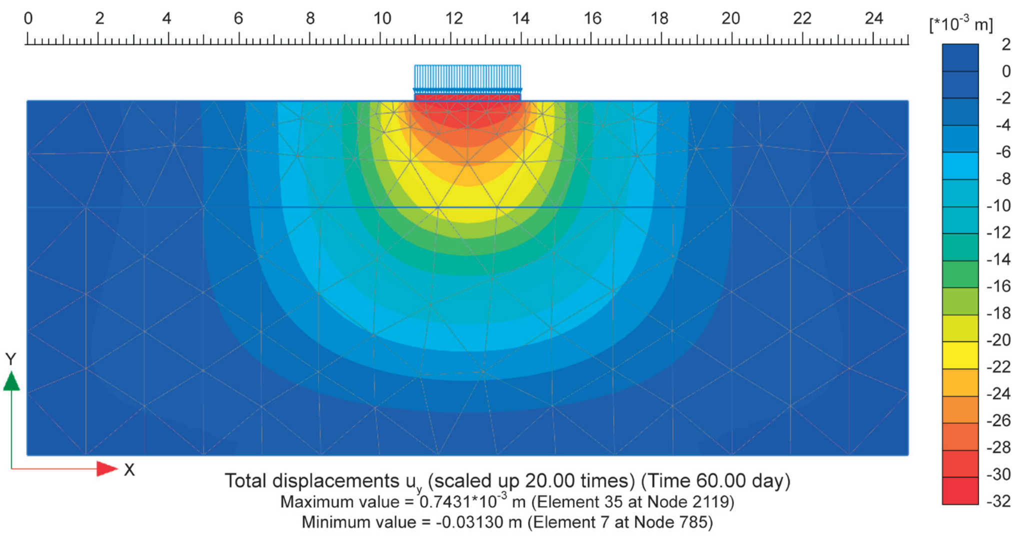

Fig. 13 Thickness of limestone layer 3 meters

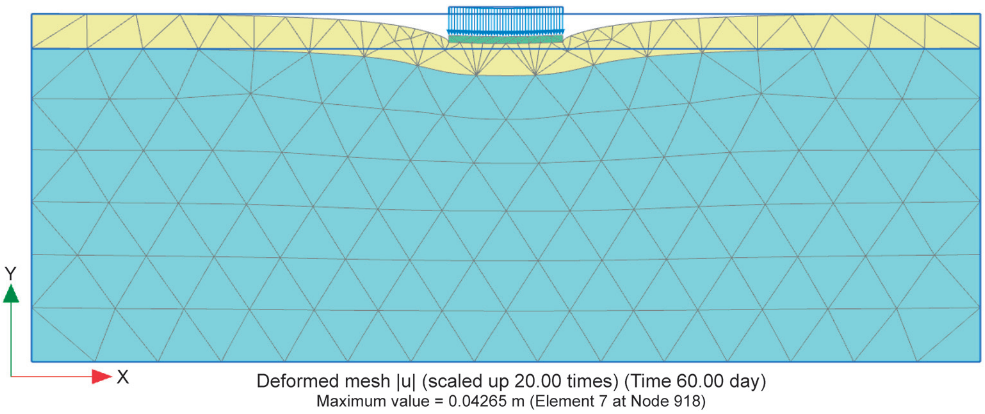

Fig. 14 Thickness of limestone layer 1 meter

greatest directly beneath the center of the footing, decreasing outwards from there.

Influence of soil stiffness

A number of numerical computations were carried out to test the influence of soil stiffness on the final heave of footing and a significant effect of soil stiffness on the final swelling of soil was revealed as shown in Figs 9 and 10.

The fully coupled deformation option in Plaxis was used for coupling effect between mechanical and hydraulic behaviour of soil. The expansive soil model was simulated in this section using test data and model parameters. Figure 11 shows the history of tension cut-off and elastic points. However, no plastic points are seen in the results. The deformed shape of the model after swelling is shown in Fig. 12.

The soil profile of the study area consists of shale and weathered limestone; however, their depth and sequence differ at different locations. In this study, to observe the effect of rock layer on swelling, limestone was placed below the shale layer. No swelling was observed beneath the footing in the case of the first layer of limestone as shown in Figs 13 and 14.

CONCLUSION

Expansive soil behaviour was simulated in Plaxis using a user-defined swelling rock model. The laboratory and field testing showed that soil in the study area is expansive shale, and, according to AASHTO and USCS, is classified as A-7-5 and CH, respectively. The model has that the swelling increased with a water level increase, and decreased with load. Suction does not affect the swelling phenomenon significantly. The limestone layer above the expansive soil ceases soil swelling. In future, the effect of unsaturated expansive soil with the application of rainfall will be simulated.

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REFERENCES

Anagnostou, G. 1993. A model for swelling rock in tunnelling. *Rock Mechanics and Rock Engineering 26 (4)*, 307–331, https://doi.org/10.1007/BF01027115

Desai, V.M., Moogi, V.V. 2016 (September). Study of Interference of Strip Footing using PLAXIS-2D. *International Advanced Research Journal in Science, Engineering and Technology, 3 (9)*, 13–17, doi 10.17148/IARJSET.2016.3903

Grob, H. 1972. Schwelldruck im Belchentunnel. In: Grob, H., K. Kovari (eds). *Berichte, Internationales Symposium für Untertagebau*, Luzern, 11–14 September 1972, 99–119.

Hamdhan, I., Schweiger, H. 2013. Finite element method – based analysis of an unsaturated soil slope subjected to rainfall infiltration. *International Journal of Geomechanics 13 (5),* 653–658.

Heidkamp, H., Katz, C. 2002. Soils with swelling potential – Proposal of a final state formulation within an implicit integration scheme and illustrative FE-calculations. In: Mang, H.A., Rammerstorfer, F.G., Eberhardsteiner, J. (eds). *Fifth World Congress on Computational Mechanics (WCCM V)*, July 7–12, 2002, Vienna, Austria, 1–10.

Hosseinpour, I., Almeida, M.S.S., Riccio, M., Baroni, M. 2017. Strength and Compressibility Characteristics of a Soft Clay Subjected to Ground Treatment. *Geotechnical* and *Geological Engineering 35*, 1051–1066, https://doi.org/10.1007/s10706-017-0161-8

Hosseinzadeh, S. 2012. Numerical assessment and validation of a swelling rock model. Master's Thesis, Geoscience & Engineering, Delft University of Technology (TU Delft), http://resolver.tudelft.nl/uuid:fcd2a9bf-0df8-4e27-9d2a-b687194c9c3c

Khan, M.S., Hossain, S., Ahmed, A., Faysal, M. 2019. Investigation of a shallow slope failure on expansive clay in Texas. *Engineering Geology 219*, 118–129, http://dx.doi.org/10.1016/j.enggeo.2016.10.004

Madsen, F.T., Müller-Vonmoos, M. 1989. The swelling behavior of clays. *Applied Clay Science 4 (2)*, 143–156, https://doi.org/10.1016/0169-1317(89)90005-7

Mokhtari, M., Dehghani, M. 2012. Swell-shrink behavior of expansive soils, damage and control. *Electronic Journal of Geotechnical Engineering 17*, 2673–2682.

Mosadegh, A., Nikraz, H. 2015. Bearing Capacity Evaluation of Footing on a Layered-Soil using ABAQUS. *Journal of Earth Science & Climatic Change 6 (3)*, 264, https://doi.org/10.4172/2157-7617.1000264

Phuor, Ty., Harahap, Indra S.H., Ng, C.Y., Al-Bared, M.A.M. 2021. Development of the skew boundary condition for soil-structure interaction in three-dimensional finite element analysis. *Computers and Geotechnics 137*, 104264, https://doi.org/10.1016/j.compgeo.2021.104264.

Phuor, T., Harahap, I.S., Ng, C.Y. 2022. Bearing capacity factors for rough conical footing by viscoplasticity finite-element analysis. *International Journal of Geomechanics 22 (1)*, article number 04021266, https://doi.org/10.1061/(ASCE)GM.1943-5622.0002256

Puppala, A.J., Manosuthikij, T., Chittoori, B.C.S. 2013. Swell and shrinkage characterizations of unsaturated expansive clays from Texas. *Engineering Geology 164*, 187–194, https://doi.org/10.1016/j.enggeo.2013.07.001.

Sabtan, A.A. 2005. Geotechnical properties of expansive clay shale in Tabuk, Saudi Arabia. *Journal of Asian Earth Sciences 25 (5)*, 747–757.

Sheng, D., Sloan, S.W., Gens, A., Smith, D.W. 2003. Finite element formulation and algorithms for unsaturated soils. Part I: Theory. *International Journal for Numerical and Analytical Methods in Geomechanics 27*, 745–765, https://doi.org/10.1002/nag.295

Wray, W.K., El-Garhy, B.M., Youssef, A.A. 2005. Three-Dimensional Model for Moisture and Volume Changes Prediction in Expansive Soils. *Journal of Geotechnical and Geoenvironmental Engineering 131 (3),* 311–324, https://doi.org/10.1061/ASCE 1090-0241 2005 131:3 311

Internet sources

Plaxis, 2014. Swelling Rock model. User-Defined Soil Model (UDSM), https://communities.bentley.com/products/geotech-analysis/w/plaxis-soilvision-wiki/46113/udsm---swelling-rock-model