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Swelling Prediction of Expansive Soil Using Numerical Method Analysis

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ABSTRACT Expansive soil is one of the factors that cause road damage in Indonesia. Its behavior is influenced by moisture content. At high moisture content, expansive clay has a very low bearing capacity and high swelling and shrinkage rate compared to other soil types. This soil expansion causes a heave force on the road pavement. When the force exceeds the strength of the pavement, the pavement will deform and break as the initial damage is created. Therefore, it is critical to investigate the effect of moisture content on the swelling-shrinkage behavior of expansive soil. In this study, soil expansion is numerically predicted using the finite element approach on ABAQUS compared to the laboratory expansion index test. The geometric shape and loading of the soil model are the same as the sample shape and loading of a laboratory expansion index test. The Mohr-Coulomb soil constitutive model with sorption is used to simulate water absorption in partially saturated soils. Coupled wetting liquid flow and porous medium stress analysis are used to simulate swelling and shrinkage. The simulation is divided into two types: geostatic, which simulates soil model loading, and coupled pore fluid, which simulates changes in water content. The simulation is then compared to the laboratory test for validation. The numerical analysis results show that the model's accuracy depends highly on the constitutive soil model, whereas the Mohr-Coulomb model shows a limitation in accuracy with the maximum swelling in the simulation is 21.704%, while the average maximum swelling in laboratory testing is 15.515%.

KEYWORDS Expansive Soil, Swelling, Shrinkage, Moisture Content, Finite Element Method.

1 INTRODUCTION

Expansive soil is one of the causes of road damage in Indonesia. This is due to the soil's low bearing capacity and extremely high level of activity and swelling when compared to other soil types. This soil expansion causes a heave force on the pavement structure. When the lifting force exceeds the pavement's strength, the pavement will break as the initial damage is created (Muntohar, 2006). Road damage may be prevented if we can predict the index of potential expansion in the soil and how much stress is exerted on the pavement. With the rapid growth of technology and mathematics, Finite Element Methods (FEM) can be used to simulate soil behaviors and their geotechnical problems. Chittoori and Mishra (2017) have successfully predicted the swelling behavior of expansive soil by using ABAQUS.

Based on a soil sample collected from a road damage case in Malingping, Banten, a simulation model to predict the expansion behavior of clay and its effect on road pavement was developed. This study aims to predict the expansion behavior of soils subjected to changes in water content using numerical method analysis, which is then validated using the expansion index test.

2 OVERVIEW

2.1 Expansive soil

Depending on the type of clay minerals present in a soil, clay expands at a different rate. The ASTM D-4829 expansion index test is one of the tests used to determine the level of expansive soil. This test is performed by compressing and immersing a cylindrical soil sample with a vertical load of 6.9 kPa. The expansion index is used to determine the level of expansiveness of the expansive soil based on volume change after 24 hours of immersion. The expansion index value is classified into five levels of swelling potential: very low, low, medium, high, and very high (Table 1).

Table 1. Classification of expansion index with swelling potential

Expansion Index, EI	Swelling Potential
0-20	Very Low
21-50	Low
51-90	Medium
91-130	High
>130	Very High

2.2 Mohr-Coulomb

Mohr-Coulomb is a widely used soil model because of its simplicity and is based on the concept of linear elastic-perfectly plastic. In this soil model, linear elasticity is based on Hooke's law for isotropic materials, while plastic elasticity is based on Mohr-Coulomb failure. Figure. 1 depicts a description of this linear elastic-perfectly plastic behaviour.

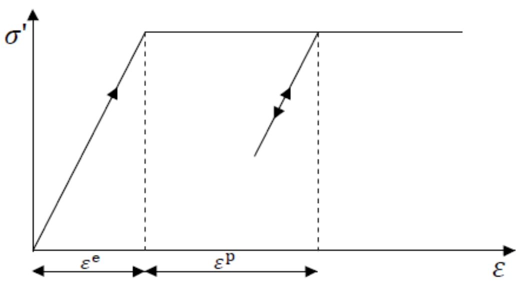

Figure 1. Mohr-Coloumb constitutive model (Brinkgreve et al., 2021)

2.3 Partially saturated soil

Partially saturated soils consist of air, water, and solid phases; as the name implies, soil pores are partially filled with water and air. Over time, the water content may increase due to infiltration and the soil will experience saturation. As a result of infiltration, soil will lose strength, and swelling or shrinkage can also occur (Berney, 2004). Terzaghi (1943) introduced the concept of effective stress to represent the response of soil to changes in water and air content, as expressed in Equation (1).

$$\sigma'_{ij} = \sigma_{ij} - u_w \delta_{ij} \quad (1)$$

where:

σ'_{ij} : Effective stress

σ_{ij} : Cauchy or boundary stress

u_w : Pore water pressure

2.4 Matric Suction and Soil Volume Change

Frequent rain in tropical regions such as Indonesia causes changes in soil water content, which in turn causes changes in matric suction, altering the mechanical behavior of soil. Matric suction is the potential energy of the physical bonds that provide tensile resistance between capillaries and solid soil particles. Matric suction influences soil behavior because the response of soil changes with change of air and water pressures. There will be no change in soil behavior if the air pressure and pore water pressure stay constant (Berney, 2004). Bishop pioneered a new concept involving the suction change potential of partially saturated soils in 1960, as expressed in Equation (2).

$$\sigma'_{ij} = \sigma_{ij} - u_a\delta_{ij} + \mathcal{X}(u_a - u_w)\delta_{ij} \tag{2}$$

where:

σ'_{ij} : Effective stress

σ_{ij} : Cauchy or boundary stress

δ_{ij} : Kronecker Delta

u_w : Pore water pressure

u_a : Pore air pressure

$\mathcal{X}$: Parameters that are influenced by the structure and type of soil when there is a change in water content

Matyas and Radakrishna (1968) introduced applied stress $(\sigma - u_a)$ as an independent stress variable. There are different mechanisms for the effect of volume changes between applied stress and matric suction. However, the theoretical concept only considers isotropically increasing load and ignores the effect of soil water content reduction. Fredlund & Morgenstern (1976) conducted a series of consolidation tests and discovered that three independent stress variables affected the volume change, which were defined as applied stress $(\sigma - u_a)$, effective stress $(\sigma - u_w)$, and matric suction $(u_a - u_w)$. According to Fredlund, two of the three variables are required to describe changes in soil volume, with the third variable being redundant. Fredlund also developed the equation for calculating soil shear strength, which is expressed in Equation (3).

$$\tau = (\sigma_{ij} - u_a\delta_{ij})\tan\phi' + (u_a - u_w)\delta_{ij}\tan\phi'' + c' \tag{3}$$

where

τ : Shear stress

ϕ' : Friction

ϕ'' : Friction affected by suction

2.5 Finite Element Method

There are three stages in the numerical simulation on ABAQUS: preprocessing, simulation, and postprocessing.

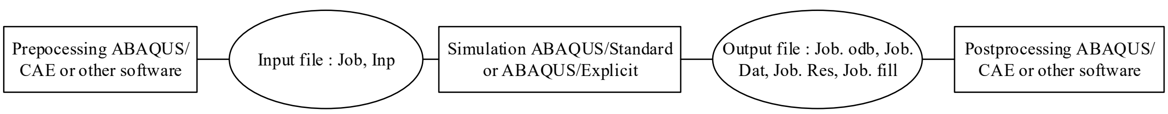

Figure 2. Modelling and simulation, ABAQUS (2018)

3 METHOD

3.1 Soil Parameters

The type of soil modeled in this research is expansive soil, which has an increase in value of matric suction and degree of saturation. In this study, the soil properties are assumed to be isotropic, which means that the material properties are uniform in all directions. For input parameters, laboratory test results such as specific gravity, cohesion, friction angle, void ratio, matrix suction, saturation, permeability, and modulus of elasticity were used. In addition, Poisson's ratio value is assumed based on soil type (Das & Sobhan, 2014) and permeability value is obtained based on grain size correlation (Irawan et al., 2012). Correlation between pore pressure and degree of saturation is obtained based on soil water characteristic curve (SWCC) to relate the water variation with matric suction data of the soil samples as per ASTM D 5298 (Filter Paper method). The soil parameters used for modeling input are listed in Table 2.

Table 2. Input soil parameters

Data Type	Parameter Description		Value
General	Density (kg/m^3)	γ_{dry}	1635.1
Mechanical	Elasticity	Poisson Ratio, v*	0.3
		Elasticity modulus, E_{50} (kPa)	1361.16
	Mohr-Coulomb	Cohesion, c (kPa)	36.415
		Internal friction angle, φ	7^o
		Dilatancy	0^o
Other	Permeability	Permeability, k (m/s)**	6.31×10^{-08}
	Initial Pore Condition	Void ratio	0.6
		Saturation	0.51
	Model Sorption		
	Pore Water (pa)	Saturation	
	-10000	0.05	
	-4500	0.1	
	-3500	0.18	
	-2000	0.45	
	-1000	0.91	
	0	1	

* assumed from Das & Sobhan (2014)
** correlated from Irawan et al. (2012)

3.2 Modelling

This expansive soil model simulates a 1-D (one dimensional) expansion based on the expansion index test using an Oedometer, so the loading and geometric shape of the model follow the shape of the expansion index test. The model is cylindrical, with a height of 1.35 cm and a diameter of 5 cm. The sorption model, which simulates water absorption in partially saturated soils, was used as the material model (Chittoori and Mishra, 2017). Furthermore, the modeled material's properties are assumed to be isotropic.

Coupled wetting liquid flow and porous medium stress analysis are used to simulate swelling and shrinkage. The study is divided into two types: geostatic, which simulates loading on the soil model and couple pore fluid, which simulates changes in water content. The boundary conditions (BC) used in this model are displacement BC and pore water pressure BC. Pore water pressure BC was used to define a source of water for the expansive soil, displacement BC was used to specify the free and fixed directions for the model movement. To simulate the 1-D swell situation, the bottom and outside radius of the soil were restricted in both directions, and water pressure BC was present at the top and bottom of the soil. The model's elements are 0.005 m in size. This model employed 8-node brick, trilinear displacement, and trilinear pore pressure element types with the C3D8P code. This element type allows pore pressure changes in the model system. In addition, there is a 6.9 kPa preloading on top of the soil to replicate the laboratory tests.

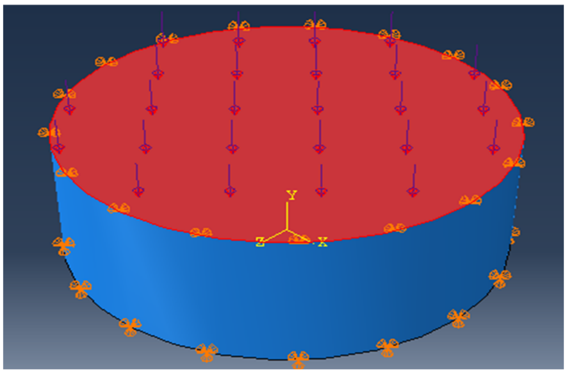

Figure 3. Expansive soil model in ABAQUS

4 ANALYSIS AND DISCUSSION

This study presents the development of the three-dimensional finite-element analysis for the one-dimensional swelling behavior of expansive soil using ABAQUS software. The result of the analysis is then compared to laboratory testing results as model verification.

4.1 Laboratory Testing

Laboratory tests were conducted for two soil samples from Malingping area which were named (MA) and (MB). The soil samples were obtained at 2 meters depth from the nearby boreholes and the sample has 1.35 cm in height and 5 cm in diameter. Expansion index test was then conducted for the two samples. The expansion index test results of MA and MB soils are shown in Table 3.

Table 3. Expansion index measurements for MA and MB sample

Time		**Deformation Reading (cm)**	
No Water Addition		**MA**	**MB**
(A) 10	Minute	0.006	-0.005
With Water Addition			
0	Seconds	0.006	0.001
6	Seconds	0.007	0.007
15	Seconds	0.010	0.009
30	Seconds	0.015	0.011
1	Minute	0.023	0.015
2	Minutes	0.033	0.020
4	Minutes	0.047	0.029
8	Minutes	0.063	0.041
15	Minutes	0.079	0.061
30	Minutes	0.105	0.097
1	Hour	0.143	0.149
2	Hours	0.185	0.176
4	Hours	0.192	0.183
8	Hours	0.209	0.186
(B) 24	Hours	0.222	0.198
	Maximum Swelling (B -A)	0.216	0.203

It is found that the measurement of maximum swelling in saturated condition of MA soil after 24 hours of readings is 0.216 cm with 16% swelling; MB soil has 0.203 cm of maximum swelling with 15.03% swelling. The test results are in a close match and demonstrate a good agreement due to the soil samples being taken from nearby location.

4.2 Results of Modelling

The modelling output is presented as a vertical displacement in Figure 4. The maximum swelling value that occurs is 0.293 cm, which equals to 21.7% swelling.

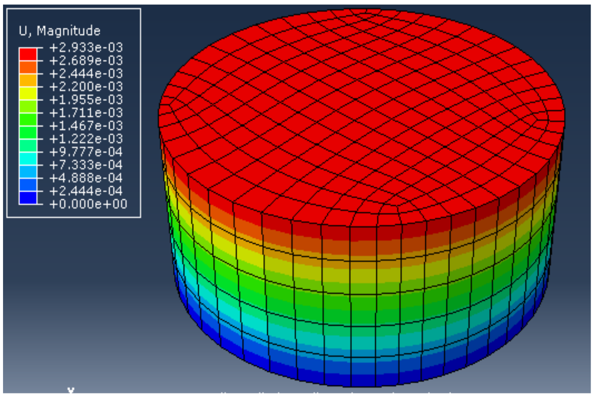

Figure 4. Result of Modelling

4.3 Discussion

Table 4 shows that the maximum swelling result in ABAQUS is 0.293 cm with a percent swelling of 21.7%, while the maximum swelling in MA soil testing is 0.216 cm with a percent swelling of 16%, and the maximum swelling in MB soil testing is 0.203 cm with a percent swelling of 15.03%. ABAQUS' swelling value is higher than that of laboratory testing.

Table 4. Results comparison of testing and modelling

Parameter	MA	MB	ABAQUS
Initial Height of Soil (cm)	1.35	1.35	1.35
Final Height of Soil (cm)	1.566	1.553	1.643
Vertical Displacement (cm)	0.216	0.203	0.293
%Vertical Swell	16.0%	15.03%	21.7%

The difference between the lab test results and the model simulation result might be due to the limitation of the Mohr-Coulomb soil model to accurately represent the actual swelling mechanism in soil, which is mainly related to stress-strain behavior. The type of soil model used has a significant impact on the stress-strain simulation of the soil and thus significantly influences the accuracy of the swelling. The more representative the model, the more accurate the desired result is. According to Sari (2012), the Mohr-Coulomb model produces a higher soil deformation value compared to the hardening soil model. This is due to the various approaches to represent the soil's stress-strain relationship. The Mohr-Coulomb model represents linear elastic-perfectly plastic behavior, whereas the hardening soil model represents a hyperbolic model, so the hardening soil model produces a more accurate soil stress-strain pattern than the Mohr-Coulomb model. However, the Mohr-Coulomb model is still quite commonly applied in practical use due to its simplicity in terms of soil input parameters and is generally more conservative.

The assumption of an isotropic material is another factor that can affect the difference between simulation and laboratory testing results. The actual soil condition is simplified using this assumption.

5 CONCLUSIONS AND SUGGESTION

5.1 Conclusions

The paper presents the laboratory tests and numerical models on the expansion behavior of expansive soils in Malingping, Banten. Laboratory tests provide consistent results and play an essential role in enabling the calibration of the chosen numerical models and soil constitutive parameters.

The finite element method using ABAQUS software shows a good approach to the laboratory test results, where the method used is able to represent the swelling behavior experienced by expansive soils using the Mohr-Coulomb soil model. However, the model's accuracy highly depends on the constitutive soil model used. Various options are available to develop the numerical model approach further for cases where the substantial soil modeling is involved.

5.2 Suggestion

The swelling behavior of expansive soil in ABAQUS can be modeled by considering the effect of temperature to complete the overall analysis.

DISCLAIMER

The authors declare no conflict of interest

DISCLAIMER

All data are available from the authors.

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