



Numerical simulation of a trial wall on expansive soil in Sudan

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Introduction

The expansive soil shows obvious volumetric changes under changing moisture conditions. These volumetric deformations usually result in differential movements of shallow foundations resting on it. Consequently, structural damages could happen if no special measures would have been taken during the design process. This article illustrates the possibility to predict such movements using PLAXIS provided that a suitable constitutive model for unsaturated soil behaviour is used.

Trial Wall on Expansive Soil

Nine trial walls were built on swelling soil in Barakat site in Sudan. The area is known for its highly expansive soil. The test were carried out in order to investigate the effect of soil replacement on the walls vertical movement [SAEED 2004]. The walls are made of brick (1 1/2 brick) with a length of 1.2 m and a height of 1.9 m above the ground level. The foundation depth is 0.6 m. A schematic representation of the walls with their dimensions is given in Figure 1. The expansive soil underneath the walls was replaced with different materials namely A1, A2, A3, B1, B2, B3, C1, C2 and C3 where:

A1: plain concrete, A2: Reinforced concrete with 20 % voids, A3: Big stones, B1: 25 cm of Cohesive Nonexpansive Soil (CNS), B2: 50 cm of CNS, B3: 75 cm of CNS, C1: Natural soil, C2: Natural soil with 6 % lime, C3: Sand.

The soil was then exposed to two successive wetting-drying cycles for a period of about 18 months. Detailed data about the vertical displacements of the trial walls is reported by [SAEED 2004], Figure 2 presents only the displacements of the wall C1 with no replacement as the purpose of this study is to simulate the behaviour of the expansive soil itself. On investigating the measurements one finds that the test has four stages. The first one is a wetting phase of about 270 days resulting in a total heave of about 6.0 cm. The wetting phase was followed by a drying phase of 90 days resulting in 2.5 cm of shrinkage. The second wetting stage lasted 127 days and resulted in 2.5 cm of heave, which indicates an elastic behaviour by recovering the settlement in the previous drying phase in almost similar time. The final phase was relatively short of about 50 days and resulted in 0.5 cm of shrinkage.

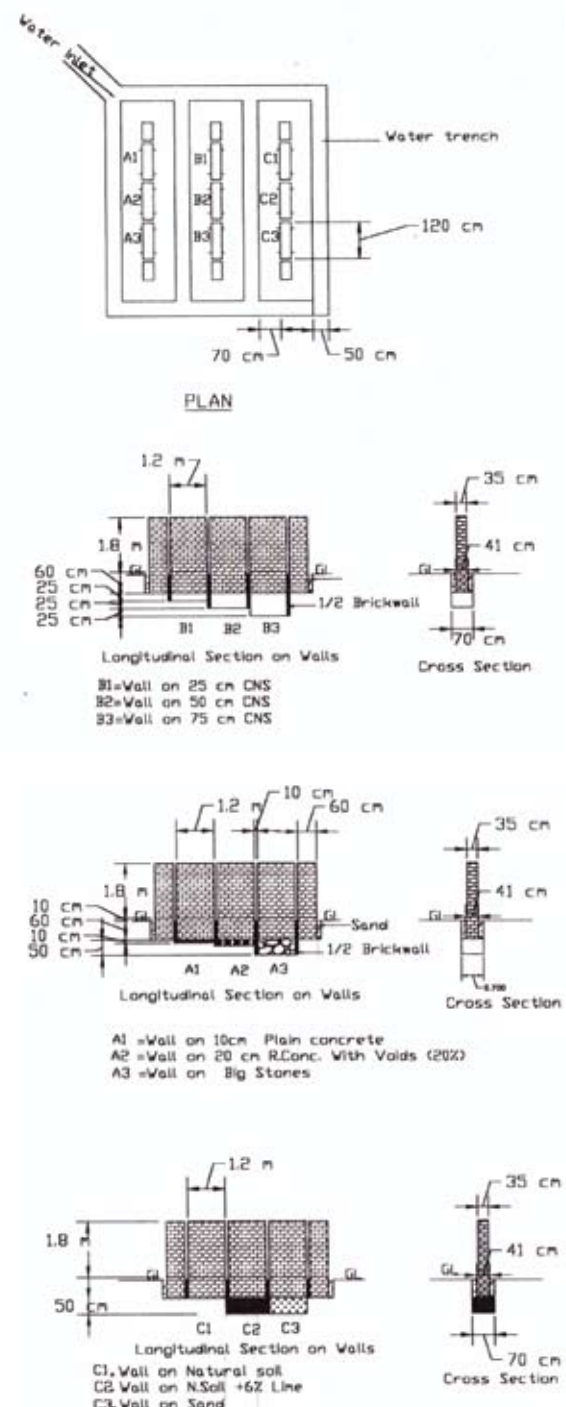


Figure 1. Geometrical details of the walls

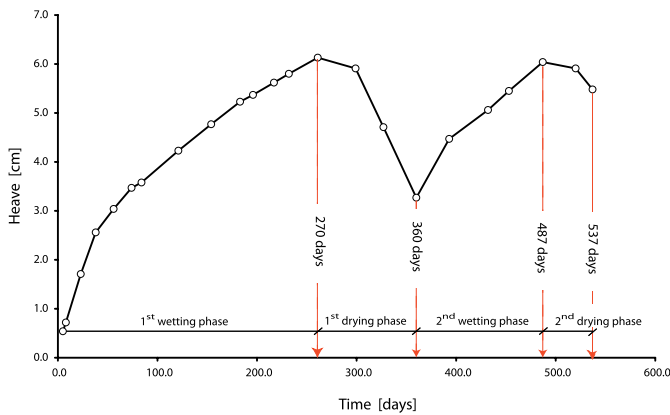


Figure 2. Measured displacements of the wall C1 as provided by [SAEED 2004]

Soil Properties

The soil is classified as a clayey silt with a liquid limit $LL = 68\%$ and a plastic index $PI = 36\%$. The 1-D compression results in Figure 3 shows that the soil is overconsolidated and it has a modified compression index $\lambda^* = C_c / 2.3 = 0.098$ and a modified swelling index $\kappa^* = C_s / 2.3 = 0.03$. The high K value is typical for an expansive soil. Other available soil properties are listed in Table 1.

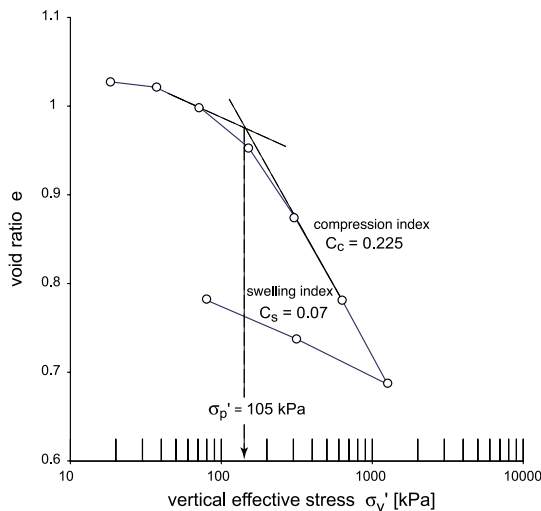


Figure 3. One dimensional compression results

Table 1. Other soil properties

ϕ'	c'	σ'_p	k_{sat}	γ_b
30°	0.0	105 kPa	0.02 m/day	17.6 kN/m ³

where ϕ' : soil friction angle
 c' : effective cohesion
 k_{sat} : saturated permeability
 γ_b : humid unit weight
 σ'_p : preconsolidation pressure

Material Model for Soil

Barcelona Basic Model [ALONSO & GENS 1990] is used as a constitutive model in this work. The model adopts the idea of two independent stress measures namely, the net stress σ^* and the suction s . The net stress is defined as the difference between the total stress σ and the pore air pressure u_a whereas suction is the difference between pore air pressure u_a and pore water pressure u_w . In what follows the air pressure is assumed to be atmospheric everywhere in the soil which means that the net stress in this special case is simply the total stress and the suction is equal to $-u_w$. The model is an extension of the Modified Cam Clay Model by adding the effect of suction on soil strength and stiffness. At full saturation, when suction = 0, the model coincides with the Modified Cam Clay Model.

On drying the soil (increasing the suction), a capillary cohesion develops and consequently the yield ellipse grows into the tension region with a rate equal to the model parameter a as it shown in Figure 4.a. The soil preconsolidation pressure p_p increases as well. It can be related to the preconsolidation pressure at full saturation p_{p0} through the following formula

$$p_p = p^c \cdot \left(\frac{p_{p0}}{p^c} \right)^{\frac{\lambda_s - \kappa}{\lambda_s - \kappa}} \quad (1)$$

where p^c is a reference pressure and

$$\lambda = \lambda_\infty - (\lambda_\infty - \lambda_0) \cdot e^{-\beta \cdot s} \quad (2)$$

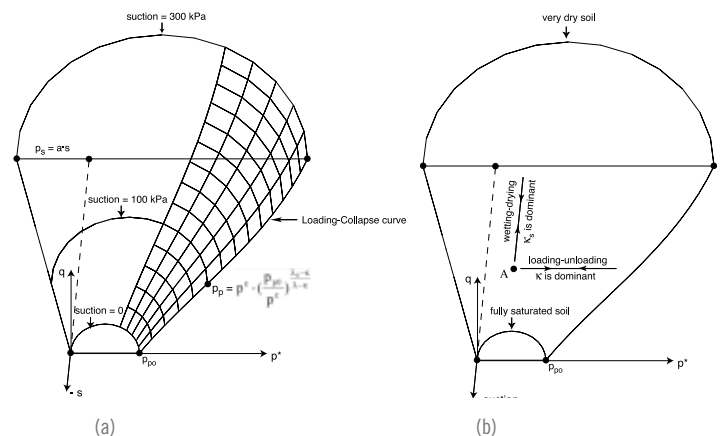


Figure 4. The yield surface of Barcelona Basic Model



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λ is the suction dependent compression index. Hence, for full saturation we have $s = 0$, $\lambda = \lambda_s$ and $p_p = p_{ps}$. The larger the suction, the smaller the compression index λ . In the limit for $s = \infty$ the above expression yields $\lambda = \lambda_\infty$. The constant b controls the rate of decrease of the compression index with suction.

When the deviatoric stress $q = 0$, the yield surface of Barcelona Basic Model degenerates to the so-called Loading-Collapse curve as it clear in Figure 4.a where p^* and q are the stress invariants being defined as

$$p^* = \frac{1}{3}(\sigma_1^* + \sigma_2^* + \sigma_3^*) - u_a;$$

$$q = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1^* - \sigma_2^*)^2 + (\sigma_2^* - \sigma_3^*)^2 + (\sigma_3^* - \sigma_1^*)^2} \quad (3)$$

For the elastic behaviour, the model assumes that the soil has different stiffness parameters for changes of net stress and changes of suction. For example starting from stress state A in Figure 4.b the soil shows different stiffness depending on whether it is exposed to net stress change or suction change. In the latter case the soil swelling index with respect to suction κ_s controls the soil response while the normal swelling index κ dominates the other case. This model has been implemented into PLAXIS finite element code as a user defined model by [ABED & VERMEER 2006] where the full mathematical description of the model is also presented. The swelling index with respect to suction κ_s is the most important parameter in the trial wall case as suction is the only variable during the test. It is assumed that the reader is aware of the fact that the change of moisture content and the change of suction are synonym.

Finite Element Calculations

The calculations involve transient unsaturated flow as well as deformation analyses. As the calculations are done in an uncoupled way, the unsaturated ground water flow analyses are done first and the resulted suction fields are used for later deformation calculations. The PLAXFLOW finite element code [BRINKGREVE et al. 2003] is used to simulate the unsaturated groundwater flow and to determine the suction variation with time. The deformation analyses are done using the Barcelona Basic Model as implemented in the PLAXIS finite element code.

Geometry, Boundary and Initial Conditions

Figure 5.a shows the boundary conditions, the initial conditions and the finite element mesh being used. The ground water calculation is found to be decisive for choosing the depth of the mesh. No local deformations are expected to take place around the wall footing, for that reason no further mesh refinement is needed in that region. The ground water table lies at a depth of 30 m below the ground level. The initial pore water pressure is assumed to be hydrostatic, with tension above the phreatic line. According to [SAEED 2004], the soil was always soaked with water during wetting phase, which suggests an infiltration rate equal to the saturated soil permeability k_{sat} . A high evaporation rate of 10 mm/day is applied during the drying phase to account for the observed severe shrinkage. The applied surface discharge with time is illustrated in Figure 5.b. PLAXFLOW requires information about the suction-degree of saturation and the suction-relative permeability

relationships. The first one is known as the Soil Water Characteristic Curve while the second is the relative permeability function. The term relative permeability stands for the ratio between soil permeability k at a certain suction level and k_{sat} . Both curves are shown in Figure 6.

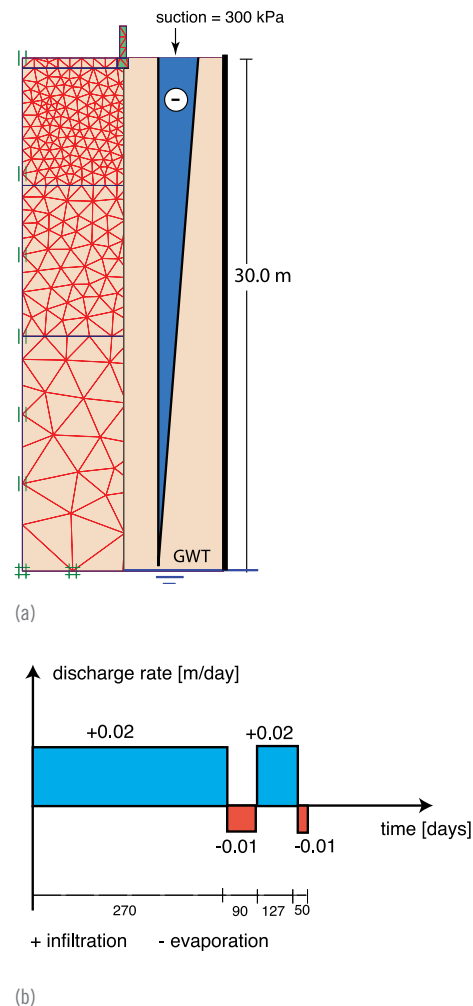


Figure 5. Geometry, boundary and initial conditions

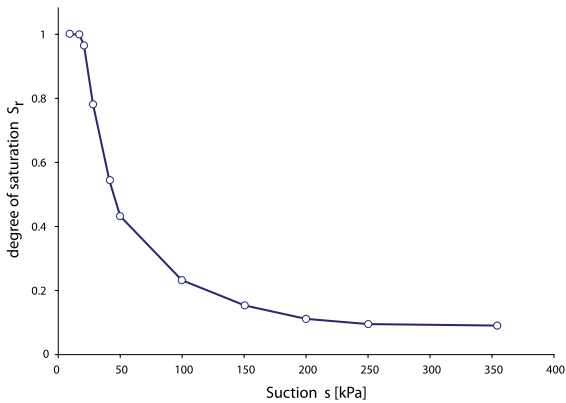


Figure 6. Soil Water Characteristic Curve and relative permeability function

PLAXFLOW output

Figure 7 illustrates the variation of suction and degree of saturation with time underneath the wall as calculated by PLAXFLOW. The suction drops from 300 kPa to about 30 kPa at the end of the first wetting phase. Then it increases again to 240 kPa at the end of the first drying phase. Then behaviour is repeated in the next wetting-drying cycle. It is also interesting to see how the degree of saturation is increasing with the decrease of suction and vice versa. Figure 8 presents the calculated suction profiles at the end of the first wetting phase as well as at the end of the first drying phase. They resembles typical suction distributions under infiltration and evaporation boundary conditions

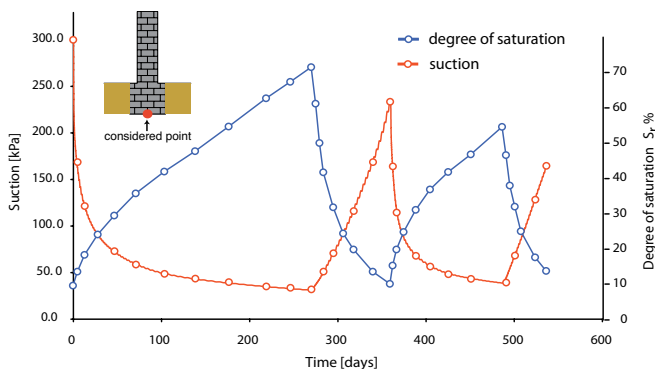


Figure 7. Suction and degree of saturation underneath the wall

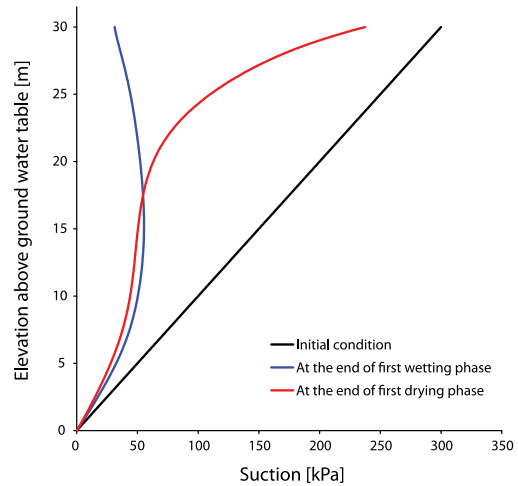


Figure 8. Suction profile at different time steps

Deformation analyses

Suction values resulted from ground water flow calculations are transferred to PLAXIS for deformation calculations. The material properties in Table 2 are used for the Barcelona Basic Model.

No information is provided about the soil swelling index with respect to suction κ_s , for that reason it is the calibration parameter in these calculations. Its value is varied between 0.005 to 0.03 which covers the most common values for this index as mentioned in literature [FREDLUND & RAHARDJO 1993]. A value of $\kappa_s = 0.015$ is found to give the best fit to the field measurements. Indeed this value is satisfactory in the sense that it also reflects the expansive nature of the soil being studied.

On using the material properties as listed in Table 2 the calculated deformations are in good agreement with measured data as shown in Figure 9. The deviation at the end of the first drying phase suggests that one should use a higher swelling index during shrinkage. As the model uses the same index for both swelling and shrinking it would be better for further improvement to use the idea of yielding on the shrinkage path as it proposed also by the Barcelona Basic Model [ALONSO & GENS 1990] where after a certain suction level the soil tends to yield with lower stiffness and giving more shrinkage.

Table 2. Barcelona Basic Model parameters

Strength parameters		Stiffness parameters		Stiffness parameters with respect to suction	
ϕ'	30°	λ_0	0.098	κ_s	0.015
c'	0.0	κ	0.03	λ_∞	0.07
a	0.5	ν	0.2	β	0.013 kPa ⁻¹
		p_{co}	97 kPa	p^c	50 kPa

where ν : soil Poisson's ratio for unloading-reloading



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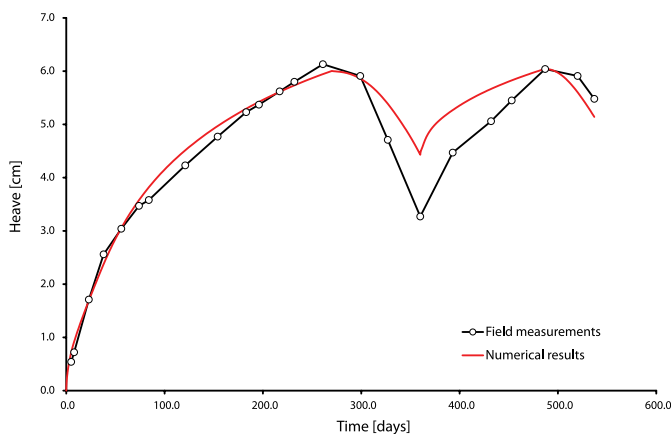


Figure 9. Calculated versus measured data

Conclusions

The PLAXFLOW-PLAXIS interaction offers a nice tool to simulate the mechanical behaviour of unsaturated soil. In this study PLAXFLOW is used to solve suction variation in time whereas the Barcelona Basic Model as implemented in PLAXIS is used to calculate the deformations. It shows clearly how much this procedure is efficient. However, one should always emphasize on the comprehensive understanding of the constitutive model being used and its limitations. The use of suction in deformation or stability calculation is always critical and need special model to handle it. Using it with the wrong model or without full awareness leads in most cases to a non-conservative estimation.

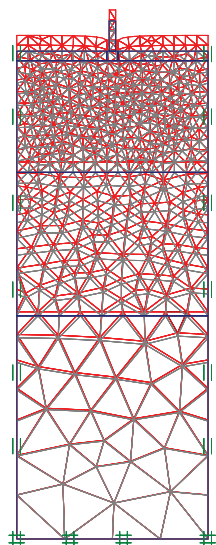


Figure 10. Deformed mesh at the end of calculations

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