Modelling of Stable Desiccation Crack Depths Due to Cyclic Wetting and Drying

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ABSTRACT: Desiccation cracking is a major problem in many fields. In addition to introducing speedy pathways for water ingress, cracks can also compromise the structural integrity of the geo-structures. In this regard, prediction of the depth of cracking is an important aspect in evaluating system performance. Modelling of desiccation cracks has received significant attention during the past few decades. This paper attempted to numerically model compacted clay liners by considering the cyclic effect of wet and dry cycles to predict the stable crack depths. The UDEC program was used in this study to predict the crack depths for several soil types. The effects of several parameters such as climate condition and compaction density on depth of cracking were analysed and discussed. The predicted crack depths using the numerical model represent the generally observed depths of cracking in the field reasonably well.

1 INTRODUCTION

Seasonal movements of soil can be observed in response to the change of soil moisture content resulting in a change of suction stresses. It was also well known that this soil shrinking and swelling becomes stable with the aging of soil. After the soil response becomes stabilised, it behaves reversibly during wetting and drying (Tripathy et al., 2002; Wijesooriya, 2012). Mitchell (1979) provided models to predict the suction profiles below the ground surface after this stable condition has been attained. The standard values of suctions to be used under such conditions are also given in the Australian Standards (Residential slabs and footings, AS2870) for design purposes.

Significant differences in suction profiles can be observed depending on the water table depth. With the use of the suction profile proposed by Mitchell (1979), the stable crack depths can be calculated using the elastic theory. In this paper crack depths were calculated using the above method for several clay soils from different parts of Australia and from some other countries. The evaluation of crack depth in different climate conditions was considered.

2 SUCTION PROFILES

The suction variation below the ground has been measured by several researchers and presented as the observed suction profiles during different climate conditions (Corte and Higashi, 1964; Richards, 1985; Morris et al., 1992; Wijesooriya and Kodikara, 2012). The position of the water table was considered as a key factor in these studies and the depth of soil from the surface was also identified as critical when the suction profile changes significantly according to seasonal effects. The water table was considered as shallow when the water table is less than 6m deep in clay soil, 3m in sandy clay and silts and 1m in sand (Corte and Higashi, 1964). Otherwise it was considered as a deep water table.

When shallow water table depths were presented, several appropriate suction profiles were presented by Morris et al. (1992). However, the depth to water table could increase when the soil layer is subjected to arid climatic conditions.

Corte (1964) suggested that the equilibrium suction profile should be based on the direct influence of the hydrostatic water table, regardless of the climate, where shallow water tables exist. However, it is well known that the suction profile fluctuates seasonally and during wet and dry conditions.

When deep water tables are present, the moisture conditions within the soil are controlled by the moisture balance between rainfall and evapotranspiration (Russam and Coleman, 1961; Richards, 1985). Richards (1985) predicted equilibrium suction profiles using empirical relations between soil suction and climatic indices such as Thornthwaite's Moisture Index (TMI) in terms of total suction. These suction profiles are based on the curve proposed by Russam and Coleman (1961) for optimum drainage conditions considering the practical purposes.

A more detailed theoretical model for predicting the suction profiles below the ground has been developed by Mitchell (1979). In his model, the suction variation with depth was represented according to the soil characteristics and the time. The model is given in equation (1).

$$S(z,t)=S_e+\Delta S e^{-\sqrt{\frac{n\pi}{\alpha_{dc}}}z}\cos\left(2n\pi t-\sqrt{\frac{n\pi}{\alpha_{dc}}}z\right) \qquad (1)$$

where S(z,t) is the suction at any depth z in metres at the time t in years, S_e is the equilibrium suction below the depth of seasonal suction change (or reactive zone depth), ΔS is the amplitude of suction variation at the surface. All the suction values have the unit pF, which is defined as $pF=\log_{10}$ |suction in cm of water|. n is the frequency of seasonal variations given by cycles per year, α_{dc} is the diffusion co-efficient of soil with the units of m^2 per year.

Eq. (1) defines the suction decay along the depth and its oscillation with time which is symmetric about the equilibrium suction S_e. Although this model covers the seasonal effects on the suction profile and the variation of suction with the depth, it is based on some unrealistic assumptions. Basically, it assumes that the suction varies purely due to the climatic conditions and the moisture with in the soil is neglected, which is not accurate if the water table is not deeper than 10m (Aubeny and Long, 2007). Furthermore, at or near the surface the model (Eq. (1)) is valid only if the soil layer has a very shallow root depth or bare surface which is highly unlikely.

However due to the usefulness in modelling the seasonal variation of suction profile with depth as represented by Eq. (1), this model was selected as the basis for the numerical model.

3 THE SUCTION IN DIFFERENT CLIMATE CONDITIONS

Despite all the different empirical, theoretical and numerical models developed to predict the suction below ground, it is essential to measure the actual suction profile in the field under natural conditions. These real observations should be used as a benchmark to validate the other developed models. Hence the literature provides some useful data on observed suction profiles in different areas of the world.

Considering the observed suctions in the past, it was decided to select a matric suction variation from 10kPa to 2.5MPa (2.0pF to 4.4pF, with 1.2pF difference to equilibrium suction) from wet season to dry season in semi-arid climate conditions. Also, in arid climate conditions the suction was changed from 20kPa to 5MPa (2.3pF to 4.7pF, with 1.2pF difference to equilibrium suction) from the wet season to dry season. The suction profiles are illustrated in Fig. 1 for arid and semi-arid conditions.

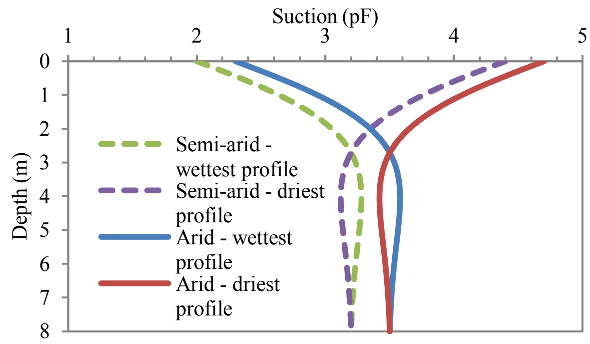

Fig. 1 Typical Suction Profile for arid and semi-arid conditions used in the present study

4 DEVELOPMENT OF NUMERICAL MODEL FOR COMPACTED CLAY LAYERS UNDER CYCLIC ATMOSPHERIC CONDITIONS

A numerical model was developed using UDEC programme incorporating the suction profile change with the climatic condition (Wijesooriya, 2012). The stress change due to the suction change was calculated on the basis of water content change instead of the suction change.

The suction profiles assumed for arid climates and semi-arid climates are the same as shown in Fig. 1. The suction corresponding to each zone was calculated using Eq. (1). However to relate suction to water content, the soil water characteristics curve (SWCC) is used to obtain the water content change corresponding to the suction change applied.

The horizontal strain due to matric suction can be written as,

$$\varepsilon_x=\frac{\Delta S}{H}=\alpha\Delta W \qquad (2)$$

The stress change can be written as,

$$\Delta\sigma=E\varepsilon_x/(1\text{-}2\nu) \qquad (3)$$

By substituting the Eq. (2) and the value of α in equation (3), the stress change becomes,

$$\Delta\sigma=\frac{EG_s}{(1\text{-}2\nu)}\Delta W\frac{\alpha^*}{(1+e_0)} \qquad (4)$$

Eq. (4) was then used to calculate the stress change in the continuum. The void ratio was obtained from either void ratio vs. suction or void ratio vs. water content curve. Then, from the void ratio vs. moisture ratio curve the hydric coefficient (α^*) was obtained.

The results obtained matched well with the actual field results. Hence it was decided to continue to use this method for further analysis.

In order to examine typical crack depths, it was decided to use several clay soils from different areas. Three soils were named on the basis of their original location as Regina clay, Horsham Clay and Altona clay. For this study the soil parameters for clay soils were selected from the literature.

5 RESULTS

5.1 *Crack depth prediction under different climatic condition*

The position of the suction profile beneath the ground surface changes significantly with the climate condition of the area. Fig. 2 shows the different suction profiles under different climatic conditions which were used to obtain the depths of cracking as shown in Fig. 3. All three clay soils used in the study showed similar crack depths under the same climatic condition.

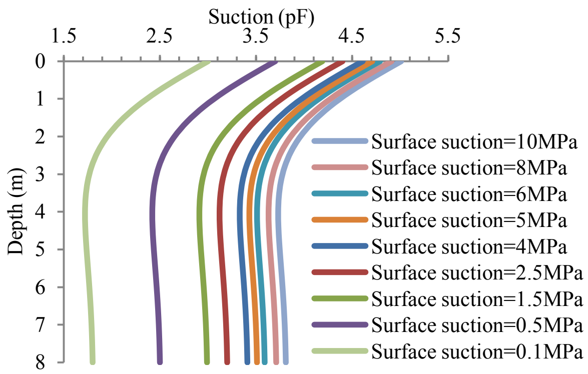

Fig. 2 Suction profiles under different climatic conditions.

The wettest profile used was 100kPa at the surface and the equilibrium suction at depth was 6.2kPa, which showed no cracks at all in all three soils. The depth of cracking value of 4.5m was observed for Regina and Altona clay soils when 10MPa surface suction was applied although for Horsham clay crack depth was about 0.5m less.

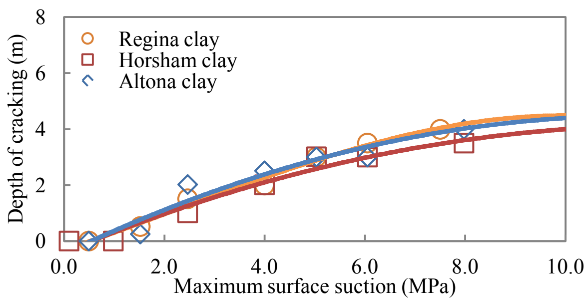

Fig. 3 Predicted depth of cracking change with climatic conditions.

In the field generally, 2 to 4m depths of cracks were observed when the matric suction at shallow depths was recorded around 3MPa values (Russam and Coleman, 1961; Corte and Higashi, 1964; Richards, 1985; Wijesooriya and Kodikara, 2012). The predicted crack depths appear to match those observed crack depths since the crack depths for 3MPa matric suction are around 2m for all three soils. It should be noted however, in these predictions, that the matric suction values given for the surface and the in the field suctions are measured at shallow depths. Hence, considering the fact that the surface suction is always higher than the suction values at shallow depths during the drying periods, the observed crack depths should be a little higher than the predicted values confirming the accuracy of the predicted results.

5.2 *Crack opening and closing with time*

Assuming that a year has only one cycle of climatic change Fig. 4 was produced. The driest time of the year was obtained when t=0.5yr which represents around January in Australia. The wettest profile was obtained when t=1yr representing around July. The broken lines in Fig. 4 show the change of suction profile from the wettest condition to driest condition and the solid lines show the change from driest to wettest condition in each time step.

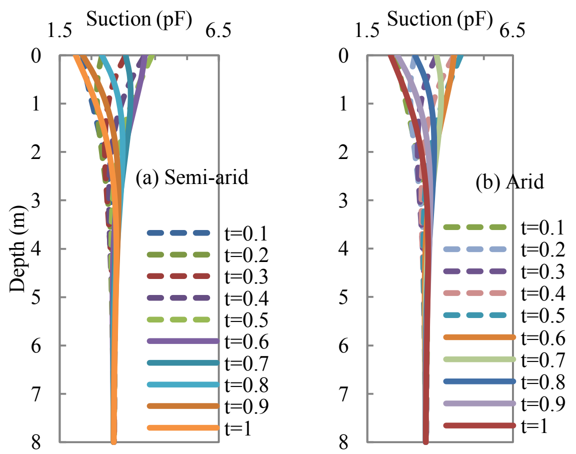

Fig. 4 Suction variation in (a) Semi-arid (b) Arid area

Depending on the suction or water content profile in the soil, the depth of the crack may vary. The cracks can be opened further if drying continues or the opened cracks can close due to soil wetting, along with erosion from the sides of the crack or plastic flow. Hence it is important to observe the behaviour of the cracks during the seasonal movements. However, the results shown in Figs. 5 and 6 do not show the continuation of suction profiles through the seasonal variation. Instead they show the crack depths observed when the suction profile changes from the initial conditions to the relevant suction profile at a particular time. Hence the results may deviate from the actual results, when actual progression of suction and associated changes in crack depth and width are considered with the moisture dynamics associated with actual wetting and drying.

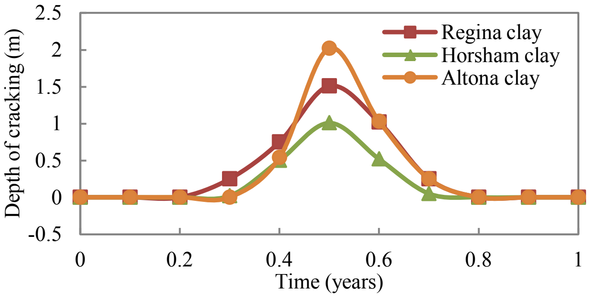

Fig. 5 Predicted depth of cracking with seasonal change in an semi-arid area

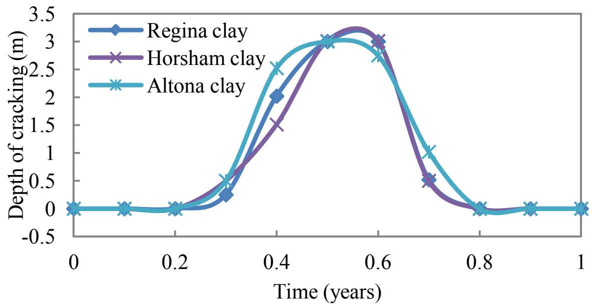

Fig. 6 Predicted depth of cracking with seasonal change in an arid area.

Figs. 5 and 6 show how the crack depths corresponding to the suction profiles at times of 0.1yr time steps in arid and semi-arid climate respectively. For Australian conditions the cycle will start from the wettest month July (0yr or 1yr) and reach the driest condition in January at 0.6yrs. The results show that the crack depths increase quickly after a certain suction level and then reach a peak when the suction becomes a maximum. During wetting the crack depths decrease sharply as suction decreases and then remain unchanged. These results suggest that the crack depth can show significant change during the year with its depth peaking rapidly during the dry period. These results appear to be consistent with the field observations that cracks close during the winter and open up during summer. However, their actual dynamics may be affected by debris flowing into the cracks and causing changes in normal pattern of behaviour.

6 CONCLUSIONS

The UDEC program was used in this chapter to predict the crack depths for several soil types. The predicted crack depths using the numerical model represent the generally observed values and patterns of depths of cracking in the field reasonably well.

Three soils were selected to represent the clay soils in different climatic locations and soil types. It is reasonable to conclude that all three soils produce similar depths of cracking under the same climate conditions. The climate condition of the area has a great influence on the depth of cracking and the predicted crack depths range between zero and 8m when the aridity increases.

While the analysis presented in this paper encompasses the major stresses that control desiccation cracking in a certain climatic location, the actual crack development and dynamics may be influenced by other factors that were not considered in this analysis. These factors include the effects of continuous drying and wetting dynamics of the soil and associated influence on the crack dynamics, and the effects of other intervening events such as debris flow into the cracks and associated changes in stress and moisture development. Nevertheless, the computed crack depths appear to be reasonable on the basis of the field observations.

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