UNIFIED FINITE ELEMENT MODEL FOR SWELLING AND SHRINKAGE BEHAVIOUR OF EXPANSIVE SOILS

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ABSTRACT: The mechanical behaviour of soil is quite complicated and depends on many factors. Expansive soils are those clayey materials which exhibit significant volume changes caused by changes in the subsoil moisture. This has been a subject of research for many years, and the advent of the numerical technique of finite element has given added impetus to these effects. A constitutive law is developed and implemented in a finite element program. The finite element technique is used to compute displacements and stresses developed in structures and soil along time of activity of the swelling. The main objective of this work is to verify the produced unified model for the swelling and shrinkage behaviour of expansive soil. To see the performance of the soil in dryness process, the computation of the heave and stress is continued after the assumed time of wetting period. The values of the heave of soil reduce after reaching a peak value. The reductions of the values of heave are different from layer to layer depending on the rate of loss of water. The main conclusions driven from the various aspects of this study are consistent with the literature findings.

Keywords: Swelling soils, Shrinkage, constitutive law, Finite Element method

1. INTRODUCTION

Soils are composed of a variety of materials, most of which do not expand in the presence of moisture. However, a number of clay minerals are expansive. Expandable soils are referred to by many names. "Expandable soils", "Swelling soils", "expansive clays", "shrink-swell soils" and "heavable soils" are some of many names used for these materials. Expansive soils are ones that swell in volume when subjected to moisture. These swelling soils typically contain clay minerals that attract and absorb water. When water is introduced to expansive soils, the water molecules are pulled into gaps between the soil plates. As more water is absorbed, the plates are forced further apart, leading to an increase in soil pore pressure (Handy, 1973).

These soils include: smectite, bentonite, montmorillonite, beidellite, vermiculite, attapulgite, nontronite, illite and chlorite. There are also some sulfate salts that will expand with changes in temperature. When a soil contains a large amount of expansive minerals it has the potential of significant expansion. When the soil contains very little expansive minerals it has little expansive potential.

Many tests and methods have been developed or modified for estimating shrink-swell potential. These include both indirect and direct measurements. Indirect methods involve the use of soil properties and classification schemes to estimate shrink-swell potential. Direct methods provide actual physical measurements of swelling (Al-Rawas, 2006)

Presently, no one method of soil analysis estimates shrink-swell potential accurately for all soils. Soil scientists recognize that shrink-swell behavior can best be predicted by examining a combination of physical, chemical, and mineralogical soil properties. Determining these properties and establishing a shrink-swell model that can be extrapolated across the same or similar parent materials is needed (Thomas, Baker and Zelazny1998).

2. FINITE ELEMENT MODEL IN EXPANSIVE SOILS

The proper constitutive models for swelling soils have to assume consideration of factors such as elastic, plastic, and viscous (time-dependent) deformations, volume change, and water diffusion in a unified manner. The main objective of this study is to drive constitutive relations representing the swelling and shrinkage behaviour of expansive soils. The constitutive law has to incorporate the visco-plastic behaviour of such soil when its moisture content increases or decreases (Elarabi, 2001).

In this study swell-shrinkage behaviour of expansive soil is simulated by a finite element model. It is usually necessary to utilise a finite element mesh to adequately model the response of the surrounding material. However the proper material behaviour is not well known in many cases. (Duddeck, 1991) states that for swelling ground more experimental and on site experiences are still needed to derive adequate material models. The numerical methods are the only methods which can indicate the limit state causing the collapse of a

underground structures.

The program VISCPLAST is a finite element program written in FORTRAN 77 and has been developed especially for this work to analyse two dimensional nonlinear structures which exhibit viscoplastic behaviour. The problems in this study are analysed using two types of elements. These element types are based all on an isoparametric formulation and are an 8-node Serendipity quadrilateral element with curved sides and a quadratic variation of the displacement field within the element as well as a 9-node Lagrangian quadrilateral element which additionally has a central node.

The finite element program developed in this work is applied to predict heave or settlement at different depths caused by wetting and drying of the soil. The output results of the program are displacements and stresses at the different depths of the ground. The computational results are presented in the form of diagrams, which give a summary of the results and enable various computed cases to be compared.

A general mathematical form, f, for constitutive equations can be expressed by:

$$f(\sigma, \dot{\sigma}, \varepsilon, \dot{\varepsilon}) = 0 \qquad (1)$$

where σ denotes stress, ε denotes (infinitesimal)strain, and the overdot denotes rate of change with respect to time.

Most useful constitute models for complex (geological) materials are obtained by using the incremental forms. Then relations between increments of stress and strain can be expressed as follows [6]

$$\dot{\sigma}_{ij} = f_{ij}(\sigma_{kl}) \, \dot{\varepsilon}_{mn} \qquad (2)$$

In this work the general form for a viscoplastic approach which simulates the behaviour is chosen as

$$\dot{\varepsilon}_q = f(\sigma, c, w) = f(\sigma).f(c).f(w) \qquad (3)$$

in which σ is the current stress, w is the water content, which may itself be a function of the time and c is the clay content. The derivation of the constitutive relation considering the effects of current stress, water content and clay content as major parameters is presented in the following sections. The effects of each of these three variables are discussed in details separately.

From the above assumptions the general form of the constitutive equation considering the effect of current stress, water content and clay content on the performance of the rate of swelling strain can be written as follow

$$\dot{\varepsilon}_q = A \, e^{b'\sigma} \cdot \frac{A'}{e^{(Bw-a)/b}} \cdot k. \qquad (4)$$

The constant A in the constitutive model (4) represents the climatic site topography and confinement and is constant for a certain expansive soil zone. Also the constant b′ is the same per expansive soil zone and takes into account the consideration of the weight of structure and soil overburden.

The effects of the initial moisture content, initial degree of saturation and availability and composition of ambient water and temperature on the constitutive model are covered by the constants B, a, b. The constant A which is different from layer to layer under the same climatic factor considers the compositional and environmental factors discussed above. The constant k represents the percentage of clay content in the soil.

3. COMPUTATION OF THE STRAIN AND STRESS INCREMENTS

The finite element program in this study uses three time stepping scheme,
-Implicit method or backward difference method,
-Semi-implicit method,
-Explicit method or forward difference method, (Owen and Hinton, 1980).

The three methods predict approximately the same steady state values. The semi-implicit and explicit methods need smaller efforts of computation than the implicit method and producing rabid results for the steady state condition in respect of the transient stage. For this reason they are used for primary computation to test the suggested parameters as well as to have an idea over the steady state values and their time. The final computation for every problem in this study is done by using the implicit method.

In the following section the strain and stress increments are computed according to the three schemes individually.

In this program the load is applied in discrete increments. An increment of load is applied and the time stepping process is followed until either steady state conditions are achieved, or a specified number of time steps is reached. Then a further increment is applied and the process repeated for all load increments.

4. APPLICATION OF THE DEVELOPED PROGRAM ON ELFAO SITE

This field experiment had been carried out at a location near Elfao town the headquarters of Rahad Irrigation Scheme in Sudan (Osman, Elsharif and Elarabi 1989). This experiment was intended to observe ground heave and the movement of piles installed at different depths. These investigations were carried out during a rainy season and also following artificial irrigation of the site.

In this section the ground heave of the site at different depths is computed using the finite element program developed in this study. While all reported material properties were used in the analysis some additional ones had to be assumed, demanded by the material laws incorporated in the model. The mesh used for the analysis, the material parameters of the sample and the proposed boundary conditions are presented in Fig. 1.
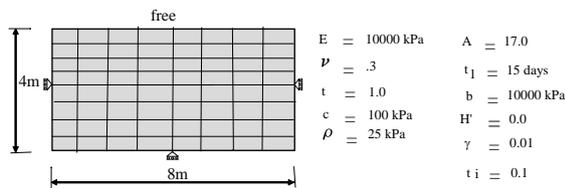
Figure 1: The considered problem for the verification and numerical analysis

5. MOISTURE DIFFUSION IN EXPANSIVE SOILS

The performance of expansive soils is depending greatly on the amount of water content in it. In the next two sections a comparison between the computed and the experimental heave due to wetting of the expansive soil is carried out followed by the performance of its contraction. The swelling of a soil is a reversible process, i.e. when a soil in a swollen state (or at natural moisture content) dries, it contracts.

4.1 Wetting Period

As the finite element program has the ability to compute the values of heave due to the increase of water content without taking into consideration the current stresses and vice versa, the results of heave due to increase in water content at constant value of current stresses are plotted in Fig. 2.

Fig. 3 shows the values of the heave of the ground at constant value of water content due to the change in the current stress i.e. the ground is fully saturated from the beginning of the heave process until its end.
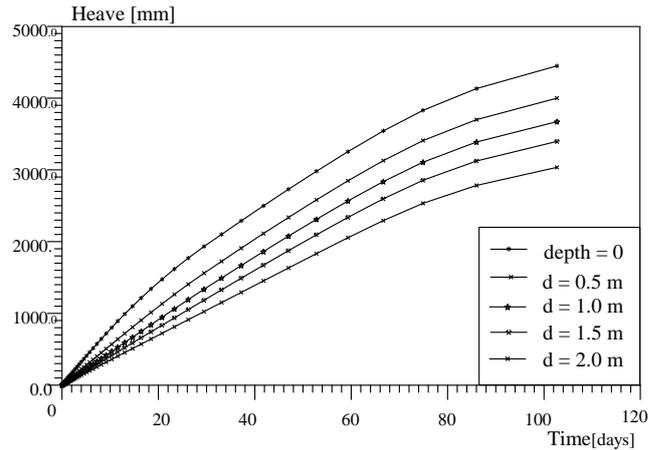
Figure 2: Heave versus time neglecting the effect of current stress
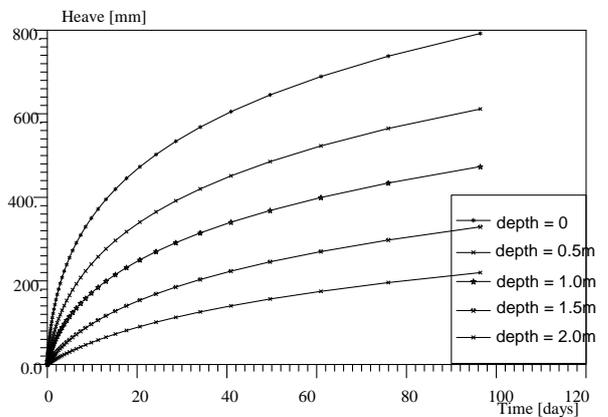
Figure 3: Heave versus time assuming the ground is fully saturated.

The general performance of the two Fig.s is acceptable compared with experience gained from the experimental results in literature (Osman, Elsharif and Elarabi 1989).

The ground heave of Elfao site and its relative time deduced from the experimental observations and the computed results obtained by the finite element program are plotted in Fig. 4.
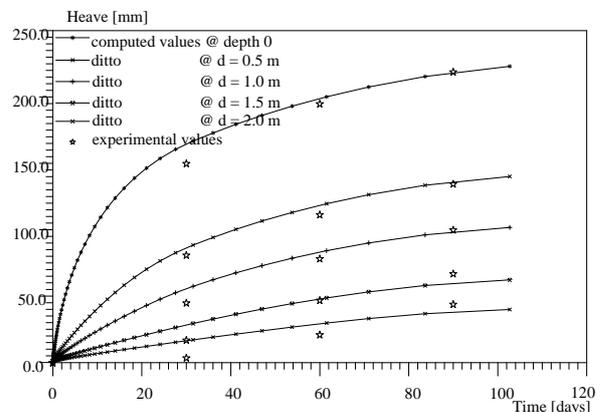
Figure 4: Theoretical and experimental results of heave against time in Elfao site.

It can be seen that the parameters chosen for the site adequately represent the observations obtained by the experiment. The values of the elastic heave at the ground level are greater than that obtained for the lower layers, in other words: The rate of heave for the upper layer is greater than that for the lower layers. This phenomenon is due to the overburden soil. The computed results represented in Fig. 4 seem to be in good agreement with the observations obtained in Elfao site. Fig. 4 represents the values of heave at Elfao site in different level of depths and at the corresponding current time.

When an expansive soil is wetted, deformations occur both vertically and horizontally. When such a soil is tested in a double shear ring apparatus where there are no horizontal deformations, a lateral pressure develops which acts on the walls of the ring. Hence in the case of supporting constructions (foundations, retaining walls, tunnels etc.) built on expansive soils, additional pressures develop due to swelling of the soil when it is wetted. Fig. 5 shows the values of the horizontal stresses in time. The curves show that the stress is depending on the heave of the ground. Great values of stress are recorded for the ground surface. Also the values of water content and densities of soil greatly affect the computed stress. The values of the vertical stress are found equal to the gravity stress of soil.

Figure 5: Horizontal stress versus Time at Elfao site
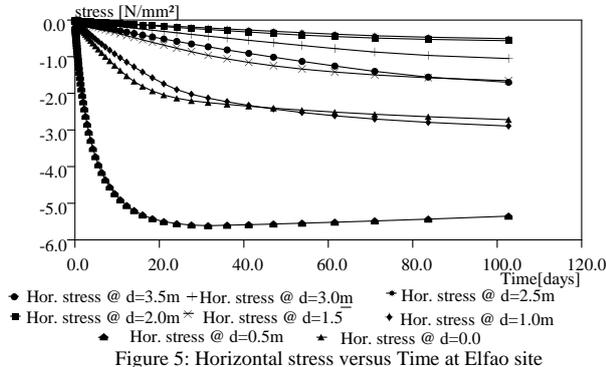
4.2 Drying Period

The soil surface is subjected to diurnal, annual and perennial temperature fluctuations. The temperature varies not only at the surface, but also along the depth of the soil mass where it fluctuates. In the absence of a thermal balance, a temperature gradient sets up giving rise to migration of moisture. Vegetation is another powerful source of moisture depletion from the soil. It has a significant influence on the changing nature of moisture content in the soil mass.

In addition to these factors the annual fluctuations in moisture content in the upper layer of the soil depend upon evaporation and wetting due to atmospheric precipitation which is related to the precipitation balance.

To see the performance of the soil in dryness process, the computation of the heave and stress is continued after the assumed time of wetting period. The results from the finite element program for the heave in wetting and drying time is presented in Fig. 6. The values of the heave of soil reduce after reaching a peak value. The reductions of the values of heave are different from layer to layer depending on the rate of loss of water. Firstly, the surface layer reaches the original level, after that follow the other layers corresponding to their depths.
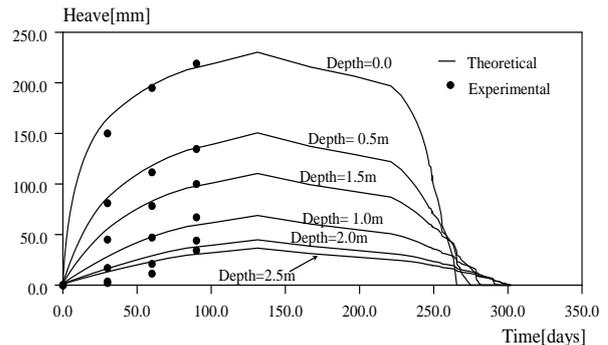
Figure 6: Theoretical and Experimental values of Ground Heave at Elfao Site.

It is obvious that processes leading to changes in moisture content and temperature continuously occur in the soil at foundations of structures. These variations are highly non-uniform both in time and space. Thus, in a layer at the surface of the soil the moisture content is observed to be smaller compared to that in layers which are located at depth. The moisture content of the upper layer does not remain constant but varies with time. This leads to violation of the equilibrium conditions which results in the emergence of various forces which cause migration of moisture. In other words, the moisture cycle continuously changes until an equilibrium state conforming to the physico-chemical properties of the soil and external conditions is established. The only way to reach this equilibrium state is the constancy of the external factors, which is almost impossible. As a consequence of that because of the unsteady nature of the moisture cycle in the soil mass, its properties vary with time. In certain cases this affects the task of building construction since an increase in the moisture content of expansive soils leads to an increase in their volume which may cause damages to structures.

6. CONCLUSIONS

A new model for unsaturated soil is proposed. The model is able to simulate both swelling and shrinkage phenomena.

Considering successive wetting drying processes, the values of the heave of soil reduce

after reaching a peak value. The reductions of the values of heave are different from layer to layer depending on the rate of loss of water. Surface layer reaches the original level before the beneath layers.

With the help of a finite element program, an understanding of stress distributions and ground movements, and its variation with time can be obtained. Furthermore, a prediction of future heave values can be made if the material properties of the considered expansive soil area and watering procedure are given. According to the numerical results reported in this paper, the visco-plastic solution procedure is capable of giving useful information for the design of foundations erected in expansive clay soils.

7. REFERENCES

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