A new approach for the prediction of long term heave

Une nouvelle approche pour la prédiction des soulèvements à long terme

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SYNOPSIS: An examination of long term laboratory heave tests and field records suggests that two different swelling mechanisms take place simultaneously.The first "primary" mechanism has been associated with nonstationary flow within the open pores of the soil structure. The second mechanism is believed to be the responsible for long term behaviour and it is the result of hydration of active clay minerals. A model accounting for these basic features has been developed. Present understanding of soil microstructure has provided a convenient framework to the theoretical formulation of the model. The model has been applied to reproduce long term oedometer tests on a swelling marl. The derived parameters were then used to predict a 10 yr ground heave record of a power station founded on the expansive marl

1 INTRODUCTION

An examination of long term laboratory swelling tests of expansive soils reveals that it is usually possible to identify two distinct phases in the curves relating deformation with time.Quite often, a slow "secondary" stage follows a relatively fast swelling period which takes place immediately after the soil is wetted. A pattern of this type may be observed in Fig. 1 (Mazurik and Komornik ,1973). It shows the results of an oedometer swelling test of an expansive clay under constant vertical stress. Similar trends may be found in experimental data reported by Mustafayev and Chigniev (1980), Haynes and Mason (1965), Livneh, Alpan and Leonov (1973) and Chen (1984). Recently performed oedometer swelling tests on an expansive marl (Bechtel, 1988) indicate a similar pattern (Fig. 4).

Some long term field records, in which the direct influence of seasonal effects is avoided, also suggest two distinct swelling mechanisms (De Bruijn,1973, Johnson,1980 and Didier et al, 1984) .

A "simple" theoretical model only based on diffusion or flow concepts does not provide a satisfactory framework for long term effects as outlined above. It is believed that the secondary swelling phase may be explained by the progressive hydration of active clay minerals within the soil. On the other hand, the first and relatively rapid swelling period,is more likely the result of total or partial release of water stresses in the partially saturated voids of the soil.

According to this interpretation, the first process will be associated with the flow of water in a Darcy sense. As a consequence, permeability and the gradients of water head will primarily control the first swelling stage. The second process implies the hydration of clay minerals and salts which absorb the available water from neighboring pores. The observed rate of secondary swelling will therefore be closely linked with hydration phenomena. This qualitative description of the swelling process is necessarily simplified since both mechanisms will certainly take place simultaneously and therefore they will interact with each other.

This paper describes a model which incorporates the preceding ideas in a fairly general framework , in order to solve simultaneously flow and hydration processes as well as the mechanical stress-strain problem which may arise, specially in two and three dimensional situations. Relevant features of soil microstructure, discussed later,have provided the conceptual basis for the model. It will be used to approximate the swelling-time curves measured in a long term oedometer test (Fig. 4). In this way model parameters will be obtained. The model will finally be used to predict the long term heave of a foundation sitting on expansive marl.

2 CONCEPTUAL FRAMEWORK

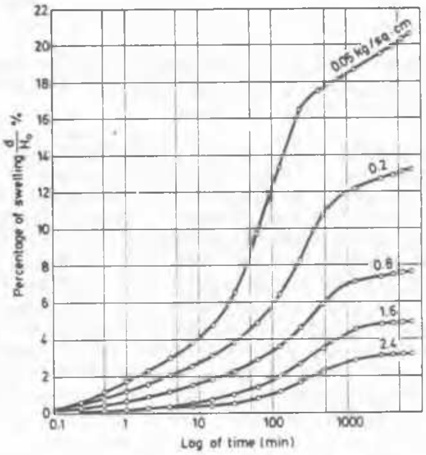

Figure 1. Percentage of swelling vs. time under various constant loads (after Mazurik and Komornik, 1973).

Visual observations of soil microfabric through the SEM show that soil particles of compacted and natural expansive clays tend to aggregate in packets or "crumbs" (Alonso, Gens and Hight, 1987). These units behave as particles as large as silt or sand grains. In a partially saturated soil, capillary water will partially fill the open and relatively larger pores and it will be subjected to a negative pressure or suction. This water is able to move rather freely through the network of conduits associated with the interaggregate porosity.

Pore sizes within the aggregates are considerably smaller. Given the size of these intraaggregate pores and the afinity for water of the clay particles surface, the aggregates will probably remain saturated. Water will reach internal equilibrium when the capillary suction of the water partially filling the open pores equals the potential for hydration of the particles inside the aggregates. Note that according to this description, the pore water may either flow along the interconnected open pores or migrate towards (or from) the saturated aggregates of clay particles. The first motion is induced by gradients of capillary suction whereas the second is a response to differences between capillary suction and water potential associated with active clay particles. Both motions change the distribution of water potentials inside the soil and induce volume changes.

In order to translate these ideas into a workable model, two levels of soil structure, mutually interacting , have been defined as follows:
1. Macrostructural level. It refers to the interconnected open pores in

which water flows due to gradients of capillary suction (and ,eventually, gradients of positive head). In the remaining, the capillary suction associated with the open pores, (p_a-p_w), will be called macrostructural suction. These open pores will be bounded by packets of active clay particles as well as silt and sand grains. Changes in macrostructural suction will modify locally the structural equilibrium and this may result in deformations. It is important to realize that the macrostructural level reacts instantaneously to changes in suction. Time effects are only a consequence of nonstationary flow and changing boundary conditions.

The flow of liquid water and air within the macrostructural pores will be governed by a generalized Darcy's law where the coefficients of permeability will vary strongly with the degree of saturation.

If volumetric deformations are of primary concern, two "state" variables are required to describe the macrostructural level: the porosity, n (defined as the ratio between the volume of open pores and the total soil volume) and the macrostructural degree of saturation, S_r (defined as the ratio of volume of water partially filling the open voids and its total volume). This definition implies that the water hydrating active clay minerals does not contribute to S_r.

The state variables S_r and n are related, in general, to stress level and to the macrostructural suction. The following expression,proposed by Lloret and Alonso (1985) for partially saturated soils ranging from clayey sand to high plasticity clay has been adopted as a state function for the degree of saturation:

$$S_r = 1 - [b' + d'(\sigma - p_a)]\left[1 - e^{a'(p_a - p_w)}\right] \tag{1}$$

where a', b', d' are constants and σ the mean total stress. The state function for n (or, more precisely, the macrostructural volumetric deformation) will be discussed later.

2. Microstructural level. Active clay minerals, often aggregated in large units, are considered at this level. A water content at microstructural level, w, is defined as the amount of water which has been transferred to the expansive clay minerals during the hydration process. Accordingly, the state variable w is defined as the ratio of the volume of water in the microstructural level and the total weight of the soil. Water migrates from the macrostructural level to hydrate the microstructure in a process which will contribute to the total amount of swelling. w will be a function of the hydration potential of the microstructure. This potential has also been named microstructural suction, s_m. The rate of transfer of water from the pores to the microstructure will be related to the relative values of (p_a - p_w) and s_m. As a first approximation the linear relationship,

$$Q = \alpha\,[s_m - (p_a - p_w)] \tag{2}$$

where α is a constant, has been used in this work. Q is the increment of volume of microstructural water for unit time and total unit volume of the soil. Therefore,

$$Q = \frac{\partial w}{\partial t} \tag{3}$$

A state function predicting a logarithmic relationship between w and s_m is also proposed as a suitable dependence:

$$w = w_0 - B_w\, log(\sigma - p_a)\; - \;D_w\, log(p_{at} + s_m) \tag{4}$$

where w_0, B_w and D_w are material parameters and p_{at} the atmospheric pressure. It should be expected that D_w will vary with total stress in the sense that increasing confining stress will progressively prevent the hydration of the clay minerals and salts. In the present formulation the following expression has been used for D_w:

$$D_w = D_{w0} - C_w\, log(\sigma - p_a) \tag{5}$$

where σ - p_a is the excess of total mean stress over air pressure and D_{wo} and C_w are constants.

Volumetric deformations originated at the microstructural suction will be dealt with later.

The formulation given so far uses a particular type of soil structure to get a physical support to the proposed conceptual framework. It is believed, however, that the model may be a general tool to describe the delayed swelling response of expansive soils and rocks irrespective of the type of microstructure.

3 PROBLEM FORMULATION

The foregoing discussion implies that the volumetric deformation of the soil, $d\varepsilon_0$, may be split into two components:

$$\boldsymbol{d\varepsilon_0 = d\varepsilon_{macro} + d\varepsilon_{micro}} \tag{6}$$

Previous work on volume change characterization of partially saturated soils (Lloret et al,1987; Alonso et al,1988) allows to relate the volumetric deformation of the soil macrostructure to changes in soil suction, as follows:

$$\varepsilon_{v_{macro}} = -b_e\, log\,[(p_a - p_w) + p_{at}] \tag{7}$$

where b_e depends on confining stress. An equation similar to (5) was also found convenient in this case:

$$b_e = b_0 - c_e\, log(\sigma - p_a) \tag{8}$$

Regarding $d\varepsilon_{micro}$, it is thought that it will be related to the change in microstructural water content. A simple expression for this relationship is

$$d\varepsilon_{micro} = \alpha_v\, dw\, \boldsymbol{m} \tag{9}$$

where $\mathbf{m}^t$ = [1, 1, 1, 0, 0, 0] and α_v is a parameter no smaller than 1 since the hydration process may induce the development of secondary pores whose volume is not accounted solely by the volume of water necessary to hydrate the active clay particles. In this regard, it is significant the experimental observation of Mustafayev and Chigniev (1980) in the sense that the swelling volumetric response of soils exceeds the volume of water absorbed by the soil.

In a general three dimensional problem, the volumetric deformations given by equations (7)-(9) play the role of an internal "autogenous" strain induced by changes in suction. These volumetric strains should be added to the stress-induced strains to obtain the total soil deformation:

$$\boldsymbol{d\varepsilon = D^{-1}\ d\sigma^* + d\varepsilon_0} \tag{10}$$

where $d\sigma^*$ is the vector of total stress over air pressure and **D** a global stiffness matrix characterizing the stress-strain response of the soil. The process of soil deformation may be viewed as follows: A local change of pore water pressure within the soil (as a consequence of the established flow) will modify the macrostructural suction and will also modify the rate of hydration of expansive minerals . Both phenomena lead to local volumetric expansion which will be prevented (in part) by the soil stiffness and the boundary conditions. As a consequence, the soil will experience stress changes and deformations. The deformation will modify the pore volume, which in turn, affects the flow regime.

In summary, the air and water flow phenomena at macrostructural level, the water content changes of the microstructure and the stress-strain response of the soil are coupled. Unknowns in this problem are: Air and water pressure, microstructural suction and soil displacements. In order to solve the problem it is necessary to require continuity of both air and water at macrostructural level; balancing the amount of water hydrating the microstructure and mechanical equilibrium. These equations are:

$$\frac{\partial}{\partial t}\,[\rho_a n(1 - S_r + HS_r)] + div\,[\rho_a(\boldsymbol{v}_a + H\boldsymbol{v}_w)] = 0 \tag{11a}$$

$$\frac{\partial(\rho_w\, nS_r)}{\partial t} + div(\rho_w\, \boldsymbol{v}_w) + Q\,\rho_w = 0 \tag{11b}$$

$$Q = \frac{\partial w}{\partial t} = \alpha \left[s_m - (p_a - p_w)\right] \qquad (11c)$$

$$\frac{\partial(\sigma_{ij} - \delta_{ij} p_a)}{\partial x_j} + \frac{\partial p_a}{\partial x_i} + b_i = 0 \qquad (11d)$$

where: b_i are body forces; γ_a and γ_w the air and water densities and H the Henry's constant. From a macrostructural point of view, Q is a local sink whose intensity is proportional to the net unbalance of the two suctions defined.

4 FEATURES OF PREDICTED BEHAVIOUR

In order to illustrate some significant features of the model it has been initially applied to reproduce an oedometer test in which a 10 mm thick sample was subjeted to an initial suction of 15 MPa (both macro and microstructural) and subsequently both suctions were reduced to zero in one of the surfaces of the sample whereas the opposite was maintained impervious to air and water transfer.

It was found that a dimensionless parameter, $\alpha H^2\gamma_w/K$, where K is the saturated permeability, controls the rate of swelling. This is illustrated in Fig. 2 where the total deformation of the sample as well as its two components (macro and micro) are plotted along time. It may be observed that the transfer rate of water to hydrate the microstructure, for a value of the dimensionless parameter $\alpha H^2\gamma_w/K$ equal to 100 is fast enough to allow the whole swelling process to be controlled by the soil permeability. On the other hand, a value of 0,0001 for the same parameter implies a slow hydration process. This leads to two distinct stages in the swelling-time curves. In the first stage (which lasts for a few days) the microstructural suction does not change (and therefore the hydration process is prevented) whereas the macrostructural suction tends to zero. The second stage starts once the first stage has almost ended and shows a progressive and slow decay of microstructural suction.

For values of the parameter $\alpha H^2\gamma_w/K$ intermediate between the two quoted values, both swelling mechanisms take place simultaneously. It can also be noted that the larger the value of α, the faster is the flow rate (or, alternatively, the deformation) within the macrostructure. This shows how the "sink effect" provided by the hydration phenomena may affect the rate of flow in the macrostructure. Both phenomena are therefore closely coupled.

Computed suction curves for two points within a sample subjected to wetting in a suction controlled oedometer test are plotted in Fig.3. The suction was reduced from the initial value of 15 MPa to zero. The upper boundary of the sample is maintained impervious to water and the air pressure was fixed. At the lower end the effect of a high air entry value membrane was simultated by means of a boundary impervious to air and imposing a water flow rate proportional to the current water pressure at the lower end of the sample. Fig.3 indicates that the reduction in macrostructural suction for a point close to the lower boundary is much faster than the variation computed at the upper boundary. However, the computed results indicate that, due to the low value of a considered in this example, the evolution of microstructural suction in both upper and lower points have a similar decaying rate. The value of the parameter $\alpha H^2\gamma_w/K$ adopted in this case (5,5) is not comparable with the value used in Fig.2 due to the retarding effect introduced by the membrane in the latter case.

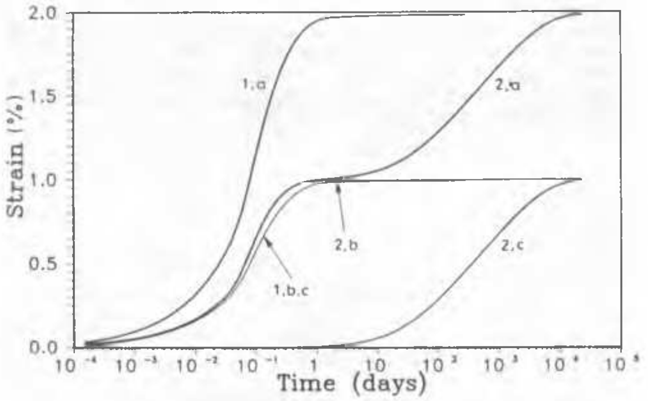

Figure 2. Model predictions for different values of $\alpha H^2\gamma_w/K$ (=100 (1);0.0001 (2)). The components of deformation are also indicated (a: total deformation;b: macrostructural deformation;c: microstructural deformation).

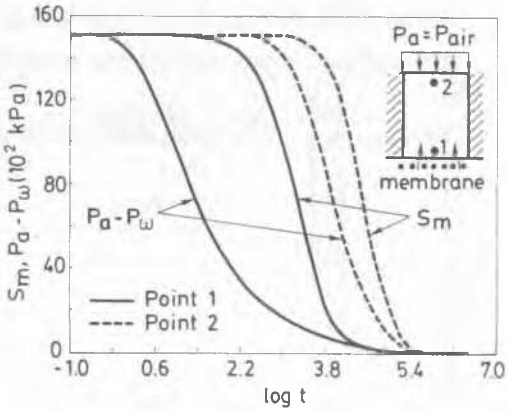

Figure 3. Suction dissipation for two points inside the sample.

Fig.4 shows a comparison between the variation of swelling strain with time in a sample of expansive marl subjected to a reduction in suction under oedometric conditions and the computed values. The agreement was obtained by varying, in the numerical model, the parameters α, K and the relative values of the two components (macro and micro) of the long term swelling deformation.

A parallel application of the model involved the prediction of foundation heave of a Power Station sitting on expansive marl. The large excavation which preceded the construction of the station is regarded as the main reason for the development of a network of fissures in the upper 10 -12 m of marl directly under the buildings foundations. Externally supplied water circulates through these fissures. In addition, the shape of the excavation allows the existence of a permanent ground water level close to the top of the marl. This water slowly percolates vertically from the surface and the water-filled fissures wetting the marl and inducig heave. Additional details concerning the marl properties, and the history of measured heave may be found in Serrano et al (1985).

Model parameters were derived from laboratory swelling tests interpreted with the aid of the proposed model. The dimensions of the Power Station foundations and the hydrological regime favour, as a reasonable approximation, a one-dimensional modelling of the problem. The numerical simulation was therefore applied to a column of rock, fissured in the upper part, the fissures being filled with water at hydrostatic pressure. Fig.5 shows the finite element

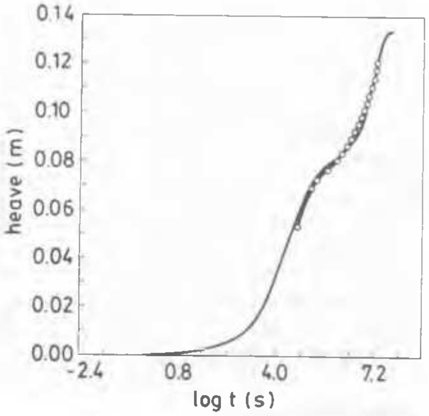

Figure 4. Measured and computed heave in an oedometer test.

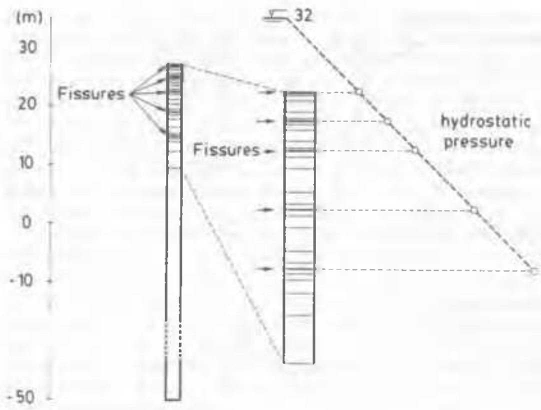

Figure 5. Finite element discretization of a column of fissured marl.

discretization adopted for this column.

A comparison between field measurements of heave in the last ten years, at a particular location of the foundation, and the model predictions is shown in Fig.6. The agreement is good and shows that the relevant field mechanisms inducing heave may be adequately represented by the model described in this paper.

5 CONCLUDING REMARKS

A two-level structure model to describe the heaving mechanisms which take place in expansive soils has been developed. Relevant features of soil microstructure, as revealed by microscope observations, have been useful to establish the conceptual basis for the model. A key characteristic of the model is the transfer of water from the open, connected pores of the soil (macrostructure) to hydrate active minerals (microstructure). The local volumetric deformations which originate at both levels (macro and micro) are added and considered as initial strains in a general framework for stress-strain analysis. In this way, coupled flow-deformation phenomena are conveniently modelled.

The equations, once discretized, have been used to interpret laboratory swelling tests under oedometer conditions. It has been found that the model reproduces the two swelling stages observed in the tests: a relatively fast "primary" swelling stage associated with the soil permeability and a second stage associated with the hydration of active clay minerals. This analysis may hopefully help to gain insight into some basic phenomena of soil swelling and the complex mechanisms involved.

The model was also applied to predict the heave history observed in the foundation of a Power Station sitting on expansive marls, using parameters derived from oedometer swelling tests of the marl. The agreement is considered satisfactory and reveals the capabilities of the model to predict long term swelling behaviour under field conditions.

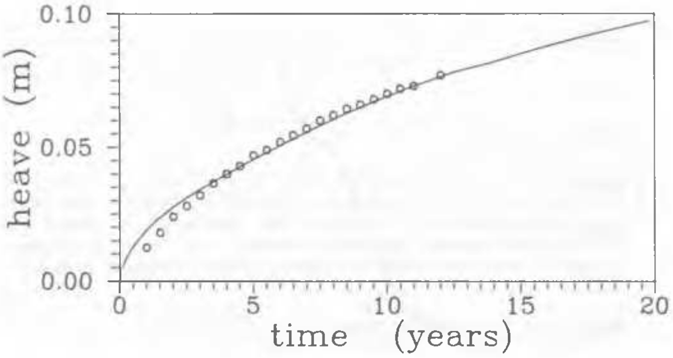

Figure 6. Comparison of model prediction and observed heave for a foundation on swelling marl.

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