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Numerical simulation of a cyclic pressuremeter test

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ABSTRACT : In this communication, a modelling of a cyclic pressuremeter test is presented, based on the use of a constitutive model using generalized elastoplasticity, and developped for the simulation of sand behaviour (Pastor et al., 1985). Through the introduction of an interpolation parameter γ , this type of model allows plastic strains to take place inside the "yield" surface, which is a very important feature to be taken into account in the case of cyclic loading. It is shown that, according to its value, the parameter γ allows to account for phenomena such as adaptation, accomodation or ratchet. This analysis constitutes a first step in the development of methods aimed at determining parameters characterizing the cyclic behaviour of sands, based on the results of an in-situ test like the pressuremeter.

1 INTRODUCTION

The pressuremeter test has the advantage, as compared to other in-situ tests, to provide, in the case of a monotonic expansion, a stress-strain relationship for the tested soil, which is very rich of information with respect to the mechanical behaviour of the material. Moreover, in the case of a cyclic sollicitation, the pressuremeter test should allow to gain valuable information on the cyclic behaviour of the soil, which is very important to be evaluated like for example in the case of earthquakes or wave loading during a storm, concerning in particular the accumulation of volumetric strains of excess pore pressures during the loading. The study presented below constitutes a first step in the development of methods aimed at evaluating parameters characterizing the cyclic behaviour of sands, based on an analysis of the results of an in-situ test like the pressuremeter. A modelling of a cyclic pressuremeter test is proposed, based on the use of a constitutive model using generalized elastoplasticity and developed for the simulation of sand behaviour (Pastor et al., 1985). The principal features of the model are first presented, followed by the modelling hypothesis taken for the pressuremeter sollicitation, by some elements on the numerical problem resolution, and a discussion of the first results obtained.

2 DESCRIPTION OF THE MODEL

The model used is the one proposed by Pastor et al. (1985). Within the frame of the generalized

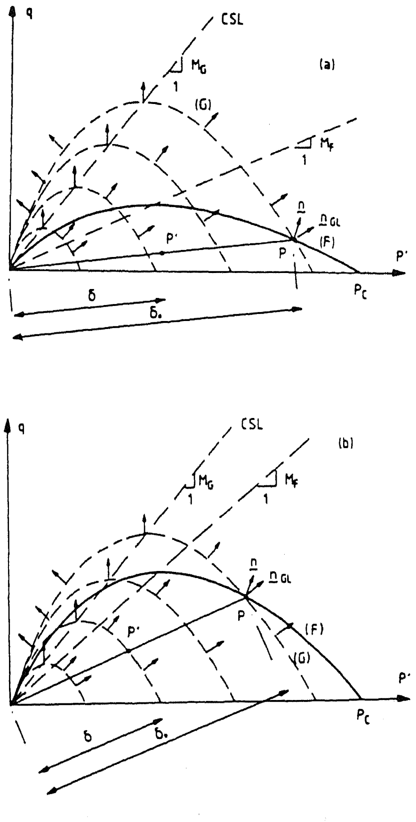

Figure 1 . Yield (boundary) surfaces and plastic potential surfaces: (a) loose sand; (b) medium/dense sand (after Pastor et al. 1985).

plasticity theory (Zienkiewicz and Mroz 1984), it takes into account irreversible deformations during cyclic loading-unloading and then can simulate cyclic phenomena such as accomodation, adaptation or ratchet.

The concept of bounding surface introduced by Dafalias and Popov (1975) and Dafalias and Herrmann (1982) allows for plastic strains development inside the "yield surface", which then becomes a "bounding surface". For states of stress located on the bounding surface, strain increments are determined based on classical elastoplasticity. For states of stress located inside the bounding surface, plastic strains are evaluated based on an interpolation rule. This rule, different from the one proposed by Dafalias and Herrmann (1982), introduces an additional parameter noted γ which controls the amount of irreversibilities inside the bounding surface.

In this context, two different models have been developped . The first one, applicable for the modelling of clays, has been proposed by Zienkiewicz et al. (1985). The first version is based on an associative flow rule with an elliptic bounding surface similar to the well-known 'Modified Cam-Clay' critical state model.

In order to represent characteristic features of sand behaviour such as dilatancy of medium/dense sands or liquefaction of loose sands, Pastor et al. (1985) have proposed a second version of the initial model by introducing a non-associative flow rule. The shape of yield surfaces and the direction of flow vectors for different stress states are represented in (q, p') plane (fig.1).

3 FORMULATION OF THE MODEL

As shown in fig. 1, for states of stress located on the yield surface (F), for example at point P, classical elastoplasticity allows to relate the incremental stress to the incremental strain tensors upon loading as follows :

$$\Delta\underline{\underline{\sigma}} = \left[\underset{\sim}{L}^{e} - \frac{(\underset{\sim}{L}^{e}:\underline{\underline{n}}_{Gl})\otimes(\underset{\sim}{L}^{e}:\underline{\underline{n}})}{H + \underline{\underline{n}}:\underset{\sim}{L}^{e}:\underline{\underline{n}}_{Gl}}\right] : \Delta\underline{\underline{\varepsilon}}$$

$$\text{with} \left[\begin{array}{l} F(\underline{\underline{\sigma}}, p_c) = 0 \\ \Delta\underline{\underline{\sigma}} : \underline{\underline{n}} \geq 0 \end{array} \right.$$

$\underset{\sim}{L}^{e}$ denotes the elastic tensor and p_C is the hardening parameter, which is a function of both volumetric and deviatoric plastic strains. The calculation of the plastic modulus H and of the elastoplastic tensor is detailed in the paper by Pastor et al. (1985).

Within the frame of the generalized plasticity theory, Pastor and co-authors propose an interesting formulation allowing to take into account plastic deformations upon unloading. This feature is also very important and should be considered with care when dealing with cyclic loading. This unloading part has not yet been taken into account in the present study, but will be the object of further development in our work. So far, the unloading phases of the cyclic sollicitation are supposed purely elastic. Upon loading and according to the bounding surface concept, the plastic strains at point P' (fig.1) are evaluated as follows:

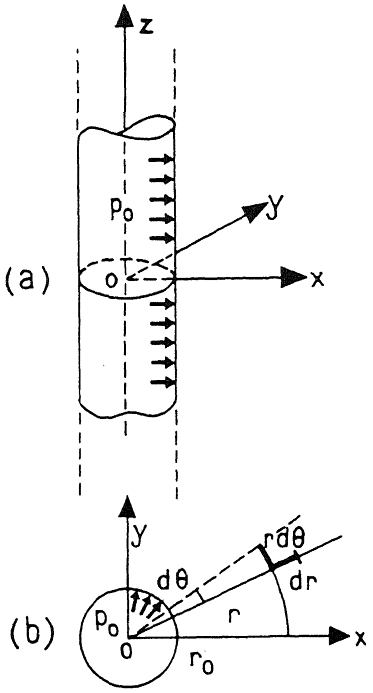

Figure 2 . Expansion of a cylindrical cavity (after Baguelin et al. 1978).

- determination of P, homothetic of P' located on the bounding surface, and defined by:

$$F(\underline{\underline{\sigma}}, p_C) = 0$$

$$\underline{\underline{\sigma}} = t.\underline{\underline{\sigma}}' \ , \quad t = \delta_0 / \delta$$

- evaluation of the plastic modulus H' at point P' based on the following interpolation rule:

$$H' = H \, . \, t^{\gamma}$$

where H is the plastic modulus at point P, and γ a new interpolation parameter, controlling the amplitude of plastic strains at point P'.

The flow direction vector $\underline{\underline{n}}'_{Gl}$ and stress direction increment vector $\underline{\underline{n}}'$ at P' are respectively equal to $\underline{\underline{n}}_{Gl}$ and $\underline{\underline{n}}$ at P (see fig.1).

The new elastoplastic tensor at point P' then becomes :

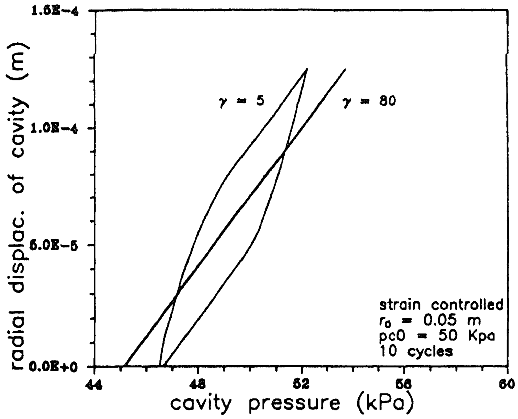

Figure 3 . Results of non-alternated simulations (strain controlled).

$$\Delta\underline{\underline{\sigma}}' = \left[\underset{\sim}{L}^{e} - \frac{(\underset{\sim}{L}^{e}:\underline{\underline{n}}_{G1})\otimes(\underset{\sim}{L}^{e}:\underline{\underline{n}})}{H.t^{\gamma} + \underline{\underline{n}}:\underset{\sim}{L}^{e}:\underline{\underline{n}}_{G1}} \right] : \Delta\underline{\underline{\varepsilon}}'$$

$$\text{with} \left[\begin{array}{l} F(t.\underline{\underline{\sigma}}', p_c) = 0 \\ \Delta\underline{\underline{\sigma}}' : \underline{\underline{n}} \geq 0 \end{array} \right.$$

4 MODELLING OF THE PRESSUREMETER LOADING

The constitutive model described above has been implemented in a finite difference code allowing to simulate the cyclic pressuremeter sollicitation. It is assumed that this sollicitation may be approximated by the expansion of an infinitly long cylindrical cavity, allowing to study the problem under plane strains condition (see figure 2). The approximation of small strains and small displacements is also considered valid. Dynamic terms are neglected in the equations, and quasi-static states equilibriums only are considered. Therefore, the equilibrium equation to be satisfied by a soil element around the cavity, written in polar coordinates, is given by:

$$\frac{\partial\sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} = 0$$

Boundary conditions at the cavity wall may be given either in term of stresses or strains so that stress or strain-controlled cyclic cavity expansion tests may be simulated. The results presented below are only concerned with drained behaviour of sand (no excess pore water pressure generation), but the computer code developped may also account for a coupling between the soil skeleton and water , and thus account for a generation of excess pore water pressure, function of the soil permeability. This last feature is particularly important in the case of fine soils for which both excess pore water pressure generation and dissipation occur upon loading.

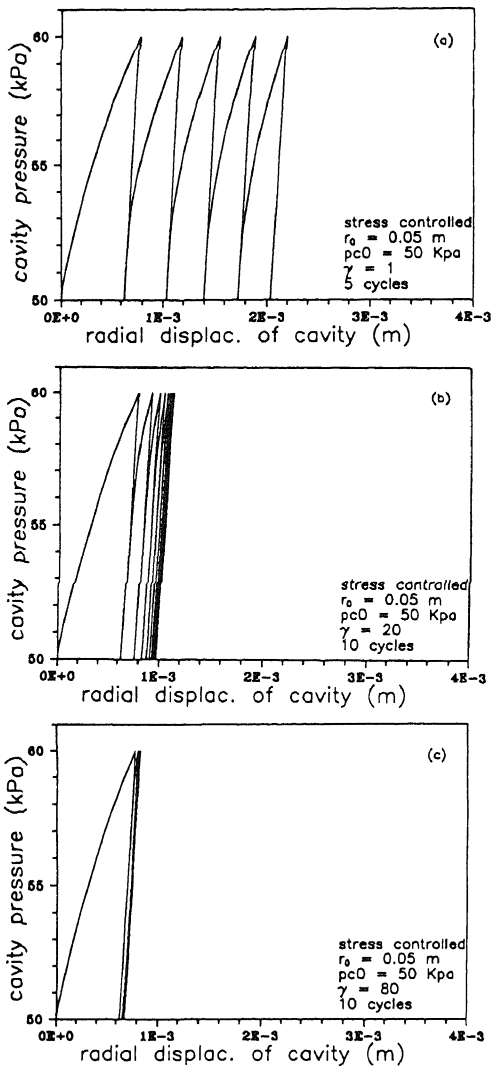

Figure 4 . Results of non-alternated simulations (stress controlled) : (a) γ=1; (b) γ=20; (c) γ=80.

5 PRESENTATION OF THE RESULTS

The first numerical simulations obtained with the model described above are presented in the following. Both non-alternated and alternated (compression and "extension") cycles have been simulated, leading to slightly different observations. These first results allow to show the interest of the interpolation parameter γ to simulate a certain amount of irreversibility in

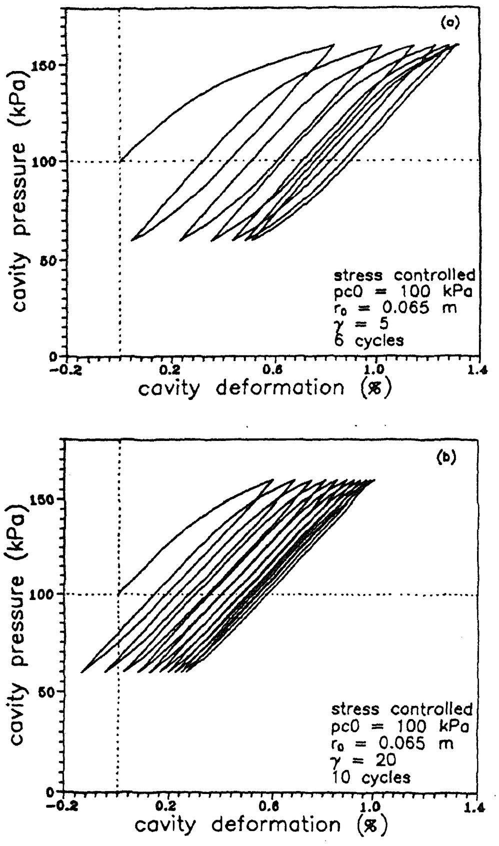

Figure 5 . Results of alternated simulations (stress controlled) : (a) γ=5; (b) γ=20.

the material during the cyclic sollicitation (accumulation of irreversible strains).

5.1 Non-alternated cycles

Both strain-controlled and stress-controlled tests have been simulated for non-alternated cycles. Figure 3 presents two strain-controlled simulations obtained for a given set of data, and different values of γ only. The tenth cycle only (stabilized cycle) has been represented for each simulation. For a value of γ equal to 80, a very rapid stabilization of the cycle (after two cycles) is obtained on an elastic path, representing the perfect adaptation of the material. For a value of γ equal to 5, the stabilization of the pressure-volume cycle on a closed loop is more progressive (after 10 cycles), and the behaviour observed is accomodation, accounting for energy dissipation on each cycle. Therefore, according to its value, the parameter γ allows to quantify a certain amount of irreversibility in the material, and to continuously go from adaptation (high values of γ) to accomodation and ratchet (low values of γ).

Figure 4 (a,b and c) presents the results of stress-controlled simulations (between 50 and 60 kPa of cavity pressure), obtained for three values of γ (80,20 and 1), the other parameters used in the simulation being held constant for the three cases. It is interesting to note that, like for strain-controlled simulations, the parameter γ allows, according to its value, to continuously go from adaptation for high values

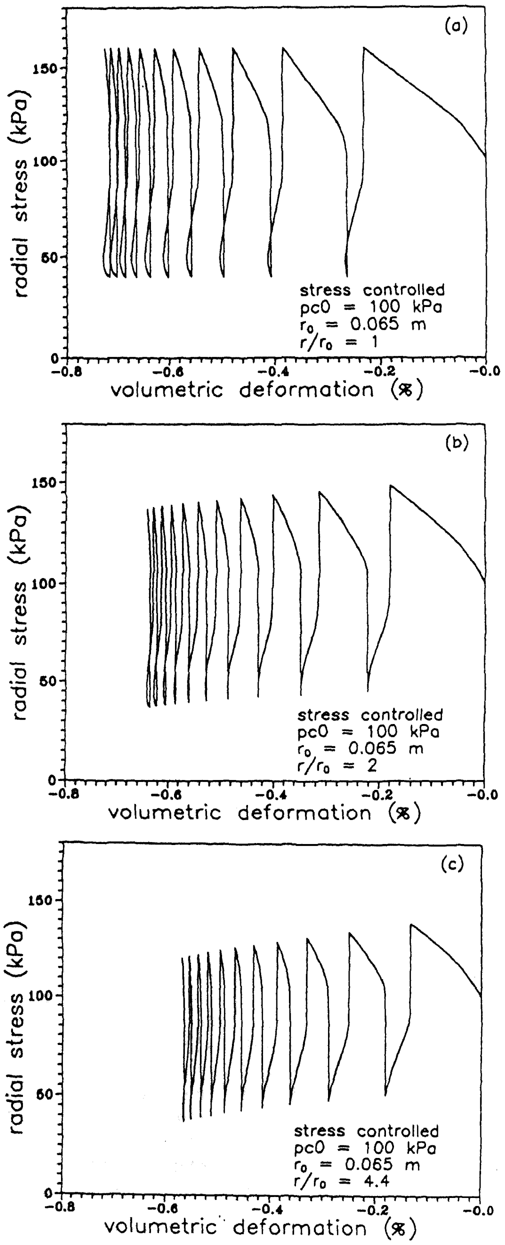

Figure 6 . Evolution of volumetric deformation at different distances r of the vertical axis of the cavity : (a) r/r_0 = 1; (b) r/r_0 = 2; (c) r/r_0 = 4.4.

of γ, to accomodation and ratchet for low values of γ with accumulation of plastic strains.

5.2 Alternated cycles

Figure 5 (a and b) presents results of simulations of stress-controlled cyclic expansion test, in which the cavity pressure is alternatively increasing and decreasing with respect to the initial p_{c0} value (alternated cycles). The cycles presented are not symetrical with respect to p_{c0} ($\Delta\sigma_r$ = +60 kPa and -40kPa). This type of sollicitation, with "extension" phases is more representative of the actual behaviour of a soil under a seism or wave action than the non-alternated cycles. It is interesting to note that, like for the non-alternated cycles, γ allows, according to its value, to generate different levels of plastic strains, and therefore it is well representative of the accumulation of irreversibilities during the loading.

Concerning the volumetric aspect of soil behaviour during the sollicitation, figure 6 (a, b and c) shows the evolution of the volumetric strain for three points located within the soil mass around the cavity : one at the cavity wall (radius r_0), one at radius $r \doteq 2 \times r_0$, one at radius $r = 4{,}4 \times r_0$. It is interesting to note that globally, the sand is contractant over the whole range of the sollicitation with a global accumulation of volumetric strains. The characteristic state ($\dot{\varepsilon}_v = 0$) is first reached in extension, and produces dilatancy loops which increase when the number of cycles increases. The dilatancy loops are well visible at the cavity wall where the strain level is the highest, and they progressively vanish with increasing distance from the cavity where the strain level is lower. It is very important to carefully study the volumetric behaviour of the sand during the sollicitation, because volumetric strains will be responsible, in the case of undrained behaviour, of liquefaction or no-liquefaction behaviour under a cyclic loading like an earthquake. The model used seems to qualitatively well represent the volumetric behaviour of sand under cyclic loading. Comparison with experimental data will be however necessary to further validate the model.

6 CONCLUSION

The application of a constitutive model of soil behaviour based on generalized elastoplasticity (Pastor et al., 1985) to the modelling of a cyclic pressuremeter sollicitation, has been presented in this communication. The interest of such type of modelling is to allow for plastic strains to occur in a realistic manner upon loading and unloading phases, which is a very important requirement in the case of cyclic loading. The results of simulations presented simply constitute a first qualitative evaluation of the model, and more work will be needed to further investigate the possibilities of the model. It will also be necessary to compare the simulations to exprimental results (hollow cylinder test, pressuremeter) which are presently being perfomed in the laboratory at CERMES. Qualitatively, the results presented show however the interest of the interpolation parameter γ, which, according to its value, allows to describe a given level of irreversibility inside the bounding surface related to a specific type of behaviour (adaptation, accomodation or ratchet). The resolution of an inverse type of problem, i.e. the identification, based on the result of a cyclic pressuremeter test, of the parameter γ, could be very interesting, in the way that γ is closely related to the type of cyclic behaviour of the material that could be predictable. Such a pressuremeter test, with low amplitude cyclic strains, should induce, during insertion of the probe, a minimum soil disturbance, and a self-boring type of test (Jezequel, 1973; Baguelin et al., 1978; Frank, 1984) could be considered.

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