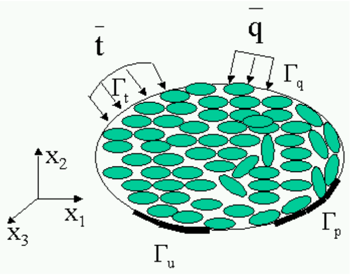
ANALYSIS OF SLOPE INSTABILITIES DUE TO RAIN, WITH Z_SOIL.PC

Introduction

Rain has usually a negative influence on the safety factor of slopes. Traditional approaches to the evaluation of the safety of slopes do not, however, provide an easy way to accurately assess this effect. The expansion of constructed areas to less stable sites also contributes to increasing the risk of rain-induced instabilities. In addition, the complexity of modern construction projects often requires taking into account the three-dimensional character of constructions, here too classical safety evaluations are inadequate. A unified three-dimensional finite-element approach to the safety evaluation of slopes under rain is presented next. The approach is implemented in Z_Soil.PC, a general purpose program for failure analysis of civil constructions[Z_SOIL.PC, 1985-2006].

Theory



Two-phase medium

The figure illustrates a partially saturated two-phase medium with displacement boundary conditions imposed on boundary Γu, total stresses on Γt, water pressures on Γp, water fluxes on Γq.

Governing equations

The balance equations of partially saturated two-phase media include equilibrium of the partially-saturated soil on the one-hand and fluid continuity on the other hand. They are coupled though the volumetric strain rate and the pore pressure. The equations follow essentially the formulation pioneered by Biot , with modifications suggested later by a number of authors:

$$\sigma'_{ij} + Sp\delta_{ij} + f_i = 0$$

$$S\dot{\varepsilon}_{kk} + v^F_{k,k} - c\dot{p} = 0$$

where σ' is the effective stress, S(p) the saturation ratio, p the pore pressure and f the body force, $\dot{\varepsilon}_{kk}$ the volumetric strain rate of the solid, v^F the Darcy velocity:

$$v_i^F = -k_{ij}\left(-\frac{p}{\gamma^F} + z\right)_{,j}$$

$k_{ij}(S)$ is the Darcy permeability

and c the storage coefficient :

$$c = \frac{nS}{K^F} - \frac{dS}{dp}$$

where n is the porosity, K^F the fluid bulk modulus; details can be found in [Z_SOIL.PC, 1985-2006].

The constitutive behavior of the soil is governed by rate-type elasto-plasticity which corresponds to an incremental constitutive equation of the following type:

$$\dot{\sigma}_{ij} = D^e_{ijkl}\left(\dot{\varepsilon}_{kl} - \dot{\varepsilon}^p_{kl}\right)$$

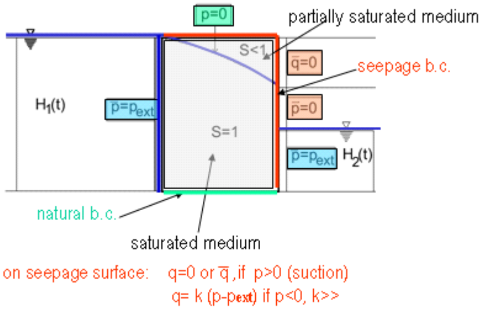
and yielding and plastic strain rate are governed by a plastic yield criterion like: Mohr-Coulomb, Cam-Clay, Cap, or ECP-Hujeux criterion e.g.

The fluid motion is governed by Darcy's law:

$$v_i^F = -k_{ij}\left(-\frac{p}{\gamma^F} + z\right)_{,j}$$

The flow problem is solved on the same mesh as the solid and the free surface is identified iteratively as the upper limit of the part of the domain which is fully saturated (S=1).

Flow boundary conditions require specification of pressure or fluid fluxes. A special treatment is required for seepage surfaces, as the intersection of the free surface of the flow with the boundary of the solid, which also corresponds to a change of type of boundary condition from imposed pressure, below the water table, to imposed flux, above the water table, is one of the unknowns of the problem. This situation is illustrated on the next figure.



Flow boundary conditions

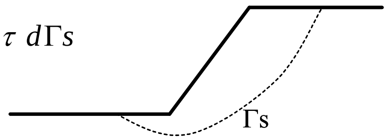
Rain

Rain corresponds to an inflow boundary condition on exposed surfaces. Saturation will progressively increase near these surfaces and the water table will rise, leading ultimately to instability. Such a situation is illustrated in the example below.

Stability

Stability is evaluated through a safety factor SF. Classical methods guess the position of an assumed failure surface and evaluate the ratio of stabilizing and destabilizing shear forces on that surface. A typical definition for a Mohr-Coulomb criterion is :

$$SF = \frac{\int_{\Gamma s} \tau_y \, d\Gamma s}{\int_{\Gamma s} \tau \, d\Gamma s}$$



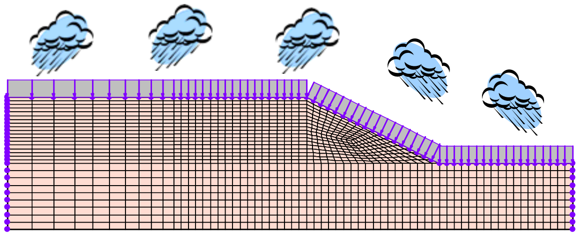
$$with\ \tau_y = C + \sigma_n \tan\phi$$

From the above equations, it is obvious that the safety factor can be identified as the maximum factor by which C, the cohesion and tanφ the friction angle can be divided before instability occurs; an algorithm in which SF is progressively increased until failure can therefore be designed. Notice that the failure surface will be identified automatically by strain localization and that no preliminary guess of the failure surface is needed. Similar safety factors can be designed for more advanced plastic criteria. Details of the formulation used are given in [Z_Soil, 1985-2006]

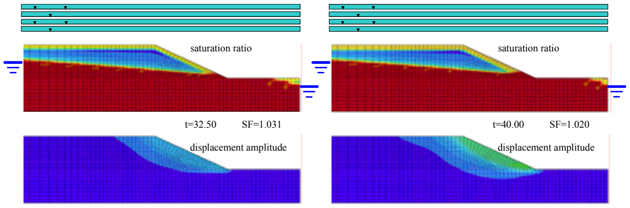
Application

A simple example

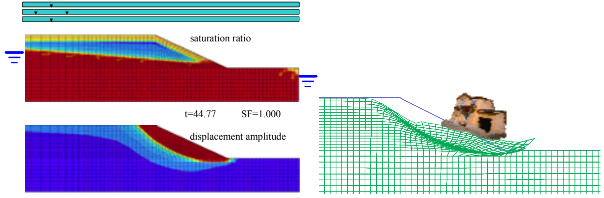
The first example which follows is academic, it illustrates the evolution of the safety factor of a slope under persistent rain. The rain inflow into the ground is specified, surface saturation increases and the water table rises while the safety factor progressively decreases intil a value of 1 is reached



Data



Saturation ration and displacement amplitude



Failure

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& J.-L.Sarf, BET J.-L.Sarf

References

Z_SOIL.PC 1985-2006. Th.Zimmermann, A.Truty, A.Urbanski, K.Podles. Z-Soil user manual, Zace Services Ltd, 1985-2006.