Collapse deformation. Some developments

Déformation d'effondrement. Quelques développements

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ABSTRACT: Low-grade rockfill materials suffer appreciable deformations when wetted. Laboratory tests permit a reasonable approach to the phenomena allowing material parameters to be obtained. This paper describes testing procedures that helped the modelling of the collapse. Schist samples from Beliche dam in southern Portugal where subjected to collapse tests and a good agreement was obtained using the proposed method.

RESUME: Les matériaux d'enrochement de qualité inférieure souffrent des déformations appréciables une fois mouillés. Les essais en laboratoire permettent une approche raisonnable aux phénomènes et permettant à des paramètres matériels d'être obtenus. Cet article décrit les méthodes d'essai qui ont aidé modeler l'effondrement. Les schistes du barrage de Beliche au Portugal où soumis aux essais de effondrement et une bonne concordance à eté obtenu avec la méthode proposée.

1 INTRODUCTION

Collapse deformations are characteristic to several fill materials and may cause important deformations in embankments. In the last years some effort has been done in both the characterization of the phenomena and its modeling. Among several materials, low grade rockfill is specially sensible to wetting. Some dams built in Portugal using this type of materials experienced important settlements due to rockfill collapse.

2 BACKGROUND

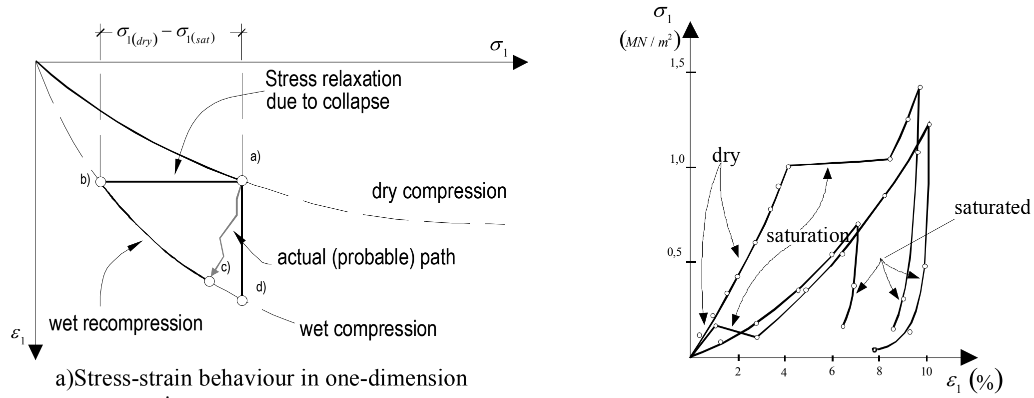
The algorithms of modeling and predictions of the effects of collapse are normally based on the comparison of the behavior between dry and saturated samples submitted to one-dimensional compression tests or to shear tests in triaxial compression.

It was first verified experimentally by Nobari and Duncan (1972), and latter confirmed by various authors (Veiga Pinto, 1985), that the deformation due to wetting is very similar to the difference between the deformations of test samples in the dry state and the saturated state at the same stress.

Figure 1 (a) shows the typical behavior of rockfill samples (dry and wet) submitted to one-dimensional compression. The addition of water to the sample at point a) provokes a sudden deformation which corresponds to a drop in stress to point b). If from this point the sample is re-compressed to a stress level similar to a) a higher deformation is obtained which is approximately the same as the deformation that would be obtained if the sample were initially tested in the saturated state.

If, on the other hand, a constant stress is maintained, the sample will deform until it reaches the curve corresponding to the saturated test, path a)-d). This path represents a maximum deformation for the applied stress level. In both cases, the final point reached is approximately the same. In an actual embankment the deformation will follow a slightly different path, as is shown in the diagram represented by a)-c). This behavior may be reproduced experimentally as in Figure 1 (b) (Maranha das Neves, et. al. 1988). Here a reasonable concordance is observed between the curves of the material in the dry state and the curves of the material in the saturated state.

With reference to numerical modeling, for example in the finite element method, it is necessary at some stage in the calculations to change the stress-strain relationship of the material from the dry state to the wet state and change the stress and strain accordingly.



a)Stress-strain behaviour in one-dimension compression tests

b)one-dimension compression tests of the Beliche Dam

Figure 1 - One-dimensional compression tests. a) theoretical, b)Beliche dam material

Nobari and Duncan (1972) proposed methods applicable to the FEM for both the oedometric and triaxial tests. These methods are very much tied to the hyperbolic stress-strain relationships very common at that time.

Naylor et al. (1989) generalized the method proposed by Nobari and Duncan to permit its application to any stress-strain law. As in the previous method, the determination of the relaxation stresses depends on the existence of two sets of parameters, characteristic of the dry and saturated materials. Consider the alternative presentation shown in Figure 2 and let {σ} represent the stress state of a point in the material in dry conditions. To attain this point it is supposed that a linear path from the origin is followed in the stress space. Assuming a division in increments, the corresponding strain path may be obtained by summing the increments of strain by:

$$\Delta\{\varepsilon\}_i = \left[D_{dry}\right]^{-1} \Delta\{\sigma\}_{i(dry)} \tag{1}$$

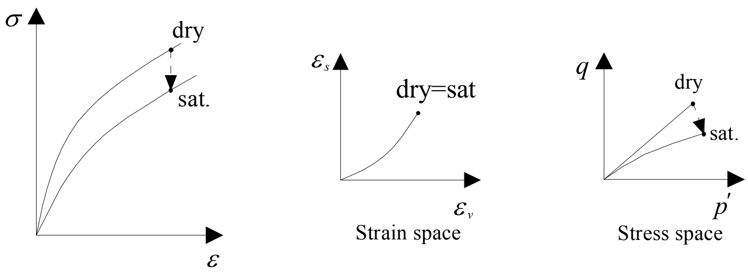


Figure 2 - Generalization of the algorithm of collapse (Naylor 1990)

Applying the same strain path to the material in the saturated state, the stress of the material is obtained on the assumption that the final state of deformation of the saturated state is the same as the dry state ($\{\varepsilon\}_{dry}=\{\varepsilon\}_{sat}$). This stress may then be determined as:

$$\{\sigma\}_{(sat)} = \sum_i \Delta\{\sigma\}_{i(sat)} = \sum_i \left[D_{sat}\right]\Delta\{\varepsilon\}_i \tag{2}$$

The final equilibrium stress state it attained applying the nodal forces equivalent to the difference of the wet and dry stress state. These forces are equivalent to the relaxation stresses:

$$\{F\} = \int_v [B]^T \left(\{\sigma\}_{dry} - \{\sigma\}_{sat}\right) dv \tag{3}$$

The algorithms for the modeling of collapse briefly described above are perfectly general and applicable to the description of other phenomena which involve an alteration of the behavior of materials. An initial state will always exist in which, to a given stress state and set of characteristics, may be associated a force field that balance the stresses. There exists afterwards a second set of mechanical characteristics and a process of transition from the first to the second. The transition is made, by changing the behavior and correcting the stresses by the simultaneous application of a force field to maintain equilibrium. A redistribution of stresses and a deformation equivalent to the collapse effect results from the alteration of the stress state and the corresponding nodal forces necessary to re-establish the balance. The method proposed by Nobari and Duncan is very closely associated with the test that is used for the characterization of the material and with the model of behavior, while the Naylor's method is independent of the model employed.

3 VISCOPLASTIC COLLAPSE ALGORITM - COLTRI

The viscoplastic nature of collapse deformation suggests an other possibility to model this phenomenon. In viscoplasticity it is possible that the stress state temporarily violates the yield surface, and if this happens a viscous flow is initiated which causes plastic deformation, Marcelino (1996).

The proposed method is based on similar considerations as the two previous algorithms (similarity of the stress-strain curves obtained in dry and saturated tests with the curve of the tests initially dry and saturated during the application of loads) but there is no explicit for the determination of the relaxation stresses. Instead, the characteristics of the material between the two states are gradually varied initiating a viscoplastic flow and the corresponding deformations. The method, named COLTRI, was applied successfully to the Cam-clay model as described below.

Supposing a sample of dry rockfill characterized by a set of Cam-clay parameters $(\kappa, \lambda, N, M, \Gamma)_d$ and another set for the wet material $(\kappa, \lambda, N, M, \Gamma)_w$, collapse deformation may be caused by a change from one set to another as shown in Figure 3.

The wetting will cause an evolution of the material characterized by the first group of parameters to a material characterized by the second. As the second group of parameters corresponds to a more deformable and less resistant material, the yield surface contracts and the state point becomes outside the yield surface, i.e. $F>0$ as is possible in visco-plasticity, and viscous flow commences. This situation is shown in Figure 3 where the current state is represented by a given point (p, q, v) in between the yield surface for the dry and wet material.

In this hypothesis the increments of viscous strain may be determined by the viscous flow rule. Perzyna´s expression (1963) is used in the determination of the increments of visco-plastic deformation and then we have:

$$\dot{\varepsilon}_{ij}^{vp} = \mu < \Phi(F) > \frac{\partial Q}{\partial \sigma_{ij}} \neq \{ 0 \} \tag{4}$$

This determines the plastic strain associated with the collapse settlement. A deformational flow is started with intensity ruled by the function $\Phi(F)$ taking the system in the direction of obtaining a stable situation in which $F<=0$, that is, inside or over the yield surface in wet conditions.

This situation may be attained not only by a change in (p,q,v) but also by a hardening of the material (now in a saturated state) and further by the combination of both affects.

4 TESTING

The laboratory tests allow a reasonable check of the collapse phenomenon in spite the possible lack of representative material by virtue of modeling (especially grading) necessary to recreate the field conditions in the limited space of the testing chambers. It is well known that one of the aspects that affect the collapse deformation is the stress level on the contact between the rockfill fragments.

Collapse tests are basically stress-deformation-resistance tests, i. e. they consist of the application of forces to the samples of rockfill material and in the measurement of the resultant deformations. Based on the measured values, the parameters which define the deformability, may be quantified, (e.g.

E, ν) and those which define resistance (e.g. c, ϕ) for the rockfill material. The tests are typically triaxial and oedometric compression tests but with equipment dimensions adequate to rockfill gradings.

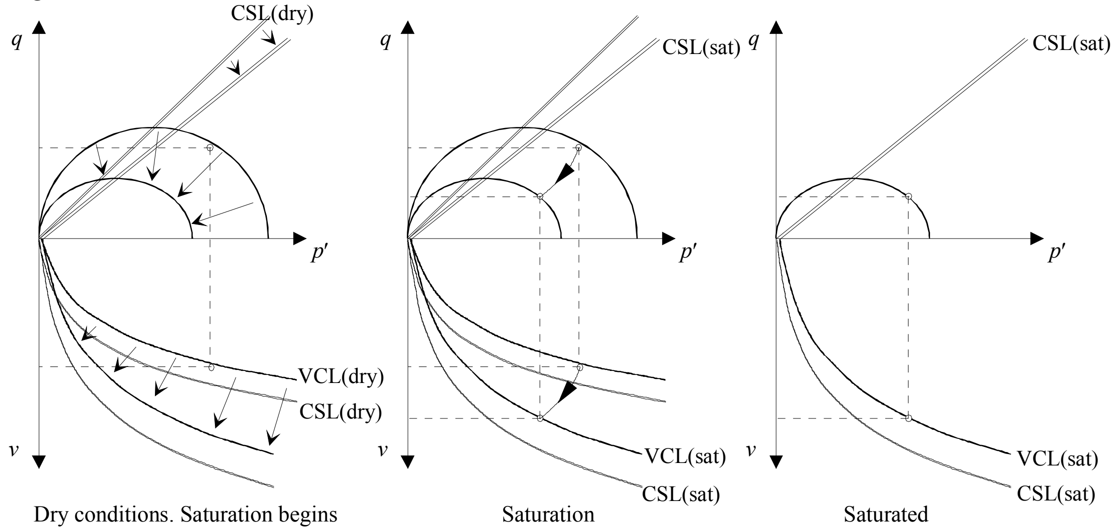


Figure 3 - Algorithm proposed to simulation of collapse

To validate the algorithm proposed for the modeling of the collapse various special triaxial tests were carried out. These were multiphase tests were the determination of the parameters in the dry and wet states was possible, and the detailed study of the behavior during the collapse was achieved.

These tests were carried out using the LNEC's rockfill triaxial equipment. Figure 4 shows a photograph of the equipment where the test chamber and of one the rockfill samples after being tested.

Figure 5 shows the determination of the parameters for a triaxial compression test.

The identification of the plastic deformations which occur in the application of deviator stress allows by application of the previous expression to determine the value of M.

Figure 4 – Triaxial test equipment and a rockfill sample

The collapse phase of the test sample proceeded with constant confinement stress and variable deviator stress corresponding to holding the loading ram steady during that phase. This stress eventually drop to zero due to the high axial deformation caused by the collapse. The (σ1−σ3)-ε1 and ε1−εv diagrams are shown in Figure 6. The deformation stabilized at the end of 22 hours, which is more than strictly necessary to complete the saturation. The parameters for the Cam-clay model are summarized in Table 1.

In order to evaluate the ability of the COLTRI algorithm to simulate the collapse phenomena a special test was made. This test was similar to the previous one but, during wetting, the deviator stress was kept (approximately) constant (Figure 7).

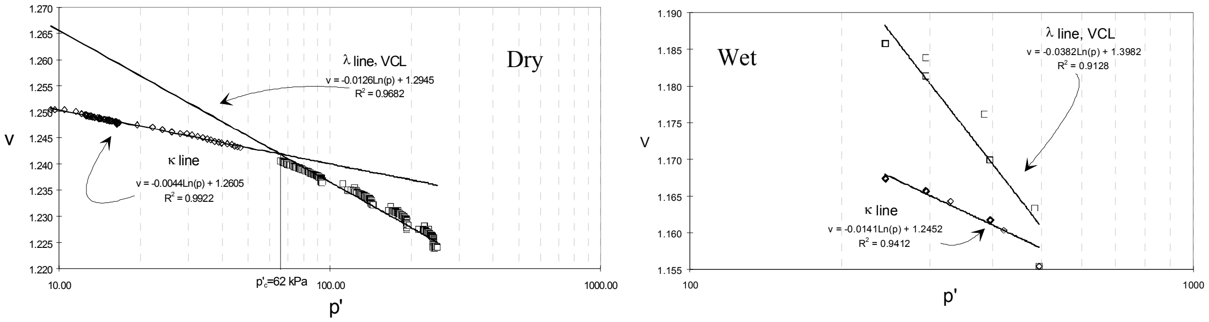


Figure 5- Determination of the parameters N, λ, k , dry and wet rockfill.

Table 1- Summary of the parameters of the Cam-clay model for schist rockfill - T1 test

Material	M	$\phi=\phi(M)$	K	λ	N	υ	pc
Dry rockfill	1.809	44	0.0044	0.0126	1.2945	0.3*	61.6
Wet rockfill	1.507	37	0.0141	0.0382	1.3982	0.3*	-

* - Estimated value

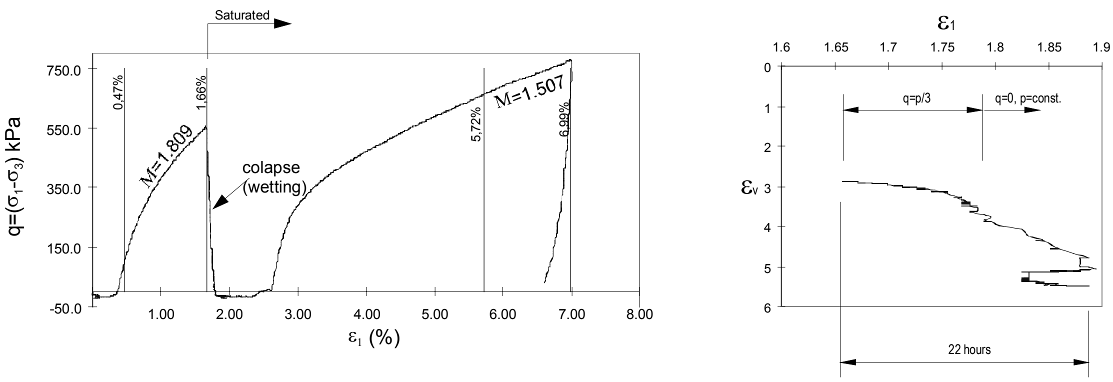


Figure 6 - Complete diagram of test and intervals for the determination of M.

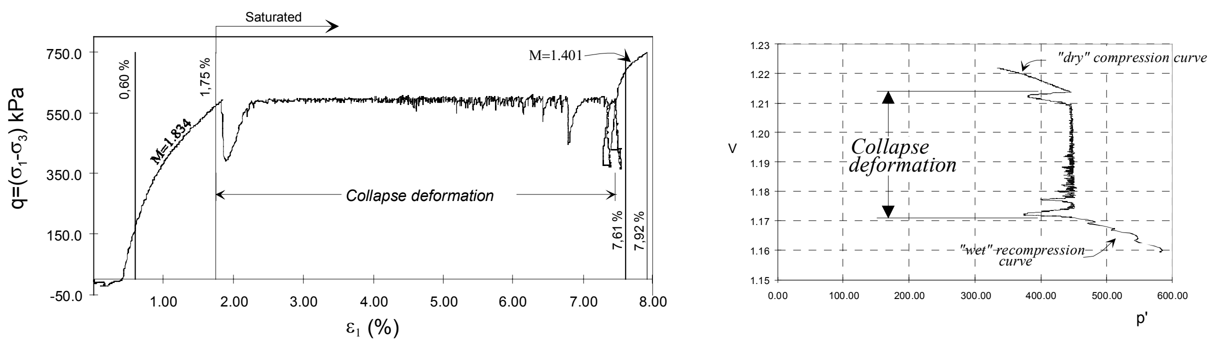


Figure 7 - Special collapse test

The simulation of this triaxial test is made following the COLTRI algorithm. The collapse corresponds to the change of the parameters between the two states which define the extreme behaviours of the material: $(M, N, \lambda, k, v)_{dry} \rightarrow (M, N, \lambda, k, v)_{saturated}$. The variation is arbitrarily made in 200 increments although in this case 10 increments would be sufficient without significantly altering the results. The comparison of the test and model results is summarized in Figure 8.

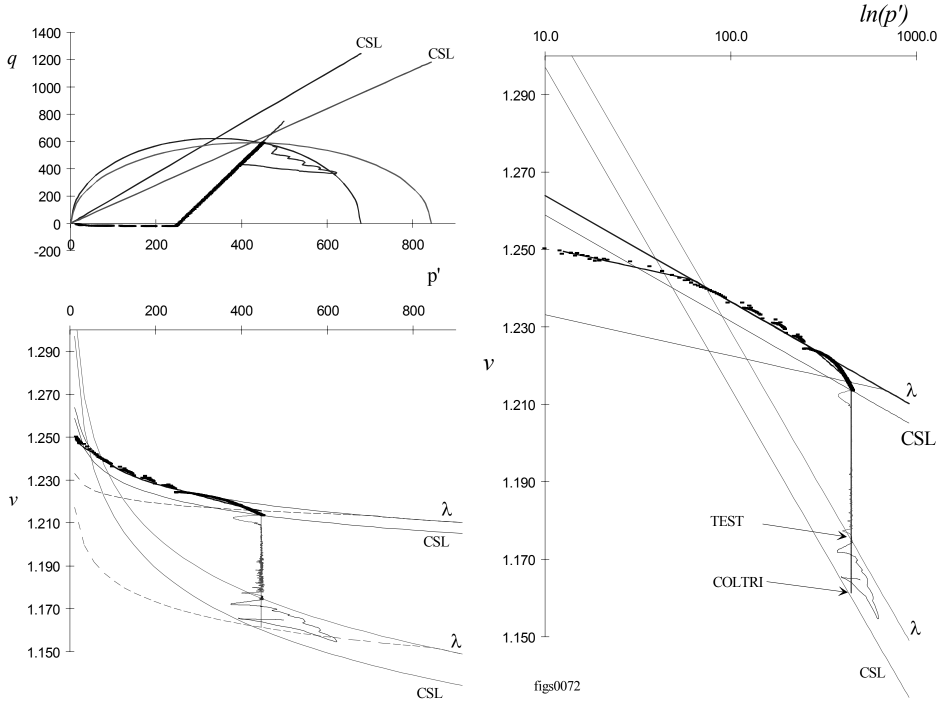


Figure 8 - Comparison of the test and model results

5 CONCLUSIONS

Collapse deformations characteristic of some materials, particularly of rockfill materials can be modeled using several approaches. The first rational treatment of the phenomena was proposed by Nobary and Ducan and latter another approach was proposed by Naylor.

The method presented in this paper was proposed by the author and is supported by a good agreement between laboratory tests and model results. In fact, this method was able to follow both the stress path and the stain path during the collapse deformation.

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