International Journal of Rock Mechanics & Mining Sciences 76 (2015) 33–43

Contents lists available at ScienceDirect

International Journal of
Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Three-dimensional numerical modeling of hydrostatic tests of porous rocks in a triaxial cell

Alexandre I. Chemenda*

Université de Nice Sophia-Antipolis, CNRS, Observatoire de la Côte d'Azur, Géoazur, 250 av Einstein, 06560 Valbonne, France

ARTICLE INFO

Article history:
Received 17 September 2014
Received in revised form
20 February 2015
Accepted 24 February 2015
Available online 17 March 2015

Keywords:
Rock mechanics
Hydrostatic test
Compaction
Constitutive model
Numerical modeling
Boundary effect

ABSTRACT

It is known that there is stress concentration at specimen ends during experimental rock tests. This causes a deviation of the measured nominal (average) stresses and strains from the actual ones, but it is not completely clear how strong it could be. We investigate this issue by numerical modeling of the hydrostatic tests using a reasonably simple constitutive model that reproduces the principal features of the behavior of porous rocks at high confining pressure, P_c. The model setup includes the stiff (steel) platens and the cylindrical model rock specimen separated from the platens by the frictional interfaces with friction angle ϕ_{int}. The whole model is subjected to the quasi-statically increasing normal stress P_c. During this process, the hydrostats $P_c(\varepsilon)$ are computed in the same way as in the real tests (ε is the average volume strain). The numerical hydrostats are very similar to the real ones and are practically insensitive to ϕ_{int}. On the contrary the stresses and strains within the specimen, are extremely sensitive to ϕ_{int}. They are very heterogeneous and are characterized by a strong (proportional to ϕ_{int}) along-axis gradient, which evolves with deformation. A strong deviation of the stress state at the specimen ends from the isotropic state results in inelastic deformation there at early loading stages. It follows that the nominal stresses and strains measured in the experimental tests can be very different from the actual ones, but they can be used to calibrate constitutive models via numerical simulations.

1. Introduction

Poor knowledge of the constitutive properties of geomaterials (or more generally, granular, frictional, and dilatant/compactive materials) is the principal obstacle to modeling their deformation and failure necessary for various applications. There is a very extensive literature from different communities (physics, plasticity, structural engineering, rock and soil mechanics) on the constitutive modeling of geomaterials within a purely phenomenological framework [1–7], or micromechanical models based on various approaches, hypotheses, and assumptions [8–17], to mention only a few papers. Despite all that, there are still open questions which make it difficult to formulate adequate and sufficiently simple models. This reflects the very complex and not completely understood nature of the deformation of geomaterials, which suggests that models cannot be simple and highlights the importance of the experimental studies for further progress.

Apart from the fact that experimental data are limited and are mostly from a single loading configuration tests (axisymmetric compression), it is not completely clear how far the nominal strains and stresses measured (calculated) in the experimental tests correspond to the actual strains and stresses within the tested specimens. Both nominal and real stresses and strains are respectively equal only when the specimen is strained strictly uniformly, i.e., before the onset of strain localization and if the boundary effects at the specimen ends are negligible. Several experimental, theoretical, and numerical studies show that these effects can be very significant [18–24]. The principal practical conclusion from these studies is that the interface friction between the specimen and loading platens must be considerably reduced to obtain meaningful mechanical measurements. An efficient way to achieve such a reduction is to lubricate the specimen–platen contacts using adapted lubricants (both for the tested rock and the loading conditions), but even in this case the end effects can be significant. They grow dramatically with increasing axial stress σ_{ax} indicative of the normal stress between the specimen and platens. For sandstone, for example, such an increase starts at $\sigma_{ax} \approx 60$ MPa [23,25].

To appreciate the impact of the end conditions on the stress-state within the specimen, Peng [18] and Brady [19,20] used purely elastic analysis, while Pellegrino et al. [23] and Albert and Rudnicki [24] carried out finite element modeling of the specimen compression with zero [23] and small confinement (corresponding to brittle deformation) [24]. In both cases, the numerical simulations were 2-D and used the Drucker–Prager constitutive model.

---

* Tel.: +33 4 83618661; fax: +33 4 83618610.
E-mail address: chem@geoazur.unice.fr

http://dx.doi.org/10.1016/j.ijrmms.2015.02.008
1365-1609/

In the present study we investigate high-pressure deformation conditions by simulating numerically the hydrostatic tests in three dimensions. This work has been motivated by numerous recent studies of deformation of porous rocks under high pressure investigating the compaction mechanisms and formation of the compaction bands. The hydrostatic loading configuration has been chosen as the simplest one in the sense that it does not lead to the mechanical instabilities and the associated difficulties of the numerical analysis. The modeling setup was designed to be as close to the real experimental conditions as possible. Not only specimens of porous rocks are simulated but also the steel loading platens contacting with the specimen through frictional interfaces. An original constitutive model with a single cap-type yield function $F(\overline{\tau}, \sigma_m, \overline{\gamma}^p)$ is introduced that meets the requirement of being as simple as possible but capturing at the same time the principal features of the behavior of porous rocks at high confining pressure P_c ($\overline{\tau}$ is the von Mises stress, $\overline{\gamma}^p$ is the accumulated inelastic equivalent shear strain, and σ_m is the mean stress). This model has been implemented into the finite-difference 3-D time-matching explicit dynamic code Flac3D. The hydrostats (plots $P_c(\varepsilon)$) obtained in the numerical models reproduce very well the corresponding experimental curves (ε is the volume strain average over the specimen). Surprisingly, they are practically insensitive to the specimen–platens interface friction angle ϕ_{int}, while stresses and strains within the model are, on the contrary, strongly dependent on this parameter. The results obtained clearly show that the 'global' (external) measurements of σ_m (which is supposed to correspond to P_c) and ε provide only the first order estimation of the stresses and strains within the specimens and can be very different from the actual values. This is particularly true at the specimen ends where the compactive inelastic deformation is initiated first and then propagates toward the specimen center, forming a sort of expanding compaction zones. It follows that ideally the laboratory measurements should be coupled with the numerical simulations to define the stress-state of the specimen. The global measurements can serve to validate and calibrate the constitutive model used.

2. Mechanical data from rock tests

The hydrostatic experimental tests are conducted in the same way as the conventional triaxial tests. The difference is that the isotropic loading of a jacketed cylindrical specimen with the steel platens (Fig. 1a) in the pressure cell is not followed by the additional axial loading. The confining pressure P_c is usually increased to large values to cause grain crushing. Basically two principal parameters are measured: P_c (the pressure of a liquid in the pressure cell), and the average over the whole specimen (nominal) volume strain ε. The latter is computed from the reduction of the specimen volume (equal to the water volume squeezed from the saturated specimen during the loading) or from the axial and radial displacements of points on the specimen surface measured with the LVDTs (or other) gauges.

The examples of the experimental hydrostats in Fig. 2 show that they all have the same trend (the same slope change with P_c). Firstly the slope increases due to the adjustments of the contact between the specimen and platens, but mainly due to microscale processes such as progressive crack closure and grain boundary compression, which corresponds to a nonlinear elasticity [26]. Then, the slope remains more or less constant (linear elasticity). After reaching a certain pressure $P_c = P^*$, there is a rapid reduction of the slope. This pressure typically corresponds to the onset of grain crushing [27], although in a granular rock analog material GRAM1 (inset in Fig. 2) there is no grain crushing as the pressure is too small. The rapid slope reduction at $P_c \approx P^*$ is caused in this material by the breakage of grain bonds and grain reorganization resulting in the inelastic volume reduction (compaction). It follows that the rapid reduction of the hydrostat slope at $P_c \approx P^*$ is due to the reduction of the dilatancy factor β (negative at high P_c), whatever the micromechanism of this reduction, grain breakage/pore collapse or grain reorganization or both. This independence of (or low sensitivity to) micromechanics is important for the constitutive modeling and is also confirmed by different microstructures of the compaction bands forming at high P_c and very

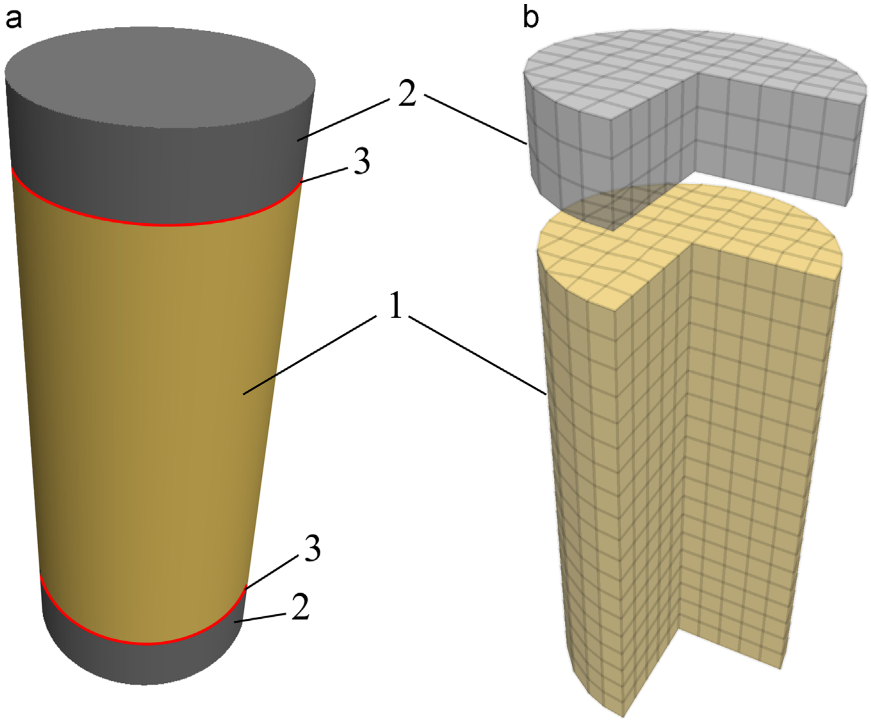

Fig. 1. (a) Set up of the hydrostatic tests both in the laboratory and the presented numerical models. (b) Numerical grid in the numerical models. 1. Cylindrical specimen; 2. Stiff (steel) platens; 3. Lubricant layers and\or low-friction gaskets in the laboratory tests, and frictional interfaces in the numerical models. Radius of the model specimens is 2 cm and their height is 8 cm. The platen thickness in the models is 1.2 cm. Their Young modulus is 200 GPa and Poisson ratio 0.3.