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ScienceDirect

Procedia Engineering 191 (2017) 332 – 341

Procedia Engineering

www.elsevier.com/locate/procedia

Symposium of the International Society for Rock Mechanics

Deformational Response of Rocks to Uniaxial, Biaxial, and Triaxial Loading or Unloading Regimes

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Abstract

In material sciences, it is a well-known fact that linear or linearized theory based on Hooke's law does not offer a satisfactory description of solids in special regimes, which include e.g. too high strains under large uniaxial stresses. Therefore, in general, the response to biaxial or triaxial loading cannot be obtained as superposition of uniaxial load responses. Striking paper book example of material demonstrating such behavior is rubber subjected to uniaxial or isotropic compression. Despite this fact, linear mechanical moduli, being secant or differential, determined through standard rock-mechanics tests, mostly from the uniaxial compression, are still widely used for description of deformational behavior of rocks. Without doubt, an appropriate interpretation of these effective quasi-elastic or stiffness moduli can give useful information about mechanical properties of the rocks, especially in comparative sense. However, for more reliable constitutive modeling of any solid materials, paricularly rocks, an experimental investigation of deformational responses to uniaxial, biaxial and triaxial loading or unloading regimes is very useful. This contribution presents the results of an experimental case study on homogeneous sandstone exposed to isotropic triaxial, and equi-biaxial or uniaxial loading regimes. The measured deformational response of this rock is compared with behavior of elastic solid materials. Finally, benefit of the experimental testing for constitutive modeling based on phenomenological description is briefly discussed.

Peer-review under responsibility of the organizing committee of EUROCK 2017

Keywords: *triaxial testing; rocks; compressibility; uniaxial loading; equi-biaxialloading; isotropic compression; Hooke's law*

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Peer-review under responsibility of the organizing committee of EUROCK 2017
doi:10.1016/j.proeng.2017.05.189

1. Introduction

1.1. Triaxial experiment for study of mechanical behavior of rocks in variable stress conditions

Investigation of mechanical behavior of rocks under applied external stress fields constitutes necessary base for understanding many natural geophysical processes in the Earth's crust, or for solutions of engineering problems connected with a wide spectrum of human activities. For these tasks, simple or very sophisticated numerical models can be adopted. However, for a satisfactory prediction of mechanical evolutions, these models need experimental data in the form of basic mechanical parameters. Rocks usually represent the complicated aggregates of mineral grains of variable size, chemical compositions, or magnitude of binding forces. Such microscopically heterogeneous materials, when subjected to increasing external stress, from the start of loading, undergo reversible elastic deformation, as well as permanent deformation originating preferably from microfractures.

Standard material engineering can successfully adopt generalized Hook's law, describing elastic and mostly linear response through constant elastic moduli, for majority of construction materials at sufficiently low strains. However, in rock mechanics, the mechanical moduli determined from laboratory experiments play the role of linearized effective coefficients rather than constant intrinsic material parameters. For ideal material described through linear relations between strain and stress, a deformational response to general loading conditions can be determined through superposition of uniaxial loads. Therefore, the simplest uniaxial compression/extension laboratory test may be often sufficient to estimate the deformational response in other loading regimes including general triaxial stress state. This consideration is widely used also in geomechanical modeling, i.e. Young moduli and Poisson ratios determined from uniaxial tests on rocks as secant or linearized coefficient are accepted as inputs. However, such attempt is not fully satisfied, and laboratory investigation of the deformational behavior of rocks under alternative triaxial loading regimes is necessary.

Widely used variant of triaxial apparatus (so called "triaxial cell") is based on the pressure chamber combined with additional load by axial piston. Such solution is capable to generate only axisymmetric triaxial states (i.e. two principal stresses are equivalent). However, it can still better simulate the underground conditions, than any uniaxial test. Moreover, special triaxial devices of miscellaneous constructions (called "true triaxial apparatuses") can model general triaxial stress states, for which all three principal stresses can have different magnitudes.

The most popular test in triaxial cell is *Conventional Triaxial Compression* (CTC), which consists of two stages. Initial ramping the Pascal pressure p to given final value $p^{(i)}$ prepares isotropic stress state ($\sigma_x = \sigma_y = \sigma_z = p^{(i)}$). Then an additional *uniaxial loading* ($\sigma_z = p^{(i)} + |\dot{\sigma}|t$) is used to increase value of the differential stress ($\sigma_D = \sigma_1 - \sigma_3 = |\dot{\sigma}|t$). Less often used alternative of increasing the differential stress is *Conventional Triaxial Extension* (CTE). In this test, after applying the initial isotropic phase similar to that of CTC, an additional *equi-biaxial loading* ($\sigma_x = \sigma_y = p^{(i)} + |\dot{\sigma}|t$) is given.

However, there exist important differences between the alternative loading conditions: 1. orientation of principal stress axes directions is different with respect to axes x, y, z of laboratory system, what is important for anisotropic samples, 2. intermediate principal stress is considerably different, i.e. minimal ($\sigma_2 = \sigma_3$) for CTC and maximal ($\sigma_2 = \sigma_1$) for CTE. We remember that name of both tests (*Compression/Extension*) are related to compressional or extensional response in the vertical or axial direction[†], while in the perpendicular, lateral or horizontal, direction sample undergo deformation with opposite sign (*Extension/Compression*). However, the stress conditions are only compressive, i.e. represented by positive stresses in used reversal stress-strain convention adopted in geosciences. During both phases of CTC or CTE tests, only positive stress rates are applied in selected directions. Therefore, evolution of stress tensor represents exclusively *loading conditions.*

If necessary, the couple of *Conventional* triaxial tests, which are purely loading tests, can be logically accompanied by couple of complementary tests, in which the differential stress is increased during the second phase through unloading applied stress (alias stress *Reduction*) in selected directions. While *Reduced Triaxial Extension* (RTE) uses additional *uniaxial unloading* ($\sigma_z = p^{(i)} - |\dot{\sigma}|t$), *Reduced Triaxial Compression* (RTC) applies

[†] *vertical/horizontal* – with respect to laboratory system*; axial/lateral* – with respect to symmetry axis of usually used cylindrical sample