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Determination of the critical state of granular materials with triaxial tests

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Abstract

While the Critical State Locus (CSL) determined from triaxial compression tests is commonly adopted for the constitutive modelling of soil, the validity of the locus for other stress paths needs to be proved. Several authors have tried to experimentally verify whether the classical CSL representation in the stress invariants – void ratio space could be considered as unique or should depend on the loading direction, but the question is still being debated and a unique conclusion has not been convincingly drawn. In order to clarify this issue, compression and extension triaxial tests are performed on granular materials with different characteristics, namely, two homogeneously distributed sands and an assembly of steel spheres prepared under different initial conditions. The procedure for identifying the CSL is reviewed and indicates the limitations arising from strain localization (shear bands and necking). All the tests show that the materials head to systematically different traces in the e-p' and p'-q planes when sheared under triaxial compression and extension. Searching for the reasons for this phenomenon, small samples of sand are subjected to the same tests quantifying the whole strain field with X-ray tomography and a digital image correlation. This analysis reveals an inhomogeneous pattern of deformation that is strongly affected by the presence of the two rigid frictional bases and the flexible side membrane, even for the samples deforming in an apparently uniform manner. The different localization observed for the compression and extension tests justifies the dependence of the CSL on the stress path seen on the global scale. On the other hand, a unique trace of the CSL is obtained in the volumetric e-p' plane when the void ratio is measured limitedly to the zones affected by the largest distortion.

Keywords: Critical state; Granular soil; Triaxial tests; Stress path; Anisotropy; Strain localization

1. Introduction

In the conventional schematic representation of the mechanical soil response with stresses, strains and state variables, an analogy is implicitly assumed between the particulate materials and the continuum. It stems from this assumption that constitutive relations are inferred from laboratory tests with a macroscopic phenomenological approach, computing forces and displacements at the sample boundaries and that they are considered to be uniformly distributed over the whole volume. In this way, the particulate nature of the material is forgotten, despite the fact that the macroscopically observed response is often a summary of the complex patterns of local discontinuities (Lam and Tatsuoka, 1988).

Such a discrepancy becomes more relevant and implications need to be taken into account when the soil is sheared up to its ultimate condition. The importance of this state

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on the soil deformation has been progressively acknowledged and is presently a footstone of soil mechanics. Casagrande (1936) firstly observed that granular materials, initially compacted at different densities, tend to contract or dilate and eventually reach a unique condition when sheared with the same normal stress. In this state, termed *critical*, the volume and shear stress remain steadily constant along with the distortion of the sample. Subsequently, Wroth (1958) found that the final void ratio and shear stresses are related to the applied normal effective stress and are independent of the previously given stress history. In both cases, the authors refer to a simple shear mechanism, where normal and shear stresses acting on the failure plane are given, while the stress components out of this plane are unknown.

Thereafter, the Critical State concept was extended to triaxial compression (*e.g.*, Roscoe et al., 1958; Poorooshasb, 1961; Thurairajah, 1961; Vesic and Clough, 1968) using tests where the stress components acting on each plane were completely known. In an attempt to generalize the definition of the Critical State, normal and shear stresses were then replaced by mean effective and deviator stress invariants, respectively. Now the Critical State Locus (henceforth referred to as CSL) commonly designates the curve in the p'-q-e space defined by the following expressions (Schofield and Wroth, 1968):

$$\begin{aligned} e &= \Gamma - \lambda \cdot \ln p' \\ q &= M \cdot p' \end{aligned} \tag{1}$$

The CSL has increasingly become a fundamental concept for interpreting the mechanics of granular materials, having been validated by plenty of experimental campaigns. In particular, it has been adopted in a class of popular constitutive models as a reference for justifying the combined dependency of the soil response on the present void ratio and stresses (*e.g.*, Jefferies, 1993; Muir Wood et al., 1994; Manzari and Dafalias, 1997; Modoni et al., 2011) or for evaluating the seismic liquefaction potential of saturated loose sands based on their static behaviour (Poulos et al., 1985; Jafarian et al., 2013).

Indeed, due basically to experimental difficulties, the CSL is inferred, with few exceptions, from the results of drained or undrained triaxial compression tests ($\sigma'_1 > \sigma'_2 = \sigma'_3$) (*e.g.*, Verdugo and Ishihara, 1996; Flora et al., 2012). A generalisation of the models to other stress conditions, such as triaxial extension, cyclically alternated compression and extension or, more generally, to multiaxial stress states, is rarely provided (*e.g.*, Chiaro et al., 2013) or is sometimes accomplished by implicitly assuming that the parameters of Eq. (1) (Γ,λ) are independent of the loading direction (*e.g.*, Manzari and Dafalias, 1997; Gajo and Muir Wood, 1999; Reza Imam et al., 2005). The use of mean effective stress and deviator stress p' and q in Eq. (1) may give the impression that the CSL can be uniquely defined, irrespective of the adopted stress path (*i.e.*, the relative magnitude between all the stress components). Indeed, the stress tensor in a point is completely defined by six independent variables. Therefore, the independence of the Critical State parameters, from all the variables other than p' and q, is just a simplification and cannot be postulated without experimental validation or a theoretical demonstration.

A key assumption for the uniqueness of the CSL is that the initial soil fabric and a memory of the loading history are erased by the large deformations experienced to reach the Critical State. The non-directional soil texture in this final condition is uniquely expressed in Eq. (1) by void ratio e, which represents a cumulative index of the soil state not taking into account the possible directional dependency of the void spaces and the distribution. Thus, the soil response is governed by the friction developing in a fully remoulded material. Such a postulate does not seem to have generally gained agreement in the literature. In fact, while experiments conducted by Been et al. (1991) exhibit a unique Critical State line in the e-p' plane for undrained compression and extension tests, *i.e.*, for two loading conditions causing opposite distortional effects, different pieces of evidence emerge from the work of other authors. Among them, Vaid and Chern (1985) observe that the response of a sand subjected to undrained triaxial extension ($\sigma'_1 = \sigma'_2 > \sigma'_3$) is by far more contractive than during compression. Subsequent studies showed similar friction angles, but different traces of the CSL in the e-p' plane for compression and extension tests (Vaid et al., 1990; Vaid and Thomas, 1995; Riemer and Seed, 1997). More particularly, extension tests tend to reach lower final void ratios than compression tests at the same p' value. Furthermore, a dependency of the Critical State Line obtained with extension tests on the sample preparation technique and on the initial effective confining stress was observed. All this evidence seems to imply that the depositional history of the soil fabric is not totally erased by shearing, but that some memory still persists even at the critical state (Fonseca et al., 2013). These observations form the basis for the definition of a critical state theory including the role of inherent anisotropy (Li and Dafalias, 2002; Dafalias and Manzari 2004; Dafalias et al., 2004; Papadimitriou et al., 2005), subsequently modified by Li and Dafalias (2012) with an evolving fabric tensor.

In support of the stress path dependency of the CSL are the observations of Riemer and Seed (1997) and Yoshimine et al. (1998), both exhibiting lower Critical State traces of the e-p' plane lines in extension tests than for those in compression tests. However, there is a discrepancy between these two studies and it is related to the position of the Critical State Line obtained from simple shearing. In fact, while ultimate steady state void ratios from undrained hollow cylinder torsional shear tests (Yoshimine et al., 1998) fall within the values found for undrained triaxial compression and extension tests at the same p', Riemer and Seed (1997) found absolute lower void ratios in simple shear tests compared with the other shear modes. For the sake of clarity, it must be argued that an evaluation of the normal stress components in simple shear tests, which