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On a common critical state in localized and diffuse failure modes

Huaxiang Zhu [a,*], Hien N.G. Nguyen [b], François Nicot [a], Félix Darve [c]

[a] Irstea, Geomechanics Group, ETNA, Grenoble, France
[b] SMS-ID, INSA de Lyon, France
[c] Laboratoire Sols Solides Structures Risques, UJF-INPG-CNRS, Grenoble, France

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ABSTRACT

Accurately modeling the critical state mechanical behavior of granular material largely relies on a better understanding and characterizing the critical state fabric in different failure modes, i.e. localized and diffuse failure modes. In this paper, a mesoscopic scale is introduced, in which the organization of force-transmission paths (force-chains) and cells encompassed by contacts (meso-loops) can be taken into account. Numerical drained biaxial tests using a discrete element method are performed with different initial void ratios, in order to investigate the critical state fabric on the meso-scale in both localized and diffuse failure modes. According to the displacement and strain fields extracted from tests, the failure mode and failure area of each specimen are determined. Then convergent critical state void ratios are observed in failure area of specimens. Different mechanical features of two kinds of meso-structures (force-chains and meso-loops) are investigated, to clarify whether there exists a convergent meso-structure inside the failure area of granular material, as the signature of critical state. Numerical results support a positive answer. Failure area of both localized and diffuse failure modes therefore exhibits the same fabric in critical state. Hence, these two failure modes prove to be homological with respect to the concept of the critical state.

1. Introduction

Granular material has attracted great interest in recent decades, in both scientific and technological aspects. Its behavior diverges sensitively according to the initial state and the loading history (path dependence). It is also well-known that despite the diversity of the response, in the large strain of biaxial compression, the granular material evolves towards a steady state, in which a shear distortion progresses without any change in the shear stress and the material volume. This state, being independent of the initial state, is named Critical State. Since this concept was introduced by Roscoe et al. (1958) and developed as Critical State Soil Mechanics (*CSSM*) by Schofield and Wroth (1968), it has been the corner stone of soil mechanics for decades, allowing researchers to build the constitutive relation for the final state of the soil, as well as other granular materials (e.g. Roscoe and Burland, 1968; Wan et al., 2011; Li and Dafalias, 2012; Zhao and Guo, 2013; Gao et al., 2014).

The critical state relation in p'–q–e space forms the critical state line (*CSL*). As an asymptotic state for the granular

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[*] Corresponding author.
E-mail address: huaxiang.zhu@hotmail.com (H. Zhu).

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assembly subjected to prescribed loading path, it gives a trinary relation among void ratio e, the mean effective stress p' and the deviatoric stress q. In the large strain, e becomes constant with p' and q stopping increasing as well. Basically, constant e under shearing is considered as the signature of the critical state. However, two questions should be asked before accepting this concept: why is e so crucial among different state quantities, and how can critical void ratio e be related to the critical state stress? Given the critical state concept is initiated on the basis of macro-scale observations, the answer should be found on a smaller scale. Viewed in micro-scale, macroscopic stress response is attributed to contact forces projected on different planes. As a result, the mechanical response of granular materials basically depends on the contact arrangement (Oda et al., 1980; Rothenburg and Bathurst, 1989). Therefore, one possible answer to the former two questions may be that in the critical state, there exists a characteristic fabric in the micro-scale, which has a relatively constant void ratio and an unchanged mechanical response, disregarding the persistent shear deformation. Many attempts have been made to investigate fabric features in the shear deformation and its role in macroscopic mechanical response of granular material (Cambou, 1993; Radjai et al., 2004; Cambou et al., 2009).

Since structureless state quantities, void ratio e and mean effective stress p', are introduced to characterize the material state without considering any anisotropic nature of the soil, the classic critical state framework postulates that the soil structure is isotropic in the critical state. The pioneering work of Oda (1972a–c) in statistically characterizing the directional contact distribution in granular materials highlights the existence of the shear induced anisotropic fabric in the critical state. This compels the geo-mechanics community to analyze the shearing deformation in a new way, from a fabric viewpoint. Taking advantages of the new numerical tool, the discrete-element method *DEM* (Cundall and Strack, 1979), and the progress of experimental techniques, many later observations confirm that the shear induced fabric anisotropy prevails during or even before the critical state, acting as a signature of shear deformation (Thornton and Barnes, 1986; Rothenburg and Bathurst, 1989; Calvetti et al., 1997; Thornton and Antony, 1998; Mueth et al., 2000; Fu and Dafalias, 2011; Hasan and Alshibli, 2012; Zhao and Guo, 2013). While more fabric features are identified in shear deformation, the critical state is expected to be of fabric dependence (Been and Jefferies, 1985).

In terms of describing the fabric, although methods differ from one study to another, up to now, the basic underlying idea is to gather information of all contacts inside the considered area into one directional distribution or one quantity with directional meaning. In essence, a microscopic viewpoint (two particles scale or one single contact scale) is held when contacts are only considered independently from each other. However, the terminology of “fabric” indicates how contacts are being mutually organized, which suggests that a mesoscopic viewpoint with several interacting contacts should be adopted. In this meso-scale, two important aspects should be involved in the description of the granular assembly: (1) how the material distributes and organizes; and (2) how the forces transmit through the material. The first point explains the status and the evolution of the material, i.e. the kinematic aspect of the material, while the second tries to elucidate how the external loading is carried by the material and how it influences the material, i.e. the static aspect of the material. To this extent, two corresponding meso-structural patterns (among a variety of different patterns) can be considered in 2D granular assemblies to describe the status of the fabric in the meso-scale: (1) the loop-like cluster (hereafter called meso-loop), composed of a set of contacting grains forming a closed loop (Satake, 1992; Bagi, 1996; Kruyt and Rothenburg, 1996, 2014; Kuhn, 1999); and (2) the column-like cluster (called force-chain), which consists of grains (or contacts) carrying major forces in the material, taking in charge the force transmission in the assembly (Dantu, 1968; Drescher and De Jong, 1972; Radjai et al., 1996; Mueth et al., 1998). In quasi-static conditions, force-chains line up along the major loading direction to carry the external loading. Some of them may turn to a buckling configuration when subjected to exceeding load that probably disables them to carry the load, i.e. the force-chain instability. Massive buckling events, as a result, correspond to a decrease of the material sustainability or a so-called “*stress softening*”. In practice, force-chains are confined by meso-loops. Stability of force-chains is therefore ensured by these confining structures (Tordesillas et al., 2010, 2014). The close interaction between force-chains and meso-loops is crucial to the mechanical response of granular material, and naturally, the morphology of these two meso-structures determines the mechanical property of the granular material. To this extent, meso-structure description must be introduced to characterize the fabric of the critical state.

Another common concern in using the critical state concept to explain experimental results is the material structurization. In some cases, failure occurs homogeneously without any apparent and persistent strain concentration, called “*diffuse failure mode*” (Darve et al., 1995, 2004; Darve and Roguiez, 1998). Also well-known is that the granular assembly under shearing may experience a transition from a homogeneous deformation pattern to a discontinuous one, with strain largely localizing into a system of bands, i.e. “*shear band*”. As soon as that occurs, the material is structurized into two zones: shear band domain, where strain concentrates; and remaining domain, where material undergoes an elastic unloading to release its stored elastic energy (Nicot and Darve, 2011). This failure pattern is called “*localized failure mode*” (Rice, 1976; Vardoulakis et al., 1978; Bigoni and Hueckel, 1991; Petryk, 1993; Chambon and Caillerie, 1999; Bigoni, 2000; Sulem and Vardoulakis, 2004; Tejchman and Górski, 2008). In the presence of the structurization in specimen scale, average state quantity of the whole material is no longer valid. Instead, the state of the specimen should be described separately in different parts. This notion is reminiscent of what Oda (1972a) did in investigating deformation mechanism of dense specimens under triaxial compression, where sample volume is subdivided into several parts with respect to their void ratios. Shear deformation only occurs inside the shear band when the other domain, as a whole, acts in a quasi-elastic behavior. Hence, the non-elastic property of the material largely derives from the shear band domain, where shear deformation is dominantly active. This means that the fabric base of the critical state should be discussed more inside the shear band domain (e.g. Fu and Dafalias, 2011).