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Strain localisation in granular media

Localisation de la déformation dans les milieux granulaires

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ABSTRACT

This paper discusses strain localisation in granular media by presenting experimental, full-field analysis of mechanical tests on sand, both at a *continuum* level, as well as at the *grain scale*. At the continuum level, the development of structures of localised strain can be studied. Even at this scale, the characteristic size of the phenomena observed is in the order of a few grains. In the second part of this paper, therefore, the development of shear bands within specimen of different sands is studied at the level of the individual grains, measuring grains kinematics with x-ray tomography. The link between grain angularity and grain rotation within shear bands is shown, allowing a grain-scale explanation of the difference in macroscopic residual stresses for materials with different grain shapes. Finally, rarely described precursors of localisation, emerging well before the stress peak are observed and commented.

RÉSUMÉ

Cet article est une introduction à la physique de la localisation de la déformation dans les milieux granulaires. Il présente les caractéristiques essentielles du phénomène d'émergence et de développement de structures de déformation localisée, qu'on appelle généralement des bandes de cisaillement. Il s'appuie sur l'observation expérimentale de champs de déformation dans des essais mécaniques de laboratoire, à deux échelles d'observation : l'une, macroscopique, à laquelle le milieu granulaire est observé comme un milieu continu, et l'autre, qu'on qualifiera de microscopique sans notion d'unités de mesure, à l'échelle du grain. À l'échelle macroscopique, l'observation continue quantitative par des techniques photogrammétriques révèle l'apparition du phénomène et son développement sous forme de structures à l'échelle de l'échantillon. Même à cette échelle, la taille caractéristique des phénomènes observés se révèle être de quelques grains. À l'échelle microscopique, un suivi exhaustif en 3D de tous les grains d'échantillon de sables soumis au même type d'essais peut désormais être réalisé en utilisant la microtomographie à rayons X, et c'est l'objet de la seconde partie de cet article. Le lien entre l'angularité des grains et leur rotation dans les bandes est montré, ce qui permet d'avancer des explication microscopiques à diverses observations macroscopiques qui ignorent l'aspect discret du milieu. Incidemment,

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des phénomènes rarement décrits – qui paraissent être des précurseurs de localisation apparaissant bien avant le pic – sont observés et commentés.

1. Introduction

Strain localisation in granular media is both a commonplace and fascinating phenomenon. Indeed, it is common experience that dykes, levees, trench walls, and other man-made as well as natural soil structures most often show so-called "failure surfaces" at rupture, rather than overall plastic deformation; on the other hand, the sudden emergence of a shear band in a carefully prepared homogeneous laboratory specimen loaded with well-controlled boundary conditions that do not introduce measurable symmetry breakage or heterogeneity seed, is a wonder for the experimentalist trying to catch the mysteries of strain localisation. It is much less a wonder for his engineering colleagues, who perform such tests to characterise the stress–strain response of the material, and usually rely on elasto-plastic constitutive equations to model it as a continuum medium and apply numerical methods, *e.g.*, Finite Element Method, in order to design structures: they need constitutive data, measured with reasonably good repeatability on supposedly homogeneous specimens. Strain localisation does not enter easily into the mould of constitutive modelling and numerical simulations: it contradicts the basic assumptions of homogeneous and unique response of the specimens, and it requires significant mathematical refinements in the theoretical and numerical frameworks in order to be accounted for rigorously and efficiently.

This issue of strain localisation in granular media in the context of continuum mechanics has been studied by different researchers around the world, both experimentally and theoretically, since the beginning of the 1970s [1–11]. The present article, being in the context of a set of papers devoted to "granular physics", will try to bridge the gap between this long-standing and intensive quest and the more recent emergence of grain-scale approaches to the behaviour of granular media. In fact, it appears that none of the two perspectives can be simply disregarded: strain localisation belongs essentially to both the structural scale, let us call it macroscale, and the material scale, which is in essence a matter of microstructural evolution, *i.e.*, grains in the case of granular media. Hence, the paper will be organised in two parts, one presenting a brief synthesis of the macroscale or continuum observations of strain localisation, and the second dealing with the new results on the microstructural aspects of strain localisation, that become increasingly accessible to observation thanks to the formidable progresses of imaging techniques in the last 10 years.

2. Macroscopic observation of strain localisation

Strain localisation in soils has been recognised implicitly as the essential issue regarding natural and man-made geotechnical structures' stability for centuries by engineers. Coulomb's paper on a theoretical approach of soils mass stability [12] is probably the most famous "foundation" text of soil mechanics, introducing the concept of internal friction in bulk granular media. Indeed, this paper relies on the hypothesis of a sliding rigid block over a (rectilinear) rupture surface to analyse this situation: here we find strain localisation. However, the essence of the link between the small strain response of granular media as a continuum, and the occurrence of strain localisation, has started to be the object of intensive experimental and theoretical studies only since the 1970s, parallel with the development of constitutive and numerical modelling for granular media.

2.1. Methods for analysis of strain localisation in the continuum framework

The methods used to experimentally explore the onset and development of strain localisation in granular media, like in other solids essentially resort to image analysis. More precisely, speaking of the development of a deformation process over a domain, a differential approach based on a comparison of successive images of a deforming object is required. False Relief Stereophotogrammetry (FRS – used on such images in the 1980s and 1990s [13,14][1]), followed by digital image correlation have allowed the precise quantification of the strain field in sand and rock specimens subjected to plane strain tests. The increasing resolution of the acquired images, as well as the performance of image correlation are still allowing new measurements to be made today, especially on the multiscale aspects of localisation. Simultaneously, computerised tomography (CT) has allowed the non-destructive imaging not only of the surface of specimens, but throughout their volume as well. With the increasing resolution of CT scanners, Digital Image Correlation (sometimes referred to as DVC – since 3D images are sometimes called "volumes") has become applicable in 3D since the middle of the 2000s. It is possible today to accurately characterise the complex 3D strain fields that develop in bulk specimens subjected to non-homogeneous mechanical tests performed in situ, *i.e.*, directly in the x-ray beam. This was initially done using powerful x-ray sources

[1] The False Relief Stereophotogrammetry technique relies on a human operator based, quantitative interpretation of the false vertical relief obtained when observing a pair of successive 2D images of a plane object. The *false* relief is interpreted as a displacement field. This operation is performed on a suitable machine (stereocomparator) such as the one used for topographic measurements.