Geomechanics for Energy and the Environment 3 (2015) 1–10

Contents lists available at ScienceDirect

Geomechanics for Energy and the Environment

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

Micro-texture and petrophysical properties of dilation and compaction shear bands in sand

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HIGHLIGHTS

- Impact of stress level on micro-texture of deformation bands.
- Different porosity evolution of shear bands for rounded sand vs. angular sand.
- Higher dilatancy factor of rounded sand compared to angular sand.

ARTICLE INFO

Article history:
Received 6 March 2015
Received in revised form 11 May 2015
Accepted 17 June 2015
Available online 23 June 2015

Keywords:
Deformation band
Porosity
Dilatancy
Micro-texture

ABSTRACT

We have studied micro-textural and petrophysical properties of dilation and compaction shear bands (zones) created during deformation of two quartz sands (Ottawa and Hostun sands), differing in angularity, under triaxial compression experiments. Image processing of in-situ CT-scan images taken during the experiments allowed both qualitative study of micro-texture, and quantitative study of porosity and dilatancy. Our results indicate that, in both sands at low confining pressure, i.e. 100 kPa, a zone of enhanced porosity (dilation shear band) is initiated with dilatancy factor ∼ 0.5–0.6, and towards the end of the tests the porosity continuously increases, especially at the center of the zone (from ∼33% to ∼45% for Ottawa sand and from ∼40% to ∼52% for Hostun sand). However at high confining pressure (7000 kPa), the tested sands reveal different dilatancy and porosity evolution. In rounded Ottawa sand, first a wide dilated zone (dilatancy factor ∼0.26) forms, and by progressive shear loading, a compacted zone is developed inside this dilated zone (dilatancy factor ∼ −0.11). For the angular Hostun sand the dilatancy is negative both at the initiation and the final stage, which is reflected by a wide zone of compaction.

1. Introduction

Deformation of sand and porous sandstone localizes in the form of deformation bands. Deformation bands are small-scale mm-thick tabular structures with millimeter to centimeters displacement that encompass different types of deformation mechanisms. At shallow burial depth (low stress condition) grain rolling and rearrangement are the dominant deformation mechanisms in sand and porous sandstone which makes disaggregation bands. While at deeper condition or higher stress levels grain breakage (cataclasis) at different degrees is the dominant deformation mechanism which leads to the development of cataclastic bands. Grain rolling and sliding which are active at the initiation of almost every kind of bands may result in porosity increase (dilation) in sand or sandstone, while grain breakage usually leads to pore collapse and porosity reduction. This has been observed in experimentally created deformation bands[1–8] as well as in the natural examples from outcrop studies.[9–13]

The volumetric change during shearing of sand and porous sandstone is usually described by a dilatancy factor,

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http://dx.doi.org/10.1016/j.gete.2015.06.001
2352-3808/

which is defined as a ratio of plastic volumetric strain change over plastic shear strain change.[14–16] The value and the sign of the dilatancy factor are determined in order to assess whether the samples under shear deformation show volume increase (enhanced porosity) or volume decrease (porosity reduction). As a result deformation bands could be divided into five classes of bands, namely: pure dilation bands, dilation shear bands, pure shear bands, compaction shear bands and pure compaction bands.[12,17–19]

Micro-textural zonation of deformation bands has been first addressed by Aydin[9] and later by several researchers.[3,7,20] According to Gabrielsen and Aarland,[20] a complete deformation band (a mature cataclastic band) includes a zone of three main layers of compacted and crushed grains. In the model described by Gabrielsen and Aarland,[20] both the intensity of cataclasis and compaction increase inward from the host rock towards the center of the band. In some cases, an open fracture overprints the central part of the cataclastic band with major grain crushing. Lothe et al.[3] have experimentally investigated the micro-texture of deformation bands formed in consolidated sandstone in relation to their petrophysical properties such as porosity and permeability. They found out that the initial stage of band formation is accompanied by grain reorganization and sliding which results in dilation and porosity increase in the sample. This stage is further overprinted by a compacted zone in a more mature deformation band at the end of the experiments. The final picture of a mature cataclastic band shows a zoned structure with increasing compaction (porosity reduction) towards the center of band similar to the model introduced by Gabrielsen and Aarland.[20]

Torabi et al.[7] identified two distinct shear zones (bands) in their ring shear experiments and outcrop samples, a shear zone with a diffuse boundary formed at low level of stress involved grain flaking and low degree of cataclasis, while a sharp boundary shear zone formed at higher level of stress included grain splitting and crushing to a higher degree. The sharp boundary shear zones in Torabi et al.[7] encompass a zoned micro-texture (similar to the one introduced by Lothe et al.[3] and Gabrielsen and Aarland[20]), in which porosity and grain size decrease gradually from outside the localized zone towards the margins and the central part of the zone. However, detailed investigation of the micro-texture, porosity evolution and dilatancy of granular materials such as sand during a deformation process, rather than only the end-state or net sample deformation, is needed in order to understand micro-mechanism involved in the band formation at different stress levels (corresponding to confining pressures). This is investigated here using processed CT-scan images of deformed sand executed during triaxial compression experiments. The dynamic development of localization and the mechanical and petrophysical properties such as porosity and microstructure, captured by our results, can be used to improve the continuum and discrete mechanical models of porous media.

We further analyze some of the experimental data reported by Alikarami et al.[21] performed on rounded Ottawa and angular Hostun sands in order to discover the evolution of dilatancy factor and porosity under different confining pressure in these two sands. Alikarami et al.[21] address the effect of angularity on grain breakage in sands under different confining pressure. In this paper we present how a change in deformation mechanism causes different types of bands to form as a result of micro-textural and porosity evolution in the tested samples.

2. Methodology

A series of triaxial tests at different confining pressures, ranging from 100 to 7000 kPa, was carried out at the Laboratoire 3SR in Grenoble on small cylindrical specimens of dry rounded Ottawa and angular Hostun sands. In addition, several tests on Ottawa and Hostun Sands, at low confining pressure, 100 kPa,[22] and two tests, on Ottawa Sand, at high confining pressure, 7000 kPa,[21] have been performed to examine the reproducibility of the results. The results of experiments conducted under same condition were completely comparable and consistent.

These sands have similar grain size distribution[13] with the D_{50} values of about 340 μm and 310 μm for Hostun and Ottawa sands, respectively. The specimens of about 22 mm height and 11 mm diameter, with non-lubricated ends are prepared using the air pluviation method. The tests are conducted using a specifically designed triaxial setup that can be placed in the X-ray cabinet (X-ray tomograph) allowing the specimens to be scanned under the load.

The triaxial tests began with isotropic compression until the desired stress level (with a rate of 21 μm per minute) was reached, and then the deviatoric loading, with constant lateral stress, was applied to reach the desired strain.

To observe and visualize the deformation patterns of the studied sands during deformation, the X-ray tomography was performed in-situ on the sample at certain axial strains. The 2D scans are then used to reconstruct the specimen images employing the DigiCT 2.4.2 (Digisens). The 3D reconstructed grayscale images are used for porosity and strain (both volumetric and shear) measurements on the deformed samples. The 3D images are 1250 × 1250 × 1600 pixels; with a pixel size of 15.6 μm. For more details about the Triaxial setup see Alikarami et al.[21] and Andó et al.[22]

Local measurements of porosity are performed on the 3D images by defining local subvolumes, centered on a number of regularly spaced nodes, inside which the porosity can be measured. The sizes of the selected cubic subvolumes are 470 × 470 × 470 μm and 620 × 620 × 620 μm for Ottawa and Hostun sands, respectively. The local porosity of specimens at low confining pressure, e.g. with no grain breakage, is measured using a binarized image. Whereas, at high confining pressure because of grain breakage and creation of fines smaller than pixel size, the grayscale values of the 3D images from tomography are used.[21] In this paper, porosity maps of the samples were produced using the above mentioned approaches. Then, the porosity values of selected spots (presented by circles on the image in Fig. 1) across a deformation band were extracted from the maps.

Continuum Digital Image Correlation (DIC) method[23] was used to estimate the volumetric and shear strain increments (Eqs. (1) and (2)) on X-ray tomography images. This method tries to find a best match between a pattern extracted from the reference configuration and the one in