# Experimental study of compaction bands in diatomaceous porous rock

# Takeshi Kodaka \* — Fusao Oka\*\* — Jun Otani\*\*\*— Hideki Kitahara\*\* — Hirofumi Ohta\*\*

\* Address of T. Kodaka Department of Civil Engineering ,Meijo University, Japan kodaka@ccmfs.meijo-u.ac.jp

\*\* Address of F. Oka, H. Kitahara and H. Ohta Department of Civil and Earth Resources Engineering, Kyoto University, Japan foka@mbox.kudpc.kyoto-u.ac.jp, h-kitahara@k8.dion.ne.jp, ota.hirofumi@t02.mbox.media.kyoto-u.ac.jp

\*\*\*Address of J. Otani Department of Civil and Environmental Engineering Kumamoto University, Japan junotani@kumamoto-u.ac.jp

ABSTRACT: To observe the strain localization of both shear and compaction bands, a series of triaxial compression tests under the drained condition was performed on diatomaceous porous rock. A rectangular-shaped prismatic specimen was used to easily measure the strain distributions on the specimen surface. The distributions of local strain, i.e., shear strain, axial strain, and volumetric strain, were measured on the surface of the specimen by using an image analysis technique newly developed for this experiment. After the shear testing, the changes in density of the specimen were measured by an X-ray CT scanner. Some high density regions were found to correspond to the compaction bands observed in the image analysis in the cases of relatively high confining pressure levels.

KEY WORDS: compaction band, strain localization, image analysis, X-ray CT, soft rock, diatomaceous mudstone.

## 1. Introduction

Compaction bands constitute a kind of strain localization phenomenon. The bands occur as perpendicular or very slightly inclined deformation bands with respect to the most compressive stress direction, with volumetric compression. In particular, compaction bands have been observed in the natural outcrops of sandstone (*e.g.*, Mollema & Antonellini 1996). Based on recent research,

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compaction bands have been recognized as horizontal deformation bands with volumetric compression which are caused by only vertical compression under generally high lateral confining pressure (*e.g.*, Olsson 1999; Issen & Rudnicki 2000, 2001; Issen 2002; Rudnicki 2002). The purpose of the present study is to observe compaction bands in the laboratory. A highly structured and very porous rock, diatomaceous mudstone, is used for this purpose.

### 2. Testing method

The geomaterial used for this testing program is Noto diatomaceous mudstone, which contains rich diatomite and is found at the tip of the Noto Peninsula in Ishikawa Prefecture, Japan. The void ratio and water content in the natural conditions are 2.72 and 115%, respectively. Although diatomaceous mudstone is rather stiff, the porosity is very high compared with other soft rocks. A series of conventional drained shear tests (CD tests) are performed using a rectangular-shaped prismatic specimen; it is 4 cm square in the transverse section and 8 cm high. The back pressure used in this test is 1MPa. Since the loading rate is very low, *i.e.* 0.01%/min, the excess pore pressure seems to be not generated in the specimen. The specimen is enclosed in a thin rubber membrane, 0.5 mm thick. The special lubrication technique was not performed at between the ends of the specimen and the stainless pedestals. A newly-developed high pressure steel triaxial chamber, equipped with two digital CCD cameras, is used for all the tests. It is possible to observe the deformation field on the two distinct surfaces of the specimen, which are perpendicular to each other, during the shear testing with the CCD cameras. The distributions of local strain on the surface of the specimen can be obtained by an image analysis, which is developed by the authors based on the PTV technique. The resolution of the CCD camera is 0.125mm/pixel.

#### 3. Macroscopic test results

Figure 1(a) shows the stress-strain relations for the CD tests. For the cases with relatively low confining pressure levels, namely, CD-1 (0.25 MPa) and CD-2 (0.5 MPa), the stress-strain relations show strain-softening behavior. On the other hand, for the cases with higher confining pressure levels, namely, CD-3 ~ CD-6, i.e., 0.75, 1.0, 1.5 and 2.0 MPa, only strain-hardening behavior occurs. Figure 1(b) shows the relations between the volumetric strain and the mean effective stress during the shearing. The material has a contractive behavior, even at low confining pressure. As shown in this figure, the yield points exist as inflection points, marking the condition when volume changes increase rapidly with an increasing mean effective stress. These yield points also correspond to the inflection points in the stress-strain curves. The yield locus determined by connecting the yield points on the effective



stress spaces is illustrated in Figure 1(c). A cap-shaped yield locus can be assumed for this material, as shown in the figure.

Figure 1. Test results for the CD tests

Figure 2 shows the strain distributions at 20% of the global axial strain.  $\varepsilon_a$ ,  $\gamma$  and  $\varepsilon_v$  express axial, shear and volumetric strains, respectively, which are locally distributed on the surface of specimens. These distributions have been obtained through the image analysis by assuming a two-dimensional deformation on the surface. In all cases, upper and lower distributions are obtained by CCD camera 1 and 2, respectively. In the case of CD-1 (0.25 MPa), clear steep shear bands can be observed. The local axial strain levels are concentrated in the same region as that where the shear strain levels are concentrated. It can be seen that one of the shear bands splits the specimen into two pieces. In the case of CD-2 (0.5 MPa), the local axial strain and shear strain are concentrated in the middle of the specimen. By observing the specimen without a membrane, after the shear tests, clear shear bands

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were observed in the middle of the specimen. In the cases of CD-3 (0.75 MPa) and CD-4 (1.0 MPa), not only steep shear bands, but also horizontal axial and shear strain concentrations can be observed. The small parallelepipedic patterns in CD-4 are errors of the image analysis. These cases can be considered to have a mixed deformation pattern. In the regions where the strain is horizontally concentrated, the volumetric strain is also concentrated. Therefore, the horizontal strain concentrations can be considered as compaction bands. In the cases of a larger confining pressure, i.e., CD-5 (1.5MPa) and CD-6 (2.0MPa), periodic compaction bands can be seen.



**Figure 2.** Local strains distributions on the surfaces of the specimen at 20% of the global axial strain obtained by the PTV image analysis

# 4. Observation of density distributions by X-ray CT

The specimen was vacuum-packed just after the shear tests to maintain a constant water content. Then it was taken to Kumamoto University for observation of the density distribution in the specimen by an X-ray CT scanner.

Six longitudinal sections were scanned for the present study. Selected CT images in some sections, which describe a typical trend, are shown in this paper. In all CT images shown below, common value 400 is adopted for both WW (window width) and WL (window level). The scanner spatial resolution is 0.293mm/voxel.



**Figure 3.** *CT* images for the initial state of Noto diatomaceous mudstone and failed specimens. For each sample, the three pictures correspond to three parallel axial slices at different depths.

Figure 3(a) shows the CT images of the Noto diatomaceous mudstone specimen, which is a representative sample used to observe the initial state before the shear testing. Therefore, this specimen is completely different from the specimens shown later. As can be seen, some low density regions are randomly distributed all over the specimen. In the CT images, lower density regions are expressed in the darker regions as same as the X-ray photo images. In each case, there are three images; the left one shows the center cross section, and the others are the outer cross sections. Figure 3 (b) shows the CT images of the CD-1 test. There are inclined cracks in the

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specimen. The shear band splits the specimen into two pieces. Although shear bands are also observed in CD-2 case, we cannot clearly see the density changes along the shear band in the specimen as shown in Figure 3(c). In the case of CD-3, as shown in Figure 3(d), the initially low density regions remain in the specimen. It seems that high density regions were partially generated by the pore compaction due to the axial compression. In the cases of higher level of confining pressure cases, namely CD-4 and 6 as shown in Figure 3(e) and 3(f), respectively, the initially low density regions seem to disappear. Furthermore, as can be seen in the CT images for CD-6, the high density region is concentrated in the lower part of the specimen. This trend corresponds to the results of the image analysis, in which compaction bands were observed in the lower part of the specimen.

### **5.** Conclusions

Triaxial compression tests under drained conditions with various stress paths have been performed on a specimen of Noto diatomaceous mudstone, which is a very porous and highly structured geomaterial. From the observations of local strain on the surface of the specimen, using an image analysis, shear bands were clearly observed in the cases of CD tests under low confining pressure levels. On the other hand, compaction bands were observed in the cases of CD tests under high confining pressure levels. By observing the specimen with an X-ray CT scanner, shear bands were clearly observed as inclined cracks in the CD-1 tests. Compaction bands were confirmed by the heterogeneous distributions in the high density regions of the specimen at the relative high confining pressures.

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