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Seismically induced soft-sediment deformation structures revealed by X-ray computed tomography of boring cores

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X-ray computed tomography (CT) allows us to visualize three-dimensional structures hidden in boring cores nondestructively. We applied medical X-ray CT to cores containing seismically induced soft-sediment deformation structures (SSDSs) obtained from the Kanto region of Japan, where the 2011 off the Pacific coast of Tohoku Earthquake occurred. The CT images obtained clearly revealed various types of the seismically induced SSDSs embedded in the cores: a propagating sand dyke bent complexly by the preexisting geological structure, deformed laminations of fluidized sandy layers, and two types of downward mass movement (ductile downward folding and brittle normal faulting) as compensation for upward sand transport through sand dykes. Two advanced image analysis techniques were applied to the sand dyke CT images for the first time. The GrowCut algorithm, a specific digital image segmentation technique that uses cellular automata, was used successfully to extract the three-dimensional complex sand dyke structures embedded in the sandy sediments, which would have been difficult to achieve using a conventional image processing technique. Local autocorrelation image analysis was performed to detect the flow pattern aligned along the sand dykes objectively. The results demonstrate that X-ray CT coupled with advanced digital image analysis techniques is a promising approach to studying the seismically induced SSDSs in boring cores.

1. Introduction

Seismically induced soft-sediment deformation structures (SSDSs) such as sand dykes form as a result of liquefaction and fluidization processes, and are important records of seismic activity (e.g., Obermeier, 1996; Moretti et al., 1999; Hurst et al., 2011; Berra and Felletti, 2011; Owen and Moretti, 2011; Owen et al., 2011). Accurate determination of the depth, spatial extent, and susceptibility of seismically induced SSDSs using boring cores (e.g., Duranti and Hurst, 2004; Jonk et al., 2005; Ezquerro et al., 2015) is useful in seismic risk assessment of sites. However, because seismically induced SSDSs are spatially localized (e.g., as sand dykes), accurate determination is difficult using traditional observation of the two-dimensional (2-D) surfaces of half-cut boring cores. X-ray computed tomography (CT) allows us to visualize the three-dimensional (3-D) structures of cores nondestructively (e.g., Nakashima et al., 2011). However, X-ray CT has rarely been applied to the analysis of cores containing seismically induced SSDSs (Flisch and Becker, 2003; Taira et al., 2012). In the present study, we applied medical X-ray CT to cores obtained from the Kanto region of Japan, where the 2011 off the Pacific coast of Tohoku Earthquake occurred (Nakashima et al., 2013; Nakashima and Komatsubara, 2015). The objective was to detect all seismically induced SSDSs (e.g., sand dykes and deformed laminations) embedded in the boring cores and to analyze the 3-D structures in detail, particularly with respect to the sand dykes.

Only simple observations of CT images of sand dykes and deformed laminations have been made in previous X-ray CT studies of cores with the seismically induced SSDSs (Flisch and Becker, 2003; Taira et al., 2012). In this study, in contrast, we applied two advanced image processing methods, the GrowCut algorithm and local autocorrelation, to CT images of sand dykes for the first time. It is essential to distinguish an intruding sand dyke body from an intruded host phase to obtain a 3-D sand dyke image. However, the image processing involved is not straightforward, particularly when the intruded host phase is a sandy sediment, the CT number of which is almost the same as that of a sand dyke body. The GrowCut algorithm (Vezhnevets and Konouchine, 2005), a specific digital image segmentation technique that uses cellular automata, was successfully applied to the extraction of complex 3-D sand dyke structures embedded in sandy sediments, which would have been difficult to achieve using a conventional image processing technique. Field observations have revealed flow patterns within sand dykes and clastic injections (e.g., Sangawa, 1992; Bezerra et al., 2005; Phillips et al., 2013; Cox et al., 2014; Ravier et al., 2015), which are important evidence of flow of fluidized sediments along fractures. Autocorrelation image analysis (e.g., Ikeda et al., 2000) is useful in

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detecting anisotropic structures such as flow patterns. We modified the method to calculate the autocorrelation function for each small region of interest in a large 2-D CT image. This modified autocorrelation analysis method (referred to hereafter as local autocorrelation analysis) was successfully applied to CT images of the boring cores with SSDSs to detect the anisotropy associated with fluidization processes along the dykes objectively.

2. Geological setting

The geographic details of the boring sites and geological descriptions of the cores obtained have been reported elsewhere (e.g., Mizuno et al., 2013; Komatsubara et al., 2014a; Tanabe et al., 2014). This information is briefly summarized here. Cores (diameter ≈ 64 mm) from two sites, the GS-INS-1 site in the city of Inashiki and the GS-ITK-2 site in the city of Itako, were imaged by X-ray CT in the present study. The GS-INS-1 site is located at latitude 35°55′10.7″N, longitude 140°26′52.3″E, and elevation + 0.77 m. The GS-ITK-2 site is located at latitude 35°55′58.3″N, longitude 140°33′48.6″E, and elevation + 1.24 m. Both sites are in the downstream basin of the Tone River. The GS-INS-1 site is a flood plain, and a detailed core analysis revealed that the uppermost layer is an artificial soil (depth 0 to ≈ 1 m), which is underlain by tidal channel sediments consisting of sand and silt (depth ≈ 1 to ≈ 13 m). Carbon-14 dating using plant fragments found in the core indicated an age of 0.5 ky BP at a depth of 2.7 m and an age of 0.7 ky BP at a depth of 4.3 m. The GS-ITK-2 site was formerly the site of the Uchinasakaura Lake and was reclaimed beginning in the 1940's (Tsukamoto et al., 2012). The uppermost layer is an artificial soil (depth 0 to ≈ 0.5 m), which is underlain by reclaimed sandy soil (depth ≈ 0.5 to ≈ 5 m) and natural bay sediments (depth ≈ 5 to ≈ 15 m). Carbon-14 dating of a shell found in the core indicated an age of 0.2 ky BP at a depth of 1.9 m. The groundwater level at the two sites is as shallow as approximately one meter beneath the ground surface.

The 2011 off the Pacific coast of Tohoku Earthquake (Mw = 9.0) hit the downstream basin of the Tone River (Hirose et al., 2011; Towhata et al., 2014). The maximum acceleration recorded in Itako was as large as 5.2 m/s^2. Boiling of sand due to liquefaction followed by fluidization was observed on the ground surface at the two sites. A detailed core analysis revealed that the boiling sand was probably derived from the tidal channel sediment at the GS-INS-1 site and from the layer of reclaimed sandy soil at the GS-ITK-2 site (Mizuno et al., 2013; Tanabe et al., 2014).

3. X-ray CT scanning of boring cores

We used a medical whole-body CT scanner, model W2000, manufactured by the Hitachi Medical Co. (Tokyo, Japan) and located at the GSJ-Lab, AIST. Details about the scanner are presented elsewhere (Nakashima, 2000, 2003; Nakashima et al., 2011). A core sample covered with a polyvinyl chloride (PVC) tube being scanned is shown in the Electronic Supplementary Material (Fig. ESM1a). A single 2-D X-ray CT image (i.e., a slice) of the core was obtained by a single shot of the rotating X-ray fan beam. The next 2-D slice of the adjacent portion of the core was obtained by moving the core in the longitudinal direction on the patient bed. By stacking these serial 2-D slices, we were able to construct digital 3-D images of the core on a computer. Circular regions of interest were extracted from the original slice images to exclude the PVC tube from further image analysis (Fig. ESM1bc). Programs developed by Nakashima and Kamiya (2007) were used in the image analysis. A CT number greyscale of the reconstructed CT image was in conventional Hounsfield units (HU) produced with air and water considered to be standards.

The choice of the acceleration voltage of the X-ray tube is important because it affects the CT numbers of the imaged samples significantly (e.g., Nakashima and Nakano, 2014). Two acceleration voltages, 100 and 120 kV, are available for the W2000 scanner. In advance of the core scanning, we scanned phantoms of bentonite clay and sand saturated with water for the best choice of the acceleration voltage. The results are shown in Fig. ESM2. Based on the results obtained, we decided to perform scanning of the cores from the GS-INS-1 and GS-ITK-2 sites at 100 kV. This acceleration voltage yielded reasonable contrast between the sand and silt, showing the sand dyke intruding in the silt clearly (Fig. ESM1bc).

Each core was 1 m in length (see Fig. ESM1a), and a total of 10 m of cores were obtained for CT scanning from each site, corresponding to a depth range of 0 to 10 m. First, all of the cores (a total of 20 m in length) were scanned at a relatively low resolution (i.e., at a slice thickness of 2 mm) to identify liquefied and fluidized portions embedded in the cores quickly and without fail. We identified several small-scale thin sand dykes and blurred deformed laminations (Jinguuji and Nakashima, 2014), but their further description is omitted here; only four portions exhibiting clear large-scale liquefaction and fluidization were analyzed in the present study. Three of these four portions were from the GS-INS-1 site (depths ≈ 2.8, ≈4.8, and ≈5.8 m), and one was from the GS-ITK-2 site (depth ≈ 1.6 m). CT scanning with small values for the slice thickness was applied to the four portions to obtain high-resolution images. A slice thickness of 0.5 mm was used for the three portions from the GS-INS-1 site (thus, the 3-D voxel dimensions were $0.31 \times 0.31 \times 0.5$ mm^3). A slice thickness of 1 mm was used for the one portion from the GS-ITK-2 site (thus, the 3-D voxel dimensions were $0.31 \times 0.31 \times 1$ mm^3).

After the nondestructive acquisition of the CT images, the cores were analyzed by the following destructive methods. The cores were half cut so that photographs of the cross sections could be taken. Slab-like plastic containers (5×25 cm^2, slab thickness 1 cm) were pushed onto the half-cut surfaces to obtain undisturbed slab samples and were imaged by soft X-ray radiography at 40 kV and 3 mA (Tanabe et al., 2014). Serial sampling was performed on the half-cut planes at 5-cm intervals to obtain the particle size distribution using an LA-950V2 laser diffraction particle size distribution analyzer (Horiba, Kyoto, Japan; Jinguuji and Nakashima, 2014).

4. Post-CT image analyses

4.1. Image analysis using the GrowCut algorithm

One of our objectives was to analyze the complex 3-D structures of the sand dykes. Thus, it is essential to extract the sand dyke bodies embedded in the cores using digital image processing. However, this image processing (i.e., segmentation of sand dykes and the surrounding undisturbed layers) is not straightforward. The conventional segmentation technique is the global thresholding method (e.g., Peth, 2010), in which voxels with greyscale values greater than a threshold value are assigned to the sand dyke and those less than the threshold value are assigned to the silt surrounding the sand dyke. An example of the use of the Otsu method (Otsu, 1979), a well-known global thresholding method, is to try to extract a sand dyke intruded into a silt layer which is shown in Fig. ESM3. Because of the reasonable density difference between silt and sand and the choice of an appropriate acceleration voltage, the greyscale contrast between the bright sand and dark silt may seem to be reasonable (Fig. ESM3c), yielding the well-separated bimodal distribution shown in the histogram in Fig. ESM3d. However, the segmentation outcome (Fig. ESM3b) is poor because, for example, isolated sand spots are misassigned to white voxels, and suspended silt fragments in the sand dyke are misassigned to black voxels (see Fig. ESM3b for detail). The global thresholding method yields a segmentation outcome much poorer than that shown in Fig. ESM3 when the intruded host phase is a sandy sediment (not silt), the CT number of which is almost the same as that of the sand dyke (Fig. ESM4).

The GrowCut algorithm (Vezhnevets and Konouchine, 2005), a specific digital image segmentation technique, was successfully applied to the extraction of a sand dyke body embedded in an undisturbed silty/