Shear Behavior and Shear Zone Structure of Granular Materials in Naturally Drained Ring Shear Tests

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Abstract. “Sliding Surface Liquefaction” is a process causing strength loss and consequent rapid motion and long runout of certain landslides. Using a new ring shear apparatus with a transparent shear box and digital video camera system, shear-speed-controlled tests were conducted on mixed grains (mixture of three different sizes of sand and gravel) and mixed beads to study shear behavior and shear zone development process under the naturally drained condition in which pore pressure is allowed to dissipate through the opened upper drainage valve during shearing. Higher excess pore water pressure and lower minimum apparent friction were observed in the tests where grain crushing was more extensive under higher normal stress and higher shear speed. Along with the diffusion of silty water generated by grain crushing, smaller particles were transported upward and downward from the shear zone. Concentration of larger grains to the central and upper part of the shear zone was confirmed by means of visual observation together with grain size analysis of sliced samples from several layers after the test. On the other hand, smaller particles were accumulated mostly below the layer where larger grains were accumulated. The reason why larger grains were accumulated into the shear zone may be interpreted as follows: grains under shearing are also subjected to vertical movement, the penetration resistance of larger grains into a layer of moving grains is smaller than that into the static layer. Therefore, larger grains tend to move into the layer of moving grains. At the same time, smaller particles can drop into the pores of underlying larger grains downward due to gravity.

Keywords. Naturally drained and speed-controlled ring shear tests, transparent shear box, shear zone development, concentration of grains and particles, velocity distribution profile, grain size distribution

7.1 Introduction

Every year, many rapid and long-travel landslides take place due to earthquakes and heavy rainfall. These landslides brought about casualties and property damage, worsened by the widespread development of towns and cities into upland areas. To reduce such landslide disasters, the development of reliable risk assessment has the first priority. Practical assessment of future landslide runout distance towards development areas requires precise prediction of the friction characteristics of the materials. Based on geotechnical and experimental studies using an undrained ring shear apparatus on the January 1995 Nikawa landslide in Japan, Sassa and colleagues found that granular materials show very high mobility under saturated undrained conditions. They named the mechanism as “Sliding Surface Liquefaction”, (Sassa 1996, 2000; Sassa et al. 1996) hereafter often abbreviated as SSL.

Studies of the friction of granular materials for the purpose of landslide runout mechanism were conducted by many researchers using geological, geotechnical, and geophysical approaches. The effect of shear speed and normal stress on shear characteristics of granular materials had been widely examined (Novosad 1964; Scarlett and Todd 1969; Bridgwater 1972; Hungr and Morgenstern 1984; Sassa 1984; Vibert et al. 1989; Fukuoka et al. 1990; Fukuoka 1991; Tika 1989; Tika and Hutchinson 1999; Lemos 2003). These experimental studies were conducted by ring shear apparatus or torsion shear apparatus. Existing apparatuses have not allowed the experimenters to observe the grains of the sample during the test, nor to detect the development of a shear zone during shearing. Lang et al. 1991 tried to use a transparent shear box for the low-stress ring shear apparatus which was developed by Sassa 1984 and used a video image processing system to track the movement of the samples’ grains. They conducted a series of tests on glass beads of 2–6 mm diameters under low normal stresses of 2.9 kPa and 29 kPa and shear speeds of 1 cm s⁻¹ and 10 cm s⁻¹. They found that shear zone thickness decreased under higher normal stress in the test on beads of smaller diameter, and that the shear zone thickness was slightly greater during faster shear. However, these tests used only glass beads and did not use natural materials. Moreover, their apparatus was not capable of maintaining undrained conditions, or to measure pore water pressure.

Sassa and his colleagues have developed seven designs of ring shear apparatus since 1984 (Sassa et al. 2004a). The first apparatus (DPRI Ver.1) was used in the study of Vibert et al. (1989), Lang et al. (1991), and DPRI Ver.2 was used by Fukuoka (1991). Wang and Sassa 2002 examined the shear zone structure by exposing sections of silica sand samples in the ring shear apparatus DPRI Ver.6 after undrained tests of large shear displacement. However, their sample box of DPRI Ver.6 was metallic and they could not observe the sample during shear. Wafid et al. (2004) investigated the development of shear zones in undrained ring shear tests by observing the sections of sand samples.
stopped at different stages of shear displacement from the initiation of failure to the steady state. They found coarse grains accumulated in the shear zone and proposed a segregation model for shear zone development under undrained conditions. However, continuous monitoring from outside of the shear box and detection of horizontal and vertical movement of the grains were still impossible.

The authors deployed the DPRI Ver.7 with a transparent shear box and conducted shear-speed-controlled tests on coarse grained silica sands to study the shear zone formation process in granular materials (Fukuoka et al. 2005a,b). Velocity distribution profiles of grains under shear at various stages in the ring shear tests were observed through processing the video image. They found that after shear resistance reached peak strength, the thickness of the shear zone tends to decrease. However, these two studies focused on the variation of the velocity distribution profiles, and the variation of mechanical properties was not examined in thorough detail.

In this study, the main purpose is to study the influence of shear speed and normal stress on the shear behavior from an approach of shear zone development process observation through examining mechanical properties and variation of grain size distribution in the sample.

### 7.2 Ring Shear Apparatus and Observation System

The ring shear apparatus DPRI Ver.7, the latest model of undrained ring shear apparatus, has a transparent shear box which enables the observation of sand grains during slow to high speed shearing (Sassa et al. 2004a). The overview of the ring shear apparatus DPRI Ver.7 is shown in Fig. 7.1 and its transparent shear box is shown in Fig. 7.2. The basic structure of this apparatus is the same as DPRI-5 and DPRI-6 which are introduced by Sassa et al. (2003, 2004).

The basic structure of the DPRI Ver.7 is similar to its predecessors DPRI Ver.5 and DPRI Ver.6, introduced by Sassa et al. (2003, 2004a). The specifications of the DPRI Ver.7 apparatus are given by Sassa et al. (2004a) and Fukuoka et al. (2005a,b). The most important detail of the DPRI Ver.7 is the transparent sample box which allows direct observation of grains inside the shear box during shearing from outside.

The schematic illustration of the samples in the apparatus and set-up of two digital video cameras are shown in Fig. 7.3a. Movies of the sample during shear are taken by two digital video cameras (hereafter, abbreviated as DV cameras) 1 and 2. Initially, only a floor-mounted DV camera 1 was used. The image obtained by DV camera 1 is shown in the middle photo of Fig. 7.3b. As shown in the left photo of Fig. 7.3b, the image of the upper and lower shear box sample is clear enough to distinguish each sand grain before shear. However, during shear, the image of the lower shear box (inside the blue box in the middle photo of Fig. 7.3b) was severely blurred and it became impossible to distinguish each grain. Another digital video camera (fixed on the rotating table of the lower shear box) shown as “DV camera 2” in Fig. 7.3a was then installed. In the right photo of the Fig. 7.3b is a sample image taken by DV camera 2 during shear. Although grains in the upper shear box (in the blue box) cannot be distinguished in this photo because the upper shear box was