Earthquake-Induced Mudflow Mechanism from a Viewpoint of Unsaturated Soil Dynamics

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Summary. This paper discusses the general liquefaction state of unsaturated soil related to the mudflow type slope failures observed during earthquakes in areas covered with volcanic ash sand deposits. It is found that the volume compressibility of soil structure, the degree of saturation and the confining pressure are key factors governing the liquefaction of unsaturated soils.

Key words: cyclic shear, suction change, air volume change, liquefaction, mudflow

1 Introduction

Japan has had many experiences of mudflow type slope failures involving volcanic sandy soil during the several earthquakes. It has been suspected that most of the soil of the failed slopes was under unsaturated condition. So far, the unsaturated condition has been assumed tacitly safer against cyclic shear because of the high compressibility of the pore air. Therefore, little attentions has been paid to the shear strength reduction of unsaturated soils subjected to cyclic shear in practical engineering. In facts, it is known that when the degree of saturation decreases to 90%, the cyclic shear strength is double that of fully saturated soil under ordinary testing conditions in the case of fine clean sand Yoshimi et al. (1989). In this paper, firstly the necessity of the research on unsaturated soil dynamics is explained. Secondary, the liquefaction state of unsaturated soils as a three phase material is discussed based on the results of cyclic triaxial test for fine clean sand, with pore air and water responses taken into consideration.

1.1 Mudflow Type Slope Failure During Earthquakes

Mudflow type failures of artificial fill and natural slope have occurred during several earthquakes around the world. Such failures occur especially in regions covered with the volcanic ash sandy soil. Las Colinas landslide, which

Fig. 1. Mudflow type slope failure during the 2003 earthquake in Japan

occurred in El Salvador in 2001 earthquake and resulted in the deaths of over 500 people, is a typical example Konagai et al. (2002). Figure 1 shows an example in Japan which occurred during a 2003 earthquake Uzuoka et al. (2004). The collapsed portion was about 40 m wide and 80 m long, with a depth of about 5 m and an averaged original slope angle of about 7 degrees. It is estimated that the volume of the collapsed soil was about 8,100 m^3. The mudflow destroyed some houses in its path, but fortunately, there was no loss of life.

According to the investigation report, the flowed fill material was a pyroclastic sediment that was classified as a volcanic sandy soil with pumice, and it was unsaturated. Therefore, in the first stage of the research, the authors conducted laboratory shaking table tests to examine the change of the water retention nature of this volcanic sand under an unsaturated condition Unno et al. (2006). It was found that the apparent volumetric water content increased by shaking when the water content was at a certain level. The level of water content corresponded to an in-situ one. This observed behaviour is thought to be attributable to the peculiarity of volcanic sandy soil with pumice, and may be related to mudflow-type slope failure.

1.2 Why Is Unsaturated Soil Dynamics Important?

Past experiences implied that the water retention nature of volcanic sandy soil plays an important role in mudflow type slope failures during earthquakes. This can be explained by soil water characteristic curves. Figure 2 shows the comparison of physical properties between an ordinary fine clean sand and volcanic sandy soil. These two soils are actual soils we have used in experiments.

As shown in the figure, because volcanic sand particles have many micro cavities, its capacity to retain water is much larger than fine clean sand. It

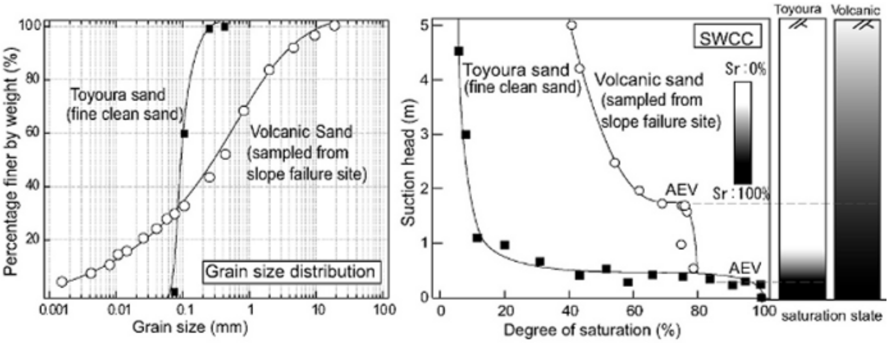

Fig. 2. Comparison of properties between fine clean sand and volcanic sand

results in a high degree of saturation several meters from the free water table. This is a clear indication of the need to study dynamics of unsaturated soils. In the second stage of the research, using the volcanic sandy soil samples from slope failure site, the authors performed cyclic triaxial tests under the unsaturated condition Kazama et al. (2006). In this paper, the general liquefaction state of unsaturated sandy soil is discussed, using a fine clean sand as a representative sand.

2 Cyclic Triaxial Test for Unsaturated Sandy Soils

2.1 Physical Properties of Soils used in the study

As was mentioned in a previous section, for the under unsaturated condition, the cyclic behavior of soils with a high water retention capacity is much more important than that of clean sand from a practical engineering viewpoint. However, the test results of fine clean sand are presented in this section to explain the general liquefaction state for unsaturated soils. Figure 2 shows the grain size distribution of the fine clean sand used in this study. The sand, called Toyoura sand, is representative of fine clean sand in Japan. It has no fine content, and density of soil particle is $2.643\,\mathrm{g/cm^3}$. Its maximum and minimum void ratios are 0.967 and 0.956, respectively. From Figure 2, air entry value can be seen to be 4 to 5 kPa.

2.2 Testing Method

We have conducted cyclic triaxial test for unsaturated soils under the undrained condition and measured the pore air and water pressure responses. The initial soil conditions before cyclic shear loading, such as dry density ($\mathrm{Dr}_0 =$ 60% and 26%), the degree of saturation (0–100%), the confining pressure ($\sigma_{\mathrm{net0}} = 20\,\mathrm{kPa}$ and $60\,\mathrm{kPa}$ in target value) and initial suction (0–11 kPa), were the testing parameters.

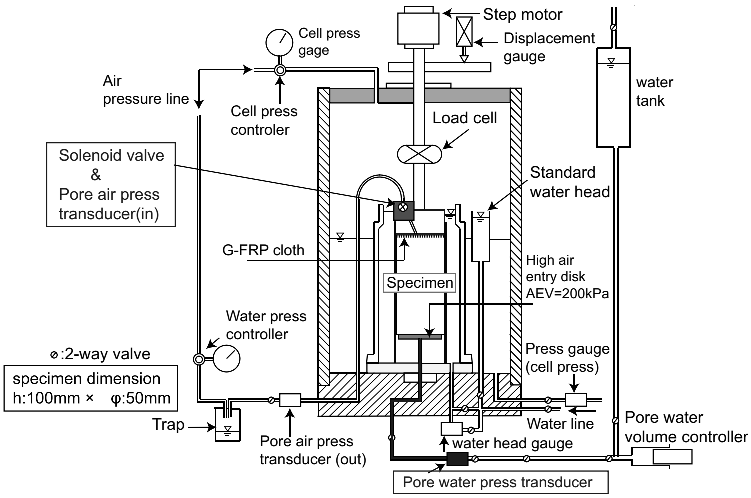

Fig. 3. Cyclic triaxial test apparatus for unsaturated soils

Testing Apparatus

Figure 3 shows a testing apparatus used in this study. The specimens were $d = 50$ mm in diameter and $h = 100$ mm in height. A grass fiber filter and a ceramic disk with an AEV of 200 kPa were installed at the top and bottom of specimen, respectively. The pore air pressure during cyclic shear was measured by the air pressure transducer attached directly above the specimen. A solenoid valve is attached at the right after in order to avoid the effect of the aerial compressibility in the pipe line. The volume of the inner pipe from top of the specimen to the solenoid valve is 0.18 cm^3, which is small enough for accuracy.

Specimen Preparation Method

The method for making the initial condition was as follows. To begin with, 75 cc of water was put into the mold. This corresponds to 95% saturation, or a water content of about 25%. Next, dried sand was dropped through air into the mold. In this condition, the sand absorbs the water, and the specimen becomes a uniform moisture state. In the consolidation process, confining pressure is applied step by step, as shown in Fig. 4. Because of the difficulty controlling the air pressure to achieve the prescribed initial suction state, we controlled the drained water volume. That is, when the target degree of saturation was achieved during a consolidation step, the route of the pore water was closed. After that, the air pressure was controlled to achieve a pore water pressure of 98 kPa (= atmospheric pressure), as shown in Fig. 4.

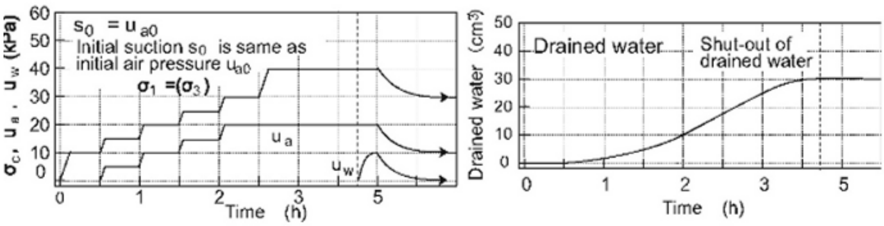

Fig. 4. Specimen consolidation process for achieving initial suction state

Loading Condition

After making the initial isotropical stress state as described, cyclic axial strain was applied under the undrained condition. The axial strain single amplitude of the sinusoidal wave was 0.2, 0.4, 0.8, 1.2, 1.6, 2.0% with every ten cycles. The concept of a strain controlled cyclic shear test is shown in the literature by the first author Kazama et al. (2000). The loading frequency was 0.005 Hz, which was slow enough allow the pore air and pore water response for clean sand to be followed. This point was confirmed in a preliminary test.

Definition of Stress State Variables

It is well known that there are many definitions of effective stress for unsaturated soils. For simplicity, in this study, Bishop's proposed equation was used to evaluate the effective stress Bishop et al. (1960). In the equation, the degree of saturation at initial state was adopted as a suction parameter. Therefore,

$$\sigma'_m = (\sigma_c - u_a) + \frac{S_{r0}}{100}(u_a - u_w) \tag{1}$$

By using the definition above, the effective stress reduction ratio during the cyclic shear can be determined as $1 - (\sigma'_m/\sigma'_{m0})$, where σ'_{m0} is the initial mean effective stress before cyclic shear. This index indicates the degree of effective stress loss ranging from zero to unity, which corresponds that of the initial state to a zero effective stress state due to cyclic shear.

3 Test Results and Discussion

3.1 Representative Test Results

Figure 5 shows an example of a stress strain relationship and an effective stress path for unsaturated soil with a relatively low degree of saturation. It is noteworthy that, even in the case where the degree of saturation is considered relatively small, the soil particle skeleton is degraded by the cyclic shear

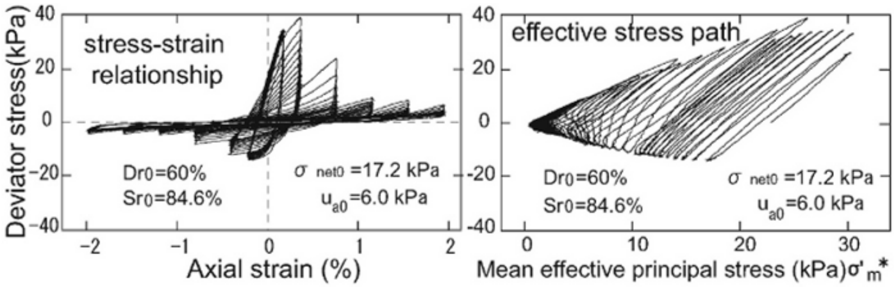

Fig. 5. Test results ($Dr_0 = 60\%$, $Sr_0 = 85\%$, $u_{a0} = 6.0\,kPa$, $\sigma_{net0} = 17.2\,kPa$)

and reaches to the zero effective stress state, thereby causing a failure of the microstructure and engendering the reduction of the soil shear strength.

Figure 6 shows the pore air and water pressure response during the cyclic shear. In the figure, the difference between u_a and u_w, which is indicated by shading in the figure, represents the suction. It is found that pore air pressure gradually increased and reached to the initial mean confining stress at around 3000 seconds. At this point, the net stress reaches zero. The pore water pressure also gradually increased but with relatively large fluctuation and reached the initial mean confining stress at around 7000 seconds. At this point, it can be regarded that netstress and suction contribution to effective stress were completely diminished.

Figure 7 shows the time histories of effective stress reduction ratio for several specimens. As shown in the figure, when the same axial strain history is applied, it is more difficult to reach the effective stress reduction ratio to unity, when the degree of saturation is lower, and the initial confining stress and relative density are higher. Consequently, the final effective stress after cyclic shear of all cases can be written as a function of the initial degree of saturation, as shown in Fig. 8. The liquefaction of unsaturated soils is affected

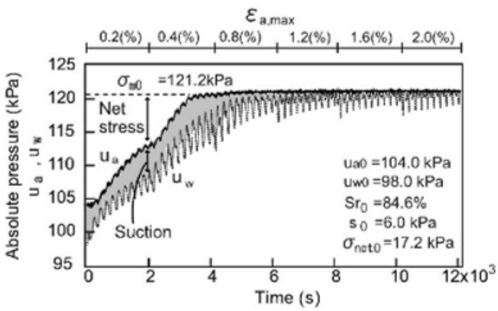

Fig. 6. Time histories of pore air pressure and pore water pressure during the cyclic shear ($Dr_0 = 60\%$, $Sr_0 = 85\%$, $u_{a0} = 6.0\,kPa$, $\sigma_{net0} = 17.2\,kPa$)

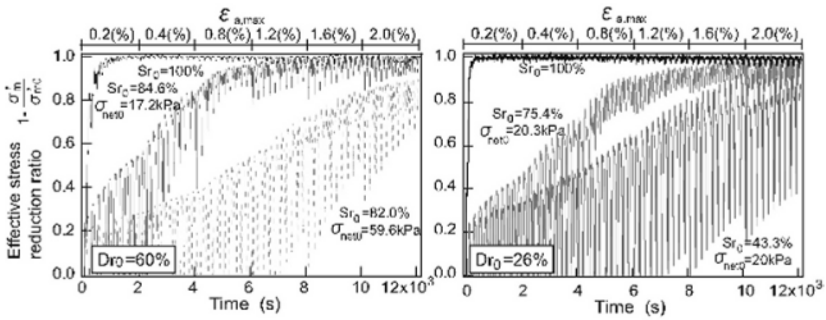

Fig. 7. Time histories of effective stress reduction ratio ($\mathrm{Dr}_0 = 60\%$ and 26%)

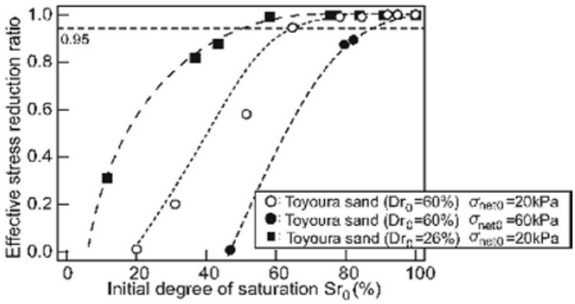

Fig. 8. Effective stress reduction ratio versus the initial degree of saturation

not only by the volume compressibility of the soil structure, which is reflected by dry density, but also by the degree of saturation and the initial confining pressure.

3.2 Discussion on the Liquefaction State for Unsaturated Soils

Based on the test results and equation (1), it can be understood that a complete liquefaction state for unsaturated soils is the condition in which both pore air and water pressure are at the same pressure as the initial mean total confining pressure. If we consider the volume change of pore air ΔV_a between the initial and final full liquefaction states, and if the pore air is assumed to be an ideal gas, the following equation can be obtained.

$$u_{a0}V_{a0} = \sigma'_{m0}(V_{a0} - \Delta V_a) \tag{2}$$

where V_{a0} is the initial volume of pore air. The volume change of pore air ΔV_a represents the volume change of the soil particle structure required to cause complete liquefaction. The relationship expressed in equation (2) can be rewritten by the change of void ratio as follows:

$$e_0 - e_{u_a=\sigma'_{m0}} = \left(1 - \frac{u_{a0}}{\sigma'_{m0}}\right)(1 - S_{r0}/100)e_0. \tag{3}$$

It can be understood that void ratio change required to cause liquefaction is a function of the initial degree of saturation and confining stress.

4 Conclusions

1) Generally speaking, because volcanic sand has a higher water retention capacity than ordinary fine clean sand, the unsaturated zone with a high degree of saturation is thicker. This points to the necessity of further investigations into unsaturated soil dynamics in order to develop an understanding of the mechanism of the mudflow type slope failure.
2) The liquefaction state for unsaturated soil can be defined by the same concept of effective stress used in saturated soil. That is, the liquefaction state is the zero effective stress state.
3) For unsaturated soils subjected to cyclic shear under the undrained condition, both pore air and pore water pressure can reach the initial confining stress, when the volume compressibility of the soil particle structure is high enough.
4) The liquefaction of unsaturated soils is affected not only by the volume compressibility of the soil structure but also by the degree of saturation and initial confining pressure.

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