EXPERIMENTAL STUDY ON THE MECHANISM OF LONG-DISTANCE FLOW-SLIDE IN PALU, CENTRAL SULAWESI, INDONESIA

Risqi Faris HIDAYAT[1], Takashi KIYOTA[2], Hasbullah NAWIR[3], Muhammad UMAR[4], ROSIYANI[5], Toshihiko KATAGIRI[6]

ABSTRACT: This paper examines the possibility of long-distance flow-slide caused by the 2018 Sulawesi earthquake by an experimental approach. A triaxial apparatus and a torsional shear apparatus were used to conduct a series of undrained cyclic loading tests (triaxial) and a static liquefaction test (torsional shear). Besides these, an undrained cyclic loading test followed by a monotonic loading was also performed in the torsional shear apparatus to determine if flow can be observed in undrained condition. It was found that the liquefaction resistance of gravelly sand samples collected from Sibalaya trench No. 3 was relatively low, which was determined to be 0.17. Also, even at the low static shear stress, the sand sample collected from the flowed layer at Sibalaya trench No. 3 could flow due to water inflow when the volumetric strain reached 1.8% at the shear strain of 5.5%. On the other hand, undrained cyclic test showed that even though the sandy specimen was liquified (shear strain reached 10.2%), the undrained monotonic behavior of this sample did not show flow behavior. This meant water inflow is needed to observe flow-slide. In conclusion, this study showed that the long-distance flow-slide could occur even on a very gentle slope, considering the inflow of confined groundwater to the surface sandy layer.

Key Words: *Liquefaction, Flow-slide, Confined Aquifer, Sulawesi Earthquake*

INTRODUCTION

Long-distance flow-slide disaster had been observed in several places in Palu city (Petobo, Balaroa, Jono Oge, Lolu, and Sibalaya) after a 7.5 M_w intra-plate earthquake hit Central Sulawesi and the surrounding area on September 28, 2018. The United States Geological Survey (2018) found the epicenter (0.256 S and 119.846 E) was located 70 km from the northern part of Palu city at the shallow depth of around 20 km. This earthquake also triggered a tsunami in the coastal areas of Palu, Donggala, and Mamuju.

Site investigation has been conducted to reveal the mechanism of this long-distance flow failure. This ground movement could flow, massively, at the very gently sloping ground, ranging around 1-5% (Hidayat et al., 2020; Kiyota et al., 2020; Okamura et al., 2020). Hidayat et al. (2020) found sand ejecta in several locations around the affected areas, indicating occurrence of soil liquefaction. Furthermore, springs and freshwater ponds inside the affected area could still be observed even two weeks after the

[1] Ph.D candidate, Department of Civil Engineering, The University of Tokyo
[2] Associate Professor, Institute of Industrial Science, The University of Tokyo, Dr. Eng.
[3] Associate Professor, Department of Civil Engineering, Bandung Institute of Technology Indonesia, Dr. Eng.
[4] Post-doctoral researcher, Institute of Industrial Science, The University of Tokyo, Dr. Eng.
[5] Graduate student, Department of Civil Engineering, The University of Tokyo
[6] Technical Director, Institute of Industrial Science, The University of Tokyo

earthquake. Kiyota et al. (2020) described that the shallow groundwater in the affected areas was under-pressure, based on the interview with the residents. They considered that the cause of this long-distance flow-slide was a significant reduction in the effective stress and shear strength of the surface ground due to a large amount of groundwater supplied from the confined aquifer.

Kokusho (1999) reported, based on his experimental results, that when the water interlayer is formed below the sloped less permeable layer, a large deformation takes place in the less permeable layer and its upper layers due to the gravity force while maintaining their shape. However, this water interlayer concept could not fully explain the occurrence of long-distance flow slides in Palu City. Okamura et al. (2020), who conducted several trench surveys in the Sibalaya area, reported that in order to employ the water interlayer as the only factor to promote this long-distance flow slide, the water interlayer should be smooth and continuous all over the area and this assumption was not always met with the investigation results.

In typical laboratory undrained shear tests, positive dilatancy associated with increasing shear strain is restrained, and strength and stiffness are eventually recovered even in very loose sand (Kiyota et al., 2013). These experimental results probably suggest that the long-distance flow-slide is unlikely to occur in gently sloped ground under the undrained condition. However, considering the inflow of the groundwater from the confined aquifer, the significant positive dilatancy can develop for surface ground due to the water absorption. This causes significant reduction in shear resistance of the surface ground, resulting in a long-distance flow-slide even in gently sloped ground.

This paper aims to investigate the possibility of this mechanism by using the experimental laboratory approach. There are two series of experiments conducted in this study. The first experiment is the undrained cyclic loading test using a strain-controlled triaxial apparatus to evaluate the liquefaction resistance of the gravelly layer, collected from Sibalaya trench No. 3 (Okamura et al., 2020). The second experiment is the static liquefaction test with constant deviatoric stress to identify the possibility of the surface sandy layer to flow under drained conditions using hollow cylindrical modified torsional shear apparatus. By using the same sandy sample, undrained cyclic loading test followed by monotonic loading were also conducted to observe the flow behavior of this specimen under undrained condition.

MATERIAL, APPARATUS, AND TESTING PROCEDURES

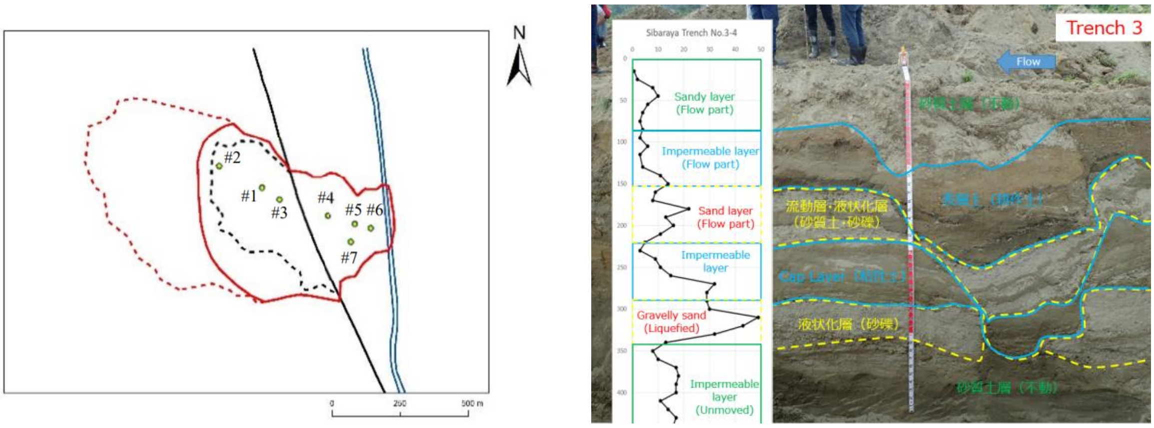
Material properties

Okamura et al. (2020) conducted trench investigations in Sibalaya after the disaster. The disturbed samples of gravelly sand layer and flowed sandy layer were collected from trench No. 3 (Figure 1). The grain size distribution of the disturbed samples is shown in Figure 2.

Undrained cyclic loading test on strain-controlled triaxial apparatus

A strain controlled triaxial apparatus shown in Fig. 3a was used in this study. The specimen sizes were 75mm in diameter and 150 mm in height. The specimens were gravelly sand (G_s=2.642, e_{max}=1.207, e_{min}=0.645) from Sibalaya trench No. 3. This sample has 5% fines content (non-plastic). The specimens were prepared using a dry tamping method with five layers to obtain the desired density. Following the preparation stage, a double vacuum method was employed to remove the air inside the specimen for 12 hours, and then the specimen was saturated with de-aired water for 3 hours. Skempton’s B value was assured to be more than 0.96 for all specimens.

The specimen was isotropically consolidated to an effective mean stress of p'=70 kPa, with the back pressure of 200 kPa. Each sample was subjected to the undrained cyclic loading test with an axial loading rate of 0.2%/min.



(a) Location of the excavated trenches in Sibalaya area (Okamura, 2020)

(b) Soil layer characteristics at Trench 3 at Sibalaya after the flow failure

Figure 1 Location and soil layers in trench No. 3 Sibalaya area

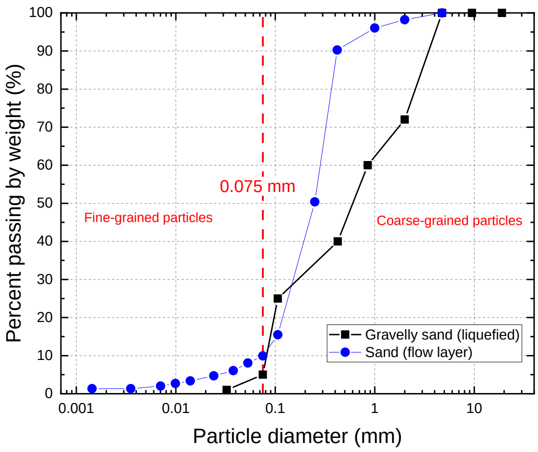


Figure 2 Particle size distribution of disturbed samples taken from Trench No. 3 Sibalaya area

Static liquefaction test with water inflow under constant shear stress on hollow cylindrical torsional shear apparatus

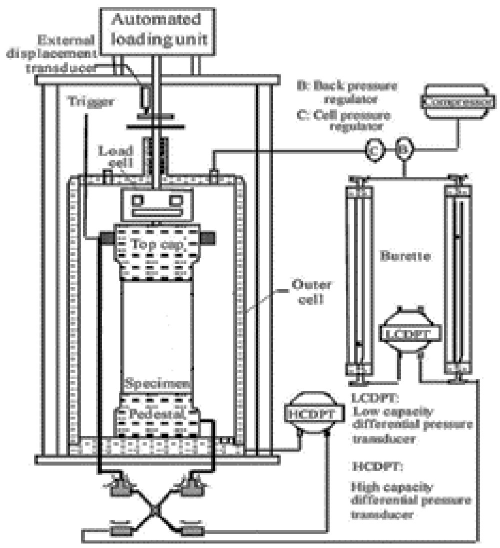
A fully-automated torsional shear apparatus with a hollow cylindrical specimen was used in this study (Fig. 3b). The specimen was 100 mm in outer diameter, 60 mm in inner diameter, and 200 mm in height. This device was developed in the Institute of Industrial Science, University of Tokyo (Kiyota, 2008). It could achieve double amplitude shear strain (γ_{DA}) levels exceeding 100% on the specimen by using a belt-driven torsional loading system that is connected to an AC servomotor through electromagnetic clutches and a series of reduction gears. An external potentiometer with a wire and a pulley was employed to measure large torsional deformations. Specified shear stress amplitude was controlled by a data acquisition system connected to a computer, which monitors the outputs from the load cell and calculates the shear stress. The measured shear stress was corrected for the effects of the membrane force by utilizing an empirical equation for the same specimen size from Umar (2019).

The specimen was sand (G_s=2.639, e_{max}=0.948, e_{min}=0.519), extracted from Sibalaya trench No. 3. This specimen has 10% fines content (non-plastic). The static liquefaction with constant shear stress was conducted in torsional shear apparatus with the maximum measured shear strain rate of 8%/min. The specimen was prepared by the air pluviation method to achieve the desired density. For the saturation process, the double vacuum method was employed for 12 hours to remove the air inside the specimen, and then the specimen was saturated with de-aired water for 6 hours.

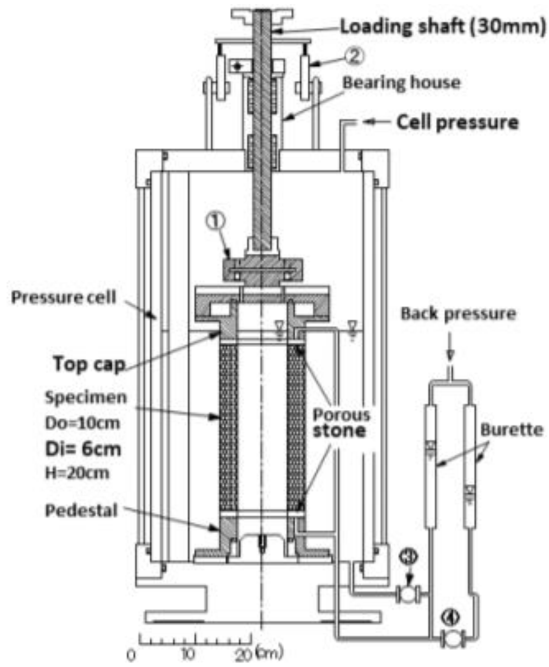
The saturated specimen was isotropically consolidated to an effective mean stress of p'=50 kPa. This step was followed by increasing the shear stress (τ) to induce the initial static shear stress of 4 kPa under the drained condition with constant back-pressure of 200 kPa. The static liquefaction test was preceded by increasing the back-pressure manually to reduce the effective stress, with the rate of reduction was 5 kPa/min. This step was directly followed by a creep for 3 minutes to ensure that the deformation was not continuous. At the same time, the shear stress was controlled to be constant. The specimen height was not kept fixed to allow axial strain development. In this test, the deviator stress (q) was controlled to be 0 kPa. Both effective stress reduction and creep were repeatedly continued until the failure point.

Undrained cyclic loading followed by monotonic loading test on hollow cylindrical torsional shear apparatus

By using the same specimen condition, apparatus, and consolidation procedure as the previous test, an undrained cyclic test was conducted. After consolidating the specimen to p'=50 kPa with a back-pressure 200 kPa and inducing a small initial static shear stress of 4 kPa, the specimen was subjected to cyclic loading with a double amplitude of shear stress of 10 kPa, until the specimen reached a liquified state where the shear strain was 10.2%. After this state, the specimen was directly subjected to undrained monotonic loading to observe the post-liquefaction flow behavior.



(a) Schematic diagram of strain-controlled Triaxial Apparatus



(b) Schematic diagram of hollow cylindrical Torsional Shear Apparatus (Umar, 2019)

Figure 3 Schematic diagram of apparatuses

TEST RESULTS AND DISCUSSION

Liquefaction resistance of in-situ gravelly sand

Four specimens of gravelly sand samples were prepared with the same density, ranging from 1.579-1.617 g/cm^3. The results of the undrained cyclic loading test are presented in Table 1, Figs. 4 and 5. As pore water pressure increased during undrained cyclic loading, the effective pressure of the specimen was reduced. Furthermore, it was observed that when excess pore water pressure ratio reached nearly 95%, all specimens started to develop axial strain in the plastic behavior.

Fig. 6 shows liquefaction resistance curve of the tested samples. The liquefaction resistance, defined as cyclic stress ratio at 20 cycles to induce a double amplitude vertical strain of 5%, was 0.17 which is relatively small. Therefore, the gravelly sand layer was probably liquefied due to the main shock of the 2018 Sulawesi earthquake.

Table 1 The experiment result of the undrained cyclic test of gravelly sand from Sibalaya Trench 3

Specimen code	Density, ρ_{sat} (g/cm^3)	Mean effective stress, *p'* (kPa)	CSR	Number of cyclic, $Nc_{(DA=5\%)}$
TX UCL 1	1.579	70	0.3	2
TX UCL 2	1.603	70	0.2	3.5
TX UCL 3	1.579	70	0.1	706
TX UCL 4	1.617	70	0.17	14

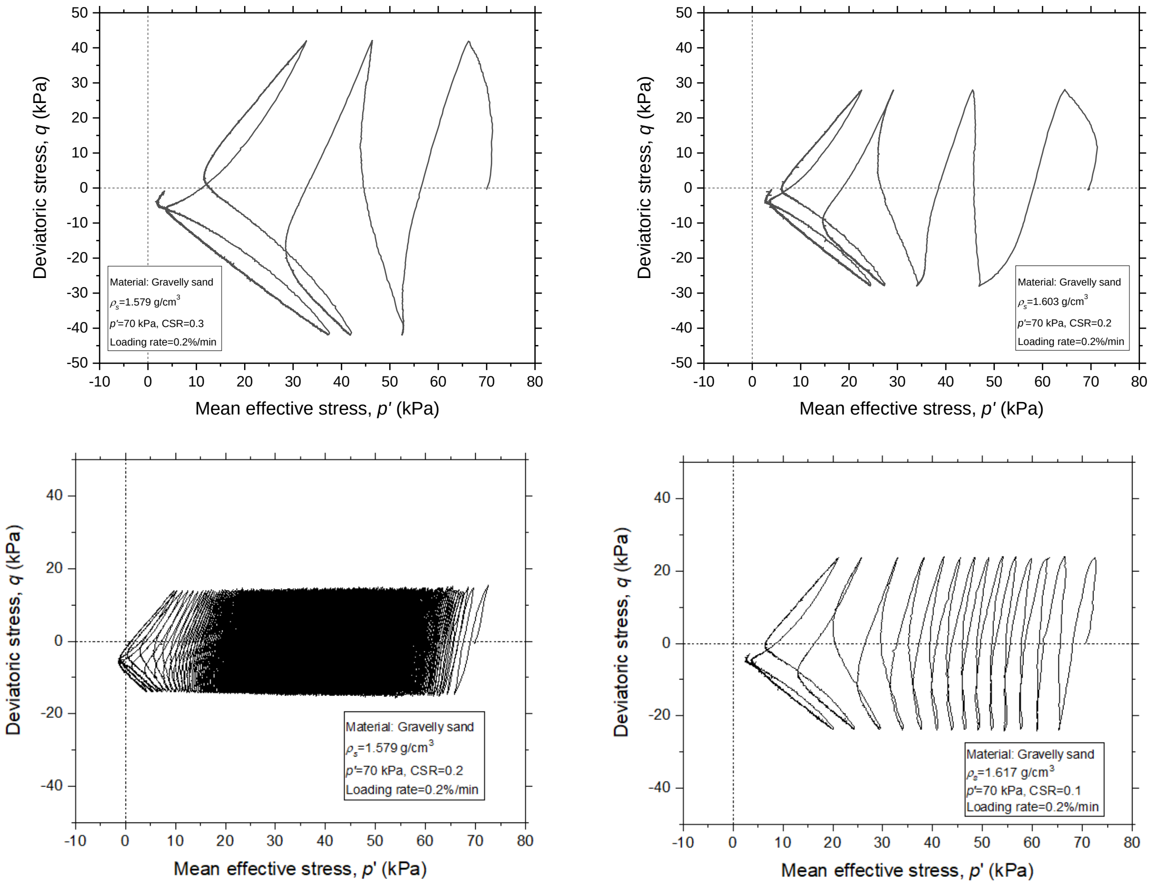


Figure 4 Effective stress path of undrained cyclic triaxial test of the gravelly sand

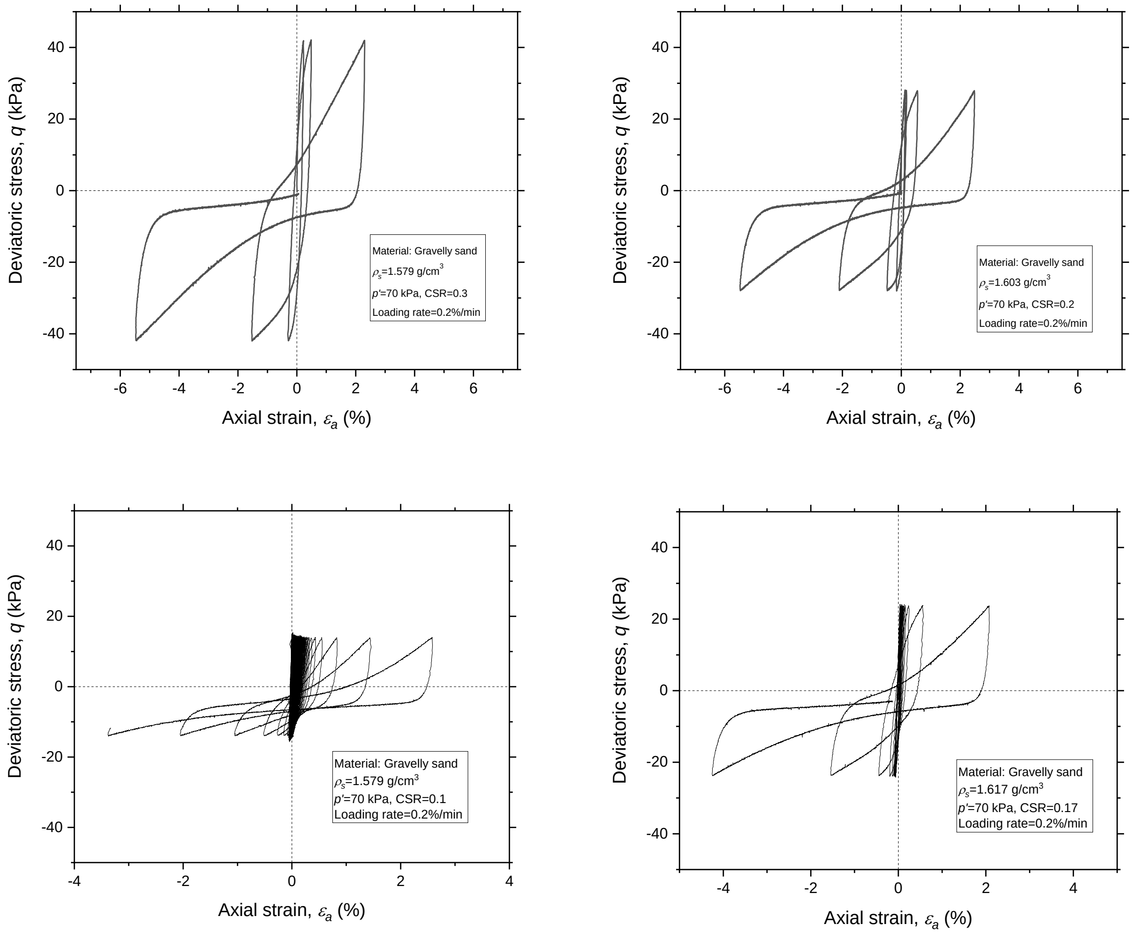


Figure 5 Stress-strain relationship of undrained cyclic triaxial test of the gravelly sand

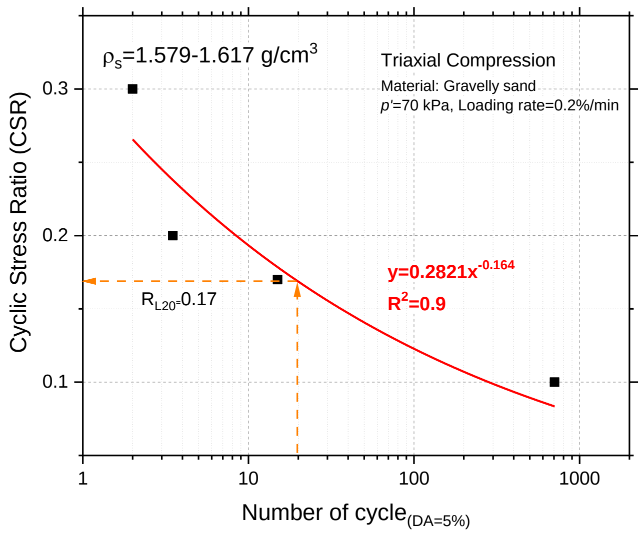


Figure 6 Liquefaction resistance curve of the gravelly sand taken from Sibalaya trench No. 3

Flow deformation behavior of in-situ sandy soil

In this test, the initial static shear stress was set to 4 kPa, assuming that the ground inclination is around 1.5%. From the experimental results shown in Figs. 7 and 8, it was found that the sand specimen taken from Sibalaya trench No. 3 could flow under the drained condition, with the injection of water under constant shear stress. When the volumetric strain reached 1.8%, the shear strain could develop continuously in the constant stress condition. It was also revealed that even when static shear stress was small (4 kPa), the flow behavior could be observed. The collapse of specimen was observed when the volumetric strain reached 4.4% at the shear strain of 35%. In this state, the effective stress, the deviator stress, as well as the static shear stress, were uncontrollably dropped.

An undrained cyclic loading test followed by undrained monotonic loading was also done as a comparison to the above-mentioned static liquefaction test. In this experiment, cyclic shear loading was applied with the specimen reaching liquefaction when shear strain was around 10.2%. The effective stress path and the stress-strain relationships are shown in Figs. 9 and 10, respectively. Unlike the static liquefaction test, soil can still mobilize the shear stress even after reaching the liquefaction state (γ_{zq}>7.5%). The specimen showed non-flow behavior or strain hardening phenomenon even after the liquefied state. This result indicates that the flow behavior occurred after the Sulawesi earthquake cannot be explained by the typical undrained loading tests.

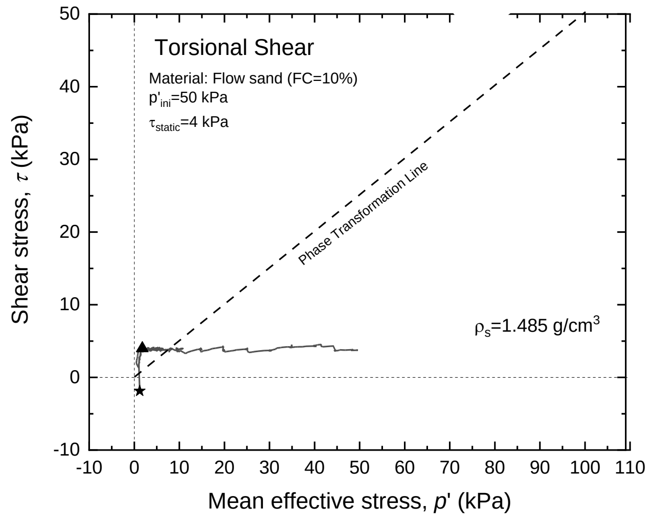
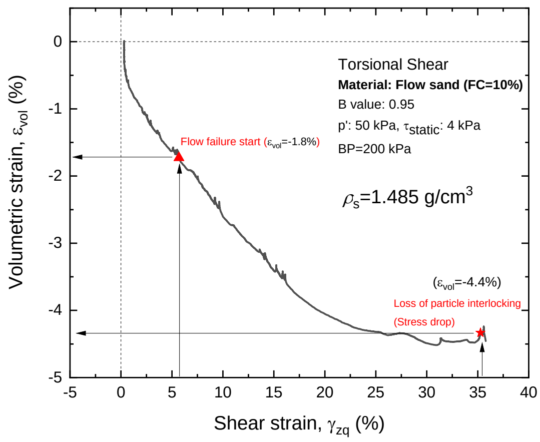


Figure 7 Effective stress path of static liquefaction test of sandy soil



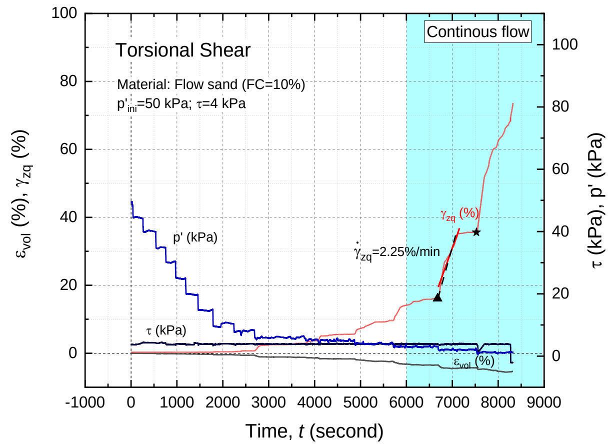
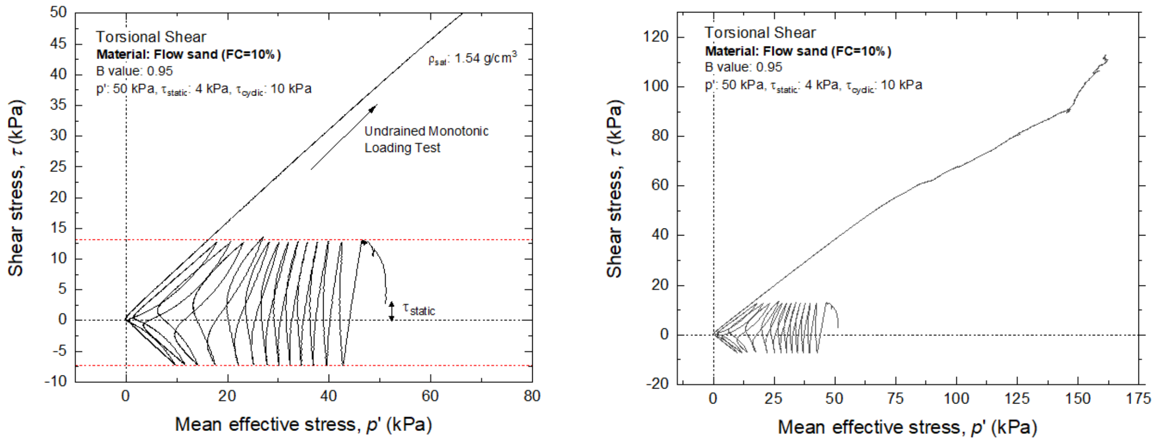


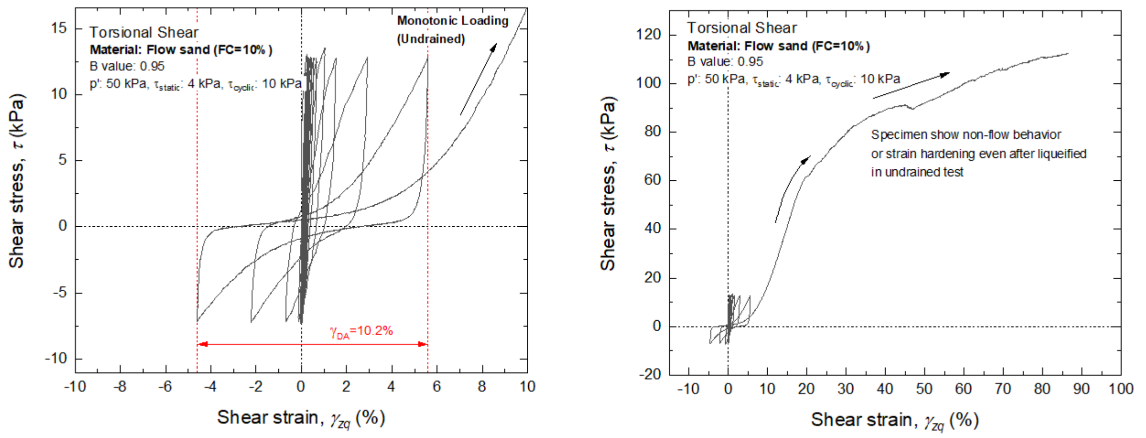
Figure 8 Shear stress and shear strain relationship of static liquefaction test of sandy soil



(a) Effective stress path during the undrained cyclic loading

(b) Effective stress path after undrained cyclic loading (ML)

Figure 9 Effective stress path of sandy soil under undrained cyclic loading test followed by ML



(a) Shear stress and shear strain relationship during the undrained cyclic loading

(b) Shear stress and shear strain relationship during the undrained monotonic loading

Figure 10 Shear stress and shear strain relationship of sandy soil under undrained cyclic loading until shear strain ($\boldsymbol{\gamma_{zq}}$) reached 10.2% (DA) followed by undrained monotonic loading

CONCLUSION

In order to investigate the mechanism of long-distance flow-slide occurred after the 2018 Sulawesi Earthquake, a series of triaxial undrained cyclic loading tests have been conducted on reconstituted samples of gravelly sand taken from the Sibalaya trench No. 3. The results indicate that this sample has low liquefaction resistance and probably liquefied during the earthquake. Since the previous field survey indicated that the sandy soil above the gravelly sand layer is assumed as the flow layer, a static liquefaction test has been conducted on this sand sample while permitting water inflow to the specimen during the shearing process. The result showed that significant flow behavior was observed after shear strain reached 5.5%, with the volumetric strain of around 1.8%. In addition, the experiment in the undrained condition showed that even after the sand specimen liquefied, the sand specimen hardly showed any flow behavior under the undrained condition. As a conclusion from the experiment of this research, it was shown that the flow-slide could occur even on a very gentle slope considering the inflow of confined groundwater to the surface sandy soil.

ACKNOWLEDGEMENT

This work was partly supported by JSPS KAKENHI Grant Number JP19KK0108 and grant funding from the JSCE Committee of Promoting Innovation in Infrastructure Management.

REFERENCES

Hidayat, R. F., Kiyota, T., Tada, N., Hayakawa, J., & Nawir, H. (2020). Reconnaissance on Liquefaction-induced flow failure caused by the 2018 Mw 7.5 Sulawesi Earthquake, Palu, Indonesia. *Journal of Engineering and Technological Sciences, 52*(No. 1).

Kiyota, T., Furuichi, H., Tada, N., Nawir, H., & Hidayat, R. F. (2020). Overview of long-distance flow-slide caused by the 2018 Sulawesi earthquake, Indonesia. *Soils and Foundations (accepted)*.

Kiyota, T., Koseki, J., & Sato, T. (2013). Relationship between limiting shear strain and reduction of shear moduli due to liquefaction in large strain torsional shear tests. *Soil Dynamics and Earthquake Engineering, 49*, 122-134.

Kiyota, T., Sato, T., Koseki, J., & Abadimarand, M. (2008). Behavior of liqueified sands under extremely large strain levels in cyclic torsional shear tests. *Soils and Foundations, 48*(5), 727-739.

Kokusho, T. (1999). Water film in liquefied sand and its effect on lateral spread. *Journal of Geotechnical and Geoenvironmental Engineering, 125*(10), 817-826.

Okamura, M., Ono, K., Arsyad, A., Minaka, U. S., & Nurdin, S. (2020). Large-scale flowslide in Sibalaya caused by the 2018 Sulawesi Earthquake. *Soils and Foundations (accepted)*.

The United States Geological Survey, Earthquake Hazards Program, The United States Geological Survey. (2018, 10 28). *https://earthquake.usgs.gov/earthquakes/eventpage/us1000h3p4/executive*. Retrieved from https://earthquake.usgs.gov/earthquakes/eventpage/us1000h3p4/executive

Umar, M. (2019). *Degradation of stress-strain properties of sand in undrained torsional shear tests.* Tokyo: Ph.D. Thesis, The University of Tokyo.