論文の内容の要旨
Thesis Summary

論文題目　Flow Deformation Characteristics of Sandy Soils under Constant Shear Stress

（一定せん断応力条件下における砂質土の流動変形特性）

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The phenomena and problems associated with liquefaction can vigorous in perspective by considering two different conditions encountered in the field; level ground condition and the sloping ground. In the level of ground condition, the soil liquefaction itself becomes the primary concern. However, for the sloping ground case, the associated phenomenon resulted from the soil liquefaction, such as flow failure or massive lateral movement should become the main attention, in addition to the occurrence of soil liquefaction itself.

The recent 2018 Sulawesi earthquake in Indonesia proves that large-scale flow failure could occur even in the gently sloping ground (1-5%). This very gentle slope, logically, could not trigger massive movement. Thus, the flow failure that occurred in the gently sloping ground could not be explained by the framework of the previous concept of the initiation of the flow liquefaction, which emphasizing the static shear stress as the main factor of the movement.

Several hypotheses have been proposed to explain how this flow failure could travel in a long distance in the gentle slope. The scenario of the water infiltrating to the sandy soil undergoes the earthquake shaking is one of the appropriate concepts, considering its possibility in the field. The water could be coming from the seepage forces from the sub-liquefied layer or the confined aquifer as part of geological features, that infiltrates to the upper-sandy-layer.

This study will utilize the water inflow concept to trigger large movement using static liquefaction test in strain-controlled Triaxial Apparatus as well as hollow cylindrical Torsional Shear Apparatus. As far as the author investigated in the literature study, there exists no previous study on the role of investigating the flow rate characteristics of sandy soils under constant static shear stress associated with the failure points, emphasizing on the start of flow failure and the rate at the failure point. In the previous studies, several researchers had conducted static liquefaction tests on clean sand to understand the dilation behavior under these circumstances by controlling the density and static shear stress variables.

In the static liquefaction test, after consolidating specimen to a specific condition, in this test was p'_{ini}=100 kPa, the specimen was subjected to initial static shear stress to illustrate the inclination of ground slope. From this point, the mean effective stress (p'_{ini}) will be reduced by increasing the back-pressure, while keeping the static shear stress constant under drained condition. The specimen failed when the effective mean stress reached the failure line. In this state, the shear strain and the volumetric strain were developed continuously and the rate of shear strain development could be measured under the constant static shear stress and constant mean effective stress condition.

With the intention of investigating the flow rate characteristics of sandy soils under constant static shear, a series of static liquefaction test was performed on Toyoura sand (clean sand) using the strain-controlled Triaxial Apparatus by varying densities, static shear stresses, and fines contents of the material. The observation was terminated when the axial strain reached 20% in Triaxial Apparatus. In order to understand the flow behavior and characteristics in the larger strain, series of static liquefaction tests were also performed on Toyoura sand (clean sand) and disturbed samples from flow failure sites on the 2018 Sulawesi Earthquake using the hollow cylindrical Torsional Shear Apparatus. This apparatus has been modified to achieve 100% of the shear strain rate in a single amplitude. Furthermore, as this apparatus has the non-coupled stress mode, it could perform the static liquefaction test under the low static shear stress to illustrate the gentle slope condition.

According to the study of flow deformation behavior on the different static shear stress and initial density, the development of shear strain and volumetric strain can be distinguished into three stages: initial stage, limited flow, and continuous flow. The measurement of flow rate was conducted at the continuous flow stage by calculating the differentiation of shear strain increment to the time under constant static shear stress and mean effective stress.

The consequence of conducting the static liquefaction test under drained condition is the specimen showed dilation behavior, showed by volume expansion. Experiment on Toyoura Sand showed that the specimen would dilate toward the steady-state line, regardless of the initial densities and static shear stress applied to the specimen.

This condition corresponded to the void redistribution phenomenon of the sandy specimen during this type of shearing process.

In the strain-controlled Triaxial Apparatus, the static shear stress is notated as the deviatoric stress. It is found that the static shear stress has no major effect on the dilation behavior of the specimen. Nevertheless, the dilation behavior, represented by volume expansion, is more pronounced by the initial density of the sandy soil. The dense materials showed more volume expansion compared to the loose materials. According to the previous research, all the sandy soils will dilate toward their critical state line and dense material will expand more to reach the critical state line, compared to the loose soil.

Nevertheless, it is confirmed that static shear stress has a significant effect on the flow failure rate, represented by the shear strain rate. Under the controlled condition, the higher the static shear stress, the faster the rate of the flow failure. This condition can be explained by imagining that when the angle of friction of specimen is reduced due to the shearing process, by keeping the stress ratio constant, the dilatancy will not recover the soil strength and the progressive failure is continued, shown by the development of strains. In this condition, as the soil loses its strength, the shear strain rate is more driven by the amount of static shear stress acting on the soil.

On the other side, the initial density also showed a significant effect on the shear strain rate. The denser the initial density, the faster the rate of the flow failure will be. By using the same analogy, when the angle of friction is reduced and the soil loses its strength, the state of volume expansion will define the soil viscosity. The more water absorbed in the starting of flow failure, the more fluid the soil-water mixture will be and the faster the volumetric strain rate and the shear strain rate will be developed after the failure occurs.

It is noted that from the clean sand, the rate of flow failure is affected by both static shear stress and the initial density of the specimen. However, the effect of static shear stress are more prominent on the dense specimen and decayed as the initial density of the specimen is looser. Thus, it could be concluded that the effect of static shear stress acting on the specimen during the flow failure state will be not significant if the volume of expansion is small.

In order to understand the effect of fines content on the flow rate characteristics, static liquefaction tests were conducted to the mixed sand with various fines content (FC=0-20%), and various initial densities. It is found that the volume of expansion of sand with fines is mostly affected by the amount of fines content. The experiment results on the Triaxial apparatus showed that the higher the amount of fines content, the less the volume expansion will be developed. The sand with plastic fines (FC=20%, IP=11) even showed contractive behavior then follow by the dilative behavior under this static liquefaction test. This mechanism shows that the fines content terminates the development of volumetric strain as well as the void redistribution. Under the examined conditions, sand with fines content showing the different trends as the Toyoura sand. In the Toyoura sand (clean sand), the densest the specimen is, the faster the shear strain rate will be developed. Nevertheless, as the fines content terminate the void redistribution, the densest material is likely to have smaller volume expansion making the shear strain rate will become slower.

Observing the flow deformation and rate characteristics of sandy soils at large deformation, the author conducted a series of static liquefaction tests on hollow cylindrical Torsional Shear Apparatus using Toyoura sand (clean sand) under the small static shear stress. It is found that even at the small static shear stress, the flow failure could be observed on the clean sand specimen. The experiment conducted at Torsional Shear Apparatus with a hollow cylindrical specimen showed a good agreement as at the Triaxial Apparatus in terms of dilation behavior of clean sand, in which the more the volume expansion will be developed for denser initial density. Also, in the shear strain rate characteristic, the relationship between the initial density and the shear strain rate showed the same tendency for both apparatuses.

In the Torsional Shear Apparatus, after the shear strain rate developed largely, the sudden stress drop can be observed, particularly on medium dense to dense specimens at the large shear strain. This phenomenon might correspond to the phenomenon of particle soil loss their contact or buckling. After the drop, the stress was recovered showing that the void redistribution happens to make the soil strength recovered. This phenomenon was not observed in the Triaxial Apparatus.

In order to promote a hypothesis of the mechanism of this long-distance flow failure, series of the undrained cyclic test have been conducted to the disturbed sample of gravelly sand layer taken from the Sibalaya Trench 3 in Triaxial Apparatus. The results indicate that this sample has low liquefaction resistance and probably liquefied during the 2018 Sulawesi Earthquake. In addition, a sandy soil layer above the gravelly layer is assumed as the flow layer.

In order to investigate whether this sample could flow under a mechanism solely by soil liquefaction, an undrained cyclic loading test follow by the undrained monotonic loading test has been conducted in Torsional Shear Apparatus. The result shows that even after the liquefied state, the specimen still can mobilize the stress from the monotonic loading, showing no flow behavior. On the other hand, a static liquefaction test also has been conducted to this sand layer using Torsional Shear Apparatus, permitting water injected to the specimen during the shearing process. The result shows that flow behavior can be observed after shear strain reaches 5.5%, with the volumetric strain around -1.8% (dilation). These test results indicate that the phenomenon of long-distance flow failure in Palu City could not be explained solely by undrained conditions and conventional soil liquefaction theory.

By elaborating on the field observation and the soil element testings conducted in the laboratory, a mechanism of lateral flow with confined aquifer is proposed to explain how this long-distance flow failure is possibly promoted by an external factor, which is a confined aquifer.