Analyzing Failure Characteristics and Potential of Landslides in Hai Van Mountain, Vietnam

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Abstract

Many slope failures and reactive landslides took place in Hai Van mountain where is located in weathered granite rocks and monsoon tropical region of Vietnam. Those landslide disasters not only destroyed the infrastructure of the national railway but also it posed a serious threat to safe railway operations in many times. The objectives of this research topic are to study failure characteristics and to assess the potential of landslide occurrences on slopes induced by factors of rainfalls and earthquakes. Some causative factors of landslide events such as geology and topography were explored during a site survey in 2014. In this trip, two of landslide prone soil samples, namely less weathered granite materials and strongly weathered granite materials, were taken at failed slopes to further investigate their shear behaviors by performing laboratory ring shear tests. The test results revealed that the mobility behavior of two landslide samples in the same conditions are quite different and dependent on the liquefaction at sliding surface under un-drained conditions (Sassa, 2000). In this crucial regard, only landslide samples of the slightly weathered granitic sands were highly susceptible to the sliding surface liquefaction and rapid motion while landslides of the strongly weathered granitic sands were not apt to move at the high speed. In addition, an assessment of the potential of landslide occurrences triggered by only rainfalls or earthquakes with ring shear tests showed that failures are more likely to occur in less weathered granite material areas than the occurrence on slopes of heavily weathered granite materials due to the smaller value of their shear strength parameters under un-drained testing conditions.

Keywords: landslides, characteristics, granite materials, ring shear apparatus, Hai Van, Vietnam

1. Introduction

Since granite rocks are very susceptible to the processes of weathering and decomposition, a great number of landslides have commonly occurred in mountainous terrains of weathered granite rocks worldwide. For example, numerous rainfall-induced shallow landslides occurred or reoccurred in granitic areas in Japan, which resulted in more than 1500 casualties over the last 70 years (Chigira, 2011). As the most recent natural disaster, the Hiroshima landslide triggered by the historically largest rainfall intensity of 217 mm per 3 hours that caused 50 fatalities and 38 missing on 20 August, 2014 (Sassa et al., 2014). Due to great losses of people and property from disasters, such kind of landslides have been taking a great interest of many researchers, such as Shimane in 1964 (Oyagi, 1968), Aichi in 1972 (Tobe, 2006), Hiroshima in 1999 (Chigira, 2001), Shikoku Island in 2004 (Dahal, 2008) in Japan. Similar phenomena have occurred in southern Italy (Calcaterra et al., 1996), northeastern Spain (Palacios et al., 2003) and Central Korea (Lee et al., 2002). Among researches, some authors tried to correlated the relationships between the distribution and density of landslides, and precipitation or to analyzed causative factors and failure characteristics in term of petrologic texture and the weathering types of granite rocks. While others attempted to employ methods of slope stability analysis by obtaining physical-mechanical soil properties from laboratory and filed tests. In addition, with an empirical approach, landslide-triggering thresholds depending on rainfall intensities and duration were also investigated so as interpret and predict its occurrences in granite areas. Specifically, some results from previous researches revealed that the landslide occurrences are greatly related to the weathering manner and grade of granitic rock materials and the disasters mostly occurred in slightly and/or moderately weathered granitic rock regions. It means that landslides took place frequently in areas of weakly weathered granite than in areas of strongly weathered granite. Such characteristics and mechanism of landslides were reported by Durgin (1977), Oyagi, (1968) Yairi, (1973) and Suzuki et al. (2002).

Although landslide occurrence are commonly known in many granitic terrain places, its mechanism of failure has not been studied deeply because of the complexity of weathering materials and triggering factors like rainfalls. Therefore, this study firstly presents some influencing factors on landslide phenomena and then try to analyze the potential of its occurrence in the slope behind the Hai Van station in granitic rock area in Hai Van Mountain, Vietnam through ring shear tests in order to interpret initiation and motion mechanism of landslides due to triggers of rainfall or earthquake. The simulation of natural landslides so far has been the first time to be applied to a study case in Vietnam with ring shear apparatus under un-drained conditions.

2. The study area and a case study

The study area is located on Hai Van Mountain (Fig. 1), which is one part of the Annamite Range dominated by a complex geological structure of weathering granitic rocks and very high precipitation in monsoon tropical climate region. The annual average rainfall mostly ranges from 2000 mm to 3600 mm and about 63 % to 85% of this amount falls during the wet season between September and December. According to rainfall data collected at a Da Nang rain gauge station being far away 17 km southeast of Hai Van Mountain in the 38-year period from 1975 to 2013, the annually 3-day maximum accumulated precipitation varies between 200 mm and 748.4 mm except for 133.8 mm in the year 2004. The topography runs across dangerous cleavage terrain due to tectogenesis with many fault system fracture zones. There are a lot of slopes that are highly susceptible to landslides around Hai Van area in which an active slope failure on the slope behind Hai Van station of the national railway at Km 766+770 (hereinafter called as Hai Van station landslide) is selected as a case study for a detail investigation of the mechanism. Currently, a set of equipments for landslide movement monitoring and data collecting has been setting up on the back slope of Hai Van station, such as extensometers, alarming and earning warning extensometers, GPS stations, and rain gauges. A clear evidence of the movement of Hai Van station landslide which is approximately 19 mm was recorded due to a precipitation accumulation during the rainy season in 2013 (Asano, 2014). The location of Hai Van station has a great significance to increasing traffic flow efficiency along the national railway. However, traffic safety and infrastructures of the station are always threatened by landslide hazard impacts, namely traffic congestions and structural damages.

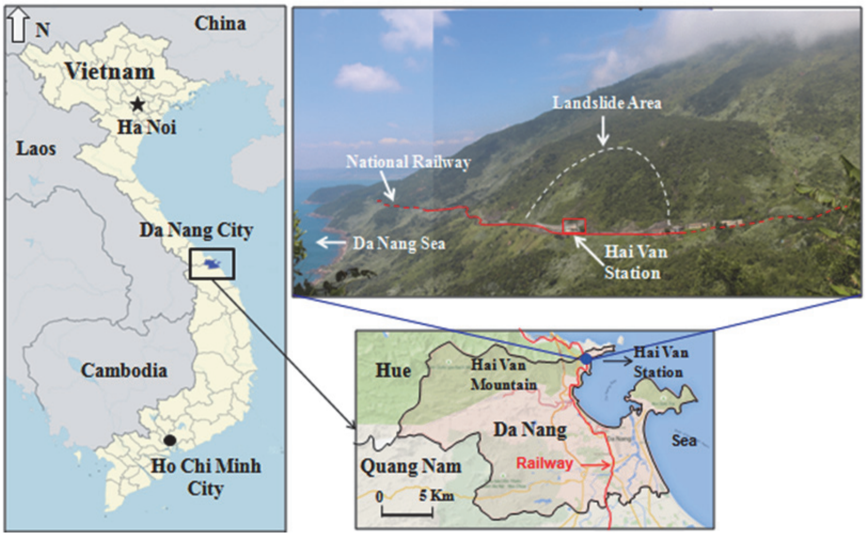

Fig. 1 Location of study area and the landslide in Hai Van Mountain

The main trigger of heavy and prolonged rainfalls is directly responsible to all previous events in 1999, 2004 and 2005 (according to statistical data of Management Unit for roads and Tam et al., 2008). Besides, there is still a medium potential of landslide occurrence triggering by seismicity during earthquakes because the study area is very near a large Da Nang-Khe Sanh fault zone with a maximum magnitude of 5.5 degree in the Richter scale. Therefore, both of rainfalls and earthquakes are commonly known as one of the potential trigger that can result in landslides in the Hai Van area.

3. Material and Methods

3.1 Site investigation and soil sampling

To take an overview of the latest landslide status and its causative factors, an site survey was conducted in May, 2014. During this trip, two landslide prone soil samples were taken from the surface of failed slopes near the Hai Van station of which materials are assumed to be the same at the potential sliding surface of the station landslides, namely strongly weathered granite materials (HV1 sample) and slightly/moderately weathered granite materials (HV2 sample). HV2 sample was taken at the middle position of the mountain while HV1 sample was from the mountain ridge (Fig. 2). HV1 sample is slightly silty sands and fine to course grained in red brown color whereas HV2 is coarse grained sands with whitish grey spotted black and silk white. Grain-size distribution of samples is presented in the Fig. 3.

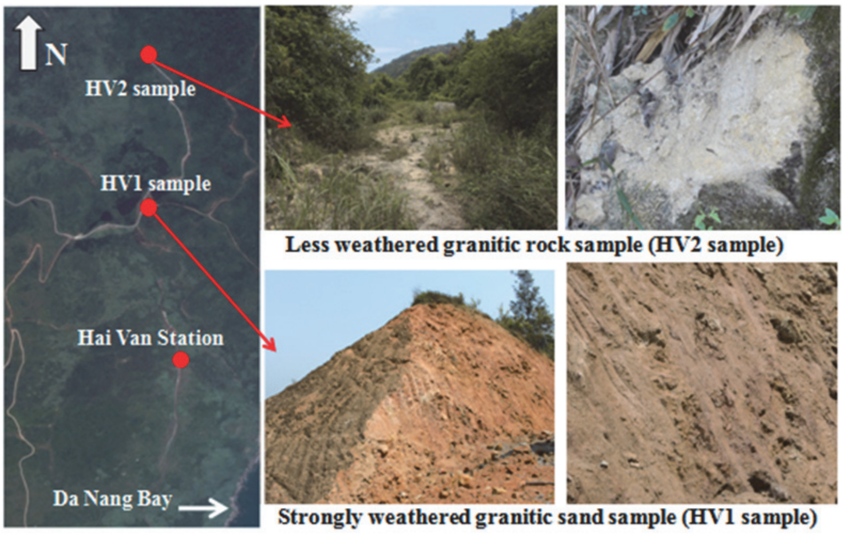

Fig. 2 Location of soil sampling

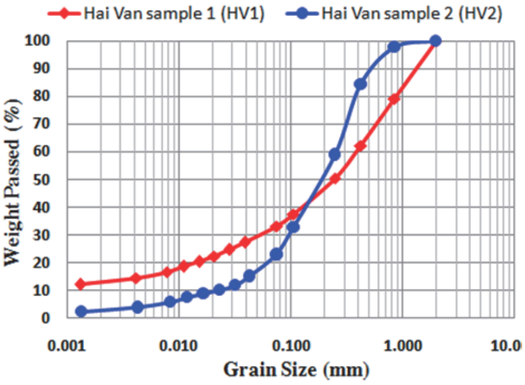

Fig. 3 Grain-size distribution of the samples

3.2 Portable ring shear apparatus ICL-1

The un-drained portable ring shear apparatus ICL-1 developed by Prof. Sassa and his colleagues in International Consortium on Landslides (ICL) in 2010 for SAPTREPS projects in Croatia was employed in this study (Fig. 4). The capacity of ICL-1 to keep un-drained condition is up to 1 MPa of normal stress and pore-water pressure, that is almost double than in previous versions (up to 500 kPa in DPRI 5, 6 and 7) (Ostric, 2012). The maximum shear velocity is only 5.3 cm/sec which is smaller than that in previous versions due to a reduction in dimensions. In order to investigate and compare failure characteristics as well as the mechanism of two different landslide prone samples, these samples were normally consolidated under the same initial stress state of their specimens with pre-decided normal and shear stress, depending on the specimen depth, slope angle and unit weight of the soil. The depth of potential sliding surfaces of the Hai Van station landslide was estimated in site investigation from 15 m to 20 m. Thus, the parameters of 230 kPa for normal stress and 120 kPa for shear stress were used in the calculation of the initial stress corresponding to 15 m of a depth and a slope angle of 26 degree.

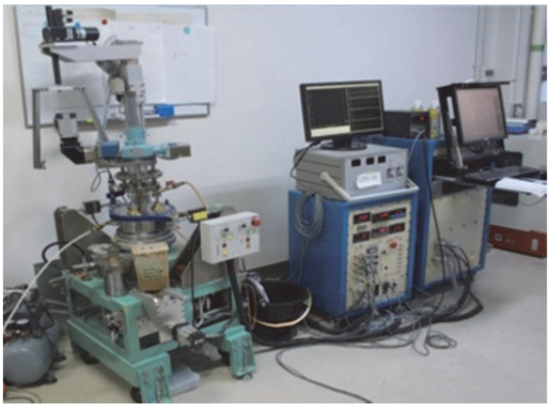

Fig. 4 Portable ring shear apparatus ICL-1 with its instrument box, monitoring box and control box

4. Results

4.1 Site investigation

Field investigations indicated an active deep landslide with main scarp (a black color line) and body parts (a red color dotted line) on the slope behind the Hai Van station (Fig. 5). It is very clear to see that the landslide body have a tongue-shape and a convex surface. Estimated size and extent of landslide are about 150 m and 250 m of width and length, respectively. Landslide types are translational or rotational modes like a tongue-like shape landslide, which has a potential sliding surface existing in the layer of weathered granitic rocks with a depth more than 15 m.

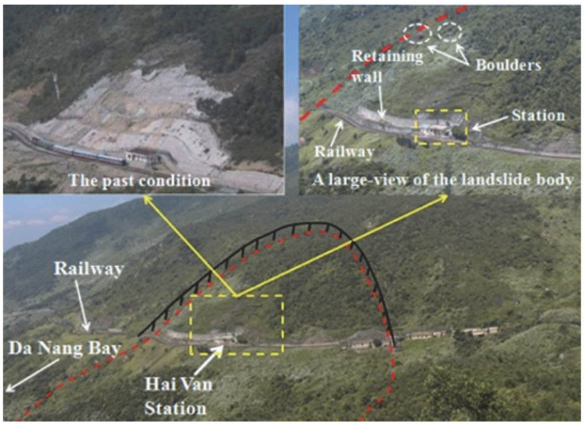

Fig. 5 Landslide description in May, 2014 and its past condition (a photo taken by Institute of Transport Science and Technology in Vietnam)

4.2Causative factors of landslides

(1) Internal changes of slope material properties

Various materials of granite rocks with different weathering grades were found around the landslide area in the site survey such as a thin layer of colluviums, loose soil-like materials, slightly soft and fine grained materials, clayed or silty soil-like material and sand-like materials. The detailed description of various weathered granite materials is presented in the Fig. 6. Among them, granites are in both fresh or decomposed types completely with strong or less weathering degree in different layers and directions. The weathering of granitic rocks not only results in decreasing of material strength on the slopes but also the materials are very sensitive to slide. In addition, in the layer of high permeable materials like sands, rainwater is easily to infiltrate into sub-surface resulting in increasing of pore-water pressure of which poses the slope to failures.

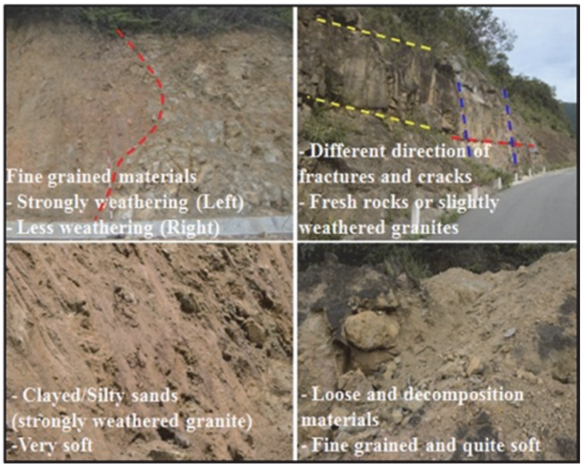

Fig. 6 Materials of weathered granite rocks

(2) The complexity of morphological settings

The terrain in Hai Van Mountain is very complex due to its topography running across dangerous cleavage terrain. Although the angle of slopes is commonly between 20 degree and 35 degree, entire area is cleaved into a lot of valleys, gullies and erosion slots. Those factors pose the study areas to occurrence of slope failures with diverse mechanisms.

(3) Monsoon tropical climate

The climate firstly increases the weathering of granite resulting in decreasing of shear resistance of slope materials. Heavy and prolonged rainfalls brought from monsoon climate generate pore water pressure in soil layer on the slope resulting in the slides. Rainwater not only makes the weathering more quickly by infiltration into rock cracks but also it can erode loose materials on slopes and trigger debris flow, earth flow or mud flow.

(4) The anthropic factor

Former construction and widening of the Hai Van station on the national railway resulted in losing the equilibrium state of slopes through cutting down foots of slopes or grading side slopes. According to a report on causes of the failure (Tam, 2005), after undercutting the foot of the slope up to 50,000 cubic meters for constructing Hai Van station, many transversal long cracks of 20 centimeters occurred sparsely in a large slope. Then the slope and its minor blocks started to move down slowly until temporarily constructing countermeasures were implemented urgently in the year 2005.

4.3 Results of ring shear test and its interpretation

(1) Un-drained shear stress control tests

The shear stress control tests are not only to measure physical mechanical soil properties but the simulation is also very useful to investigate failure behavior of landslide during motion and post-failure period (Sassa, 2004). The test results of two samples are presented in the Fig. 7 that shows the effective stress path (a red color line) and the total stress path (a black color line) as well as physical parameters monitored including shear stress at peak τ_p and at steady state τ_{ss}, friction angle during motion φ_m, peak friction angle φ_P, apparent friction angle $\varphi_{a(ss)}$. For HV2 sample, stress path that reached the failure line (red color line) and then moved down rapidly along the failure line to the steady state stress point at a very low value of residual strength (24.1 kPa). In contrast, after reaching the failure line, shear resistance of HV1 sample gradually decreased to a constant value of a higher residual strength (93.2 kPa) before the stress path had a tendency to go inversely along with a negative in pore-water pressure value. The reason is because there was excess pore-water pressure generation during shear displacement after the failure of HV2 sample whereas there was not much increasing of pore pressure for HV1 sample. The peak friction angle (φ_P) of HV1 sample and HV2 sample are around 41.0° and 36.0° with 143.5 kPa and 133.1 kPa of maximum shear resistance, respectively. The friction angle during motion (φ_m) of two landslide samples at large displacement are about 38.0° for HV1 soil sample and 33.5° for HV2 sand sample.

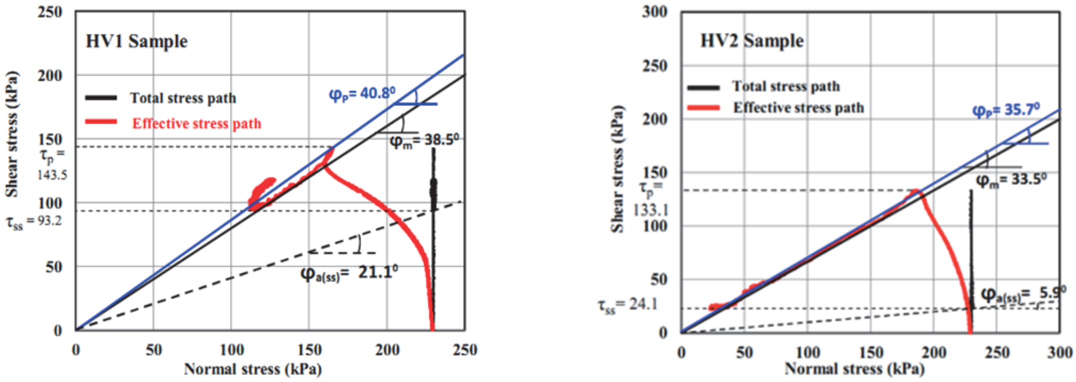

Fig. 7 Effective stress path of un-drained shear stress control test for HV1 sample (left) and HV2 sample (right)

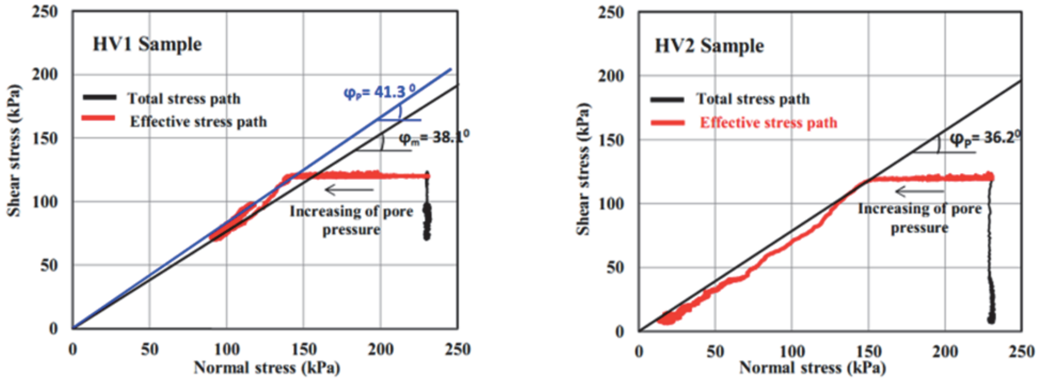

Fig. 8 Effective stress path of pore-water pressure control tests on HV1 sample (left) and HV2 sample (right)

(2) Rainfall-induced landslide simulation with pore-water pressure control tests

Rainfall-induced landslides were produced by increasing gradually pore-water pressure simulating the rise of ground-water level during rainfalls. In these tests, both samples were consolidated to 230kPa in normal stress and 120 kPa in shear stress. Then pore-water pressure was increased up to 200 kPa at a rate of 1.5 kPa/sec for HV2 sample and at a lower rate of 0.2 kPa/sec for HV1 sample due to its low permeability. The test results of two landslide samples are shown in the Fig. 8, with red color line showing effective stress path and black color line showing total stress path.

The results show that HV1 sample failed around 95 kPa of pore-water pressure increment while failure occurrence of HV2 sample was earlier to occur with about 80 kPa of additional pore-water pressure value. The critical pore pressure ratios of HV1 sample and HV2 sample (r_{u1} and r_{u2}) are corresponding to 0.41 and 0.34. For the HV1 sample, the friction angle at peak (φ_P) stayed at about 41.3° and for the HV2 sample, this angle value was only 36.4°.

(3) Earthquake-induced landslide simulation with un-drained cyclic loading tests

Initially the initial stress condition on sliding surface was created at 230 kPa of normal stress and at 120 kPa of shear stress in the drained condition. Next, the initial cycle of shear stress increment ±10 kPa in sine curve and the second cycle of shear stress increment is also ±10 kPa until 7th cycle and 5th cycle of shear stress increment for HV1 sample and HV2 sample respectively under un-drained condition. The results of cyclic tests of HV1 sample and HV2 sample are presented in the Fig. 9&10, respectively. Figures 9-(a) and 10-(a) present time series data of cyclic tests, where the black line represents normal stress, the red line shows the shear resistance mobilized on the sliding surface and the green line shows the control signal for shear stress which was given by the servo-stress control motor. During tests, the pore-water pressure (a blue color line) was monitored along with the shear displacement (a purple color line). Figures 9-(b) and 10-(b) show the stress path, with a red color line showing effective stress path and a blue color line showing total stress path. Similarly to the results of un-drained shear stress control tests, friction angles at peak of landslides are approximately 41.1° for HV1 sample and 36.5° for the HV2 sample.

Although shear stress of two samples reached the failure line at the last cycles of cyclic loading, shear behaviors of two samples are very different in post-failure stage. Shear displacement ceased at large displacement of 10 m for HV2 sample landslides while movement of HV1 sample landslides stopped after cyclic loading and start to move very slowly at the next cycles. The rapidly accelerated motion was produced after failure of HV2 sample. By contrast, shear displacement and deformation of HV1 sample were accumulated only during cyclic loading. Consequently, at the last cycle of shear stress loading, there was no more shear displacement and pore-water pressure generation. Thus, landslide movement stopped at around 8.4 m of shear displacement before the termination of simulation tests.

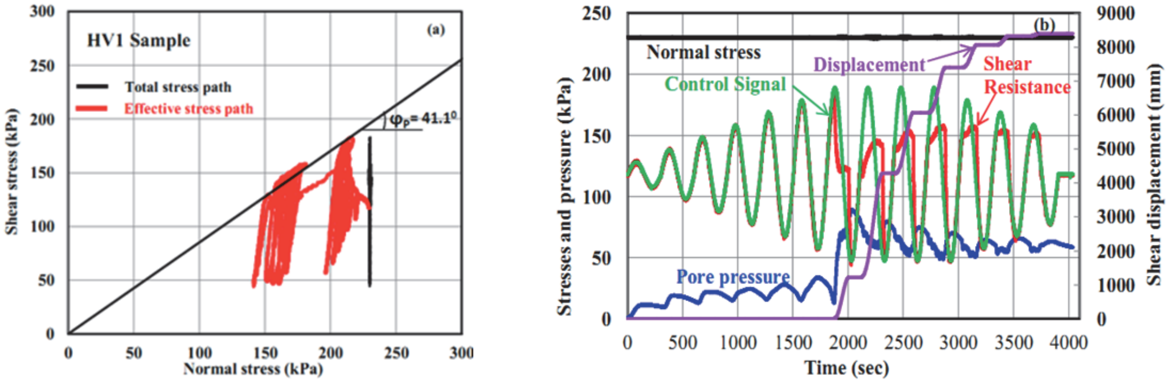

Fig. 9 Effective stress path (left) and time series of cyclic loading test for HV1 sample

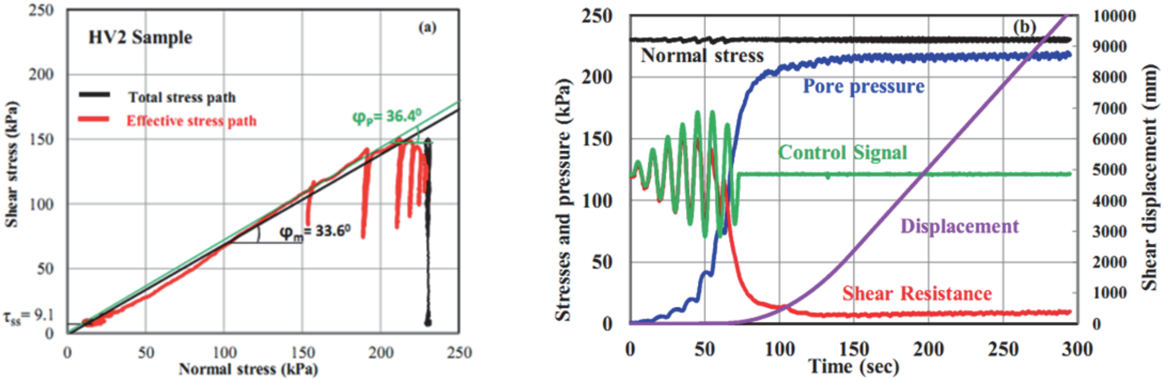

Fig. 10 Effective stress path (left) and time series of cyclic loading test for HV2 sample

5. Discussions

Test results show that HV1 sample have not generated much amount of pore-water pressure during shearing while HV2 sample produced excess pore-water pressure. Similarly, there was a much reduction in shear strength of HV2 sample whereas HV1 samples showed a small decreasing in shear strength. It means that only HV2 sample experienced liquefaction at sliding surface (Sassa, 1996 and 2000) while the phenomena did not occur in HV1 sample. Basically, this different characteristic mainly results from particular shear behaviors of two landslide prone samples of weathered granite rocks.

As seen in the results, the effective friction angle and peak angle of HV1 sample (41.0° and 36.0°, respectively) is higher than that in HV2 sample (38.0° in effective friction angle and 33.5° in peak angle). Similarly, the apparent friction angle 22.1° for HV1 sample is also larger than 5.9° of apparent friction angle of HV2 sample. Moreover, the peak shear strength of HV1 sample is about 143.5 kPa while that value is only 133.1 kPa for HV2 sample. Those values show that HV1 sample is stronger than HV2 sample in strength during shearing.

Potential of landslides occurrences can be revealed from its failure mechanism that is mainly controlled by the nature of the weathered material and mass structure of granite rocks. Based on the results from the simulation of rainfall/earthquake induced landslides, it showed that failures are more likely to occur on slopes of less weathering granitic rocks than that in slopes of strong weathering granitic rocks due to less shear strength parameters of the sample in the less weathering granitic rocks region.

Basically, the motion of the landslides on the slope behind Hai Van station can be dominated significantly by shear behaviors of both HV1 sample soil layer and the HV2 sample soil layer. Among them, HV2 sample is highly susceptible to rapid motion while HV1 sample shows a low mobility which can trigger a slow motion of landslides only. Since a very slow movement of the Hai Van station landslide monitored in the 2013 rainy season, a high possibility of potential sliding surface of landslides exists in the layer of HV1 sample. From the point of view, the landslide will continue moving at very slow speed like a creep landslide under impacts of rainfalls along a sliding surface existing in the layer of weathered granite rocks.

6. Conclusions

The understanding of failure mechanisms and assessment of landslide potential can be examined reliably by using ring shear apparatus ICL-1 in this research, including shear stress control tests, pore-water pressure control test and cyclic loading tests. As presented in the results and discussion parts of this paper, slope failures are more susceptible to occur in the layer of HV2 sample than the occurrences in HV1 sample because the clayed-like soil sample is stronger than the sand sample in shear resistance as well as HV1 sample is more resilient to sliding surface liquefaction than the same behavior of HV2 sample. Consequently, the landslide movement is very rapid for landslides of HV2 samples but is very slow for landslides of HV1 samples. The failure characteristics of different landslide soil samples show that landslides are more likely to occur on slopes of less weathering granitic rocks than their occurrences in slopes of strong weathering granitic rocks under loading of rainfalls and earthquakes due to lower shear strength parameters of the sample in the less weathering granitic rocks region. This finding is similar like findings from previous researches on landslides in weathered granitic rocks regions, which was found by other researches before. In short, landslides are highly susceptible to occur in both slopes of Hai Van station and others in Hai Van Mountain in the future. Therefore, it is very necessary to take countermeasures to control the movement of the slope as using structural measures as well as monitoring and early warning system.

In addition, this research presented and analyzed some causative factors of landslides in Hai Van Mountain on which Hai Van landslides were induced by combination of contributing factors including climatic, morphological and geological conditions of weathered granitic area, human activities as well as rainfalls.

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