Shear deformation in unsaturated slope models due to wetting with various densities, inclination and overburden pressures

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ABSTRACT

This paper discusses an experimental study and existing site condition of rainfall induced landslide sensitive mountainous site. Soil behavior of the site was understood by using slope angle, soil gradation test. Disturbed and undisturbed soil samples were taken from the site for testing purpose. Shear deformation with the change of volumetric water content was checked by using 1.3 g/m³ and 1.4 g/m³ bulk density sample. The modified shear test apparatus was used to determine the shear failure at different slope angle such as 25, 30 and 35 degrees. Shear box sample size was 30cm x 20cm x 7cm and overburden pressure on the sample was applied by using steel plates. Constant water flow was uniformly applied on top and bottom surface of the soil sample which is enclosed by the shear box. Numbers of three moisture sensors were used in shear plane to measure the volumetric water content (VWC) and displacement transducer was used to measure the shear displacement of the shear box. The results suggest that ground with high bulk density is more resist to shear failure. The results also shown that the required moisture content for the shear failure is decreasing when increasing the sample slope angle of the similar bulk density condition.

Keywords: volumetric water content, shear failure, bulk density.

1 INTRODUCTION

Rainfall induced landslide is a major environmental problem in Japan. Shallow landslides mostly occur during the rainy season in mountainous area. Natural mountains mainly consist with unsaturated or partially saturated soil. Soil shear strength is decreased due to increase of water content of soil. Rain water penetrates in to the soil and caused to increase the soil bulk density. Water infiltration is varied according to the natural, slope angle, soil grain size distribution, void ratio, degree of saturation, etc.,(Rolando P. Orenese, 2004) large porosity is facilitating to pass the rain water in loose soil. Soil pore water pressure is increased and reduced the effective soil shear strength significant amount. Finer particles of mountain soil are accumulating in valley area and which create clogging situation for infiltrated rain water. This valley area is turned to unstable state when the pore water pressure reached critical state. Change of volumetric water content of soil is used as a method to early warning for landslide (Chae and Kim, 2011).

“Mansawa” slope site is located Yamanashi prefecture (35°12'1"N 138°31'25.0"E) in Japan. Currently one portion is starting to landslide onwards to major road and brook (Fig. 1). Currently blue colour polythene layer is used to cover the failure area to avoid the water infiltration. There are valley and crest area on the mountain as knuckle shape of the hand.

Fig. 1. Landslide area of “Mansawa” slope site.

2 METHODOLOGY

2.1 General observations

Soil samples were taken from different location to check the soil gradation, Specific Gravity and
maximum dry density. Natural slope angle also was measured by using a clinometer and which was very from 25 to 49 degrees (Fig. 2(a)). Undisturbed soil core samples were taken by using metal rings (Fig. 2(b)).

Soil gradation is shown different curve according to the location (Fig 3). Sample no 01 was taken from crest part of the mountain. Its medium grain size is 0.8 (Table 1). Sample no. 02 and 04 was taken near the existing failure location and its medium grain size is 1.6mm. Natural slope angle of above three samples is varying about 25 to 38 degrees. Sample no. 03 was taken at a natural slope angle about 49 degrees (Fig. 1). Its medium grain size is 5.5mm. The stabilizing force of the soil is reduced with the soften of intermediate particles. Granular soil is created a thicker shear band which creates a high stability than fine particle arrangement. Shear strength is a physical force that held by the soil mass.

Standard Test for Specific Gravity test was conducted for the “Mansawa” soil (ASTM D 854-00) and which was 2.58. Standard proctor compaction test was used to determine the optimum moisture content.

| Sample no. | Slope angle (Degree) | Site behavior | Medium grain size ($D_{50}$) |
|------------|----------------------|---------------|------------------------------|
| 01         | 35°                  | Crest part    | 0.8                          |
| 02         | 30°                  | Valley part   | 1.6                          |
| 03         | 49°                  | Crest part    | 5.5                          |
| 04         | 25°                  | Valley part   | 1.6                          |

Its moisture content was 14.8% when it reaches the 1.81 g/cm$^3$ maximum dry densities (Fig. 4).

### 2.2 Shear apparatus and test method

Volumetric water content (VWC) and shear displacement is varied according to the bulk density of soil. Series of shear experiment were used to investigate the relationship between the soil bulk density and volumetric water content under the different overburden pressure. The modified shear apparatus was used to observe the shear failure of “Mansawa” soil samples.

Model of surface layer is subjected to constant overburden pressure during the entire period of the test. Water is supplied from the top surface and the bottom surface as constant pressure (0.05MPa) to the soil sample. Soil sample size is 4200cm$^3$ (30cm x 20cm x 7cm). Water is absorbed by soil sample and drained water collected to the volumetric flask. Supplied water amount and drained out water amounts were measured and recorded by manually. The sample was prepared on a horizontal bed before incline the required slope angle (Fig. 5). Shear box consists with 10th plates. The upper 5th plates and the lower 5th plates were bound by pins. Only one slip plane is allowed center part of the shear box. Each plate has a rectangular opening of 30cm x 20cm. The thickness of each aluminum plate is 5mm. Teflon layers used between the two aluminum plates to reduce the friction between the confining plates. The thickness of a Teflon layer was 1 mm, soil is filled into a space surrounded by stacking 10 confining plates.

Displacement transducer is used to measure the shear displacement. Shear plane is the center of the sample box. The upper portion of the sample box is moving downward along the slip surface during the shearing stage. Displacement transducer was connected to the upper part of the sample box to read the displacement in every second (Uchimura. et al. 2011).
Volumetric water content is measured by using moisture sensors which located upper, middle and top location of the soil sample in shear plane (Fig. 06). The soil is used to fill the sample box up to top level over the three sensors. Every second it was created the data regarding the volumetric water content of the sample.

“Mansawa” site soil was used for the experiment. Fine content of this soil is 2.1%, $D_{50} = 1.6mm$, specific gravity $G_s = 2.58$, porosity = 0.6 (Fig. 3). Soil sample was compacted to have a relative compaction of 55% (sample dry density of 1.309 g/cm$^3$ and maximum dry density of 1.81 g/cm$^3$) and a water content of 12%. Bed angle was tested at 25, 30 and 35 degree s. Overburden pressure is given by the steel plates which located over the soil sample. The total weight of the steel plates and the top plate on the soil mass is 728N and surface area of the sample is 600cm$^2$ (20cm x 30cm). Soil sample is subjected 13.4kPa (728N/ (600cm$^2$ x cos25$^\circ$)) =13.4kPa vertical stress during the shearing process.

3 TEST RESULTS

3.1 Shear failure of different density samples
Shear test was conducted by changing the bulk density of the sample. Details are given table 1 as follow

| Test no (Fig. no.) | Overburden pressure (kPa) | Soil bulk density (g/cm$^3$) | Slope angle (degree) |
|-------------------|---------------------------|----------------------------|---------------------|
| 7                 | 13.4                      | 1.3                        | 30                  |
| 8                 | 13.4                      | 1.4                        | 30                  |

Shear displacement of soil (different density) mass with volumetric water content is shown in Figure 7 and 8. Soil mass was subjected 1.3g/cm$^3$, and 1.4g/cm$^3$ bulk density. Slope angle was 30 degree and other condition kept the same. The displacement developed according to the increment in volumetric water content. Figure 7 and Figure 8 are shown high increment of volumetric water content of lower sensor. The shear displacement path pattern had changed due to increasing the bulk density of the sample. Average volumetric water content was 0.15m$^3$/m$^3$ and 0.16m$^3$/m$^3$ at Shear failure stage of Fig. 7 and Fig 8 samples respectively.

These behaviors can be summarized as shown in Figure 9. Time is plotted on the horizontal axis, while the shear displacement and volumetric water content are plotted on the both vertical axis. The shear displacement rate is decreasing when increasing the bulk density (Fig. 9). More time was consumed to shear failure when increasing the bulk density of the sample.

Shear displacement of 1.3g/cm$^3$ samples is increased with the increase of volumetric water content (Fig. 9). It had taken 1540 second (01 hours 01 minutes and 05 second) for shear fail. Shear displacement of 1.4g/cm$^3$ samples also is increased with the increase of volumetric water content, but its taken 3184 second (02 hours 16 minutes and 40 second) for shear fail (Fig. 9). Thus, we can find a relationship between volumetric water content and shear deformation with the different bulk density of the soil mass. It is shown in Figure 9.
Fig. 8. Shear displacement Vs Average volumetric water content at 1.4 g/cm³ bulk densities, slope angle at 30° degree and 13.4 kPa overburden pressure.

Fig. 9. Time Vs volumetric water content Vs Shear displacement of different density (1.3g/cm³ and 1.4g/cm³), slope angle at 30 degree and 13.4 kPa overburden pressure.

3.2 Shear failure of different slope angle samples
Shear tests were conducted by changing the slope angle while the overburden pressure of the sample and density was not changed. Details are given Table 3 as follow:

Table 3. Volumetric water content changes of different bed level samples.

| Test no (Fig. no.) | Overburden pressure (kPa) | Soil bulk density (g/cm³) | Slope angle (degree) |
|--------------------|--------------------------|--------------------------|---------------------|
| 10                 | 8.5                      | 1.3                      | 25                  |
| 11                 | 8.5                      | 1.3                      | 30                  |
| 12                 | 8.5                      | 1.3                      | 35                  |

Figs. 10, 11 and 12 show the increment of volumetric water content at slope angle 25, 30 and 35 degrees respectively. Failure moisture content value is 0.41m³/m³, 0.31m³/m³ and 0.19m³/m³ respectively. Summary of the results is shown in Table 4:

Table 4. Result of volumetric water content changes after the shear failure.

| Slope angle (degree) | Volumetric water content at the failure |
|----------------------|----------------------------------------|
|                      | Upper | Middle | Lower | Average |
| 25                   | 0.41  | 0.39   | 0.41  | 0.40    |
| 30                   | 0.07  | 0.34   | 0.18  | 0.19    |
| 35                   | 0.05  | 0.19   | 0.10  | 0.11    |
All three sensors reading was shown similar behavior of slope angle 25 degree sample (Fig. 10). It is shown that water had penetrated as parallel to the shear plane. When increasing the slope angle water penetration path was changed. Slope angle 30 and 35 degree sample shown different moisture content in upper, middle and lower sensors. Average volumetric water content with time and displacement changes shows in Figure 13. Average volumetric water content at failure was decreased when increasing the slope angle according to Table 4.

![Shear displacement Vs Volumetric water content Vs time at 1.3 g/cm³ bulk densities, slope angle at 25, 30 and 35 degree at 8.5 kPa overburden pressure.](image)

Fig. 13. Shear displacement Vs Volumetric water content Vs time at 1.3 g/cm³ bulk densities, slope angle at 25, 30 and 35 degree at 8.5 kPa overburden pressure.

5 CONCLUSIONS

Some of the slopes in “Mansawa” site are still stable even it showed 49 degree slope angle. According to soil gradation test which is shown higher value of Medium grain size ($D_{50}$). It means more granular soil were included in this steep slope area.

Geological behavior is also shown very stable crest part of the mountain. Water retaining ability is relatively low on the crest part when compare with the valley part of the mountain.

Shear displacement time is increasing when increasing the bulk density of the sample

Shear displacement time is increasing when increasing the slope angle of the sample.

Low slope angle (example 25 degrees) need more moisture content and more time to shear failure rather than a high slope angle condition.

The authors tried to understand the soil behavior of “Mansawa” site by using soil gradation, relative density test and the specific gravity test. Shear displacement behavior was studied by using scaled model test under the different bulk density condition. Volumetric water content and slope angle were maintained in constant value and observed shear displacement with time. Soil sample was subjected different bulk density and shear displacement result changed according to the change of density. When increasing the bulk density of the sample shear displacement rate is decreasing. Site bulk density can be measured by using a manual cone penetration test. Then these data can be used for early warning purpose by using above experiment data.

ACKNOWLEDGEMENTS

This work was supported by Council for Science, Technology and Innovation, “Cross-ministerial Strategic Innovation Promotion Program (SIP), Infrastructure Maintenance, Renovation, and Management”. (funding agency: NEDO), as well as Grants-in-Aid for Scientific Research of Japan Society for the Promotion of Science (JSPS), and Coreto-Core Program “B. Asia-Africa Science Platforms” (JSPS).

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