The mechanism of long-time displacement in a colluvium slope underlain by mudstone

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ABSTRACT

This paper aims to investigate the mechanism of an unstable slope with a long-time displacement. The unstable slope is located along the coast and covered with colluvium underlain by mudstone. Rainfall is considered the main source for triggering the slope displacement. Slope inclinometers are installed at the site, and sensors for measuring soil water content are installed in the colluvium and in the mudstone deposits. The water content in the colluvium with a thickness of 0.5~1 m above the mudstone increases considerably during rainfall, and the mudstone deposit is also highly saturated. These data imply that discontinuities or thin permeable deposits, e.g. sand layer, may exist in the mudstone and provide channels for rainfall-induced subsurface runoff to reach the inside of the mudstone. The mudstone deposit underneath the colluvium undergoes displacements during high-intensity rainfall based on data of slope inclinometers. Creep behavior in the mudstone deposit may take place due to its high saturation. The high saturation with a thickness of 1 m above the colluvium-mudstone interface during rainfall and high saturation in the mudstone deposit are major reasons for the long-time displacement in the colluvium slope.

Keywords: colluvium, mudstone, soil water content, rainfall, slope displacement

1 INTRODUCTION

Slope failures are mainly governed by topography, geology, vegetation and rainfall characteristics etc. Rainfall-induced infiltration in the slope results in an increase in soil water contents and possible rise in the groundwater table. These behaviors are strongly relevant to the stability of the slope. Early warning for slope failures can be issued based on rainfall characteristics. Caine (1980) collected the correlation between rainfall intensity (I) and duration (T) based on field failure cases for establishing the rainfall threshold of occurrence of debris flow. Researchers also established the I-T threshold of slope failures in some of the countries and regions (Iverson, 2000; Guzzetti et al., 2008; Dahal and Hasegawa, 2008; Saito et al., 2010). However, the reliability of the model may be questioned due to the variation of geological condition, soil composition, vegetation, topography and characteristics of the catchment area, etc, in the local area.

Rainfall is considered the major cause for triggering slope failures in the Pacific region. The influence of rainfall on the soil stability in a slope is affected by the local topography, soil composition and vegetation. The behavior of soil water content in a slope during rainfall is one of the main reasons relevant to slope instability.

This research aims to investigate the mechanism of a long-time displacement in a colluvium slope by carrying out field instrumentations on soil water contents and slope displacements. In addition, explorations of electric resistivity in the slope are also conducted to investigate the distribution of liquid (water) in the geological deposit.

2 MATERIALS AND METHODS

2.1 Geology, topography and hydrology at the site

The slope is located along the coast and covered with colluvium underlain by mudstone. The colluvium is resulted from old landslides of limestone deposit. The thickness of the colluvium, consisting of mainly decomposed limestone and soils with different particle sizes, varies from 3 meters to about fifteen meters in the area with noticeable slope displacements. Figure 1 shows the aerial view of the slope.

The slope is westward with an average gradient of 15°-25°. A village (Chai-san) is located at the lower
elevation of the slope. Subsidence on the paved road, tension cracks on the slope and displacements in the buildings can be identified at the site. Figure 2 shows an abandoned building with a displacement of 3 to 4 m away from a paved road. The catchment area for the slope is about 30 hectares. The village is located at the downslope of the catchment. Figure 3 shows the topographic map for the area.

Fig. 1. The aerial view of the slope.

Fig. 2. The displaced building beside a paved road.

Fig. 3. Topographic map at the site.

2.2 Instrumentations
Slope inclinometers, observation wells for ground water and settlement points are installed at different locations in the slope. In addition, moisture sensors are also installed at various depths at the site and are monitored every hour by an auto-logging system. The location of the instrumentation station SM12 in the village is shown in Figure 3.

2.3 Exploration of electric resistivity
The electrical resistivity is relevant to soil constituents (particle size distribution, mineralogy), arrangement of voids (porosity, pore size distribution, connectivity), degree of saturation (water content), electrical resistivity of the fluid (solute concentration) and temperature (Samouelian, et al., 2005). The exploration of electric resistivity is conducted in a number of vertical cross-sections in the slope. The electrical resistivity is closely correlated with the distribution of soil water content in the slope.

3 RESULTS AND DISCUSSION
3.1 Displacement in the slope
The village in the slope has been experiencing a noticeable displacement for the past 30 years. Figure 4 shows the displacement vector on the slope recorded from 2013 thru 2016 by GPS data. Some of the area in the slope experience displacements of more than 10 cm in a year. Additionally, a number of slope inclinometers cannot work properly after operation for a number of years due to considerable lateral displacements in the inclinometer at a given depth.

Fig. 4. Displacement vector on the ground surface of the slope from 2013 thru 2016 (5 cm in the figure: displacement scale).

3.2 Variation of soil water content with time
Soil shear strength in a slope is expected to be downgraded by rainfall-induced infiltration. Variation of soil water contents with time from April thru December of 2107 at various depths (0.15~8m) for the instrumentation stations SM12 with noticeable slope displacements is shown in Figure 5. Soil water contents at the shallow depths varied closely with the precipitation. The mudstone is located at 3.5 m below the ground surface at the instrumentation station SM12. The mudstone at the depth of 5~8 m is highly saturated.
based on test data for most of period in a year. In addition, a tremendous increase in (volumetric) soil water content is observed at the depth above the colluvium-mudstone interface following the rainfall, and the soil water content at the depth drop to a low value (about 10-15%) after the rainfall. The large catchment area for the slope results in a considerable infiltration and subsurface runoff during rainfall.

In addition, observation wells for the groundwater table are installed in various locations in the slope. The groundwater level at the instrumentation station SM12 from 2016 thru 2017 is shown in Figure 6. No groundwater is observed during dry season in a year, whereas, rainfall-induced groundwater accumulates in the colluvium above the colluvium-mudstone interface. The groundwater in the colluvium may last for a couple of days in a heavy rainfall. The subsurface flow along the soil-mudstone interface may downgrade the shear resistance of the slope and cause displacements in the interface. Additionally, the high saturation in the mudstone deposit may soften the strength of the mudstone and trigger displacements in the slope.

![Figure 6. Variation of groundwater level at the instrumentation station SM12 from 2016 thru 2017.](image)

3.3 Electrical resistivity

The exploration of electrical resistivity of the soil in a slope is an indicator of the spatial distribution of soil water content in the geologic deposit. The exploration of electrical resistivity in the slope was conducted near the instrumentation station SM12 from the higher elevation to lower elevation of the slope. Figure 7 shows the distribution of the electrical resistivity in the vertical cross section of the slope close to the instrumentation station SM12 (shown in Figure 3). The electric resistivity in the geological materials is closely relevant to the level of water saturation in the geological material. The electrical resistivity for most of the mudstone deposit is less than 20 Ohm-m. For the electrical resistivity less than 10 to 20 Ohm-m, the voids in the geological material is expected to be filled with water. A geological exploration to a depth of 8 m was carried out at the station SM12 in 2018. The degree of saturation in the mudstone samples from the depth of 4 m to 8 m was in a range from 75% to 90%.

![Figure 7. Distribution of electric resistivity in a vertical cross section in the slope (Modified from Kaohsiung city government, 2014).](image)

3.4 Slope displacement

The slope displacement near the instrumentation station SM12 was measured for the past years by the slope inclinometer installed at the site. Lateral slope displacements with depth at the instrumentation station (SM12) from Nov. 2016 thru July 2017 are shown in Figure 8. The slip plane in the slope can be identified at a depth of 3 m. It is located at the colluvium-mudstone interface, a depth of 3.6 m based on the geological exploration. Nevertheless, the data show significant lateral displacement in the mudstone deposit, below the depth of 3.6 m. Highly saturated condition in the mudstone deposit is one of the reason blamed for the significant lateral displacement.
4 MECHANISM OF SLOPE DISPLACEMENT

Noticeable lateral displacement in the mudstone deposit is observed by the long-time monitoring of slope inclinometers in the slope. The groundwater level is not observed in the colluvium for most of the year in dry season. The colluvium deposit collects subsurface runoff during rainfall, and the runoff flows towards the shoreline in a short period of time (in a couple of days) following the rainfall event. Nevertheless, a highly saturated condition is identified in the mudstone deposit by testing the mudstone core in a geological exploration at the instrumentation station SM12. An illustration demonstrating the geological formation and hydrological condition in the area is shown in Figure 9. The slope dips towards the shoreline. The mudstone deposit can be identified along some area of the shoreline, and colluvium may rarely exist under the sea level. A fresh water-salt water interface is present somewhere in the mudstone deposit in this area (Figure 9). The salt water has a higher density than fresh water. The rainfall-induced infiltration at the catchment area of the slope accumulates at the lower elevation of the slope near the coast, and the fresh water may have little chance to flow into sea due to the barrier of salt water in the mudstone (Figure 9). The highly moist condition in the mudstone deposit underneath the colluvium softens its shear resistance, and creep deformation may occur in the mudstone with a high saturation. The hydrological condition in the slope, especially in the mudstone deposit results in the long-time displacement in the slope.

5 CONCLUSIONS

This paper presents a failure case of a long-time displacement for a slope near the coastline. The slope is covered with colluvium, underlain by mudstone deposit, at a depth of 3~8 meters. Slope displacement along the depth, soil water contents and the groundwater level are monitored for the slope. The fresh water-salt water interface exists in the mudstone deposit, and it intrudes somewhere in the slope. A high saturation in the mudstone deposit in the slope is observed, and it may be resulted from the presence of the fresh water-salt water interface. The lateral displacement in the mudstone deposit is clearly identified. Creep deformations in the mudstone deposit may be present. The displacement in the colluvium induced during rainfall and the potential creep deformations in the mudstone deposit are major failure mechanism for the slope

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