Velocity and Acceleration of Surface Displacement in Sandy Model Slope with Various Slope Conditions

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Abstract

Measurement of surface displacement was implemented in three model slope test cases under constant intensity of artificial rainfall with different initial water content or slope inclination. The aim was to examine the relationship between velocity and acceleration of the increase in the surface displacement, which is the basis for predicting the failure time of a slope (Fukuzono T (1985) A New Method for Predicting the Failure Time of a Slope. In Proceedings of the IVth International Conference and Field Workshop on Landslides, Tokyo, Japan, pp 145–150.). The velocity and acceleration were derived from actual measured surface displacements. The relationship between the velocity and acceleration of the increase in the surface displacement was unique at different locations on the slope and with different pore pressure loading mechanisms (under unsaturated conditions or increased groundwater levels). The relationship was also unique under different slope inclination. This suggests the possibility of deriving the relationship by indoor shear tests with the same soil of actual slopes before monitoring of displacement on the slope, for predicting the failure time of the slope.

Keywords

Monitoring • Surface displacement • Model slope • Slope angle • Water content

Introduction

Measurement of slope displacement or deformation has often been adopted for early warning against landslides. This has also been implemented in many experiments involving model or natural slopes to examine the mechanism of landslides.

Acceleration of slope displacement or deformation have been observed prior to failure in many reports such as Moriwaki et al. (2004) for a model slope, and Ochiai et al. (2004) and Askarinejad et al. (2018) for natural slopes. Kromer et al. (2015) observed variation in the topography of a rock wall surface before and after collapse and identified accelerating increase in displacement by analysing the displacement of targets on the wall. Accelerative increase in displacement has been recognised as a precursor of slope instability. Many studies (Saito 1965; Saito and Yamada 1973; Varns 1982; Fukuzono 1985; Voight 1988, 1989; Xiao et al. 2009; Bozzano and Mazzanti, 2012) helped establish the method for better prediction of time of an onset of slope failure, based on the measurement of an accelerative increase in displacement.

Fukuzono (1985) reported that there is a linear relationship between velocity and acceleration of an increase in surface displacement (hereafter the displacement velocity and acceleration) on a logarithmic scale prior to slope failure of the model, and showed that any prediction method of slope failure time is preferable to be based on the relationship. This idea proposed by Fukuzono has been widely adopted around the world. Further, he insisted that the relationship could only be established during the tertiary creep stage, when there is an accelerating increase in displacement. It is for now not clear whether unique relationship can be derived for slopes with different geometry or initial conditions even though they are made of the same soil. An attempt is made herein to examine, through a series of indoor experiments, if we can derive a unique relationship for various slope models of the same soil, expecting that the

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N. Casagli et al. (eds.), *Understanding and Reducing Landslide Disaster Risk*,
ICL Contribution to Landslide Disaster Risk Reduction,
https://doi.org/10.1007/978-3-030-60311-3_37

result would help develop a rational protocol for early warnings.

Displacements and groundwater levels in model slopes with different initial conditions were measured and those data were analysed to clarify whether the relationship between the displacement velocity and acceleration is unique under different initial conditions of the slope model in this study.

Methodology

Experimental Apparatus

Figure 1 shows a lateral view of the model slope and arrangement of monitoring devices. The model slope was in a steel flume with a lateral wall of glass and consisted of granite soil, with the grain size distribution shown in Fig. 2. The density of soil particles was 2.489 (g/cm^3), and the maximum and minimum densities were 1.307 (g/cm^3) and 1.073 (g/cm^3), respectively. The upper slope was 110 cm long, 60 cm wide, 12 cm thick, and with a inclination of 40°. The lower slope was 50 cm long, 60 cm wide, 12 cm thick at the boundary of both slopes, with 10° of surface slope. The shape of the upper slope was rectangular, and that of the lower slope was triangular. Steel blades (1 cm high) were set at every 50 cm in a downward direction, and coarse sand was glued on the base plate of the flume to prevent slippage between the soil and the base plate.

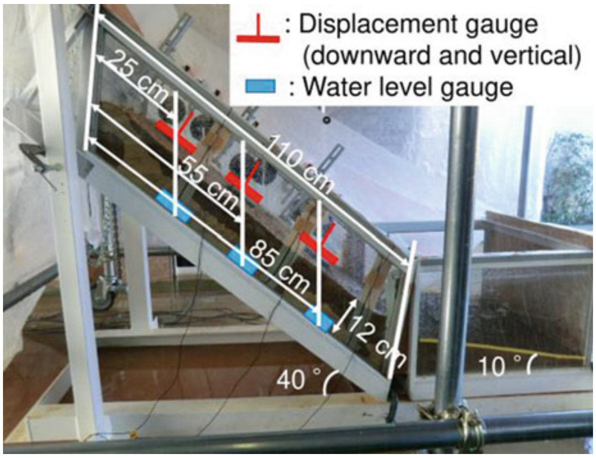


Fig. 1 Model slope and arrangement of monitoring devices in Case 1

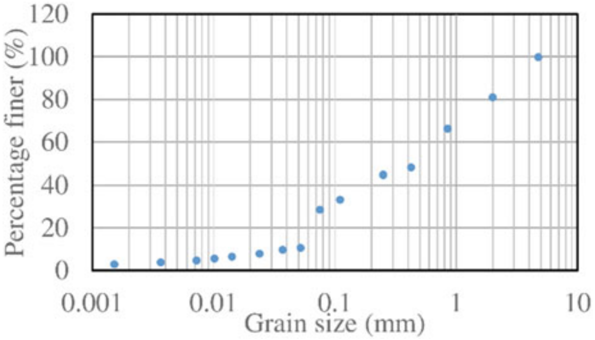


Fig. 2 Grain size distribution of the soil of the model

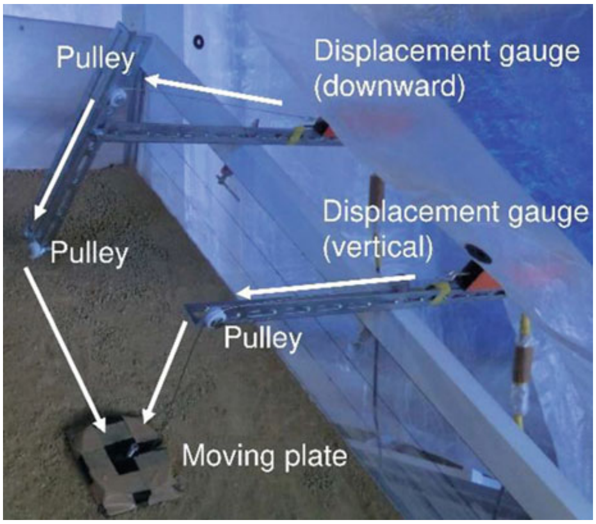


Fig. 3 Measurement of downward and vertical displacements

Downward and vertical displacement at the surface and pore pressure at the bottom of the upper slope were measured at distances of 25, 55, and 85 cm from the upper boundary of the flume. The downward and vertical displacements were measured by the system shown in Fig. 3. Downward or vertical movement of the moving plate on the surface of the slope pulled wires connected to displacement gauges, which were set lateral to the flume. Dimension of moving plate is 10 by 10 cm with four steel blades of 1 cm height behind it to prevent slippage on the surface. Weight of the moving plate was 700 g to resist reaction force of displacement gauge. The direction of the wire was changed from downward to vertical and from vertical to lateral by two pulleys for the measurement of downward displacement, while it was changed from vertical to lateral by a pulley for the measurement of vertical measurement. Pullies were made of acrylic resin to prevent friction between pullies and wires. Only downward displacement was adopted as the surface displacement in this study, because vertical displacement could not be accurately measured. Many noises and scattering were found in the vertical displacement measurements. The accuracy of the displacement gauge was 0.2 mm, and the accuracy of the pore pressure gauge was 50 Pa, which corresponded to 0.5 mm of water level. The measured pore pressure was converted into a water level in this study. Trial in small scale model revealed the accuracy of the measurement in groundwater level was around 1 cm.

Table 1. Conditions of the model slope

	Case1	Case2	Case3
Rainfall intensity (mm/h)	46	46	46
Dry unit weight (g/cm^3)	1.32	1.21	1.32
Water content (%)	0	15.1	0
Upper slope angle (deg.)	40	40	35

Water was sprinkled at a constant rate on the model slope from the rainfall simulator above the flume. The quantity of water sprinkled was expressed in rainfall intensity (mm/h) in these experiments, as shown in Table 1.

Experimental Conditions

Three cases of the experiment with different model slope conditions (Table 1) were implemented to examine the relationship between surface displacement velocity and acceleration for different slope conditions. Water content was different between Case 1 and Case 2. It was 0 and 15.1% in Case 1 and Case 2, respectively. Soil was dried in oven before the construction of the model and water content was measured by soil moisture gauge of METER EC-5 with 2–3% resolution. The wet unit weight in Case 2 was 1.32 (g/cm^3), which was the same as the dry unit weight of Case 1. Oven dry soil with this dry unit weight was adopted after many trial using small model to make non-uniformity of soil quantities in model slope least. The upper slope angle was 40° in both cases. The upper slope angle was 40° and 35° in Case 1 and Case 3, respectively. The slope of the model was almost same with shallow landslides in Japan. The dry unit weight and water content was the same in both cases, and the rainfall intensity was 46 mm/h in all cases. This was also decided by actual rainfall intensity at landslide disaster in Japan. Two times of tests with the condition of Case 1 were conducted and results of both cases were compared to ensure the repeatability of the experiment. The surface displacement was 22 cm at 8,400 s in first case while it was 25 cm at the same time in second case.

The surface displacement velocity and acceleration were derived from measured data of surface displacement, by the process shown in Fig. 4. Quantitative variation of the vector of the surface displacement was adopted here. Surface displacement velocity was defined as the increase in surface displacement divided by the difference in time. Surface displacement acceleration was derived as the increase in surface velocity divided by the difference in time.

Video images were recorded from lateral side of the model and no slippage was observed from the images.

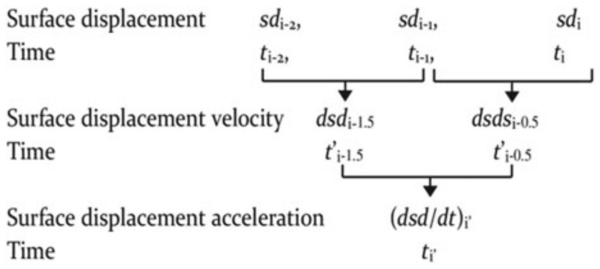
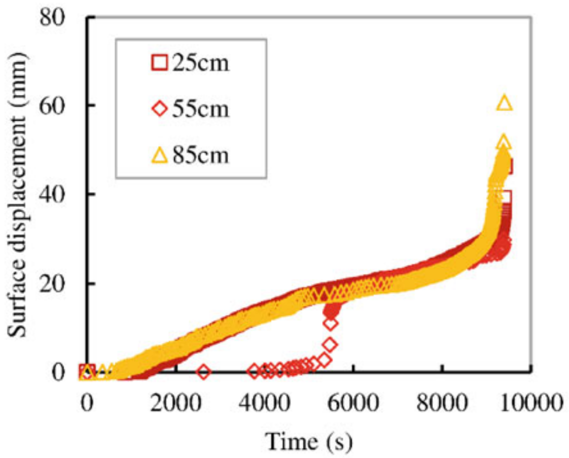


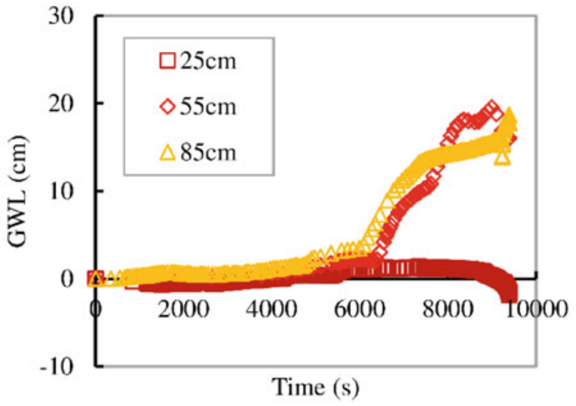
Fig. 4 Definition of surface displacement velocity and acceleration

Results of the Experiments

Figure 5a and b show the time variation in the surface displacement and the groundwater levels, respectively, at different locations on the model slope for Case 1. The surface displacement gradually increased from the start of the water



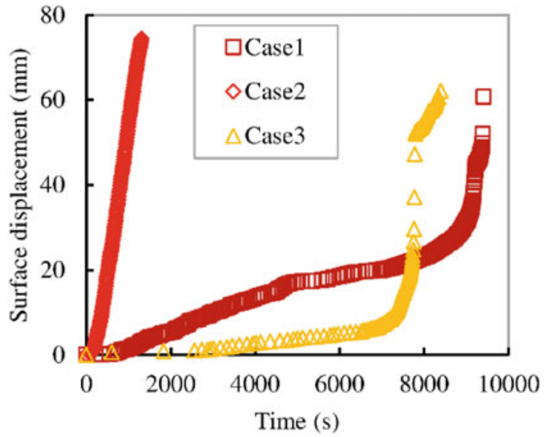
(a) The surface displacement



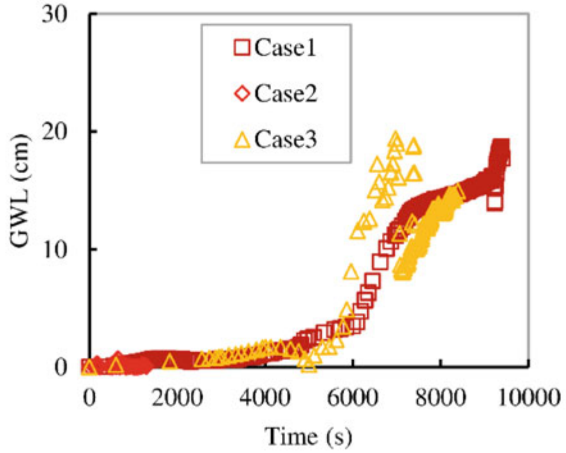
(b) The groundwater level

Fig. 5 Time variation of the surface displacement and the groundwater level at Case 1. GWL: groundwater level sprinkling, and exhibited an accelerative increase just prior to failure of the slope at 25 and 85 cm, while it remained at almost zero until 5,500 s and then significantly increased until 20 at 55 cm. It subsequently increased gradually, and increased again acceleratively up to failure at 55 cm. Groundwater levels remained almost zero until 6,000 s, and increased up to 15–20 cm until the failure at 55 and 85 cm, while it remained almost zero until the failure at 25 cm. It is noteworthy that surface displacement increased even before the generation of the groundwater level. Shear deformation of the slope might have been generated even under unsaturated conditions at this stage. The surface displacement increase accelerated with the increase in groundwater level. Time variations in the surface displacement and the groundwater level also had the same tendency in Case 3, which showed a different tendency to Case 2.

Figure 6a and b show comparisons between the surface displacement and the groundwater level at 85 cm in each case. The surface displacement significantly increased after the generation of the groundwater level, and exhibited accelerative increase with the increase in groundwater level just prior to failure in Case 1 and Case 3. It increased linearly with time without the generation of the groundwater level in Case 2. Failed soil mass moved into earth flow and deposited on the surface of the lower slope in Case 1 and Case 3. It contained a considerable quantity of water because the groundwater level was high at slope failure; thus, it could flow into the earth flow. While the failed soil mass was relatively dry in Case2. This was because the groundwater level was almost zero at failure, even if the initial water content was higher in Case 2 than in the other cases. It was observed by video image that the dry soil mass moved almost in one-piece, and it was pushed back by the soil layer of the lower slope in Case 2. Movement and deformation of the soil mass of the upper slope might have been restrained in this way in Case 2.



(a) The surface displacement



(b) The Groundwater level

Fig. 6 Comparison of the surface displacement and the groundwater level at 85 cm from upper boundary in each case. GWL: the groundwater level

Discussion

Figure 7 shows the relationship between the surface displacement velocity and acceleration at different distances from the upper boundary of the slope in Case 1 on a logarithmic scale. It was recognised that the relationship may have been linear on a logarithmic scale with some scatter, while the time variation of the surface displacement was different in each case. The relationship may have been almost unique, even though there was some scatter at different locations on the model slope.

Figure 8 shows the relationship between the surface displacement velocity and acceleration before and after the generation of the groundwater level at 85 cm from the upper

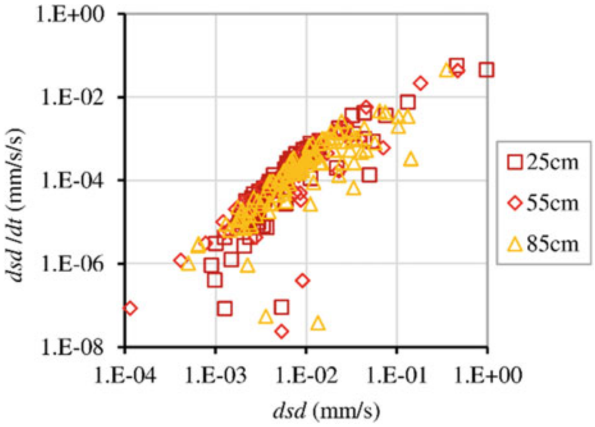


Fig. 7 Relationship between the surface displacement velocity and acceleration at different locations in Case 1. *dsd*: surface displacement velocity (mm/s). *dsd/dt*: surface displacement acceleration (mm/s/s)

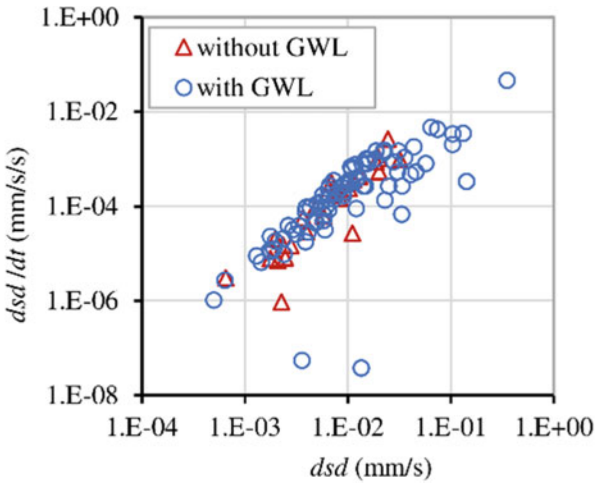


Fig. 8 Relationship between the surface displacement velocity the acceleration before and after the generation of the groundwater level at 85 cm from the upper boundary of the slope in Case 1. *dsd*: surface displacement velocity (mm/s). *dsd*/*dt*: surface displacement acceleration (mm/s/s). GWL: groundwater level

boundary of the model in Case 1. Red triangles symbolise before the generation of the groundwater level, while blue circles represent after the generation of the groundwater level. The relationship before the generation of the groundwater level was linear on a logarithmic scale, and almost the same as after the generation of the groundwater levels. The surface displacement was generated by the decrease in the suction of the slope (in unsaturated conditions) before the generation of the groundwater level, while it was generated by the decrease of effective stress in the slope due to the increase of static pore pressure (groundwater level) after the generation of the groundwater level. The relationship between the surface displacement velocity and acceleration was the same in both cases.

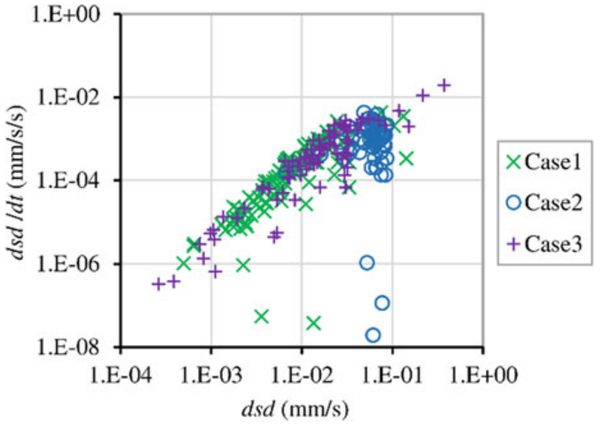


Fig. 9 Comparison of the relationship between the surface displacement velocity and acceleration at 85 cm from the upper boundary of the slope in each case. *dsd*: surface displacement velocity (mm/s). *dsd*/*dt*: surface displacement acceleration (mm/s/s)

Figure 9 shows a comparison of the relationship between the surface displacement velocity and acceleration at the same distance (85 cm) from the upper boundary of the slope in each case on a logarithmic scale. The relationship in Case3 was also linear on a logarithmic scale and almost the same as that in Case1 in the range of the surface displacement velocity from 1E-03 to 1E-01 mm/s. While the relationship in Case 2 gathered around the linear trend in Case1 and Case3 from 1E-02 to 1E-01 mm/s of the surface displacement velocity and did not indicate a clear trend. The range of the surface displacement velocity in Case2 was from 1E-02 to 1E-01, much smaller than the range (1E-03 to 1E-01 m/s) in Case1 and Case3. These might have been due to the restraint of the movement of soil mass in Case2. It was revealed that the relationship between the surface displacement velocity and acceleration was unique under different inclination of model slope.

Conclusion

Measurement of surface displacement was implemented in three cases of model slope test under artificial rainfall conditions. Initial water content and slope inclination were different in the three cases. The surface displacement velocity and acceleration were derived from the measured surface displacement and the relationship between those in each case was compared. Following are the results of the examination.

(1) The surface displacement showed accelerative increase just prior to the failure of the slope with the increase in the groundwater level in Case 1 and Case 2 with different slope inclinations, while it increased monotonically with time in Case 2 without the generation of the groundwater level. Movement of the soil mass in upper slope was restrained by the lower slope in a relatively dry condition for Case 2.

(2) The relationships between the surface displacement velocity and acceleration at different locations were unique in Case 1 and Case 3.

(3) The relationship between the surface displacement velocity and acceleration before the generation of the groundwater level was similar to that during the increase of the groundwater level. The relationship in unsaturated conditions was same with that after the generation of the groundwater level.

(4) The relationship between the surface displacement velocity and acceleration was unique under different slope inclinations. However, the influence of initial water content to the relationship was not clear in this

study. Accordingly, further examination is necessary to reveal the influence of the water content to the relationship.

It was recognised that the relationship between the surface displacement velocity and acceleration was unique under different slope inclinations with the same soil. This fact suggests the possibility of deriving the relationship by indoor shear test before monitoring the displacement of actual slopes to predict the failure time of the slope. While much more examination are necessary to verify the relationship in a different condition and scale in a slope.

Part of this research is supported by the Grant-in-Aid for Scientific Research B -KAKENHI-, 18H01674, JSPS.

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