Long-term landslide creep and the effect of rainfall-driven criterion and catchpits utilizing SAA monitoring and rainfall data

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ABSTRACT

In this study, SSA and real-time rainfall monitoring data are used to discuss the long-term creep of a landslide, typhoons and torrential rain, and the interpretation criterion for rain-driven landslide displacement and to examine the effect of retarding the displacement trend of the landslide after the renovation of catchpits. The results showed that the rainfall-driven displacement after the construction of the catchpits is less than that before the construction.

Keywords: landslide creep; landslide prewarning interpretation; rainfall threshold values

1 INTRODUCTION

A typical landslide displacement–time curve has three stages of evolutionary characteristics: initial displacement, constant velocity displacement, and accelerated increment displacement. Xu et al. (2009) proposed the concept of a displacement tangent angle according to the characteristics of the accumulated displacement slope of the time curve at different stages of the landslide and, on this basis, established the landslide prewarning interpretation criterion. However, owing to the differences between the physical dimensions of the vertical and horizontal coordinates of the landslide displacement–time curve, the displacement tangent angle contains imprecisely defined defects and uncertain numerical values. The research by Xu et al. (2009) served as a reference to propose a new method for obtaining a relatively explicit displacement tangent angle using the same dimensional vertical and horizontal coordinates based on coordinate transformation of the landslide accumulated displacement–time curve. Next, the landslide accelerated deformation stage was further subdivided into an initial accelerated stage, medium accelerated stage, and rapid accelerated stage by utilizing the modified displacement tangent angle to serve as the quantitative classification standard for accelerated displacement and the landslide prewarning interpretation criterion

2 SITE INFORMATION AND RESEARCH REVIEW

Figure 1 shows the location of the study site and parts of the monitoring system at Huafan University in northeastern Taiwan that are studied here. The main exposed stratum under the site is the Mushan Formation, with the bedrock being mainly interbedded with sandstone and shale. It is a dip slope striking toward the east, dipping southward approximately 10°–20°. The monitoring system set up in this site includes inclinometers, tiltmeters, crack gages, water-level observation wells, settlement and displacement monitoring marks, rebar strain gages, concrete strain gages, and rain gages. All of these monitoring instruments are continuously operational in taking regular artificial measurements (see Jeng et al., 2015, 2017). In 2014, two shape acceleration array (SAA) measurements and four piezometers were added and are taken as the reference basis for hazard prevention and maintenance of the slope. Jeng and Yang (2018) examined the monitoring and numerical analysis of groundwater variation and inclinometer displacement. The high-rise groundwater level during typhoons is thought to be the main cause of triggering the slope displacement. Two catchpits were therefore renovated to draw down the groundwater level as a countermeasure for slope stability. A preliminary study has set typhoon rainfall of more than 300 mm as the alert threshold. The long-term landslide creep, the effect of the rainfall-driven criterion, and the draining effectiveness of the two catchpits are discussed in detail.

According to Xu et al. (2009), because the slope displacement–time (S–t) curve (hereinafter referred to as the S–t curve) is significantly different in dimensions between the vertical and horizontal coordinates, if either the vertical or horizontal coordinate is stretched or compressed, the displacement–time curve can still maintain its three-stage evolution characteristics. However, the displacement tangent angle at the same time point changes because of stretching or compression transformation. For the deformation monitoring data of the same landslide, if the S–t curve is made with different coordinate dimensions, the measured values of the displacement tangent angle at the same time point will be different. That is, directly using the S–t curve to define the displacement tangent angle will have the problem of uncertainty. Therefore, Xu et al. proposed a method to determine the displacement tangent angle and make it unique through coordinate transformation and established the criteria for landslide warning based on the method.

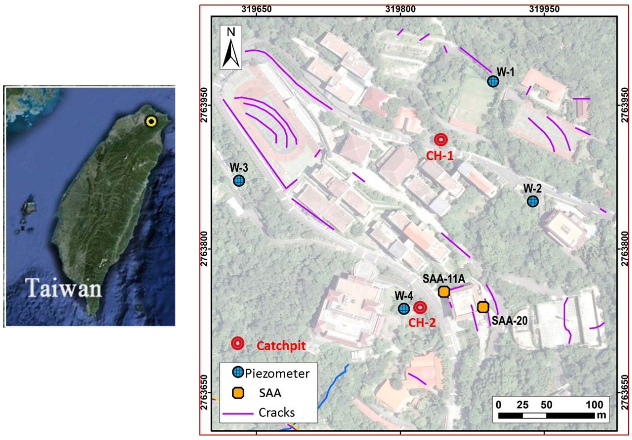

Fig. 1. Location of the study site and monitoring instruments

When using the method proposed by Xu et al. (2009) to transform the S–t curve, there should be a distinct constant velocity deformation stage in the development and evolution of the slope. During such a deformation stage, the slope deformation rate remains constant, and the displacement S has a linear relationship with time t, i.e., S = vt, where v is the displacement rate at the constant velocity deformation stage. The displacement rate v at the constant velocity deformation stage is a constant value. Then, the vertical ordinate of the S–t curve can be transformed to have the same temporal dimension as the horizontal coordinate by dividing displacement by v. That is, it is defined that $T(i)= \triangle S(i)/v$, where $\triangle S(i)$ is the amount of change in the slope displacement within a unit time period (generally one monitoring cycle is used, such as one day and one week), v is the displacement rate of the constant velocity deformation stage, and T(i) is the ordinate value with the same temporal dimension after the transformation.

After the above transformation method is applied, the corresponding T–t curve can be obtained. According to the T–t curve, an improved expression of the tangent angle αi can be obtained, $\alpha i= \arctan (\Delta T/\Delta t)$. Where αi is the improved tangent angle, Δt is the unit time period corresponding to the time of calculation of ΔS (generally one monitoring cycle is used, such as one day and one week), and ΔT is the amount of change in T(i) in the unit time period.

According to Xu et al. (2009), the three-stage law of slope deformation evolution is defined as: when $\alpha i < 45°$, the slope is at the initial deformation stage; when $\alpha i \fallingdotseq 45°$, the slope is at the constant velocity deformation stage; and when $\alpha i > 45°$, the slope is at the accelerated deformation stage.

The improved tangent angle can be used to give the corresponding quantitative division criteria for the three substages of accelerated deformation, namely: $\alpha i > 45°$, the slope deformation enters the initial accelerated deformation stage; $\alpha i > 80°$, the slope deformation enters the medium accelerated deformation stage; and $\alpha i > 85°$, the slope deformation enters the rapid accelerated deformation (critical sliding) stage.

3. RESULTS OF MONITORING CASES

Figures 2 are the comparison diagrams of the duration curves of cumulated displacement in the SAA automatic inclinometer of No. 11 hole versus rainfall amount. The figure shows that the main displacement of the No. 11 hole occurs at a depth above 14.5 m. In addition, the displacement increment is mainly related to typhoon and heavy rain, whereas slow creep also exists in normal times. The red dotted line in the figures is the previously obtained warning value of a daily rainfall of 300 mm.

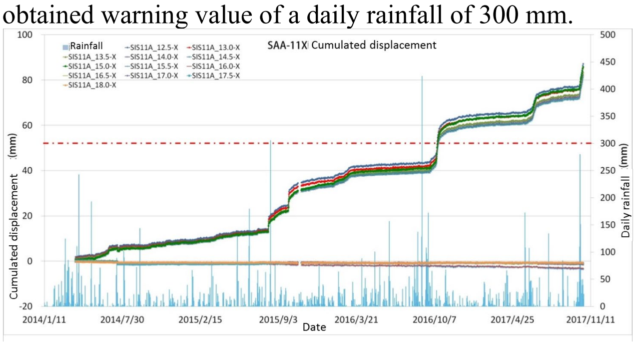

Fig. 2. Duration curve of displacement monitored by SAA embedded in the SIS11A inclinometer versus rainfall amount

In this study, the information from SAA in the inclinometer numbered SIS-11A during the period of Typhoon Aere in October 2016 was used. The method proposed by Xu et al. (2009) was used to convert the S–t curve, and the resulting T–t curve is shown in Figures 3. The curve after October 13, 2016 clearly has a distinct upward trend. The overall tangent angle approximately equals 45°. The slope displacement was at the constant velocity deformation stage at that time, while the effective rainfall amount that can result in this condition is approximately 70 mm or more, and the SAA displacement curve starts to rise when the effective rainfall amount is reached. The lag time for this period of rainfall-driven displacement can be as long as five days. The lower part of the figure also shows the duration curve of the automatic water-level observation results of No. W1 in up-slope of this inclinometer. The water-level curve shows that, at the time when the effective rainfall amount of Typhoon Aere was reached, the groundwater level was affected by the previous Typhoon Megi, which occurred on September 26 to 27. The groundwater level had not yet fully recovered to the lowest water level in normal times. At this time, the rainfall of Typhoon Aere continued to occur, and, although Typhoon Aere did not land in Taiwan, because of its formidable moisture, which had been trapped in northern Taiwan for a week, the cumulated rainfall amount was as high as 430 mm. As a result, the SAA displacement amount suddenly increased by more than 1 cm in this typhoon rainfall event, which was approximately half of the average annual displacement increment.

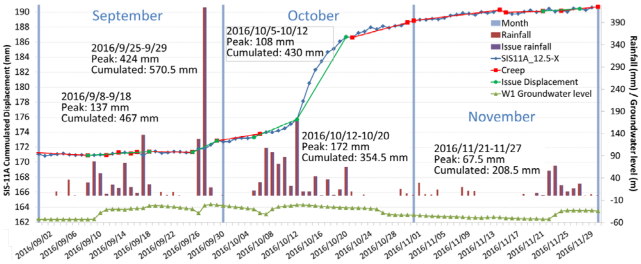

Fig. 3. Example of the T–t curve converted from the S–t curve (accelerated displacement curve tangent angle of the Typhoon Aere event in 2016)

4 COMPARISON OF DISPLACEMENT TRENDS OF SAA BEFORE AND AFTER RENOVATION OF CATCHPITS

To understand the effect of the renovation of catchpits on the reduction of slope displacement in this study area, this study compared the displacement monitored by the SAA embedded in the depth of the sliding layers in No. 11A. Figures 2 show the relationship between cumulated displacement and rainfall for holes SIS-11A in front of the Wuming Building. The figure shows that most of the slope displacement occurred during the typhoon season. The rainfall amount in the plum rain season only slightly drives the displacement of the slope, while the slowly cumulated creep exists in normal times.

Before the renovation of the CH1 catchpit on the upper slope, the results over time were monitored from April 2014 to October 2015. After the renovation of the CH1 catchpit, the monitoring results over time for the period from November 2015 to November 2017 were observed. During the period from September to October 2016, Typhoon Megi and Typhoon Aere continued to invade, causing the displacement curve to become significantly steeper. Comparing the changes of the curves before and after the renovation of catchpits, it was found that the threshold value of the rainfall-driven displacement had changed. That is, after the renovation of the catchpits, they can endure a greater rainfall amount before the same displacement amount is driven, and the occurrence time of driving displacement is delayed. In other words, after renovation, the displacement is smaller under the same rainfall amount than before renovation.

Figures 4 is relationship diagram of SIS-11A cumulated rainfall amount with the driven displacement rate. Another hole No. 20 has the same trend curves. The figures show that the trend line of the displacement rate has a more significant relationship with the accumulated rainfall amount than with the peak rainfall amount. The results of the curves of the two holes show that after the renovation of catchpits, the driven displacement rate of the slope is significantly reduced under the same rainfall amount. This indicates that after the renovation of catchpits, they indeed exert a certain degree of effect on the stability of the slope.

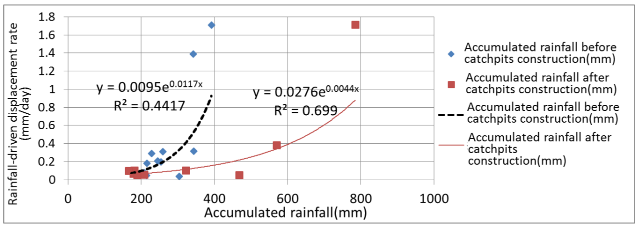

Fig. 4. Relationship curves of rainfall-driven displacement vs. accumulated rainfall before and after the renovation of catchpits

5 TANGENT ANGLES AFTER NORMALIZATION OF SLOPE DISPLACEMENT RATE

To understand whether the displacement rate currently achieved by the slope land in this study driven by typhoon and heavy rain has reached the critical sliding stage or to discover what acceleration stage it is at after it is converted to the tangent angle of the displacement rate curve according to the method proposed by Xu, in this study, its tangent angle was made by converting the s–t curve to a T–t curve using the above-mentioned displacement monitoring curve data to be used for further investigation. Figure 5 is a relationship diagram of normalized displacement and time with the rainfall amount after SIS-11A transformation (before CH1 catchpit renovation). In the figure, only rainfall events with a daily rainfall amount greater than 150 mm are selected for analysis, and the segmented rainfall events are marked with dark red columns. From the relationship diagram between the tangent angle and the rainfall amount, it is known that under the condition of meeting the rules for analyzing rain events (differentiated by rainfall amount less than 10 mm for two consecutive days), when the rain event spacing does not exceed seven days and the continuous single-day rainfall intensity is greater than 150 mm, the conversion curve produces a significant rise. Figure 5 shows that SIS-11A had an α angle of up to 73°, 83°, and 84° before renovation, and SIS-11A had an α angle of up to 70° and 82° after renovation. Because current data on large typhoons are still limited, the results before and after the renovation of catchpits were only preliminarily compared. There seems to be a larger angle before renovation than after renovation. The current maximum angle is about 84°. According to the statistical analysis of a large number of landslide examples by Wang and Zhang (1999), the displacement tangent angle of the slope before the instability and failure is generally 89° to 89.5°. This is considered one of the early warning and forecasting criteria for landslides, i.e., it is used as the criterion for judging the accelerated displacement tangent angle. When the angle reaches 45°, it enters the initial acceleration stage. When it reaches 80°, it enters the medium acceleration stage. When it reaches 85°, it enters the accelerated or critical sliding stage. Taking this as the reference, although the typhoon rainfall events that occurred on the current slope had not yet reached the critical sliding stage, a few events had approached the critical sliding stage. Fortunately, the rainfall did not last long, and the displacement gradually became slow creep after the events. However, remediation and protection should be carried out as soon as possible to prevent further threats from subsequent critical situations.

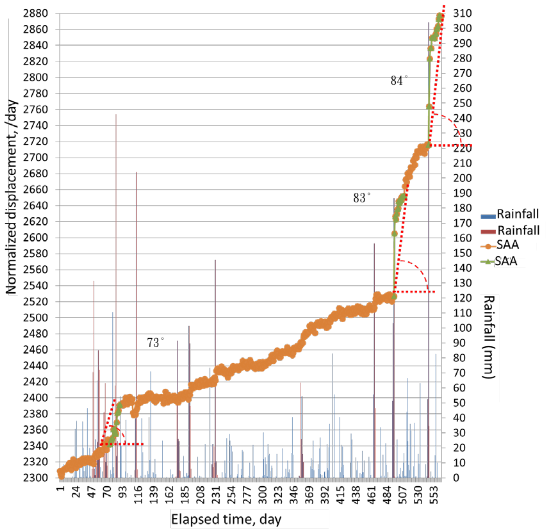

Fig. 5. Relationship diagram of SIS-11A normalized displacement and rainfall amount (before T1 renovation)

6 LONG-TERM CREEP AT THE SITE

In addition to the above-mentioned typhoon and heavy-rain events, there are still long-term slow creep behaviors at the research site in this study. As for the data selection rules for analyzing creep, the data segment with the daily rainfall of less than 40 mm is selected, and the displacement change rate of the segment is calculated. According to comparison, when positive mean values are adopted for creep before and after the renovation, the two values are similar, indicating that the overall creep rate before and after renovation is almost unchanged. The mean creep is approximately 0.05 to 0.06 mm/day for SIS-11A and approximately 0.07 mm/day for SIS-20.

7 CONCLUSIONS

A. After the invasion of Typhoon Megi in 2016, the groundwater level did not fully recovered to the lowest water level in the normal state. Afterward, the rainfall of Typhoon Aere continued to occur, and its formidable moisture was trapped in northern Taiwan for a week, resulting in a cumulated rainfall of 430 mm. As a result, the SAA displacement amount suddenly increased by more than 1 cm in this typhoon rainfall event, which was about half of the average annual displacement increment.

B. Before the renovation of SIS-11A, the α angle had once reached 84°, which means that it had entered the medium acceleration stage. Because the data of the large typhoon is still limited, it is preliminarily compared with the results before and after the renovation of catchpits, and there seems to be a larger angle phenomenon after renovation than before renovation. Although the typhoon rainfall events that occurred on the current slope have not yet reached the critical sliding stage, a few events have approached the critical sliding stage. Fortunately, the rainfall did not last long, and the displacement gradually became slow creep after the events. However, remediation and protection should be carried out as soon as possible to prevent further threats from subsequent critical situations.

C. The trend line of the displacement rate has a more significant relationship with the accumulated rainfall amount than with the peak rainfall amount. The results of the curves of the two holes show that after the renovation of catchpits, the driven displacement rate of the slope is significantly reduced under the same rainfall amount. This indicates that, after the renovation of catchpits, they indeed exert a certain degree of effect on the stability of the slope.

D. The overall creep rate before and after renovation is almost unchanged. The mean creep is approximately 0.05 to 0.06 mm/day for SIS-11A and approximately 0.07 mm/day for SIS-20.

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