A case study of slope hazardous mitigation by ground monitoring system

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Abstract. The western foothills geological zone of Taiwan contains sedimentary rocks such as conglomerate, sandstone, shale, and mudstone. These formations often cause severe damage to life and property during a natural disaster such as earthquake and rainstorm, especially on a dip slope. This paper presents the results of long-term ground monitoring on a high sliding potential dip slope located in the western foothills of central Taiwan. The slope has been went through substantial movements induced by rainstorms during the monsoon season or after a typhoon. By comparing the rainfall data and long-term in-situ measurement of ground displacement using total station and inclinometer, we find that the movement of this slope is highly related to regional rainfall. The slide mechanism can be attributed to the infiltration of rainfall that tends to increase the driving force of the upper sliding mass and decrease shear resistance on the interface between sandstone and shale.

1. Introduction
Taiwan is located at the junction of the Eurasia plate and the Philippine sea plate. Due to the convergence of these two tectonic plates, two-third of the surface area of Taiwan is covered by mountains. In the past few decades, rapid development of the metropolitan area and the limitation of available plain ground, the development and use of hillside land has become inevitable. The western foothills geological zone of Taiwan contains sedimentary rocks such as conglomerate, sandstone, shale, and mudstone. These formations often cause severe damage to life and property during a natural disaster such as earthquake and rainstorm, especially on a dip slope.

Monitoring the slopes of natural ground or manmade excavation can prevent damage to properties and loss of life. The effectiveness of such monitoring depends on the extent to which slopes give adequate advanced warning before failing, and on the ability of the monitoring system to detect such warning. Ding et al. [1] pointed out that slopes do give ample warning, thus it is well worth to implement the slopes with appropriate monitoring systems. The use of total station for monitoring the movement of structures with good results were reported by many authors [2-5]. This surveying instrument was also used in open pit mines to ensure safety and predicting the stability of the mine slope [6-8].

Bore-hole inclinometer has been used in the monitoring of slope stability, retaining structure performance, excavation near facilities, and in landslide investigations for more than 50 years [9]. The
advantages of this instrument is that it can measure displacement in two perpendicular planes; therefore, displacement magnitudes and directions (vectors) with depth can be calculated.

This paper presents the results of long-term ground monitoring on a high sliding potential dip slope located in the western foothills of central Taiwan. The slope has been went through substantial movements induced by rainstorms during the monsoon season or after a typhoon. Rainfall data and long-term in-situ measurement of ground displacement using total station and bore-hole inclinometer are compared to investigate the mechanism causing the movement of the slope.

2. Geological and geomorphological characteristics of the slope investigated

The slope investigated in this paper is located at the southeastern corner of the Taichung metropolitan area, within the Western Foothills geological zone as shown in figure 1. The Western Foothills geological zone in central Taiwan consists of sedimentary rocks deposited during Miocene, Pliocene, and Pleistocene. Outcrops of the investigated slope are primary consist of interbedded layers of sandstone and shale of the Toukoshan formation which deposited during the Pleistocene.

![Figure 1. Geological characteristic of the slope investigated [10].](image)
The slope investigated in this study is a dip slope. Failure of this slope occurred after Typhoon Songda in May 2011. The slope was restored by the end of September 2011 with 5 benches of geogrid and micro piles reinforced backfills. Observation points (figure 2) were installed to monitor the surface movement of this slope using a total station. The slope remained stable for a period of about 9 months. However, after the monsoon season (May and June) and Typhoon Saola on Aug. 02, 2012, the slope had went through substantial movements. Significant relative displacements were observed between the sink pit (P1), micro-piles (P2), lateral drainage ditch (P3) and the ground surface as shown in figure 3. Therefore, in order to prevent further damage, six boreholes were drilled to carry out in-depth geological investigation. Access tubes for inclinometer were also installed inside these boreholes to enhance the monitoring system.

3. Results of in-situ monitoring

3.1. Rainfall
Rainfall data collected from a weather station located a few kilometres from the site are summarized in figure 4. It can be seen that rainfall around the investigated area was concentrated between the months of April and September. The monthly accumulative rainfall ranges from a minimum of essentially no rain to a maximum of 660 mm in the August of 2013. Maximum daily precipitation is also highly variable for the 3-year period, ranging from 118 mm in 2014, to 358 mm brought by Typhoon Saola in 2012.

3.2. Surface movement
The surface displacement (figure 5) of each observation points was derived from the difference between the measured spatial coordinates (relative to the reference point) and their initial values. As can be seen from figure 5, the surface displacements at the top (C7 and C8) of the slope are generally higher than those of the toe (C1). The slope experiences substantial amount of surface movements during the observation period. The surface movement is strongly correlated to the daily rainfall. There is usually a significant surface movement whenever the daily rainfall surpasses 100 mm. A maximum surface displacement induced by a single event (Typhoon Saola in August 2nd of 2012) of about 110 mm (from 178 to 287 mm) was observed at the observation point C7. An accumulative surface displacement higher than 350 mm was observed by the end of 2014. It is evident that the flexible reinforced earth slope can sustain higher amount of surface displacement than conventional retaining structures.
3.3. Subsurface lateral movement
Six access tubes for inclinometer were installed after Typhoon Saola in 2012 to monitor the subsurface lateral movement of the slope investigated. The depth of the two boreholes (BH 16&17) at the top of slope is 25 meters, 20 meters for the two boreholes (BH 18&19) at the middle, and 15 meters for the two boreholes (BH 20&21) at the toe. An electrical probe (inclinometer) is lowered through a guide casing to the base of a borehole. The probe is then pulled up while the inclination information of the probe in two orthogonal planes, one (A-direction) is parallel to the slope while the other (B-direction) is perpendicular to slope, is registered at every 500 mm intervals. From this information, profiles of the borehole in the two planes can be derived and reviewed graphically. The lateral displacements of the borehole can be determined by comparing the measured profiles of the borehole obtained at different times.

The accumulated subsurface lateral movement profiles in A-direction (parallel to the slope) are shown in figure 6a for the three boreholes (BH 17, 19, &21) along cross section A-A in figure 2, and in
figure 6b for the three boreholes (BH 16, 18, &20) along cross section B-B. For the three boreholes along section A-A, two distinctive lateral displacements were observed. One located at a depth of about 5 meters while the other located at a depth around 10 meters. The maximum accumulated lateral displacement occurs near the ground surface for these three boreholes. A maximum value of accumulated lateral displacement of 73 mm at the top of borehole BH17 was observed. This borehole is right next to observation point C7 where the maximum surface displacement was registered. From September 2012 (when the access tubes for inclinometer were installed) to December 2014, observation point C7 has moved 75 mm. These two values are consistent thus the reliability of the two monitoring techniques can be warranted.

Figure 6. Subsurface lateral movement profiles in A-direction.
The accumulative lateral displacements at the top of the six boreholes are summarized in figure 7, together with daily rainfall data. A maximum accumulative lateral displacement of 73 mm was observed for borehole BH19. As shown in figure 7, there is a strong correlation between the accumulative lateral displacement and the daily precipitation. As for the surface movement, there is usually a significant lateral displacement whenever the daily rainfall surpasses 100 mm. On the other hand, the effect of daily precipitation on the lateral displacement is insignificant if it is less than 50 mm. It is thus concluded that precipitation plays an important role on the surface and ground movement of a slope.

![Figure 7. Accumulative lateral displacement at the top of boreholes measured by inclinometer.](image)

4. Sliding mechanism
Correlation between lateral displacement and geological stratum is shown in figure 8 for cross section A-A and in figure 9 for cross section B-B. By the end of 2014, the accumulated lateral displacement at the top of borehole BH17 is 73 mm. From September 2012 (when the access tubes for inclinometer were installed) to December 2014, observation point C7 has moved 75 mm. These two values are comparable. Along cross section A-A, the thickness of back-fill is usually greater than 5 m. The slope was renovated with 5 benches of geogrid and micro pile reinforced backfill. Therefore, two distinct zones of lateral displacement were observed. One located at the interface between back-fill and sandstone (the upper red dash-line in figure 8) where major lateral movement had occurred. The other located at the interface between sandstone and underlying shale (the lower red dash-line in figure 8). On the other hand, the thickness of back-fill is usually less than 2 meters along cross section B-B (figure 9). There are no bench and reinforcement used for the back-fill. The lateral displacement mainly occurs at the interface between sandstone and underlying shale. By comparing these two plots, it can also be seen that significant lateral displacement was observed along this dip slope due to the weak strength of the back-fill/sandstone and sandstone/shale interface. However, the slope did not reach failure because of the passive resistance at the toe of the slope.

5. Summary and conclusion
The objective of this paper is to investigate the behaviour of a dip slope through surface and ground movement monitoring. Based on the results of this study, the following conclusion can be drawn:

- There is a strong correlation between the surface/ground movement and the daily precipitation. A significant surface/ground movement usually occurs when the daily rainfall surpasses 100 mm. On the other hand, the effect of daily precipitation on the surface/ground movement is insignificant if it is less than 50 mm.
• Surface displacements measured using a total station are in good correlation with accumulated lateral displacements at the top of bore-holes using an inclinometer. The reliability of the two monitoring techniques can thus be warranted.

• In addition to the daily precipitation, the surface/ground movement is also strongly correlated to the thickness back-fill, geological stratum, type and amount of reinforcement of a slope.

• Passive resistance at the toe of a dip slope plays an important role on the stability of a slope. It is better not to cut the toe of a dip slope.

Figure 8. Correlation between lateral displacement and geological stratum along cross section A-A.

Figure 9. Correlation between lateral displacement and geological stratum along cross section B-B.
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