Using Time Domain Reflectometry for Monitoring Slope Movement in the Jiufenershan Landslide

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ABSTRACT: This paper applied time domain reflectometry (TDR) technology to monitor slope movement of a landslide. The TDR system was installed from 2012 to 2017 in order to monitor slope movement in the Jiufenershan landslide. TDR waveform signature showed a cable ruptured by extension at 7.51 m and 35.72 m in depth of TDR_N2 station between 2012 and 2013. Compared to the inclinometer data of the area only appears some sliding phenomena in a range of 0 m and 8 m in depth. Overall, the TDR technology shows that the locations of failure planes and the magnitude of the displacements can be determined by the changes and quantification of TDR reflected waveforms in the landslide.

Keywords: Time Domain Reflectometry, slope movement, landslide monitoring.

1. INTRODUCTION

This paper uses Time Domain Reflectometry (TDR) technology to monitor slope movement of a landslide and compares other on-site measures such as inclinometers to TDR monitoring data.

It is the most important for monitoring slope deformation to determine the location of the sliding surface and the magnitude of displacements in a landslide. However, traditional monitoring equipment, such as an inclinometer, is time-consuming and difficult to interpret an accurate location of sliding surface (Dowding and Pierce, 1994; Dowding et al., 2003). Thus, TDR technology is a new method of slope movement monitoring which is a continuous sensor to detect any deformation along its cable length when sliding deformation occurs (O'Connor and Dowding, 1999). They argue that TDR has been used for slope deformation by comparing to mechanical inclinometers and the differences of TDR reflected waveforms can monitor the locations of cable deformation. Su et al. (2009) demonstrate that TDR would be applied to long-term monitoring of underground sliding planes in alpine landslide areas effectively, fast and economically.

However, the magnitude of the cable deformation cannot be directly determined in the field although the instrumentation of TDR would monitor suitably deep underground movement (Su et al., 2009; Osasan and Afeni, 2010). The paper explains the data of TDR monitoring in a case study compared to the data of inclinometers; moreover, the paper measured the magnitude of rock displacement corresponding to TDR reflected waveforms in laboratory experiments. Generally, drill-log reports can determine in situ geological conditions. According to Su, et al. (2009), they indicate that the TDR system of coaxial cables grouted inside a drill hole can detect sliding surfaces and their movements as the function of a traditional in-place inclinometer, which showed sliding planes between layers of colluvium and strongly weathered slate compared with the reports of rock cores. TDR has been used for rock and soil movements in slope monitoring (Federico et al., 2012; Lin, 2014; Drusa and Bulko, 2016).

In terms of the qualification of TDR monitoring slope deformation, the technique has been employed to identify zones of rock mass deformation and blasting performance (Dowding et al., 1988; Dowding et al., 1989). Then, much research has been completed with good results in relation to TDR indoor experiments, including the effect of TDR cable length on reflection signal and different types of deformation of TDR waveforms (Su, 1990). Furthermore, the methodology to quantify TDR waveform change and correlate to ground deformation has made the TDR monitoring system used in landslides more useful and advanced (Su and Chen, 1998). Su and Chen (1998) declare that an integrated area method is proposed to quantify the magnitude of a TDR reflected waveform on the deformation of rock masses and concrete structures through TDR theories and bench tests. By this method, the study applies laboratory experiments of shear tests to determine equations in the relation between the integrated area of TDR reflection coefficient and the magnitude of a cable deformation (Su and Chen, 2000). Furthermore, whether shearing deformations are big or small, the magnitude of TDR reflected waveforms is significant correlation with the deformation (Drusa and Bulko, 2016). They point out that there is a correlation between TDR reflection coefficient and shear deformation in a laboratory test so that a regression equation of them can be determined.

The paper analyzes the waveforms interrogated by TDR monitoring stations in a landslide area and compares to the data of on-site inclinometers in order to understand the location, type and deformation magnitude of slope movement in the field.

2. JIUFENERSHAN LANDSLIDE

A case study is located in the Jiufenershan landslide in Taiwan with TDR technique where occurred severe landslides by the 1999 earthquake. The area of the landslide is 195 ha and the amount of the collapse is 35 million cubic meters that blocked two creeks, namely Jiucaihu and Sezikeng creeks, and caused two dammed lakes. The area of the Jiucaihu and Sezikeng dammed lakes is 4.4 ha and 6.4 ha, respectively. Since 2003, there has been a monitoring landslide project in the Jiufenershan landslide with some monitoring equipment, including extensometers, inclinometers, groundwater lever gauges, etc. TDR was installed in the area from 2012 in order to monitor the slope movement.

The geology of the landslide is underlain mainly by Miocene sedimentary rocks where the strike is N36°E and the dip is 21°SE with an N–S trending synclinal axis of Daanshan syncline in the eastern part; the geologic formation of the syncline axis is the Kueichulin Formation which unconformably contacted with the underlain Changhukeng Shale; the lower formations include Miocene strata of Shihmen Formation (Shou & Wang, 2003).

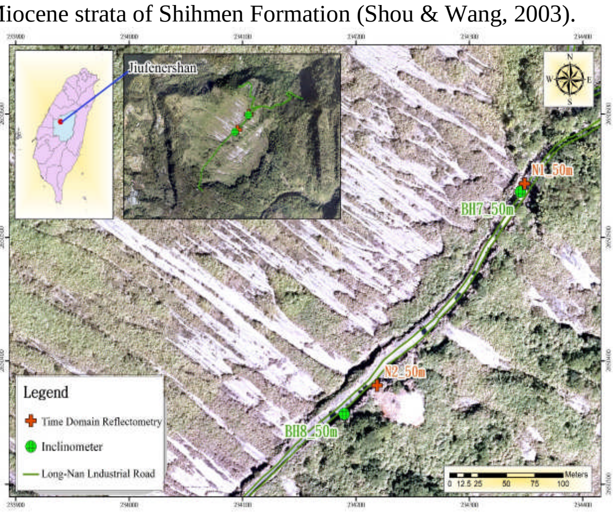

Figure 1 Location map of the monitoring stations of the Jiufenershan landslide

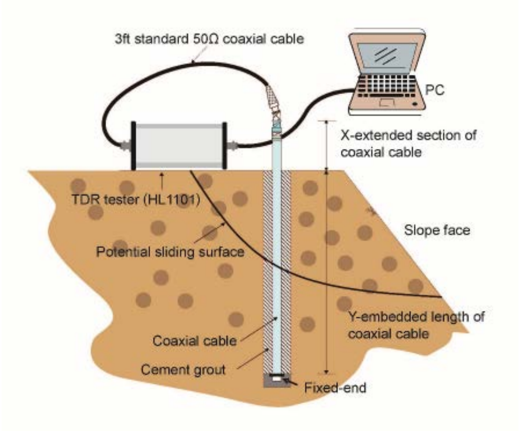

Figure 2 Diagram of on-site TDR instrumentation

There are two TDR monitoring stations in the area where coaxial cables were grouted. Also, there are two inclinometers, as shown in Figure 1. A diagram of on-site TDR instrumentation is shown in Figure 2. A TDR cable tester (HL 1101) sends a voltage pulse waveform which travels along a metallic coaxial cable through a connector. The cable was grouted into a borehole in a landslide with cement. When the waveform of TDR encounters a change in the characteristic impedance of the cable, it is partially reflected by the deformation of the cable in a potential sliding surface. The change could be determined as the location of the shear or extension zone in a landslide.

3. MAGNITUDE OF CABLE DEFORMATIONS IN LABORATORY EXPERIMENTS

A semi-rigid coaxial cable was grouted into a cement test specimen which was one-meter in length and connected a TDR cable tester (HL 1101). Then, the test specimen was installed on the bench test. The purpose of the test setup was twofold. They are: (1) to determine the relation between the magnitude of cable deformations and TDR reflected waveforms by shear displacement (Figure 3). (2) to measure a change length of the cable with TDR reflected waveforms by extension displacement (Figure 4). The properties of the cable and the grout in tests are shown in Table 1.

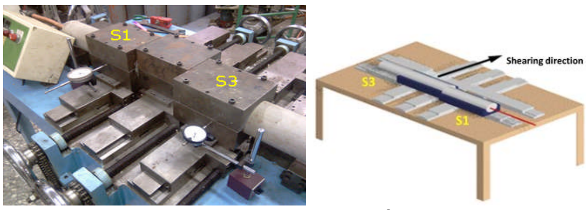

Figure 3 Instrumentation of shear bench test

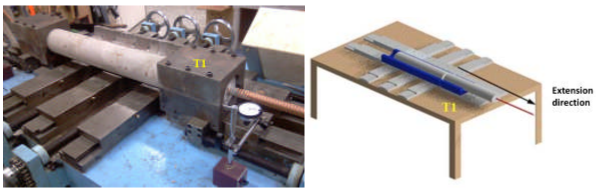

Figure 4 Instrumentation of extension bench test

Table 1 TDR coaxial cable and grout properties

Coaxial cable		Grout		
Type	Diameter (mm)	Cement type	Grout mixed ratio	Compressive strength (kgf/cm2)
CTLLCX 7/8" CFC	φ25.0 mm	Portland Cement I	1:3	146.5

For the shear test, a test specimen was installed on the bench test shown in Figure 3 and was design as two shearing units, S1 and S3. While the amount of shear displacement at S1 location was fixed to 0, 10, 20, 30 and 40 mm, the amount of shear displacement at S3 location incremented by every 2 mm until the cable ruptured, respectively. Meanwhile, a TDR tester interrogated the reflected waveforms of the cable displacements at the two locations. The results of TDR interrogated waveforms are plotted in Figure 5. The TDR cable signature (reflection coefficient, unit: millirhos) represents the amplitude of reflected waveform at a given distance (unit: meter) of grouted cable. The zoom-in graph of the reflected waveforms is shown in Figure 8 that illustrates the increase of the shear displacement on S3 plane until the cable ruptured by 54 mm.

All shear tests are the same tendencies as the graph of Figure 5 at S3 plane when the amount of S1 displacement is 10, 20, 30 and 40 mm, respectively. Above all shear tests, the average maximum magnitude of cable displacement by shear is about 60 mm. According to the results of the shear tests, there is a significant relationship between shear displacements and the magnitude of reflection coefficients. As can be seen in Figure 6, a quadratic regression equation is built up in the relations between the reflection coefficient and shearing deformation (The R-Square of each equation is more than 0.99). As a result, it is applied to determine the magnitude of shear slips in field corresponding to the magnitude of reflection coefficients interrogated by on-site TDR system.

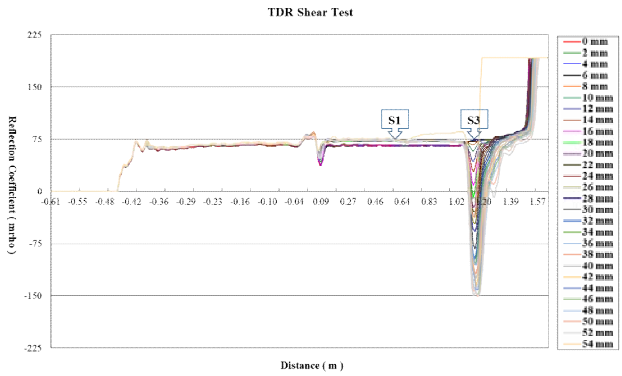

Figure 5 Graph of reflected waveform changes at S3 shear plane

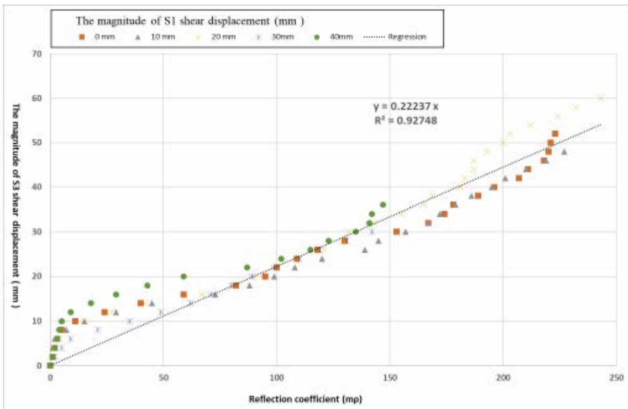

Figure 6 Graph of the relationship between the shear displacement (millimeters) and reflection coefficient (mρ) in shear tests

For the extension test, a test specimen was installed on the bench test shown in Figure 4 and the amount of extension displacement at T1 location incremented by every 5 mm until the cable ruptured. Again, the TDR tester interrogated the reflected waveforms of the cable displacements at the location. The results of TDR interrogated waveforms are plotted in Figure 7. The magnitude of extension displacement was 35 mm as the cable ruptured. O'Connor and Dowding (1999) suggest that it has also been possible to quantify the extension deformation by changes in distance between the locations of crimping cable made prior to installation in a borehole. As the result of the test, the change in distance between first waveform and the waveform of cable ruptured in the extension test was measured to 0.0347 m that was almost the same as the magnitude of extension displacement at 35 mm. Therefore, the result can be applied to measure the magnitude of extended cable in field by comparing to the initial length of the grouted cable with on-site TDR monitoring.

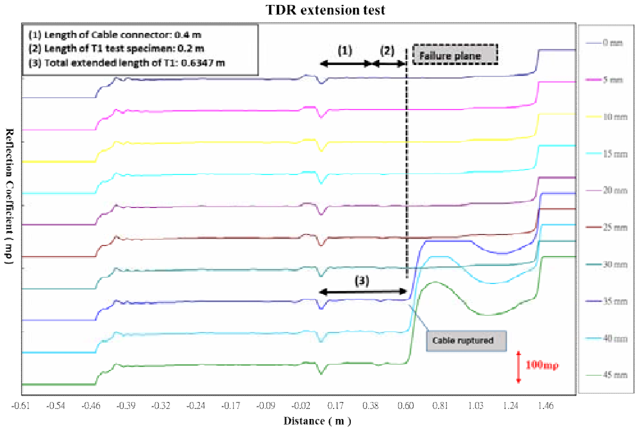

Figure 7 Graph of reflected waveform changes in extension tests

4. RESULTS OF TDR MONITORING IN FIELD TESTS

As mentioned above, there are two TDR monitoring stations in the area and each coaxial cable of the station was grouted into a borehole. The TDR monitoring waveforms are plotted in Figure 8 and Figure 9 that show the changes of the reflection coefficients at N1 and N2 TDR monitoring stations. The TDR cable signature shows the amplitude of reflected waveform at a given distance corresponding to a depth of grouted cable at TDR monitoring stations. All recorded waveforms of different date are plotted in the same graph every station so that it is easy to interpret a change of waveforms at a depth where a shear failure or extension failure occurred.

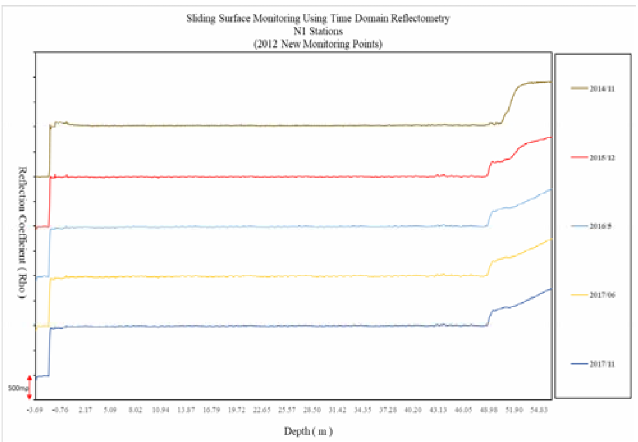

Figure 8. Recorded waveform at the N1 TDR monitoring station

With regards to the changes of TDR waveforms in Figure 8, there was not a significant change of the waveforms at N1 station from 11/2014 to 11/2017. However, some TDR waveforms were formed as the type of extension failure at 7.51 m and 35.72 m in depth of N2 station because the type of the waveforms was similar to the type of extension experiment in the laboratory. Furthermore, the length of the TDR cables was extended at the end of them. As shown by the Nov/2012 TDR record in Figure 9, there was an extended displacement at a depth of approximately 50 m of N2 station by 0.31 m.

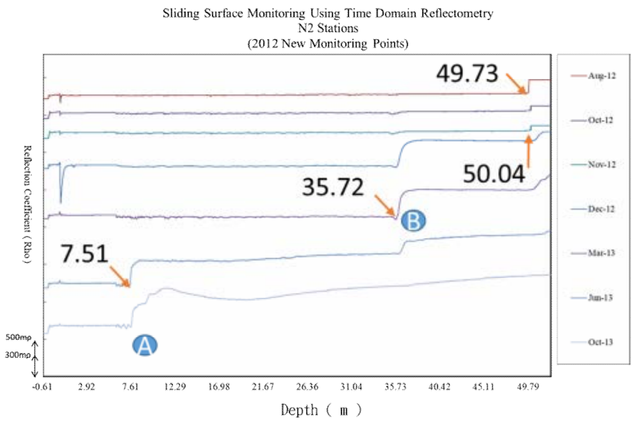

Figure 9. Recorded waveform at the N2 TDR monitoring station

5. COMPARISON OF INCLINOMETER DATA

Two TDR monitoring stations have been set up in this landslide area since 2012. Each station is also equipped with facilities including the piezometer for measuring the groundwater level, the in-place inclinometer near two TDR monitoring stations. The inclinometer sensors detect the angles of slope deformations in a borehole which are measured to determine the location, displacement, and slide direction (Su, et al., 2009). An inclinometer probe is sensitive to gradual changes in the inclinometer casing where is localized at shear zone. On the other hand, a metallic coaxial cable of TDR deforms easily when subjected to rock mass deformations (O'Connor and Dowding, 1999). The difference between the inclinometer and TDR is that the former can detect the accumulation of displacement in the inclinometer casing, while the TDR cable can detect deformation at any point along its length.

Two inclinometers were installed near the TDR monitoring stations in the landslide area between 2012 and 2017. Table 2 shows the comparison between the inclinometer and the TDR characteristics in the research. There are some results of two TDR monitoring stations comparing to the bore logs of core drilling and inclinometer data.

Table 2. Overview and characteristics of slope monitoring methods in the field

Method	Specification	Tester type	Price
Inclinometer	Accuracy:0.01° Range:-15°~ +30°	KOWA,GIC-45S	$600 per sensor
TDR	Diameter : 12.7 mm Gain: 20 mrho Ddiv: 0.1 meter Vp:0.85	HL1101	$6-10 per meter

5.1 N2 monitoring station

There was an extended displacement at a depth of 35.72 m at TDR_N2 station (see Figure 9) in which the extended length of the end cable was 0.31 m from July to November in 2012. Also, the TDR waveform signature showed the cable ruptured by extension at a depth of 7.51 m in April 2013. In terms of inclinometer monitoring, the inclinometer data only shows some sliding phenomena in a range of 0 m and 8 m in depth, which cannot determine accurate location of sliding plane from 06/2012 to 10/2017, as shown in Fig 10. Also, a failure plane cannot be interpreted at the range of upper 30 m in depth in despite of a slight signature of displacement.

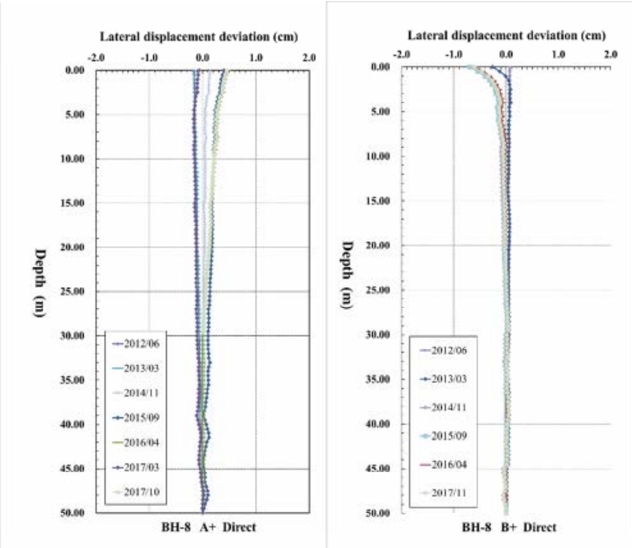

Figure 10 Results of BH8 inclinometer measures

5.2 N1 monitoring station

There was not a significant change of the waveforms at TDR_N1 station from 2012 to 2017, which means no slope movement occurred. Meanwhile, the inclinometer data did not detect any sliding phenomenon in Figure 11. The station could be located at the outside of the landslide area but the monitoring data still needs to be detected for long-term observation.

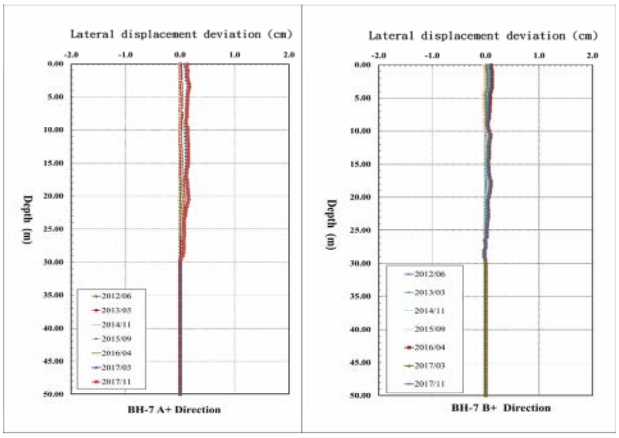

Figure 11 Results of BH7 inclinometer measures

To summary, there were some extended displacements at different depths over time at N2 TDR monitoring station in the landslide area, which was the same as the interpretation of rock core data. Meanwhile, the locations of failure planes and the magnitude of the displacements can be determined by the changes and quantification of TDR reflected waveforms. However, the data of inclinometers was not significant result of monitoring. Inclinometers may not detect smaller changes in the displacement of slope movement. It is obvious that TDR is an efficient and economical method of locating the depth and measuring the magnitude of slope movement in the landslide.

6. CONCLUSIONS

The research applied TDR to detect the displacement of slope movement and to measure the type and magnitude of the deformation in the Jiufenershan landslide. Compared to the data of on-site inclinometers, it proved that there was an extended displacement at a depth of 35.72 m at N2 TDR monitoring station by 0.31 meters and TDR waveform signature showed the cable ruptured by extension at a depth of 7.51 m from 2012 and 2013. Meanwhile, TDR did not detect any displacement at N1 TDR monitoring station from 2012 to 2017.

Overall, the results of the TDR monitoring system show that it is useful and accurate to detect the locations of sliding surfaces in the landslide area. The locations of failure planes and the magnitude of the displacements can be determined by the changes and quantification of TDR reflected waveforms. Thus, TDR is an efficient and economical method of locating the depth and measuring the magnitude of slope movement in landslides. In the future, it could be a real-time monitoring and pre-warning system.

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