Using TDR Cables and GPS for Landslide Monitoring in High Mountain Area

Miau-Bin Su[1]; I-Hui Chen[2]; and Chien-Hsin Liao[3]

Abstract: Time domain reflectometry (TDR) is performed as a complement to the monitoring methods in subsurface deformation in slope together with the global positioning system (GPS) to monitor ground deformation of high-altitude landslides in Li-shan. Four TDR cables were installed in drill holes near the monitoring stations in the landslide area. According to the recorded TDR waveforms, there were shear and tensile zones under the B-5, B-9, C-1, and C-2 stations. A comparison of the TDR waveforms with the monitored data and boring log revealed that the subsurface sliding occurred between layers of colluvium and strongly weathered slate. Three GPS receivers were installed to measure ground displacement in the landslide area. The results from the GPS were compared with the surface extensometers data on-site. The two initial baseline lengths were 451,188.10 and 908,212.4 mm, respectively. The optimal data reduction achieved used a 3 h session with moving average for each hour's GPS data. The standard deviation values of the GPS were 2.16 and 2.44 mm, respectively, on-site. The results of TDR and GPS measurements showed their applicability in the deformation monitoring of high-mountain landslides.

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Introduction

In a landslide monitoring system, the determination of the location of the sliding surface and the distribution of displacements are the most important considerations. Traditional monitoring equipment is sometimes not suitable for landslides covering wide areas or in high-altitude mountain zones. For example, the data analysis of inclinometers is time consuming and difficult to interpret. The data must be plotted, usually off-site, before any movement can be determined (Kane 2000). Extensometers can be applied to measure the continuous deformation of a slope. It is a simple method that connects one or more "moving" points to some "fixed" reference points and records the variations of these connections through time (Malet et al. 2002). If there are large-scale landsides or small sliding blocks in wide landslide areas, the data gathered by the extensometer will not be correct without a definite installed position of a fixed point.

When using the time domain reflectometry (TDR) monitoring system, a coaxial cable is inserted and grouted into a borehole. This cable becomes a continuous sensor that can monitor any deformation along its length when sliding deformation occurs. When properly installed and sealed, this embedded cable will not be affected by groundwater, moisture, temperature, or other materials underground (Dowding et al. 1988). Aside from landslides or rock displacements, structures can also use the TDR cable to monitor their deformation (Dowding and Pierce 1994). Another function of the TDR application is water content measurement in the soil. The TDR can also be designed to be a water-level indicator. 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).

Identifying the location of shear planes with TDR cables is relatively straightforward. However, determining the magnitude of movement along them is not. TDR continued to provide useful monitoring capability long (several months) after nearby slope inclinometer installations had failed, but damage to the protective coating of the TDR cable can allow water intrusion, which changes the electrical properties of the cable making traces difficult to interpret (FHwA 2004).

Grout strength must be durable enough to deform the cable yet weak enough to fracture before the bearing capacity of the soil outside the shear zone is exceeded (Cole 1999). The metallic coaxial cable must be installed in its own hole, and the grout must fracture early so that the cable can be deformed as movement occurs in the surrounding soil (Pierce 1998). This consideration is not so critical for rock installation due to the rock's relatively high strength and hardness.

Borehole reports can reveal on-site geological conditions. The length of the coaxial cable should always reach the parent rock to ensure it is deep enough to detect all the potential deep sliding. To capture the sliding surface, two or more holes located in the uphill and downhill parts separately should be made to install the TDR cables.

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Four TDR coaxial cables were installed near the monitoring station since March 2000. The FAX12-50 cable (diameter: 12.7 mm, flexible) was grouted within a poly vinyl chloride (PVC) pipe that served as a protective sleeve. Multiple holes were predrilled into the PVC pipe, allowing the grout to fill up the space between the bore hole and the PVC pipe, and the space between the PVC pipe and the coaxial cable.

Using global positioning system (GPS) to monitor the ground displacement of a landslide is another new application. There have been many reports on the use of GPS in landslide monitoring in recent years (Kodama et al. 1997; Gili et al. 2000; Malet et al. 2002). All the authors used GPS in large-scale landslides to monitor their displacement continuously and compare it with the current extensometer. Most of the results showed that GPS was suitable for landslide monitoring. Moss (2000) used a rapid static measurement of GPS to measure a region destroyed by a landslide. This region covered around 10 km^2 and the measured displacement was 6 mm–1 m. Hofmann-Wellenhof et al. (1997) and Blewitt (1997) made a thorough description of GPS and its application, which proved to be suitable for unstable monitoring network.

Three GPS receivers for long-term monitoring are used to estimate the length variation of surface displacement. Between each of the two GPS devices, one fixed and the other mobile, the baseline vector calculation of the relative positions of the two points is called the static baseline measurement (Yang et al. 2001). The static baseline measurement adopted for 24 h receives data and calculations of the baseline variation between the fixed and moving points to calculate the ground displacement.

Li-shan Landslide

The landslide area studied in Li-shan village is located at the intersection of the east-west cross-island highway Route 8 and Route 7A in central Taiwan (Fig. 1). Topographically, Li-shan is located at the west wing of the Central Ridge with an elevation between 1,800 and 2,100 m (mean sea level). Most slopes dip to the northwest with slope angles between 15 and 30° down to the Teh-Chi Water Reservoir. In April 1990, an intense and spectacular landslide occurred in this area following prolonged torrential rain. The catastrophe led to a destroyed pavement foundation on Route 7A and disrupted transportation facilities. This landslide also affected nearby buildings such as the Li-shan Grand Hotel that suffered severe settlement and deteriorated cracks. The accumulated rainfall from April 10 to April 20 was 585 mm, while the monthly rainfall record for that April was 957.5 mm. Both rainfall records exceeded the record of a 50-year return period based on the frequency analysis. The continuous rainfall could have caused a tremendous amount of water infiltration and accumulation inside the slope. The infiltrated water may have increased the pore-water pressure, subsequently decreasing the effective stress in the soil or rock mass and resulting in the instability of the slope. Based on this, it can be confirmed that the rainfall-induced increase of water pressure is the main factor that triggered the landslide of the highly weathered rock slope (ITRI 1993).

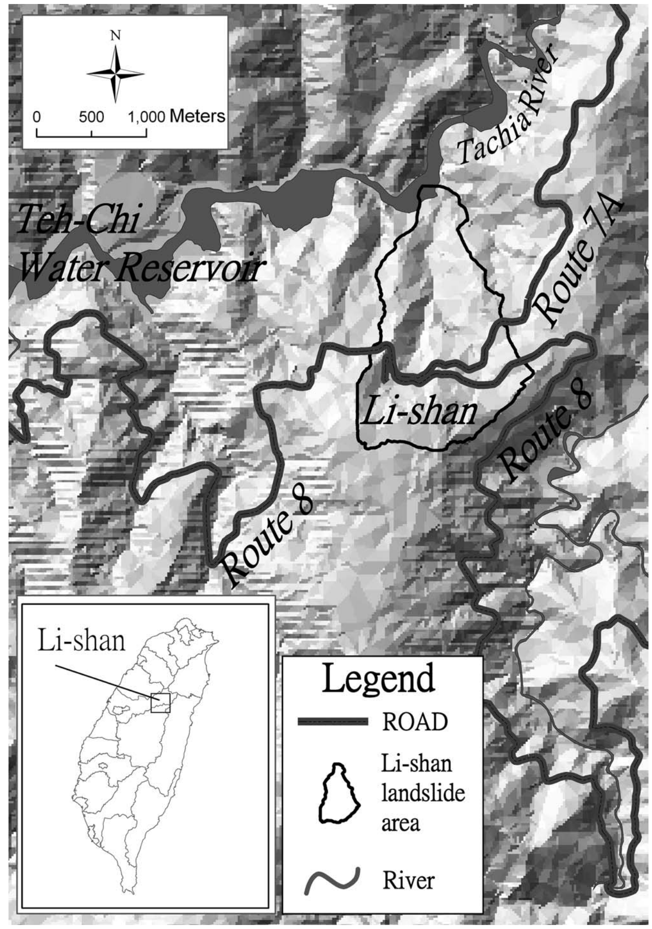

Fig. 1. Topography of Li-shan landslide

Geologically, the Li-shan area is located in colluvial formations originally from the Miocene Lushan slate formation. Due to the dynamic tectonic activities as well as the high precipitation, the surficial slate formations in this area are highly weathered. It is strongly supported by the occurrence of slaty cleavages, foliation shears, and interlayers of silty residual soil. The results of the compression strength test show that the Lushan unweathered slate is about 2.76 t/m^3 in unit weight. The mechanical properties of the geomaterials with different weathering conditions are summarized in Table 1 (Shou and Chen 2005).

Table 1. Mechanical Properties of Geomaterials in Li-shan Area (Shou and Chen 2005)

Geomaterial type	Unit weight[a] (t/m^3)	Cohesion c (t/m^2)	Friction angle Ψ (°)
Colluvium	2.06	0.75	30
Medium–highly weathered slate	2.69	3.00	28
Fresh–medium weathered slate	276	30.00	33
Sliding plane	2.69	3.00	28

[a]Unit weight is used for dry solid particles.

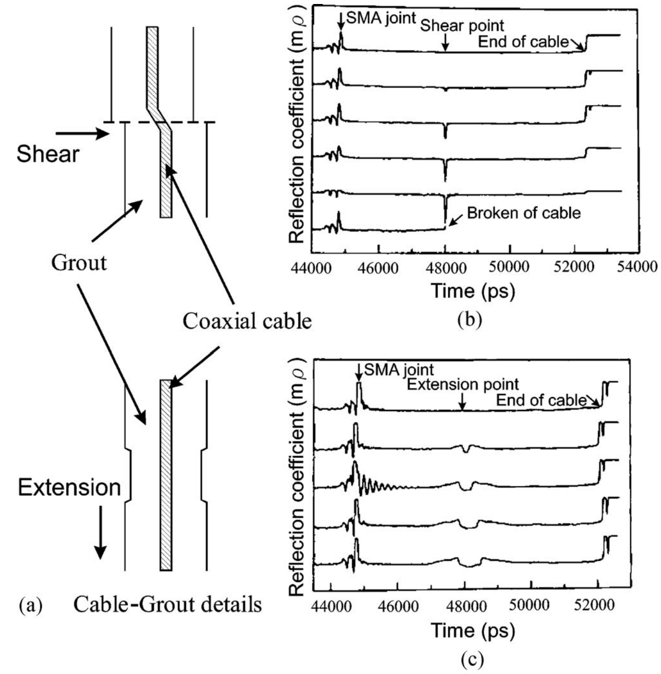

Fig. 2. Shearing and extension mechanism and induced reflection on grouted TDR sensor cable (Su and Chen 2000; Dowding et al. 2003)

Methodology

Application of TDR Cables in Landslide Monitoring

TDR was developed by electrical engineers as a method to locate discontinuities in coaxial transmission cables. The technique has been extended to measure the properties of materials in which conductors are embedded such as soil water content and evaluation of material dielectric behavior. In rock mechanics, the technique has been employed to identify zones of rock mass deformation and blasting performance (Dowding et al. 1988; 1989; Blackburn and Dowding 2004).

This technique can be applied to monitor sliding within slopes (Su and Chen 1998). When a coaxial cable is embedded in a drill hole, it works like a continuous sensor that can detect fracturing and relative movement at any location along its length. An electromagnetic pulse is launched down the cable and reflection from the points of the deformed cable can be located precisely. The differences of TDR waveforms in the reflected signal can be employed to quantify the magnitude of cable deformation (O'Connor and Dowding 1999). TDR monitoring provides a viable tool when the location of the deformation is not known in advance. This is the major advantage of TDR compared with other monitoring systems (Su and Chen 2000). Telemetric monitoring based on TDR theories has been proven to be applicable.

As shown in Fig. 2(a), a cable is grouted into a drill hole. When localized shear and tensile movements in rock or soil are sufficient to fracture the grout, cable deformation occurs and can be detected using a TDR cable tester that launches a voltage pulse along the cable. The geometry (impedance) of the cable between the inner and outer conductors will change. The change in the reflected waveform during shearing is illustrated in Fig. 2(b) where it can be seen that a negative reflection coefficient spike is found at the shear point along the waveform. Its magnitude increases as the shearing increases. The subminiature series A (SMA) joint is a specific type of connector between the coaxial cable and the TDR tester. Eventual failure of the outer conductor forms an open circuit, and the waveform ends at that point. Typical extension test results are presented in Fig. 2(c) where the arrow corresponds to the location of the extension point on the waveform. As can be seen from the figure, extension causes a necking down the outer conductor over a certain length. The length of the waveform change increases as the cable is extended until either of the outer conductors fail (Su and Chen 2000). The travel time of the reflected pulse determines the location of the shearing zone. The amplitude of the voltage reflection is proportional to the amount of the cable deformation that is correlated with the rock or soil movement (Dowding et al. 2003).

TDR has been applied to monitor the landslide region in Lishan. The findings indicate that the location of the sliding surface detected by using this technique compared favorably with the log of the boring exploration and inclinometer data, in which the sliding surface was found at the interface between the highly weathered slate and the intact rock.

Four TDR coaxial cables were installed in the drill holes in some of the monitoring stations. Fig. 3 shows the location of the monitoring stations. Cables were grouted within a PVC pipe that served as a protective sleeve. The PVC pipes had multiple holes predrilled in them so that the grout could fill up the space between the drill hole and PVC pipe, and the space between the PVC pipe and the coaxial cable. The properties of the cable and the grout used for the four drill holes described in this paper are summarized in Table 2.

Eight monitoring stations have been set up in this landslide area since 1996. Each station is equipped with facilities including the piezometer for measuring the groundwater level, the in-place inclinometer for measuring the deep horizontal displacements, and the extensometer for monitoring the ground deformation.

The inclinometer sensors detect the angle of slope in a borehole. The tilt angles along two perpendicular planes are measured to determine the location, displacement, and slide direction. The sensor packages are spaced along a standard grooved casing. Readings can be obtained by measuring the change in the tilt of the sensor and then multiplying it by the gauge length or spacing between sensors. The results are expressed as the relative displacement of each sensor and these relative displacements can be summed up to determine the total displacement for each sensor.

A metallic coaxial cable deforms easily when subjected to a highly localized shear, and it has been found to be useful in rock formations where deformation occurs along joints, bedding planes, and fractures. On the other hand, inclinometer probes are sensitive to gradual changes in the inclination of the inclinometer casing. Localized shearing of the inclinometer casing causes kinking such that a probe cannot be moved through the deformed casing. The thinner the localized shear zone is, the greater the TDR response and the smaller the slope inclinometer response become (O'Connor and Dowding, 1999). Table 3 shows a comparison between the inclinometer and the TDR characteristics.

The difference between the inclinometer and TDR is that the former can detect the vector of displacement of an interval of the casing, while the TDR cable works like a continuous sensor that can detect deformation at any point along its length, although it cannot determine sliding direction.

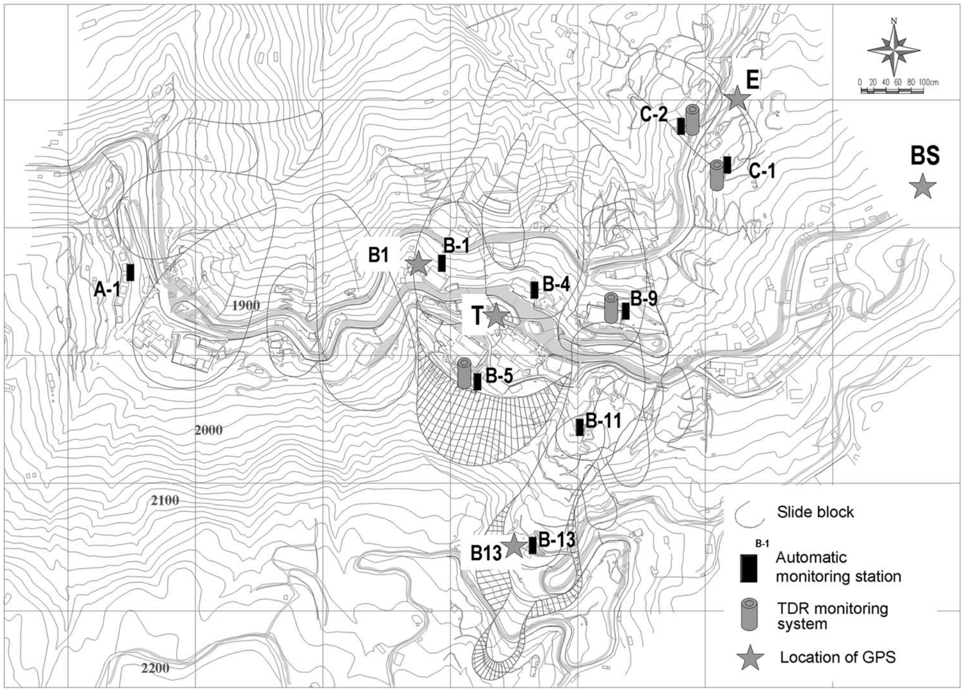

Fig. 3. Location map of monitoring stations

Application of GPS Measurement in High-Altitude Landslides

The GPS receives data from more than two survey stations simultaneously. At least one station is with known coordinates, while the others are with coordinates that have yet to be sought. The purpose of this research is to survey the static baselines and obtain the relative positions between two GPS receivers in rapid measurement. Only the baseline variation between the two survey stations is calculated and not the actual coordinates of the stations since they require the application of the least squares in the GPS data at a national tracking station level, and the collection of data takes around 1 week, which cannot meet the needs of this research's real-time displacement monitoring. Therefore, this research uses the relative positioning baseline vector solution of the GPS with one station as the fixed station of a known coordinate, while the others as the moving stations that reference the base station (BS) to calculate the length variation between the fixed station and moving stations for the analysis of the length of the baseline and the calculation of the ground displacement value.

Three GPS receivers (Fig. 3) were set up in the Li-shan landslide area, receiving satellite data with 24 h static measurement. The calculated results obtained with the static baseline measurement are used to retrieve the baseline variation and compare the length variation between the actual movement value and the GPS result. The difference between these two values can tell the accuracy and applicability of the landslide displacement monitoring.

Malet et al. (2002) surveyed the landslide displacement with GPS and compared it with the extensometer at Alpes-de-Haute-Provence. The results indicated that the two methods had the same tendency with regard to ground movement. The same method was applied in this research. Since there was no significant slide in Li-shan during the measuring period (Shou and Su 2002), this study aimed to determine the experimental accuracy of the GPS measurements for the continuous monitoring of landslides. Three GPS receivers were respectively installed at the workstation and the monitoring stations B1 and B13 in Li-shan (Fig. 3). The workstation was located outside the landslide and was set to be the fixed station with known coordinates called the BS. The other receivers were temporarily set to be the moving stations. The GPS setup was programmed to receive a set of satellite information every second, and the cutoff was 10°. The receiving time for the GPS static baseline measurement was set to be longer than 3 h and use a 3 h. session to perform the calculation. The PINNACLE software imported data from the received satellite information to calculate the baseline vectors of the relative positions (TOPCON 2004). The baseline measurement during the first time on March 5, 2004 between 1200 and 1600 hrs was treated as the base length. The baseline length obtained by the

Table 2. TDR and Grout Properties

TDR				Grout			
Type	Diameter (mm)	Bend radius (mm)	Tensile Strength, N	Grout mix (water:cement:sand)	Compressive strength (k_{gf}/cm^2)	Tensile strength (k_{gf}/cm^2)	Flow[a] (%)
FAX12-50	12.7	127	1,792	1:2:3	288.1	22.94	105

[a]Flow means the resulting increase in average base diameter of the grout, expressed as a percentage of the original base diameter. Flow (%)=((average of four readings in millimeters—the original inside base diameter in millimeters) ÷ the original base diameter in millimeters) × 100.

Table 3. Overview and Characteristics of Monitoring Methods

Method	Specification	Type	Price	Advantage	Disadvantage
Inclinometer	Accuracy:0.01° Range: −15～+30°	KOWA, GIC-45S	$600 per sensor	1. Theory is simple. 2. It can provide the direction of movement and magnitude.	1. It has a relatively high cost. 2. It has a limiting factor of hole depth. 3. It is not a continuous sensor that can be installed at each interval.
TDR	Diameter: 12.7 mm Gain: 20 mrho Ddiv: 0.1 m V_p:0.85	FAX12-50 Cable (flexible)	$6–10 per meter	1. Cheaper. 2 This cable is a continuous sensor. 3. It can interpret a sliding type by shear or tension.	1. Theory is complex. 2. It cannot provide the direction of the movement. 3. The magnitude of monitoring movements is smaller.
Extensometer	Accuracy: 0.025 mm Range: 0–100 cm Length: Up to 100 m	Celesco Transducer Products Inc., PT-101	$600–1,500 per station	1. Cheaper. 2. It is easy to interpret the received data.	1. Installed location is easily affected by topography. 2. Length is limited.
GPS	Accuracy: 3 mm+1 ppm Dual frequency GPS+GLONASS	TOPCON, Legacy-E	$6,000–10,000 per station	1. It does not require a direct line of sight between moving and reference sites. 2. It can provide the displacements of *XYZ* direction. 3. Baseline is up to 20 km.	1. More expensive. 2. Analysis theory is difficult.

GPS static measurement at different dates minus the base length is the variation for the baseline length as shown in Table 4.

The maximum variation of the baseline lengths between BS and B1 was 5.6 mm and that between BS and B13 was 4.9 mm. From the monitoring information of the surface extensometers at the B1 and B13 monitoring stations between March 1, 2004 and April 5, 2004 from the previous research report, the variation of B1 was between −0.5 and 0 mm and that of B13 was between −0.2 and 0.5 mm. These variations on data were regarded as the error of the extensometer system; therefore, the data monitored using the surface extensometer did not show any movement (Su et al. 2004). The followup study on the GPS was set to a fixed type in the above-mentioned methods with 24 h static measurement, and it discussed the experimental accuracy of the GPS measurements for continuous monitoring of landslides.

Table 4. Baseline Variation between BS and Moving Stations B1 and B13

	BS-B1 baseline		BS-B13 baseline	
Date	Length (mm)	Variation (mm)	Length (mm)	Variation (mm)
March 5, 2004 (1200–1600 hrs)	924,736.5	—	989,498.1	—
March 12, 2004 (1200–1600 hrs)	924,735.2	−1.3	989,501.7	3.6
March 13, 2004 (900～300 hrs)	924,731.3	−5.2	989,500.0	1.9
March 27, 2004 (1200–1600 hrs)	924,740.6	4.1	989,498.5	0.4
April 02, 2004 (1200–1600 hrs)	924,731.7	−4.8	989,493.2	−4.9
April 03, 2004 (1300–1700 hrs)	924,730.9	−5.6	989,495.6	−2.5

Results and Discussion

TDR Cable for Sliding Surface Measurement

Four TDR monitoring stations were installed near the monitoring stations in the Li-shan landslide area between March 2000 and October 2003. By comparing the TDR waveforms with the monitored data and ground investigation report, the results are described in the following discussion.

B-5 Monitoring Station

According to the B5-TDR waveforms as shown in Fig. 4, locations at a depth of 2 and 14 m indicated the sliding tendency of the landslide. For the shallow sliding surface, the distances of the marks premade along the cable were not extended clearly. It indicated that the landslide was mainly caused by shear force because of the sliding movement. In the signature for the deep sliding surface, the end of signature showed the elongation of the pulse from 50.7 to 53 m, which means that the extension results were presented by tensile force (Su and Chen 2000). The peak of the TDR waveform indicated the cable's outer conductor was broken on June 18, 2002. As the peak grew continuously, more and more parts of the outer conductor were broken. The variation of the TDR waveforms indicated that the sliding surface continuously slid and caused the cable shearing. Finally, the cable deformation was too large and caused the cable to shear off completely, that is, the outer conductor terminated at that point. The waveform moved upward at a depth of 14 m. According to the indoor experiments of TDR, the limitation of cable deformation is

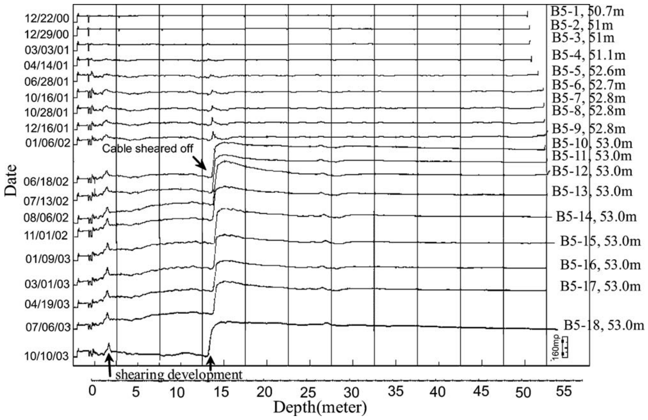

Fig. 4. Recorded waveform at B-5 TDR monitoring station

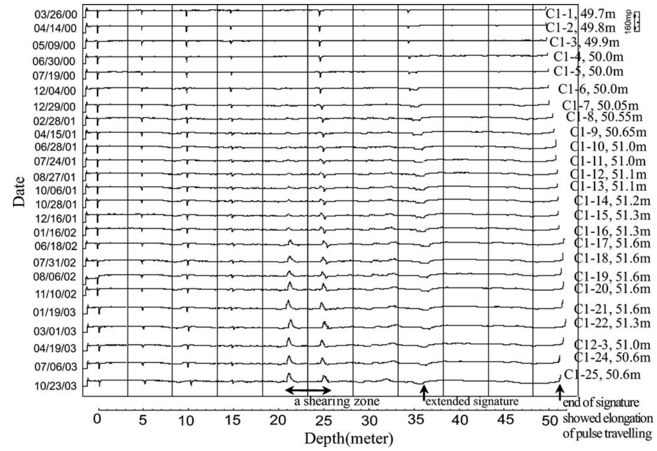

Fig. 6. Recorded waveform at C-1 TDR monitoring station

10 mm by shear force for a closely space slit (Su 1990). It was more than the TDR cable's limitation, causing it to be cut off.

B-9 Monitoring Station

According to the B9-TDR recorded waveform as shown in Fig. 5, two sliding surfaces at depths of 17–18 m and 29–30 m were found. The variation of the TDR waveforms indicated that the sliding surface continuously slid and caused the cable shearing. Finally, the quantity of cable deformation exceeded the maximum. The TDR cable was cut off, so the waveform showed up trends in the records for January 16, 2002 and July 13, 2002. By investigating the waveform, the types of cable deformation (shear, extension, or mix) can be determined (Su and Chen 2000). The TDR result indicated that at least two sliding surfaces developed in this region, making it unstable.

C-1, C-2 Monitoring Stations

C1 and C2 stations are located at the northeast region. C1 is uphill of Route 7A, while C2 is on the downhill. In Figs. 6 and 7, shear surfaces and shear zones can be found especially in the TDR waveform at a 36 m depth of the C2 station. At this location, a clearly extended signature indicated that the cable was pulled, and the variation of the TDR waveforms with time clearly showed the rapid sliding development.

The monitored data of the inclinometer was used to interpret the subsurface sliding location from 1998 to 2002 by previous research reports, and the data of the drill core were used to establish the geological profile (Su et al. 2004). The sliding location defined by the TDR and inclinometer were compared with the projected location in the profile. The compared result is shown in Fig. 8. The figure shows that the figures under the C-1, C-2 monitoring stations refer to the depth of the sliding plane interpreted by the inclinometer, and those under the C1-TDR, C2-TDR refer to the relative position of the TDR system instrument and the depth of sliding plane interpreted by the TDR. It showed that the sliding planes were continuous and extended from uphill to downhill.

The relationship between rainfall intensity, groundwater level, and surface deformation of the C1 station is shown in Fig. 9. Recorded data showed that a drop of the groundwater level of more than 10 m was observed after the completion of the drainage gallery of remediation work between July 2001 and October 2002 (Su et al. 2004). The relationship between the groundwater level, rainfall data, surface deformation, and the TDR monitoring data are interesting, but their correlations need further research.

GPS for Long-Term Displacement Monitoring

Theoretically, the accuracy of the baseline calculated with Topcon's GPS receivers can reach 3 mm+1 ppm×baseline length (mm) (TOPCON 2000). The above-mentioned GPS static baseline measurement was applied in the long-term displacement monitoring of high-mountain landslides. Three GPS receivers were set up at fixed locations in the Li-shan landslide area for a long period of time, receiving satellite data continuously. One was

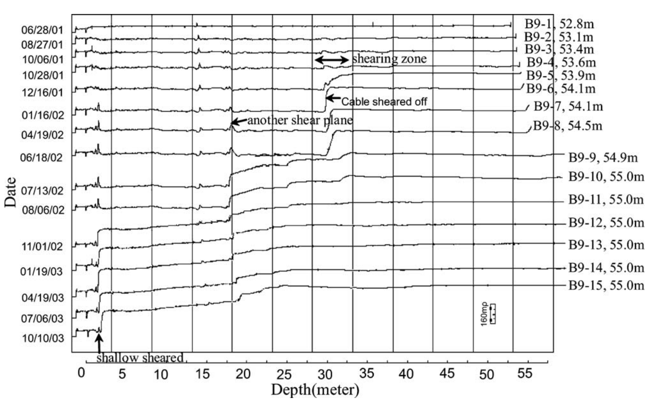

Fig. 5. Recorded waveform at B-9 TDR monitoring station

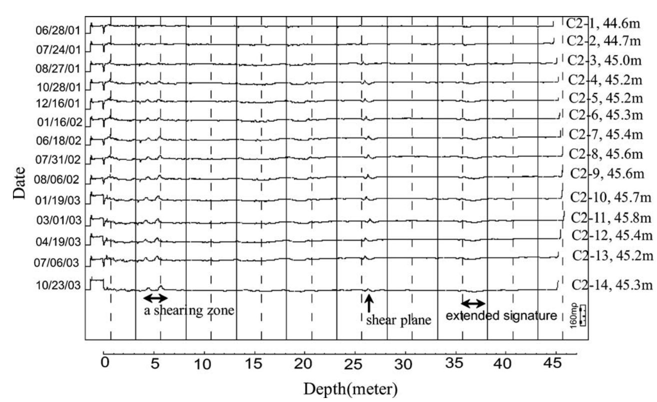

Fig. 7. Recorded waveform at C-2 TDR monitoring station

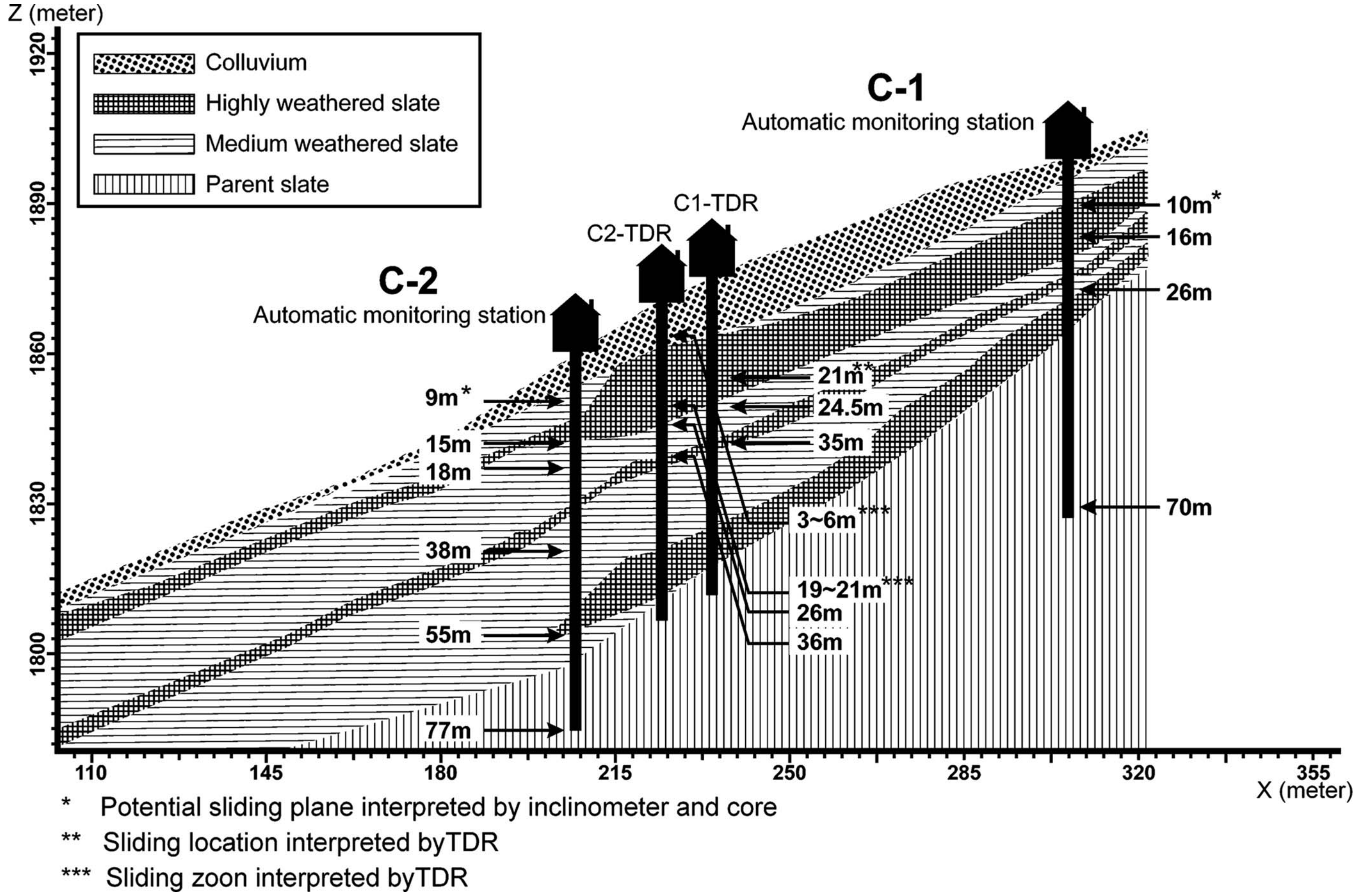

Fig. 8. Profile of slope including C1-TDR and C2-TDR cables

set up at the BS, a fixed point with known coordinate values, while the other two could not be set up at the monitoring stations B1 and B13 due to safety and electricity concerns in on-site installation. Therefore, they were established on the roof of an existing building. The E GPS station was set up on the roof of the Taiwan Power Company building, while the T GPS was placed on

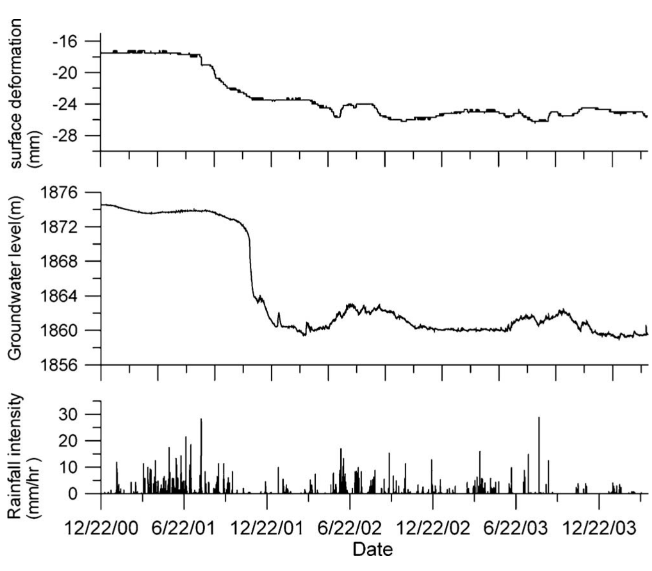

Fig. 9. Relationship between rainfall intensity, groundwater level, and surface deformation in C1 station

the roof of the Visitor Center building (Fig. 3). The three stations started operating between May 15, 2004 and June 7, 2004. The BS-E and BS-T refer to the baseline lengths between BS and E stations and BS and T stations, respectively.

For long-term real-time monitoring of ground displacement, a set of data was recorded for a 1 h period for on-site calculation. The moving average was applied to calculate the GPS baseline vector. The moving average per hour was represented as the sequential baseline vector calculation for the GPS static measuring data of the previous 3 h sessions; therefore, a set of monitoring data every hour was obtained. Using this method, the three GPS stations were monitored continuously, and the receiving time was between May 15, 2004 and June 7, 2004. The relationship between the BS-E and BS-T baselines length and time are shown in Figs. 10 and 11.

The BS-E and BS-T baseline variations are sorted out in Table 5. The two initial baseline lengths were 451,188.10 and 908,212.4 mm, respectively. The BS-E baseline variation was between −5.1 and 4.3 mm with a standard deviation of 2.16 mm. The BS-T baseline variation was between −7.4 and 2.0 mm with a standard deviation of 2.44 mm.

The landslide monitoring data obtained from the surface extensometer at the monitoring stations B1 and B13 between May 15, 2004 and June 7, 2004 gave a variation between −0.2 and 0.3 mm at B1 and between −0.5 and 0.2 mm at B13. According to the previous research report, the data showed no displacement in the areas of monitoring stations (Su et al. 2004). Therefore, Table 4 shows that the maximum absolute error of baseline variation between the BS and moving stations B1 and B13 is 5.6 mm.

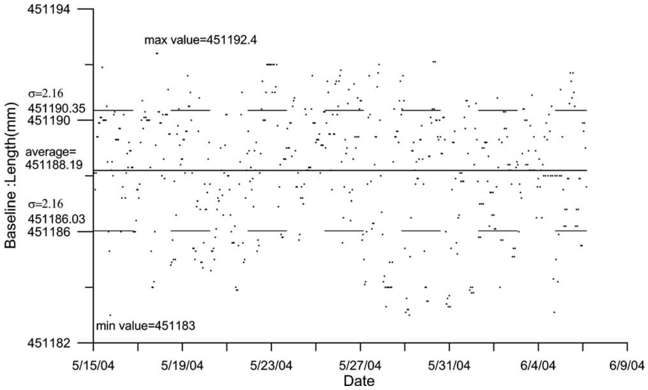

Fig. 10. Relationship between baseline length and date for GPS long-term monitoring in Li-shan landslide area (BS-E baseline)

Table 5 shows that the maximum absolute error of baseline variation using the long-term measurement of the GPS in the landslide area is 7.4 mm; however, the standard deviation is within 3 mm of the Topcon's specification. This may be because the BS-E baseline length of 451.1881 m and BS-T baseline length of 908.2124 m in the landslide area had an elevation difference of around 120 m. This study aimed to determine the experimental accuracy of the GPS measurements for the continuous monitoring of landslides in the high-mountain area.

Conclusions

The use of the TDR coaxial cables and GPS to monitor landslides has proven to be effective for landslides occurring in highly weathered rock slopes in the high-mountain area. The TDR system of coaxial cables grouted inside a drill hole can detect sliding surfaces and theirs movements as the function of a traditional in-place inclinometer. The TDR material is much cheaper than that of the inclinometer. According to the TDR waveforms, the presence of a shear zone (movement caused by shear force) was found at a depth of 2 m and a tensile zone (movement caused by tensile force) at a depth of 14 m under the B-5 monitoring station. There were also shear and tensile zones under the B-9, C-1, and C-2 stations. At every TDR station, the sliding signature of TDR waveforms was observed. The variation of waveforms could be explained by the shear or tensile force causing the deformation of

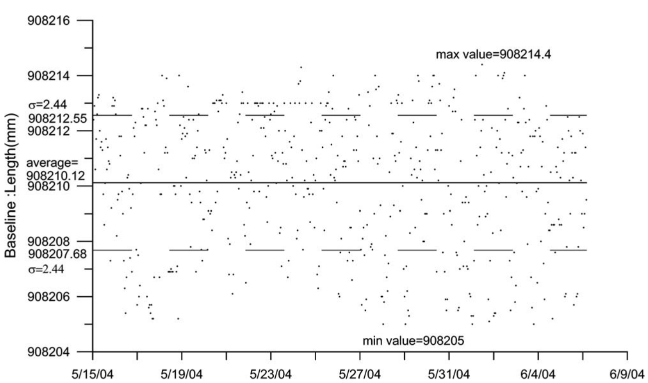

Fig. 11. Relationship between baseline length and date for GPS long-term monitoring in Li-shan landslide area (BS-T baseline)

Table 5. Baseline Variations among BS and Moving Stations E and T

	BS-E baseline (mm)	BS-T baseline (mm)
Initial length	451,188.1	908,212.4
Maximum length	451,192.4	908,214.4
Extension variation	4.3	2.0
Minimum length	451,183.0	908,205.0
Diminished variation	−5.1	−7.4
Average length	451,188.2	908,210.12
Standard deviation	2.16	2.44

the TDR cables. The result of the TDR monitoring system showed that it was useful and reliable to judge the locations of sliding surfaces in the high-altitude landslide area.

With regard to the GPS monitoring of landslides, this study aimed to determine the experimental accuracy of GPS measurements for continuous monitoring. Three GPS receivers were installed to measure ground displacement for 24 h. The two initial baseline lengths were 451,188 and 908,212.4 mm, respectively. The result showed that the standard deviations of the GPS were 2.16 and 2.44 mm, respectively. The maximum difference of the baseline variations between the initial and measuring value was 7.4 mm.

This research proves that TDR and GPS can be used in the long-term monitoring of high-mountain landslides and their interpreted methods and accuracy. Furthermore, they can be used effectively as a new monitoring system in larger landslide areas offering faster, easier, and more cost-effective monitoring methods.

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