Comparison of TDR and Inclinometers for Slope Monitoring

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Abstract

As TDR technology grows in acceptance, its use stimulates further innovative applications and comparison with slope inclinometer measurements. This paper presents cases in which the opportunity arose to compare these two technologies to detect and measure subsurface deformation in slopes. Among the main points addressed are (1) the comparison of TDR reflection magnitude and inclinometer incremental displacement to help quantify deformation with TDR technology, and (2) the comparison of the accuracy of the two technologies in detecting and measuring shear deformation in localized versus general shear. Case histories are presented that involve monitoring movement in soil and rock slopes and embankments as well as retrofitting deformed inclinometer casing with coaxial cables. This paper describes installation details. When monitoring to detect narrow shear zones in soils, it is best to use small ratios of hole-to-cable diameter, and prudent use requires that larger diameter, solid, metallic coaxial cables be installed in separate holes. Grout strength should be (1) low enough to fail before bearing capacity of the surrounding soil is reached, and (2) high enough to deform the cable it encapsulates. It is recommended that other users publish cases in which theses two technologies are compared in order to expedite continued assessment.

Coaxial Cable Geometry used for TDR Monitoring

TDR is analogous to radar in a coaxial cable. Consequently, it is possible to display all reflections along a cable and identify the type and location of cable

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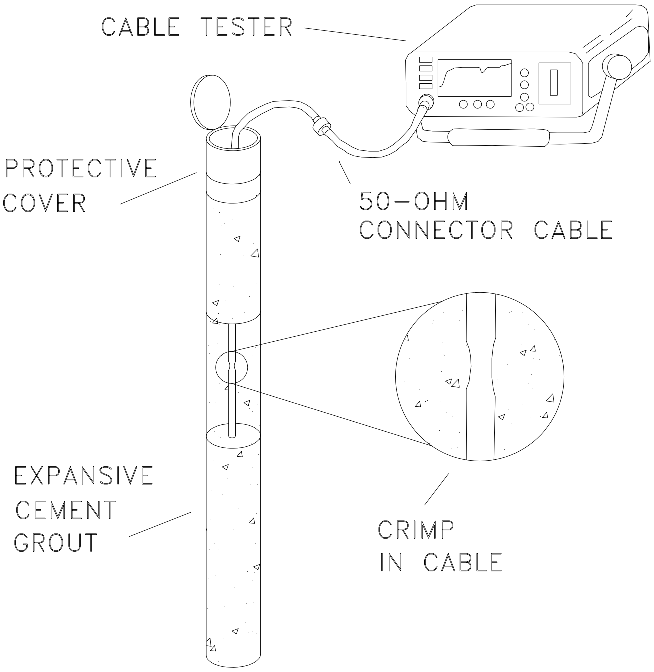

Figure 1.-Schematic of cable installation and monitoring.

deformities producing these reflections. As shown in Figure 1, a metallic coaxial cable can be placed in a drill hole and anchored to the walls by tremie placement of an expansive cement grout. When localized shear movements in rock or soil are sufficient to fracture the grout, cable deformation occurs and can be detected using a TDR cable tester which launches a voltage pulse along the cable. At each location where deformation has occurred, a portion of the voltage is reflected back to the TDR unit which displays the reflections. Travel time of each reflection distinguishes the locations where cable deformation is occurring, and differences in the reflected signal magnitudes can be employed to quantify the magnitude of cable deformation (O’Connor and Dowding, 1999). When a cable is crimped prior to placement in the hole as shown in Figure 1, a reflection from each crimp serves as a distance reference marker in the TDR record.

Strip Mine Highwall Slope (Case 1)

The example shown in Figure 2 involved installation of coaxial cable in the highwall slope of an oil sands mine. Details of the installation are compared with the other cases in Tables 1 and 2. The bituminous sands contain numerous thin consolidated clay layers that cause highwall slope instability. Consequently, slope movement is an operational problem and many kilometers of inclinometer casing have

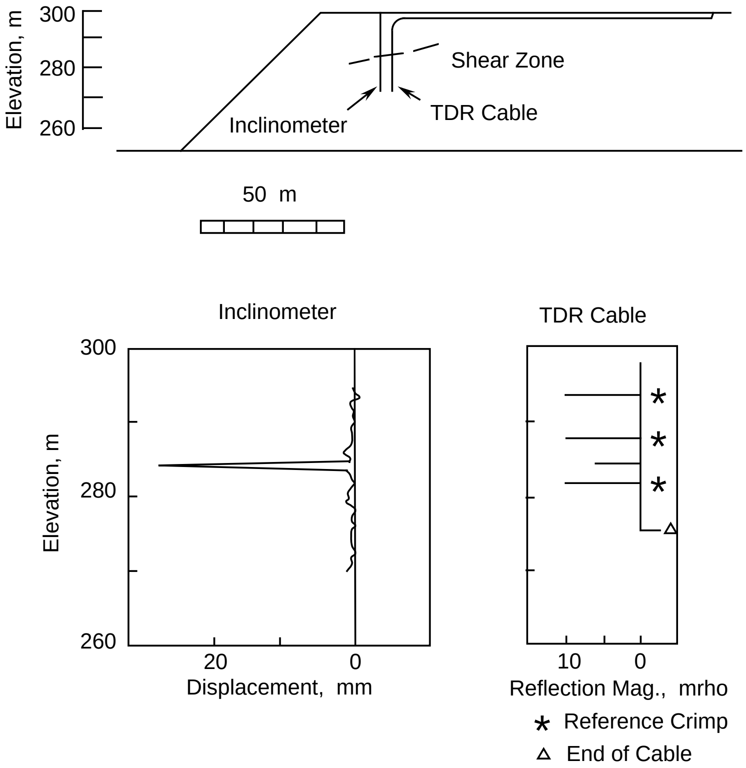

Figure 2.- Installation of coaxial cable and inclinometer in Case 1; *A*, location; *B*, inclinometer incremental displacement and TDR waveform for one reading

been installed to continuously monitor this movement in the vicinity of the multimillion dollar dragline. Given the large commitment to man-hours and hardware required for monitoring, the mining company investigated the potential of TDR for remote monitoring.

At three locations in the mine, a coaxial cable was grouted into a hole located 10 m from an inclinometer and the results from one comparison are shown in Figure 2. Note the reflection which developed at a depth of 18 m. It is consistent with both the shear zone location and the inclinometer incremental displacement profile. When the TDR reflection magnitude of 6 mrho (1 mrho = 1/1000th of the launched voltage) is compared with the inclinometer incremental displacement (28 mm over the inclinometer probe wheel base of 2 ft), the linear correlation is 6 mrho/28 mm or approximately 0.2 mrho/mm. As will be seen in Case 2, this sensitivity is low and can be enhanced by reducing both the hole diameter and grout strength.

Landfill Slope Deformation (Case 2)

Deformation of an industrial landfill presented another opportunity to compare inclinometer and TDR response. The landfill rests on 1 m of silt and sand, underlain

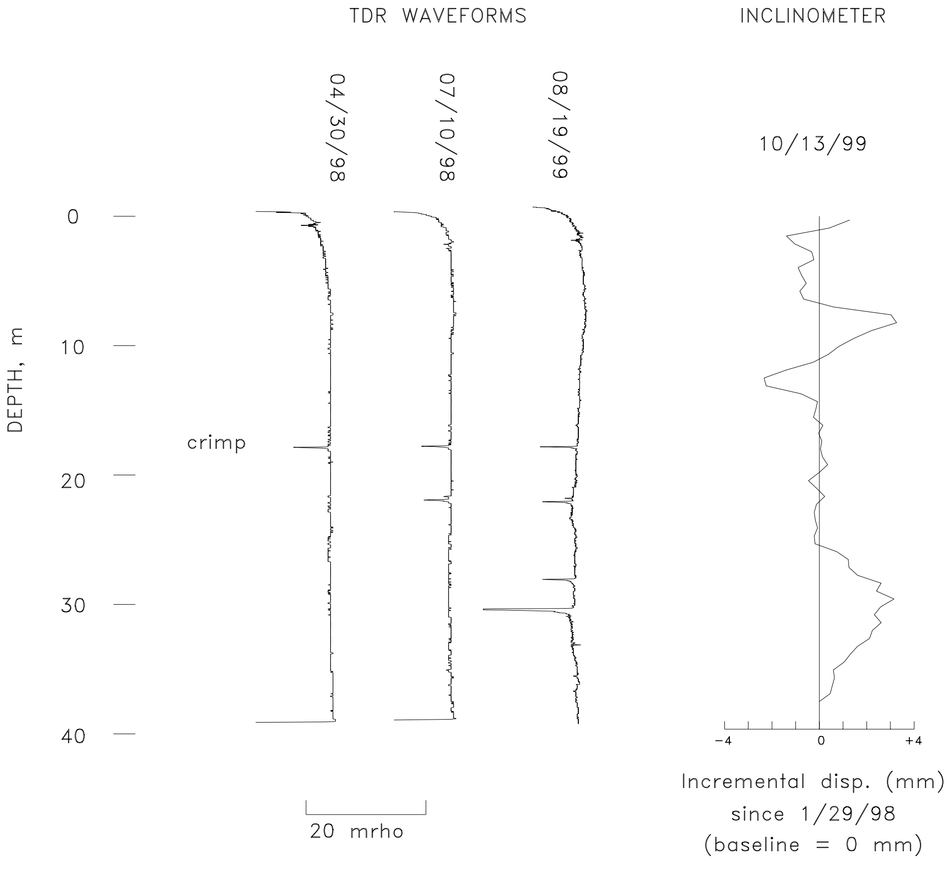

Figure 3.-TDR waveforms and inclinometer profile for Case 2.

by 9 to 12 m of soft clay, which in turn is underlain by stiffer clay. In accordance with the current standard of practice, inclinometers and piezometers were installed to define the extent of the deformation and monitor effective stress changes. As a field trial of TDR technology to detect and quantify shear within soft clays, coaxial cables were installed in boreholes adjacent to two of the inclinometers.

As shown by the lower bulge at the right of Figure 3, inclinometer incremental displacements indicate that subsurface deformation occurred within a shear zone at a depth of approximately 30 m within the soft clay. As shown by the 5 mrho reflection at a depth of 22 m, deformation of the coaxial cable first occurred on 7/10/98 at this depth which is the contact between the fill material and underlying layer of silt and sand. On 8/19/99, a spike of 8 mrho appeared at a depth of 28 m and a second spike of 23 mrho at a depth of 31 m. At both depths, the inclinometer incremental displacement was 2.6 mm. These responses yield a sensitivity of 8 mrho/2.6 mm = 2.7 mrho/mm and 23 mrho/3 mm = 7.7 mrho/mm. As shown by the summary in Tables 1 and 2, the increased sensitivity compared with Case 1 may have

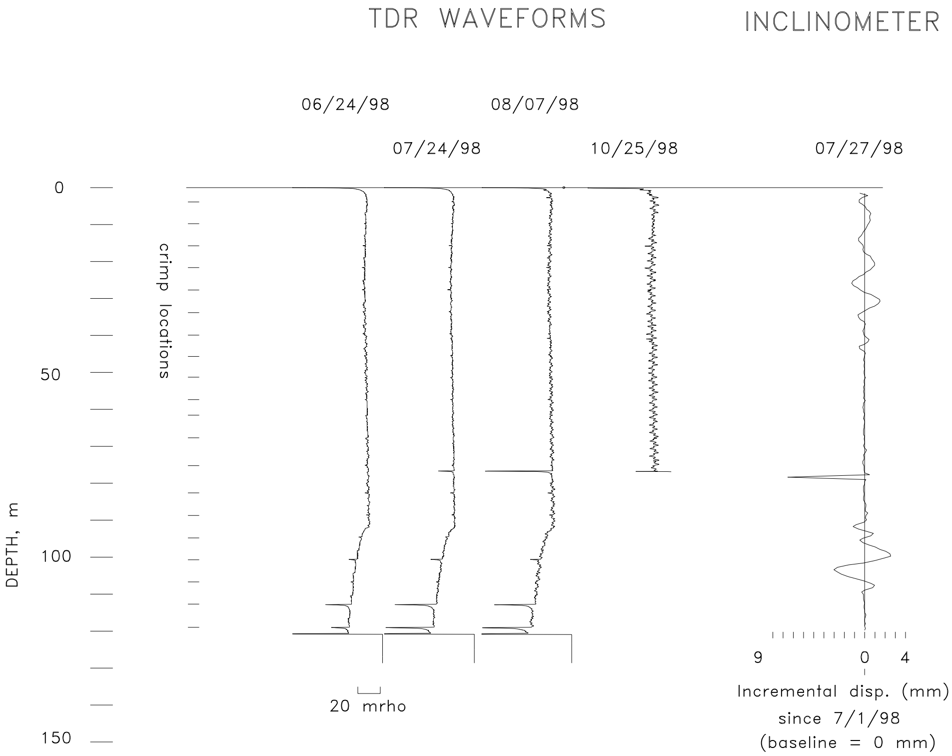

Figure 4.-TDR waveforms and inclinometer profile for Case 3.

resulted from the decreased hole diameter and grout strength. The magnitude of the larger TDR reflection (23 mrho at a depth of 31 m) is a minimal value as it exceeded the maximum range setting used for data acquisition.

Road Distress and Retrofit of Inclinometer Casing (Case 3)

Distress in a limestone causeway supporting a major highway presented yet another opportunity to compare TDR and inclinometer response. Movements had been occurring since December of 1997, and an instrumentation program was formulated to determine the cause of movement. Among the instruments installed to monitor subsurface movement were inclinometers and coaxial cables (Figure 1).

Comparison between TDR and inclinometer measurements in Figure 4 shows consistent response at a depth of 76.5 m. Movement at this depth occurred within a zone of greater fracture density in the limestone. The reflections at depths of 113 m and 119 m were caused by movement along dolomite-shale contacts. The TDR reflections at a depth of 76.5 m between 6/24/98 and 8/7/98 indicate that the reflection grew by 58 mrhos. The growth in inclinometer incremental displacement

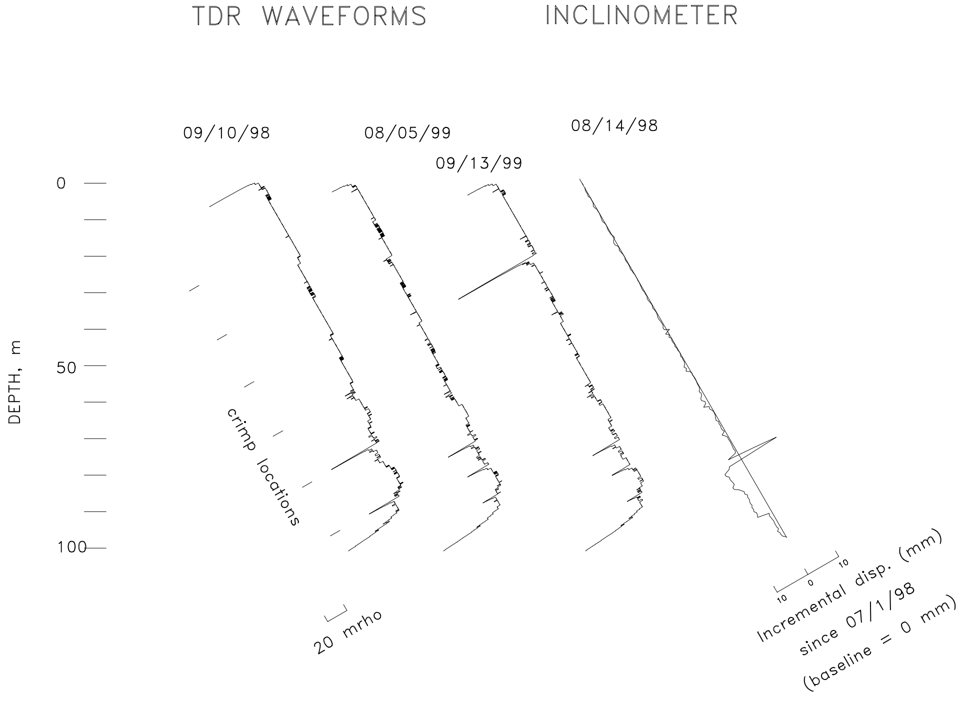

Figure 5.- TDR waveforms and inclinometer profile for retrofit of inclinometer casing in an inclined hole.

at this depth, over the same time period, was 12.4 mm so the sensitivity was 58 mrho/12.4 mm or approximately 5 mrho/mm. When the reading was taken on 8/19/98, it was found that the cable had been sheared off at this depth.

Kinking of the inclinometer casing provided an opportunity to demonstrate the use of TDR technology to extend the useful life of this casing. On 3/2/99 it was not possible to lower a probe down past a depth of 75.6 m in the adjacent inclinometer hole, and on 6/25/99 this inclinometer casing was retrofitted with a grouted coaxial cable to continue monitoring. Ultimately, five of the eight original inclinometer casings were retrofitted with grouted coaxial cables, and TDR waveforms for one of these are shown in Figure 5. This hole is inclined at 30 degrees from vertical and on 8/14/99 it was not possible to get the inclinometer probe past a downhole distance of 86.6 m which corresponds with an actual depth of 75 m. The TDR waveforms acquired since 9/10/98 show that it has been possible to continue monitoring movement at this depth.

Abutment Embankment Deformation (Case 4)

Suspected deformation of bridge abutments provided another opportunity to

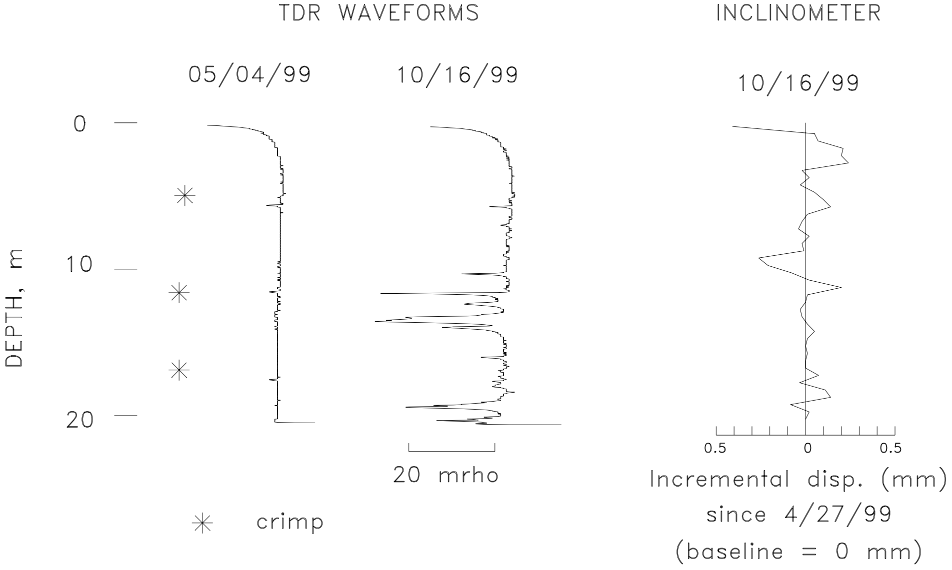

Figure 6.- TDR waveforms and inclinometer profile for installation in Case 4.

compare inclinometer and TDR response. The approaches of two highway bridges were constructed by building embankments over existing soils on the west abutment and over rock on the east abutment. The embankment fill consists of stiff silty clay and rock fragments and, on the west abutment, it overlies native alluvial soft clay and loose sand. The underlying rock on both abutments is shale and limestone. The shale is soft and erodible while the limestone is conspicuous as ledges in exposures along the highway.

Inclinometer casing and coaxial cables were installed in separate holes on both the east and west abutment slopes. The TDR waveforms and inclinometer incremental displacement profile shown in Figure 6 were acquired on the east abutment where the embankment was constructed over rock. Both the coaxial cable and inclinometer casing were deformed at depths of 12 m and 19 m. However, deformation of the coaxial cable was also detected at depths of 11, 13, 16, and 20 m. The fill extends to a depth of 13 m where it rests on the soft shale which is underlain by limestone at a depth of 20 m. The water table is located at the top of the shale layer. The largest TDR reflections correspond to depths at which contacts exist—29 mrho at a depth of 12 m and 26 mrho at 13 m at the contact between fill and shale, and 21 mrho at a depth of 19 m at the contact between shale and limestone. By comparison, the inclinometer incremental displacement was only 0.2 mm at depths of 12 m and 19 m. This implies a sensitivity which varies from 21 mrho/0.2 mm to 29 mrho/0.2 mm or 105-145 mrho/mm. These values are considered to be unusual, and reasons for such a large difference in response between TDR and inclinometers are discussed below.

Deformation of Coaxial Cables versus Inclinometer Casing

Plastic inclinometer casing and solid metallic coaxial cables deform differently when subjected to very localized shearing. Metallic coaxial cable deforms easily when subjected to highly localized shear and has been found useful in rock where deformation occurs along joints, bedding planes, and fractures. On the other hand, inclinometer probes are sensitive to gradual changes in inclination of the inclinometer casing. Localized shearing of inclinometer casing causes kinking such that a probe cannot be moved through the deformed casing. The thinner the localized shear zone, the greater the TDR response and the smaller the slope inclinometer response (O'Connor and Dowding, 1999). Thus, in situations involving both general shear and localized shear, it should be expected that the two technologies will respond differently as illustrated by the case histories summarized in this paper.

Shear Strain versus Incremental Displacement

There are two methods commonly used to plot slope inclinometer measurements—cumulative displacement (change in profile of the casing) and incremental displacement (local changes in inclination of the casing). While reported as displacement, slope inclinometer incremental displacement (SIID) is also the inclination of an inclinometer probe, and can be interpreted as local shear strain (over the base length between wheels of the probe).

As a consequence of the difference in response of TDR and inclinometer technologies, SIID under-represents localized shear while TDR under-represents general shear. This difference results from the span over which relative displacement is measured. SIID is the change in angle over a base length of 600 mm (or 24 in.), the wheel-base of the standard probe. Thus a SIID of 1 mm over 600 mm (or 0.04 in. over 24 in.) is a shear strain of 0.17%. This shear strain is averaged over the base length which is fairly large when compared to localized shearing along rock fractures (that may be less than 2 cm in width), or along thin shear zones in soil.

It has been shown that cable-grout composites respond poorly when shear occurs across large shear zones. Peterson (1993) found that sensitivity declined by a factor of 2 when the distance between clamps used in a laboratory direct shear test was increased from 1 mm to 40 mm. Sensitivity declined by a factor of 20 for a clamp spacing greater than 80 mm. These results indicate that cable-grout composites respond optimally to localized shear across zones less than 40 mm wide (e.g., shear strain of 1 mm/40 mm or 2.5%).

Most importantly, data from Case 2 indicate that TDR technology may respond to abrupt changes in shear strains at the boundaries of thick shear zones. The TDR reflections at depths of 28 m and 31 m in Figure 3 define the upper and lower boundaries of the shear zone within the soft clay. Peterson's laboratory tests indicate that in this case, the fractured grout was confined by the soil in the shear zone and localized shearing of the cable occurred.

Installation Details

Details of the coaxial cable installations in these four cases varied considerably due to local practices for drilling and installation of slope inclinometers. These details are summarized in Tales 1 and 2 that describe (1) coaxial cables and (2) the grout and soil/rock properties. Local drilling practices varied from rotary wash drilling of unlined 75-106 mm diameter holes in medium clay to 200 mm diameter hollow stem auger holes in miscellaneous rock and soil fill. It is important to keep the ratio of hole diameter to cable diameter as small as possible to ensure that the grout fractures with the least relative deformation. Coaxial cables will not be deformed until the grout fractures which is one reason that TDR technology responds poorly to gradual deformation of soil over large shear zones (general shear).

All the grouts used in these cases were tremied into place with the drilling rig water pump - even the thickest and strongest. However, grout strengths varied considerably as shown in Table 2. Early installations (i.e., Case 1) employed very strong grouts that were standard mixes established for inclinometer installation at that site. More recent installations (e.g., Case 2) have employed cement-bentonite grouts with unconfined compressive strengths that are only 2% to 3% of those used in Case 1. Case 4 encountered loss of the low viscosity grout, and it was necessary to resort to a thicker grout mix to minimize loss through rock fractures and sand lenses.

Grout strengths must be large enough to deform the cable; yet they must be 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 within the surrounding soil (Pierce, 1998). For installation in rock, this consideration is not as critical due to the relatively high strength and stiffness of rock. In order to maximize cable/grout composite sensitivity in soil, it is hypothesized that the shear capacity of the grout should be less than the bearing capacity of the soil just outside the localized shear plane.

Strength and stiffness of the cable, grout, and soil/rock for the four sites described in this paper are summarized in Tables 1 and 2. Based on laboratory tests, grouted 22-mm-diameter CommScope solid aluminum coaxial cable (P3-75-875CA) has a stiffness of 88 MPa and a shear strength of 1.6 MPa. This cable has performed satisfactorily at sites where the deformation occurs in fractured rock. Case 2 indicates that this solid aluminum cable installed in small diameter (100 mm and smaller) holes with weak grout may respond satisfactorily even when installed in soft clay.

Summary

Comparisons of slope inclinometer and TDR responses for the cases presented in this paper indicate that both technologies provide useful information. TDR technology is especially sensitive to localized shear so it is most responsive to concentrated shear strain. On the other hand, slope inclinometers are especially sensitive to gradual changes in inclination so they are most responsive in soils undergoing general shear. TDR technology will also respond to abrupt changes in shear strain at the boundaries of a thick shear band.

These differences do not imply that either technology is more correct; rather, the two techniques respond optimally under different conditions. The real challenge is to provide a more precise and rational explanation for these different responses. In order to expedite this process it is recommended that other users publish case histories in which the two technologies are compared.

Finally, solid aluminum coaxial cables can be installed in deformed inclinometer casing to allow continued monitoring. The results of installing and monitoring coaxial cables installed in deformed inclinometer casing indicate that this will be effective whether the casing has been installed in rock or in soil. Such retrofitting allows continued monitoring of subsurface deformation without the need to drill additional holes.

References

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Table 1 - TDR Cable Details

Case	Reason for Monitoring	Sensor Cable			Sensor Cable Length (m)	Lead Cable Length (m)
		Type	Strength (MPa)	Stiffness (MPa)		
1	highwall slope	A	1.6	88.0	23	107
2	landfill slope	A			40	0
3	road distress	A			60 to 120	0
4	abutment embankment slope	A			29	0
		B	0.4	8.0	11	19

A: CommScope solid aluminum, expanded polyethylene foam dielectric, P3-75-750CA, 22.2 mm dia., 75-ohm

B: Type A with solid aluminum outer conductor removed; exposed polyethylene foam dielectric was coated with silver paint then wrapped with vinyl electrical tape, 20 mm dia.

Table 2 – Grout, Soil and Rock Properties

Case	Hole Diameter (mm)	Grout Properties†					Rock / Soil Properties			Installation and Comments
		Strength (MPa)	Stiffness (MPa)	Grout Mix (lb)			Description	Strength (MPa)	Stiffness (MPa)	
				W	C	B				
1	140	22	-	324	688	49	stiff clay , soft seams	0.06	40 - 125‡	rotary drilled
2	106	0.5	100	361	188	10	fill over soft clay	0.03	-	rotary drilled
3	75 to 125	7	1500	1054	1983	0	fractured dolomite and shale	110	2200	rotary drilled
	75									installed in deformed inclinometer casing
4	200	20	4700	240	235	15	sand and clay fill with boulders	0.1	30	hollow stem auger
	75	19	4300	168	329	12	shale	2	600	rotary drilled

‡ estimated

† W = water, C = Portland cement, B = bentonite