

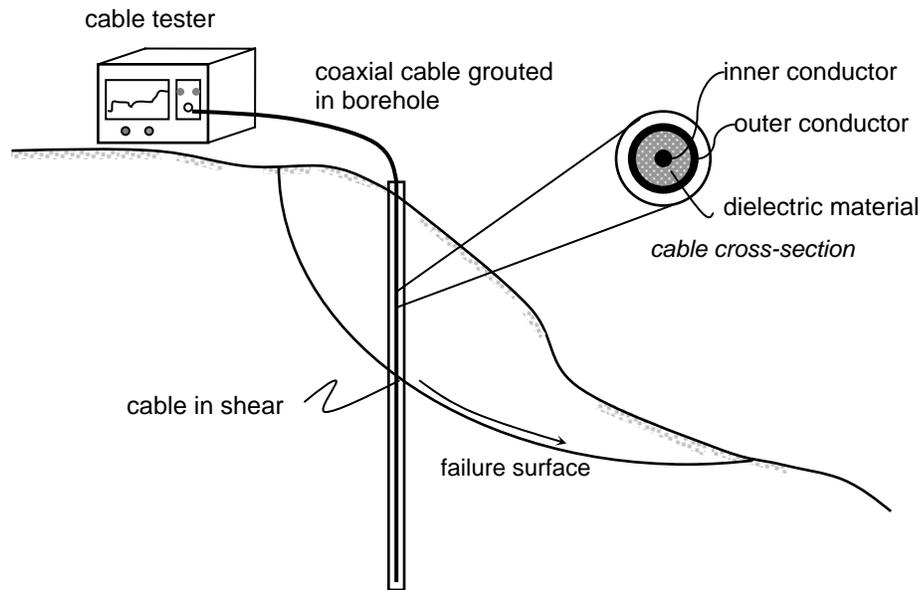


# FINAL REPORT

## FHWA-WY-06/03F

State of Wyoming  
Department of Transportation

U.S. Department of Transportation  
Federal Highway Administration



# TIME DOMAIN REFLECTOMETRY FOR MONITORING SLOPE MOVEMENTS

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Abstract  A study of time domain reflectometry was conducted for application to monitoring of highway slopes. Laboratory shear tests were carried out in an attempt to develop a correlation between shear displacement and TDR signals from grouted cables in sand deposits. Laboratory tests were also conducted to evaluate the potential use of air-dielectric, or hollow, coaxial cable for measuring groundwater elevations and for combined measurements of groundwater and slope movements. Grouted cables were installed at roadway landslide sites at four locations in Wyoming and monitored for periods ranging from one to six and a half years.  Results of laboratory shear tests demonstrate that cable deformation is sensitive to boundary conditions and that it is difficult, if not impossible, to obtain consistent, repeatable results. Each test yielded a significantly different relationship between cable signal and shear deformation. It is concluded that no reliable correlation can be established for laboratory test conditions. Hollow-cable TDR was found to provide a quick and reliable method for determining groundwater elevations and is recommended for field implementation.  Four landslide sites were instrumented with coaxial cable for TDR monitoring and slope inclinometer readings. Results are presented and discussed in detail. TDR readings are compared to slope inclinometer readings at each site. Based on the lab and field testing results, it is concluded that TDR can be a cost-effective and useful method for monitoring the occurrence and depth of slide planes when applied appropriately. TDR is not sufficient to establish the magnitude of slope deformation. Recommendations are given for continuing implementation by WYDOT of TDR for slope monitoring.			
Key Words Time domain reflectometry, slope stability, landslides, monitoring		Distribution Statement Unlimited	
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# SI\* (Modern Metric) Conversion Factors

Approximate Conversions from SI Units					Approximate Conversions to SI Units				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
<b>Length</b>					<b>Length</b>				
mm	millimeters	0.039	inches	In	in	inches	25.4	millimeters	mm
m	meters	3.28	feet	Ft	ft	feet	0.305	meters	m
m	meters	1.09	yards	Yd	yd	yards	0.914	meters	m
km	kilometers	0.621	miles	Mi	mi	miles	1.61	kilometers	km
<b>Area</b>					<b>Area</b>				
mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>	in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>
m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>	ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>
m <sup>2</sup>	square meters	1.195	square yards	Yd <sup>2</sup>	yd <sup>2</sup>	square yards	0.836	square meters	m <sup>2</sup>
ha	hectares	2.47	acres	Ac	ac	acres	0.405	hectares	ha
km <sup>2</sup>	square kilometers	0.386	square miles	Mi <sup>2</sup>	mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>
<b>Volume</b>					<b>Volume</b>				
ml	milliliters	0.034	fluid ounces	fl oz	fl oz	fluid ounces	29.57	milliliters	ml
l	liters	0.264	gallons	gal	gal	gallons	3.785	liters	l
m <sup>3</sup>	cubic meters	35.71	cubic feet	ft <sup>3</sup>	ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>
m <sup>3</sup>	cubic meters	1.307	cubic yards	Yd <sup>3</sup>	yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>
<b>Mass</b>					<b>Mass</b>				
g	grams	0.035	ounces	Oz	oz	ounces	28.35	grams	g
kg	kilograms	2.202	pounds	Lb	lb	pounds	0.454	kilograms	kg
Mg	megagrams	1.103	short tons (2000 lbs)	T	T	short tons (2000 lbs)	0.907	megagrams	Mg
<b>Temperature (exact)</b>					<b>Temperature (exact)</b>				
°C	Centigrade temperature	1.8 C + 32	Fahrenheit temperature	°F	°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C
<b>Illumination</b>					<b>Illumination</b>				
lx	lux	0.0929	foot-candles	Fc	fc	foot-candles	10.76	lux	lx
cd/m <sup>2</sup>	candela/m <sup>2</sup>	0.2919	foot-Lamberts	Fl	fl	foot-Lamberts	3.426	candela/m <sup>2</sup>	cd/m <sup>2</sup>
<b>Force and Pressure or Stress</b>					<b>Force and Pressure or Stress</b>				
N	newtons	0.225	poundforce	Lbf	lbf	pound-force	4.45	newtons	N
kPa	kilopascals	0.145	pound-force per square inch	psi	psi	pound-force per square inch	6.89	kilopascals	kPa

## ACKNOWLEDGMENTS

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## **EXECUTIVE SUMMARY**

A study of time domain reflectometry was conducted for application to monitoring of highway slopes. Laboratory shear tests were carried out in an attempt to develop a correlation between shear displacement and TDR signals from grouted cables in sand deposits. Laboratory tests were also conducted to evaluate the potential use of air-dielectric, or hollow, coaxial cable for measuring groundwater elevations and for combined measurements of groundwater and slope movements. Grouted cables were installed at roadway landslide sites at four locations in Wyoming and monitored for periods ranging from one to six and a half years. TDR measurements are compared to slope inclinometer measurements at each site.

Results of laboratory shear tests demonstrate that cable deformation is sensitive to boundary conditions and that it is difficult, if not impossible, to obtain consistent, repeatable results. Each test yielded a significantly different relationship between cable signal and shear deformation. It is concluded that no reliable correlation can be established for laboratory test conditions. Hollow-cable TDR was found to provide a quick and reliable method for determining groundwater elevations. Below the groundwater elevation, the TDR signal is distorted and a correction factor must be applied to readings below the groundwater elevation. Shearing of the hollow cable below the water level is detectable but the signal is not as pronounced as the signal induced by the same magnitude of shearing above the water level. Hollow cable can therefore be used to monitor both slope movements and groundwater elevations, but detection of slope movement below groundwater is more difficult.

Four landslide sites were instrumented with coaxial cable for TDR monitoring and slope inclinometer readings. At two sites (Campstool and Togwotee Pass) ground movements have been insufficient to shear the coaxial cables. TDR monitoring of cables at The Narrows slide demonstrates that the TDR method can work for detecting the presence and depth of a slide plane. In general, the magnitude of the TDR signal increased with increasing deformation, although measurements at a single location are not sufficient to develop a quantitative correlation between TDR readings and slide movement. TDR measurements at the Flying V slide, which was the first site instrumented for this study, failed to produce useful results even though inclinometer readings showed distinct slide planes undergoing significant deformation.

Based on the lab and field testing results, recommendations are given for continuing implementation by WYDOT of TDR for slope monitoring.

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# CHAPTER 1

## INTRODUCTION AND BACKGROUND

### 1.1 Introduction

Time Domain Reflectometry (TDR) is a technology with potentially useful applications in the monitoring of highway slopes. TDR is based on measuring voltage reflections from an electrical pulse as it travels through a coaxial cable. A cable testing device provides a readout of cable reflection coefficient versus cable length. When installed in a borehole, cable reflection coefficient is significantly affected by shear and tensile deformations caused by ground movements, thus providing a fast method to determine the depth of a slide plane. It may also be possible to determine the magnitude of deformation based on the intensity of the measured change in reflection coefficient. Preliminary research on this topic has been encouraging, however a proven and generally applicable method to convert TDR measurements directly to slope deformation has not yet been developed.

The University of Wyoming and the Wyoming DOT conducted a research and development project to investigate the capabilities of TDR for monitoring highway slopes. Capabilities investigated include: (1) development of correlations between TDR measurements and slope movements for commercially available cables (2) use of TDR for monitoring ground water levels and slope movements simultaneously. Research consisted of laboratory and field testing of cable installations subjected to a wide range of deformation conditions, including active landslides where both TDR and slope inclinometer measurements were obtained.

TDR can potentially lower the cost of slope monitoring. TDR readings are obtained in a matter of minutes by an operator using a cable tester and computer. Slope inclinometers require the operator to lower a probe to the bottom of a casing and take individual measurements at specified intervals, typically requiring a minimum of 30 minutes for one monitoring point. TDR can be monitored remotely, further reducing personnel and travel costs associated with landslide monitoring. TDR monitoring of groundwater levels to determine pore water pressures in landslides also offers a lower cost alternative to installation and monitoring of traditional piezometers. A second benefit is improved safety of workers when monitoring locations on or close to the roadway. TDR cables can be extended to a location off the roadway, eliminating the need for traffic control and risk to workers.

### 1.2 Review of Previous Work

TDR was developed originally as a method to locate discontinuities or faults in power transmission cables and then later in coaxial cables used in telecommunications. Recently, the technique has been extended to locate zones of ground deformation by measuring reflection signatures of coaxial cables grouted in boreholes. As the grouted

cable deforms in response to ground movements, changes in cable capacitance are measured as changes in reflection signature. Interpretation of the measured reflection signature can provide information on the location and possibly the magnitude of ground deformation.

### 1.2.1 Fundamentals of TDR

A TDR testing system consists of the components shown in Figure 1. A coaxial cable is installed in a borehole and backfilled with cement grout. The borehole can be drilled using standard soil exploration or water well drilling equipment. To obtain readings, the top of the cable is connected via a standard UHF connector to a portable, battery operated cable tester. A widely used cable tester and the type used for this project is the Tektronix Model 1502C. The cable tester has a built-in monitor for viewing the cable signature. The cable tester can be connected through a serial port to a notebook computer, allowing an operator to transfer the cable signature to the computer in digital form. The cable signature can then be stored, analyzed, and re-plotted using a variety of software packages for data processing.

The coaxial cable used in a TDR system provides a one-dimensional path for propagation of an electromagnetic wave which is generated by a voltage pulse from the cable tester. The cable consists of outer and inner conductors separated by a material with a known dielectric constant (commonly referred to as the "dielectric material"), as shown in Figure 1. Propagation of the voltage wave along the coaxial cable is controlled by four fundamental properties of the cable: inductance ( $L$ ), resistance ( $R$ ), capacitance ( $C$ ), and conductance ( $G$ ). For relatively short cables ( $< 100$  m), resistance and conductance can

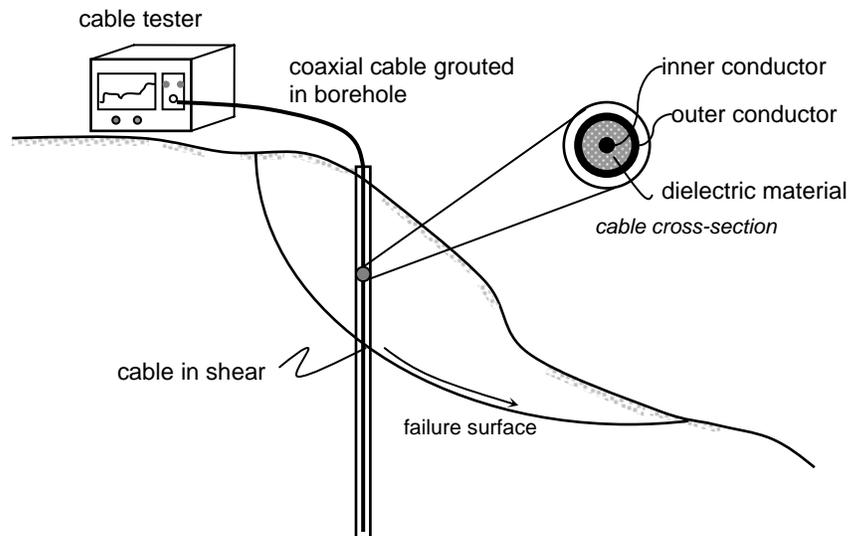


Figure 1. Components of TDR system for monitoring slope movements.

be assumed to be constant. Propagation of the electromagnetic wave is analyzed by assuming that the governing differential equation takes the form of the well-known wave equation for a voltage pulse  $V$  as a function of distance  $x$  and time  $t$ :

$$\frac{\partial^2 V}{\partial x \partial t} = (LC) \frac{\partial^2 V}{\partial t^2} \quad (1)$$

The reflected electrical signal at any distance  $x$  along the cable is analyzed by solving Eq. (1) in the time domain (*i.e.*, at a given instant in time) with the applicable boundary conditions. The cable tester presents the solution graphically as a plot of reflection coefficient,  $\rho$ , versus distance along the cable,  $x$ . Reflection coefficient is defined as the ratio of reflected voltage to incident voltage and expressed in units of millirhos. The cable signature, or plot of  $\rho$  versus  $x$ , therefore represents the amount of energy reflected at a given distance ( $x$ ) from the source of the pulse, analyzed at a given instant in time, hence the term Time Domain Reflectometry. An important property of the cable needed to analyze the distance to a given reflection point is the voltage pulse propagation velocity ( $v_p$ ), given by:

$$v_p = (L^*C)^{1/2} \quad (2)$$

Another important cable parameter is the characteristic impedance,  $Z_o$ , also defined as a function of cable inductance and capacitance:

$$Z_o = (L/C)^{1/2} \quad (3)$$

### 1.2.2 Effects of Cable Deformation on Voltage Reflections

Dowding et al. (1988) showed that various modes of cable deformation can be modeled approximately as changes in capacitance and impedance. For shear deformation the change in reflection coefficient,  $\rho$ , is modeled as a localized change in capacitance and can be approximated by the following relationship:

$$\rho = \Delta C \frac{Z_o}{2 t_r} \quad (4)$$

where:  $\Delta C$  = change in capacitance at the location of cable deformation,  $Z_o$  = characteristic impedance of the undeformed cable, and  $t_r$  = rise time of the voltage pulse, typically 100-200 psec. Changes in  $\rho$  caused by shear appear as sharp downward spikes in the cable signature, as illustrated in Figure 2, and the amplitude of the spike increases in direct proportion to the magnitude of shear deformation.

Changes in reflection coefficient caused by tensile deformation of the cable are best modeled in terms of changes in impedance, and expressed as follows:

$$\rho = \frac{Z_1 - Z_0}{Z_1 + Z_0} \quad (5)$$

where  $Z_1$  = characteristic impedance of the deformed section of cable and  $Z_0$  = characteristic impedance of the undeformed cable. Changes in  $\rho$  caused by tensile deformation appear as a subtle, trough-like depression in the cable signature (Figure 2) and are more difficult to detect than the signal caused by shearing.

### 1.2.3 Cable Signature and Ground Movement

The magnitude of the spike in a TDR cable signature increases as the magnitude of shear deformation increases. It would therefore seem logical that a general relationship could be developed to relate change in reflection coefficient to the magnitude of shear deformation in the ground. A literature review was conducted to determine the state of practice for using TDR to estimate magnitude of slope movement.

Dowding et al. (1988, 1989) conducted a laboratory study in which the type and magnitude of reflected TDR signatures caused by shearing and extension of coaxial cables were investigated. A coaxial cable was grouted into a steel pipe in an effort to simulate a borehole. The grout and pipe were cut in two locations in order to simulate joint planes along which sliding would occur in a jointed rock mass. The grout and embedded cable were sheared by pushing the middle segment down while restraining the end segments, as illustrated schematically in Figure 3. Test results are presented in the form of graphs showing reflection coefficient in millirhos versus shear deformation in millimeters. All of the graphs showed a linear relationship between reflection coefficient and deformation. This result was considered encouraging because it suggests that, for a given type of cable, there is a direct, linear, and measurable relationship between the cable signal and shear deformation.

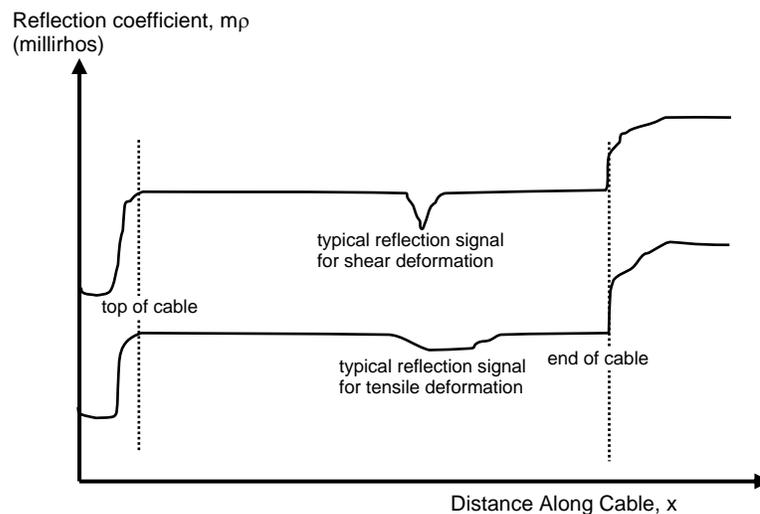


Figure 2. Examples of cable signatures for shear and tensile deformation.

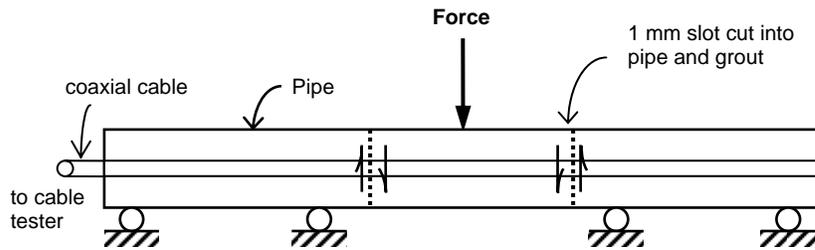


Figure 3. Model of lab test for cable in shear.

Since the initial laboratory study by Dowding et al., several researchers have conducted laboratory shear tests on grouted coaxial cables in order to quantify the relationship between reflection coefficient and shear deformation. Results of these studies are summarized in Table 1 (O'Connor and Dowding, 1997). Consider the column listing values of “slope  $\rho/\text{mm}$ ”, which quantifies the relationship between reflection coefficient and shear displacement. An important observation is the slope varies significantly both between different cable types and for a single type of cable. Review of the testing conditions (as indicated by “Test Objective” in Table 1) reveals that the cable signature-deformation relationship varies with several factors, including: width of the shear zone (Peterson, 1993); the presence of voids in the grout (Peterson, 1993); whether the cable coating is left intact or stripped to obtain better bonding between cable and grout (Kim, 1989); and the distance between the cable tester and the sheared portion of the cable (Kim, 1989). Furthermore, tests conducted by Logan (1989) show that the slope and intercept are considerably different if the borehole containing the cable is backfilled with gravel instead of grout.

Variability in the relationship between reflection coefficient and shear deformation with the factors noted above makes it difficult to determine what, if any, slope value would enable a highway engineer or geologist to convert field TDR readings to slope movement. The factors which appear to be most important are width of the shear zone and distance from the cable tester to the shear zone. The width of the shear zone refers to the length of cable over which shear deformation occurs. In the laboratory tests described by Dowding et al. (1988) shear deformation in the cable was concentrated in a zone approximately twice the diameter of the cable, and this was controlled by the width of the slot cut into the pipe and grout, which was approximately 1.0 mm. Tests were conducted by Peterson (1993; Table 1) in which gaps ranging from 5 mm to 80 mm were placed between adjacent sections of pipe, as shown in Figure 4, resulting in a significant decrease in the slope of the reflection coefficient versus deformation. By increasing the length of cable over which shear deformation occurs, the cable deforms more in tension than in shear, decreasing the magnitude of the voltage reflection. The logical conclusion from these laboratory studies is that if the interaction between the ground, grout, and cable is such that the deformation is highly concentrated over a small length of cable, then correlations based on lab tests which simulate this condition may apply to field

conditions (with due considerations of other factors, described below). An example in which TDR was used successfully for quantifying field deformation in rock is described by Aimone-Martin et al. (1994). In this study, a well-conceived program of laboratory correlations and field measurements of both TDR and rock mass deformations using extensometers led to reliable use of TDR for measuring displacements along joints in rock salt. However, if field loading results in significant bending instead of shearing of the cable because of a relatively large length of cable over which deformation occurs (large shear zone), then laboratory correlations based on a thin shear zone are not valid.

Table 1. Summary of Laboratory Shear Tests on Grouted Coaxial Cables (O'Connor and Dowding 1997).

Test Objective	Cable Manufacturer	Part No.	Diameter mm	Linear Regression			Comment	Reference	
				slope mrho/mm	x-intercept mm	r <sup>2</sup>			
Localized direct shear	Cablewave	FXA38-50	9.5	19.5	1.8	0.8987		5	
				22.8	1.0	0.9383		2	
		FXA12-50	12.7	31.0	1.2	0.9100		5	
	9.7			1.8	0.8282	fracture/debond	4		
				24.8	2.4	0.9944		4	
				19.7	0.5	0.9999		3	
				20.0	0.5	0.9354	7/1% bentonite	4	
				19.5	0.4	0.8947	0% bentonite	4	
				15.1	1.4	0.9567		2	
		FXA78-50	22.2	16.5	7.9	0.9360		5	
18.8	6.1			0.9465		2			
		FLC12-50	13.7	13.9	0.0	0.9640	corrugated copper	1	
		HCC12-50	12.3	25.9	0.0	0.9810	outer conductor	1	
Shear zone width	CommScope	P3 75-750CA	19.1	14.9	1.7	0.9723	5 mm gap	4	
				8.3	1.2	0.9696	20 mm gap	4	
				9.9	1.6	0.9738	40 mm gap	4	
				1.0	2.4	0.9606	80 mm gap	4	
Grout voids	Cablewave	FXA12-50	12.7	15.8		0.8888	no void	4	
				7.7		0.9780	void @90	4	
				24.2		0.8812	void @135	4	
				9.8		0.9395	void @270	4	
		CommScope	P3 75-750CA	19.1	9.8		0.9455	void @90	4
	16.4					0.9190	void @135	4	
Cable coating	Cablewave	FXA12-50	12.7	19.0		0.9566	void @180	4	
				15.0	1.4	0.9579	coated	2	
Distance from tester	Cablewave	FXA12-50	12.7	13.7	2.1	0.9432	bare	2	
				15.1	1.4	0.9588	1 m	2	
				11.5	1.6	0.9545	12 m	2	
				10.9	1.8	0.9634	24.4 m	2	
				6.7	1.8	0.9436	41 m	2	
				4.7	1.9	0.9445	59 m	2	
				10.7	1.8	0.9475	51 m, calculated	2	
				4.5	1.7	0.9383	51 m, calculated	2	
		FXA78-50	22.2	18.8	6.1	0.9471	1 m	2	
				13.9	5.0	0.8694	51 m, calculated	2	
				15.2	6.7	0.9313	51 m, calculated	2	

References: 1 = Aimone-Martin et al. (1994); 2 = Kim (1989); 3 = O'Connor (1991); 4 = Peterson (1993); 5 = Su (1987)

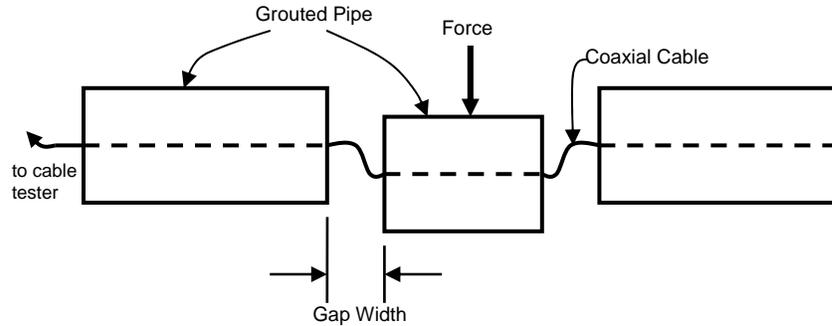


Figure 4. Deformation mode in tests by Peterson (1993).

Field research aimed at developing correlations between TDR readings and ground deformation in soil tends to support the conclusions based on laboratory studies. Consider the experience described by Peterson (personal communication). A series of carefully designed laboratory tests was conducted in which coaxial cables grouted into steel pipe were sheared, much in the same manner as described by Dowding et al. (1988) and illustrated in Figure 3. In the field, several cables were grouted into boreholes adjacent to the highwall of an open-pit tar sands mine in Canada. Slope inclinometer casings were located within several feet of the coaxial cables for independent measurements of slope movement. Although the slope inclinometer measured shear deformation of 3 to 4 inches, the spikes in the cable signatures were very small and did not indicate anything close to this magnitude of movement. Slope inclinometer casings were removed to observe their deformed shapes. When coaxial cables were fixed to the deformed casings and monitored, the signatures were similar to those observed in the field, leading the researchers to conclude that the cables were undergoing lateral deformation over a length of approximately 6 to 7 inches, resulting in bending instead of localized shear. Two possible explanations are (1) ground deformations occurred over a finite depth of 6 to 7 inches and the grouted cable simply deformed in compliance with the ground, or (2) ground deformation occurred along a discrete failure surface but the stiffness of the cable and grout compared to the stiffness of the soil prevented compliance with shearing in the ground, resulting in cable deformation over a length of 6 to 7 inches.

Pierce and Dowding (1994) reached a similar conclusion regarding the use of coaxial cables in soils. They proposed the use of highly compliant cables and low-strength, low-modulus grout in order to obtain compatibility between shear deformation of the ground and shearing of the cable. This appears to be a logical way to develop TDR capabilities in soil slopes, however, the idea was presented as a hypothesis and no experimental data were presented.

Effects of distance between the cable tester and shear zone in the cable are described by Kim (1989). It was found that the slope of the reflection coefficient versus shear deformation curve decreases with increasing distance from the tester, as shown in Figure 5. Although this makes it more difficult to interpret field measurements, with proper calibration this effect can be measured, quantified mathematically, and its effect

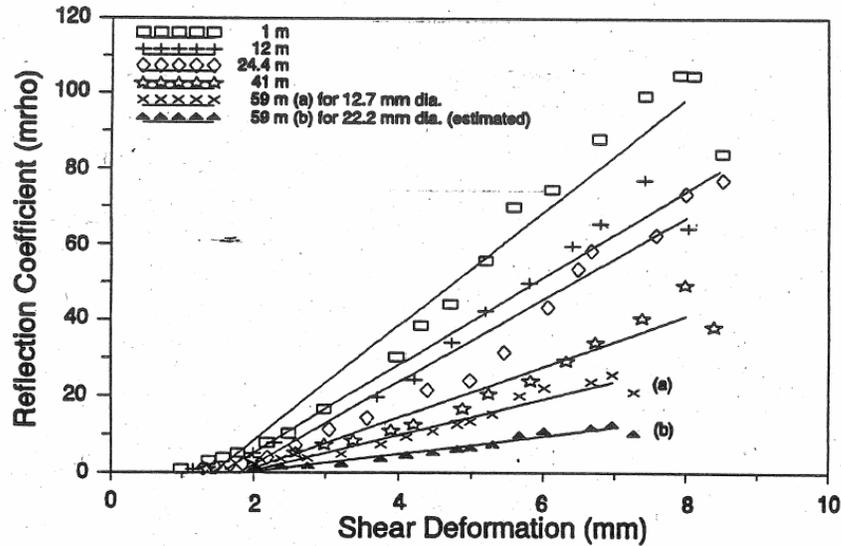


Figure 5. Reflection coefficient versus shear deformation for varying distances (Kim 1989).

accounted for in field measurements. From a practical standpoint, the effect is insignificant for distances less than 100 meters (305 ft), which would be the case for most slope monitoring applications.

Other researchers have correlated field TDR measurements directly to slope inclinometer measurements either by attaching coaxial cable directly to inclinometer casings or by locating cables in grouted boreholes close to slope inclinometer casings. For example, Caltrans is monitoring several slopes at which coaxial cables are attached to inclinometer casings. Beck and Kane (1996) describe some of these sites, and Gwinnup-Green (1996) presents inclinometer and TDR measurement data at an embankment slide in the form of curves of surface displacement (from slope inclinometer) and TDR reflection coefficient versus time. These data are useful, but to date no consistent method to interpret these field measurements has been proposed that would allow prediction of ground movements from TDR data at sites other than those at which slope inclinometer data are also available. Also it is not clear whether TDR cables attached directly to inclinometer casings will give the same signals as cables in grouted boreholes. Most likely the two installation methods would result in different modes of cable deformation, depending on the relative stiffness of casing versus that of grout. Kane (1997) concludes “At this time, TDR cannot be used to determine the exact amounts of movement”, but that with further research this capability can be developed.

Based on a careful review of the literature, it seems reasonable that reliable correlations between TDR cable signatures and landslide movements can be developed, under the following conditions:

1. For sites at which failure occurs in very stiff materials, such as rock or very stiff soils, it should be possible to use laboratory tests in which shear is concentrated to a relatively

small length of cable to interpret field TDR measurements. However, these correlations need to be verified by independent field measurements of ground movements using slope inclinometer, surveying, or some combination of methods. Furthermore, correlations should also account for effects of the distance between the cable tester and the shear zone, and laboratory tests must simulate as closely as possible the field setup (thickness and properties of grout, cable characteristics, etc.).

2. For sites at which shear failure occurs in less stiff materials (soil) it will be necessary to develop grout mixes and to use cables which will comply with the ground deformations, in order to concentrate shear deformation over a relatively short length of cable.

3. At field sites where ground deformation occurs over some finite depth which is more than several cm thick, TDR may not be an appropriate technology for replacing currently used methods.

#### 1.2.4 *TDR for Groundwater Monitoring*

The dielectric properties of the material between the two conductors in a coaxial cable determine the cable impedance, and therefore the cable signature. Some commercially available cables contain air as the dielectric material. If water enters the cable and replaces air in the annular space between conductors, a sharp decrease is measured in the cable reflection coefficient. This ability to clearly identify the presence of water in air-dielectric coaxial cables can be exploited to locate groundwater in a borehole. Dowding and Huang (1994) describe a laboratory study in which air-dielectric coaxial cable was used to measure the distance to water in a tank. The TDR-calculated distance to the reflection caused by the air-water interface corresponded to the physically measured distances, for both rising and falling water levels. Dowding et al. (1996) showed that calculations of pore water pressures based on TDR groundwater measurements match the resolution of commercially available electronic pressure transducers while offering the advantage of “up-hole” electronics as opposed to electronic devices placed in the ground or at the bottom of a standpipe piezometer well.

The ability of air-dielectric cables to measure groundwater levels combined with TDR for detecting shear deformations suggests the possibility of a single cable for monitoring both ground deformation and groundwater levels. This would be particularly useful for monitoring highway slopes because changes in groundwater have a profound effect on the stability of slopes. When the groundwater level increases, pore water pressure increases which decreases the shearing resistance available along potential failure surfaces. Rising groundwater levels also increase the weight of the sliding mass. This combined effect of reduced resistance and increased driving force is often identified as the triggering mechanism for landslides that occur during spring runoff in Wyoming. A question which must be addressed before a combined groundwater deformation TDR system can be developed is whether the cable is capable of detecting shear deformation below the water table.

Kane (1997) describes a field study in which an attempt was made to monitor both ground deformation and groundwater levels using an air-dielectric coaxial cable. The cable signature clearly showed the position of the groundwater, which agree well with observations from an adjacent standpipe well. The signature also showed shear deformation at a location above the water table. Unfortunately the cable ruptured at the upper shear zone before shear deformation developed below the water table, so it is still not known whether TDR can measure deformation below the water table.

#### 1.2.5. *Conclusions from Literature Review*

Review of previous work pertaining to applications of TDR for monitoring landslide sites suggests that this technology warrants investigation and field trials to evaluate its use by the Wyoming DOT. The principal benefit would be lower costs of slope monitoring by reducing the amount of time required for readings. The critical issues to be resolved before WYDOT commits to TDR are (1) whether the technology is sufficiently reliable to replace existing methods, such as slope inclinometer readings, for establishing the depth to a slide plane and (2) whether TDR can provide quantitative measurements of the amount of slope movement. A third issue is whether hollow coaxial cable provides a means to monitor groundwater levels, slope deformation, or both.

To address these issues, a program of field and laboratory testing was carried out by the author in cooperation with WYDOT Geology. The laboratory testing program, described in Chapter 2, was conducted at the University of Wyoming and consisted of large-scale direct shear tests intended to characterize coaxial cable signatures as a function of shear displacement. Additional laboratory tests were conducted to evaluate the ability of hollow coaxial cable to monitor both groundwater levels and shear deformation below the water level. The field program, described in Chapter 3, was conducted jointly by the author and WYDOT Geology personnel and consisted of installation and monitoring of coaxial cables using TDR at highway landslide sites throughout the state.

## CHAPTER 2

### LABORATORY STUDY OF TDR

#### 2.1 Laboratory Tests for TDR Calibration

A principal objective of this study was to develop a methodology to quantify the magnitude of slope movement using TDR field measurements. The research plan was to use both laboratory and field tests to achieve the objective. The laboratory study consisted of large-scale direct shear tests intended to simulate as closely as possible the interaction that occurs between soil, grout, and coaxial cable along a shear failure surface in a landslide. Previous research, summarized in Chapter 1, has led to mixed results for correlating the magnitude of TDR signal to magnitude of slope movement. The goal of this study was to determine if such correlations could be developed and then verified by field measurements.

##### 2.1.1. *Methods and Materials*

The basic concept of the laboratory tests is illustrated in Figure 6. A soil chamber consisting of a 16-inch diameter pipe is cut in half to create upper and lower sections which can be displaced relative to each other in the horizontal plane. With the upper and lower halves of the pipe initially aligned, the chamber is filled with soil. A 4-inch diameter hole is then created in the center of the soil deposit. A coaxial cable is centered in the hole and the hole is grouted. Following a curing period, the specimen is subjected to direct shear by applying a horizontal force ( $T$ ) to the upper section of the pipe. The bottom section is fixed while the top section is displaced horizontally, creating a shear failure surface in the soil along a horizontal plane between the two sections of pipe. A known normal stress ( $\sigma$ ) is created by applying load to the top of the soil deposit. Measurements are made of horizontal displacement of the upper section of pipe (shear displacement) and the cable signature (reflection coefficient versus cable length). Cable signatures are analyzed to determine the magnitude of the spike as the cable is sheared, and test results are presented in terms of the spike magnitude (in millirhos) versus shear displacement.

To facilitate direct shear tests, a concrete base was fabricated to accommodate the bottom halves of three sections of 16-inch diameter pipe. The 15-inch thick concrete base, with the plastic pipe, is shown in Figure 7. In the photo, the base is placed on edge. Direct shear specimens were fabricated as follows. With the concrete base lying flush on the concrete floor, the top half of each pipe was placed into position. Sand was then placed into each of the three chambers, using a 4-inch diameter PVC pipe as a blockout into which the cable and grout would be cast. This part of the procedure is shown in Figure 8. The coaxial cable was fixed by stapling it to a piece of timber placed at the bottom of the chamber. During grout placement, the cable was held straight up in tension and centered as best as possible in the grout tube. Following grout placement, the 4-inch grout tube was removed. Grout was allowed to cure for at least two weeks prior to shear testing.

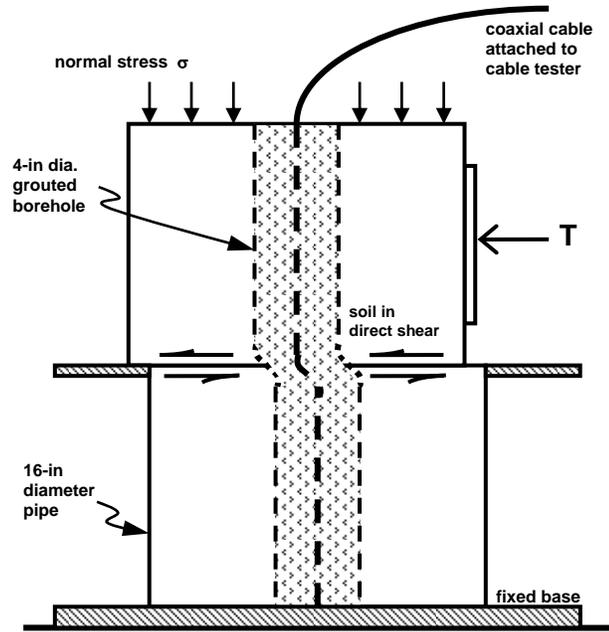


Figure 6. Schematic of direct shear cable testing device.



Figure 7. Concrete base with three direct shear testing chambers.

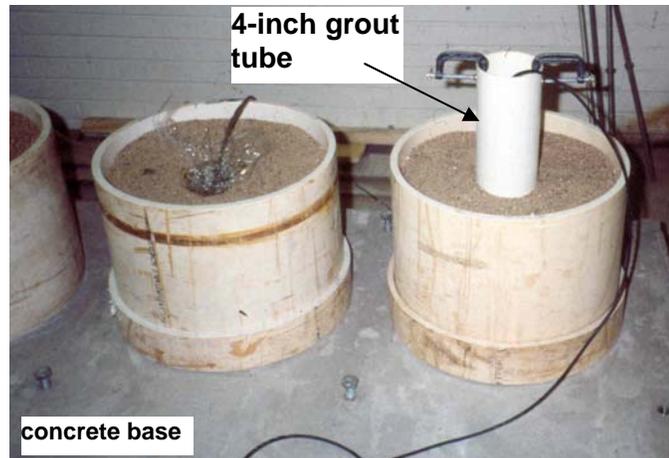


Figure 8. Placement of sand and grout tubes for direct shear specimens.

Normal (vertical) stress was simulated to approximate the overburden stress that would exist in the ground. This was accomplished by applying a vertical compressive force against a steel plate bearing on the top surface of the soil deposit. The force was provided by a hydraulic jack. To provide the necessary reaction, a steel plate was fixed above the testing chamber. The plate was held in place by  $\frac{1}{2}$  inch diameter threaded rods that were anchored in the concrete base. This arrangement is shown in Figure 9. Roller bearings were placed between the jack and the reaction plate to accommodate the horizontal displacement during direct shear testing. A constant normal stress of  $\sigma = 20$  psi was used for all tests. The shear (horizontal) force was applied to the top half of the chamber through a nylon strap wrapped around the top half of the pipe. The strap was fastened to a section of steel channel. A center hole hydraulic jack was then used to apply a tensile load to a steel rod fastened to the channel section, thus pulling the top half of the pipe horizontally. A bearing plate was used between the jack and the concrete. The entire testing arrangement is shown in Figure 10. Load in the jack applying the vertical load was determined using the pressure gage on the hydraulic pump, while load in the jack applying the shear load was measured by a calibrated load cell placed at the top end of the jack. Horizontal shear displacement of the upper half of the chamber was measured using a linear variable displacement transducer (LVDT).

The first challenge in conducting the laboratory shear tests was to determine a grout mix design that would allow the hardened grout to undergo shear deformation with the soil and that would transfer the shear deformation to the coaxial cable. The initial trial mix design was adopted from research by WYDOT Geology on mix designs for inclinometer casings as described in two memos from M. Falk (WYDOT 1989). The criteria for grouted inclinometer casing is similar, in that the grout must be sufficiently compliant to deform with the surrounding soil, but also sufficiently stiff to transfer ground movements to the casing. The Slope Inclinometer Company recommends a grout with 28-day compressive strength of approximately 50 psi. Falk (WYDOT 1989) found that several mix designs could provide the necessary strength by using Portland cement with varying



Figure 9. Assembly used to apply a vertical normal stress to the soil deposit.

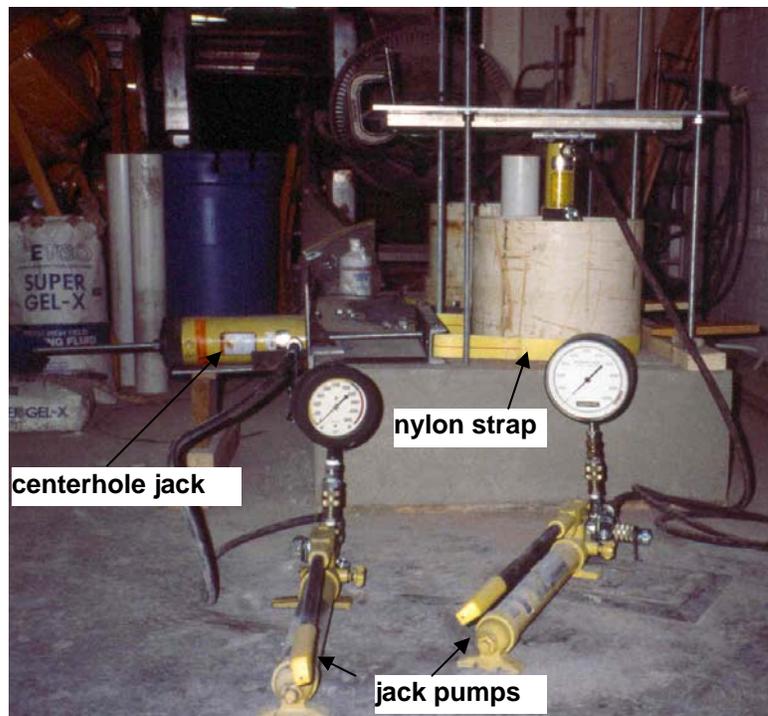


Figure 10. Direct shear test apparatus.

proportions of bentonite, lime, and water. The two mix designs recommended for inclinometer casing are:

1. 2 shovels of bentonite and 2 shovels of cement with 5 gallons of water
2. 3 shovels of hydrated lime and 3 shovels of cement with 5 gallons of water

Charts are provided in terms of the number of 94-lb bags of cement and 50-lb bags of bentonite or hydrated lime required for various hole diameters and depths. It is further recommended that the dry materials be mixed prior to adding water whenever the materials are mixed manually, and that for deeper holes the grout be mixed in a mud pump and the cement/bentonite mix design be used.

As a starting point, mix No. 1 above (cement-bentonite) was used. In terms of weight, this mix design corresponds to an approximate ratio of cement to bentonite (C:B) of 2.3 and a water to cement ratio (W:C) of approximately 2.7. This mix proved to be problematic for the following reason. The grout columns sheared with displacement of the upper section of pipe, but the cable slipped through the grout and did not shear. For the next set of three tests, the same grout mix was used, but the outside jacket of the cable was roughened using a sharpening stone attached to a drill in an attempt to provide better bonding between the cable and grout. The cable slipped in two of the tests. In the third test, the cable failed, but did not exhibit any spike prior to failure. Examination of the cable after the test suggested that it had failed in tension. The next several sets of tests (3 tests per set) involved a trial and error approach to modifying the mix design to achieve compliance. It was hypothesized that the lack of sufficient bond between cable and grout was due to insufficient development length, but that the presence of bentonite could also be a contributing factor. The proportion of bentonite was gradually decreased and sand was added to the mix. The water to cement ratio was also varied to achieve strength and stiffness of the grout that would allow it to shear with the soil. A problem that occurred in several tests was that the grout column did not deform in direct shear, but instead underwent a rigid body rotation prior to shearing. In a few tests, the grout column cracked at locations other than the plane of direct shear, for example at the one-third points, suggesting that flexure was the controlling mode of deformation instead of shear. Another problem observed in several tests was that the cable would eventually fail, either in shear or tension, but would not exhibit a clear spike in the cable signature prior to failure.

#### 2.1.2. *Results*

Figure 11 shows the results of Test No. 13, which exhibits the type of response described above. No evidence of cable shearing is apparent through a shear displacement of 1.5 inches. At a displacement of 1.87 inches, a trough in the cable signature appears at a distance of approximately 39 inches from the cable tester. The top of the grout column is at 24 inches from the tester, so 39 inches corresponds approximately to the shear plane of the test apparatus. At a displacement of 1.92 inches the trough is still apparent. However, with further displacement the trough disappears as indicated in the cable signatures for displacements of 2.00 and 2.04 inches. At a displacement of 2.1 inches,

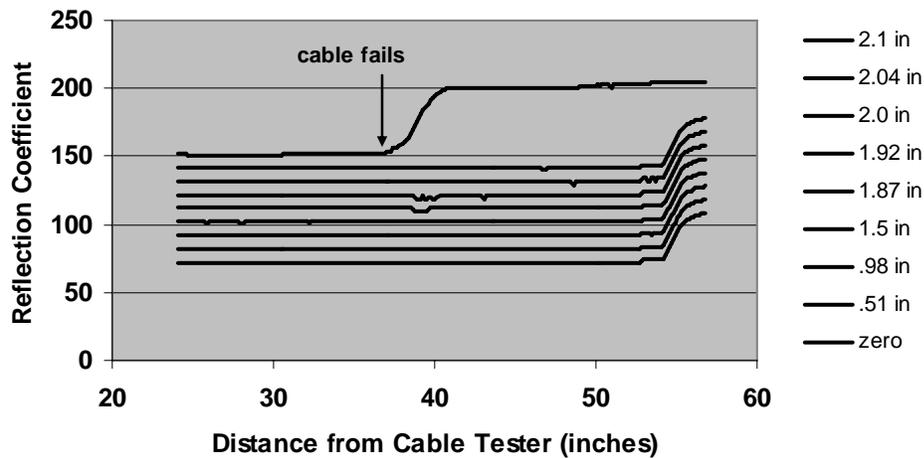


Figure 11. Results of Direct Shear Test No. 13.

the cable fails abruptly at a distance of 38 inches from the tester, or 14 inches from the top of the grout column.

A total of 21 direct shear tests were conducted in an effort to establish a grout mix design and procedure that would provide adequate compliance between the sand, grout, and cable. The final mix design consisted of a cement-sand mix with no bentonite. By weight, the dry ingredients consisted of 5 percent cement (1 lb of cement per 20 lb of sand). The water to cement ratio was 0.23. This mix yielded a grout strength of approximately 100 psi and provided bonding between the grout and cable without the need for artificial roughening. To insure shearing of the grout in the horizontal plane between the two sections of pipe, a cold joint was created at this location. The bottom half of the grout column was poured and allowed to cure overnight prior to pouring of the upper half.

Twelve additional tests (4 sets of three tests per set) were conducted with this mix and procedure. Three sets of tests were conducted with RG 59/U coaxial cable and one set of tests with ½ inch diameter Flexwell hollow cable. These twelve tests are considered to be our best attempt at developing a correlation between shear displacement and cable TDR signatures. The test sets are identified by numbers 1 through 4. Within each set, the three test specimens are labeled A, B, and C. The type of behavior observed in all of the tests can be illustrated by considering the results of Test Set 1, as described in the following. Figure 12 shows the cable signatures measured during shearing of specimen 1A. With increasing shear displacement, a spike appears and increases in magnitude (Note: the spike at the left side of each signature is due to a cable connector). At a displacement between 3.75 in and 3.83 in, the cable fails in shear. A graph was prepared showing the magnitude of the spike in the cable signature versus shear displacement (Figure 13). The data can be approximated using a best-fit straight line by regression analysis, as shown. The value  $R$  = coefficient of correlation and a value of  $R^2 = 0.96$  indicates a strong correlation between the cable signal and shear displacement of the soil deposit.

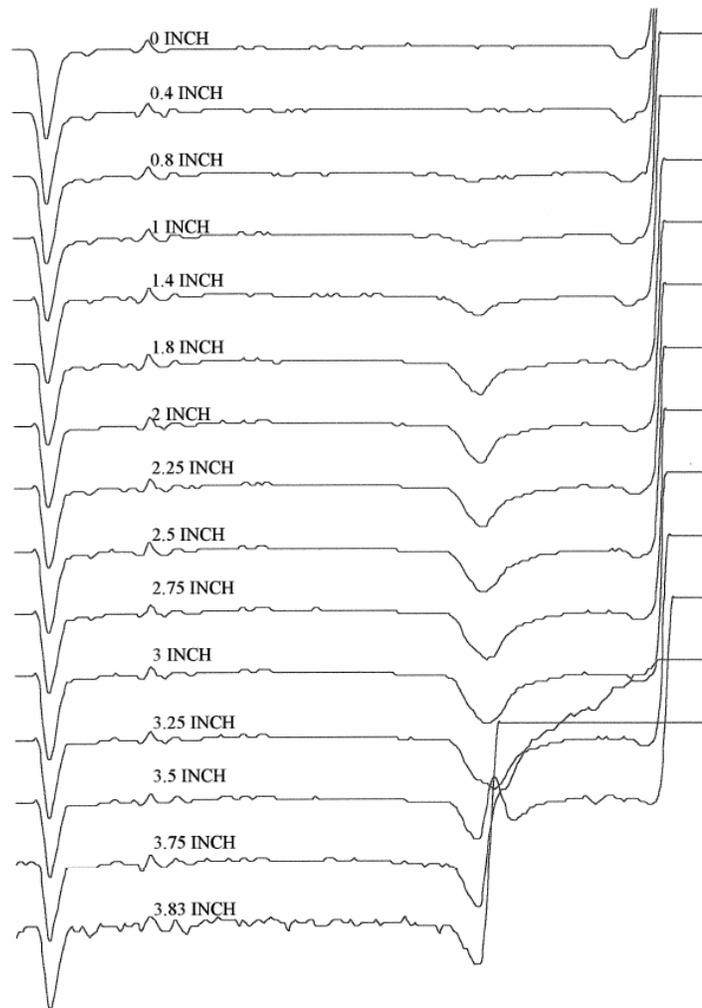


Figure 12. TDR signals for varying shear displacement levels, Sample 1A.

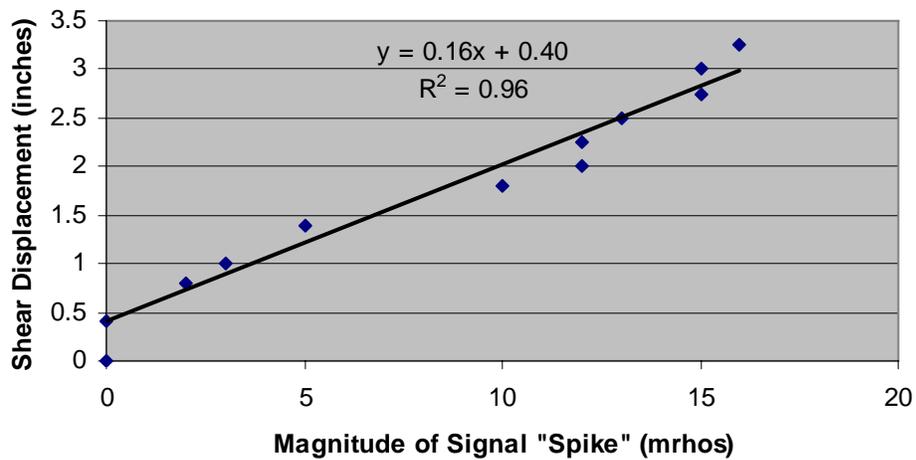


Figure 13. Cable signature "spike" versus shear displacement.

Samples 1B and 1C were prepared and tested identically to Specimen 1A. The measured cable signatures for varying levels of shear displacement are shown in Figures 14 and 15. In Figure 16, results of all three tests (1A, 1B, and 1C) are shown, in terms of the magnitude of the cable signature spike versus shear displacement. Figure 16 shows that the regression lines are different for each specimen, despite an effort to replicate the test conditions as closely as possible. The slopes of the lines for Specimens 1A and 1B are similar, but the intercept, *i.e.*, the displacement at which a spike first appears, is significantly different, in this case more than 1 inch. Specimen 1C exhibits a zero intercept but the slope is much different than for the other two specimens. Results of Test Sets 2 and 3 gave similar results. Individual tests yielded strong correlations, but the intercepts and slopes varied between tests and no consistent, repeatable correlation equation could be established.

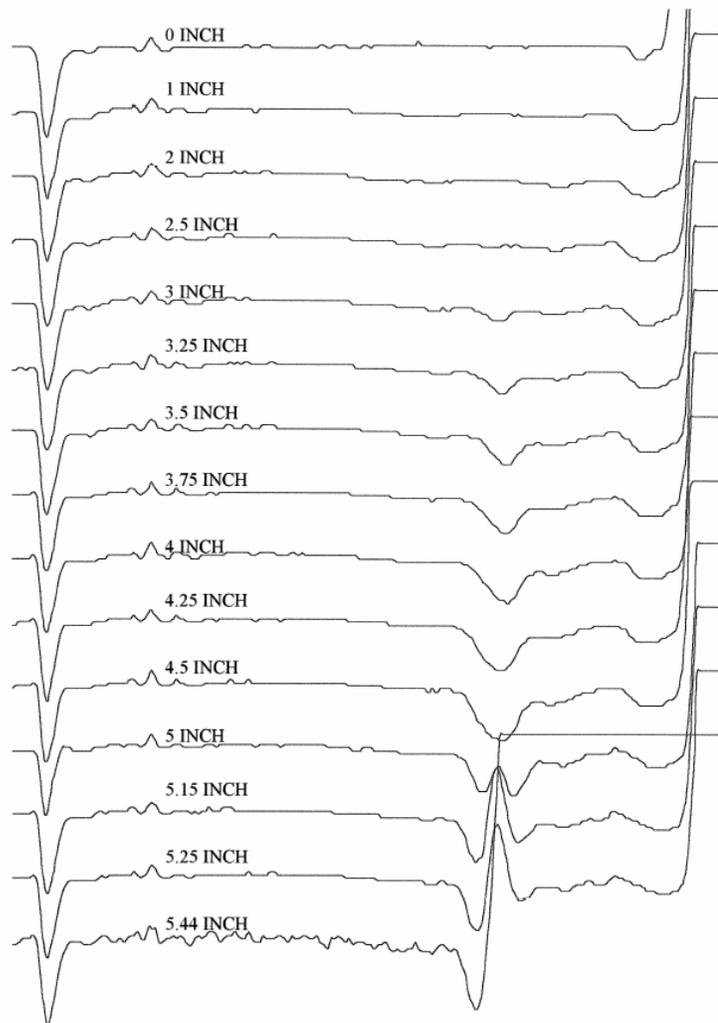


Figure 14. TDR signals for varying shear displacement levels, Sample 1B.

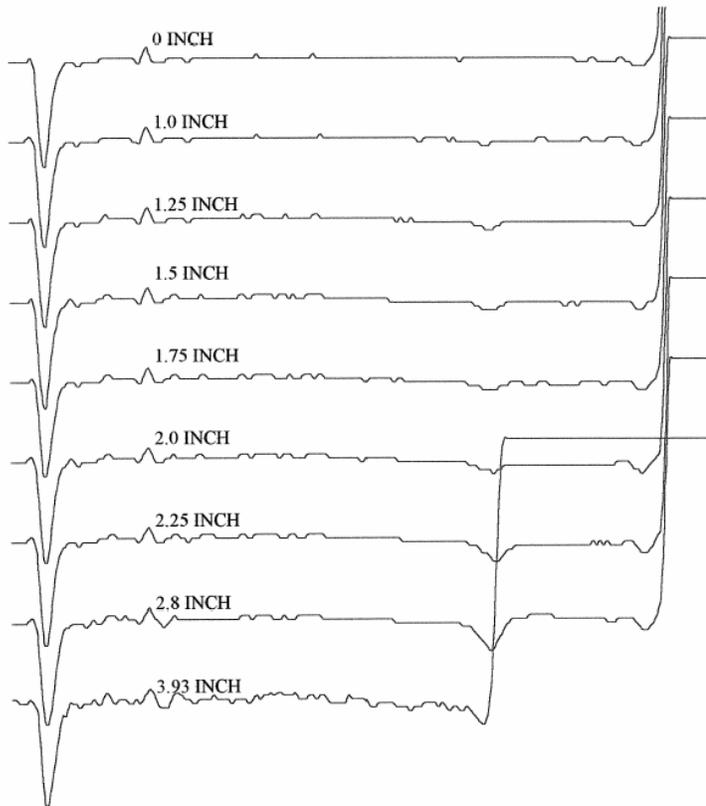


Figure 15. TDR signals for varying shear displacement levels, Sample 1C.

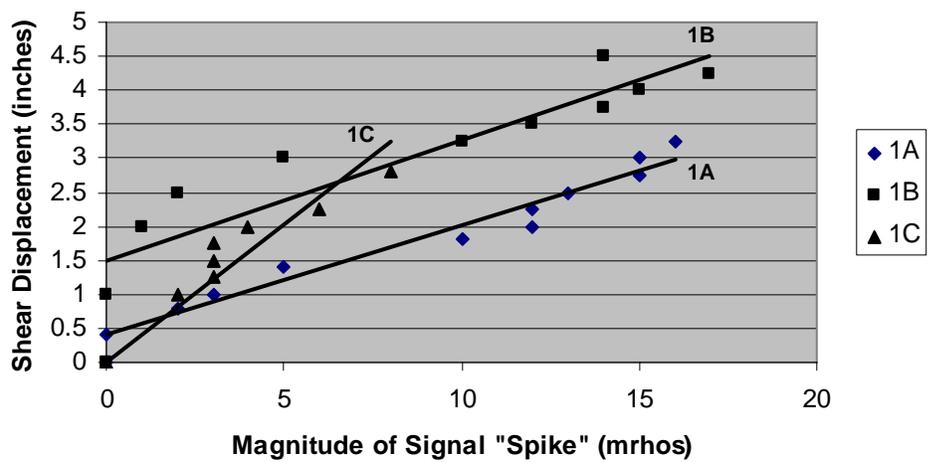


Figure 16. Regression lines for Specimens 1A, 1B, and 1C.

In Test Set 4, half-inch diameter Flexwell air dielectric cable was tested. This type of cable can be used to detect groundwater and was tested for that purpose as described in the next section of this report. The cable is stiffer than RG 59/U because the outer conductor consists of a heavier gage of copper. Figure 17 shows the cable signature obtained from Specimen 4A. With increasing shear displacement, very little change is observed in the cable signal, until the deformation reaches 4.0 inches and then the cable fails suddenly at a displacement of 4.5 inches. For the three specimens, cable failure occurred at displacements of 1.58, 3.76, and 4.5 inches. It was concluded that no consistent, repeatable correlation equation could be developed.

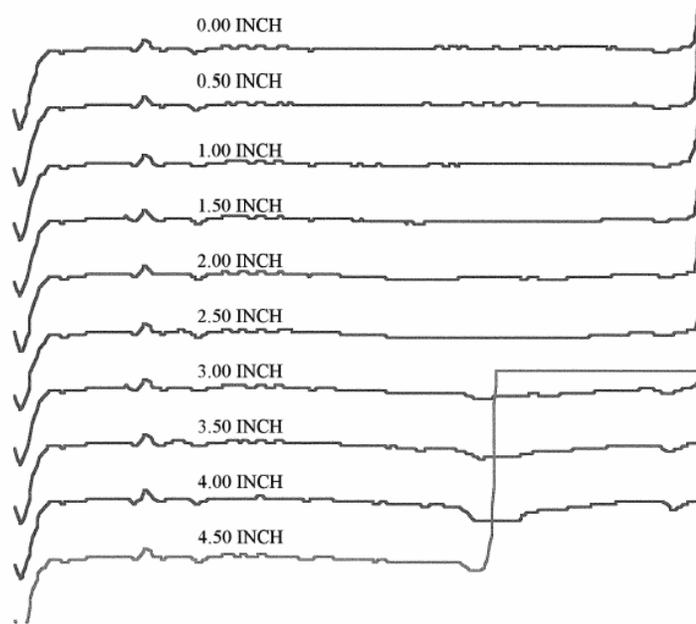


Figure 17. TDR signals for varying shear displacement levels, Sample 4A.

### 2.1.3 Summary of Laboratory Direct Shear Tests

The laboratory tests provided insight into the behavior of coaxial cables grouted in soil and subjected to shear displacement. These tests demonstrate that cable deformation is very sensitive to boundary conditions and that it is difficult, if not impossible, to obtain consistent, repeatable results, even in a laboratory setting in which many of the test conditions are controlled to a degree that would not be possible under field conditions. The three sets of tests involving RG 59/U cable were all prepared with the same soil compacted to the same density and with the same grout mix design. The test was conducted exactly the same way for each of the nine specimens. Yet each test yielded a significantly different relationship between cable signal and shear deformation. From these tests, it is concluded that no reliable correlation can be established for laboratory test conditions.

## 2.2 Groundwater Detection

Knowledge of groundwater elevation is important at landslide sites and also in other geotechnical applications such as embankments, foundations, excavations, and pavements. Current WYDOT practice for monitoring groundwater involves the use of monitoring wells and piezometers. A monitoring well must be installed and then checked regularly by lowering a measuring tape or sounder into the well. A sounder is an electronic device combined with a graduated cable. When immersed in water a circuit is completed and signals the operator that the water table has been reached. Piezometers are electronic transducers installed at a specific location “down-the-hole” and are used to measure pore water pressure. Pressure is converted to head to infer the depth of groundwater above the piezometer elevation. Installation can be complex and piezometers require field calibration. Also, the most expensive component (electronic device) is placed in the hole, creating the risk of cost penalties if a malfunction occurs.

TDR is a potential alternative method to measure the depth to groundwater. If the presence of water in a coaxial cable affects the reflection signal, as measured using a cable tester, the depth at which the signal changes will indicate the depth to water. Dowding et al. (1996) suggested that coaxial cables with a hollow space between the inner and outer conductors can be configured to allow ground water to enter the cable. In this way, air is replaced by water as the dielectric material in portions of the cable submerged below the water table and the reflection signal is changed. Coaxial cable with air as the dielectric material is sometimes referred to as hollow cable.

Use of hollow-cable TDR may be advantageous for some applications. Once a cable is installed, readings are fast and can be obtained remotely, which can eliminate the hazards of roadway access and other difficult location measurements. With TDR, only the cable (low cost item) is lowered into the hole while the most expensive component (cable tester) is operated from the surface. For landslide sites, a desirable combination would be to use one TDR cable to monitor both the groundwater elevation and slope movement. To evaluate this potential, laboratory tests were conducted as described below.

### 2.2.1 Methodology

All tests were conducted using ½-inch diameter hollow cable manufactured by Cablewave Systems, Inc. The cable is shown in Figure 18 and consists of copper clad aluminum inner conductor, helical corrugated copper outer conductor, a spiral polyethylene separator between the conductors, and a black polyethylene jacket. The product is identified as Flexwell Air HCC12-50J (1/2") and the purchased cost in 1999 was \$3.37 per ft. Tests were focused on addressing two questions: (1) whether the water elevation could be detected reliably from the TDR signal and (2) whether shearing of the cable below the water elevation could be detected reliably. Two sets of tests were carried out. The first set involved placing the cable in a clear, vertical Plexiglas tube and monitoring the TDR signal while the water elevation in the tube was varied. The second set of tests involved the creation of “crimps” at known locations in the cable, to simulate shearing of the cable. The signal produced by the crimps was then measured under both

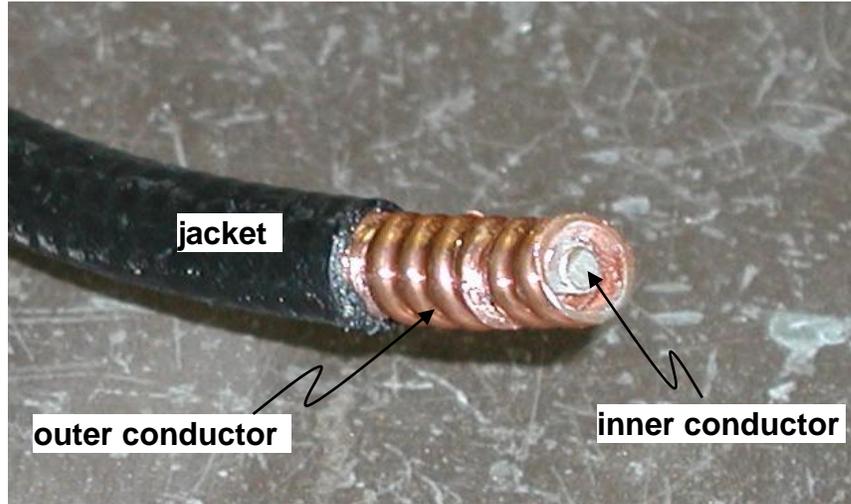


Figure 18. Flexwell hollow coaxial cable.

dry and submerged conditions in order to determine the effects of submergence on the strength of the signal. Figure 19 is a schematic of the test setup, which was conducted in the Hydraulics Engineering Lab at the University of Wyoming. The Plexiglas tube is 4 inches in diameter and 17 ft in length. The hollow cable has a total length of 25 ft (17 ft in the tube and 8 ft from the top of the tube to the cable tester). Water was able to enter the cable through the submerged lower end, left open. Holes were drilled near the top of the cable to allow for air to escape during water entry. The Tektronix 1052C cable tester was used to measure the cable signal, which was then downloaded to a notebook computer for processing.

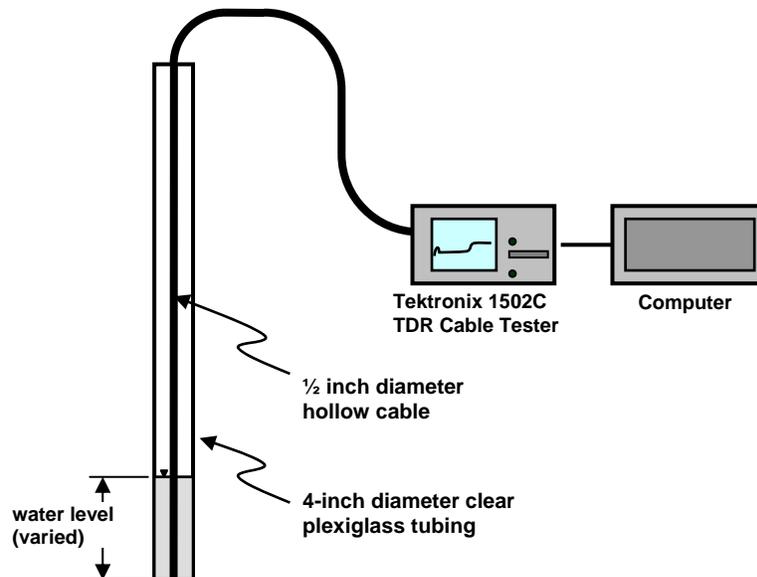


Figure 19. Schematic of test setup (not to scale).

### 2.2.2. Results

In the first set of tests, water level in the Plexiglas tube was increased from zero to 10 ft, then lowered from 10 ft back to zero. Measurements of the TDR signal were recorded at each 1-ft increment during both filling and draining of the tube. Figure 20 illustrates the results during filling. Three TDR signals are shown, corresponding to water levels of zero, 1 ft, and 2 ft. For the zero water level reading, the end of the cable is clearly indicated by the upward step at 25 ft. For a 1-ft water level, a downward change in the signal occurs at 24 ft, corresponding to the location of the water along the length of the cable. Similarly, at a water level of 2 ft, the water location along the cable ( $25 - 2 = 23$  ft) coincides exactly with the water level in the tube. Results were similar and consistent up to a water level of 10 ft. It was also observed that the response was immediate, that is, there was no time lag between reaching a water level in the tube and obtaining the corresponding signal using the cable tester.

An important observation made from these tests is that the TDR signal for portions of the cable below the water level is changed in a way that alters the apparent cable length. This occurs because the propagation velocity of the cable is changed when water replaces air as the dielectric material. For the particular cable used in these tests, portions of the cable that are submerged appear longer by a factor of 10 (*i.e.*, each 1 ft of cable appears to be 10 ft). If distances below the water table are needed, it is a simple matter to apply a correction factor to account for this attenuation.

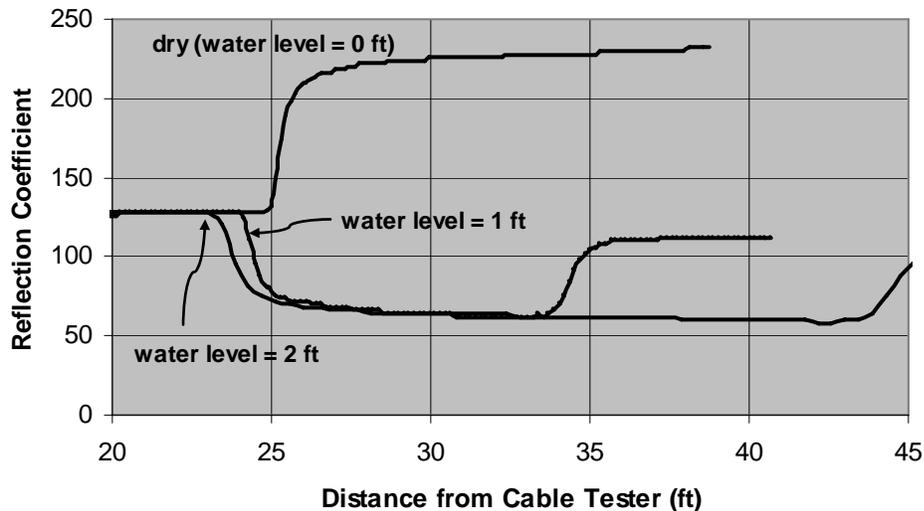


Figure 20. TDR signals showing water levels in Plexiglas tube.

During draining of the tube, results were essentially identical to those obtained during filling. For example, Figure 21 shows a direct comparison of TDR signals when the water level was at 3 ft, one during filling and the other during draining. These results indicate that water enters and exits the hollow cable freely in response to rising or lowering water levels outside of the cable. This suggests that the Flexwell ½-inch diameter hollow cable is capable of monitoring fluctuating water table elevations in field applications.

The second set of tests was conducted to evaluate the effect of water on the signal below the water level. Crimps were placed at three locations in the cable. Figure 22 shows the TDR signals for two cases. The upper curve shows the signal when the cable was dry (water level = 0). In this case, all three crimps are easily distinguished in the signal. The lower curve shows the signal when the lower two crimps are submerged. In this case, the spikes are masked by the water and very difficult to identify. In fact, they blend in with the signal noise and would be very difficult to locate if they were not known beforehand. Attenuation of the signal also distorts their location.

### *2.2.3. Discussion of Hollow Cable Lab Tests*

- (1) Hollow-cable TDR provides a quick and reliable method for determining groundwater elevations. As groundwater elevations change, the TDR reading responds immediately and is not affected by capillary water trapped in the annular space between conductors.
- (2) Below the groundwater elevation, the TDR signal is distorted in a way that makes elevation readings incorrect. A correction factor must be applied to all subsequent readings below the groundwater elevation. For the cable used in these tests, each 1-ft increment of cable length below the groundwater appears to be 10 ft.
- (3) Shearing of the hollow cable below the water level is detectable but the signal is not as pronounced as the signal induced by the same magnitude of shearing above the water level. Hollow cable can therefore be used to monitor both slope movements and groundwater elevations, but detection of slope movement below groundwater is more difficult.

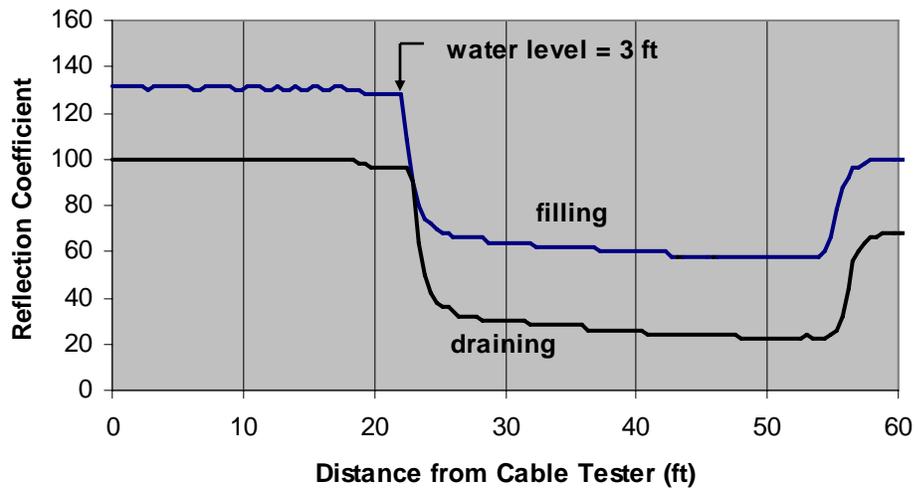


Figure 21. TDR signals with water level at 3 ft for filling and draining (note: curves are offset vertically for clarity).

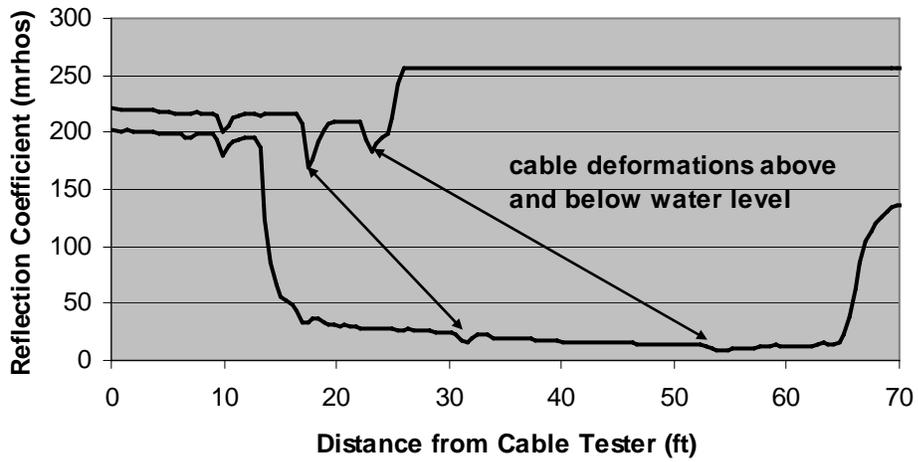


Figure 22. TDR signals from crimped cable.

## CHAPTER 3

### FIELD STUDY OF TDR

A field study was conducted jointly by UW Engineering and WYDOT Geology personnel. The program consisted of installation and monitoring of coaxial cable using TDR at active landslides. The initial plan called for monitoring of six different field sites representing three geologic conditions. Two sites were to be selected to represent each of the three geologic settings, which are described in terms of whether shear occurs at (a) a rock/rock interface, (b) a soil/rock interface, or (c) in soil. The sites were selected by the Chief Engineering Geologist. At each site, field instrumentation consists of TDR cable installations in grouted boreholes. In most locations, slope inclinometer installations are either next to the cables or at a location relatively close for comparative measurements. All of the sites had been identified as locations requiring slope monitoring by inclinometer and the cable installations were added.

Over the course of this study, cables were installed at five locations. However, at one of these (Deer Creek), access to the cables was eliminated by subsequent construction. No movements were detected prior to construction. Cables were installed at the remaining sites between 1999 and 2005. Each site has been monitored since its initial installation and all of the sites were monitored most recently in May or June of 2006. Table 2 summarizes the four sites in terms of installation date and type of coaxial cable. Each site and the monitoring results are described in the following.

Table 2. TDR Field Installations

Site Name	Location	Installation Date(s)	No. of Cables	Type of Cable	Depths (ft)
Flying V	US 85 N of Newcastle	Nov 1999	2	RG-59/U	53, 75
Campstool	WYO 24 Devils Tower	Dec 2001 – March 2002	2	P3-75-750	93, 101
Narrows	WYO 220 W of Casper	Oct 2002	2	P3-75-750	35, 70
Togwotee Pass	US 287 N of Dubois	June 2005	2	RG-8	76, 81

#### 3.1 Flying V

A section of US Highway 85 approximately nine miles north of Newcastle, Wyoming, has experienced ongoing damage caused by ground deformations associated with a large ancient landslide that currently exhibits four active areas. Limits of the ancient slide extend 600 feet upslope and 150 feet down slope from the centerline of the roadway. Approximately 2700 feet of Highway 85 is affected by the four active landslide areas. Inclinometer readings show that movement of the slide averaged approximately 1 inch/year between 2000 and 2003. The history of the slide and geologic conditions are described in an internal Wyoming DOT memo by Vanderveen (WYDOT 2004). The area is described by WYDOT geologists as "landslide deposits overlying sandstone and shale belonging to the Sundance Formation". The Flying V has been the target of

remediation measures and monitoring since 1982. Most recently the site was considered for stabilization using permanent ground anchors and pre-design load tests were conducted. This anchor testing program is described in a research report by Turner and Sackett (2005).

In November of 1999 two RG-59/U coaxial cables were installed at the Flying V as part of a program of exploratory borings and inclinometer installation. RG-59/U is a highly flexible cable of relatively small diameter (0.242 in) and is the cable type used in most of the laboratory tests described in Chapter 2. One cable is located on the south end of the slide area, on the west side of the road, and approximately 60 ft above the road. This cable is denoted by 'Flying V South' and is in the same location as WYDOT boring 99-9 and inclinometer FV-8. The cable length is 80 ft which includes approximately 5 ft of cable above ground. The second cable is at the north end of the slide, east of the roadway in the shoulder of the road. WYDOT boring 99-5 and inclinometer FV-7 are located approximately 6 ft from the cable installation. This cable is denoted by 'Flying V North' and is 58 ft in length, including 5 ft above ground. Both cables were installed on November 19, 1999. Grout was ordered from a ready mix plant and is described on the delivery ticket as "lean concrete". The ticket gives the following mix design for 3 cubic yards of grout: 190 gallons of water, 9,000 lb of fine aggregate, and 300 lb of Portland cement. The 28-day compressive strength is not known. Holes were drilled by WYDOT drilling rigs and crews and grout was tremied through a small diameter plastic pipe to the bottom of each hole.

Figure 23 shows TDR signals from the Flying V South installation. The cable has been in place for over 6 years and has not exhibited any signal. Slope inclinometer readings have shown movements at this location, suggesting that the TDR has not performed as expected. Readings from FV-8 are shown in Figure 24 for a period between 2004 and 2006. The inclinometer readings show a distinct slide plane over a depth interval between 31 ft and 34 ft, with a cumulative displacement of over 1.4 inches during this period.

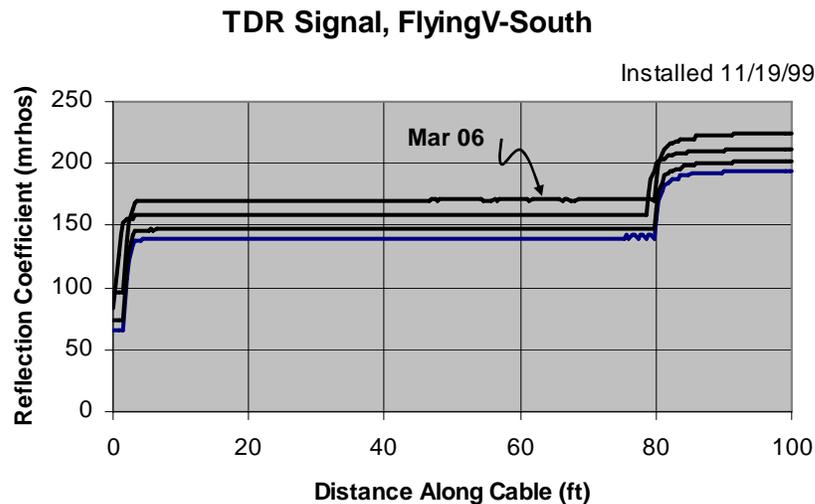


Figure 23. TDR cable signatures through March 06, Flying V South.

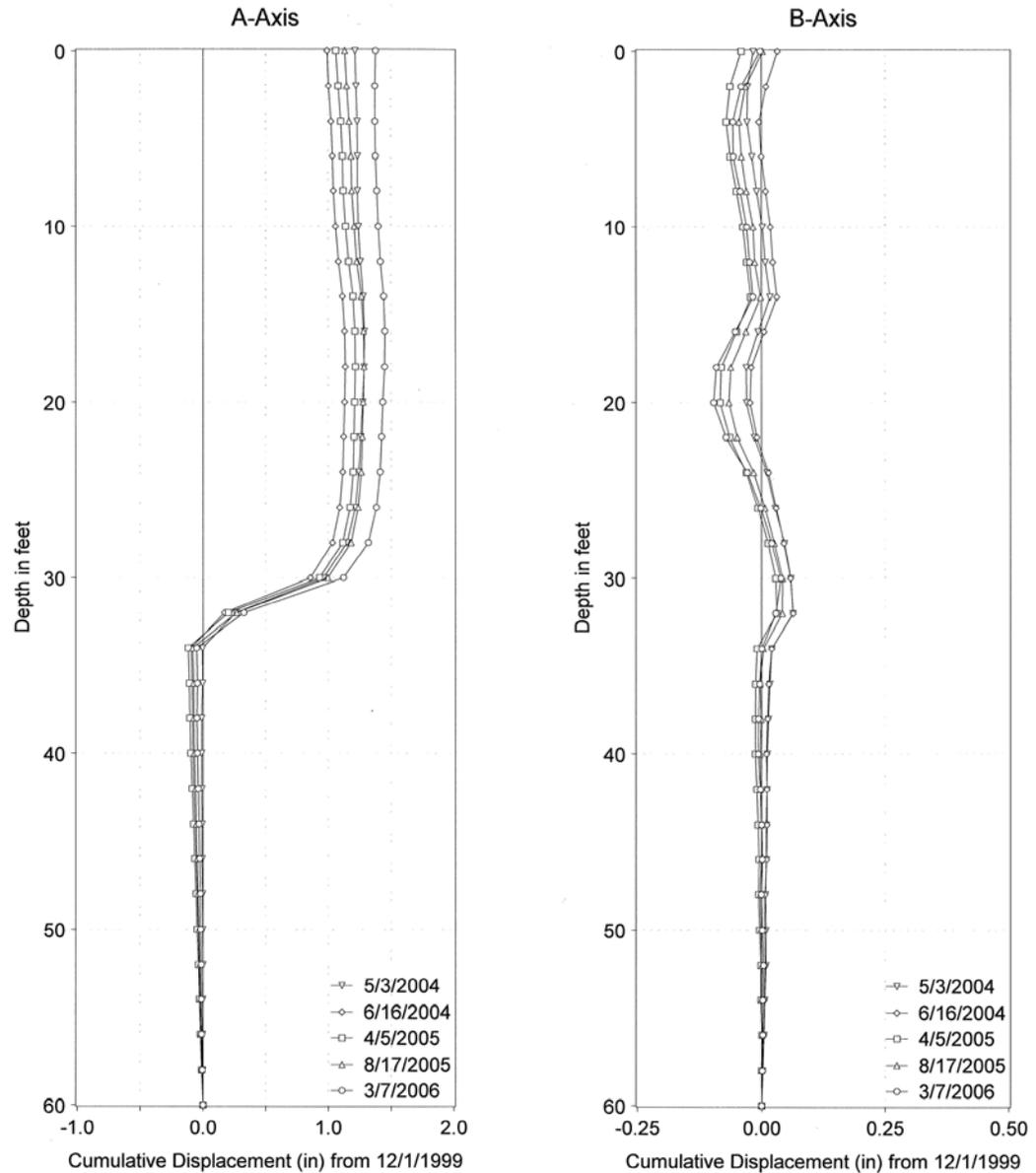


Figure 24. Slope inclinometer readings, FV-8, Flying V South.

Figures 25 and 26 show TDR and inclinometer readings from Flying V North and FV-7, respectively. Since being installed, this cable has shown evidence of distress, but there has not been a distinctive spike indicating a well-defined failure plane. In contrast, the inclinometer readings show a well-defined shear zone at a depth of 40 ft with deformation exceeding 2 inches. Since April 2005 it has not been possible to monitor FV-7 because the inclinometer casing has sheared. In the most recent monitoring (March 06), there is a recognizable spike in the TDR signal at around 33 ft (depth of approximately 28 ft). Without inclinometer readings for verification, it is not known whether a new shear plane has developed at this depth, but the TDR signal suggests the

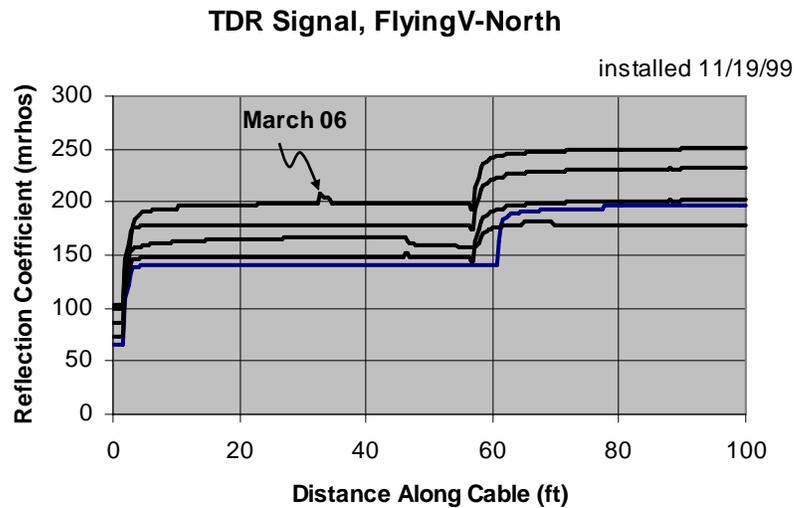


Figure 25. TDR cable signatures through March 06, Flying V North.

possibility. In view of the inclinometer readings and lack of corresponding TDR signals, it has to be concluded that this installation did not perform its intended function.

A number of factors could be responsible for the poor performance of cables at the Flying V. These include grout mix design and cable type. Using information from the ready mix ticket, the mix has a low cement content (less than 3 percent by weight of the sand) and a relatively high water to cement ratio (W:C = 5.3). No test results were provided on the compressive strength, but the grout may be too weak to transmit shear to the cable effectively. The cables may be slipping through the grout as the ground deforms. Alternatively, the grout may be sufficiently stiff that it may be resisting deformation and not shearing the cable. With respect to cable type, various researchers have reported mixed results with the use of RG-59/U in field applications. Kane (1998) reports strong response, in terms of a clear spike in the cable signature, using RG-59/U cable grouted into a borehole in a levee embankment. However, slope inclinometer readings showed deformations up to 8 inches. Researchers at Northwestern University suggested that RG-59/U and similar small-diameter, flexible cables do not provide results that are reliable, compared to larger-diameter stiffer cable types (O'Connor, personal communication, 2001). They recommended the use of Commscope P3-75-750. This type of cable is 19 mm in diameter (about  $\frac{3}{4}$  inch) and has a relatively stiff outer jacket. A recent study by Dennis (2004), in which several cable types were evaluated in field studies involving monitoring slope movements for the Arkansas DOT, concluded that RG-8 coaxial cable provided the best performance in terms of providing detectable signals in response to ground deformation. RG-8 is intermediate in stiffness between RG-59/U and the Commscope cable. In subsequent field installations, both RG8 and Commscope P3-75-750 cables were used.

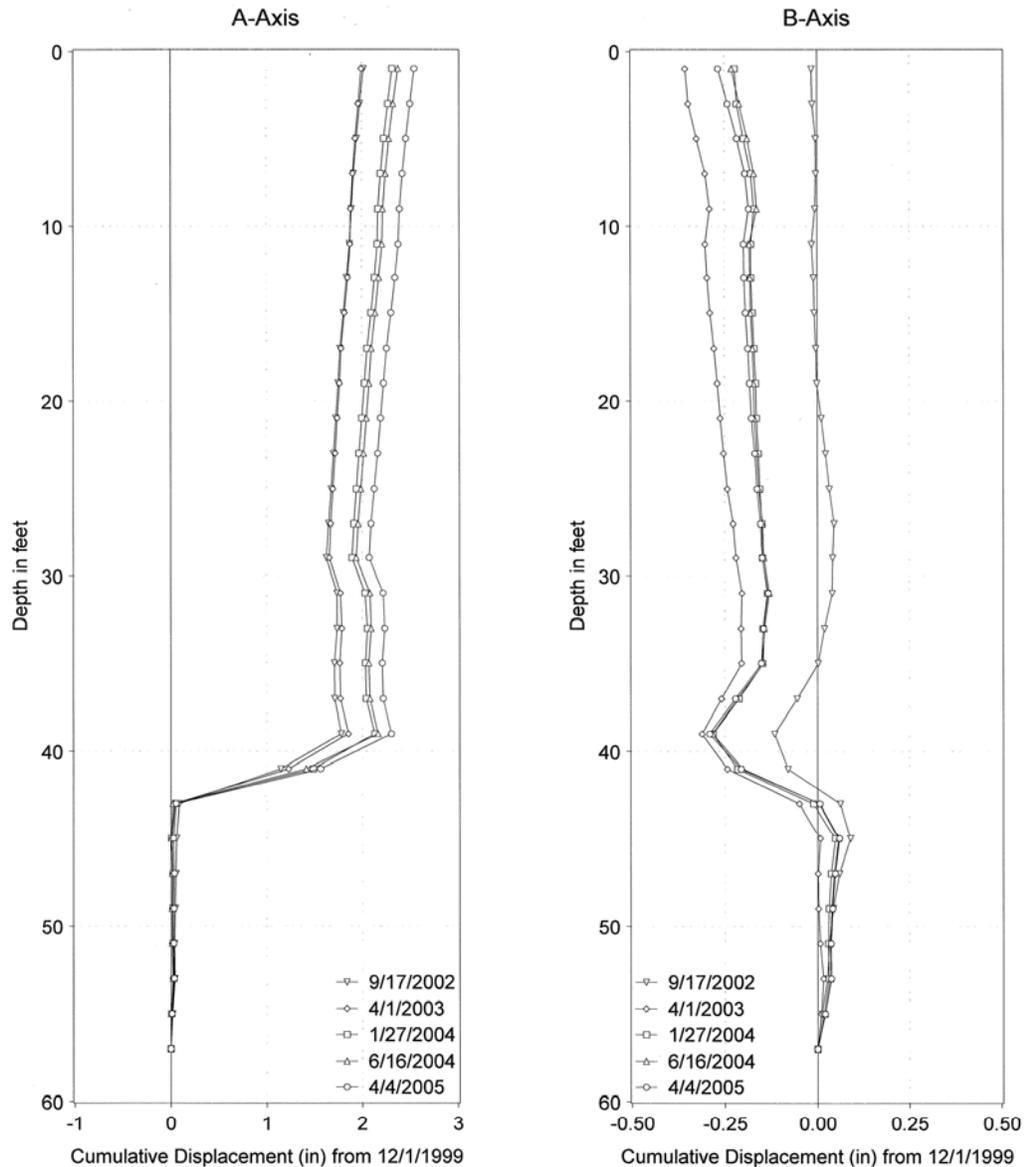


Figure 26. Slope inclinometer readings, FV-7, Flying V North.

### 3.2 Campstool

The Campstool site is located at the Devils Tower turnout at M.P. 4.5 on State Highway 24. Voids were observed to be opening parallel to the roadway on the east shoulder. It is suspected that the voids may be the result of sandstone blocks sliding on a layer of moist to wet, highly plastic shale that appears in boreholes at a depth of 75 – 80 ft below the surface. WYDOT Geology drilled several boreholes for core logging and installation of inclinometer casing and coaxial cable during December 2001 and April 2002. The general conditions are described in a memorandum from D. Vanderveen (WYDOT 2002). All rock units belong to the Jurassic Sundance Formation. Two distinct units are

apparent. The upper unit extends to a depth of 55 – 65 ft and consists of fine to coarse-grained quartz sandstone. Underlying the sandstone is 35 – 45 ft of interbedded sandstone and shale. This site was selected for its potential to test TDR at a site where sliding is occurring along a rock/rock contact.

The cables used at this site are Commscope P3-75-750. This type of cable is 19 mm in diameter (about  $\frac{3}{4}$  inch) and has a relatively stiff outer aluminum jacket. This outer jacket is also the outer conductor. The dielectric material is expanded polyethylene foam, which is why this type of cable is sometimes referred to as foam-dielectric. The inner conductor is copper-clad aluminum. This cable was recommended by researchers at Northwestern University, who report good results at sites where movement has occurred in both soil and rock. Figure 27 is a photo of the Commscope cable, with the RG-59/U for comparison.

Both cables are located in the parking area (turnout) at the Campstool site. One is at the north end of the parking area and is 93 ft deep (Campstool North), while the second is located at the south end and is 101 ft deep (Campstool South). Grout mix design for this site was based on recommendations given by Dowding et al. (2001), specifically for use with the Commscope P3-75-750 cable installed in rock. The mix design calls for the following percentages, by weight: water: 65%, cement: 38%, and bentonite: 2%. Dowding et al. (2001) also recommend that bentonite be hydrated for at least 12 hours prior to mixing with the other ingredients. This procedure was followed and the grout was mixed on site and pumped through the mud pump of the drilling rig. Installation of the Commscope cable proved to be difficult. When purchased, the cable arrives on a spool with approximately 1,000 ft of cable. Figure 28 shows the spool of cable in the laboratory at the University of Wyoming. It was not practical to transport the entire spool to the site. The expected length of cable was removed from the spool. When removed the cable retains its coiled shape with a radius of approximately 3 ft. To install the cable

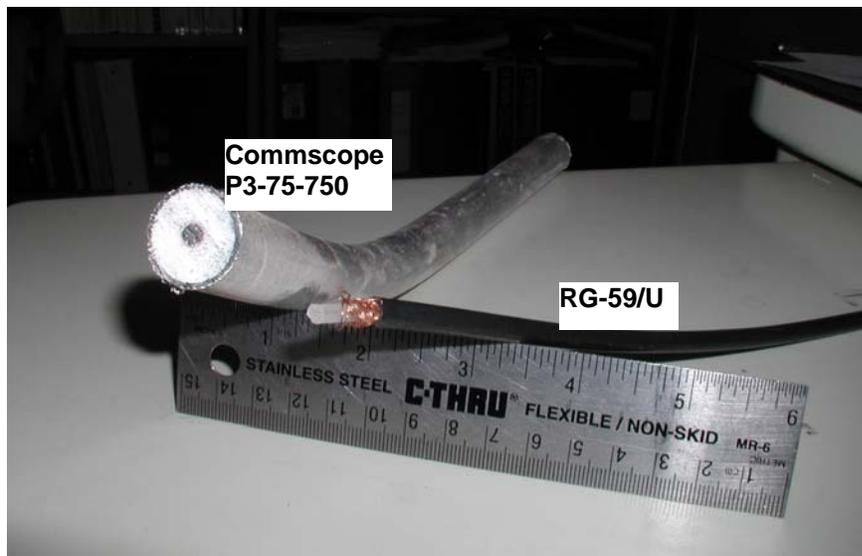


Figure 27. Photo showing Commscope cable and RG-59/U cable.

it is necessary to lay it out on the ground. It is quite difficult and unwieldy to lay the cable out to a straight length and to install it into the ground. Center-hole spacers were used to center the cable in the hole. A piece of cable with a spacer and the female BNC connector required for attachment to the cable tester are shown in Figure 29. Dowding (personal communication, 2002) describes a unit that can be attached to the front of a drill rig or truck on which the cable spool can be mounted, allowing the cable to be placed directly into the hole from the spool. If this type of cable were to be used regularly, this type of equipment is highly recommended.

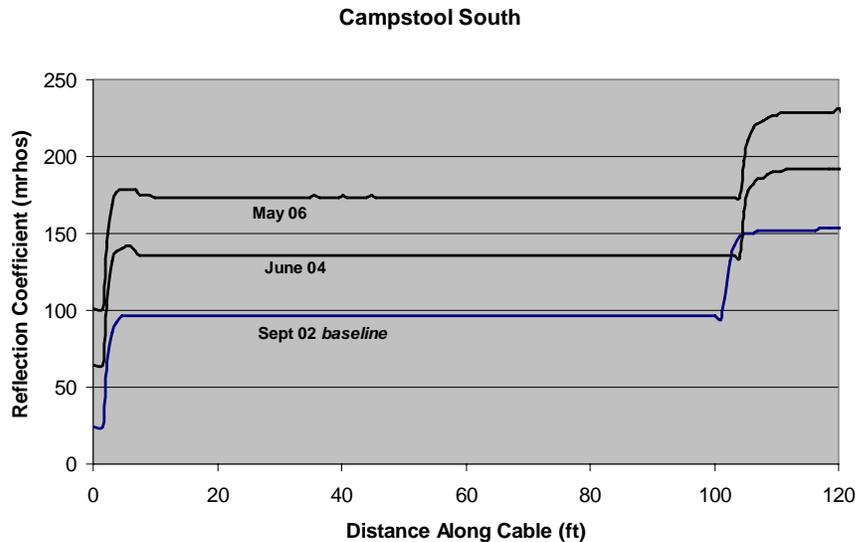
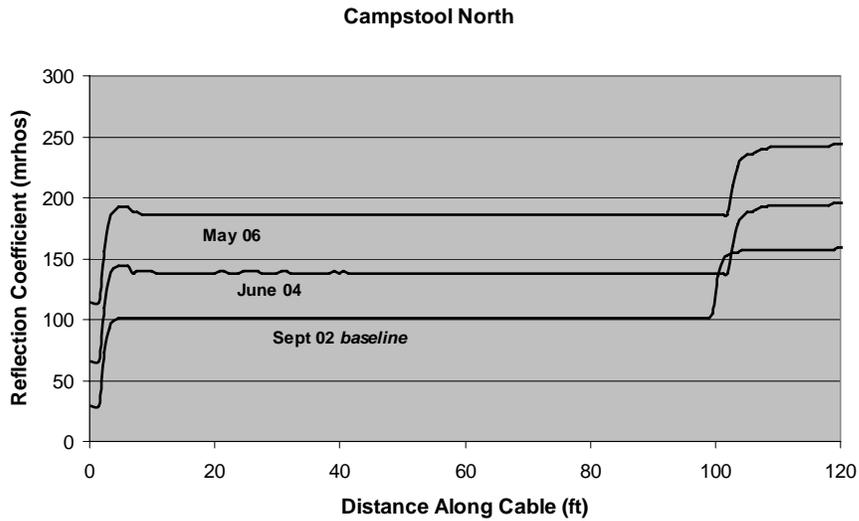


Figure 28. Commscope P3-75-750 coaxial cable spool.



Figure 29. Commscope cable with center-hole spacer and BNC connector.

Figures 30 and 31 show TDR signals at Campstool North and Campstool South, respectively, for a period of nearly four years. The cables show no sign of shearing. Figures 32 and 33 show corresponding inclinometer readings for Campstool North and South, respectively. The inclinometer readings also show no measurable deformation, in agreement with the TDR measurements. No conclusions can be made about the performance of the cables at Campstool because deformation has not been sufficient to shear or otherwise damage the cables. This site should be considered for further monitoring by both TDR and slope inclinometer. If sliding occurs in a weak shale layer, it will be possible to evaluate performance of the TDR system.



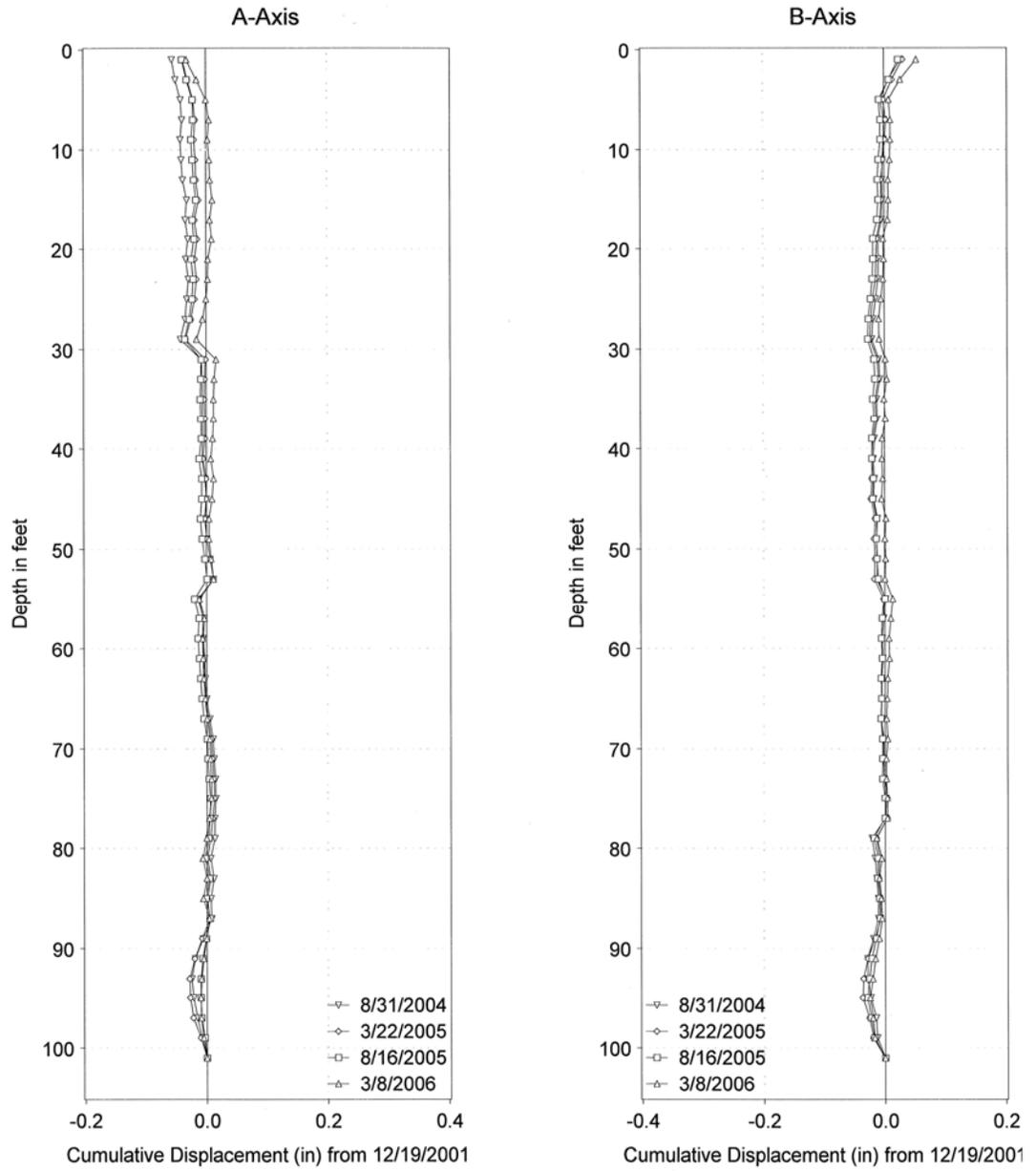


Figure 32. Slope inclinometer readings, Campstool North.

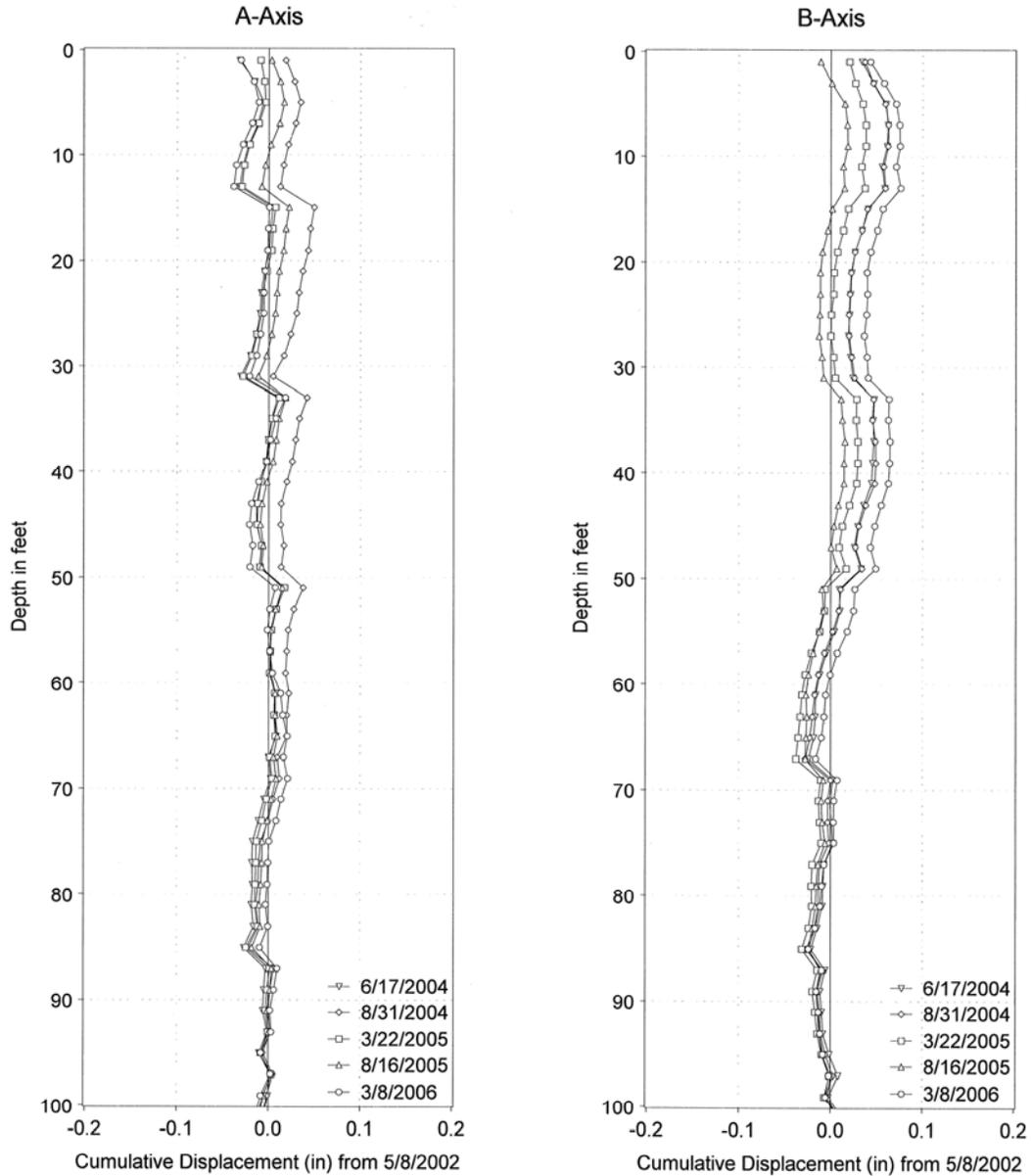


Figure 33. Slope inclinometer readings, Campstool South.

### 3.3 The Narrows

Two cables were installed in October of 2002 at the Narrows slide along WYO 220 west of Casper. Both cables are Commscope P3-75-750. Figure 34 shows the drilling operation for the cable installation on the south side of the roadway. In this photo, the Commscope cable is shown on the ground prior to placement in the hole. The stiffness of the uncoiled cable that makes it difficult to install manually is apparent.

Figure 35 shows TDR measurements for the Narrows South installation. A distinct change in signal has been apparent since October 2003, at a distance of approximately 31

ft from the cable tester (approximate depth of 26 ft). The magnitude of signal change at this depth has generally increased with each subsequent reading and corresponds to increased movement at this depth, as indicated by inclinometer readings that show a clear slide plane at a depth of 26 ft. (Figure 36). However, the most recent reading (May 06) exhibits a small decrease in the magnitude of the signal at the slide depth. The behavior



Figure 34. Drilling for cable installation, Narrows South.

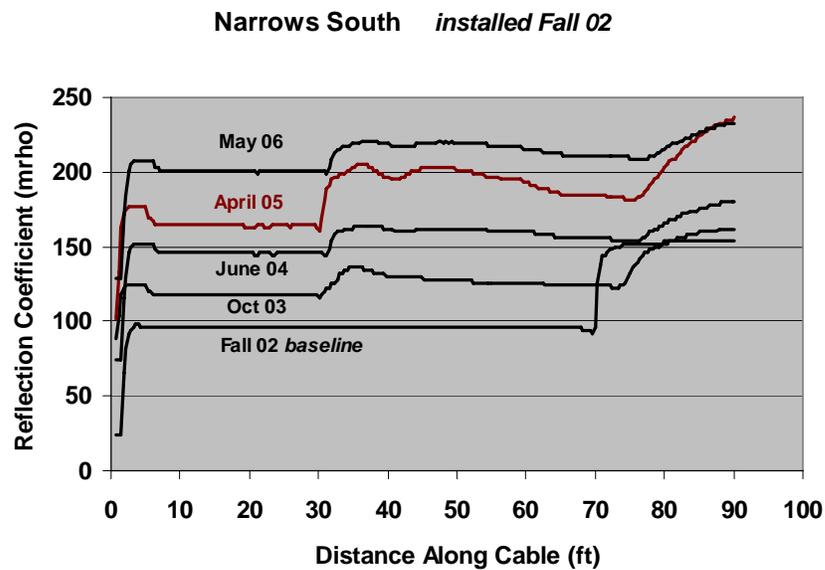


Figure 35. TDR signals, Narrows South.

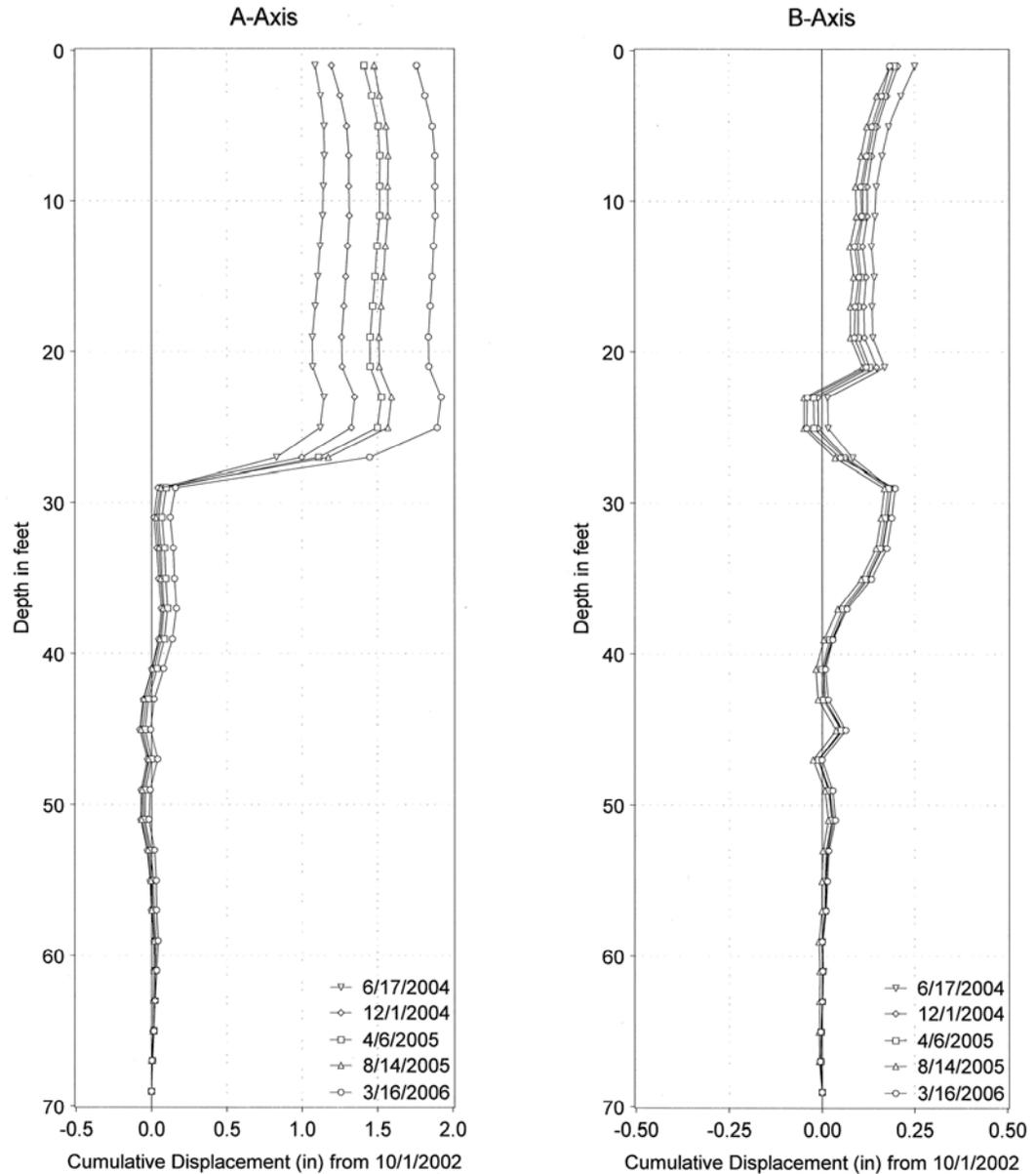


Figure 36. Slope inclinometer readings, Narrows South.

of RG/59-U cable in laboratory tests showed that the cable signature decreases slightly right before cable rupture. It is not known whether this is the case at Narrows South, but further monitoring might provide additional information. Also, the signal does not exhibit a well-defined spike, but rather increases at the shear depth and then gradually decreases until the bottom of the cable is reached. Interpretation of this signal is not entirely clear, but it could be caused by some combination of shear and tension. Despite some uncertainties, Narrows South represents the most encouraging performance of a TDR field installation to date. The TDR clearly shows evidence of sliding that correlates well with slope inclinometer readings.

Narrows South was initially the only TDR installation planned at the Narrows slide. After setting up the installation, approximately 35 ft of Commscope cable was left over. It was decided to install this available length of cable at a second installation on the north (downslope) side of the road. Figures 37 and 38 show the TDR and inclinometer readings for Narrows North. The inclinometer readings clearly show a shear zone at approximately 52 ft. Unfortunately the cable installation does not reach this depth. A second shear zone may be developing at a depth of approximately 24 ft, but the cable does not show any signal to date.

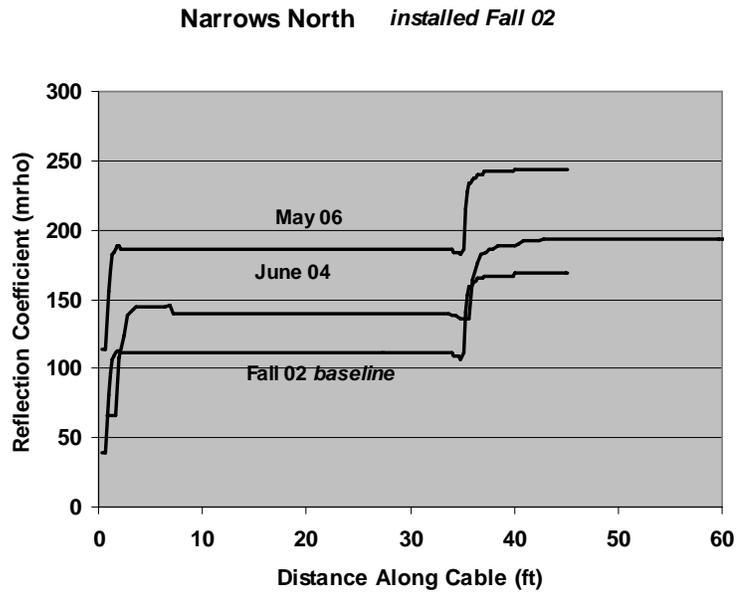


Figure 37. TDR signals, Narrows North.

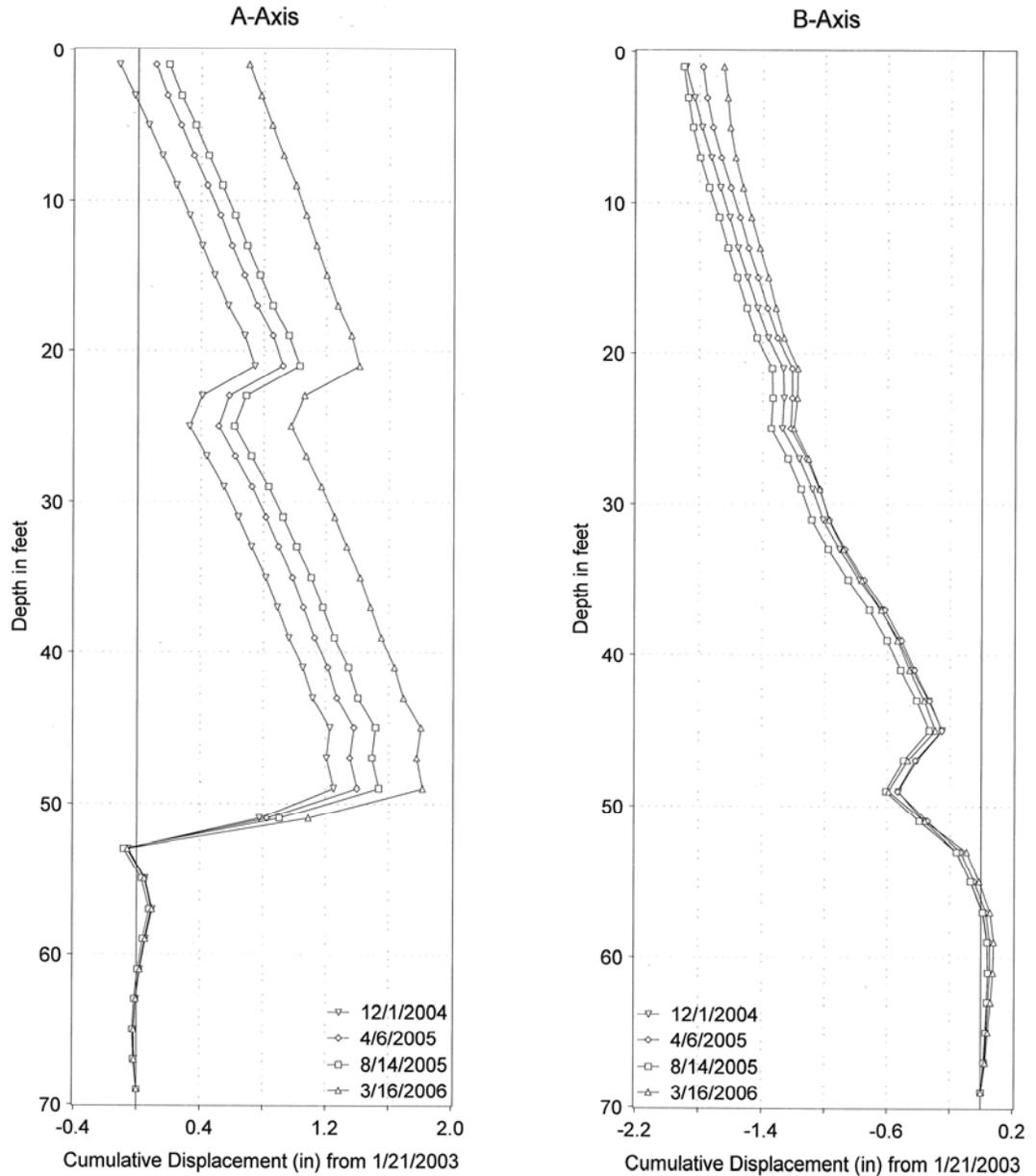


Figure 38. Slope inclinometer readings, Narrows North.

### 3.4 Togwotee Pass

Cables were installed at two locations along US 287 north of Dubois. This section of highway is under planning for reconstruction and WYDOT Geology is studying several sites being affected by active landslides. The two installations are (1) County Line and (2) Hickerson Curve. The cables were installed during the summer of 2005 and were last recorded in June 2006. The cable at County Line is 81 ft in length and the Hickerson Curve cable is 76 ft in length (includes 2-3 ft of cable above ground). The cable used for these installations is RG-8, a smaller diameter (12.5 mm or about ½ inch), more flexible cable than Commscope P3-750-75. This cable type was selected based on the study by

Dennis et al. (2004) in which RG-8 provided the best signal for monitoring slope movements at sites monitored for the Arkansas DOT. RG-8 cable is more easy to handle and install than the Commscope cable.

The most recent readings at Togwotee Pass were obtained using a new TDR unit purchased by WYDOT Geology. The TDR 100 is a lighter and more convenient unit than the 1502C used for most of this study. The system consists of a power source, the TDR cable reader, and a computer. Figure 39 is a photo of the field setup for reading cables. The operator is observing and storing the TDR readings using a notebook computer on the front seat of the vehicle.

A reading obtained recently using the TDR 100 for Hickerson Curve is shown in Figure 40. The closest inclinometer reading on the downhill side of the roadway is shown in Figure 41 and shows a slide plane at approximately 8 ft deep with movement exceeding 1.4 inches. The cable signature does not show any clear signal, although there is a slight signal change which may represent initiation of cable damage over this depth interval. Additional inclinometer readings above the roadway show zero movement, so it is not entirely clear whether there is movement at the cable installation.

Figure 42 shows the TDR reading obtained during June 2006 at the County Line site. This cable is located on the upslope shoulder of the roadway and shows no clear sign of shearing or other damage. There are three inclinometer installations at this site, all of which are located below the roadway (downslope slide). The inclinometer casings do not



Figure 39. TDR readings at County Line using the TDR 100.

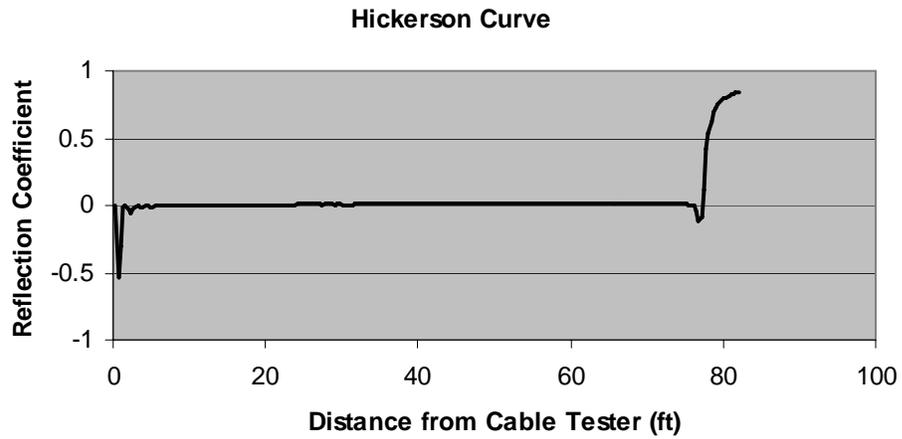


Figure 40. TDR signals, Hickerson Curve site.

correspond to the cable location. Figure 43 shows inclinometer readings for the casing that is closest to the roadway. A slide plane is evident at a depth of approximately 35 ft. The other two inclinometers show slide plane depths of 60 ft and 52 ft. It is apparent that the slide plane depth varies with location and it is not known whether the slide plane extends through the cable location or at what depth. Nevertheless, the cable does not show any signs of movement to date.

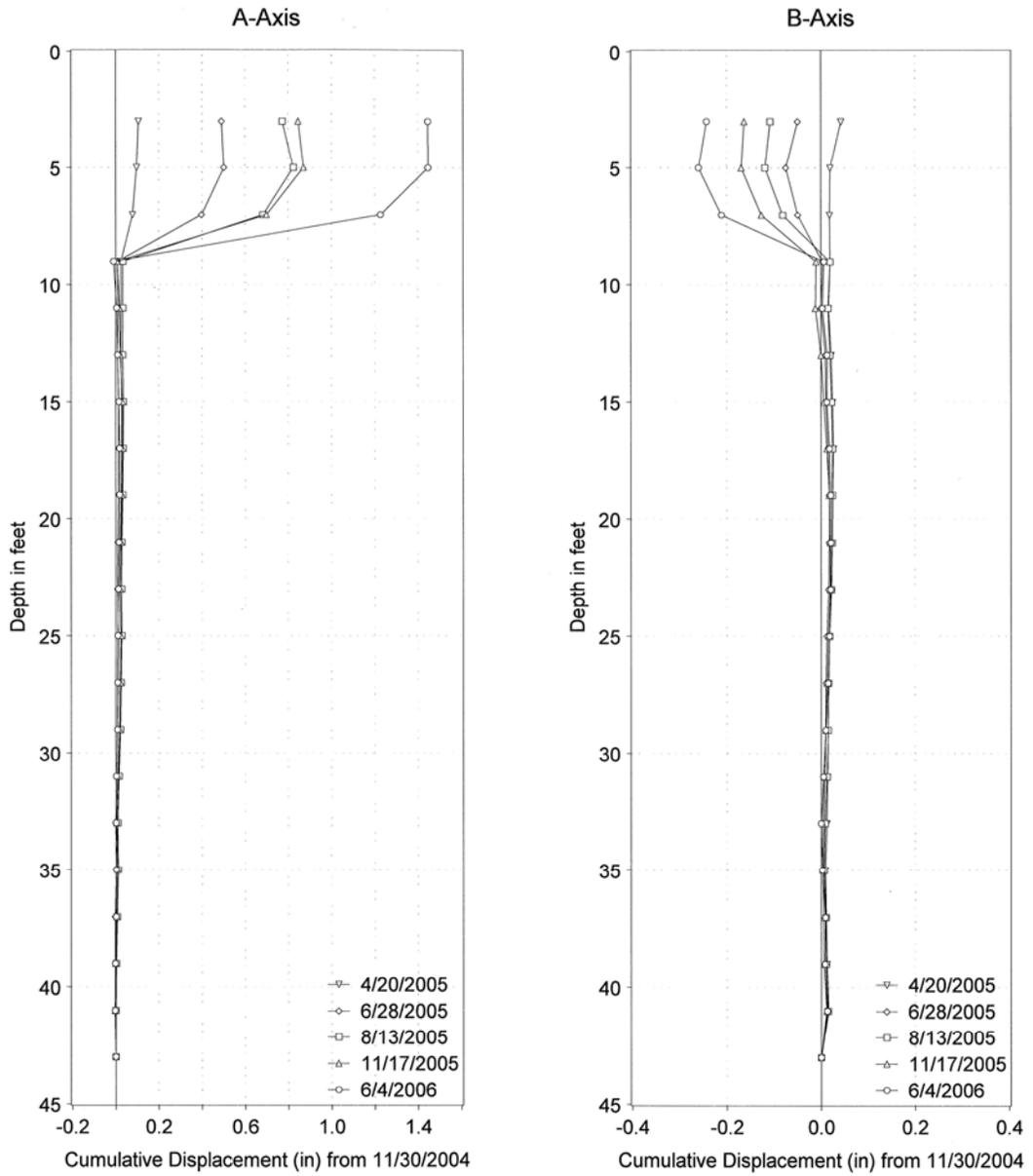


Figure 41. Slope inclinometer readings, Hickerson Curve, below the roadway.

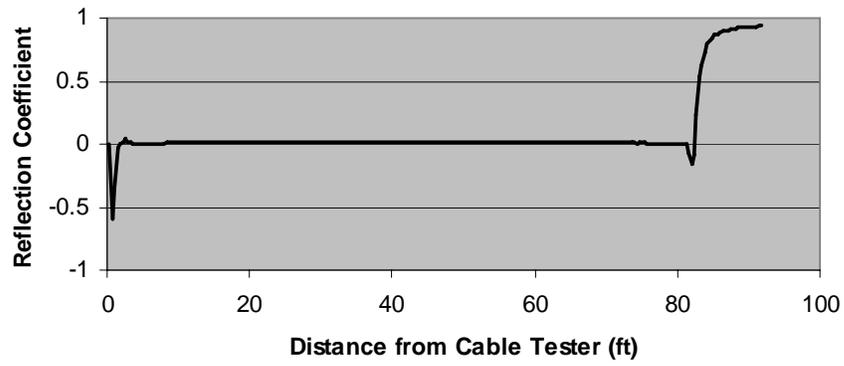


Figure 42. TDR signals, County Line site.

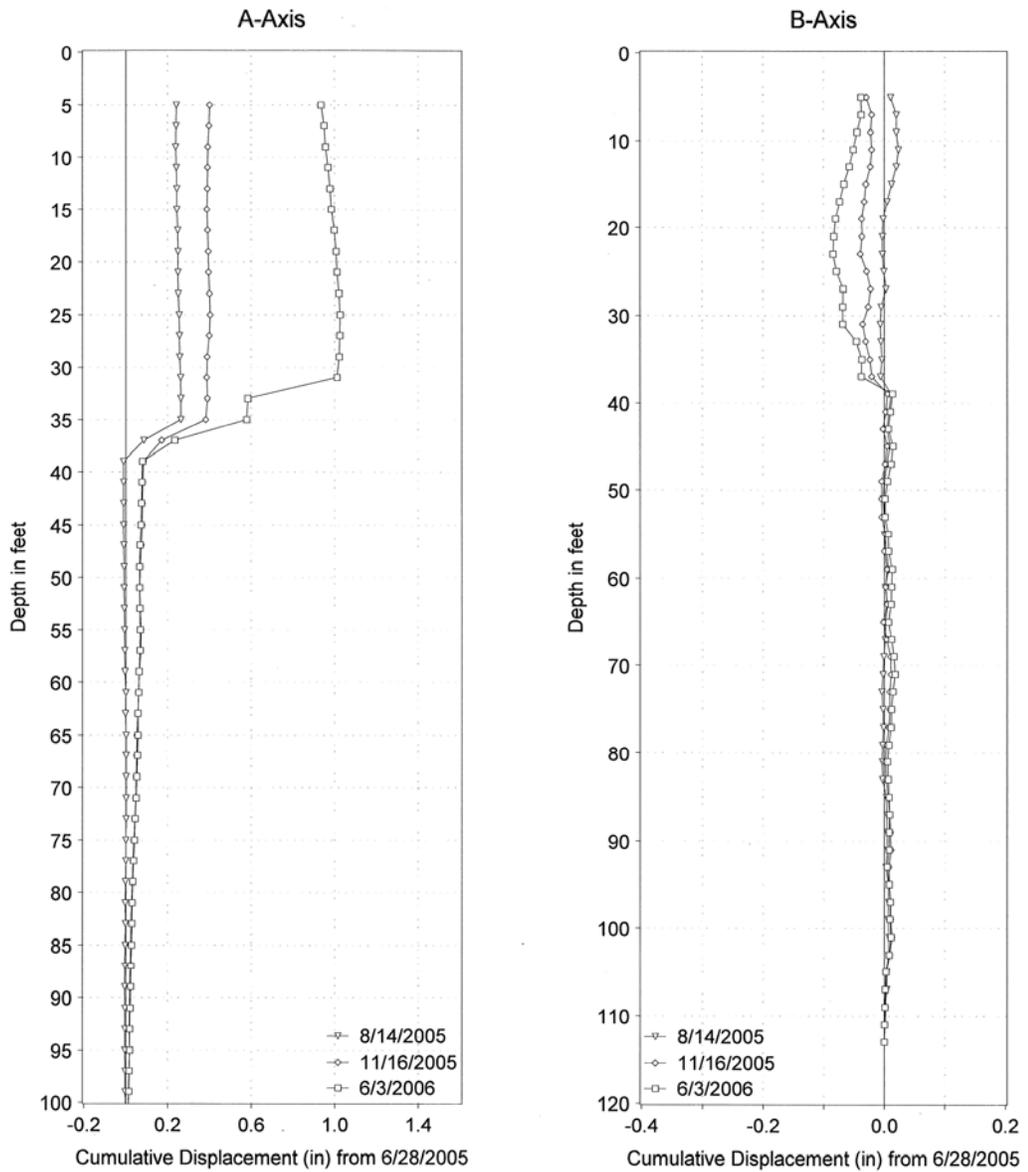


Figure 43. Slope inclinometer readings, County Line, below the roadway.

### 3.5 Discussion of Field Sites

The TDR field installations used in this study produced mixed results with respect to detection of slope movements. TDR was not successful in detecting slope movements at the Flying V. At the Campstool site, performance of TDR is inconclusive at this time due to insufficient shear deformation. The Narrows site is the most positive, with TDR readings providing a clear signal of slope deformation at a depth that agrees with slope inclinometer readings at the same location. The Togwotee Pass installations at Hickerson Curve and County Line have not shown evidence of shearing to date, but ground movements may not be sufficient and so results at this site are inconclusive.

The experience with TDR in this study is similar to a study conducted for the Arkansas DOT and described by Dennis et al. (2004). In that study, four different cable types were installed at an active landslide site. The four cable types included RG-8, RG 58, an air dielectric (hollow) cable, and a foam dielectric cable. The site consisted of 6 to 16 ft of soil underlain by shale and was cut on a 3 to 1 slope. After one year of monitoring, slope inclinometer readings showed a clear zone of sliding at a depth of approximately 8 ft while none of the cables showed any signs of movement. The authors attribute the lack of response by the cables to a reinforcing effect caused by the grout columns that limited movement at the location of the cables. All of the cables had been grouted into 8-inch (200-mm) diameter boreholes using a weak sand-cement grout. The mix design was composed of five parts sand to one part cement and a W:C ratio of 2.65.

A second active slide site was selected for further study, consisting of 10 to 16 ft of mixed clays over shale and also on a 3 to 1 slope. Cables were installed in 2.8 inch (70 mm) diameter holes using a weak cement-bentonite grout consisting of one part bentonite to one part cement and a W:C ratio of 4.0. After four weeks of monitoring it was concluded that the grout would not develop sufficient strength to deform the cables. Additional cables were installed at the same site but into 4-inch (100 mm) diameter holes using a grout consisting of 22 lb bentonite, 95 lb cement, and 37 gal of water, giving a W:C ratio of approximately 3.5. According to the authors, this mix yielded a hardened grout that was significantly weaker than the sand-cement grout used at the first site, but sufficiently strong to deform the cables. After one year of monitoring, the cables reportedly exhibited the characteristic shear spike at a depth corresponding to movement measured by the inclinometer. Only data from the foam dielectric cable are presented. The foam cable first registered a signal when the inclinometer readings showed approximately 0.8 inches (20 mm) of shear deformation.

Finally, two RG-8 cables were installed at a third site. Cables were grouted into 4-inch (200 mm) diameter holes using a cement-bentonite mix consisting of one part bentonite to two parts cement and a W:C ratio of 2.7. After six months of monitoring, one of the cables registered an initial spike when the inclinometer readings indicated 1.3 inches (33 mm) of movement. The second cable began showing a signal when the corresponding inclinometer reading reached 1 inch (25 mm). Both cables exhibited increasing magnitude of spike with further shear deformation. The inclinometer readings at this site show a shear zone over a depth of approximately 3 ft rather than a well defined, localized

shear surface. The authors conclude that this mode of deformation increases the threshold deformation required to shear the cables (Dennis et al. 2004).

Our experience at the Flying V is similar to the Arkansas experience at the first site where no signals were observed, despite inclinometer readings showing a slope movement. In the Arkansas case, the failure of the cables to register deformation is attributed to the grout (too weak). At the Flying V, poor performance may be due to the grout or the cable (RG-59/U), or possibly a combination of factors. In this study, two sites (Campstool and Togwotee Pass) may not have undergone sufficient deformation to begin shearing of the cables. The Arkansas study suggests threshold deformations required to cause cable shear in the range of 0.8 to 1.3 inches (20 to 30 mm). If that is the case, the Campstool and Togwotee Pass cable installations should be monitored in the future for signs of movement. The Narrows site, as discussed previously, has provided us with the best evidence that TDR is capable of detecting slope movements.

None of the field studies conducted to date, including the present study, have been successful in developing a reliable, quantitative relationship between TDR signals and the magnitude of slope movement.

## CHAPTER 4

### CONCLUSIONS AND RECOMMENDATIONS

A study of time domain reflectometry for application to monitoring of highway slopes was conducted. Laboratory shear tests were carried out in an attempt to develop a correlation between shear displacement and TDR signals from grouted cables in sand deposits. Laboratory tests were also conducted to evaluate the potential use of air-dielectric, or hollow, coaxial cable for measuring groundwater elevations and for combined measurements of groundwater and slope movements. Grouted cables were installed at roadway landslide sites at various locations in Wyoming and monitored for periods ranging from one to six and a half years. TDR measurements are compared to slope inclinometer measurements at each site.

#### 4.1 Conclusions

The principal conclusions of the laboratory studies are:

1. Laboratory direct shear tests of grouted cables in sand did not produce consistent, repeatable results sufficient to establish a meaningful correlation between TDR signature spikes and shear displacement of the sand. While individual tests did show a reasonable and linear relationship between TDR signal and displacement, results were different for every specimen tested. Slope and intercept varied significantly between each test, leading to the conclusion that laboratory test results can not be extrapolated to field conditions.
2. TDR monitoring of air-dielectric coaxial cable provides a fast, reliable, and inexpensive method for monitoring groundwater elevations. Below the groundwater elevation, the TDR signal is distorted in a way that makes elevation readings incorrect. A correction factor must be applied to all readings below the groundwater elevation. Application of the correction factor is straightforward.
3. Shearing of hollow cable below the water level is detectable but the signal is not as pronounced as the signal induced by the same magnitude of shearing above the water level. Hollow cable can therefore be used to monitor both slope movements and groundwater elevations, but detection of slope movement below groundwater is more difficult.

TDR monitoring of field sites and comparison to slope inclinometer readings produced the following results.

1. Of four landslide sites studied, two have not undergone sufficient movement to shear the coaxial cables. These are the Campstool site and Hickerson Curve and County Line sites at Togwotee Pass. Inclinometer readings at the Togwotee Pass sites are showing movement but it is not clear at this time whether movement is occurring at the cable locations. At the Campstool site, neither the cables nor inclinometer readings show evidence of sliding.

2. TDR monitoring of cables at The Narrows slide demonstrates that the TDR method can work for detecting the presence and depth of a slide plane. In general, the magnitude of the TDR signal increased with increasing deformation, although measurements at a single location are not sufficient to develop a quantitative correlation between TDR readings and magnitude of slide movement.
3. The TDR installations at the Flying V failed to produce useful results. Possible reasons are the cable (RG-59/U), the grout, or both. Inclinometer readings show the presence of well-defined slide planes, but the cables show no evidence of damage.

## **4.2 Recommendations**

It is strongly recommended that WYDOT Geology continue to implement TDR as a tool for monitoring slopes. Although the field installations used for this study have produced mixed results, the technology has been shown to work in this study and others. The experience of other State DOT's has been similar, as illustrated by the Arkansas study described in Chapter 3 (Dennis et al. 2004). There is a learning period, during which failures may occur. If the reasons for failure can be identified and corrected at subsequent trial sites, TDR can provide an alternative or supplemental method to slope inclinometer readings. The following recommendations are based on lessons learned from this study:

1. The most practical cable type appears to be RG-8. Although Commscope P3-75-750 was used successfully at the Narrows, it is difficult to handle during installation. The handling difficulties may be overcome by mounting the cable spool on a truck or drill rig. Various researchers report best results with different cables. The Commscope cable was recommended by researchers at Northwestern University. The study by Dennis et al. (2004) identifies RG-8 as the best combination of cost, ease of handling, and ability to detect slide movement.
2. Grout mix design can have significant impact on the performance of TDR. For cables grouted into soil deposits, the interaction between soil, grout, and coaxial cable is complex. The grout must be stiff enough to deform the cable in shear, yet weak enough to fail when there is movement along a slide plane. Although this issue has not been entirely resolved, a mix consisting of one part bentonite to two parts cement and a water to cement ratio of 2.7 appears to provide the necessary stiffness when used with RG-8 cable in soil deposits. This combination of mix design and cable is recommended for future installations. Further guidance and discussion of grout mix designs for TDR is given by Dowding et al. (2003) and Dennis et al. (2004).
3. Air dielectric or hollow coaxial cable can be used as a piezometer. It is recommended that WYDOT consider the use of hollow cable for this purpose. Cable installations are less expensive than piezometers based on electronic transducers and can produce reliable measurements of groundwater elevation. The potential exists to use hollow cables for combined measurements of groundwater elevation and slope movements, but this application should be considered as a research issue that requires further field evaluation.

New developments in TDR technology have occurred during the period of this study. One area of advancement has been in data acquisition and communication systems. As described by Dowding et al. (2003), the combination of dataloggers, multiplexers, and various communication devices has made remote monitoring a possibility for TDR. The authors describe a remote monitoring technology that allows data from a TDR installation to be transmitted and displayed on a website. Technologies based on cell phone, land lines, and radio transmission are also reported. Remote monitoring offers the potential for significant cost savings because man hours involved in traveling to the site can be eliminated.

It is further recommended that WYDOT Geology continue to monitor the Campstool, Narrows, and Togwotee Pass cable installations of this study. In particular, the Togwotee Pass sites, which were installed during the summer of 2005, offer the opportunity to evaluate the performance of RG-8 cable. WYDOT Geology now has the Campbell Scientific TDR 100 and associated software for monitoring and processing TDR readings from coaxial cables and WYDOT Geology personnel have the necessary experience with TDR technology.

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