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Estimating Movement of Shallow Slope Failures Using Time Domain Reflectometry

Norman D. Dennis[1], Chong Wei Ooi[2] and Voon Huei Wong[3]

[1] Professor of Civil Engineering, University of Arkansas, 4190 Bell Engineering Center, Department of Civil Engineering, University of Arkansas, Fayetteville, AR 72701. PH: (479) 575-2933, FAX: 479-575-7168, E-mail: ndennis@uark.edu

[2] Project Engineer, CEI Engineering Associates, 3317 SW "I" Street, Bentonville, AR, PH (479) 273-9472, FFX: (479) 273-0844, cooi@ceieng.com

[3] Project Engineer, MACTEC Consulting Engineers, 2100 Riverchase Center Suite 450, Birmingham, Alabama 35244, PH: (205) 733-7600, FAX: (205) 985-2951 vhwong@mactec.com

Abstract

Time domain reflectometry (TDR) is gaining wide spread attention as a cost effective method to monitor mass movements in both soil and rock. It has been used successfully for a number of years to monitor deep seated failures in soil deposits and for monitoring many different kinds of movements in rock masses. However, its use in monitoring shallow failures in engineered cut slopes and embankments has been limited. A chief benefit of using this technology is that it can be a cost effective means of remotely monitoring the effectiveness of slope hazard remediation measures. This paper describes a study, conducted in the Arkansas' Ozark Plateau, in which TDR was used at various sites where shallow failures were imminent or had already occurred along highway cut slopes and embankments. Several different coaxial cable types were evaluated under both laboratory and field conditions to determine which type had the best potential for accurately depicting the location of failure slip surfaces. The monitoring at all sites consisted of grouted coaxial cables in combination with grouted inclinometer casings where a probe inclinometer was used to establish a reference for movements in the slopes. The TDR cables were monitored remotely through an automated data collection system while inclinometer data was collected manually on an intermittent basis. It was determined that all cable types performed differently in both the laboratory and the field, each having certain installation and maintenance issues. Field and laboratory measurements were made to determine the threshold movements required to produce a distinguishable cable signature and some efforts were made to relate the magnitude of the reflected energy pulse to the magnitude of movement along the slip surface. Based on installations at four sites and laboratory studies, recommendations relative to cable type, installation procedures and the overall effectiveness of this monitoring method for shallow slope failures are given.

Key Words Slope movement, monitoring, TDR cables, Inclinometer, Remote monitoring

Introduction

On January 8, 1999, the Arkansas State Highway and Transportation Department (AHTD) opened the final section of a new interstate quality highway designated as Interstate 540 (I-540)

which connected Ft. Smith to Fayetteville. The new 69km span, traversing the rugged terrain of the Ozark Plateau in Northwest Arkansas, incorporates 13 major bridges and a 430m twin-bore Tunnel. The overall cost of this project was $460 million, equivalent to $6.7 million per kilometer ($11 million per mile), which is an expensive project for the area. During the construction of portions of the new highway, repair of slope failures and modifications to slide prone areas cost approximately $65,000 per mile per year [1]. Additionally, the state highway department has spent over $42 million on post construction slope repairs for this section of road after only six years of service. These expenditures have made this section of I-540 not only the most expensive interstate ever built in Arkansas but also the highest maintenance highway in the state. As a result of this large investment in slope repairs, the State of Arkansas has become astutely aware of the need for cost effective repair and remediation techniques as well as the need to monitor the effectiveness of these repair and preventative efforts.

The issues with slope failures continue along this section of road, with the Highway Department documenting 18 new or repeat slope failures during the period May 2004 to May 2005 alone. In addition to the existing slope repair issue, an extension of this Highway system to the south of Ft. Smith through similar terrain promises more problems with slope stability. Currently, the principal remediation technique for failures in this area has been removal of failed material and replacement with rock or rock buttressing, which is a very expensive remediation technique that has not always been effective. With the requirement for continued slope maintenance in this section of the state, the Highway Department is seriously investigating more cost effective preventative measures for slope instability: such as the installation of drainage systems or the use of inclusions to reinforce slopes. In an effort to monitor the effectiveness of these various remediation strategies cost effective remote monitoring systems are a being developed and evaluated. This study is the result of efforts to implement Time Domain Reflectometry, (TDR), as a technology in evaluating remediation effectiveness.

Monitoring Systems

Historically, the monitoring of slope performance or the actual mass movements in slopes has been conducted with surveying instruments, inclinometers and even piezometers. These techniques, while accurate, are time consuming and costly. They require technicians to visit the site periodically to make or record physical measurements and often times the data must be interpreted to determine its inferred meaning. In addition to time and cost, the periodic nature of these techniques can sometimes cause investigators to miss significant movements. Over the past 20 years, engineers have developed many systems that can monitor movements autonomously, but most are very expensive[2] Of the newer monitoring methods Time Domain Reflectometry appears to be one of the more cost effective techniques that has been used successfully to monitor movements in rock and deep seated slope failures. However, it has been used primarily on only an intermittent basis [3, 4]. The equipment currently available to support this method promises to make it an effective remote monitoring technique that can autonomously monitor the effectiveness of slope remediation measures on a continuous basis.

Time Domain Reflectometry is similar to radar in that is uses reflected energy to determine the location of anomalies in normal energy patterns. In the case of TDR, all of the system energy is confined to a waveguide or cable. A schematic diagram of a TDR system used to monitor deformations in slopes is illustrated in Fig. 1. The TDR monitoring system essentially consists of a coaxial cable, grouted into a borehole which traverses the anticipated shear surface of a slope failure, as illustrated in Fig 1a. This system uses a pulse generator/

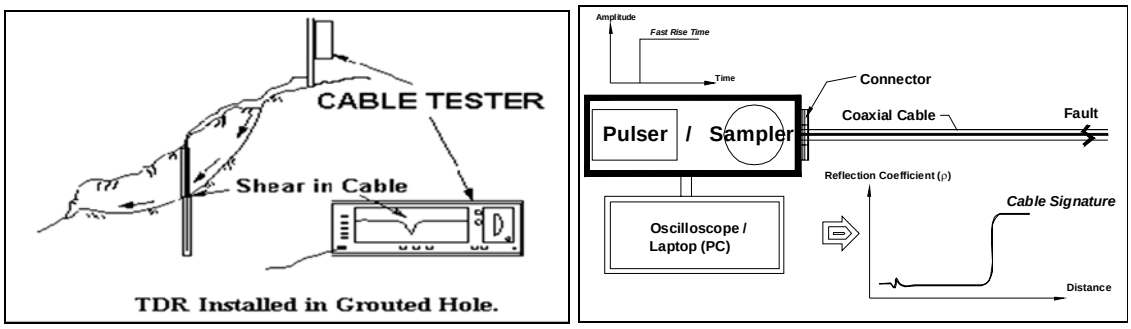

Fig. 1. (a) Schematic of the monitoring of the energy pulse generated by the cable tester. (after Kane, et al., 1996) (b) Schematic diagram of TDR installation in an actively moving slope (after Anderson, et al., 1996)

receiver, called a cable tester to send a fast rise energy pulse through the coaxial cable. The cable tester then waits for energy from that pulse to be reflected back from the end of the cable, as shown in Fig. 1b. Any anomalies or defects along the length of the cable, such as those produced by shearing will reflect a portion of the energy pulse. By knowing the propagation velocity of the energy pulse through the cable, the time of arrival of the reflected energy can be used to determine the location in the cable at which the anomaly exists.

While the TDR methods have been used successfully in the past to monitor mass movements in rock, [4, 5], or deep failures in soil masses [6, 7] they have not been used to detect shallow failures like those occurring in the I-540 right-of-way. In addition, previous TDR research has not revealed the threshold movement necessary to produce a satisfactory TDR signature.

Study Methodology

Four field sites in the Ozark Plateau were selected where failure was deemed imminent, a repair had just been completed, or where there was some evidence that the slope was actively moving. Two sites were in cut slopes along I-540 approximately 60 km north of Ft Smith, AR, one was in a cut slope on I-40 about 35 km east of Ft. Smith and one was in a fill slope on Highway 167 about 2 km south of Batesville, AR. At each of these sites probe type inclinometers and a TDR system was used to monitor movements. The inclinometers were used as the absolute reference for movement in the slope. A TDR system was also monitored to determine not only if a reflected signal could be obtained at the shearing surface indicated by the inclinometer but also to determine the threshold displacements necessary to produce such a signal and the relationship between reflectance and movement. Efforts were also made to determine the most cost effective cable type to be used in TDR applications by comparing the reflected electrical signatures of four pre-selected coaxial cable types in the laboratory.

The actual hardware used to create the TDR monitoring system in this study is depicted in Figure 2. All of the components of the TDR system are “off the shelf” and readily available. The complete monitoring system cost less than $8,000 at the time of the study.

The initial site selected for study was a cut slope located at mile marker 46 of I-540. This slope consisted of between 2 and 5 meters of sandy clay soil with SPT blow counts ranging from 13 to 18 of underlain by a medium hard gray and brown weathered shale with blow counts of between 31 and 60. The face was cut at a 3 on 1 slope and had only sparse grassland type

Fig 2. TDR Hardware used in this Study. Clockwise from top left, 16 Channel Data Logger, Cable Tester, Multiplexer, TDR moisture probe, Analog Cell Phone, Modem, Complete Field Installation in Weather Tight Enclosure.

vegetation. This site was selected because a recent failure had occurred adjacent to it and there appeared to be a toe bulge forming at the specific location selected. The plan and profile of the cable installation is depicted in Fig. 3. The face of the slope was approximately 30 m from toe to crest. Each row of the installation had four different cable types and an inclinometer installed in separate 200 mm boreholes with a weak sand-cement grout. Bore holes were spaced on a 4 m grid in both directions. The grout mixture was composed of 6 parts sand to one part cement having a water to cement ratio of 2.65 and an unconfined compressive strength of 1000 kPa (150 psi). The four cable types selected for study, along with their associated connectors, are depicted in Fig. 4. The air-dielectric and aluminum clad foam cables are considered rigid while the RG8 and RG58 are considered flexible cables. The properties and costs of these cables are itemized in Table 1. In the field installation all rigid cables were terminated about 300 mm above each borehole and connected to the monitoring system with an appropriate length of flexible RG8 cable which ran along the ground surface from the borehole to the data collection station. The flexible cable installations were continuous from the bottom of the borehole to the collection station. All cable runs from the borehole to the data collection

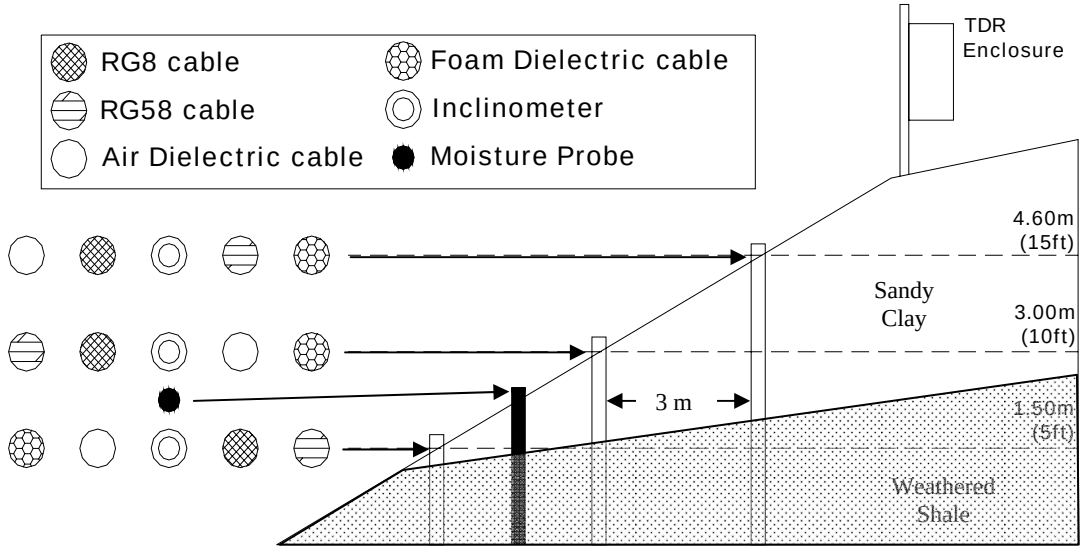

Fig 3. Schematic Diagram of Cable and Inclinometer Layout for the Mile Marker 46 Site.

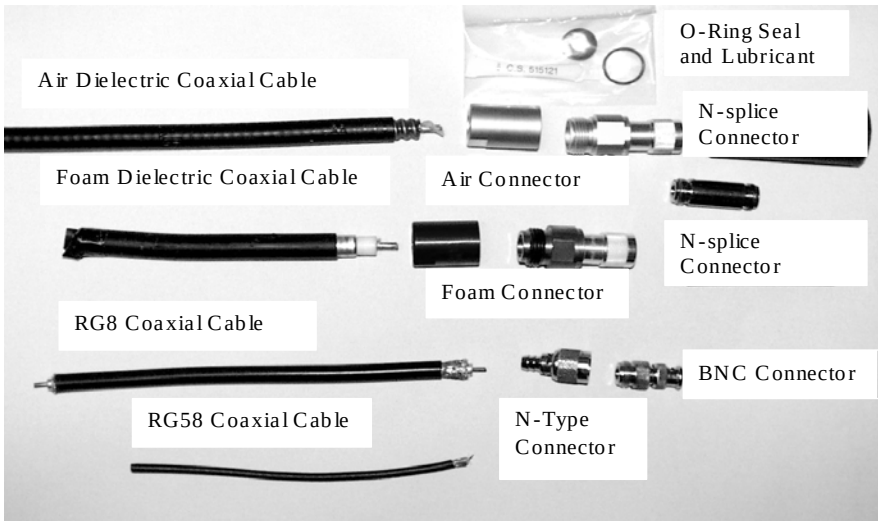

Fig. 4. Cable Types and Connectors Installed for this Study

Table 1. Summary of Cable Properties and Costs for the Cable Types used in this Study

Cable Type	Diameter (mm)	Impedance (ohms)	Propagation Velocity (%)	Cable Cost (m)	Connector Costs per (installation)
Air Dielectric	12.5	50	91.5	$13.50	$100.35
Foam Dielectric	12.5	50	81	$6.60	$40.32
RG8	12.5	50	82	$2.40	$9.20
RG58	9.5	50	66	$0.75	$3.80

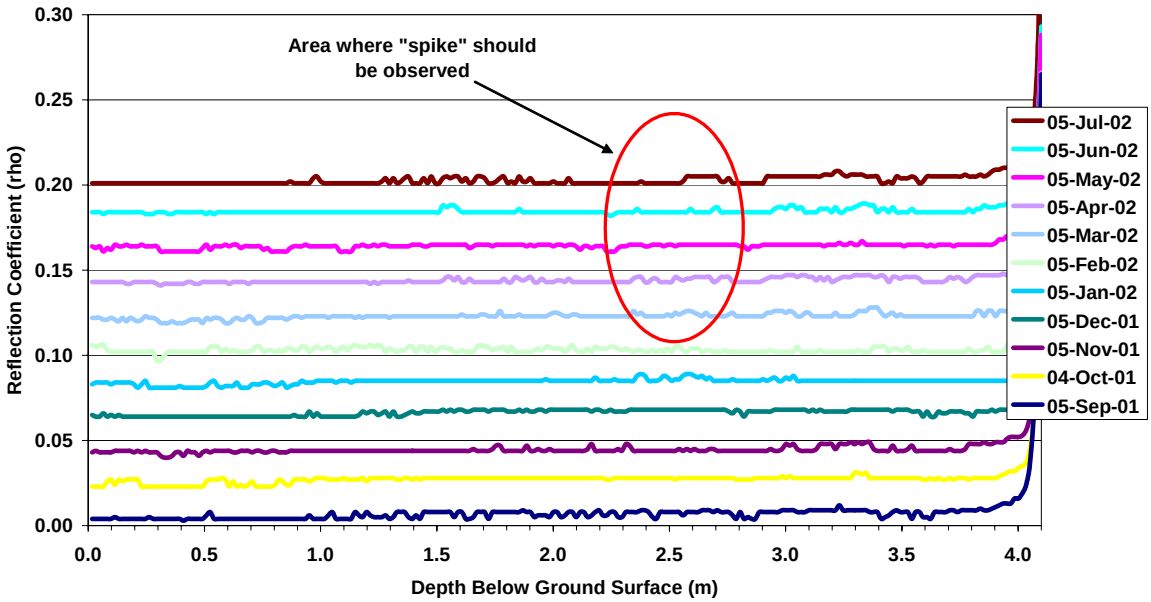

Fig. 5. Summary of Cable Signatures for RG8 TDR Cable Installed in the Top Row at Mile Marker 46.

station were covered with a thin layer of soil for protection. All cables were left jacketed when installed in the boreholes. The inclinometer casings were initially logged on a weekly basis and cable signatures from the TDR system were collected every two hours. The cable tester was programmed so that it produced a digital image of the signal trace over a window which only included the grouted portion of the cable. This image was depicted using 2048 equally spaced data points. The data logger of the TDR system had sufficient memory to store one week of cable signature data for all twelve cables before the information had to be off-loaded either by connecting a laptop computer directly to the collection system or remotely accessing the system via a the cell phone and modem.. After the first two months of operation it was concluded that the high frequency of the data collection efforts was not warranted because of a lack of movement at this site. As a result TDR cables were scanned on a two hour frequency to determine if any rapid movement had taken place, but data was only collected once a day and the frequency of inclinometer logging was reduced to once per month. The summary of a sample series of cable signatures for one year of monitoring at this location is displayed in Fig. 5. Each monthly signature has been manually offset by a relative reflection coefficient of 0.02 rho for display purposes. The baseline, or initial trace, is at the bottom of the chart while readings for subsequent months are offset above it. In summary, these traces revealed that no detectable energy reflection from a shearing surface could be detected for this cable over the one year monitoring period. The set of readings depicted in Fig. 5 for the RG8 cable in the top tier of the installation is typical of all the TDR readings taken at this site. Figure 6 portrays a summary of the inclinometer readings in the top tier for the same period as the summary of the TDR traces. The maximum incremental movement recorded in the top-row by the inclinometer was only 4.5 mm. While normal inclinometer traces show cumulative movement with depth, it was decided to display incremental displacements, rather than cumulative, to better define the location of the shearing surface in any potential failure. It became apparent after two full cycles of wet seasons that the portion of the slope selected for the study was not moving significantly. While areas on both sides of the study area exhibited obvious signs of significant movement on the surface, the test area showed none. It was hypothesized that the size and

number of grouted boreholes in a relatively small area adequately reinforced this shallow failure so that the resisting forces exceeded the driving forces. To verify this hypothesis a stability analysis was conducted on the failed slope immediately adjacent to the test site to back-calculate the soil strength along the observed slip surface. The summation of the diameters of the boreholes represented about 6 percent of the cross-slope length at this site. In a subsequent stability analysis for the study site, the boreholes were represented as 12.5 mm reinforcements having a strength of 1000 kPa and the soil along the failure surface was represented with a cohesive strength of 20 kPa. The resulting factor of safety was improved to 1.2. While this analysis does not totally confirm the hypothesis, it does support it.

Several issues arose at this site with faulty connections between the rigid cables and the RG8 runs to the collection station and with water intrusion into the air-dielectric cable. All of these problems gave false indications of anomalies in cable geometries, but the locations of these anomalies did not match the movement recorded by the inclinometers and the reason for the changes in reflectance were isolated and corrected.

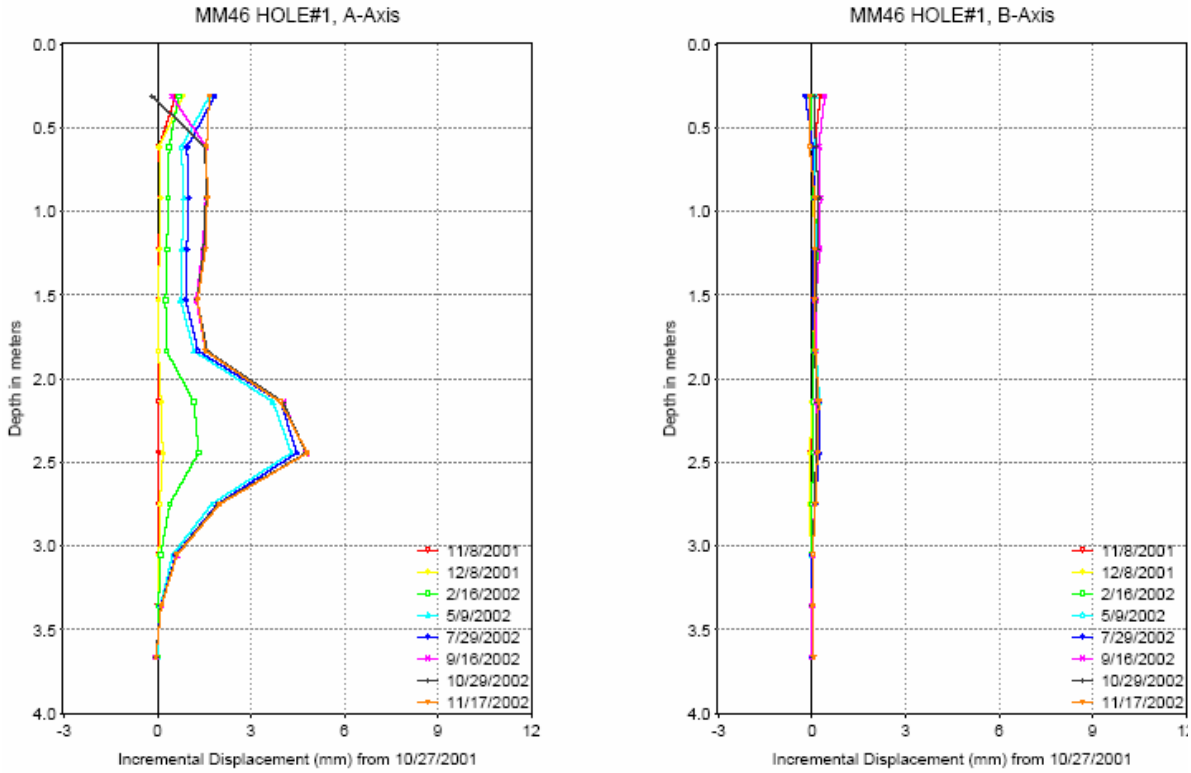

Fig. 6. Summary of Uncorrected Inclinometer Readings, showing Incremental Displacement for the Top Tier at Mile Marker 46.

As a result of these discouraging field results a laboratory investigation was conducted to determine the amount of movement along a shear surface that would be required to produce a noticeable “spike” in the TDR cable signature. A loading device, illustrated in Fig. 7 was created that could load three grouted cables in double shear at one time to a maximum deflection of 25 mm using a servo hydraulic compression tester. The cables were grouted into the wooden loading frame using a neat cement-bentonite grout having an unconfined compressive strength of 6210 kN (900 psi). The purpose of using such a strong grout was to ensure a well defined shear plane developed at the 3 mm gaps in the loading frame during shear rather than having the loading frame crush the grout. A summary of the loading results

for the aluminum clad foam dielectric cable are presented in Fig. 8. It is apparent from the information in Fig. 8 that at least 7 mm of deformation are required to produce the beginnings of a noticeable "spike" in the cable signature and that the spike increases in magnitude as deformation increases. At a deformation of approximately 12 mm the beginnings of the "spike" for the second shear plane becomes noticeable. RG8 cable produced similar results,

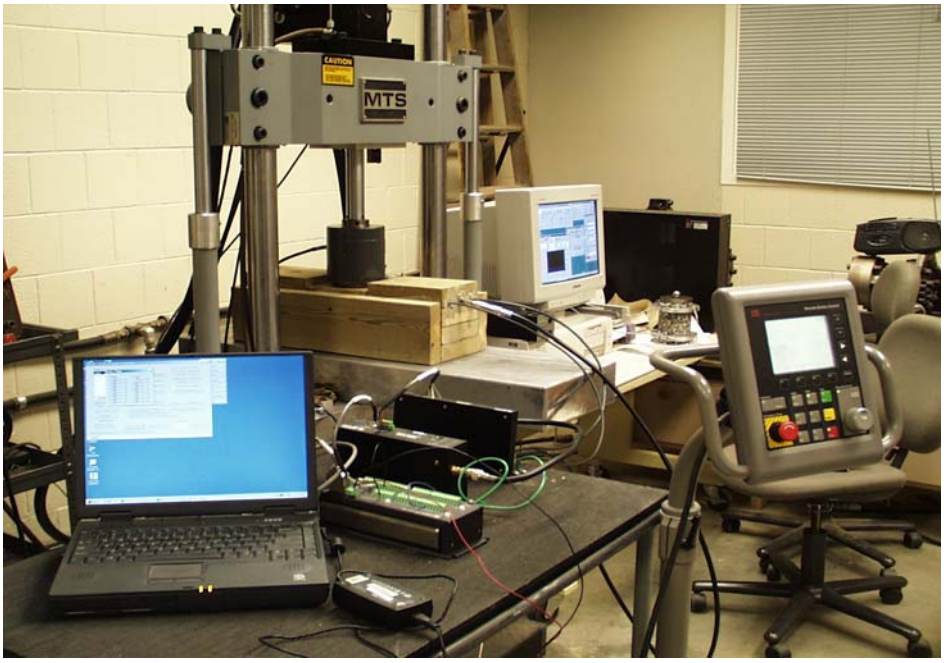

Fig. 7. Laboratory Shear Apparatus used to Determine Cable Signatures as a Function of Deformation

exhibiting the first noticeable spike at 5 mm. Both RG8 and foam dielectric cables produced a useful reflection signature over the full range of deformations investigated (up to 25 mm). Unfortunately, the results for RG58 and the air dielectric cable were not as pronounced. The first spike for these cables did not occur until 10 mm of deformation and the cables either shorted out (inner to outer conductor contact) or were severed (outer conductor) after only 15 mm of deformation.

As a result of this laboratory investigation it was concluded that RG8 and aluminum clad foam dielectric cable gave nearly identical results and the most useful reflection signatures over the widest range of deformations. However, when one compares the cost of installation of these two cable type (See Table 1) it is clear that the RG8 cable provides the most economical material cost. When peak reflection data are plotted versus deformation, as illustrated in Figures 9 and 10, it is clear that there was a linear relationship between deformation and signal once the threshold deformation had been achieved. The relationship between peak reflection and deformation for the flexible RG8 cable compared favorably to those reported by McAlister [8] who noted that the relationship could be used in the field to estimate actual deformation along the shearing surface.

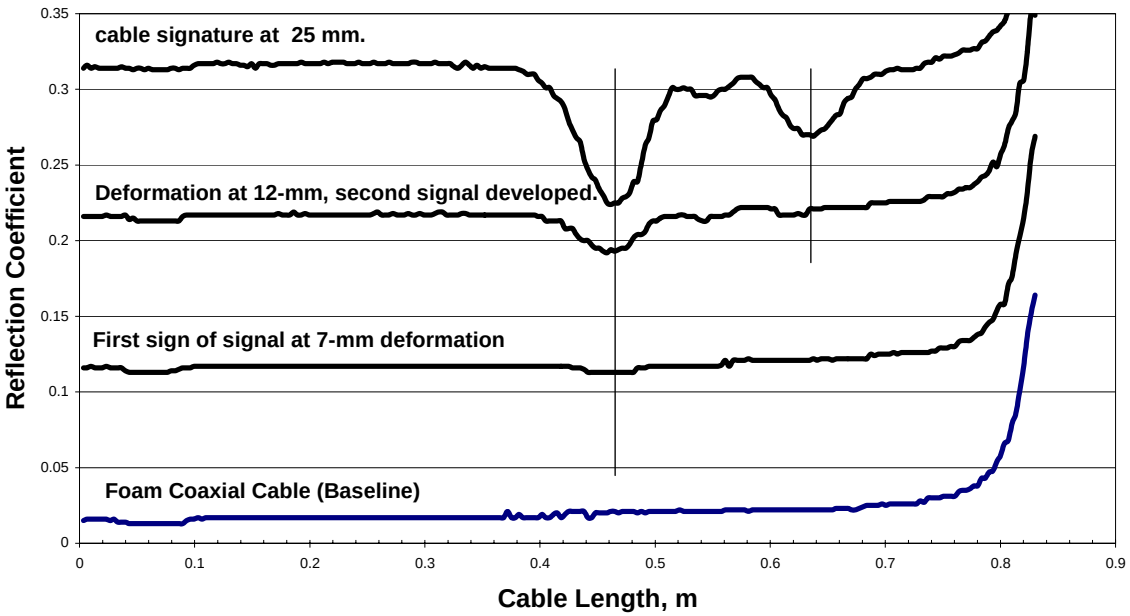

Fig. 7. Results of Laboratory Shear Testing for Foam Dielectric Cable.

At the conclusion of the laboratory testing a new study area was selected for a revised installation of the TDR monitoring sytem. The new area was located at mile marker 50 on interstate 540. This site was another 3 on 1 cut slope constisting of 3 to 5 meters of mixed clayes over shale. The mixed clays had N-Values ranging from 8 to 15, decreasing with depth, while the weathered shale's N-Values ranged from 30-60 and generally eincreased with depth. This slope had failed previously two times. Each time the failed material was simply pushed back into place with a bull-dozer. The slope was considered a likely candidate for monitoring as an actively moving slope. The schematic of the cable layout for this installation is illustrated in Fig. 11. For this installation all cables and inclinometers were grouted into 100 mm boreholes with a cement-bentonite grout. Each row of the installation was space 3-m from the next and boreholes in the same row were space 3 m apart. The grout

used in the first installation of cables at this site followed the mixture recommended by Dowding [9] for compliant grout. This grout mixture produced a grout with a compressive strenght of less than 500 kN (75 psi). The the second set of calbes were installed using a grout mixture recommended by Mikkelsen[10] for instrumentation installed in stiff soils. This

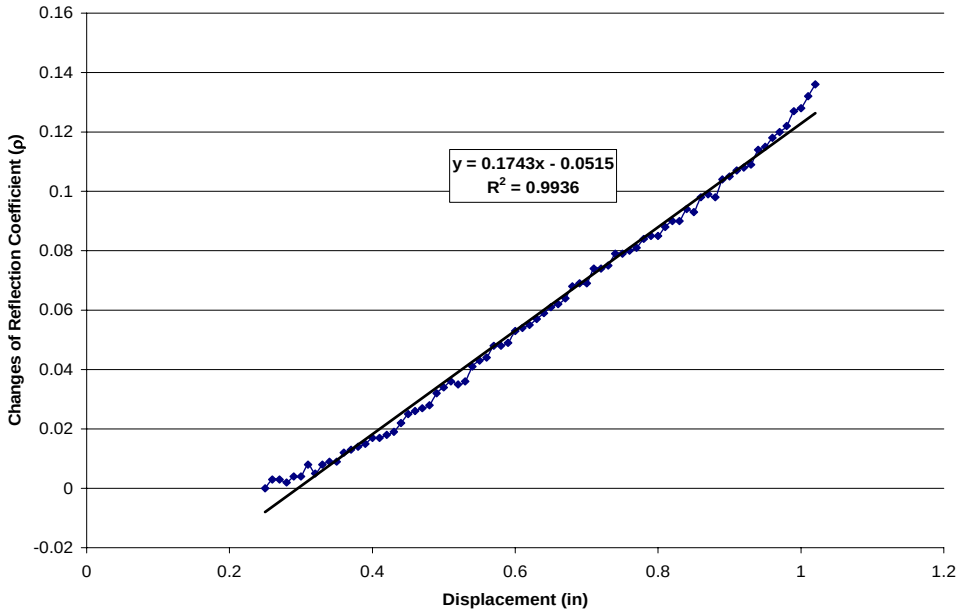

Fig. 9. Results of deformation versus peak reflection testing for RG8 cable.

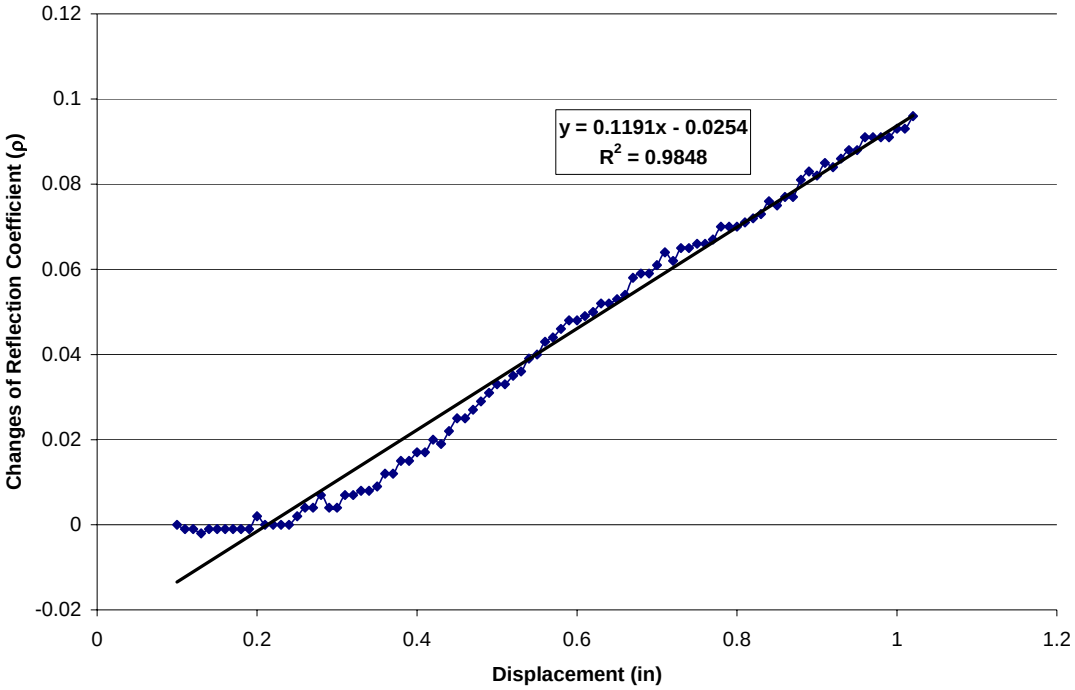

Fig. 10. Results of Deformation versus Peak Reflectance for Aluminum Clad Foam Dielectric Cable.

grout mixture consisted of 3 Kg bentonite, 43 Kg Portland Cemtent and 150 liters of water and had a compressive strenth of approximately 1200 kN, (175 psi). Both grout mixtures created significantly weaker grout columns than the larger diameter sand-cement columns used at mile marker 46. After approximately 10 months of monitoring the TDR cables in the stronger grout started to exihibit the characteristic "spike" associated with a shearing surface. Inclinometer data verified the location of the shear surface and the locations indicated by both systems matched. A summary of the cable signatures for one of the cables is given in Fig. 12 and the correspnding inclinometer data is given in Fig. 13. It is significant to note that the TDR cables did not register the presence of a shear surface until August of 2003 and the deformation required to see the beginnings of a "spike in the cable trace was approximately 14 mm, as measured by the inclinometer. This was about twice the deformation required in the laboratory study to produce the beginning of a "spike" for the same cable type. Also of significance at the mile-marker 50 site was the fact that none of the cables installed with the weaker grout produced a "spike"at any level of movement.

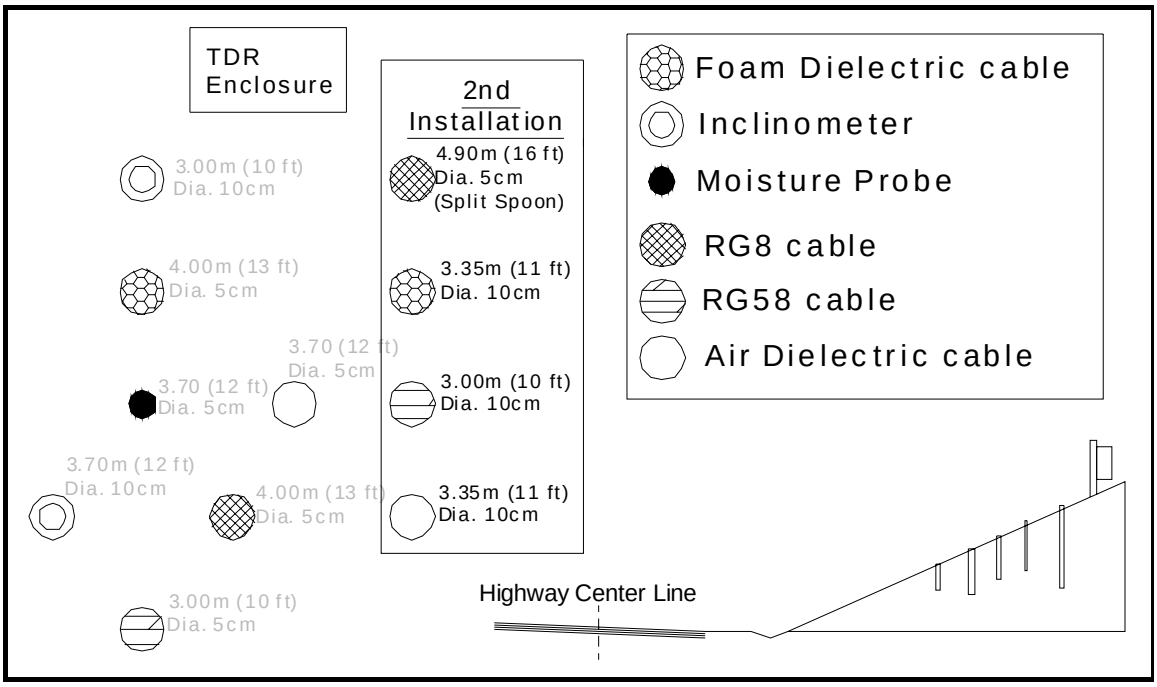

Fig. 11. Schematic of Cable Installations at Mile Marker 50

Near the end of this study a fourth installation of inclinometers and TDR cables was made in an actively moving fill slope on Highway 167 approximately 2 km south of Batesville, AR. At this location RG8 cables were grouted into 100 mm boreholes with 1725 Kn (250 psi) to a depth of approximately 12 meters. Details of that installation are illustrated in Figure 14. A complicating factor for the installation at this site was that construction activities were taking place in the vicinity of the boreholes and the data recording station containing the cable tester had to be located over 70 meters away from the location of the grouted cables. In addition, the cables had to be moved frequently so a connector had to be installed at the top of the grout column preventing a continuous run from the bottom of the borehole to the data collection unit. This additional connector and the long cable run resulted in some signal attenuation problems. A summary of the inclinometer data and corresponding TDR cable

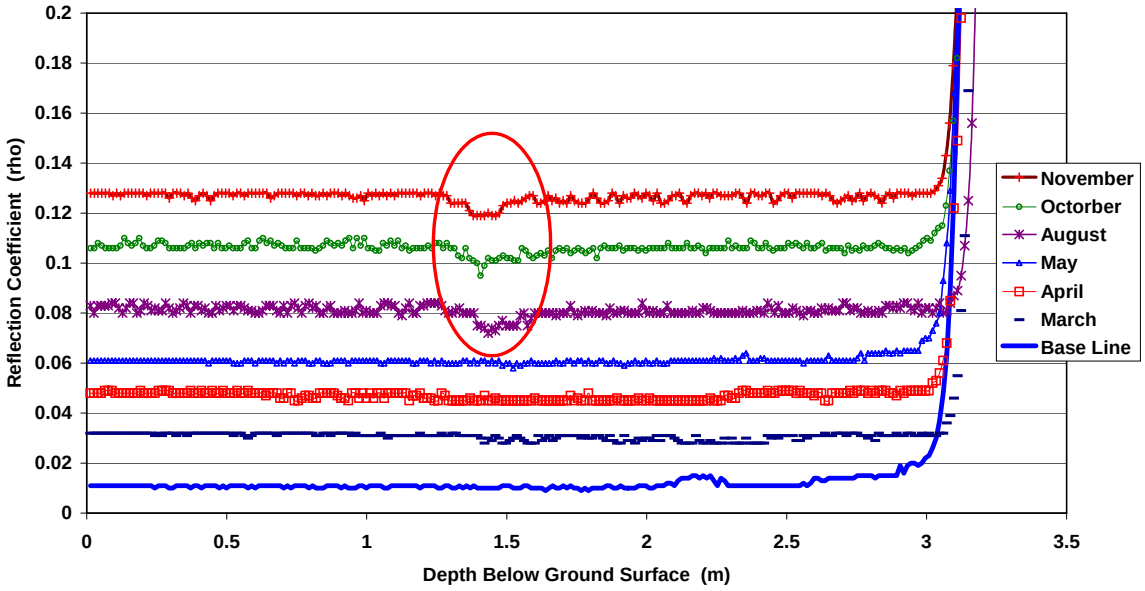

Fig. 12. Comparison of Waveforms for the Aluminum Clad Foam Dielectric Cable at Mile

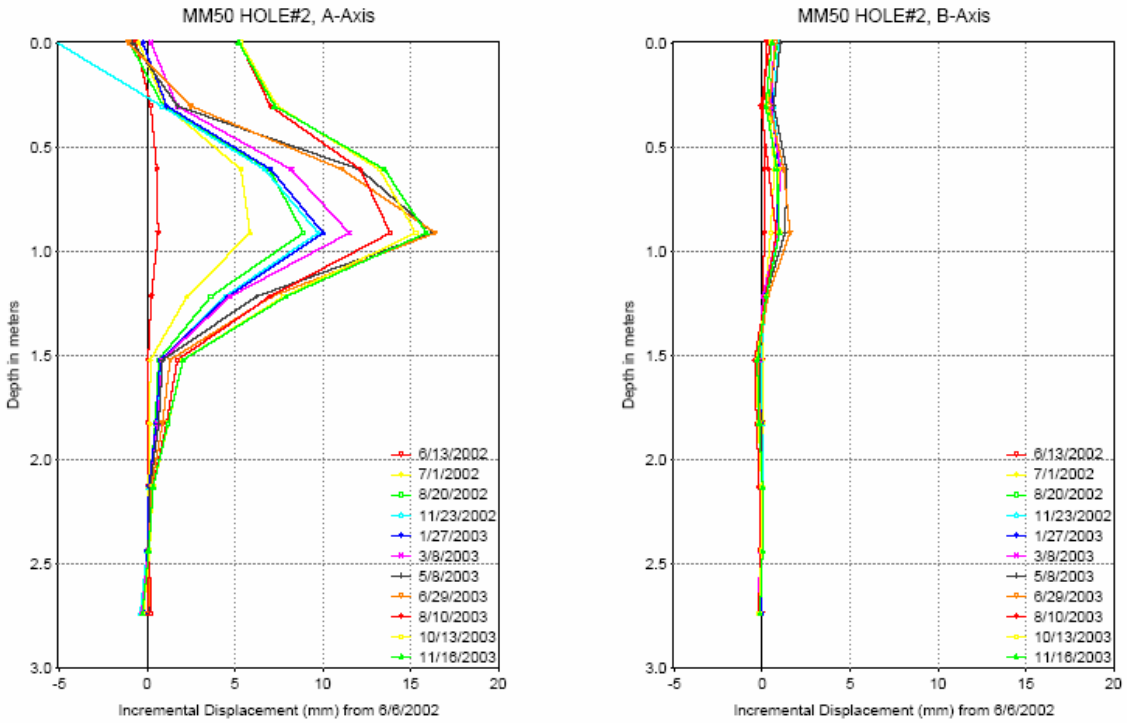

Fig. 13. Summary of Inclinometer Data for the Lower Borehole at Mile Marker 50 on Interstate 540.

signatures for the upper borings at this site are illustrated in Figures 15 and 16, respectively. Comparison of these two figures reveals a slight offset in the indicated location of the shear surface between the inclinometer and the TDR signatures. This is due to the physical

separation of the two boreholes along the plane transecting the failure surface and the steeply tilting nature of the failure surface in the vicinity of the boreholes, (see figure 14). The first

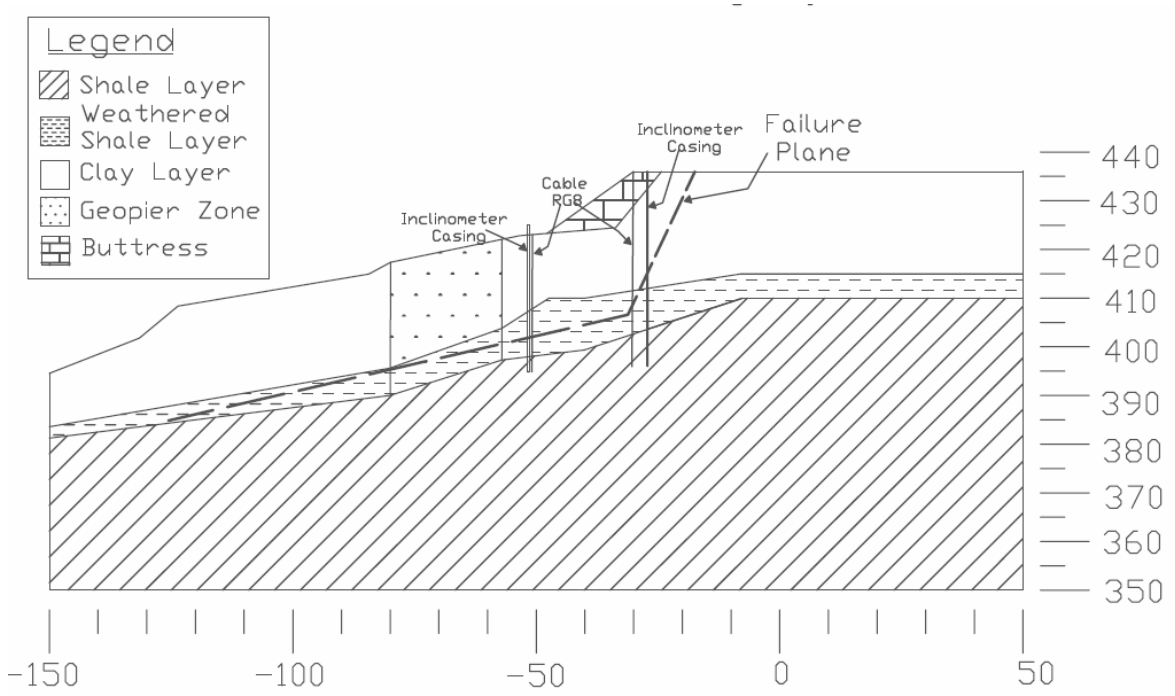

Fig.14. Slope Monitoring Installation Near Batesville, AR (all units in feet).

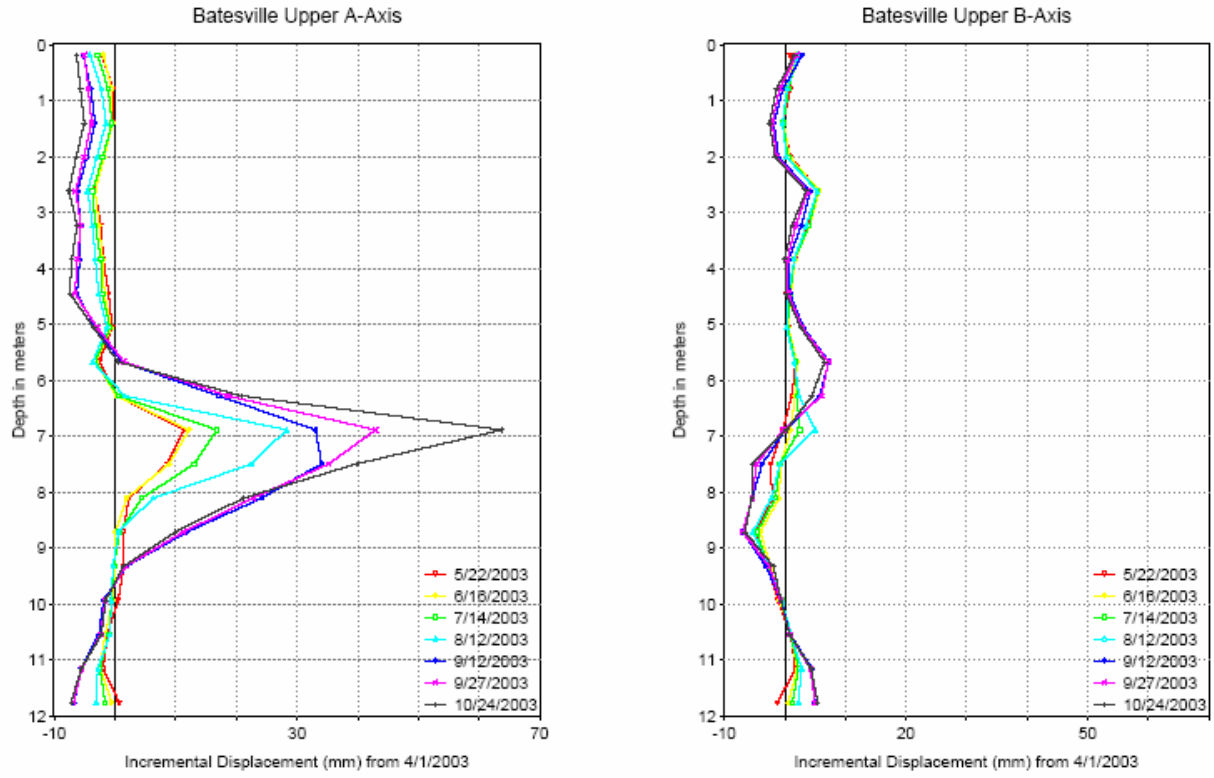

Fig. 15. Summary of Inclinometer Data for the Upper Borehole on Highway 167 near Batesville, AR. (May-Nov 2003)

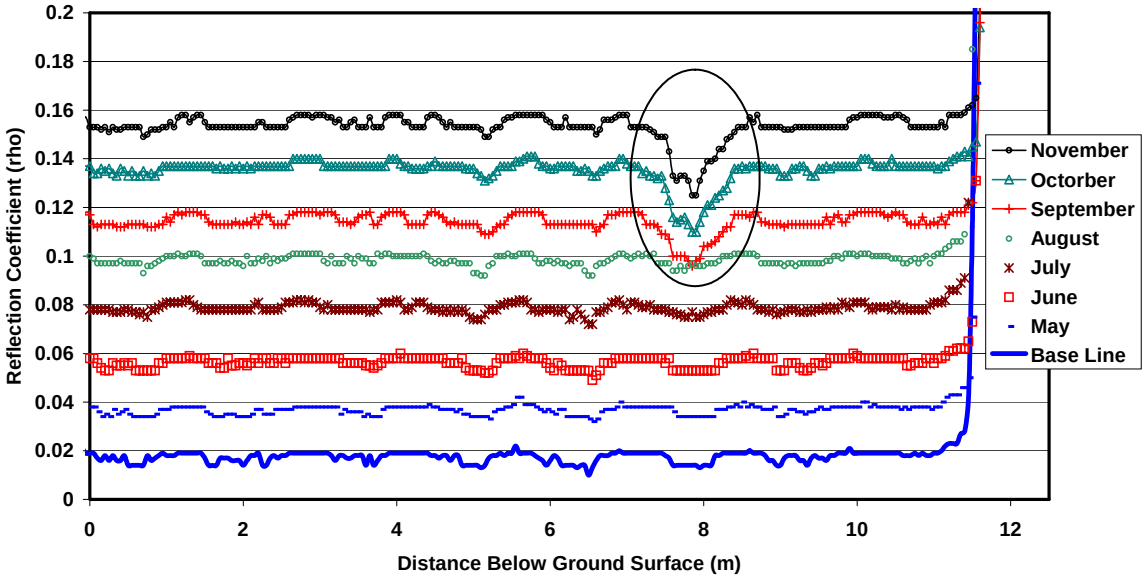

Fig. 16. Comparison of Waveforms for the RG8 Cable in the Upper Borehole on Highway 167 near Batesville, AR (May – November 2003)

discernable "spike" in the TDR cable occurred in late August when the inclinometer indicated a maximum incremental displacement of approximately 30 mm. This was about twice the threshold movement required at Mile Marker 50 on I-540 and six times the deformation required in the laboratory study. Interestingly the cable lead from the top of the bore hole to the location of the monitoring station at the Batesville site was about 6 times longer than at Mile Marker 50 and about 20 times longer than the leads in the laboratory study. A very simplistic observation would be that the required mass move movement along a shear plane required to produce a threshold cable "spike" doubles as the cable length is increased by a factor of 5. While there appears to be some relationship between cable length and the threshold displacement required to produce a "spike" in the cable, more study will be required to refine the this relationship. In addition to varying the cable length and observing changes in the required threshold movement other variables such as the number of connections and connections type, multiplexer levels, grout type, soil strength and concentration of the failure zone must be considered before a definitive relationship can be established to predict the magnitude of mass movements from TDR cable signatures.

Conclusions

This study has illustrated that monitoring slope movements remotely with TDR techniques is a feasible alternative to more labor intensive methods like using survey monuments or inclinometers. However some important findings were noted that can complicate installations for the monitoring of shallow failures:

- Care must be taken so that the installation of the TDR cables does not reinforce shallow failure areas the point where movement is prevented by the strong grout columns. This phenomenon was observed at mile marker 46 in this study. On the other hand the grout must be stiff enough to cause deformation in the cable (weak grout at mile-marker 50 did not cause deformation). A balance of grout strength and

borehole diameter must be achieved for satisfactory results. The issue of borehole reinforcement is not as important in deep seated failures where the mass of the material in the failure zone is large.

- Installations at two sites with widely varying cable lengths has verified that 14-30 mm of slope deformation along the shear surface is required before an anomaly in a TDR cable can be detected.
- Laboratory studies indicate that flexible RG8 and rigid aluminum clad foam dielectric cables produce the most useful cable signatures when deformed. However, the material cost of RG8 cable is about one third that of aluminum clad cable and RG8 performed just as well at the sites investigated in this study.
- A complete TDR system can be created and installed for less money than the purchase price of a probe type inclinometer and data logger. However, probe inclinometers can determine direction of all movements and can definitively measure the magnitude of small movements which are below the threshold of TDR systems.
- At two of the three sites described in this paper evidence of mass movement was evident at the ground surface in the form of tension cracks before either the TDR or inclinometers recorded any significant movement along a shear surface. This is contrary to experiences with deep seated failures where the inclinometer will reveal deep seated movement before it is evident at the surface. It is believed that this anomaly is the result of the combination of a shallow failure and the local reinforcement provided by the inclinometer casing and grout.
- While both laboratory and field studies indicate a strong correlation exists between deformation and reflected energy in TDR cables, the same correlations were not observed for each field site and the field correlations did not match those determined in the laboratory. More study is required to determine the variables affecting this correlation before TDR systems can be used to accurately determine movement magnitudes in field installations.

Acknowledgement

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Norman Dennis received his BS and MS degrees in civil engineering from the University of Missouri-Rolla and his Ph.D. degree from the University of Texas at Austin. He served as a Corps of Engineers officer in the US Army for 24 years. He served on the faculty of the United States Military Academy for 11 years before his retirement for the Army. He has been a member of the civil engineering faculty at the University of Arkansas since 1996.

Chongwei Ooi, a native of Malaysia, received his BS degree in civil engineering in 2002 from the University of Arkansas. He is currently employed by CEI Engineering Associates in Bentonville, AR as a geotechnical engineer and hopes to complete all requirements for his MS degree in the fall of 2006.

Voon Huei Wong, a native of Malaysia, received his BS and MS degrees in civil engineering from the University of Arkansas. He is currently employed by MACTEC Consulting Engineers in Birmingham, AL as a geotechnical engineer.