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Evaluation of Monitoring and Remediation Measures for Slope Failures

Norman D. Dennis, Jr., Chong Wei Ooi, Voon Huei Wong

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16. Abstract

Time Domain Reflectometry (TDR), was first developed during the 1950's by the power and telecommunication industries to locate and identify cable faults. TDR is now widely used in the geotechnical field to monitor deformities of soil/rock and other structures, determine the shear plane of failed slopes, monitor changes in fluid levels, and measure the water content of unsaturated soils. The goal of this study was to prove that the available TDR technology is a cost effective alternative to remotely monitor slope movements, and is a viable technology for use in monitoring the effectiveness of slope repairs.

In this study slope inclinometers were used as the control device to establish the baseline, or absolute values of movement in slopes that were in various stages of incipient failure. TDR equipment was installed adjacent to the inclinometers and used to determine slope movement in a qualitative sense. Signals from the TDR equipment were compared to the movements recoded by the inclinometers to establish a correlation between the TDR signal and the absolute movement of the slope. Field work couple with laboratory studies allowed the creation of a mathematical model to predict movement along a slip plane based on the amplitude of the reflected waveform. The results of this study provide a basis for selecting TDR cabling and installation techniques along with guidance on how to interpret the data from the TDR installation

The major benefits of using TDR to monitor slope movements include: most electrical components in the monitoring station can be reused or expanded when needed at new locations, the cable probes used for testing are inexpensive and can be up to several hundred meters in length; most of the cable types used as probes are readily available in local electronic stores. The TDR system can be used to monitor large deformations or movements; long after other devices become unusable. The TDR system can be monitored remotely, making it idea as an early warning system for potential slope failures or landslides.

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RESEARCH

Evaluation and Monitoring Measures for Slope Failures

PROJECT BACKGROUND AND OBJECTIVES

The initial area selected for this study was along Interstate 540. This highway, which connects Ft. Smith to Bella Vista, has become one of the busiest routes in Arkansas. During the construction of I-540, many slopes were created or modified. The geometry of these slopes was selected based on “rules of thumb” and local experience when selecting factors of safety. This segment of highway has suffered a number of slope failures both during its construction and since it has opened. Estimates are that $65,000 per km was expended on failure remediation during construction and over $32 million has been spent on post construction failure repairs. Commonly used remediation methods in Arkansas are to push the displaced material back into the original slope configuration or to remove the failed material and replace it with rock. The former method is clearly not a long term solution to the problem and the latter may not always be economical or effective. Clearly a cost effective strategy of evaluating the performance of slope remediation is required. The objective of this study was to evaluate the effectiveness of remote sensing technology in reporting the movements of slopes or embankments.

Time Domain Reflectometry (TDR) and Slope Inclinometer technology as applied to the monitoring of slope stability at five different installations around the State of Arkansas. The studies were aimed at discovering the relationship between TDR reflection coefficient and soil mass movement. The focus of the study was on the sensitivity of coaxial cables, used as TDR probes, to shearing distortion. An attempt was made to quantify the magnitude of displacement along a shearing plane based on the magnitude of the TDR reflection coefficient. Extensive descriptions of study locations, cables employed, grout placement, equipment used, as well as data analysis are included in this report. First, the installation locations were identified for suitability of study and potential slope movement. Second, instrumentation integration and methods to acquire data manually and remotely were described in detail to prove the effectiveness of the TDR system implementation for slope stability monitoring. Automated TDR systems were made possible by programmable data logging equipment and wireless communication instruments. The research results for both inclinometer and TDR systems concluded that both technologies are useful for detecting slope movements. Special attention was devoted to data analyses in an attempt to determine the TDR cable’s localized shear response. Most of the analysis effort was devoted to establishing the relationship between TDR reflection coefficients and the magnitude of shear displacement by correlating the results of inclinometer readings and TDR waveforms.

FINDINGS

The results of this study produced the following generalizations and conclusions:

- Slope inclinometers are much more sensitive to gradual or small slope movements when compared to TDR systems. While inclinometer equipment is capable of detecting very small movements, it is much more labor intensive than automated TDR systems. TDR equipment can continue to record large slope movements after inclinometers become ineffective or fail.
- TDR systems cannot report slope movement until a threshold displacement is achieved. This displacement varied from site to site but appears to be related to the length of the cable in the system and possibly to the number of connectors and multiplexers in the system.
- TDR systems responded better to localize shearing planes that are common with deep seated failures.
- TDR systems can successfully incorporate remote and autonomous data acquisition. With this feature, human intervention can be minimized allowing for the installation of TDR stations in locations that are far away from the polling station.
- The autonomy of data collection make TDR monitoring systems ideal for early warning of impending slope failure.
- Correlations between inclinometer displacement and TDR reflection coefficients indicate that they are directly proportional. However this relationship was not constant between sites and again appeared to be related to the length of the cable in the system.
- Based on laboratory and field studies RG-8 coaxial cable appeared to be the most cost effective and efficient cable for use in TDR studies.
- The magnitude of displacement along a shearing surface can be estimated with the prediction equation developed in this study.

EVALUATION OF MONITORING AND REMEDIATION MEASURES FOR SLOPE FAILURES

TRC-0107

By

Norman D. Dennis, Jr., Chong Wei Ooi and Voon Huei Wong

June 2013

ABSTRACT

Time Domain Reflectometry (TDR), was first developed during the 1950's by the power and telecommunication industries to locate and identify cable faults. TDR is now widely used in the geotechnical field to monitor deformities of soil/rock and other structures, determine the shear plane of failed slopes, monitor changes in fluid levels, and measure the water content of unsaturated soils. The goal of this study was to prove that the available TDR technology is a cost effective alternative to remotely monitor slope movements, and is a viable technology for the AHTD to use in monitoring the effectiveness of slope repairs.

In this study slope inclinometers were used as the control device to establish the baseline, or absolute values of movement in slopes that were in various stages of incipient failure. TDR equipment was installed adjacent to the inclinometers and used to determine slope movement in a qualitative sense. Signals from the TDR equipment were compared to the movements recoded by the inclinometers to establish a correlation between the TDR signal and the absolute movement of the slope. Field work couple with laboratory studies allowed the creation of a mathematical model to predict movement along a slip plane based on the amplitude of the reflected waveform. The results of this study provide a basis for selecting TDR cabling and installation techniques along with guidance on how to interpret the data from the TDR installation

The major benefits of using TDR to monitor slope movements include: most electrical components in the monitoring station can be reused or expanded when needed at new locations, the cable probes used for testing are inexpensive and can be up to several hundred meters in length; most of the cable types used as probes are readily

available in local electronic stores. The TDR system can be used to monitor large deformations or movements; long after other devices become unusable. The TDR system can be monitored remotely, making it idea as an early warning system for potential slope failures or landslides.

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Chapter 1

Introduction

1.1 Purpose and Scope of Research

A slope is defined as a terrain feature which has some degree of inclination. These terrain features can occur either naturally or they can be engineered by humans. Engineered slopes are considered alternative structures for retaining walls when a grade separation is necessary because they are relatively inexpensive and easy to construct. However, stability problems have been encountered in both natural and manmade slopes throughout history when the delicate balance between soil strength and internal stresses has been disrupted by human activities or nature. The increasing demand for engineered cut or fill slopes on construction projects, especially highway construction projects, has also increased the need to understand the potential for slope failures and the mechanisms which cause them. This understanding is necessary not only to prevent their occurrence but also to apply proper remedial measures as well. Any remedial action requires some form of short and long term monitoring program to insure its effectiveness. It is the purpose of this study to apply some of the more recent advances in slope monitoring techniques to engineered slopes in Northwest Arkansas to assess their effectiveness.

Although this approach simplified the design process and was inexpensive, the practice of using a universal "rules of thumb" has flaws. In general, "rules-of-thumb" will either lead to an over-designed slope or an under-designed slope if the actual soil properties and environmental conditions are unknown. As a consequence of this practice, It is clear that cost effective remediation strategies and monitoring programs to assess the effectiveness of remediation are of extreme interest to the Arkansas State Highway and Transportation Department (AHTD).

Figure 1.1 portrays a failure at mile marker 46 on I-540 that has been repaired three times using the rock replacement strategy while the failure depicted in Figure 1.2 was clearly related to water issues and until those issues are corrected the replacement strategy will not be effective. Alternative repair strategies are available, but their effectiveness must be monitored. The AHTD needs cost effective and reliable methods of slope remediation, but they also need an economical mechanism to monitor the effectiveness of any slope repair.

The purpose of this study is The study of monitoring equipment was conducted on slopes along Interstate-540 (I-540) between Alma and Fayetteville, on Interstate-40 east of the Highway 23 exit and on Highway 167, near Batesville, AR.

Figure 1.1: Failed slope was replaced by rock at MM46 on I-540

Figure 1.2: Surface cracks on Highway 167, Batesville.

The evolution of the slope stability monitoring in geotechnical engineering has followed closely with the advancement of technology in general. For example, slope monitoring techniques have evolved from labor intensive surveying or grid monitoring methods to remotely accessed electronic sensors. Historically a number of commercially available slope monitoring apparatus have been used to monitor slope movements including; extensometers, traversing and static inclinometers, tilt meters and time domain reflectometry (TDR) devices. The equipment selected for use in this study to monitor slope movements were TDR cables and a traversing inclinometer.

Inclinometers represent the classical approach to slope monitoring. They are labor intensive and require frequent visits to the site to acquire data. However inclinometers offer the highest accuracy in determining absolute slope movement. In this study the inclinometer was used as the control device to establish the baseline, or absolute values of movement, while the TDR equipment was used to determined movements in a qualitative sense. Data from the TDR equipment was compared to the movements recoded by the inclinometer for reference. Several monitoring installations were made for this study in hopes of correlating data from the two measuring devices in an effort to calibrate the TDR technique so that absolute values of movement could be determined with the TDR devices.

While inclinometers are tried and true they are expensive and labor intensive. Time domain reflectometry, on the other hand, is a relatively new technology which may offer the ability to accurately determine slope movement using a remotely controlled autonomous system. Without the need for operator intervention and the relatively low cost of the equipment, TDR may prove to be a superior alternative to inclinometers for monitoring slope movements over a broad aerial extent. If TDR proves to be a reliable and accurate method for detecting slope movement and pinpointing the location of that movement, it may be used by the AHTD as a cost effective monitoring technique to assess the effectiveness of slope repairs or even as a technique to detect impending failures.

The goal of this study is to prove that the available TDR technology is a cost effective alternative to remotely monitor slope movements, and is a viable technology for the AHTD to use in monitoring the effectiveness of slope repairs.

Chapter 2

Literature Review

2.1 Slope Failure Mechanisms and Monitoring

Slope failures are always associated with the process of increases in shear stresses or decreases in shear strength of the soil mass. In the case of residual soils and weathered bedrock, such as those found in Northwest Arkansas, the geomaterial structure can be weakened by preexisting discontinuities such as faulting, bedding surfaces, foliations, cleavages, sheared zones, relic joints, and soil dikes. Relict joints and other open structures in residual soils often lose strength when saturated. Slickensides, seams of weak material or weak dikes may also preexist in residual soils or in transition zones between soil and rock. Slope instability, in many cases, is a slow progressive process. Normally, before a catastrophic slope failure, the soil mass will creep in a slow manner. During this time, some precursor signs of a slope failure can be observed, and a monitoring process should be taken before the catastrophe occurs (Abramson 1996).

At the very beginning of a slope failure, tension cracks observed at the crest of the slope can often be the first sign of instability. All visible cracks should be monitored for changes in width and vertical offsets. Crack measurement will allow the behavior of the slope to be predicted, and often the direction of movements may be inferred from the pattern of cracking. After visual signs are noticed, it is important to determine the location of shear surface, the direction of movement, the magnitude and the rate of displacement. All this information has to be collected with the aid of suitable instruments.

When performing a detailed examination of a slope's performance, the selection of equipment for monitoring has to be carefully examined, and its operation must be fully understood. Effective application of the right equipment in the right place will reduce the monitoring time and increase the cost effectiveness of the monitoring program.

2.2 Monitoring Instrumentation

Slope monitoring methods can be divided into two major categories: surface monitoring or underground monitoring. Geotechnical instruments for both types of monitoring have evolved tremendously during the past quarter-century. Many of the instruments in use today were developed during the early 1950's. Modification and improvement of these instruments in the ensuing decades have increased the effectiveness and accuracy of testing. In addition, developments in the communication industry allow increases in the automation of data collection from these instruments and reduce human intervention. For example, computer automated data collection and data reduction have become a new trend for slope stability monitoring.

2.2.1 Surface Monitoring

2.2.1.1 Differential Global Positioning System (DGPS)

The DGPS is particularly useful for monitoring large area slope movements. The Global Positioning System consists of a constellation of satellites that produce a timing signal, a control station that monitors and reports the positions of the satellites in the constellation and a set of receivers on the ground that use the information transmitted from four or more satellites to determine a precise location on the ground. The accuracy of the ground location produced from a GPS can be degraded for a number of reasons, to include: atmospheric disturbances, poor geometric positioning of satellites and ground level obstructions. The technique of differential GPS improves position accuracy and is based on correcting a roving receiver's reported position measurements of by applying corrections to the timing signals sent from the satellite constellation. Basically, DGPS compares the known location of a stationary base station receiver to the location reported by interpreting the timing signals sent from the satellite constellation. The difference in the location is used to establish the corrections to be applied to the position of a roving receiver. The position of the base receiver is accurately determined through the use of surveying techniques (Gilbert 1995). A base station at a known location is then used to provide correction and refinement to the computed locations of one or several roving stations that are installed in unstable slope.

This technology has been widely implemented on open-pit mine deformation monitoring. A study was conducted by an Australian university, Curtin University of Technology, in which the integrated positioning technologies of NAVSTAR and GLONASS (Global Navigation Satellite System) GPS systems were utilized for open-pit mine monitoring. The satellites provided continuous real time monitoring on the areas where accessibility was dangerous or impossible. In general, this system is capable of detecting geometrical deformations of points having a motion greater than one millimeter per week with the aid of a base station and remote receivers. The system will also alert users to potential ground movements to increase the safety of those in and around the survey zone from slide hazards. (Troy Forward, 1999)

One of the main factors in limiting the performance of GPS in this application is the number and geometry of the satellites in view at any particular point in space and time. Therefore, to improve the level of positioning reliability, the number of satellites from which a rover can receive signals at any particular point has to be increased. The GLONASS network was introduced into the monitoring to increase the number of satellites. To obtain high precision results that are required for open-pit mine deformation monitoring, a mathematical model and software that allow integration between NAVSTAR and GLONASS GPS were developed. This implementation increases the complexity of the software and hardware needed for monitoring and thereby adding to the cost, but the positioning accuracy is improved tremendously.

Unfortunately, in some cases, surveying within an open-pit mine using satellite-based positioning techniques is still severely restricted by reduced satellite visibility which can be masked by the surrounding walls even with the inclusion of the GLONASS network. This is one of the major drawbacks to this technique that still needs to be resolved.

2.2.1.2 Surface Extensometers

Since crack formation is one of the first signs of slope instability, measuring and monitoring the changes in crack width allows the slope movements to be tracked. There are numerous types of surface extensometers, such as metal strips, grid crack gages, deformation gages, and electrical crack gages. Some of these instruments are illustrated in Figure 2.1. All of these instruments operate with a similar concept, which is the detection of increasing movement between two fixed points spanning the crack. As shown in Figure 2.1, those devices are installed so that the two end points of the device are fixed on both sides of the crack(s) with the device spanning the crack. As the crack enlarges, the distance between the end points of the device increases and can be recorded, either visually or through electrical means. By comparing the pre and post movement data, these devices are capable of showing the magnitude and the direction of the slope movement. (From Abramson Lee W. after Dunnicliff, 1988)

One of the major concerns when using surface extensometers is to determine the best location for the device installation. If the end point supports for the gage are installed in a weak area the stakes driven as the anchor points may become loose, resulting in inaccurate measurements. Other concerns are operator safety during system installation and subsequent return visits to take readings along with protection of the monitoring system from adverse weather conditions and animals.

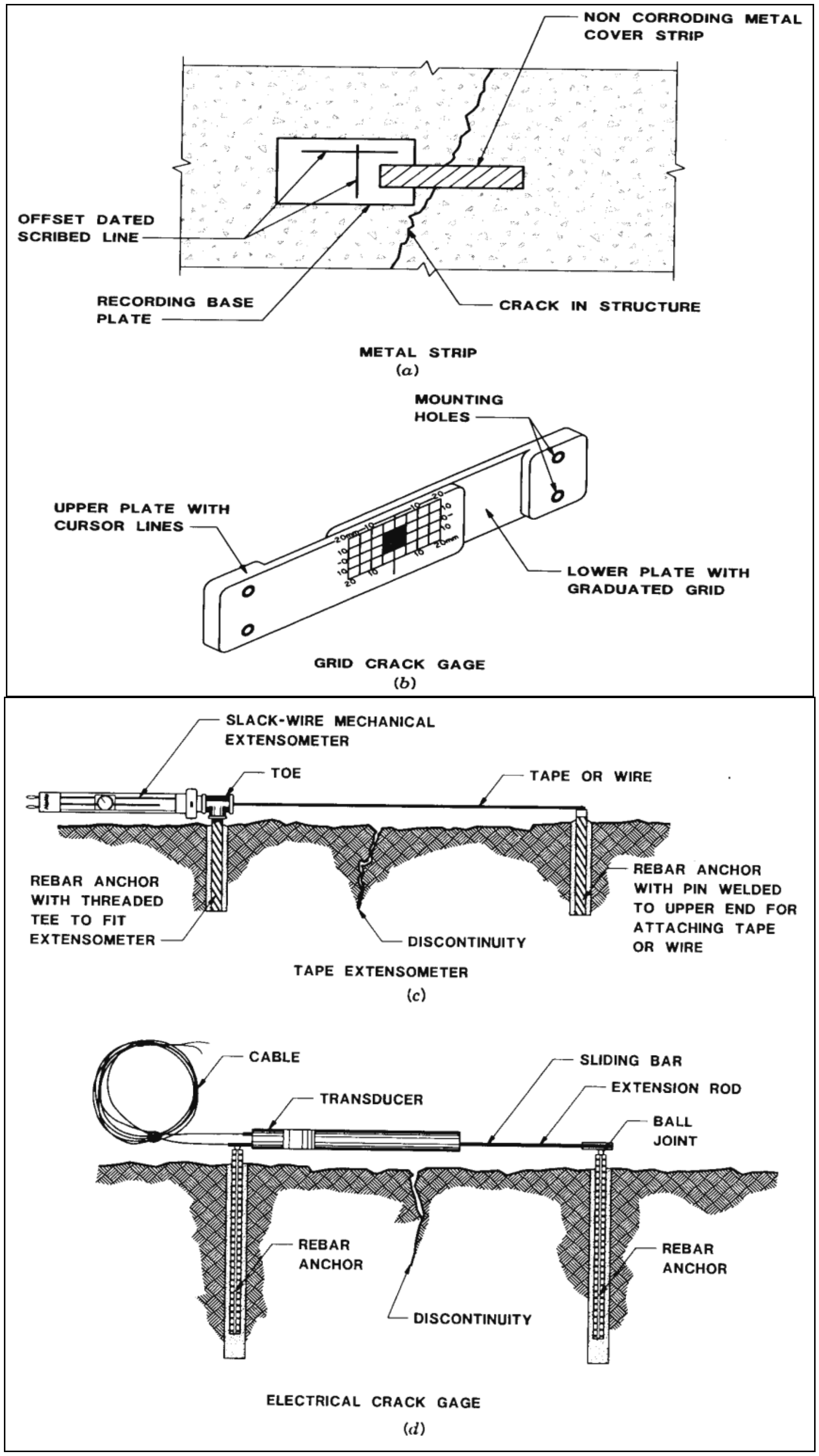


Figure 2.1: Surface extensometers types. (a) Metal strips. (b) Grid crack gage.
(c) Tape extensometer. (d) Electrical crack gage. (From Abramson Lee W. after Dunnicliff, 1988)

2.2.1.3 Radar Interferometry

2.2.1.3.1 Introduction

The advancement of modern wireless communications devices has resulted in the practical use of radar for specific applications in the movement monitoring. In general, there are two types of radar interferometry applications, either by airborne or satellite synthetic aperture systems or ground-based differential radar.

One of the successful applications of radar interferometry for change detection was accomplished at the site of the Landers earthquake of 1992 in the Mojave Desert in California (Edward L McHugh, 2004) by using satellite systems. A series of radar satellite images were taken at the study area from before and after the earthquake. Those images revealed interference fringes when topographic effects were removed by means of a digital elevation model, each cycle of interference fringe correspondence to 28mm of seismic movement. Similar applications of radar satellite data also have been used to map and monitor landslides, ice movement, and, volcano deformation (Edward L McHugh, 2004).

Ground-based interferometric radar systems with a much shorter repeat time and greater spatial resolution than airborne and satellite systems are much more suitable for unstable slope monitoring. This type of system has been successfully tested in landslide-prone natural setting and mine sites (Edward L McHugh, 2004). There are a few types of interferometry radar systems, for example the Linear Synthetic Aperture Radar (LISA), X-band interferometric SAR system (YINSAR), Slope Stability Radar (SSR) and so on.

2.2.1.3.2 Theory and Methods

Interferometry is based on the difference in signal phase between two observations and thus requires a coherent (phase-preserving) measurement system. For example, YINSAR uses two receiver antennas separated by a baseline to receive the radar echo from the target surface. The antennas are offset in the cross-track (range) direction. The phase difference in the echo from each distance (range) measured at each antenna can be related via the geometry of the measurement to the height of the surface (Edward L McHugh, 2004).

There are two approaches to the application of radar interferometry for highwall (steep slope) monitoring. They can be distinguished based on the number, characteristic, and movement of the radar antennas. One approach uses a single, two-dimensional (2D) scanning antenna: the second uses dual receiver antennas and one-dimensional (1D) scanning.

In the first approach, a single pencil beam antenna is scanned in two dimensions over the target surface (Figure 2.2). A radar signal is transmitted at each scan location and the radar echo is received and processed. The target surface is repeatedly scanned in time and the signal phase is recorded. Each time the measured signal phase will be compared to the previously scanned signal phase. Any difference in the phase between the scans is related to face movement with an estimated correction based on weather conditions. This approach requires a high precision 2D scanning system and exceptionally phase-stable radar. This approach forms the basis of a monitoring system developed in Australia (Edward L McHugh, 2004).

A fan-beam transmit antenna is used to scan the entire vertical face over a narrow horizontal distance in the second approach. The target surface is scanned repeatedly in a horizontal (1D) sweep (Figure 2.2). This approach required two receive antennas that are separated by a short base distance. The interferometeric phase difference between the receiver antennas is recorded for each scan position. Since the radar is stationary, the differential interferometric phase between scans can be easily computed. The advantage of this approach is the interferometric path length for a given scan is nearly the same, the atmospheric effects are similar for both channels and interference is minimized. Furthermore, the 1D approach does not have the stringent long-term phase stability requirements of a pencil-beam as in the first approach.

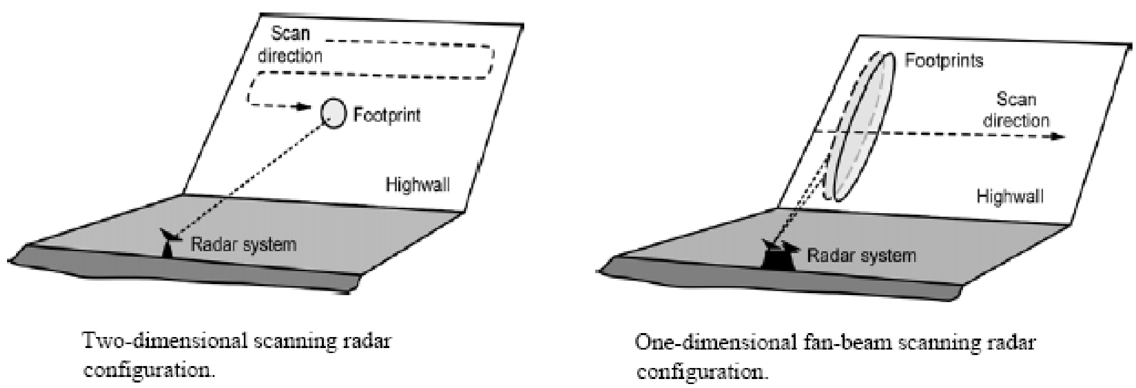


Figure 2.2: Two approaches to the application of radar interferometry (Edward L McHugh, 2004)

An advantage of ground-based interferometric radar is that it has the potential of measuring displacements over large areas of mine high walls at unprecedented resolution. According to Edward, interferometry clearly has the desired sensitivity and thus is viable approach for low-cost slope monitoring. However, there are a few issues relating to this technology; such as scanning rates, alarm detection thresholds, the effects of weather, and methods to prevent interference from ordinary mining operations that must be addressed in order to support a longer-term monitoring.

2.2.1.4 Conventional Survey

The survey method has been used in structural deformation monitoring for a long period of time and is widely accepted. The standard method for this type of monitoring is referred as "Periodic Inspection and Continuing Evaluation of Completed Civil Work Structures (PICES) Surveys". The general procedures to monitor the deformation of a structure involve measuring the spatial displacement of selected object points from reference points, where the reference points are controlled in position. Assessment of permanent deformations requires absolute data. Absolute deformation or displacement can be determined if the reference points are located outside the monitored structure. Stability of the reference point is crucial for deformation monitoring especially when long-term monitoring is required. Accuracy of the monitoring will be greatly affected if the reference point is displaced or disturbed. Vectors of surface movement can be determined by comparing the current and previous coordinates.

Many modern survey systems such as electronic total station, theodolite, bar-code levels, DGPS, and so on could provide an accurate and convenient survey, for example an electronic total station allows for a simultaneous measurement of the three basic positioning parameters: distance, horizontal direction, and vertical angle, from which relative horizontal and vertical positions of the observed points can be determined directly in the field. A good survey system can measure movement in an embankment to the 0.005-foot level (US Army Corps of Engineer, 1994). However, the conventional terrestrial surveys are labor intensive and required skilled observers.

2.2.2 Underground Monitoring

2.2.2.1 Inclinometer

2.2.2.1.1 Introduction

The inclinometer has been the one of the most common type of equipment used for landslide detection and analysis over past two decades. The inclinometer is not just widely used in landslide monitoring; it has also been applied for the monitoring of dams, bulkheads, levees, and other earth-retaining structures.

An inclinometer is an instrument used to measure the changes in position and inclination of specific points along a grouted casing from their initial position when the casing was installed. Normally, inclinometer casings are installed in a vertical, or as near vertical orientation, as possible. The first measurement of verticality is made immediately after the casing's installation and is used as the baseline, or reference reading. Subsequent readings are compared to the baseline in order to detect changes in inclination. A probe type portable inclinometer is one of the most widely used forms of inclinometer systems available. As illustrated in Figure 2.3, the portable inclinometer system consists of four elements: the casing, inclinometer probe, control cable, and a readout unit.

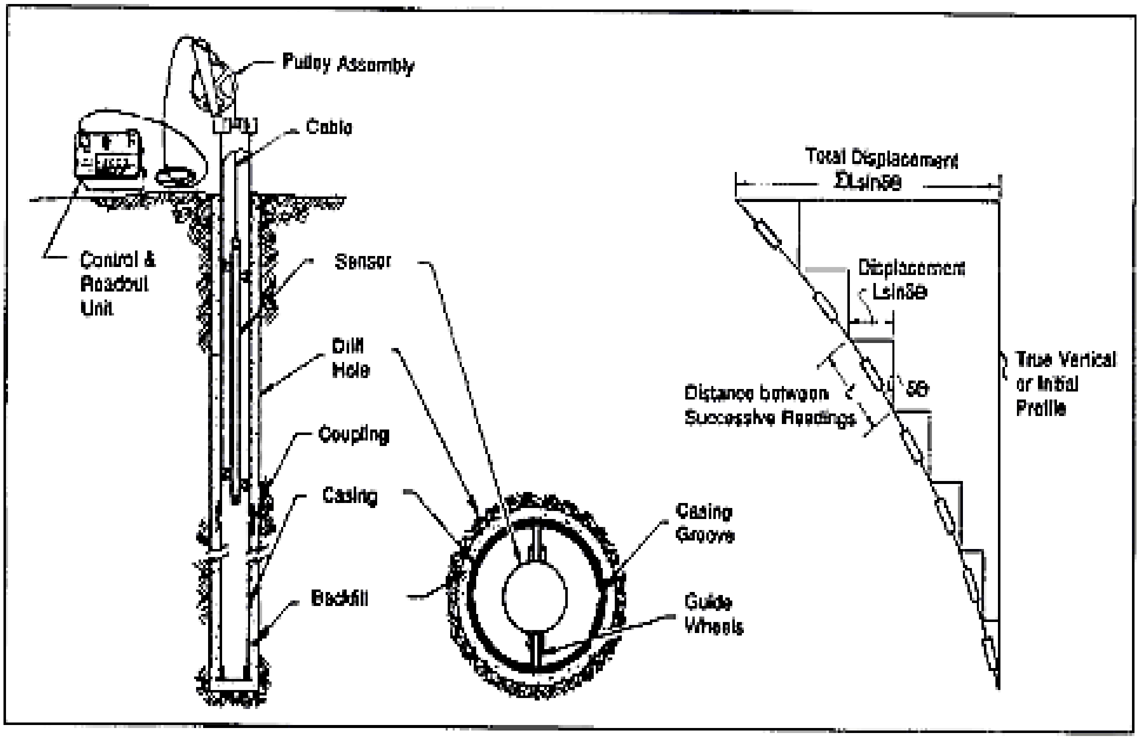


Figure 2.3: Principle of Inclinometer Operation (Green and Mikkelsen 1988)

A probe inclinometer was used in this research for slope monitoring and served as reference for the TDR system. This type of device was first built in 1952 by S.D. Wilson at Harvard University (Green and Mikkelson, 1998). The same basic concepts developed by Wilson have been incorporated into inclinometers in use today. A typical probe inclinometer consists of two servo-accelerometers at each wheel location (Figure 2.4). One accelerometer measures tilt in the plane parallel to the direction of the inclinometer wheels, which track the longitudinal grooves of the casing. The other accelerometer measures tilt in the plane that is perpendicular to the wheels. Relative inclination measurements are converted to lateral deviations over the gauge length of the probe.

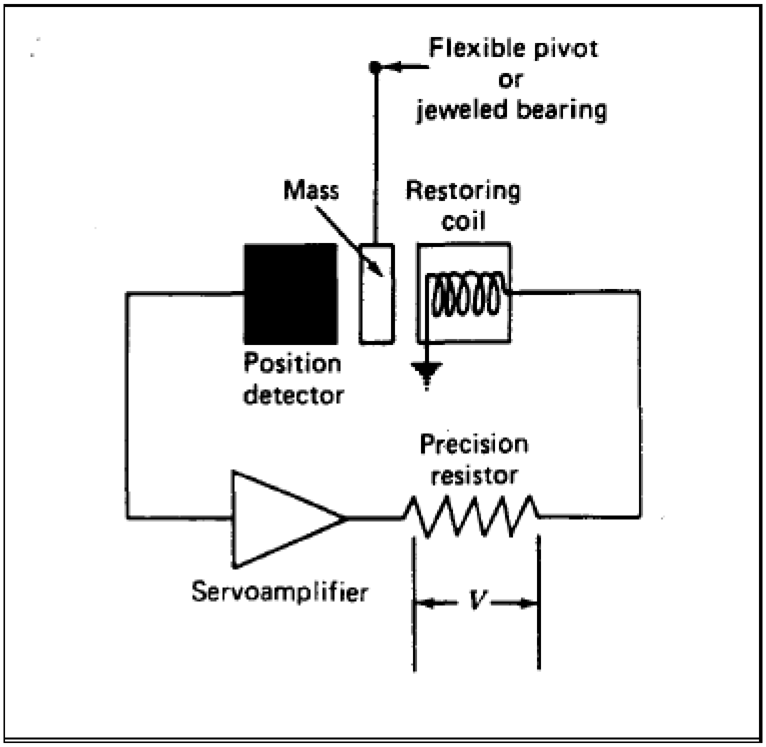


Figure 2.4: Layout of the accelerometer (Dunnicliff, 1988)

A probe inclinometer system has four main parts:

1) *A guide casing* containing four grooves that are 90° apart (refer to Figure 2.3). The grooves form two perpendicular planes. During the installation of casings, one plane is adjusted parallel to the direction of the slope movement (A-axis), and the other is perpendicular to the movement direction (B-axis).

2) *A probe sensor unit* is used to survey the guide casing; the probe is made out of stainless steel. On each side of the top and bottom of the probe has a wheel arm with two wheels. The wheel systems are separated 2ft apart measuring from center to center of the wheel arm for inclination measurement.

3) *A portable readout unit (Datalogger)* provides power and sends electric signals to the probe while subsequently recording results.

4) *A control cable* is connected between the readout unit and the inclinometer probe. It is also used as the guiding wire to raise or lower the inclinometer probe in the casing in addition to transmitting electric signals. For accurate depth control of the inclinometer probe, usually measurements are taken by lowering the cable into casing on a constant interval. A cable come with constant knobby interval provides guidance when measurement was taken. Figure 2.5 illustrated a control cable which is typically used for probe inclinometers.

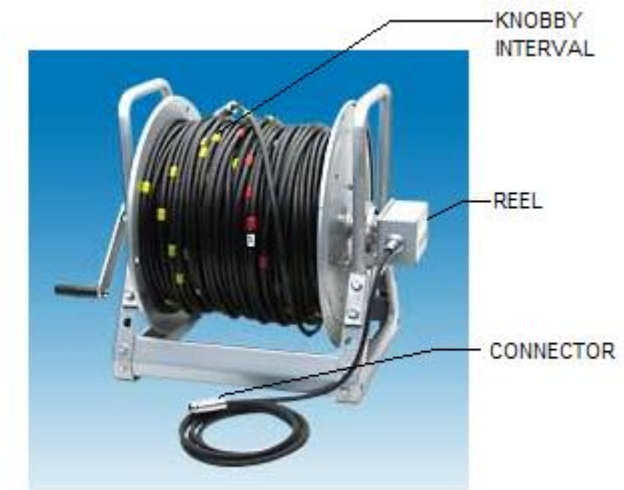


Figure 2.5: Slope Inclinometer control cable (Durham Geo Slope Indicator, 2007)

2.2.2.1.2 Operation of the Inclinometer

As mentioned earlier, the operating principle of the inclinometer is to detect any change in the casing's inclination from its original near vertical position. Therefore, consistency in the data logging process is critical. During the data logging process, the inclinometer probe is raised from the bottom of the casing to the surface and measurements are made at a preset interval as shown in Figure 2.3. This process is repeated by turning the probe 180^{o} to gain another set of readings on the same plane. The readout unit is programmed to compare the readings for these two sets of data and the average of the absolute value of these two readings is taken to improve the accuracy.

By repeating such measurements periodically, a distribution of the lateral movement as a function of time is recorded. By comparing the pattern of the movements, the magnitude and the direction of the movement can be predicted. With the aid of computer applications such as “DigiPro for Window” (Slope Indicator, 2003), visualization of the movements can be accomplished by simply plotting graphs of depth versus displacement over a period of time as shown on Figure 2.6.

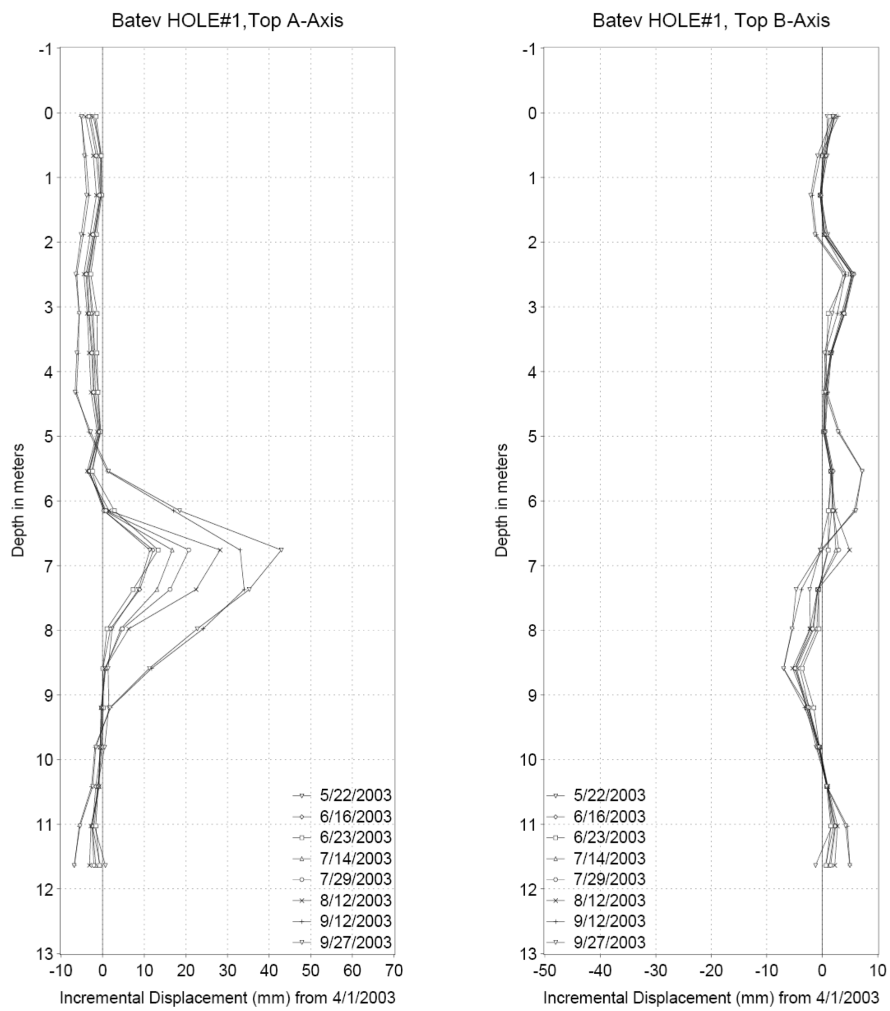


Figure 2.6: Inclinometer graphs for TDR monitoring station in Batesville, Arkansas.

The probe inclinometer is widely accepted because it is easy to use and the data reduction procedures are relatively simple. However, the major disadvantage of this method is that it is labor intensive. Therefore, for areas that require more frequent readings and larger scale monitoring, in-place inclinometers are used to reduce labor costs in monitoring.

The Little Dipper® (Applied Geomechanics, Inc., 2002) as shown in Figure 2.7 is an inclinometer which can be fixed in-place and remotely monitored. The Little Dipper® is suitable for installation into standard inclinometer casing with a diameter of 70mm (2.75”) or greater., Multiple units of the Little Dipper® are required for ground monitoring where each unit is attached to each other using flexible fiberglass rods to form a long probe chain. During installation, the fiberglass rods with Little Dippers® are lowered into the inclinometer casing to the approximate location of the sliding surface and the end of the rod is hung on the open end of the inclinometer casing. Each Little Dipper monitors a certain section of the casing’s inclination. For higher monitoring resolution, more Little Dippers can be used with smaller intervals (Rocktest 1998). The in-place inclinometer operates in a manner similar to the probe inclinometer except the in-place inclinometer stays inside the underground casing throughout the monitoring period. A datalogger can be stationed close to the monitoring site to acquire data according to a preset schedule. After a period of time, the newest data are compared to the initial data. The movement of slope can be determined by comparing change in inclination of each sensor to their original orientation.

In-place inclinometers are simple and convenient, but the resolution of the data is dependent on the number of probes being used in the monitoring system. Therefore, the cost of monitoring increases proportion to the number of probes being used. The probe inclinometer and the in-place inclinometer are two major types of inclinometers in use today.

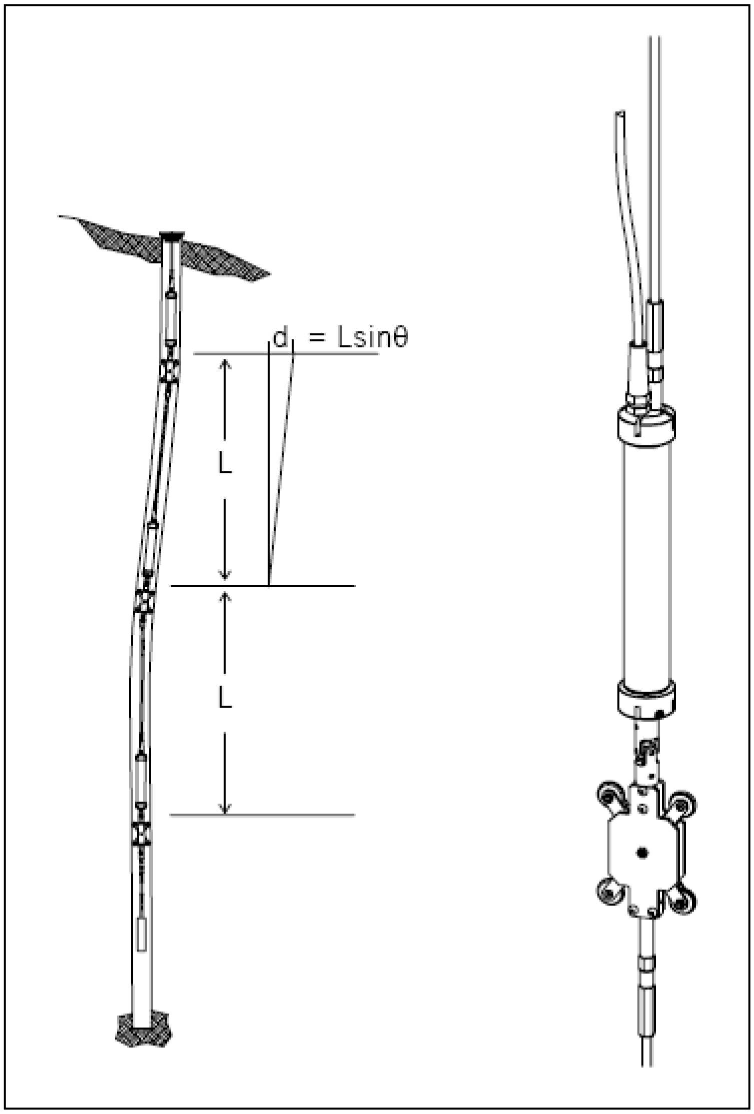


Figure 2.7: Little Dipper for In-place Installation
(From Applied Geomechanics, Inc., 2002)

2.2.2.2 Time Domain Reflectometry (TDR)

2.2.2.2.1 Introduction

Time Domain Reflectometry (TDR), was first developed during the 1950's to locate and identify cable faults in the power and telecommunication industries, and is still widely used for that purpose today (O'Connor and Dowding, 1999). The development of cable TV and computer network industries provide an even larger market for the development of TDR technology. The a schematic of the equipment necessary to monitor slope instabilities using TDR technology is illustrated in Fig. 2.8

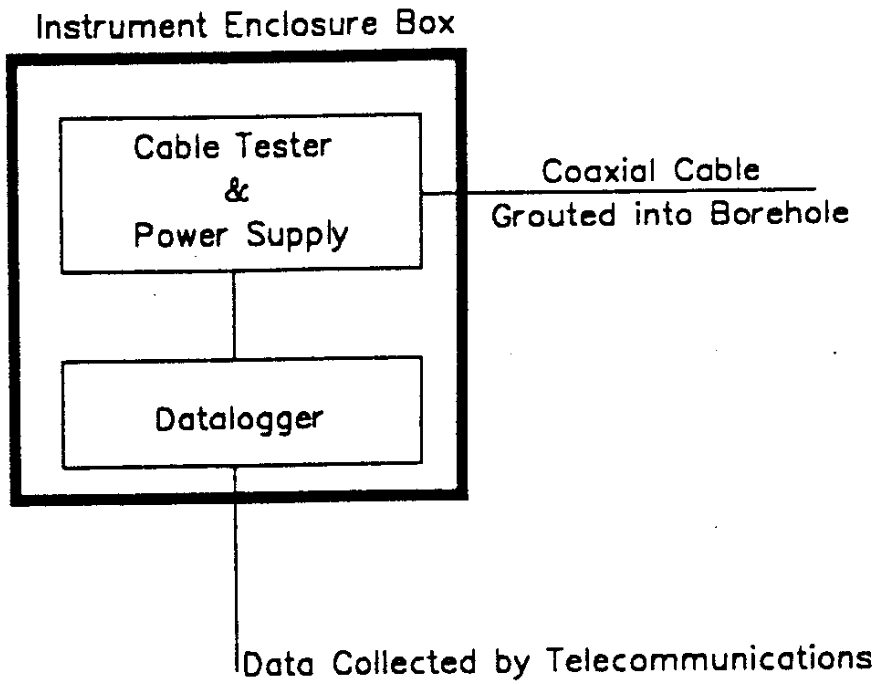


Figure 2.8: Schematic of a TDR installation (William F. Kane, 1994)

The use of TDR technology in geotechnical engineering started in the 1970's. In the late 1970's and during 1980's, the U.S. Bureau of Mines used TDR extensively to locate coal mine roof collapse zones above long wall coal mines (Dowding and Huang, 1985). Its growing popularity in the geotechnical arena and technology transfer to other fields expanded the use of TDR to soil science, agriculture, and environmental science and engineering. According to Dowding and Huang, TDR technology is utilized primarily in geotechnical field today to monitor deformities of soil/rock and other structures, determine the shear plane of failed slopes, monitor changes in fluid levels, and measure the water content of unsaturated. Figure 2.9 shows a schematic of how slope monitoring is accomplished using TDR technology.

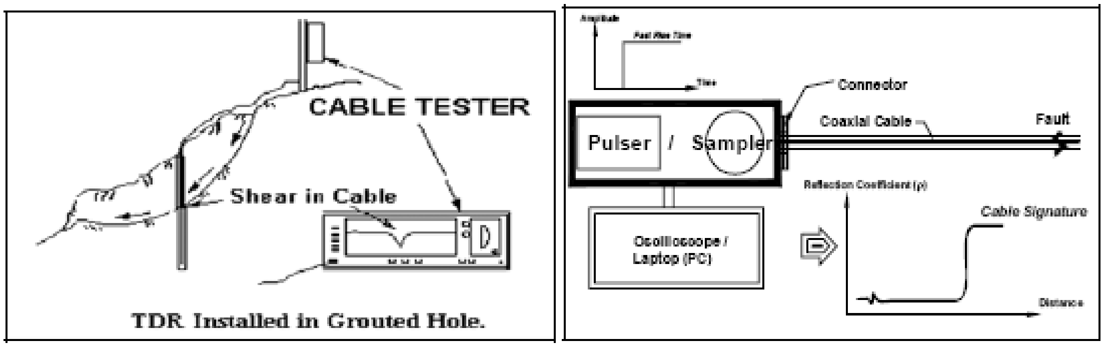


Figure 2.9: a) Schematic of the monitoring of the energy pulse generated by the cable tester. (after Kane. et al. 1996) (b) Schematic diagram of TDR installation in an actively moving slope (after Anderson, et. al., 1996)

2.2.2.2.2 Operation of TDR

Time Domain Reflectometry (TDR) is a remote sensing electrical measurement technique that is used to determine the location of a shear surface through the use of cable probes. TDR consists mainly of three important parts: a datalogger, coaxial cable probes, and a pulse generator/receiver. In some cases multiplexers are used to expand the capacity of the pulse generator/receiver to monitor multiple cable probes, s shown in Figure 2.10.

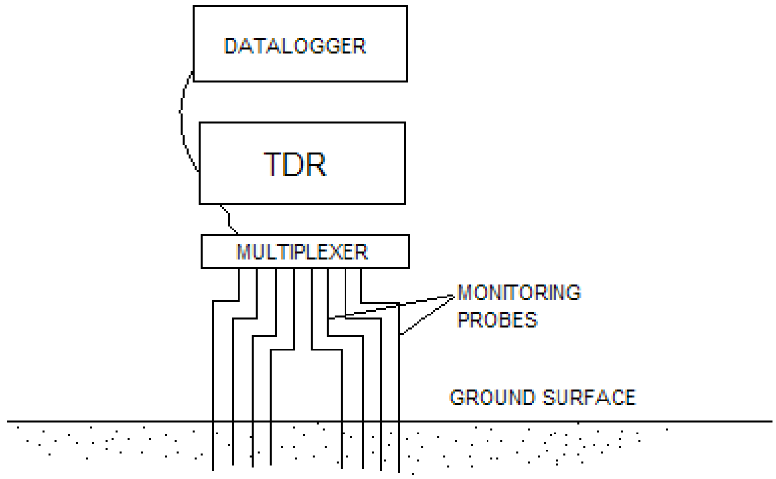


Figure 2.10: TDR with multiplexer for monitoring expansion.

In general, TDR works in the same manner as radar. A pulse generator/receiver sends out stepped energy pulse to the cable probe (waveguide). The cable probes used for slope monitoring applications are mainly coaxial cables made from different types of conducting materials. Normally, the electromagnetic pulse travels along an undisturbed cable and is reflected back to the receiver when it reaches the end of the cable. However, if any geometric deformities exist in the cable, some of the electrical energy will be reflected back to the receiver from the location of the deformity. The time delay between the transmitted pulse and the reflected pulse distinguishes the locations where cable deformations are occurring. By knowing the propagation velocity of the pulse in the cable, the distance to the reflecting location can be easily calculated. There are many software and graphing tools on the market that can be used to plot the reflected waveform. By observing the difference in shape, length, and amplitude of the reflected signal, the type of deformity in the cable can be identified as shown on Figure 2.11.

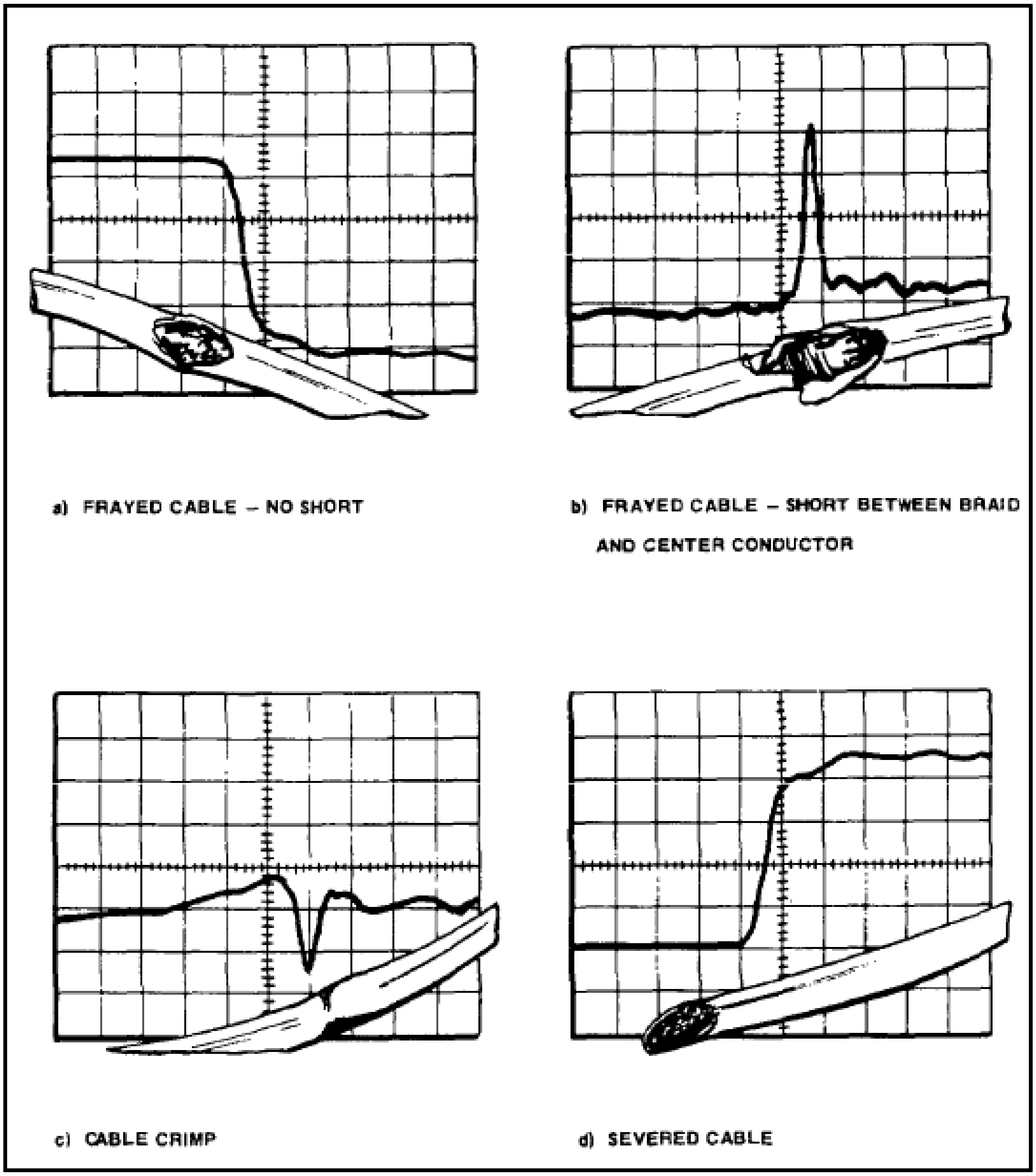


Figure 2.11: TDR Reflections Generated with Different Coaxial Cable Faults (After Tektronix, 1979)

In slope monitoring, a coaxial cable is grouted into a borehole which passes through the suspected shear surface of the failed slope. As the failed soil mass moves, a horizontal force is applied to the grout column and crack the grout column at the shear plane. Gradually, the grout column surrounding the cable will shear the cable at the shear plane and cause a deformity in the coaxial cable. The deformed cable causes the waveform to reflect which allows the determination of the exact depth of the shear plane as shown in Figure 2.12.

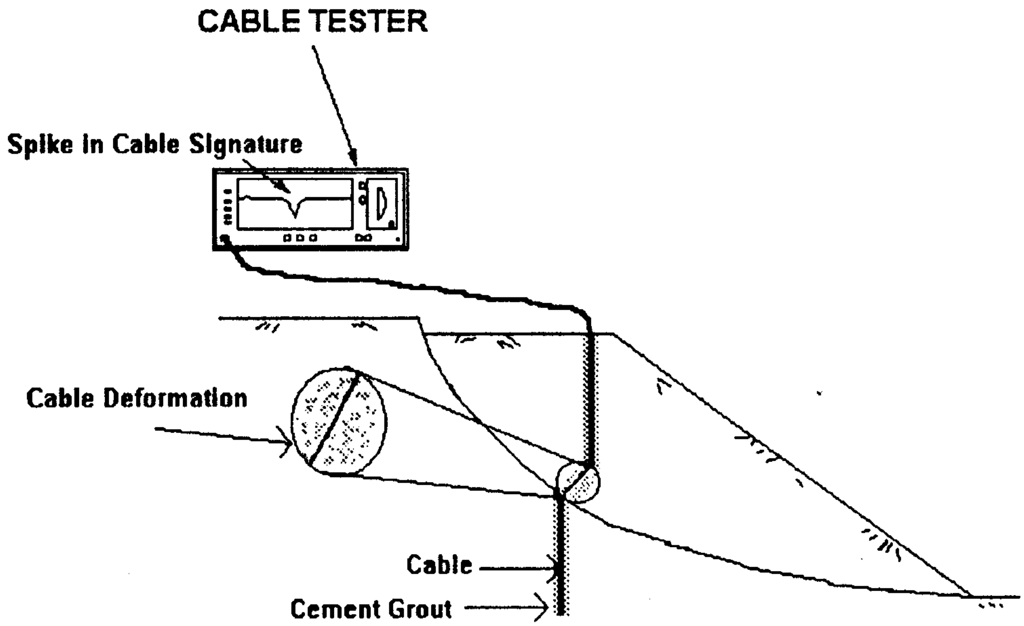


Figure 2.12: Cable Tester and Coaxial Cable for TDR Monitoring of Landslide Movement (Anderson et al. 1996)

The use of TDR techniques is relatively simple and convenient for underground stability monitoring once the station is set up. TDR requires the least operator intervention and can be operated autonomously. A fully automated remote TDR system requires supplemental equipment including a modem, cell phone, antenna, solar panel and battery. With the integrated functioning of all the equipment listed above, the TDR station will be able to monitor the suspected site accordance with operation instructions that can be programmed into a datalogger without much human intervention. The benefits of TDR include: most electrical components in the monitoring station can be reused or expanded when needed at new locations, the cable probes used for testing are inexpensive and can be extended up to several hundred meters in length; most of the cable types used as probes are readily available in local electronic stores.

2.2.2.3 Tiltmeter

A tiltmeter is an instrument that measures its own rotation and, therefore, the rotation of the structural element or portion of the ground to which it is connected. The tiltmeter, illustrated in Figure 2.13, is used to detect tilt (rotation) of a specific point of interest having a fixed depth under the ground surface. The most common geotechnical application of tilt meters is to monitor slope movements in open-pit mines and highway and railway cuts, or in any area where the failure mode of a mass of soil or rock involves a rotational component, (P. Erik Mikkelsen, 1996).

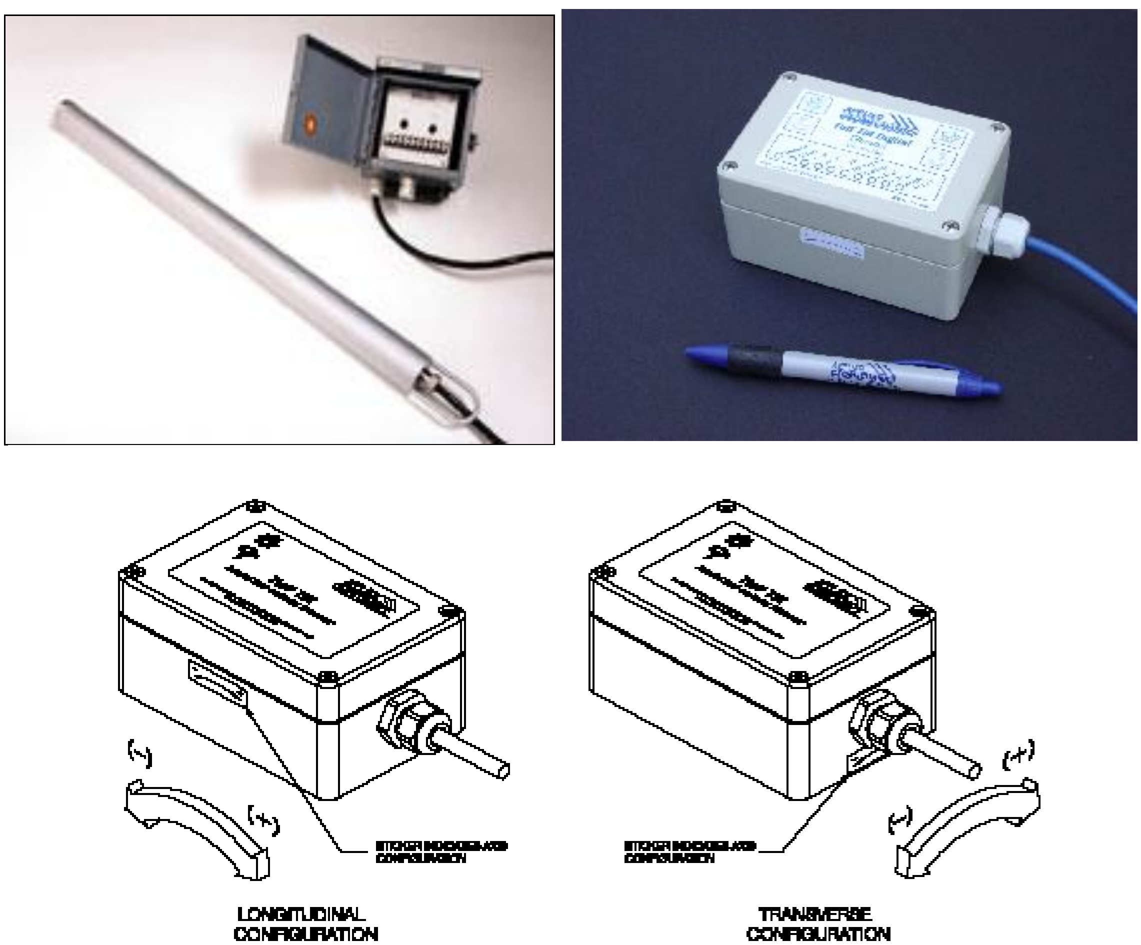


Figure 2.13: Different Types of Tiltmeters (Applied Geomechanics Inc., 2006)

Typically, tiltmeters are based on electrolytic level sensors or in some cases accelerometers and have several important practical advantages. First, all sensors and components are encased and there are no mechanical or moving parts to drift or wear out. Second, tiltmeter sensitivity and repeatability are excellent, typically they can measure to one part in a million, for example 1 micro inch per inch, which exceeds the accuracy of other similar types of instruments commonly used for geotechnical measurement (Applied Geomechanics Inc., 2006). Mechanical repositioning errors for this instrument are not a problem because tiltmeters are left in place and continuously recorded.

When an unstable slope is moving, tiltmeter surveys can determine the direction of movement. When used for slope monitoring, several tiltmeters are placed within the area of interest. In many cases, by recognizing the pattern of tilt behavior, the mechanism of movement can be determined, for example slumping, slope creep or settlement as shown in Figure 2.14.

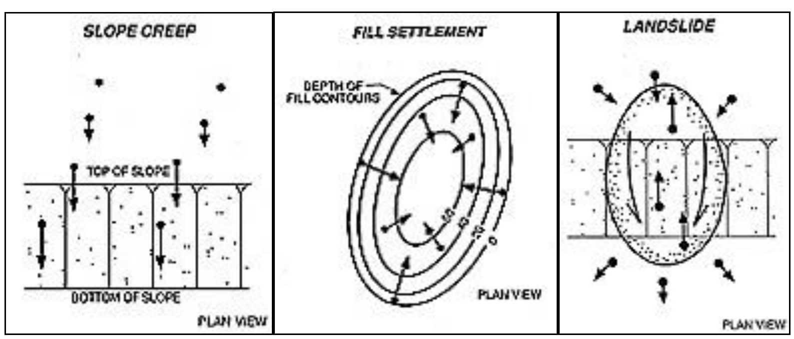


Figure 2.14: Patterns of tilt behavior. Arrows represent vector rotations (directions and magnitudes of tilt). From Tofani and Horath (1990).

The major advantages of this instrument are portability, light weight, simple operation, and compactness. Stationary electrolytic sensors with automatic data acquisition systems are gaining wider usage in landslide monitoring. Continuous tiltmeter monitoring insures all activity on the subject slope is recorded.

2.3 Case Studies

2.3.1 Case Study 1: Early Detection of Rock Movement with Time Domain Reflectometry (Dowding and Huang in 1994)

2.3.1.1 Introduction

This case study investigated the use of TDR methods to detect subsurface subsidence at the site of a coal mine. The Old Ben Coal Company's Mine No. 25 was a subsurface Longwall mine located in Franklin County near West Frankfort, Illinois. In many areas of the country where subsurface mining takes place, the authorities are worried about the affect of voids, created by mining operations, on the performance of surface structures. The major geological setting at this location is cyclotherm geology, which is typical in the South Illinois coal basin. In this type of geological condition, rock types are inconsistent. In another word, the rock density, porosity, shear modulus, and other physical characteristics vary with rock type. When a slope fails, the shear plane is potentially located in a weaker rock layer.

In this study, a TDR probe was installed directly above the route of the mining operation in an attempt to remotely provide early detection of subsurface rock movement. A long vertical coaxial TDR cable with a length of 175m was grouted into the rock mass above the longwall coal mine as shown in Figure 2.15. The thick, north-south lines identified by date represent the location of the face of the longwall along the coal seam. The dates in Figure 2.15 indicate the rate at which the longwall face was advancing westward toward the TDR hole.

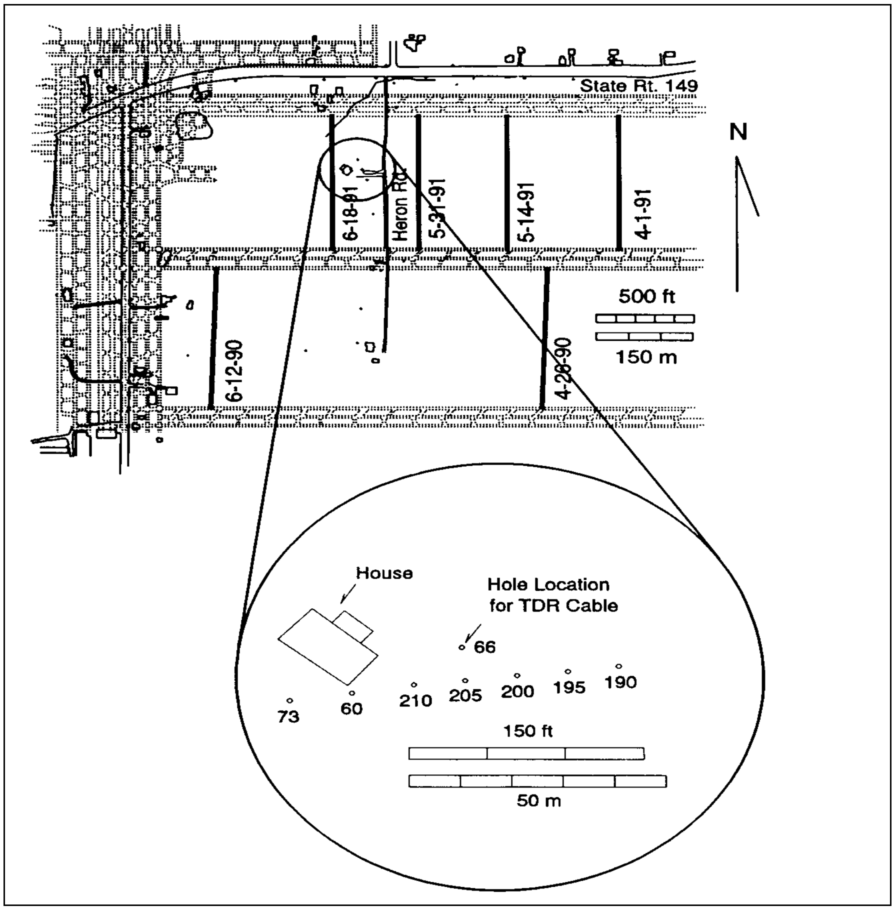


Figure 2.15: Hole location and mining site map that shows underground works, long wall-face location, date, and surface culture (After Dowding 1994).

Figure 2.16 presents the TDR results collected at a different dates and times during the advance of the longwall in the vicinity of the probe. It shows the signature pattern that occurred as the mining face approached and moved past the cable locations. The values at the bottom of each waveform indicate the distance of mining face from the TDR probe at the time of the reading, negative values indicate the face had progressed beyond the probe and a cavity existed beneath the rock mass. Waveform 1 serves as the baseline for all subsequent TDR signatures. On the baseline waveform, the ‘spikes’ labeled as *(d)* in Figure 2.16 represent locations where the cable was intentionally pre-crimped at certain distance along its length. These spikes were used as distance indicators for subsequent data comparison. The waveform records show that strata movement sheared the cable and produced increased signal reflections. The amplitude of these reflections tended to increase as the cable was stretched due to the advance of the longwall face. Ultimately, the strata movement severed the cable (which produced the open circuit marked *(b)*). Additional shear detections were marked as *(c)*.

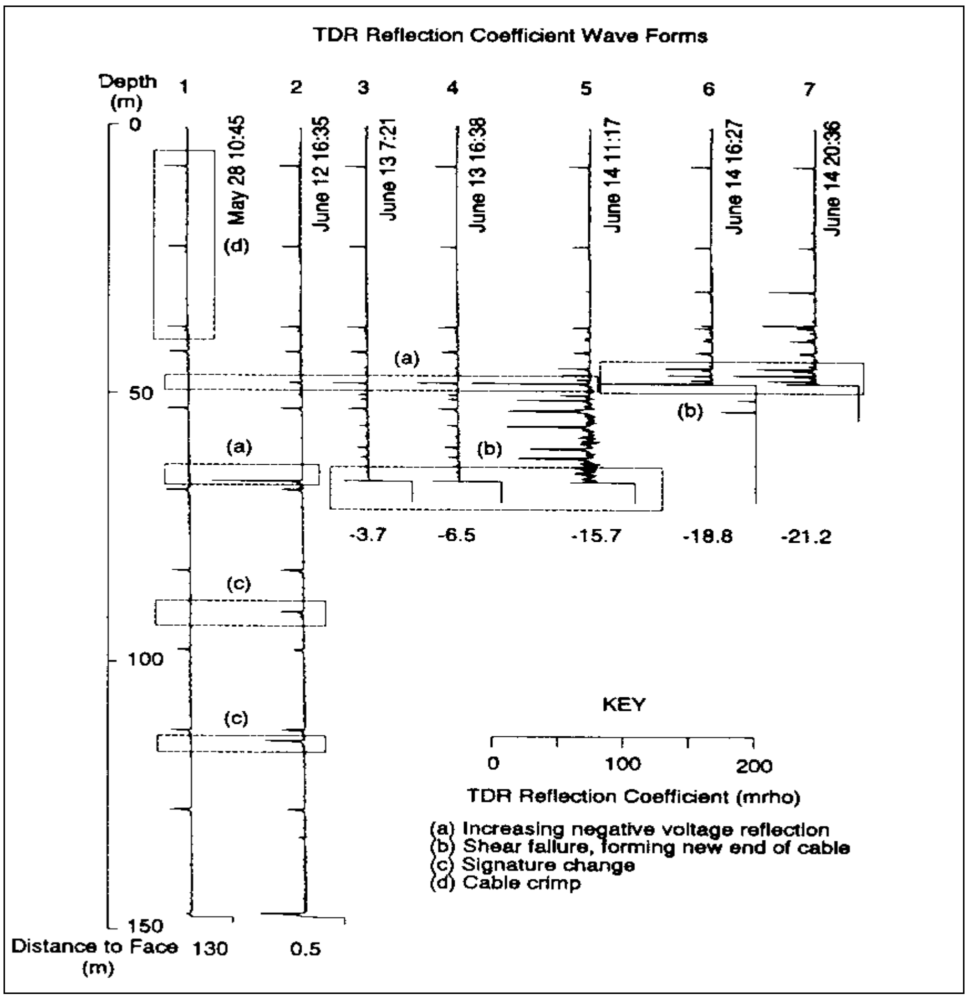


Figure 2.16**:** Sample field TDR data showing differences in signature immediately before and after complete severance (After Dowding 1994).

2.3.1.2 Distinction between shearing and extension signature for Old Ben Coal Company's Mine No. 25 TDR result

The reflective spikes on waveforms collected in this study illustrate the type of deformation can be distinguished based on the signal amplitude and width. Figure 2.17 shows the reflected signals at depths of 46m, 48m, and 66m. At a depth of 46m, the reflection amplitude increases to a maximum value then decreases as sequence A, B, and C illustrate. For the shear locations at 48m and 66m, the data indicated shearing at this location increased gradually from A to C. The monitoring cable was completely severed at of the 48m and 66m depths. TDR signatures 3 to 7 in Figure 2.16 indicates the severed cables with a shorter reflection signature after the mining face passed the cable location.

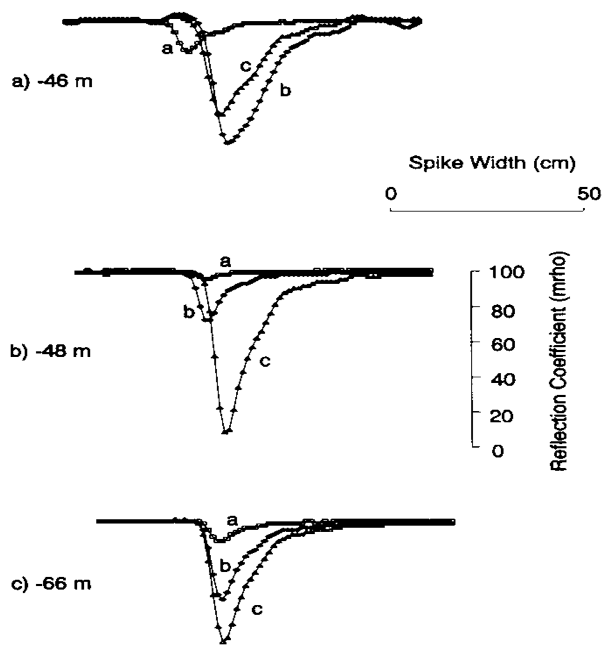


Figure 2.17: Details of TDR reflection coefficients at depth of 46, 48, and 66 meter (After Dowding 1994).

At the two severance depths, the maximum reflection coefficients had reached 86 and 68 mρ before the cables were completely severed. The spike in the signals at depths 46m and 48m was were shifted slightly which indicates that the cables were stretched due to the mining activity. On the other hand, the spike in the signal at 66m showed only growth and no extension as magnitude of shear increased. A conclusion was that shear effects cause increases reflection amplitude, whereas extension effects cause the signal to become wider with only minor increases in amplitude (Su 1987, Dowding 1988). Thus, it is possible that deformations at depths of 46m and 48m are a combination of shear and extension while cable section at a depth of 66m had only gone through shearing.

2.3.1.3 Conclusions and Recommendations

This study illustrated the successful use of Time Domain Reflectometry (TDR) for monitoring deformations in rock and soil masses above an active longwall coal-mining operation. The comparison of TDR signature changes with the distance to the longwall-face indicated localized movements were detected four days before surface subsidence was observed. At the time of the measurements, the mining activity was still 64m away. This case study shows that the TDR technique was able to detect subsurface movements while the mining face was still far away, which demonstrates the capability of providing early warning to the user. Based upon measurements and observations of this study, following the conclusions and recommendations seem valid:

1) Daily or even hourly polling of the TDR system is essential to obtain a complete history of cable deformation prior to failure.
2) Appropriate software is required to acquire and analyze the high density of data acquired over time.
3) Remote polling on demand allows TDR data collection at small time intervals to detect early ground movement activities.

4) Cable length has a significant effect on TDR reflections.
5) More laboratory investigations on the effect of length, diameter, deformation type, and number of crimps are necessary to improve the resolution of the reflection correlation with shear deformation.

2.3.2 Case Study 2: Real time monitoring of Subsidence along I-70 Washington, Pennsylvania

2.3.2.1 Project Description

This project is located just east of Washington, PA. Two coal seams at a depth of 170 to 198 m (559 to 651 ft) were extracted by the Eighty-Four Mining Company beneath I-70 by using the longwall mining technique. With this mining technique, two large blocks of coal that were approximately 1000 ft wide, 6000 to 8700 ft long, and 6 ft thick were removed. With the large amount of underground material being removed, the Pennsylvania Department of Transportation (PennDoT) was concerned that the pavement would subside and crack. If this happened, it could lead to tilting, which could affect the reinforced concrete box culverts underlying the highway and influence their hydraulic performance. PennDoT recognized that the damage occurring to the pavement and structures could shut down the highway. To ensure the safety of the public, PennDoT took several precautions including temporary support of an overpass, reduction of speed limits, a provision for lane closures and detours, visual monitoring patrols, and real time monitoring of ground movement with a call back alarm capability.

2.3.2.2 Mining Technique and Surface Subsidence

The longwall mining technique used in this project is known as an efficient, fast and, safe method. In this method, coal is excavated by a movable shearer making a cut about 1 meter (3feet) deep. The excavated coal is then conveyed to another loading point. A set of hydraulic roof supports are advanced behind the shearer. However, rock fractures can cause collapse of the mine roof into the void behind the supports. are unpreventable and may lead to subsidence at the ground surface. An example of this is illustrated by the transverse profile in this case study shown in Figure 2.18. With the loss of support, the overlying rock mass subsided gradually and the ground surface ultimately deformed into a trough with maximum subsidence of 1.0 meter and 1.5 meter (3 feet to 5 feet).

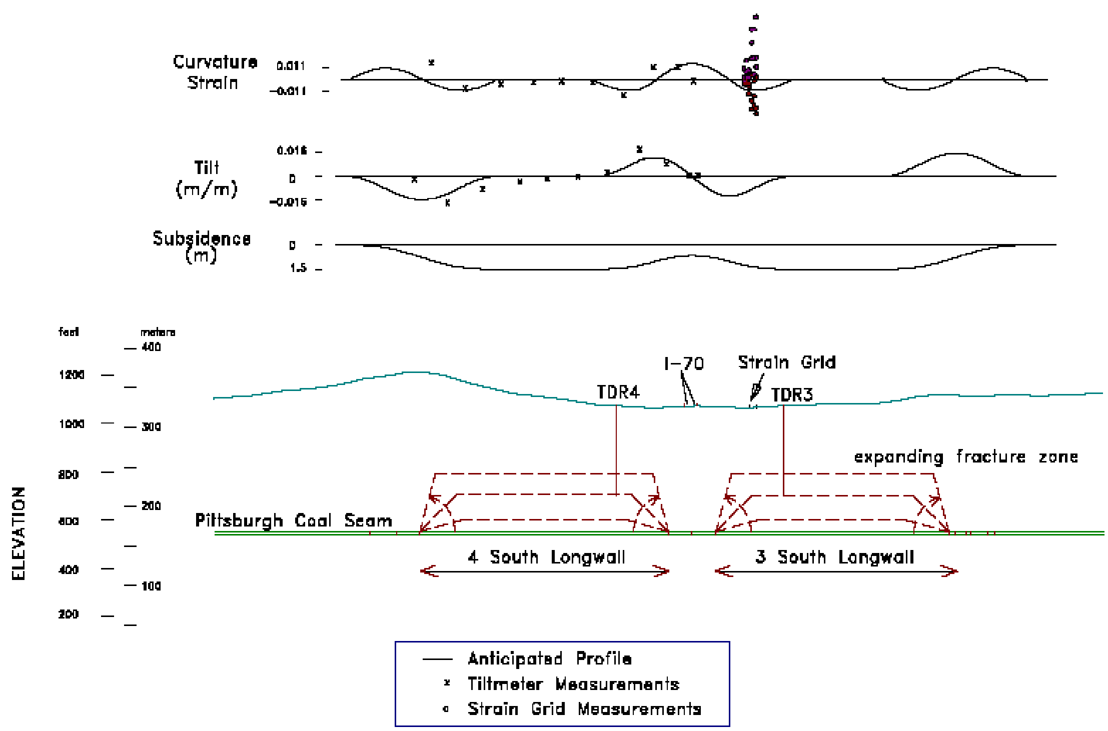


Figure 2.18: Subsidence, tilt and curvature strain profile. (Connor, 1999)

The subsided surface caused slope and curvature to develop on the highway surface. According to survey data, a 1.5 meter (4.9 feet) depth of subsidence was reported. The subsided surface caused inconvenience to the highway users where the uneven surface was blocking drivers' line of sight.

2.3.2.3 PennDot plan of action and Instrumentations

A series of ground stability monitoring installations were used to provide a real time monitoring system and to provide reliable information about ground movement. This information was used to support PennDoT's experience and database of visual observations and survey measurements.

The subsurface deformation monitoring was accomplished by using the Time Domain Reflectometry (TDR). Seven coaxial cables in total were used in monitoring this project. The coaxial cables were grouted into holes drilled from the surface to within 46 meter (150ft) of the coal seam. Among all the coaxial cables, four cables were located close to the centerlines of the mine panels, and the rest were located at an intersection between the highway and the edges of the mine panels as shown in Figure 2.19. In order to maximize the sensitivity of TDR monitoring, none of the coaxial cables used in this project were no longer than 50 meters (164 feet). The cable installation locations were spaced apart to maximize monitoring coverage of the mine panel with the available cables. In order to provide maximum coverage with short cables, the TDR waveform acquisitions were performed by using a laptop computer rather than a remote data acquisition system.

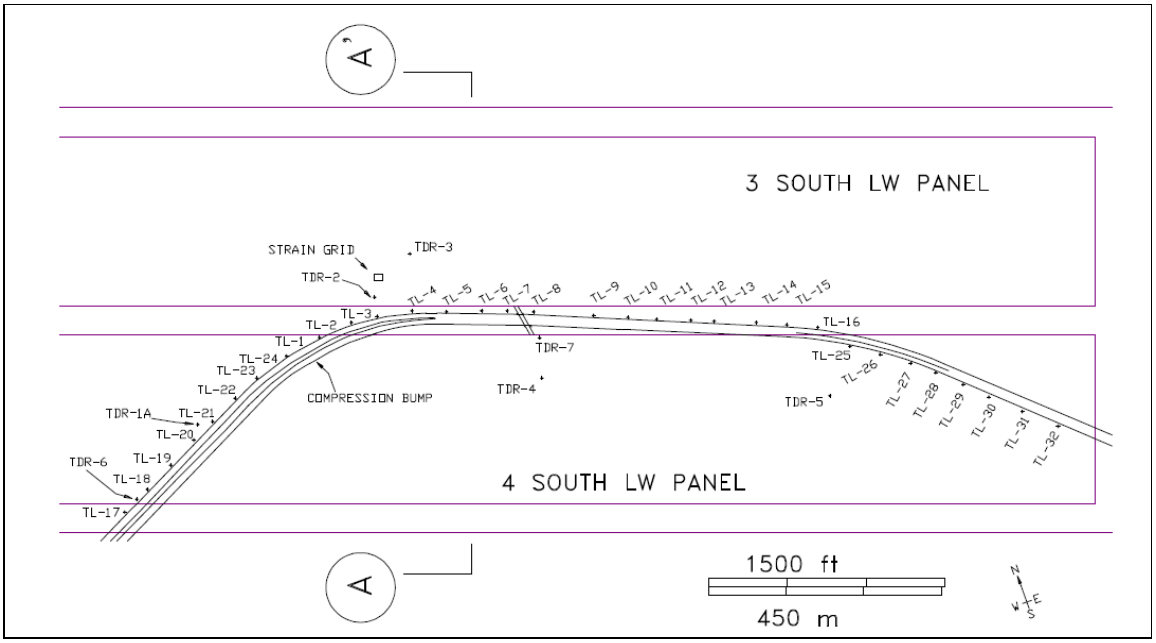


Figure 2.19: Plan of highway, instrumentation, and longwall mine, (TDR – Coaxial cable locations, TL- Tiltmeter locations). (Connor, Clark, Whitlatch, and Dowding 1999)

For automated remote monitoring, an array of thirty-two biaxial tiltmeters was installed (Figure 2.20). The tiltmeters were installed along the roadway shoulder at a spacing of 60m (200ft). The tiltmeters had detachable fins that allowed them to be installed in a slotted inclinometer casing. The tiltmeters (Applied Geomechanics Little Dipper) have a resolution of 0.006 arc-degree and a range of +/-10 arc-degree.

This set of tiltmeters provided the alarm system which was connected to a central data acquisition system. Four monitoring systems were installed in this case. The systems automation was controlled by a Campbell Scientific CR10X Datalogger. Each datalogger was capable of controlling eight tiltmeters at one time, and the greatest distance from any tiltmeter to the system was not greater than 300 meter (984.3 feet) to maintain sensitivity. All electronic devices were housed inside a weather proof moveable steel enclosure which was hooked up to a source of power and a telephone line. The dataloggers were programmed to log all eight tiltmeters every 15 minutes and save the collected data. For alarming purpose, the system was set to trigger the initial alarm with a tilt value of 0.002m/m (0.12 arc-degree or Vertical: Horizontal=1:500). This inclination value was established based on the tolerable value for resident structures due to subsidence that was obtained from the engineering literature (O'Connor, et. Al., 1999). Whenever this tilt value was exceeded, the datalogger initiated a phone call to PennDot personnel automatically. Once the alarm was received, PennDot personnel would monitor tiltmeter measurements in real time via phone line. Based on the collected information, they could make a decision about alerting other agencies for appropriate response.

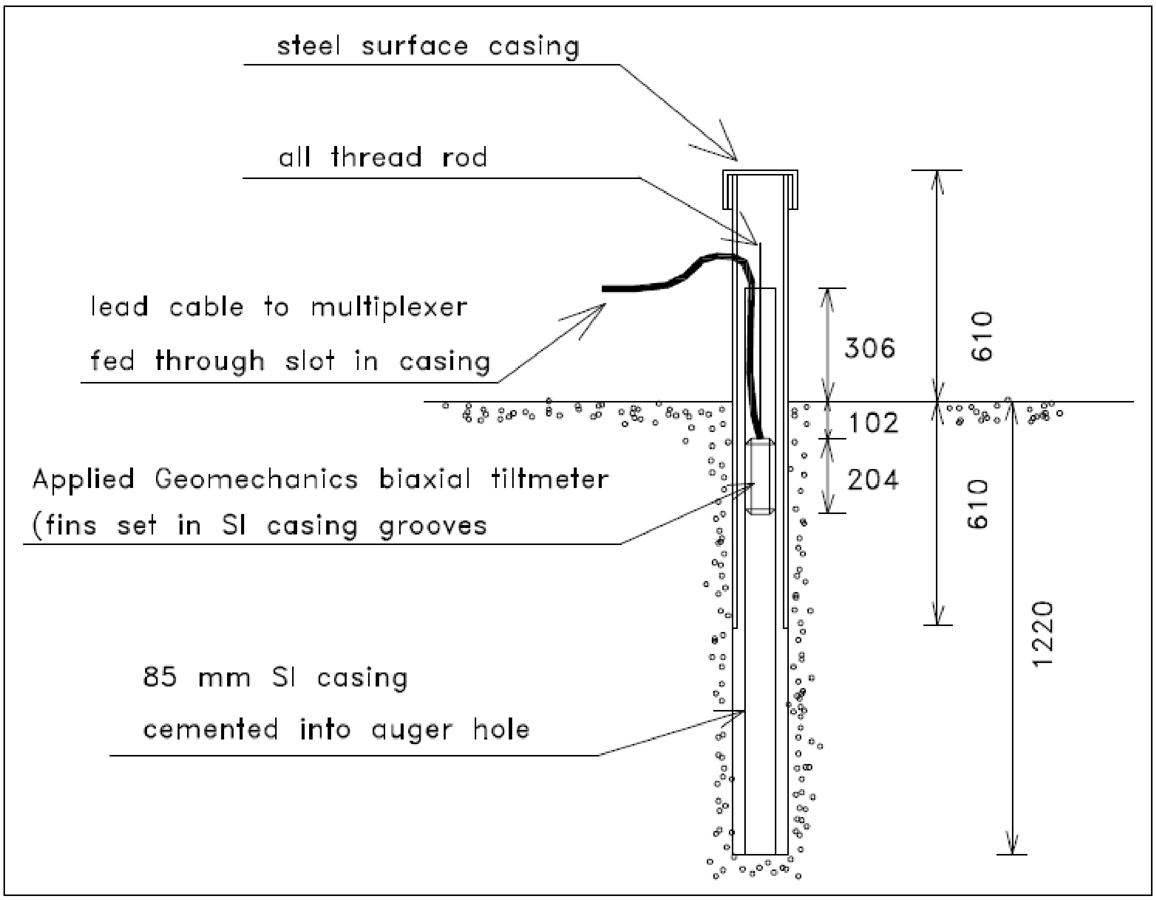


Figure 2.20: Tiltmeter installation details (Connor, Clark, Whitlatch, and Dowding 1999)

In addition, surface monitoring was also conducted using global positioning system (GPS) measurements at more than one hundred locations. The GPS system provided a more visual image of the survey area to PennDot. Furthermore, a survey network of three 9m by 9m (30ft by 30ft) grids were established to measure surface strain.

2.3.2.4 Results of Survey

As the longwall face advanced, movements occurred along discontinuities such as bedding planes that caused deformation of the coaxial cable. Figure 2.21 shows the results obtained from the TDR cable installed at location TDR4. This deformation was concentrated at depths where there were large changes in strata stiffness (as shown in the stiffness histogram on Figure 2.21).

In this case, even though the TDR system did not have alarm capability, it was still effective for detecting precursor movements which occurred ahead of the mine face. For example, according to Figure 2.21, the 6/3/00 TDR signature shows that precursor movement was detected when the mine face was over 55 meter (180 feet) from the cable. An even earlier precursor movement was detected on the waveform for 5/1/00 where the mining face was over 135m away from the cable. Typically, TDR cables were able to detect precursor movement 200 meters (656 feet) away from the active mining location. Surprisingly, one cable even detected movement as far as 365 meter (1200 feet) from the active mining location (O'Connor, et. Al., 1999). The results also indicated the TDR spikes increased in magnitude as time passed. This result corresponded to an increase in the shearing deformation of the cable. The cable was eventually sheared off by the mass movement as shown in the last two waveforms in Figure 2.21.

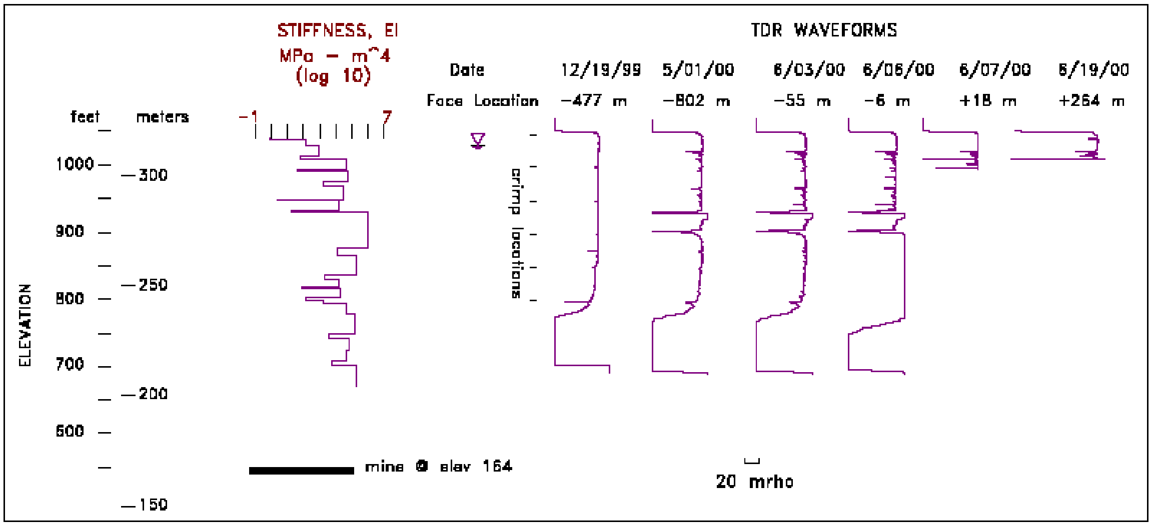


Figure 2.21: TDR waveform acquired at location TDR4. The TDR reflection spikes indicate where cable deformation occurred due to rock mass movement. They occurred at depths where there are stiffness discontinuities in the rock mass. (Connor, Clark, Whitlatch, and Dowding 1999)

As mentioned earlier, the primary purpose of the tiltmeters was to provide automated monitoring and an alarm system. Tiltmeter measurements are used to estimate the sagging curvature by comparing the difference in slope between adjacent tiltmeters. Measurements obtained along the highway from tiltmeters TL-17 to TL-3 are summarized in Table 2.1. The tiltmeters began detecting tilting as the mine face moved underneath a location, reached a peak value, and then decreased to a value close to 0.0 arc-degree after the mine face was well past the location and the subsiding rock mass approached equilibrium as indicated in Figure 2.22. The peak and final longitudinal tilt measurements across the longwall panel that are summarized in Table 2.1 illustrate a much greater transient tilt and curvature experienced by the highway as it was undermined compared to the final equilibrium profile in Figure 2.22.

Tiltmeter	Transverse (x-axis) (arc-degree)		Longitudinal (y-axis) (arc-degree)	
	Anticipated Final*	Measured Final	Measured Peak	Measured Final
TL-17	0.88	0.1		-0.1
TL-18	0.65	1.0	0.1	-0.2
TL-19	0.06	0.5	1.1	0.05
TL-20	0	0.25	1.3	0.4
TL-21	0	0.07	1.1	-0.05
TL-22	0	-0.1	1.1	0
TL-23	-0.05	-0.1	1.1	-0.05
TL-24	-0.57	-1.0	0.7	0.2
TL-1	-0.88	-0.5		0.05
TL-2	-0.72	-0.05		0
TL-3	-0.58	-0.05		0

Table 2.1: Comparison of Final and Peak Tilt Measurements (Connor, Clark, Whitlatch, and Dowding 1999)

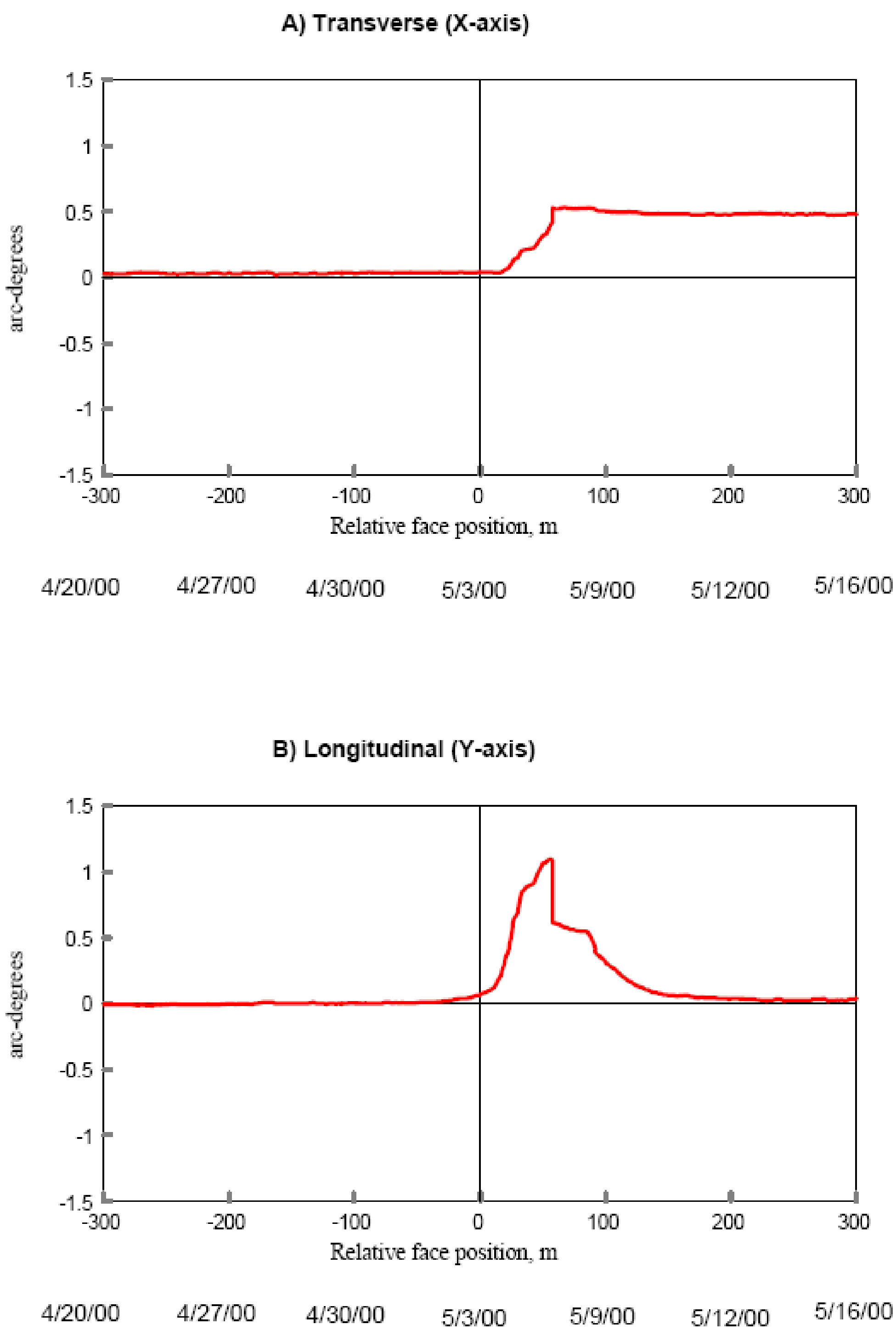


Figure 2.22: A) History of tilt at location TL19 as the mine face advanced underneath this location: A, x-axis is transverse to the panel centerline and in the plane of Figure 2.22: B) y-axis is parallel to the panel longitudinal centerline and shows the steeper transient slopes moving with the mine face.

2.3.2.5 Conclusion

Among all the instruments used, TDR provided more sensitive measurement in regard to precursor movement. Subsurface movement was detected by the TDR cables while the face was still 60m from the cable location, while the tiltmeters did not detect surface movement until the longwall face was nearly beneath them. However, tiltmeter measurements proved to be reliable for automated monitoring and for the purpose of alarming PennDOT personnel. Proper application of the instruments in this project made it possible to continuously monitor a 300m long interstate section. Furthermore, visual monitoring could be concentrated at a critical location when an alarm in the system is triggered at a particular location.

2.3.3 Case Study 3: Estimating Slope Movement with Time Domain Reflectometry (TDR)

2.3.3.1 Introduction

The purpose of this project was to compare measured slope movements with corresponding TDR reflection readings. The three main objectives for this case study were to determine: 1) the amount of slide plane movement required before detecting a TDR reflection reading in the cable; 2) the amount of movement associated with a TDR reflection as the slide mass continued to move; and 3) the influence of installation conditions on TDR readings. Data used in the evaluation was obtained from instrumented field sites as well as from laboratory testing. The California Department of transportation (Caltrans) provided field test data from past-instrumented landslides within Monterey, San Luis Obispo, and Santa Barbara Counties. The laboratory testing was carried out at

California State Polytecnic at San Luis Obispo, using a device designed to model an active slide plane with a TDR cable probe installed. Relationships between slide plane movement and TDR reflection readings were analyzed and other factors that influence these relationships including cable type, grout strength, and soil at the shear surface were also considered.

The five field sites evaluated as part of this study are listed in Table 2.2. All sites consisted of multiple TDR and inclinometer installations designed to monitor slope failures that impacted existing highways. Type RG59/U coaxial cable, which is used in most cable television hook-ups, was installed exclusively at field sites A, B, and C. Cables at these sites were strapped to casings of slope inclinometers or in separate boreholes. Field site D included two RG59/U cables and a 12.7 mm foam dielectric cable installation. Field site E included 12.7 mm foam dielectric cables that were installed separately from the slope inclinometer boreholes.

Table 2.2: Description of Field Sites (Reproduced from David C. Serafini and Gregg L. Fiegel, 2004)

Field Site	Location	No. of TDR Cables		No. of Inclinometers
		RG59/U	12.7 mm	
A	Gorda, Monterey County	6	0	8
B	Mustang grade, Monterey County	5	0	15
C	Sycamore Canyon, Santa Barbara County	4	0	3
D	Big Sur, Monterey County	2	1	2
E	Nojoqui Grade, Santa Barbara County	0	3	1

2.3.3.2 Field Test Site Results for RG-59/U and Foam Dielectric Cables

Figures 2.23 and Figure 2.24 compare TDR reflection magnitudes with slope inclinometer readings for RG-59/U and 12.7mm foam dielectric cables respectively. TDR and slope inclinometer readings at the similar depths (within 0.5 meter) and plan locations (within 15 meters) in the landslides were used to plot the figures. The results from both types of cable did not appear to illustrate a consistent correlation between TDR reflection magnitudes and the shearing plane movement detected by the slope inclinometer.

For RG-59/U cables, the poor relationship was best illustrated at Field Site B where separate boreholes showed TDR reflection changes and cable shearing without any observed slope inclinometer changes. These points plot along the vertical axis of the graph shown on Figure 2.23. If these data points are neglected, then the sensitivity of the RG-59/U cable ranged from 0.0 mrho/mm to 0.25 mrho/mm with an average 0.12 mrho/mm. Sensitivity in this study is defined as the ratio of TDR reflection reading to measured slope inclinometer displacement.

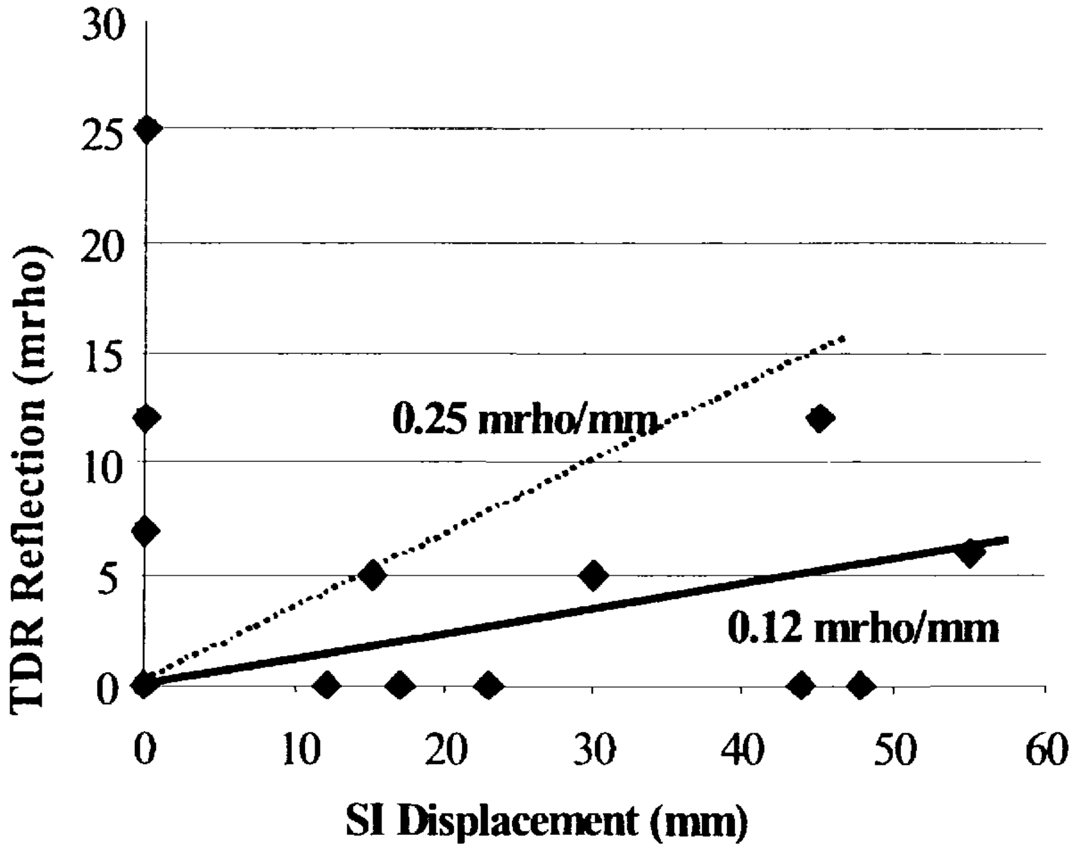


Figure 2.23: TDR Reflection versus Slope Inclinometer Displacement from Field Sites (RG59/U Cable). (David C. Serafini and Gregg L. Fiegel, 2004)

On the other hand, the results from the 12.7mm foam dielectric cable show that values of TDR reflection tended to increase with increasing of slope inclinometer displacement. The 12.7 mm foam dielectric coaxial cable installed at Field Site D indicated more than 12 mm of shearing displacement was needed to detect a reflection reading in the TDR cable. Field Site E consisted of three separate 12.7mm foam cable installations and one slope inclinometer casing. An old TDR cable (4-99) which was installed a few years prior to the other instrumentation installation was analyzed separately to evaluate sensitivity with subsequent movement. One of the latest installations of 12.7mm foam dielectric TDR cable at Field Site E showed an approximate relationship between TDR reflection and slope inclinometer displacement. As shown on Figure 2.24, the results from this field site demonstrated that a minimum displacement of 23mm was necessary to produce a detectible reflection coefficient. TDR Cable 4-99 demonstrated that after an initial reflection reading was detected, cable sensitivity ranged from 1.3 mrho/mm to 5.5 mrho/mm, with an average of 3.2 mrho/mm.

To better show the relationship between reflection coefficient and slope inclinometer displacement, a few previous laboratory studies were included in Figure 2.24 for comparison purposes. The observed sensitivity relationships between reflection coefficient and slope inclinometer displacement for the 12.7 mm foam dielectric cable grouted in rock are consistent with the studies done by Su (1987) and Aimone-Martin et al. (1994). Also shown in Figure 2.24 is a relationship proposed by Logan (1989) that was based on laboratory testing on TDR cables embedded in a gravel backfill.

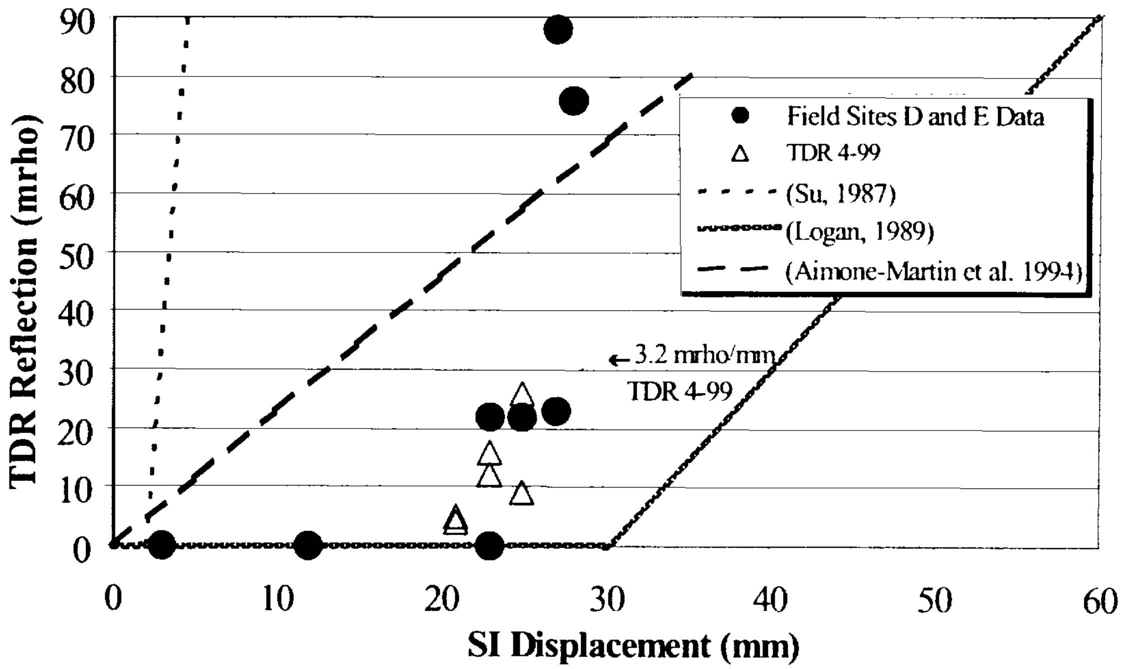


Figure 2.24: TDR Reflection versus Slope Inclinometer Displacement from Field Sites (Foam Cable). (David C. Serafini and Gregg L. Fiegel, 2004)

2.3.3.3 Laboratory Testing Device

A direct shear testing device was modified to produce a cable and grout shear testing device (CGST) to investigate the behavior of grouted TDR cables subject to ground deformation. A 660 mm (26 in) diameter, 1.3cm (0.5 in) thick steel cylinder was used to confine the backfill and grouted TDR cable. Steel plates were attached to the two halves of the cylinder to create a predefined slide plane, as shown on Figure 2.25. The device permitted approximately 305 mm (12 in) of maximum horizontal displacement.

A vertical confining piston device with minimum confining stress applied to the soil backfill was utilized to prevent passive failures of the soil backfill during shearing. A displacement scale attached to the left rail of the CGST device measured shear plane displacement. Four tell-tails attached to each grouted sample measured inclination and horizontal movement of the grouted TDR cable at various depths. Grouted TDR specimens were 10.2 cm (4 in) in diameter and a minimum of 107 cm (42 in) long. Grout mix, cable type, and attachment methods were modeled after methods used when installing TDR cables at the field sites.

The test was conducted by horizontally shearing the sample using displacement increments of 2.5 mm (0.1 in). Following each increment, the cable was tested using the Campbell Scientific TDR 100 to detect reflection coefficient changes. After sounding the cable, the four tell tails were examined. Each grouted TDR cable was tested to failure or until the maximum displacement of CGST was reached.

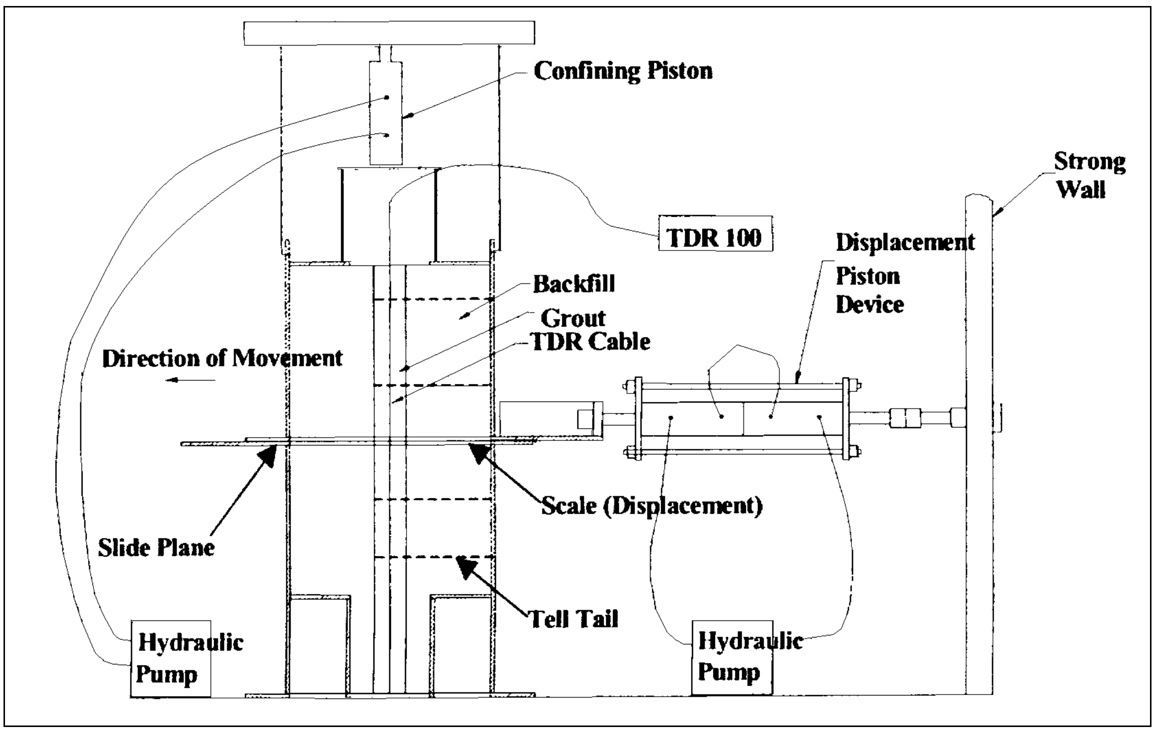


Figure 2.25: Cable and Grout Shear Testing Device (CGST) Setup (David C. Serafini and Gregg L. Fiegel, 2004)

2.3.3.4 Laboratory Test Results

Fifteen laboratory tests were conducted using the CGST device. The laboratory tests are summarized in Table 2.3. During the calibration of the CGST device several different grout strengths were tested with both the RG-59/U and 12.7 mm foam dielectric cables. The cables were tested alone or attached to a ¾ inch Schedule 40 PVC tremie pipe to act as a slope inclinometer casing. Four different cement-bentonite grout mixtures were used. However, the TDR reflection coefficient changes for the 12.7 mm foam dielectric cable were only measured when the cable (grouted alone) was tested in gravel (GP) backfill (Test 11). The relationship between the TDR reflection coefficient and shear plane displacement is presented on Figure 2.26. As shown, a reflection response was first recognized after a shear displacement of 110 mm. With further displacement, the 12.7 mm foam cable was found to produce an average sensitivity of about 0.35 mrho/mm.

Based on the study, laboratory test results were affected by two factors: 1) Passive failure of the backfill adjacent to the tremie pipe and slope inclinometer casing appeared to occur during testing. Thus, deformation of the RG59/U and 12.7 mm foam cable were not large enough to produce a reflection change; and 2) Intense fracturing of the grout near the shear plane interface was apparent after dissection of the test sample. The fracturing of the grout apparently prohibited the transfer of backfill deformation to the cable; thus, also preventing reflection changes. The water to cement ratio for the grout had no apparent effect on the reflection response. For both mix designs (w/c=1.5, 1.75) the results were similar.

Table 2.3: Laboratory CGST Results
(Reproduced from David C. Serafini and Gregg L. Fiegel, 2004)

Test #	Cable Type	Attachment	Grout Mix Ratios[a]		Max CGST Displacement (mm)	Result
			w/c	b/c ratio		
1	RG-59/U	Alone	1.1	0.10	5	CS
2	RG-59/U	Alone	1.3	0.10	6	CS
3	RG-59/U	Alone	1.3	0.10	6	CS
4	12.7 mm	Alone	1.5	0.10	300	NRC
5	RG-59/U	Alone	2.5	0.10	300	NRC[b]
6	RG-59/U	Alone	1.75	0.10	14	CS
7	RG-59/U	Tremie Pipe	1.75	0.10	300	NRC
8	RG-59/U	SI Casing	1.75	0.10	195	NRC[c]
9	12.7 mm	Alone	1.75	0.10	305	NRC
10	12.7 mm	Tremie Pipe	1.75	0.10	300	NRC
11	12.7 mm	Alone	1.75	0.10	305	RC at 110mm
12	12.7 mm	Tremie Pipe	1.75	0.10	305	NRC
13	RG-59/U	Alone	1.75	0.10	11	CS
14	RG-59/U	Tremie Pipe	1.75	0.10	305	NRC
15	RG-59/U	SI Casing	1.75	0.10	305	NRC

Note:
w=water, c=cement, b=bentonite, NRC=No Reflection Coefficient, RC=Reflection Coefficient
cs=cable sheared, [a]Ratio by Weight, [b]7.9cm of cable pullout, [c]cable pullout at 195cm

2.3.3.5 Laboratory Comparison to Field Study

The results of Test 11 as shown in Figure 2.26 reveals a trend consistent with that observed in the field results incorporating a similar cable (see Figure 2.24). Both the laboratory and field results show that a minimum amount of displacement is required to produce detectable TDR readings.

The backfill material used in the laboratory to surround the grouted cable may be one reason for the differences observed. The field sites examined as part of this study each involved landslides in rock, where a better defined shearing interface existed. Laboratory testing demonstrated that the grout might not be the primary media to transfer the deformations to the TDR cable but the backfill or native material which encompassed the grouted TDR cable. Therefore, the TDR cable may be less effective in landslides containing granular material where a lot of voids in between and easily displaced once force applied. As the result, a significant slide displacement is needed for TDR cable to detect movement (David C. Serafini and Gregg L. Fiegel, 2004).

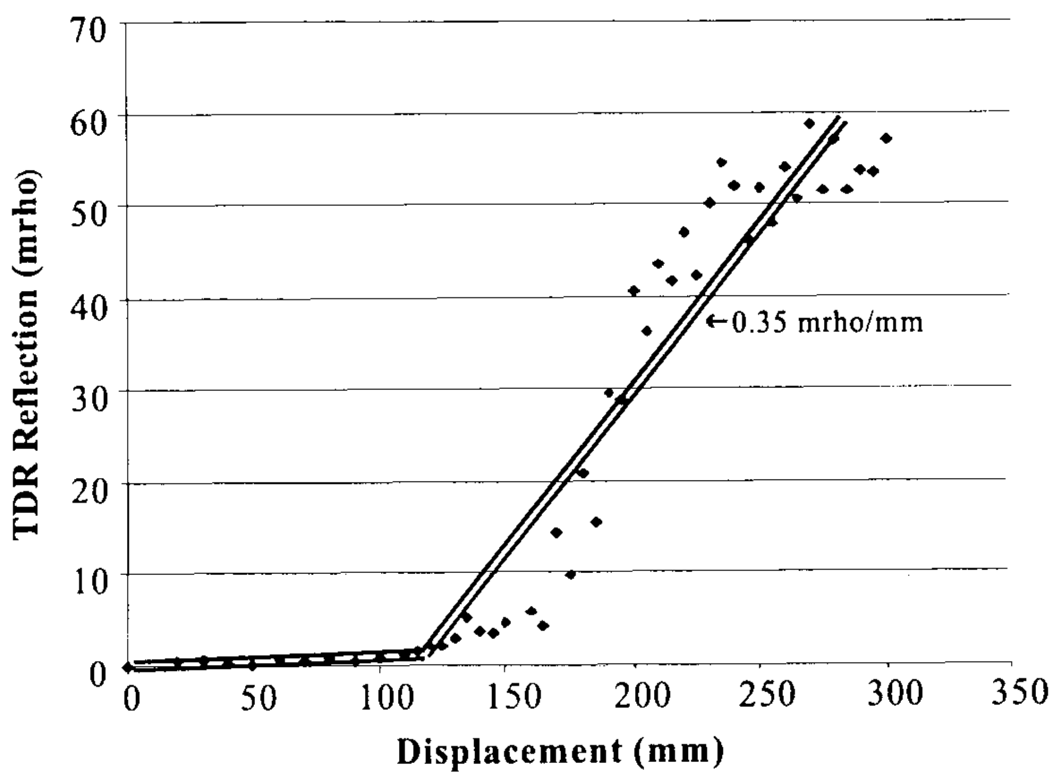


Figure 2.26**:** Laboratory TDR Reflection versus Shear Displacement for Test 11 (David C. Serafini and Gregg L. Fiegel, 2004)

2.3.3.6 Recommendations

TDR is a cost-effective solution for estimating the location of a landslide slide plane. The 12.7 mm cable appears to have the ability to monitor the progression of slope displacement. However, using the RG-59/U cable to monitor the progression of slope displacement will likely yield inconclusive results. Site data from the field studies showed good results for further monitoring of landslides past the point of inclinometer failure.

The method of cable installation and the nature of the encompassing backfill are keys to the sensitivity of the cable. The 12.7 mm foam dielectric cables are recommended to be installed alone or attached to small diameter tremie pipes within boreholes. If possible avoid attaching these cables to inclinometer casing since the stiffness of the casing limits the effectiveness of the cable. As well as the RG59/U cable should be installed alone to eliminate any potential effects form the shearing of the stiffer inclinometer casing.

2.3.4 Case Study 4: Landslide Monitoring and Emergency Notification System at Cedar Heights subdivision, Colorado Spring, Colorado

2.3.4.1 Introduction

Cedar Heights is a private subdivision located in the foothills of the Front Range of the Rocky Mountains, just west of Colorado Spring, Colorado. In 1980, a section of road embankment consisting of approximately 10 meters of engineered fill was placed over an existing landslide. The landslide in this area was reactivated during the wet periods in the spring of 1995 and the spring of 1998. The road was repaired and the embankment was rebuilt by placing a geogrid-reinforced granular fill. A geotechnical investigation during the summer of 1998 identified two separate slide surfaces below the road. Subsequent to the investigation it was determined that the landslides would be too costly to be stabilized. To protect public safety, a real-time landslide monitoring and emergency notification system was installed across the landslide area. The landslide location is shown on Figure 2.27.

A geotechnical investigation has confirmed that the unstable zone consists of two interconnected failure surfaces – the Upper and Lower Slides as shown in Figure 2.27 and Figure 2.28. Geological mapping during construction indicates that the natural soils in the vicinity of the unstable zone consist of landslide deposits and colluvium comprised of sandy clay and clayey sand with some gravel. Historical reports indicate that an active slide zone existed under the embankment footprint and toe area.

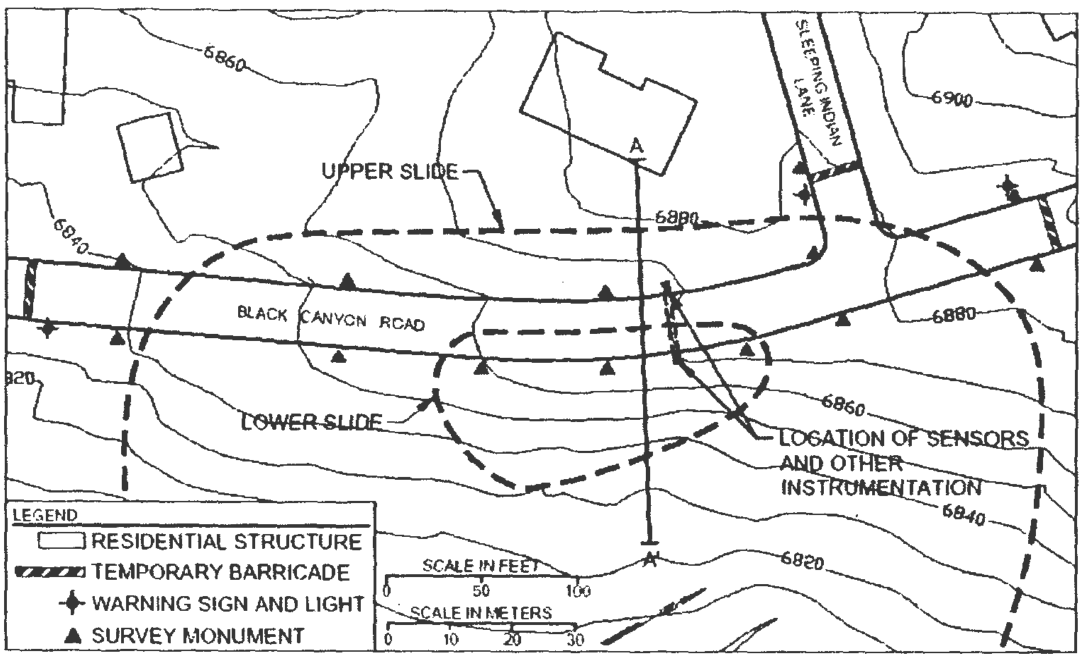


Figure 2.27: Slide Area Plan View and Location of Instrumentation (Daniel D. Overton, Robert W. Schaut, and Michael K. Lusk, 2004)

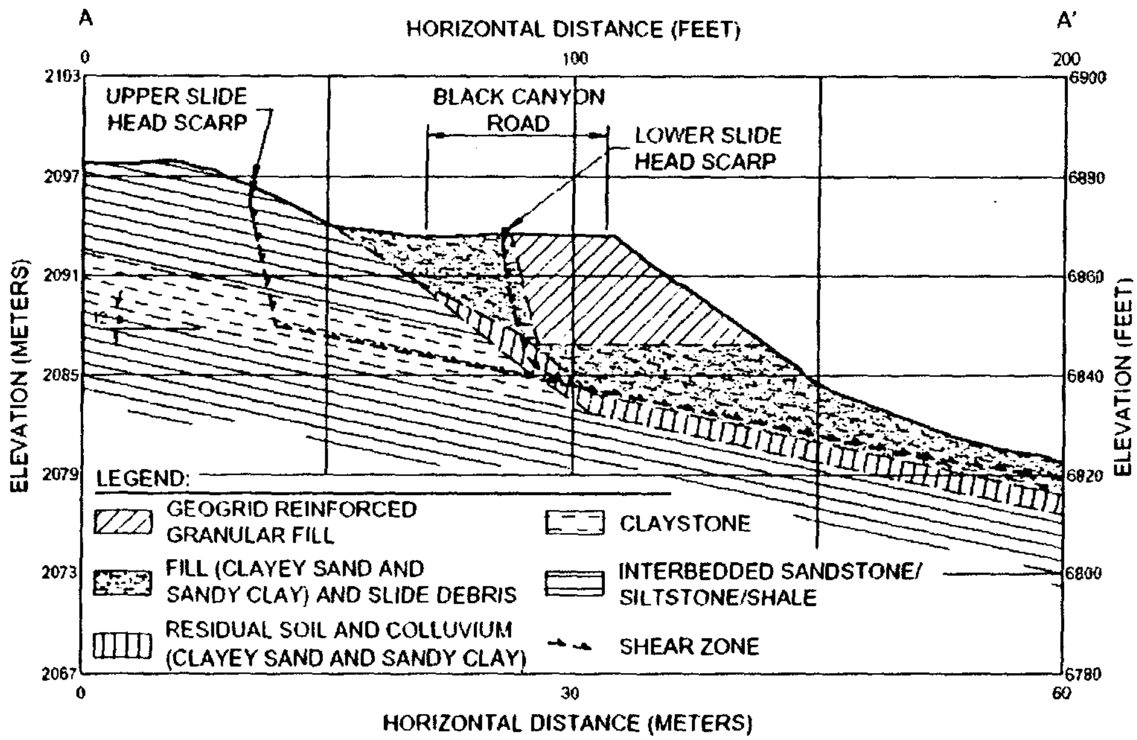


Figure 2.28: Generalized Cross Section A-A' (Daniel D. Overton, Robert W. Schaut, and Michael K. Lusk, 2004)

2.3.4.2 Sensors used to monitor the landslide movement

A landslide monitoring and emergency notification system were constructed to provide for the safety of the public which would traverse the landslide. Based on the known configuration of the landslides and other information obtained from the geotechnical evaluation, it was determined that the following parameters should be measured:

1) Displacement at the ground surface across the head scarp of the Lower Slide.

2) Movement along the failure zones of both slides deeper within the ground.

The following sensors were selected for the landslide monitoring system. A schematic of the complete monitoring system is shown in Figure 2.29. A schematic of the sensor installation is shown in Figure 2.30.

Cable Extension Position Transducer – A Model PT8420 Cable Extension Position Transducer manufactured by Celesco Transducer Products, Inc. was selected to monitor displacement at the ground surface across the head scarp of the Lower Slide. The transducer is comprised of a spring-tensioned cable attached to a variable resistance potentiometer. One end of the cable is attached to a fixed anchor on once side of the failure zone. As the cable is pulled from the unit due to movement across failure zone, the potentiometer is rotated. The current across this variable resistance is measured and recorded. If the movement limits are exceeded, the system will trigger alarm automatically.

In-place inclinometers – To monitor movement deeper within the ground, two in-place inclinometer casings made by Slope Indicator Company were being installed along the actual failure zones of the Upper and Lower Slides. Two inclinometers were installed in each of the two new inclinometer casings as shown in Figure 2.29. The in-place inclinometers were placed across the known depth of the failure zone, which was determined from portable inclinometer measurements. As movement occurs along each failure zone, the casing is deflected, causing a change in the tilt of the in-place inclinometers. A tilt limit was implemented to trigger the alarm system if movement limits are exceeded.

Survey Monuments - As a secondary method to monitor displacement at the ground surface, conventional survey monuments were installed at the locations shown in Figure 2.29.

A series of supplemental equipment was used to aid the monitoring including Datalogger, Cellular Communication System, Warning Signs and Lights, Solar Power, and Enclosure. Temporary barricades are also being used to prevent travel across the landslide area if alarm conditions are met.

2.3.4.3 System Operation

The monitoring system was set to log the cable transducer and the four in-place inclinometers every 15 seconds. The datalogger stored the data once an hour. However, when movement limits were exceeded, the datalogger continued to read the sensors every 15 seconds, but all data will was stored. The stored data was downloaded at the site or remotely using the cellular communication system.

Every time the datalogger read the sensors, it compared the latest readings with previous values over various time intervals. The latest readings were compared to the previous readings from 1, 6, 12, 24, 48 hours, and to the reading when the system was initially installed. The difference between the current reading and the previous readings was calculated. If the difference exceeded the movement limits that were programmed into the datalogger, the system alarm was activated.

Movement limits were set to trigger the alarm system based on the evaluation of the movement data from the inclinometers and the sensor data from the first few months of the system's operation. Every array of data acquired from the cables was compared to the movement limits programmed into the datalogger. When the datalogger computed the difference between the current readings and previous readings, it compared the difference to fixed movement limits. Different movement limits were used depending on the comparison time period. For the 1, 6, and 12 hour, time intervals, the movement limit was 0.05 inches (0.13 cm). For the 24 and 48-hour time intervals, the movement limit was 0.1

inches (0.25 cm). For the comparison with the initial sensor readings when the system was initially installed, the movement limit was 0.5 inches (1.27cm).

Once the movement limits were exceeded, the datalogger activated three flashing yellow lights via the wireless transmitter to warn approaching motorists of a potential hazard. This was followed by a series of automated calls to the guard shack, the pager that the security guards carry, and to relay the voice alarm message. The series of phone numbers was called three times initially and than repeated every hour if there was no response.

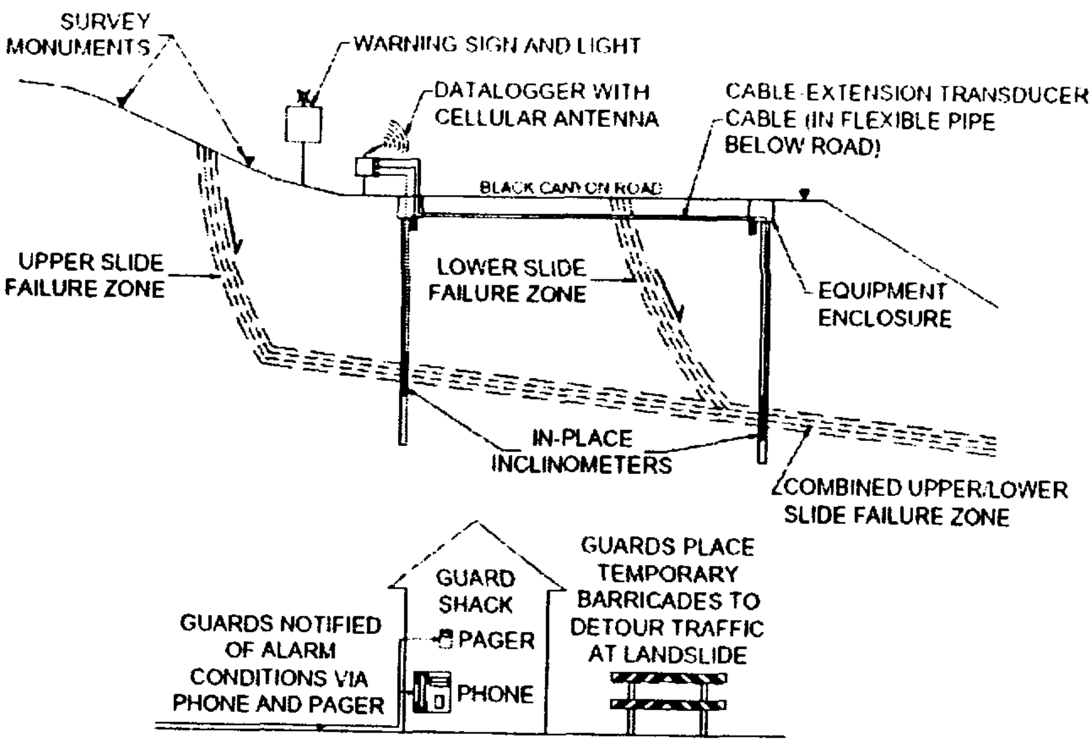


Figure 2.29: Schematic of Landslide Monitoring System (Daniel D. Overton, Robert W. Schaut, and Michael K. Lusk, 2004)

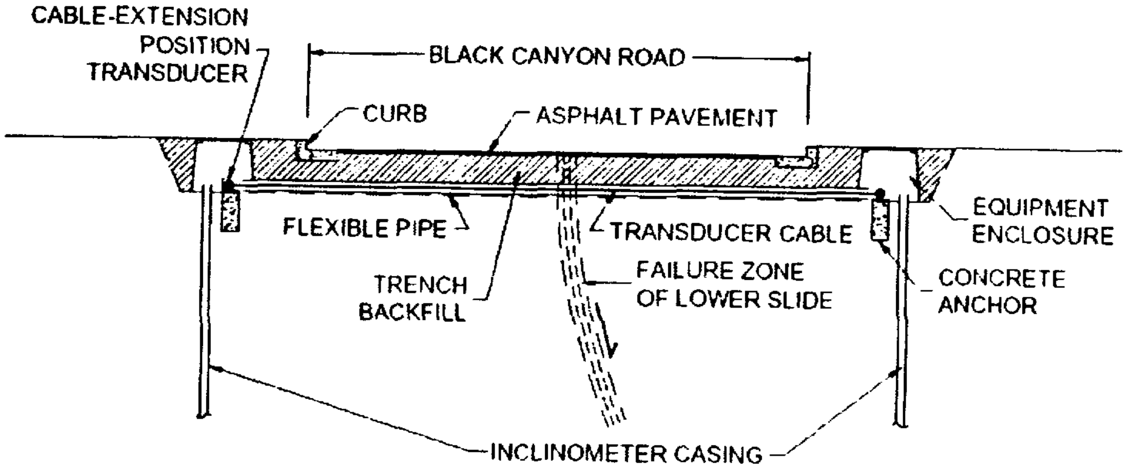


Figure 2.30: Schematic of Sensor Installation in Trench across Road (Daniel D. Overton, Robert W. Schaut, and Michael K. Lusk, 2004)

2.3.4.4 Conclusions

The landslide monitoring and emergency notification system described in this paper was designed and constructed to provide for the safety of the public which traverses a road with a known geohazard. The system has proven to be reliable, and will continue to provide a means to warn the subdivision residents in the event of the excessive slide movement.

Chapter 3

Research Methodology

The main purpose of this study was to evaluate slope monitoring equipment for effectiveness and reliability. Time Domain Reflectometry (TDR) devices were specifically targeted during this study.

3.1 Research Equipment

This chapter focuses on the preparation and installation of the TDR and inclinometer systems, the system set-up procedures, monitoring sequence, and the functionality of all the monitoring equipment. TDR technology has been used in the power industry for electric cable monitoring for some time but it is still in the preliminary stage of application for slope monitoring. As a result, a wide selection of TDR equipment and components are available on the market, but packages developed specifically for slope stability monitoring are not readily available. Therefore the best components from various manufacturers were selected to assemble the most accurate and economical TDR systems for this study.

3.1.1 TDR Components

The datalogger and the reflectometer are the two main components for the TDR system. Other subcomponents include the cellular phone, modem, antenna, battery, and solar panel for power supply. In some cases, multiplexers are also used to expand the monitoring capacity of TDR system. The functions and operation of each individual component are addressed below:

3.1.1.1 Datalogger (CR10X)

The datalogger is the main controller of the entire TDR system. It directs the execution of cable probe logging, data collection and storage, and monitors system parameters such as temperature and input voltage. The CR10X datalogger, manufactured by the Campbell Scientific, Inc., was selected for our monitoring system. The standard Campbell Scientific datalogger (CR10X) has 128 K of electrically erasable programmable read only memory (EEPROM) and 128 k of static random access memory (SRAM). The EEPROM stores the operating system and user programs while the SRAM stores data and executes the control program. When necessary, the storage capacity of CRX10X can be expanded with an optional Flash EEPROM which increases memory up to 2 Megabytes.

As illustrated in Figure 3.1, a series of built-in wiring panels are located on the fascia of CR10X datalogger. The wiring panel which consists of a 9-pin Serial I/O port and screw terminals that allows connections for sensors, monitoring devices, and power. The 9-pin Serial I/O port is not RS-232 compatible and requires a special interface box or cable in order to communicate with laptop computers or modems. The wiring panel also includes 6 single-ended channels for analog inputs. There are three terminals for excitation outputs located at the bottom middle of the panel. These terminals supply programmable excitation voltages for resistive bridge measurements. The excitation voltage is between -2500 mV and +2500 mV for DC and AC power. To the left of the excitation outputs terminals are two pulse inputs terminals. These terminals are programmable for high frequency pulses, such as low level AC, or to count switch closures. There are 8 terminals, which serve as digital input/output ports, at the bottom left of the fascia. When they are powered-up, these digital ports are configured as input ports and are commonly used for reading the status of an external signal. When configured as outputs ports they allow on/off control of external devices. The datalogger unit is powered by connecting a 12V DC power source to the 12V and power ground terminals.

The CR10X has a built-in clock powered by a lithium battery for continuous time keeping. The internal clock is used to activate the pre-installed control programs for scheduled data acquisition. The datalogger can also be programmed to initiate communication with a polling computer through a cell phone at pre-set time intervals. A software program called PC208W is the primary control of the datalogger. This software allows the user to modify and program the datalogger for specific functions and usage. A more detail explanation of PC208W is included in Section 3.3.

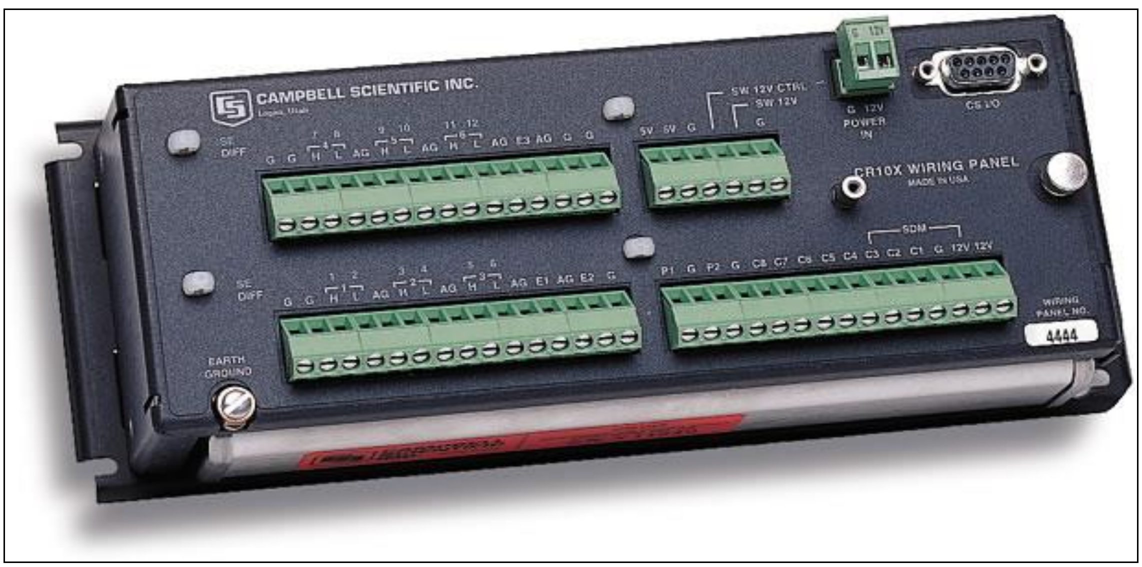


Figure 3.1: Campbell Scientific CR10X Datalogger (Campbell Scientific, 2002)

3.1.1.2 Pulse Generator/Receiver (Cable Tester) (TDR100)

The Campbell Scientific TDR100 reflectometer, as shown in Figure 3.2, is the pulse generator and receiver for the TDR system. This reflectometer sends out electric pulses to each cable probe and collects reflection pulses returning from the cable probes. The TDR100 was chosen for this project primarily because it is capable of providing a 50-ohm source impedance as the output pulse which matches the impedance of the coaxial cables used as TDR probes (Campbell Scientific, 2001). The TDR 100 receives input or commands through an I/O port which is located at the bottom right corner of the device shown in Figure 3.2. Unlike the CR10X data logger the I/O port of the TDR100 is compatible with RS232 serial communication ports on computers. A testing probe can be connected to the TDR 100 through a BNC connector. The output pulse is sent to the probe through the connector. The output pulses generated by the TDR100 are categorized as very high frequency step pulses that deliver a very sharp resolution from the low to the high voltage state. These high resolution pulses are required to accurately time the signal departure and reflection.

The TDR100 is powered by the datalogger through a 12 volt switch. However, the TDR 100 can also be operated independently, in the absence of a datalogger, by connecting it directly to a 12 volt battery and a computer running the PCTDR software program. The PCTDR software is supplied by Campbell Scientific and allows control and communicates with TDR100. This feature allows TDR100 to be used as a portable device which can be taken from site to site as well in fixed installations where the connections to the TDR probes may be semi-permanent.

Figure 3.2: Campbell Scientific TDR100 pulse generator (Campbell Scientific, 2002)

3.1.1.3 Multiplexer

The most significant limitation of the TDR100 is that it has only one cable connector and only allows monitoring of one cable at a time. Using multiple TDR100 modules in a TDR station is not cost effective and is troublesome because of the high power requirement of each device. The solution to this problem is the installation of an add-on device called a multiplexer. A multiplexer expands the capacity of the TDR100 by allowing multiple cable probes or testing tools to connect to a single source and still be addressed individually. This means all cable probes and testing tools can share the same reflectometer, datalogger, power supply, and data storage. The multiplexer used in this research was the SDMX50, illustrated in Figure 3.3, manufactured by Campbell Scientific Inc.

Figure 3.3: Campbell Scientific multiplexer (SDMX50) (Campbell Scientific, 2002)

A single SDMX50 multiplexer is designed to support up to eight connections. If necessary, multiple multiplexers can be used in series to monitor an even larger network of sensors. The network illustrated in Figure 3.4 indicates a system can hold up to 512 cable probes through three levels of multiplexing all supported by a single 12 volt DC power source, TDR100, datalogger and storage device. Figure 3.4 shows that the first level of multiplexing consists of one multiplexer. This multiplexer allows up to 8 connections, that could consist of either all cable probes or all multiplexers connections or a combination of each type of connection. If all first level connections are connected to multiplexers, the multiplexers on the second level can hold up to 64 probes or 64 multiplexers. A maximum of three levels of multiplexing are allowed on this device. In a fully expanded network, a multiplexer is connected to every connection on the first and second levels, which increases the total number of cable probes that can be supported on the third level of the network to 512. Another feature of the multiplexer is the quick-connect BNC cable connectors, which are designed for easy attachment and detachment of various types and sizes of cable probes.

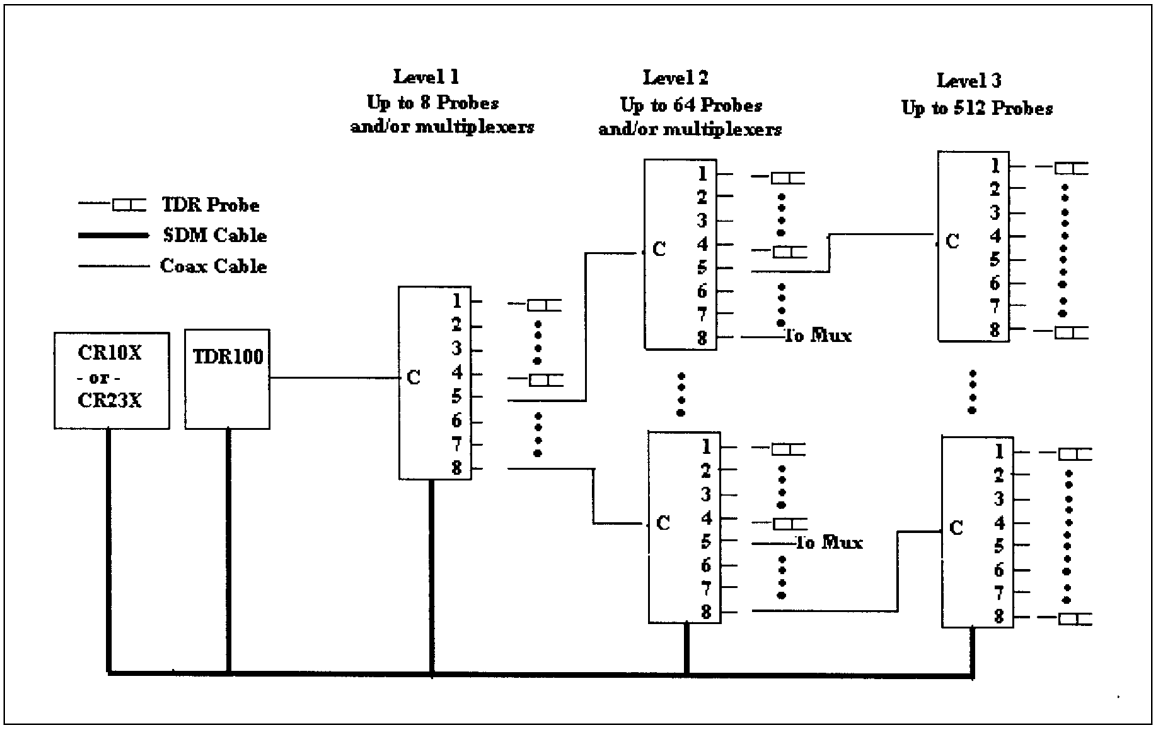


Figure 3.4: Multiplexer Connection (Campbell Scientific TDR 100 Instruction Manual, 2000-2001)

3.1.1.4 Power Supply

The TDR station was powered by a deep cycle marine battery, which provided 12 volts of DC power. The battery was connected directly to the datalogger and the cellular phone through two terminal strip adapters that allowed multiple connections to a single battery terminal. In order to maintain a constant power supply to the TDR system, the battery was recharged by a solar panel (model MSX10R) produced by Mr. Solar as shown in Figure 3.5. This solar panel provided 20 watts of power on a bright and clear day. The datalogger was connected directly to a battery, while the power for all other devices in the system was supplied through the switched voltage terminals on the electric panel of datalogger. The switched power terminals on the datalogger allowed the control programs to turn power on and off, which reduced power usage. This energy saving feature helped to conserve battery power so the system could operate reliably at night or on cloudy days when the solar panel generated little or no power. To prevent the solar panel from discharging the battery at night, it was equipped with a diode to prevent the reverse flow of energy.

Figure 3.5: Solar Panel for TDR station

3.1.1.5 Communication System

The communication system consisted of the remote TDR station and the base station. The wireless communication utilized cellular phone service which is widely available in most parts of the country. Once the communication function was activated, the modem initialized a call to the base station through a cellular phone. At the base station, a polling computer which was connected to a land line received the signal from the remote station and initiated the communication sequence that started the downloading or uploading of data. The communication connection could also be initiated by the polling computer as well. However, calling the remote TDR station could only be performed when the cellular phone was turned on at the remote station. In the system used in this study the cellular phone was only powered on according to preset schedule in the data logger's control program in order to conserve energy. A schematic of the communication concept is provided in Figure 3.6. A Campbell Scientific Com210 telephone modem was selected for this study because of its excellent compatibility with the CR10 series datalogger. This modem can transmit data at the rate of 9600 bits per seconds or more. Furthermore, it is reliable in adverse weather conditions. Time synchronization between the remote TDR system and the polling computer is important and allows automatic data acquisition according to the preset schedule.

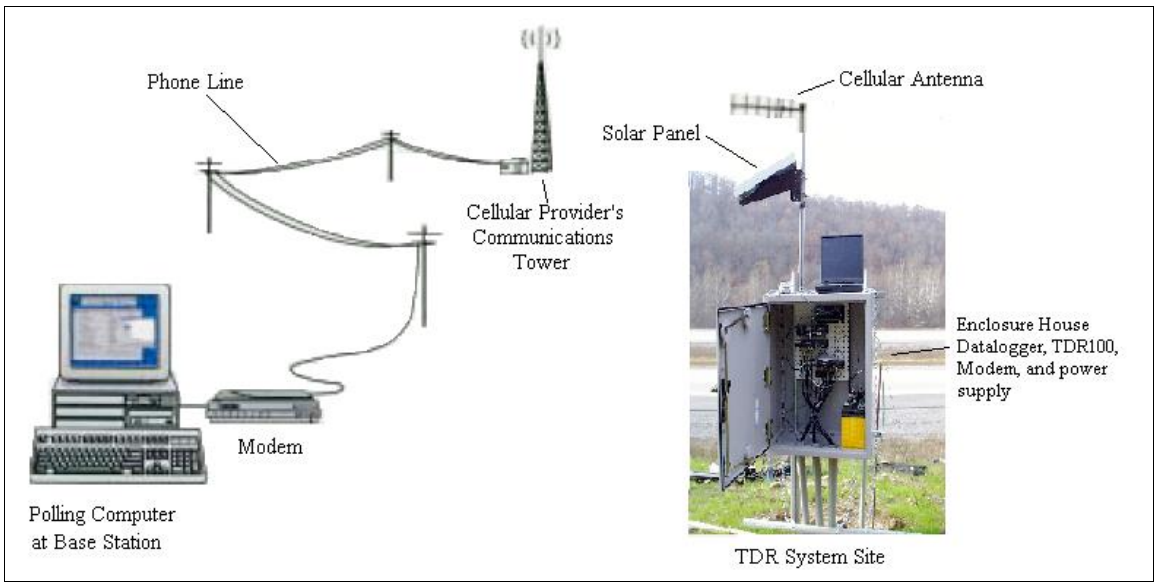


Figure 3.6: The communication system for TDR.

3.2 Coaxial Cable Probes for Slope Stability Monitoring

Coaxial cable is commonly used as TV cable and is easy to obtain. This section discusses the properties of the coaxial cables used in this study and their effectiveness in slope monitoring. Different types and sizes of coaxial cables were used in this study to determine the effectiveness of each cable type. The pre-selected coaxial cables were RG58, RG59, RG8, rigid copper air-dielectric cable, and rigid aluminum foam dielectric cable.

As illustrated in Figure 3.7, coaxial cable is a transmission line consisting of outer and inner conductors separated by a layer of dielectric material. Coaxial cables are categorized into rigid or flexible cable. A rigid cable has a solid heavy-duty sheath, while flexible cable types have a braided sheath. The rigid sheaths are typically copper or aluminum, while the flexible sheaths can be copper, aluminum or steel. The dielectric material, also called the inner insulator, is made of non-conducting materials or can simply be an air gap. The size and configuration of each of these cable components have a significant effect on the cable's properties such as its characteristic impedance, signal propagation velocity and its attenuation. The coaxial cables used in this research are illustrated in Table 3.1.

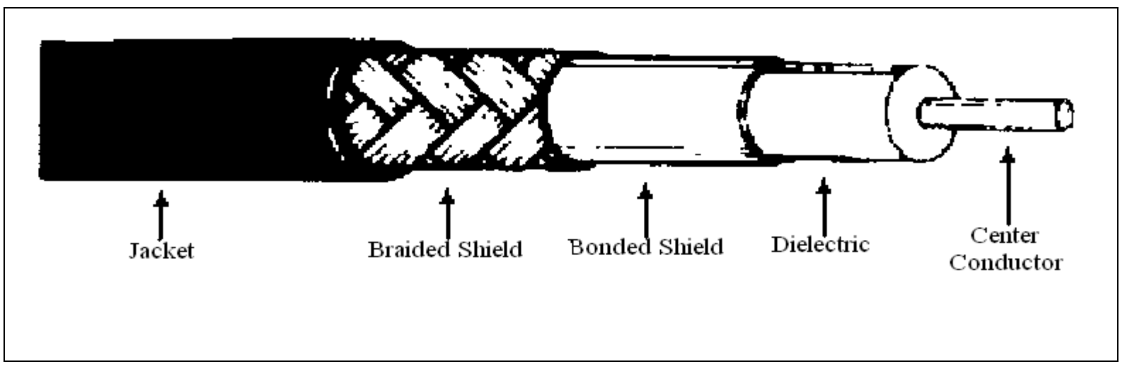


Figure 3.7: A typical flexible coaxial cable profile. (Belden, Inc.)

Table 3.1: Coaxial Cable Properties for the Four Cables Used in This Study

Cable Type	Manufacturer	Impedance (Ohm)	Diameter mm (in)	Propagation Velocity (%)
Flexwell Air Dielectric Coaxial Cable (HCC 12-50J)	Radio Frequency System Meriden, Connecticut	50	12.5 (0.5)	91.5
Foamflex Foam Dielectric Coaxial Cable (FXA 12-50J)	Radio Frequency System Meriden, Connecticut	50	12.5 (0.5)	81
RG8/U (9914)	Belden INC, St. Loius, Missouri	50	12.5 (0.5)	82
RG58A/U (8240/8259)	Belden INC, St. Loius, Missouri	50	5.0 (0.2)	66

To select the best cable for this study, the purpose of application and the cable's properties had to be well defined. A few factors considered in cable selection were:

1) sensitivity to deformation,

2) amount of shear needed to detect the initial movement,

3) maximum displacement before shear failure, and

4) type of dielectric.

Campbell Scientific, Inc recommended against using coaxial cables having PVC dielectric materials with the TDR100, unless the cable length was less than 25 feet. The reason is that PVC dielectrics cause far more attenuation than polypropylene or polyurethane dielectrics. Using PVC as the insulation material in cable might affect the frequency response and reliability of theTDR100.

Figures 3.8a through 3.8d show the coaxial cables that were used in this study. In Figure 3.8a is a (12.5mm) 0.5 inch air-dielectric cable with a corrugated copper outer conductor and solid copper inner conductor. The dielectric material is air. The corrugations in the copper wall are designed to increase this rigid cable's flexibility. The cable illustrated in Figure 3.8b is a (12.5mm) 0.5 inch foam dielectric coaxial cable with a smooth outer aluminum sheath, or, outer conductor. Its annular space is filled with a foam dielectric material, which has a fixed and uniform geometry throughout the cable. The cable in Figure 3.8c is a flexible RG8 type. Its conductor is copper which is separated from the braided steel outer conductor by a layer of foam made of high density polyethylene. Among all coaxial cables with a 12.5mm (0.5in) diameter, the RG8, with a braided outer conductor has more flexibility when compared to the air and the foam dielectric cables. The coaxial cable illustrated in Figure 3.8d is a 5mm (0.2in) RG58 with a braided and tinned copper outer conductor and a solid copper center conductor. This cable is the thinnest and most flexible cable investigated during the study. It was used in this study to determine the effectiveness for slope monitoring when compared to other larger size cables.

In this research, connectors were used in several conditions, for instance when connecting coaxial cables to the multiplexer, cable extension, and joining two different types of cables. As shown in Figures 3.8a through 3.8d, the N-type connector and BNC connector were used to connect RG8 cable to multiplexer.

Air and foam dielectric coaxial cables were used to study to determine their effectiveness as the cable probe. However, due to their high cost the difficulty in routing the cable to the field equipment enclosure, they were used only on the below ground section of the cable probe. The above ground portion of the probe consisted of RG8 cable which was connected to the rigid cables with special connectors illustrated in Figures 3.8a and 3.8b and standard N-type splices

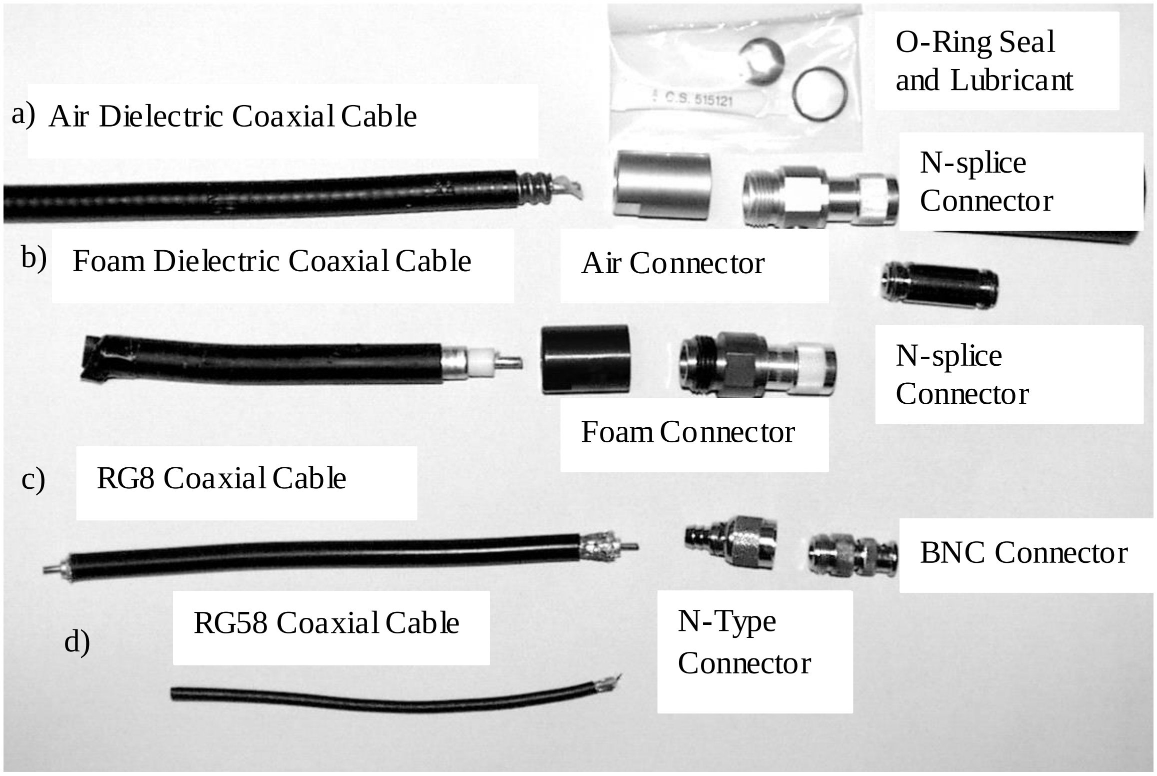


Figure 3.8: a) Air dielectric coaxial cable and connector, b) Foam dielectric coaxial cable and connector, c) RG8 coaxial cable and connector, d) RG58 coaxial cable and connector

During installation, the connectors were attached to a cable in strict accordance with the manufacturer's recommended procedure. In addition they were waterproofed to ensure proper transmission of the voltage signal from the pulse generator. The connectors exposed on the ground surface required the greatest waterproofing attention, especially those on the foam or air dielectric cables. All connections were protected with electrical tape and PVC shrink wrap. Connection points are the weak link in the trouble free operations of a cable probes. Vandalism and animal interference could cause cable damage such as discontinuity of a connector, kinking of the cable, or fraying of the outer conductor all of which will reduce the effectiveness of cable probe. They should be installed with care and maintained properly. A loose or wet connector will cause problems with attenuation or loss of signal altogether and eventually will not allow the transmission of any signals.

3.3 TDR System Control Software

3.3.1 PC208W 3.3 - The Datalogger Support Software

PC208W, distributed by Campbell Scientific, is a software program designed to control the CR10X datalogger. PC208W allows the user to manually control and modify the settings of the TDR stations. PC208W is "Windows" based software, and is relatively easy to access and operate. This software facilitates programming, communication and data exchange functions. The 8 major operating functions of this software are shown in Figure 3.9.

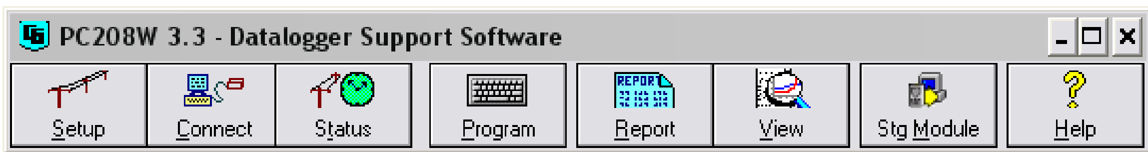


Figure 3.9: PC208W 3.3 toolbar

Each button on the toolbar is used to launch and control independent windows. The functions of each operation button are summarized below:

Setup: This window allows the user to configure the PC interface to communicate with all attached equipment. The device map under this function allows a PC to identify the type of modem, dataloggers, and COM ports used. The three major features under *setup* are:

> *Hardware* – controls the PC dialing information including phone number, call back ID number (remote station's identification number) for alarm system, communication rate (Baud Rate) and online time.
>
> *Data Collection* – controls the data storage properties, including data file name, storage format, and the source of data collection.

Schedule – controls the automated data acquisition properties. The calling schedule and calling interval can be set and adjusted here.

Connect: This window is the primary communication control between an attached computer and the datalogger either directly or remotely with the TDR stations. When the computer and the datalogger are connected, the user can synchronize the clock between the computer and the TDR station, send or retrieve programs, collect data, and view graphs. This function also allows the user to turn the ports on the datalogger's wiring panel on or off.

Status: This window basically provides status of operation for the TDR system. The "*Status* window" monitors connection and data collection of the devices. It also allows manually operated data collection when necessary. For systems with an alarm system setup, warning messages with a call back ID number can be viewed here.

Program: This window is used for creating, editing, and documenting programs for the datalogger. The program generator in this function is known as *EDLOG*. It is user-friendly and requires only minimal programming knowledge to operate. The automation of the TDR system operation is made possible by using EDLOG within PC208W to create control programs. A simplified and standardize programming sequence helps to avoid conflicts and syntax mistakes in the program. There are 133 preset system programming instructions included in this window. A complete EDLOG program must be well arranged and easy to follow. All of this information is divided into three main categories which include 1) program execution instructions, 2) cable probe testing instructions, and 3) output instructions. The system programming can be done by inserts, cuts, or pastes of the preset instructions according to the sequence that directs the TDR operation. Before a program can be executed the software's self checking features examines every new program for flaws. If errors are encountered they must be corrected before EDLOG will allow execution. The program allows the TDR system to be switched to hibernation mode for energy saving, go into probe testing and data storage mode, perform analyses of data for alarm purposes, or contact a polling computer for data retrieval and time synchronization.

Report: The main task for this window is to process data through the use of a program called SPLIT. Each unit of collected data is separated by a comma. SPLIT helps the user to convert this data to a viewable spreadsheet which is compatible with Microsoft Excel®. This window also allows users to sort or search data from a particular array by specific date and time.

View: The main function of this window is to allow a quick glance at the retrieved data. This window shows ASCII files in comma separated, columnar, or hexadecimal format.

Stg Module: this window expands functions of the TDR system by allowing the connection of other equipment to the datalogger. It allows communication between the datalogger and a testing probe that may require special instructions. This is another way to communicate with datalogger if some other communication equipment is required.

Help: To access the help window of PC208W.

The standard procedures for datalogger programming, operation sequence and data collection are summarized as follows:

Step 1: Compile an executable program by using *EDLOG* that accurately reflects the operation specifications and requirements.

Step 2: Configure the communication link between the computer and datalogger with the *setup* window.

Step 3: Install program to the datalogger using *Connect*.

Step 4: Contact and collect data from datalogger either manually or remotely with *Connect* or *Stg module* window.

Step 5: Use the *SPLIT* and *View* windows to process the collected data. Plot graphs with reflection coefficient versus depth for analysis.

3.3.2 TDR Probe Calibration and PCTDR for Cable Waveform Monitoring

3.3.2.1 Distance Measurement and Propagation Velocity (Vp) of Cable Probes

Cables manufactured with different dielectric materials have different propagation velocities. In general, the coaxial cable's propagation velocity ranges from 0.67 to 0.9 times the speed of light. For example, the RG8 cable and air dielectric cable used in this study have a Vp of 0.82 and 0.91, respectively. Usually, information about a cable's properties is included in the manufacturer's specifications. However, for precise measurements of distance the the Vp of coaxial cable should be independently determined through testing using Equation 3.8:

$$V_{pa} = \frac{D_a}{D_m} V_{ps} \qquad \textbf{3.1}$$

- *Da* = Apparent Distance: is the distance measured electronically with the PCTDR program. This distance is dependent upon the Vps selected in the PCTDR program.
- *Dm* = Actual Distance: is the physical cable distance measured by using tape or other measuring tool.
- Vps = Selected Propagation Velocity: value selected by the user in PCTDR for calculation purposes. Vp is usually set to 1.0 for cable calibration to make the calculation easy.
- Vpa = Actual Propagation Velocity

3.3.2.1 Verifying Probe Length after installation

Even though the propagation velocity of the cable can be measured and its apparent length can be determined in PCTDR, establishing exact measurements of cable length in the field can be complicated. The TDR pulse not only has to travel though the cable that makes up the cable probe, it must also travel though interior wiring of the data acquisition system, connectors and multiplexers, each of which add some apparent length to the cable. As a result, the actual starting point and length of the TDR cable probe must be verified it the field.

There are two ways to measure the actual probe length once the cable probe has been installed underground. Both require knowing how much cable is actually grouted into the slope. This is done by placing marks at 5ft intervals to simplify the measuring process. While inserting the cable into the hole, the marks were counted. Then by knowing the number of marks that when into the hole and by measuring back from the first visible mark outside the hole to the ground surface, the actual physical distance of cable underground could be calculated.

In the first method total cable length is calculated using Equation 3.1 and the measured propagation velocity, then the depth of the borehole is subtracted from this measurement. If this distance does not match the physical measurement of the cable distance from the top of the grouted probe back to the multiplexer the propagation velocity must be adjusted to make the electronic distance match the measured distance. The second method of measurement requires clamping a pair of vise grips to the cable right above the point where it is grouted into the borehole. The distortion of the dielectric material at the point of clamping will create reflected energy in the cable's waveform. This gives a known starting point for the cable probe and the window of measurement can then be adjusted based on the known length of the probe embedded in the ground., A RG8 cable waveform captured by PCTDR with a total length of 24.58m measured from the TDR unit to the end of the cable probe underground is illustrated in Figure 3.10. The cable section that was buried underground was 3.83m in length. The cable was crimped at the ground surface which occurs at 20.75 meters in the illustration and the end of the cable in the illustration appears to be at 24.5 meters.

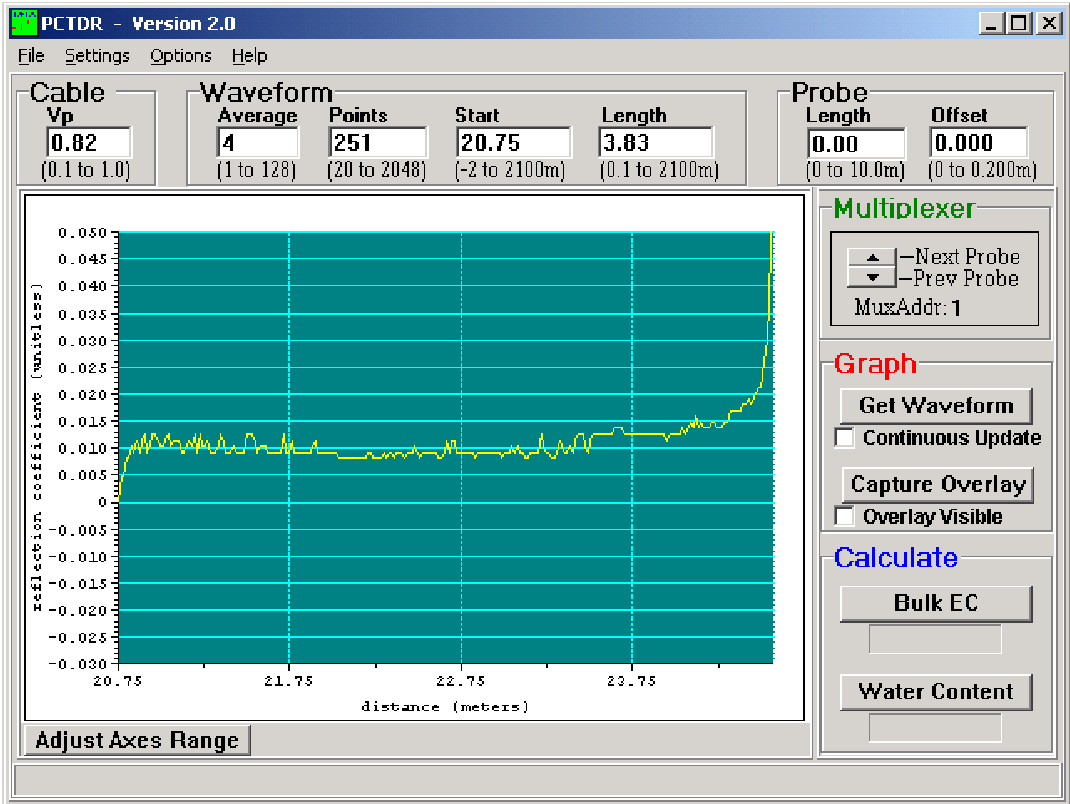


Figure 3.10: PCTDR for coaxial cable waveform monitoring

3.4 Inclinometer System

The inclinometer system that was used in this study is manufactured by Slope Indicator, Inc. As shown in Figure 3.11, this system consists of an inclinometer probe, control cable, a portable readout unit, inclinometer casing and two programs used for data analysis, DataMate Manager and DigiPro.

When the inclinometer casings were logged during this study, the 24 inch inclinometer probe was drawn upward from the bottom of the casing and stopped at 1 foot intervals to record tilt information. The maximum depth that could be monitored by the inclinometer system used in this study was 100 ft which was controlled by the length of the cable. All stations investigated in this study had at least two inclinometer casings installed. The casings were extended through the suspected zones of movement into the firm underlying material which was not subjected to movement. For the purposes of making a direct comparison between the movements reported by the inclinometer probe to those reported by the TDR system the inclinometer casings were install in close proximity to the TDR cable probes. The reason for this was to make sure that the inclinometer casing and the TDR cable(s) were sheared at similar locations and magnitudes when movement occurred.

The Digitilt DataMate readout unit, illustrated in Figure 3.11, supplies power to the inclinometer probe, records the tilt data, and provides temporary storage for the retrieved data. This device is distributed by Durham Geo /Slope Indicator, Inc. A fully charged Digitilt DataMate can power an inclinometer probe for up to 16 hours. The internal memory provides storage for up to 40 complete inclinometer surveys. The program used for data analysis and display of the inclination data is called DigiPro, also distributed by Durham geo/Slope Indicator, Inc. In DigiPro, the inclinometer data can be organized into a standard tabular form or view in graphical form as shown in Figure 3.12.

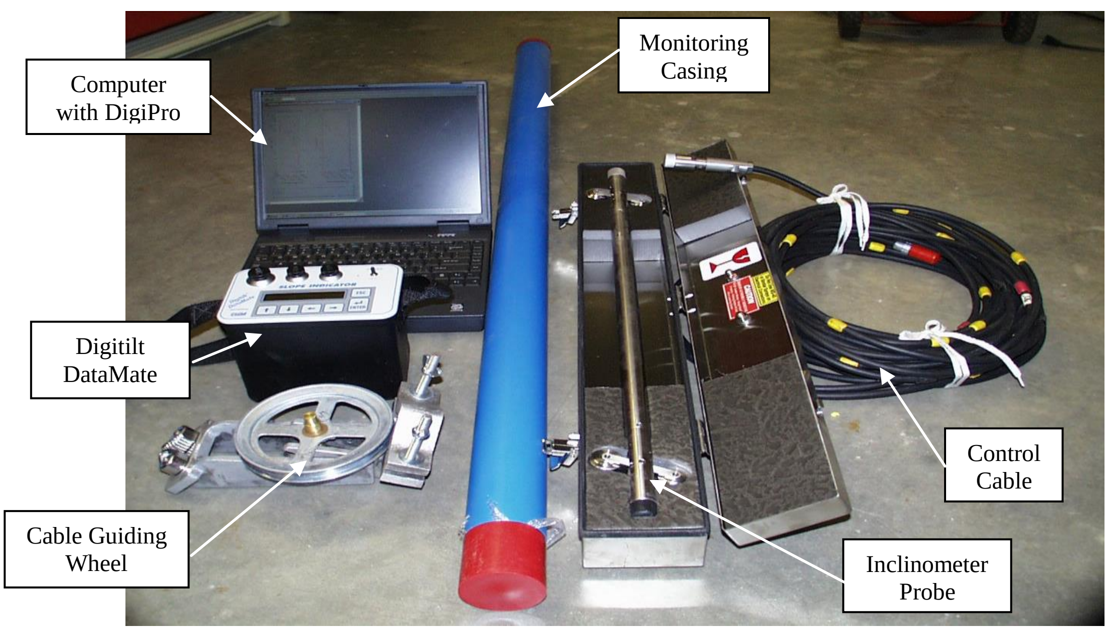


Figure 3.11: Inclinometer system by Slope Indicator.

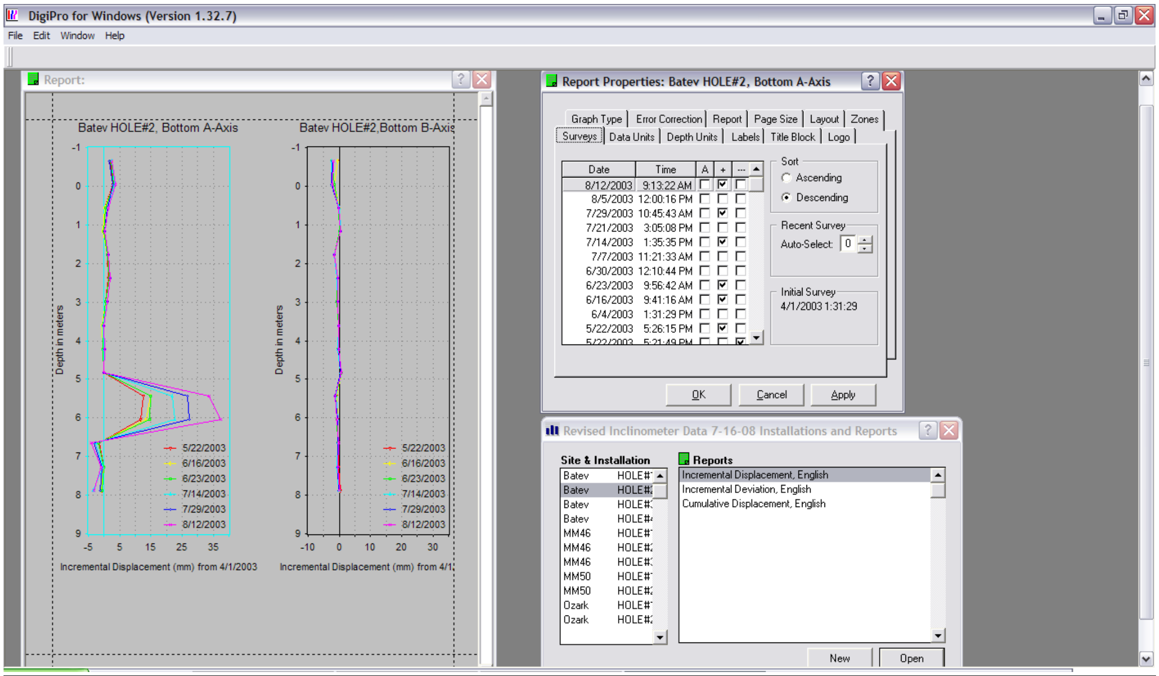


Figure 3.12: DigiPro for inclinometer data analysis

3.4.1 Inclinometer Casing Installation

An inclinometer monitoring system was used at every site in this study. The inclinometer data were compared with TDR results to determine how faithfully the TDR probes reported movement. The inclinometer data served as the absolute value for deformation along a slope plane in a slope. At least two inclinometer casings were installed at each monitoring station. Each station utilized a different approach for installing the inclinometer casing, primarily to improve on the installation method over that of the previous experience.

Typically a grout mixture is poured into the annulus between the casing and the wall of the borehole until it fills the borehole to the ground surface. This creates a problem in deep boreholes because the hollow casing tends to float in the grout and misalignment can occur. One of the criteria for inclinometer casing installation is that the internal grooves that form the two perpendicular guiding tracks for the inclinometer must be oriented such that one plane is parallel to the slope direction and the other is perpendicular. This floatation problem caused a number of inclinometer casings to not meet this installation requirement. This flaw could cause inaccuracies in the reporting of the movement magnitude if the retrieved data is not properly adjusted to account for the rotation of the inclinometer casing. The upward lifting buoyant force on the end cap of the casing also caused minor bending of the inclinometer casing when a counter weight was added at the top of casing to prevent floatation.

Most of the inclinometer casings installed for this study did not utilized full depth grout. In an attempt to make the casings dual purpose the lower reaches of the casings had a series of 2 mm diameter holes drilled in the and the annulus between the casing and the borehole wall was filled with pea gravel to within 1.5 meters of the ground surface. A blanket of bentonite pellets was placed on top of the pea gravel and the annulus was sealed with a weak cement bentonite grout to the ground surface. By installing the casings in this manner, they served as both inclinometer casings and observation wells. The pea gravel and holes hole in the casing allowed ground water to flow in and out between the casing walls to indicate the ground water level in the slope. However, the sediment ladened ground water carried small soil particles into the casing causing the casing depth to diminish, sometimes by as much as 5 inches over the course of the study.

Another potential problem with data collection was that the inclinometer probe can be sensitive to changes in temperature. When ground water fills the inclinometer casing, the temperature in the casing can be significantly different from the ambient air temperature. This temperature change can affect the accuracy of the tilt indicated by the inclinometer. Based on the manufacturer's recommendation, the inclinometer should remain at each reading interval until the temperature had stabilized before recording that data point. For this study the inclinometer probe was allowed to equilibrate for 15 minutes before any readings were taken.

3.4.2 Grout Placement Procedures

The grout mixture used for casting TDR cables underground consisted of a combination of cement, bentonite, and water. The rule of thumb for grout design is that it should be strong enough to shear the cable but weak enough that it will break when there is slope movement. Once the grout hardens, it should act as a medium to deliver the force from slope movements to shear the embedded coaxial cable.

Improper grout mix design or installation could potentially reduce the effectiveness of the TDR probe. However, there is no standard mix ratio for the grout. The combination should be based on the installation conditions. Therefore, the surrounding soil strength, flowability for pumping (if pump is used), and the depth of hole are determining factors when preparing the grout mixture.

At some installations, a high water cement ratio caused shrinkage of the grout when it hardened. This caused cavities to develop within the grout column. In some other cases, the grout mixture took days or even weeks to solidify. The slow set of the grout caused the portion of the grout column closer to the ground surface to hardened faster and caused separation of grout column. A high water content in the grout mixture caused heavier particles to settle, which eventually formed a weak layer between the surface layer and the bottom layer. Another problem was the prolonged process of solidification.

In some localized areas the liquefied grout might seep into surrounding soil cavities while in other areas it might not permeate. This scenario causes hard spots in the grout column which might cause it to break at a location different than the shear plane. This could lead to inaccuracies in determining the correct location of shear in the slope, or possibly give false readings of slope movement. The final grout mixture used in this study for grouting TDR cables consisted of 1 part bentonite, 9 parts Portland cement and 30 parts water. This mixture produced a grout with strength of approximately 2000 kPa (300 psi).

3.5 Site Installation

3.5.1 Station MM46 on Interstate-540

The first location selected for a TDR Station installation was at Mile Marker 46 (MM46) on east side of the north bound lanes of Interstate-540. The cut slope consisted of mainly sandy clay soil underlain by medium hard gray and brown weathered shale. The slope steepness was close to 3:1 with minimum vegetative cover. This location was selected based on a previous slope failure immediately adjacent to the site where the surface cracks could be observed. A few other locations on the same cut slope had similar movement problems and had been remediated by pushing the displaced soils back to the original slope grade or the failed soil had been replaced with rock.

As illustrated in Figure 3.13, 12 coaxial cables and 3 inclinometer casings were installed in three horizontal rows at Station MM46. Each row consisted of coaxial cables with different rigidities and dielectric properties and an inclinometer casing. The cables and inclinometer casings were extended to depths ranging from 3.5 to 14 feet. Each cable or casing was embedded in an eight inch diameter weak sand-cement grout column.

Subsequent compression testing on the grout indicated an unconfined compressive strength of around 900 psi.   The size of this column was dictated by the drilling equipment available from the AHTD at this location.

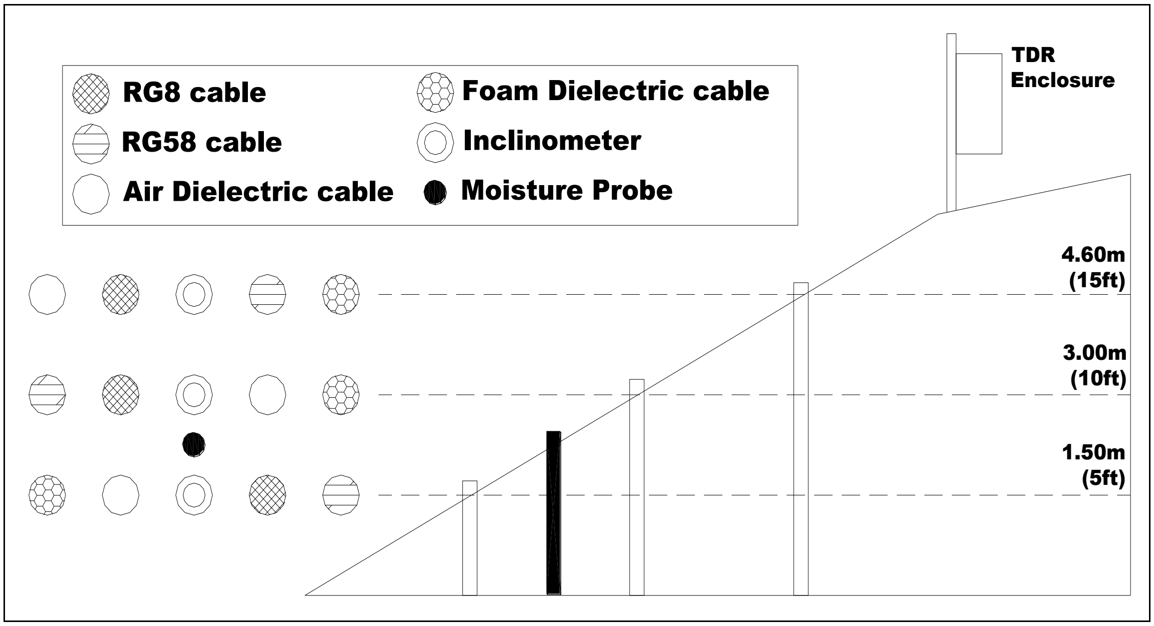


Figure 3.13: TDR cables and Inclinometer layout for the Mile Marker 46 site.

After one and a half years of monitoring, the measuring devices showed little or no movement. Even though the slope had previously failed at this location, the inclinometer readings showed less than one half inch of total movement, and the TDR probes indicated no discernable shearing of the grout column. It was hypothesized that the slope had been reinforced by the high number of large diameter grout columns installed in a relatively small area. This reinforcement improved the composite strength of the soil mass and prevented failure. This hypothesis was reinforced by observation of a slope failure immediately adjacent to the instrumented area of the slope during the period of monitoring. As illustrated in Figure 3.14, surface cracking and slope creep were noticeable adjacent to the research area. Surface cracks were extensive in this area but stopped abruptly next to the monitoring locations. Based upon the experiences at this site laboratory testing was conducted to establish the deformation threshold required to reflect energy in the TDR cables and produce a noticeable "spike" in the waveform. In addition, a revised drilling and grouting plan was developed for the next site.

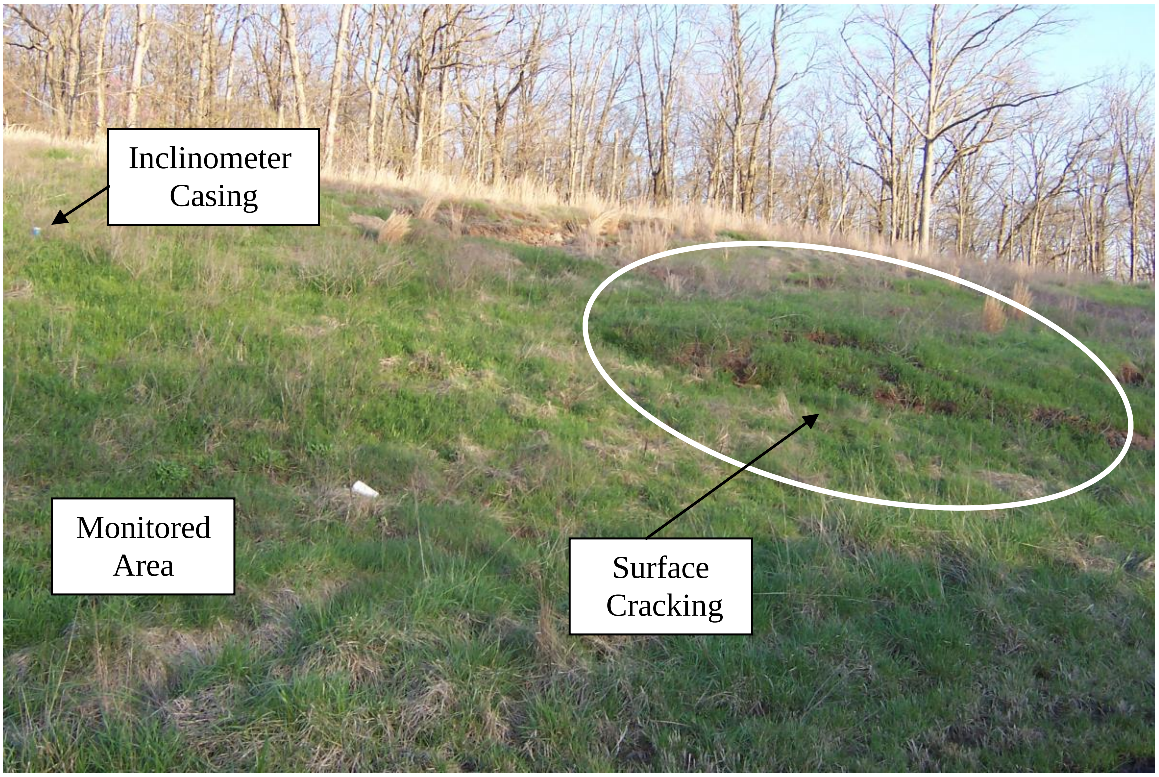


Figure 3.14: Slope failure occurred next to Station MM46.

3.5.2 Station MM50 on Interstate-540

The second station installed during this study was located at the top of a cut slope in the median along the north bound lanes of I-540 at Mile Marker 50. This location had a 3:1 slope and had failed twice previously. The soil type on this slope consisted of mixed clay over shale. A developing tension crack was discovered traversing across the upper third of the slope which was attributed to slope movement.

As illustrated in Figure 3.15, a total of 10 coaxial TDR cables, two TDR moisture probes, and two inclinometer casings were installed in the middle section of the embankment. Among the 10 cables, there were two RG58 cables, two RG8 cables, two air-dielectric cables, two foam-dielectric cables, and a RG59 cable. The cable installation was divided into two phases. The first phase of installation was completed in June 2002, when four coaxial cables, a moisture probe and two inclinometer casings were installed. The second phase was completed in July 2002 and consisted of four more coaxial cables, which were installed adjacent to those from phase one. The reason for the additional installation was that the grout used on the first phase of installation was a very weak cement-bentonite mixture, this produced a grout that did not harden and was too soft to shear the cables. The grout mixture used on the second phase of installation was a stronger cement-bentonite grout which insured a better shearing result. The second phase grout mixture was composed of 1 part bentonite to 9 parts cement having a water to cement ratio of 1.65 and an unconfined compressive strength of approximately 1400 kPa (200 psi).

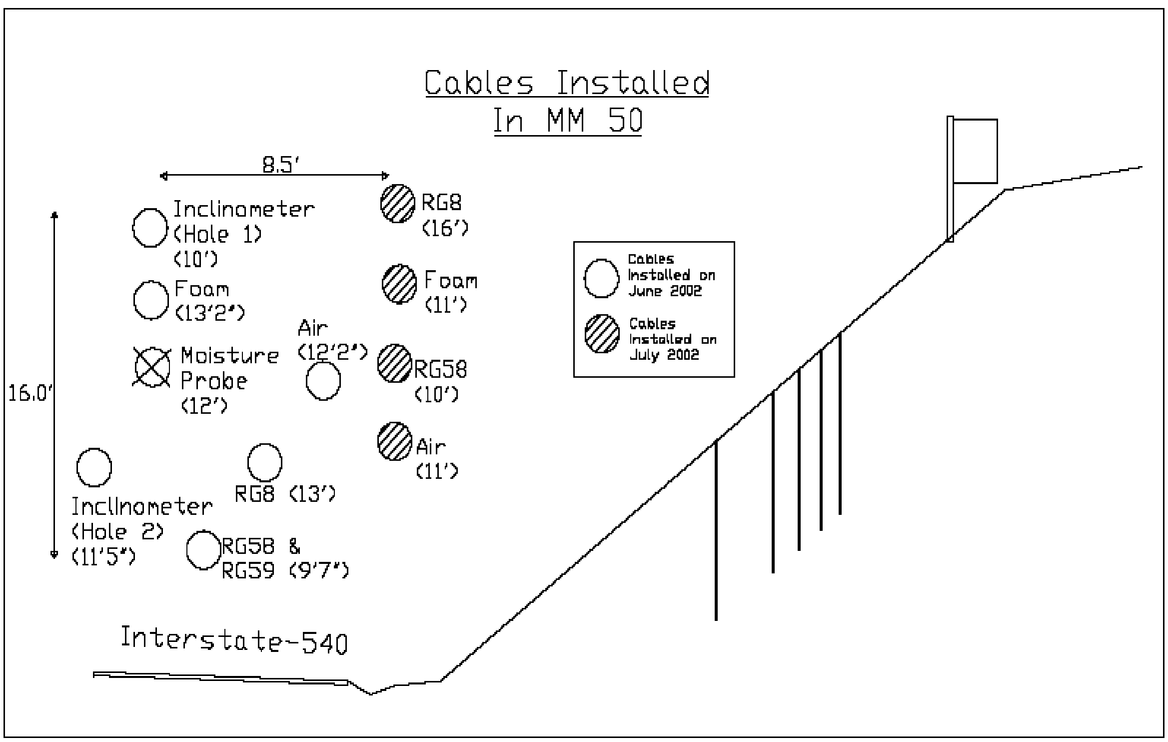


Figure 3.15: Station MM50 installations layout

On the first phase of installation, boreholes were created by driving a 50 millimeter (2 inch) standard split spoon sampler using the automatic standard safety hammer on a tracked drill rig. The main reason for using the 2 inch split spoon rather than an auger to create the borehole was to create a small as possible grout column. I was hoped that the minimal use of grout would eliminate the over reinforcement observed at MM 46. In the same area, a 4 inch diameter auger was used to create two boreholes for the 2.5 inch inclinometer casing installations.

All cables and inclinometer casings were monitored on a weekly basis for a period of 25 months. The remote monitoring of cables was discontinued at the site in May, 2003 because only limited movement was detected in the inclinometer casings. The autonomous monitoring station was relocated to a new site to monitor slope movements. Both the inclinometer casings and the TDR probes were monitored manually on a weekly cycle until August, 2003 when movement was detected. At this time the autonomous TDR station was reinstalled for further automatic monitoring. Figure 3.16 is a picture taken after the TDR monitoring station being installed.

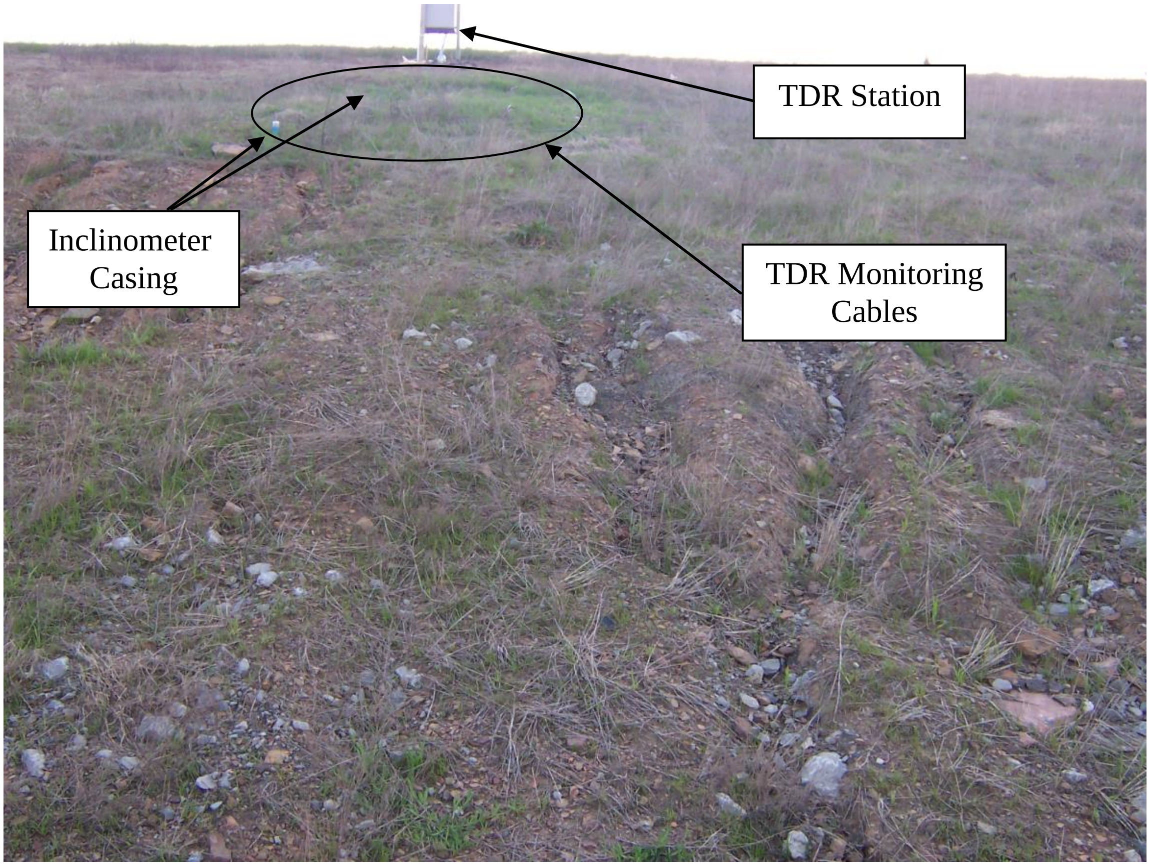


Figure 3.16: MM50 TDR monitoring station

3.5.3 Ozark Station on Interstate-40

The third TDR installation was located on the north side of the west bound lanes of Interstate 40, approximately 0.3 miles to the east of Exit 35. This station was installed on January 22, 2003. At the time of installation signs of potential movement were observed after an extensive remediation program had been completed to stabilize the slope. The remediation consisted of significant upslope drainage improvements and shallow reinforcement of the subgrade in the roadway with Geogrid. At the time of installation of the monitoring equipment a long surface crack, 34 feet in length having a width ranging from a few inches to a foot was observed approximately 20 feet from the edge of the roadway in new fill material used for stabilizing the road. The embankment had a slope of approximate 4:1.

In an attempt to inure that the unstable slope was not altered by the installation of the monitoring equipment, only 3 coaxial cables and two inclinometer casings were installed at this station. The original plan was to install the monitoring cables and inclinometer casings to a depth of 40 feet. However, after numerous attempts to achieve this depth that plan was abandoned because the drill consistently encountered auger refusal at a depths less than 20 feet. As a result, one inclinometer casing was installed to a depth of 20 feet and the TDR cables were installed to a depth of around 13 feet. Monitoring at this station was terminated after a year because no movements were observed in either the inclinometer casing or TDR probes. It was hypothesized that the drainage improvements had corrected the instability problem.

3.5.4 Batesville Station on Highway-167

A TDR station was installed along a slope on US 167 at Ramsey Hill, Batesville, Arkansas in April 2003. This slope was actively moving and the road surface had exhibited significant settlement. The AHTD wanted to monitor the slope movement in order to establish the failure geometry of the slide. The slope instability had become a public safety concern since it was on the main route into Batesville and a by-pass required a 50 mile detour.

Pavement cracking initially started at the northern shoulder of the highway. However, as the slide progressed the cracks extended toward the highway center line. To stop the slope movement, the AHTD planned to reinforce the unstable slope, but they needed data from the monitoring program to complete the remediation design. The slope monitoring process started before the remediation works took place and continued throughout the process. The monitoring work continued even after remediation to detect any continuing slope movements which would validate the reliability of the repair.

Two TDR cable probes and two inclinometer casings were installed in this slope in April, 2003. The first set of monitoring probes known as “Batesville-Top” was a combined set of an RG8 coaxial TDR cable and a 2.5 inch inclinometer casing. The monitoring probes were located in the shoulder of the road and were intended to monitor movements at the crest of the slope. The other set of monitoring probes, referred to as “Batesville-Bottom”, were installed near the middle of the slope failure. These monitoring probes were located on the downhill side of the first installation approximately 152.4 feet from the center line. Both the TDR cable and the inclinometer casing for “Batesville-Top” were installed to a depth of 40 feet while those for the “Batesville-Bottom” were extended to 30 feet below the ground surface. At this location RG8 cables were grouted into 4 inch diameter boreholes with grout having a compressive strength of approximately 1725 kN (250psi).

The inclinometer casings were logged manually every week while the TDR cable data was collected every 3 hours automatically. Data analysis indicated continuous slope movements throughout the monitoring period. When the bottom inclinometer casing was logged on 9/12/03 it was discovered that excessive movement at approximately 26 feet (8 meter) below grade had caused the casing to bend so much that the probe could not be lowered to the bottom of the casing. Further monitoring of this casing was abandoned on this date. However, the adjacent TDR probe continued to be monitored until all monitoring at this site was terminated at the start of slope repairs. The slope movement that caused the bending in the casing also triggered a signal on the adjacent coaxial cable.

As illustrated in Figure 3.17, the cable's reflection indicated a developing shear zone at the same location as the bend in the inclinometer casing.

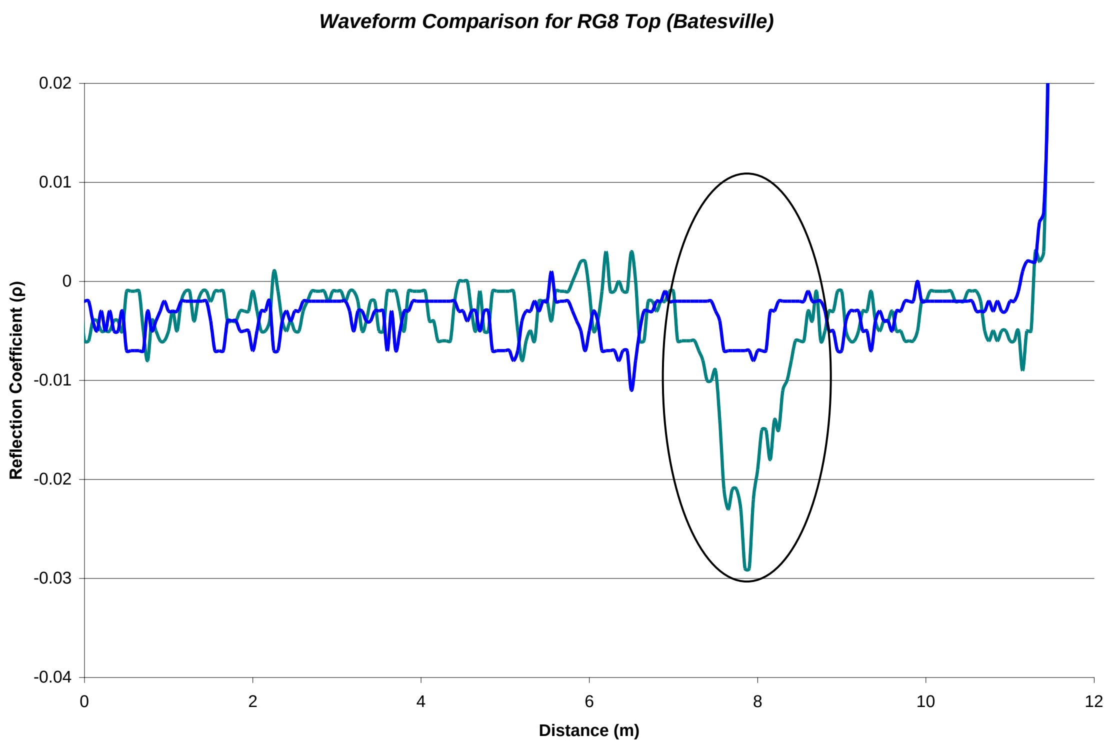


Figure 3.17: Comparison of TDR signals recorded on (05/26/2003) (baseline signal) and 12 Aug 2003 for the bottom Batesville monitoring station

3.5.4.1 Batesville Slope Remediation

The Arkansas State Highway and Transportation Department determined the best remediation method for the Batesville slope failure was installation of Geopiers® near the toe of the failure mass. This method could be performed without interrupting the traffic flow along US 167 and the most important part is that this technique did not require any major excavations in the failed zone which might endanger the travelling public.

Figure 3.18 summarizes the Geopiers® installation process. First, a hole is drilled into stable strata underlying the failure surface. Then, starting from the bottom, the cavity is filled with graded stone in approximately two foot layers. Each layer of stone is compacted by ramming with a specially shaped plate which forces lateral displacement of the aggregate into the surrounding soil. This process increases lateral stresses in the soil, making it stiffer and stronger. The ramming process is continued until the entire cavity is completely filled. The separation between two Geopiers® was around 5 feet. Altogether 680 Geopiers® were installed in three rows across the lower portion of the failure mass. The overall function of the Geopiers® was to increase soil strength provide strong aggregate inclusions in the failed area and provide some drainage through the permeable aggregate columns.

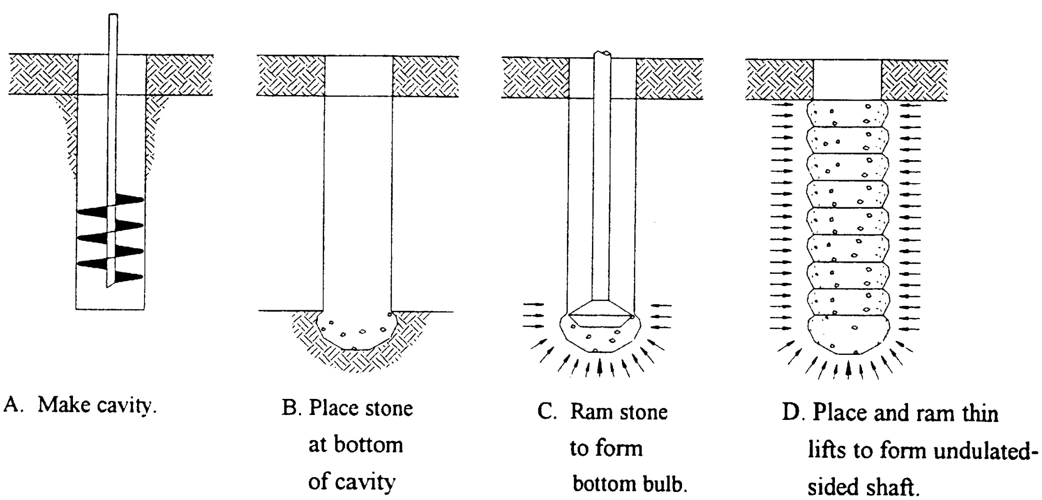


Figure 3.18: Summary of the Geopier® installation process. (Geopier®, 2003)

After the Geopier® installation was completed, two new RG8 cables and two new inclinometer casings with lengths of 34ft were installed at locations immediately adjacent to the pre-repair locations. The new layout of the Batesville monitoring station is illustrated in Figure 3.19 and Figure 3.20. The selection of these locations was to allow data comparison between the new and old monitoring programs.

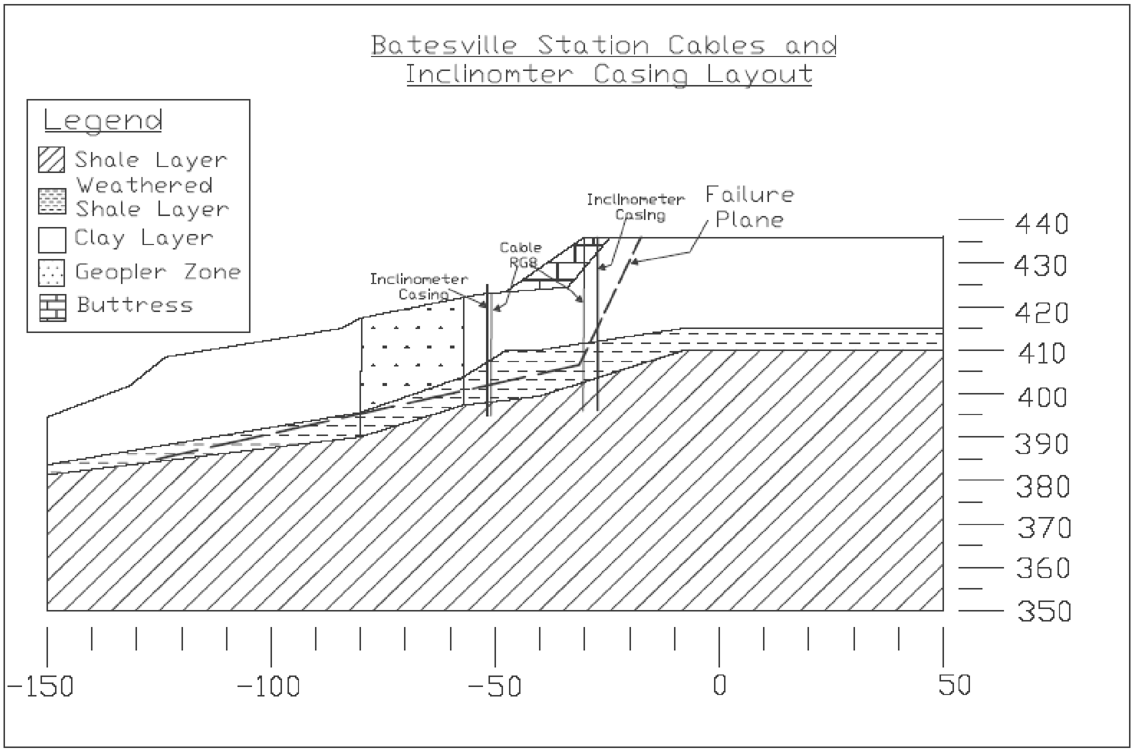


Figure 3.19: Batesville station soil profile and TDR installations layout.


Figure 3.20: Batesville TDR monitoring station

3.6 Programming and Alarm System Setup

A major advantage of the TDR system over other conventional monitoring techniques is that it provides the capability of having an automated alarm system which warns of rapid or excessive slope movement. As the coaxial cable undergoes deformation during slope movement, energy is reflected at the location of distortion. This reflected energy cases a “spike” to form in the cable’s waveform signature. The magnitude of this spike is directly proportional to the magnitude of movement and is the reason an alarm can be created for the TDR system.

One of the important steps that must be accomplished before setting up an alarm is to determine the baseline cable signature without any slope movement. This would be the cable signature immediately after installation. This allows the influence of signal interference and noise to be detected on a newly installed cable. The cable's signal does not present a constant reflection coefficient equal to zero throughout the length of the cable. As illustrated in Figure 3.17 the graph of the cable signature will not be a horizontal straight line through out the cable's length. When establishing the magnitude of reflected energy that is required to trigger the alarm, it must be selected to be beyond the baseline noise level to prevent false alarms. By selecting a constant value that would be added to the maximum reflection or subtracted from the minimum reflection of cable signature an alarm threshold can be established. If a slope movement occurs which is great enough to deform the cable and cause a change in the cable's reflection coefficient which is large enough to exceed the alarm limit, the datalogger will send back an alarm signal to the polling computer with the TDR station ID. Operations personnel can then take action immediately in response to the warning. In order create this autonomous alarm system a control program must be written in the EDLOG subroutine of PC 208W that will evaluate the reflection values that are received from the TDR100 device and determine if their magnitude is large enough to trigger an alarm. If they are, the program needs to establish cellular communication with a polling computer, pager or telephone and send a character stream or sound to alert operations personnel of a possible problem. A complete description of instruction set used in the alarm control program for the Batesville TDR station is included in Appendix A.

3.7 Data Reduction

3.7.1 Data Storage

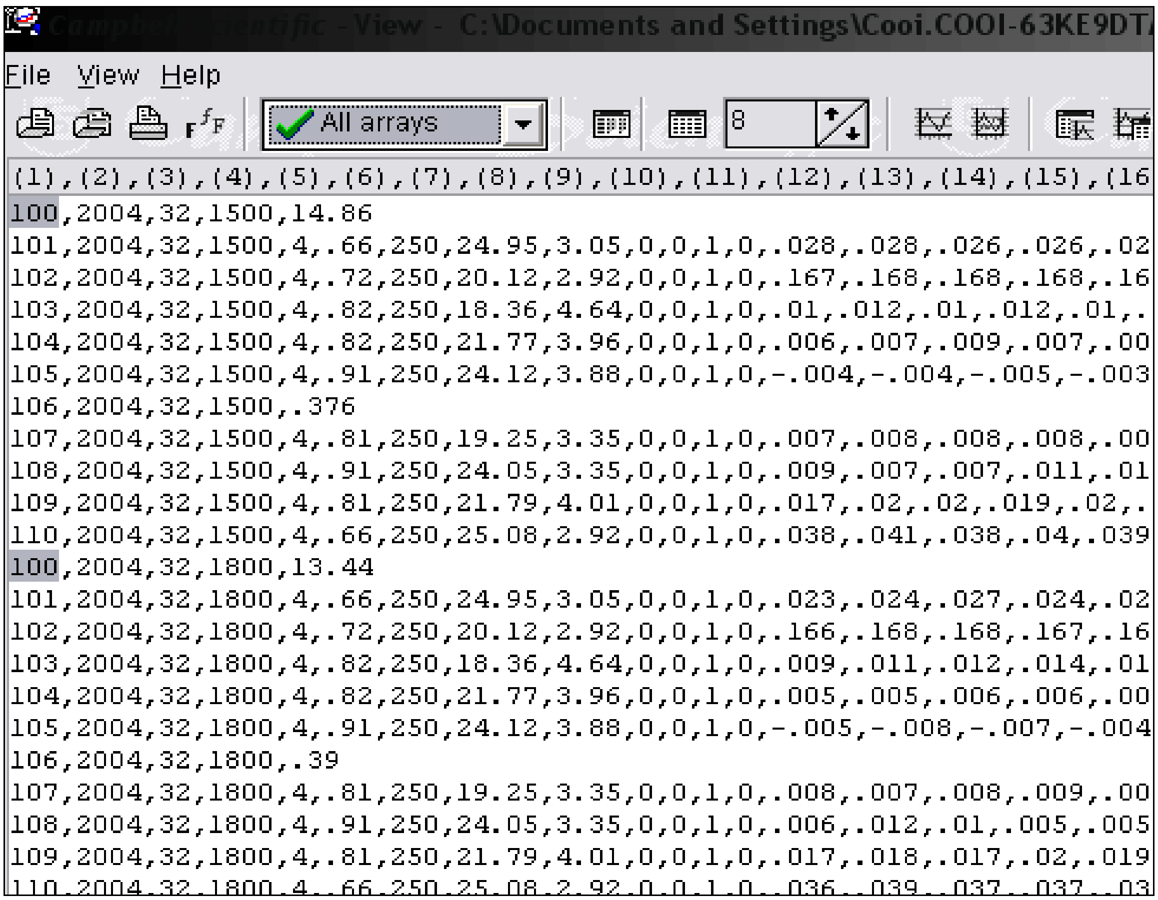
Data retrieved when scanning the TDR cables is stored within the non-volatile memory of the datalogger. The default size of this storage is 62280 memory locations. This limited memory is only capable of storing a few days worth of data. The actual days of storage depends on the frequency of data collection, the number of data points that are used to create each cable signature and the number of cable probes. Once the dataloggers memory is filled, new data will automatically overwrite the old data. Therefore, data from the datalogger's memory must be downloaded according to a pre-set schedule through remote data acquisition.

3.7.2 Data Sorting by Using View or Split Functions

3.7.2.1 View Function

Collected data can be saved as either ASCII or BINARY format. The BINARY format is 5 times more compact than ASCII. All retrieved data is stored in computer with ".DAT" extension. Users can direct the datalogger to separate the ASCII data in comma delimited format or save it as printable format. Data in ASCII format is easier to modify. Illustrated in Figure 3.21 is an example showing data in ASCII format separated by commas. There are 10 cable probes in this example for the monitoring station at MM50 where each cable probe is identified with an array number (101-105 and 107-110) in Column (1). Columns (2) to (4) indicate year, day, and time when data was collected. Column (5) is the waveform averaging number and Column (6) is the cable's propagation velocity. Column (7) is the number of data points stored for each cable. The number in

Column (8) is the length of the transmission cable aboveground and the number in Column (9) is the length of the cable probe. Beyond Column (9) are the number of reflection coefficients, specified in column 7, that define each cable signature. Array number 100 is the system temperature data and Array 106 is the data from the TDR moisture probe. All TDR data for this study were saved in the ASCII format illustrated in Figure 3.21.




```
(1),(2),(3),(4),(5),(6),(7),(8),(9),(10),(11),(12),(13),(14),(15),(16
100,2004,32,1500,14.86
101,2004,32,1500,4,.66,250,24.95,3.05,0,0,1,0,.028,.028,.026,.026,.02
102,2004,32,1500,4,.72,250,20.12,2.92,0,0,1,0,.167,.168,.168,.168,.16
103,2004,32,1500,4,.82,250,18.36,4.64,0,0,1,0,.01,.012,.01,.012,.01,.
104,2004,32,1500,4,.82,250,21.77,3.96,0,0,1,0,.006,.007,.009,.007,.00
105,2004,32,1500,4,.91,250,24.12,3.88,0,0,1,0,-.004,-.004,-.005,-.003
106,2004,32,1500,.376
107,2004,32,1500,4,.81,250,19.25,3.35,0,0,1,0,.007,.008,.008,.008,.00
108,2004,32,1500,4,.91,250,24.05,3.35,0,0,1,0,.009,.007,.007,.011,.01
109,2004,32,1500,4,.81,250,21.79,4.01,0,0,1,0,.017,.02,.02,.019,.02,.
110,2004,32,1500,4,.66,250,25.08,2.92,0,0,1,0,.038,.041,.038,.04,.039
100,2004,32,1800,13.44
101,2004,32,1800,4,.66,250,24.95,3.05,0,0,1,0,.023,.024,.027,.024,.02
102,2004,32,1800,4,.72,250,20.12,2.92,0,0,1,0,.166,.168,.168,.167,.16
103,2004,32,1800,4,.82,250,18.36,4.64,0,0,1,0,.009,.011,.012,.014,.01
104,2004,32,1800,4,.82,250,21.77,3.96,0,0,1,0,.005,.005,.006,.006,.00
105,2004,32,1800,4,.91,250,24.12,3.88,0,0,1,0,-.005,-.008,-.007,-.004
106,2004,32,1800,.39
107,2004,32,1800,4,.81,250,19.25,3.35,0,0,1,0,.008,.007,.008,.009,.00
108,2004,32,1800,4,.91,250,24.05,3.35,0,0,1,0,.006,.012,.01,.005,.005
109,2004,32,1800,4,.81,250,21.79,4.01,0,0,1,0,.017,.018,.017,.02,.019
110,2004,32,1800,4,.66,250,25.08,2.92,0,0,1,0,.036,.039,.037,.037,.03
```

Figure 3.21: ASCII format data separated by comma from station MM50

3.7.2.2 Split Function

Sorting the huge amount of data generated over an extended period is a difficult task. A software feature imbedded in PC208W called "Split" helps to resolve this problem. Each array of data for cable starts with a cable number, year, day, and time.

With this information, user can separate the data easily by sorting on a set of these variables.

Figure 3.22 is a screen capture of the operating window of “Split” function. Box 1 displays the address of the input file location. This is the location where the data downloaded from the data logger was stored on the polling computer. The parameters to describe how to locate the data to be split out are defined in box 2. In the example in Figure 3.22 the columns that are used in searching for the correct data are 3 and 4 and the actual timing parameters the program is looking for are the 32^{nd} day at 6:00 PM. The date uses Julian date while the time is based on a 24 hour clock. In box 3, using the same principle, the instruction is to copy data from Array 104 starting with column one.

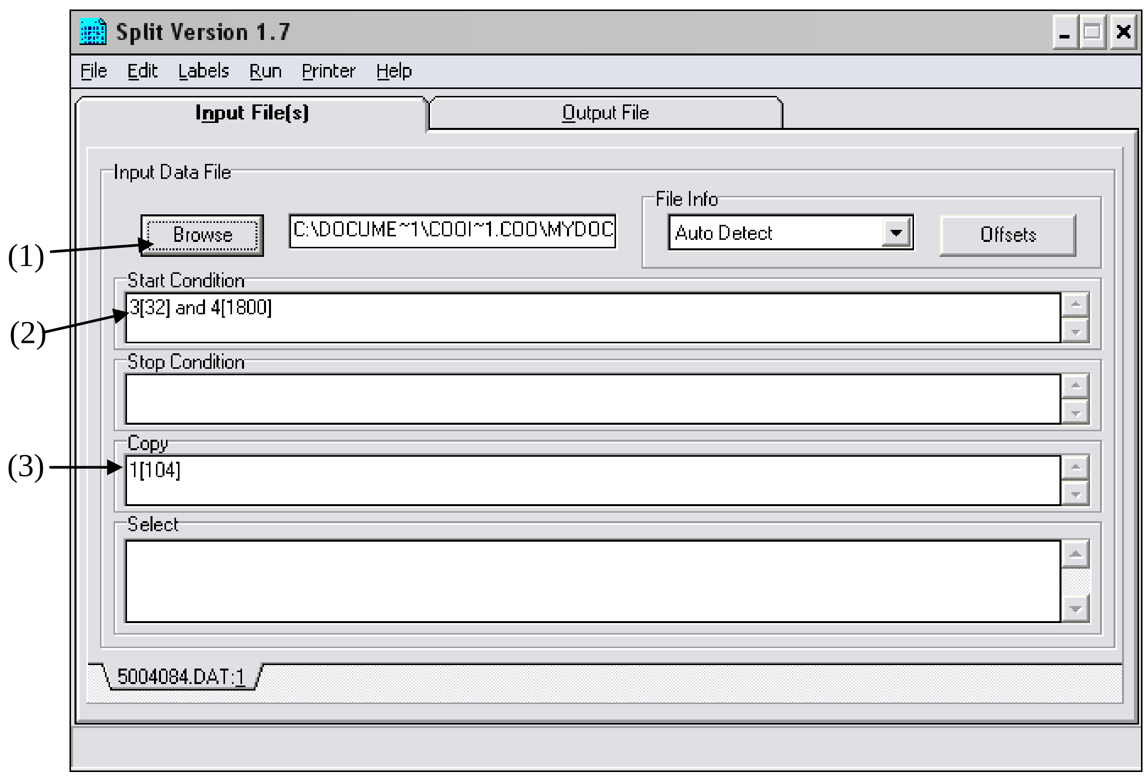


Figure 3.22: Input data file to be sorted by Split.

The next step is to specify the output location of the sorted data as specified in Output Data as shown in Box1 of Figure 3.23. In most cases, the data are transposed from row to column format by using the special function shown in Box (2) of Figure 3.23. The purpose of transposing the data is to organize the data in a more workable format in Microsoft Excel®.

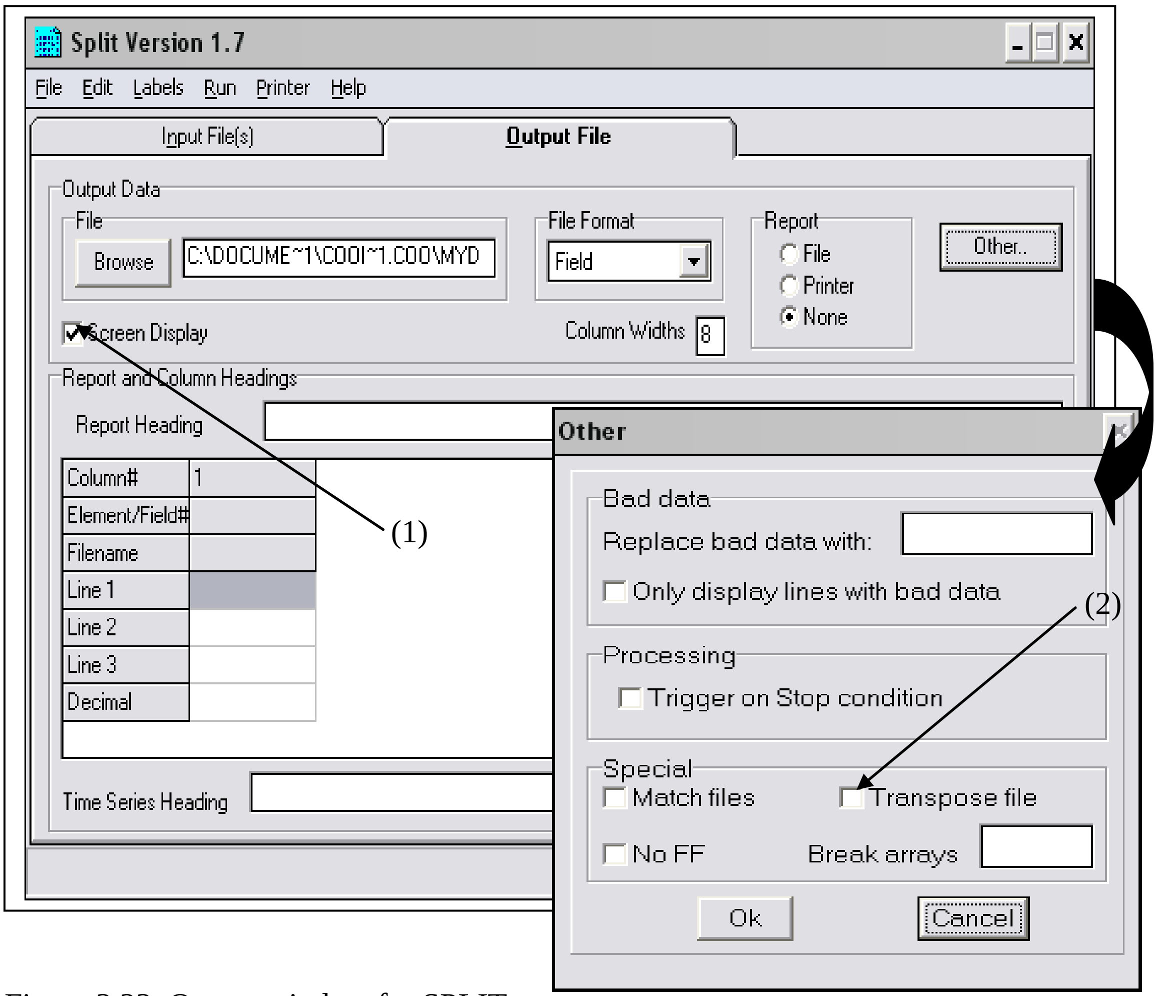


Figure 3.23: Output window for SPLIT

3.7.3 Graphing using Excel

Illustrated in Figure 3.24 is a graph of cable signatures that was created in an Excel® spreadsheet designed to hold seven days worth of data. The data is from the reading taken at midnight (24:00 hours) each day. During the course of this study it was determined that data gathered at night suffered from less noise than data gathered during the daylight hours. As a result, only night time data is reported in this study. In Figure 3.24 the waveform for each day is separated from the previous day by 0.02 rho for ease of viewing. The baseline waveform is taken from the initial reading when the cable was installed. For this installation the cable was grouted 4.75 meters into the slope and zero on the x-axis represents the ground surface. A "spike" in the waveform, or cable signature, can be observed at approximately 0.75 meters below the ground surface, indicating that there is ground movement at this location.

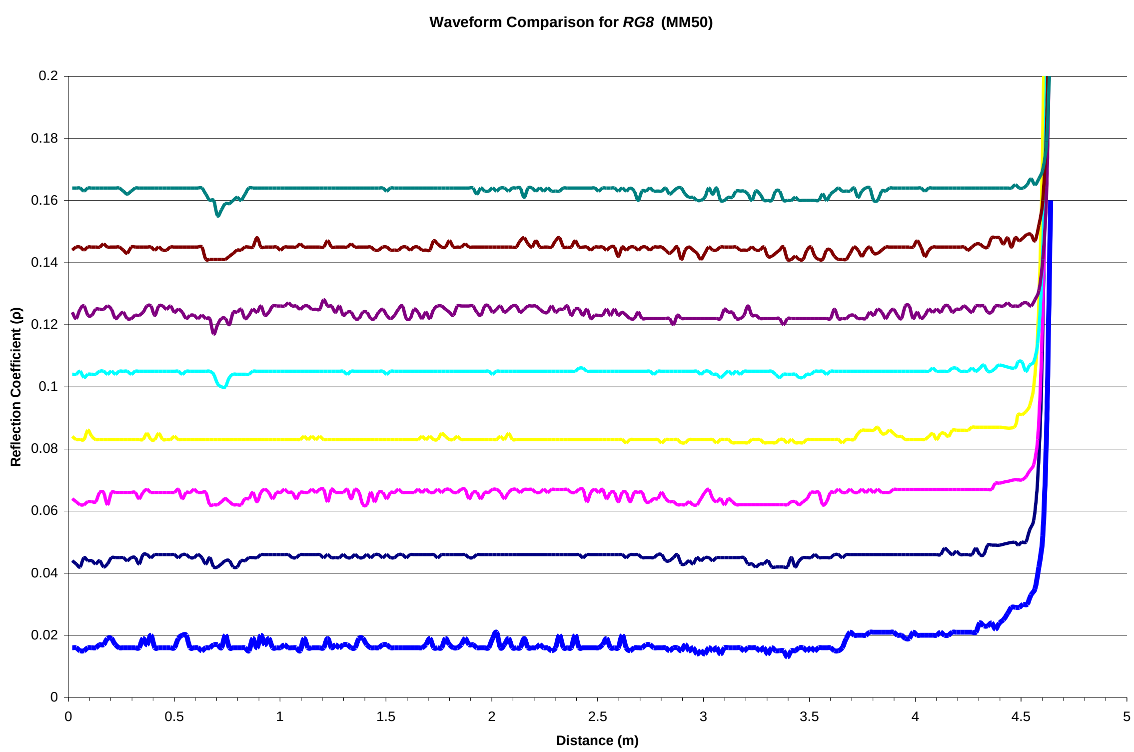


Figure 3.24: Waveform comparison for RG8 on MM50

Chapter 4

Results and Analysis

This chapter summarizes the testing results for each monitoring station. TDR monitoring results are compared to the inclinometer results in an attempt to determine if a correlation exists between the magnitude of the reflection coefficients reported by the TDR system and the magnitude of displacements. Laboratory testing results for TDR cables are also compared to the field results to determine the effect of cable length and cable connections on the shape and magnitude of the waveform.

4.1 Laboratory Testing

Laboratory testing was conducted by Voon Wong, (Wong, 2004), a former graduate student who completed a portion of the work for this project. The purpose of these tests was to determine the threshold of cable deformation required to produce a reflection in the signal under controlled shear conditions. The cables used in these tests included RG8, RG58, foam dielectric, and air dielectric. All cables used in this test and their connecters were illustrated in Figure 3.8.

The coaxial cables were pre-grouted into a wooden mold as illustrated in Figure 4.1. The wooden mold was designed to hold up to three cables for each test. Ideally the mold would have accommodated all four cables at once, but the loading frame could not uniformly load a mold with such a large width. The center section of the mold was movable relative to the two outer fixed sections. A force was applied to the central section such that the cables were loaded transversely, developing a controlled shear plane at each edge of the loading plate. The loading was strain controlled at a rate of one mm per minute and the magnitude of deformation and the changes in reflection coefficient were recorded every 30 seconds. The reflection coefficient (ρ) is defined as the ratio of voltage reflected at the discontinuity to the incident voltage. The waveforms produced during these loadings are shown in Figures 4.3 to 4.6. All shear tests were terminated when the movable section of the shear block reached 25 mm (1 inch) of displacement or when the coaxial cable(s) sheared off. The first waveform at the bottom of each graph is the control or baseline, which represents the original cable signal without any deformation. All subsequence data are compared to the control to determine the changes in reflection coefficient at various stages of shear.

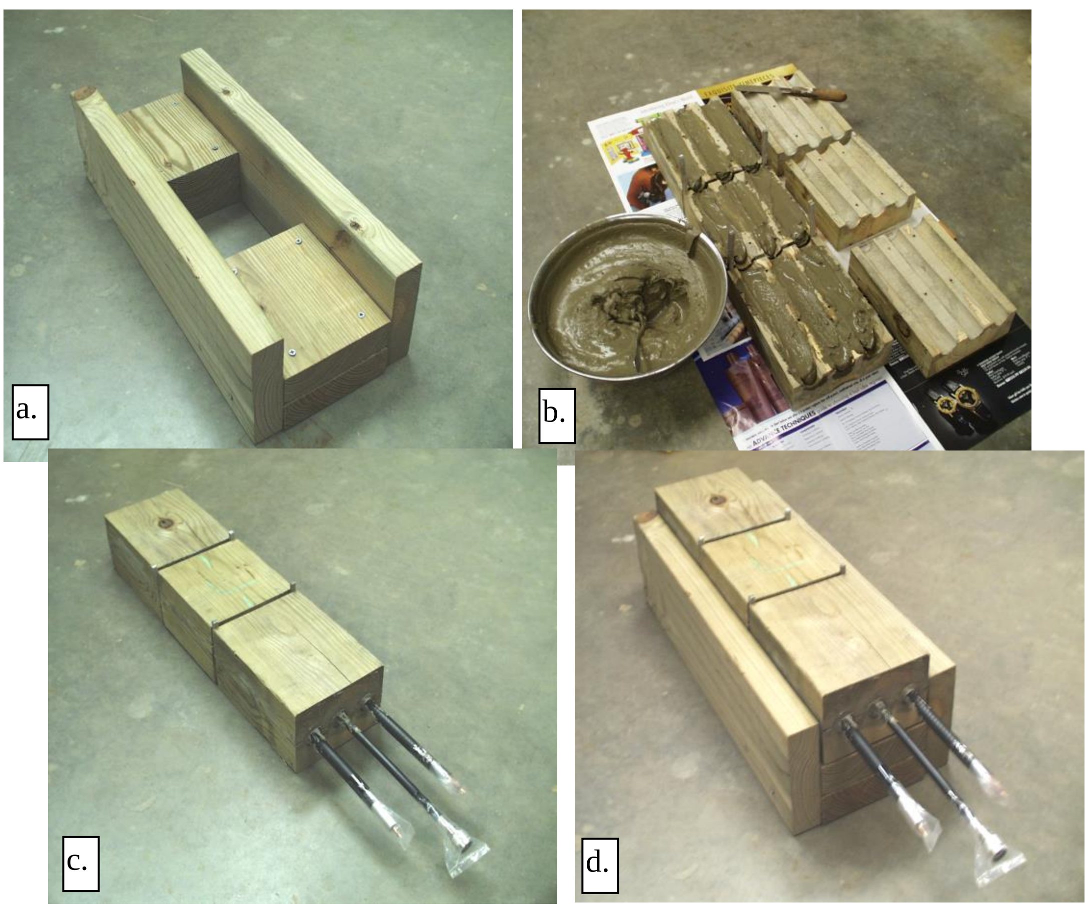


Figure 4.1: Wooden mold used for laboratory testing of cables. (a) Mold base, (b) Split mold with grout, (c) Assembled split mold, (d) Assembled double shear device.

One can see in Figure 4.3 that downward spikes form in the TDR waveform at locations where cable shear is taking place for the RG8 cable. The magnitude of the spike gradually increased as the shear box displacement progressed. Based on the mold design, it was anticipated that each test would generate two spikes in the reflected signal. The spikes are caused by two shear planes (Shear Plane A & B as shown on Figure 4.2) at both edges of the wooden mold's movable section. All test results agreed with the anticipated signal shape, except for the RG58 cable.

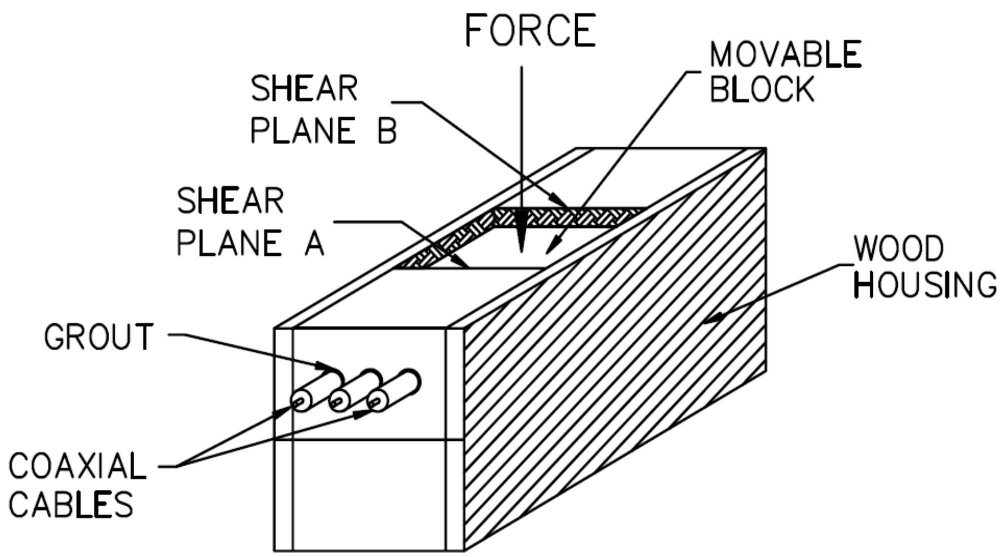


Figure 4.2: Shear Locations on the wooden mold for TDR cables testing

As illustrated in Figures 4.3 to 4.4 signal spikes closest to the pulse generator tended to be larger than the spikes at the second shear plane. Furthermore, the spikes closer to the pulse generator increased at a faster rate and were more sensitive to threshold displacement. This result suggests that each reflection consumes some of the signal's energy and that succeeding reflections will have less sensitivity to shear. So, if a cable undergoes deformations at several locations simultaneously, the energy of the pulse will attenuate at each deformation leaving less energy to be reflected at each subsequent deformation.

A negative spike on the waveform is anticipated when the coaxial cable is being sheared. As the cable undergoes greater deformation, the signal spike on the waveform gets larger in direct proportion to the deformation. As can be seen in Figures 4.3 thru 4.6, three of the cables; RG8, foam dielectric, and air dielectric exhibited the anticipated waveform. The air dielectric cable and RG58 were sheared off prior to reaching 1 inch of displacement of the testing block. As illustrated in Figure 4.6, the air dielectrics cable exhibited a short circuit at 0.75 inch of deformation as a result of the outer conductor contacting the inner conductor. The short circuit created an infinitely downward signature at the sheared location. This result could have been anticipated on the air-dielectric cable as the annulus between the inner and outer conductors was empty. This disadvantage of the air dielectric cable could reduce its useful life for shear monitoring, when compared to other cables. Conversely, the RG58 cable, with a smaller diameter never exhibited a negative spike, as illustrated in Figure 4.6. The RG58 cable, with its small diameter, was unable to develop adequate bond between the jacket and the surrounding grout. As a result, rather than shearing, it elongated through creep, fraying the outer conductor when a force was applied to the moveable block. Furthermore, it was easily sheared off at small deformations, creating an open circuit. One end of the cable was sheared off at 13 mm (0.51 inch) of displacement during the laboratory testing. The reverse U-shape spike in the signal was believed to be the result of fraying of the cable’s outer conductor. An additional test was conducted to verify the cause of the RG58 cable’s abnormal signal.

In a subsequent test an RG58 cable's outer jacket was cut off to expose the braided outer copper conductors. While observing a succession of reflected signals, the braided outer conductors were slowly cut off little by little until the entire outer conductor had been removed over a short interval of the cable. As illustrated in Figure 4.7, the overlayed (darker) waveform on both graphs represents a cable signal without any deformation. For comparison purposes, the lighter signal in Figure 4.7a shows the anticipated negative reflection when the RG58 cable was crimped. In Figure 4.7b, a positive signal spike developed when 75 percent of the RG58's outer conductors had been cut off. The positive signal spike kept growing as more outer conductors were cut off. Finally the spike went to infinity when all of the outer conductors were removed, representing an open circuit. The results of this test support the assumption that fraying of the outer conductors of the RG58 cable occurred when it was subjected to loading in the shear box.

A conclusion drawn from this work is that the coaxial cables with solid dielectric material have a much more consistent and stable cable signature when compare to air dielectric. The RG8 and foam dielectric cables provide clear, well defined signatures over the entire one inch of deformation used in the test. The size of coaxial cable may also play an important role in producing a good reflection due to shear. The smaller sized RG58 cable may be too flexible to shear easily and it seemed to be easily stretched, resulting in fraying of the braided outer conductor.

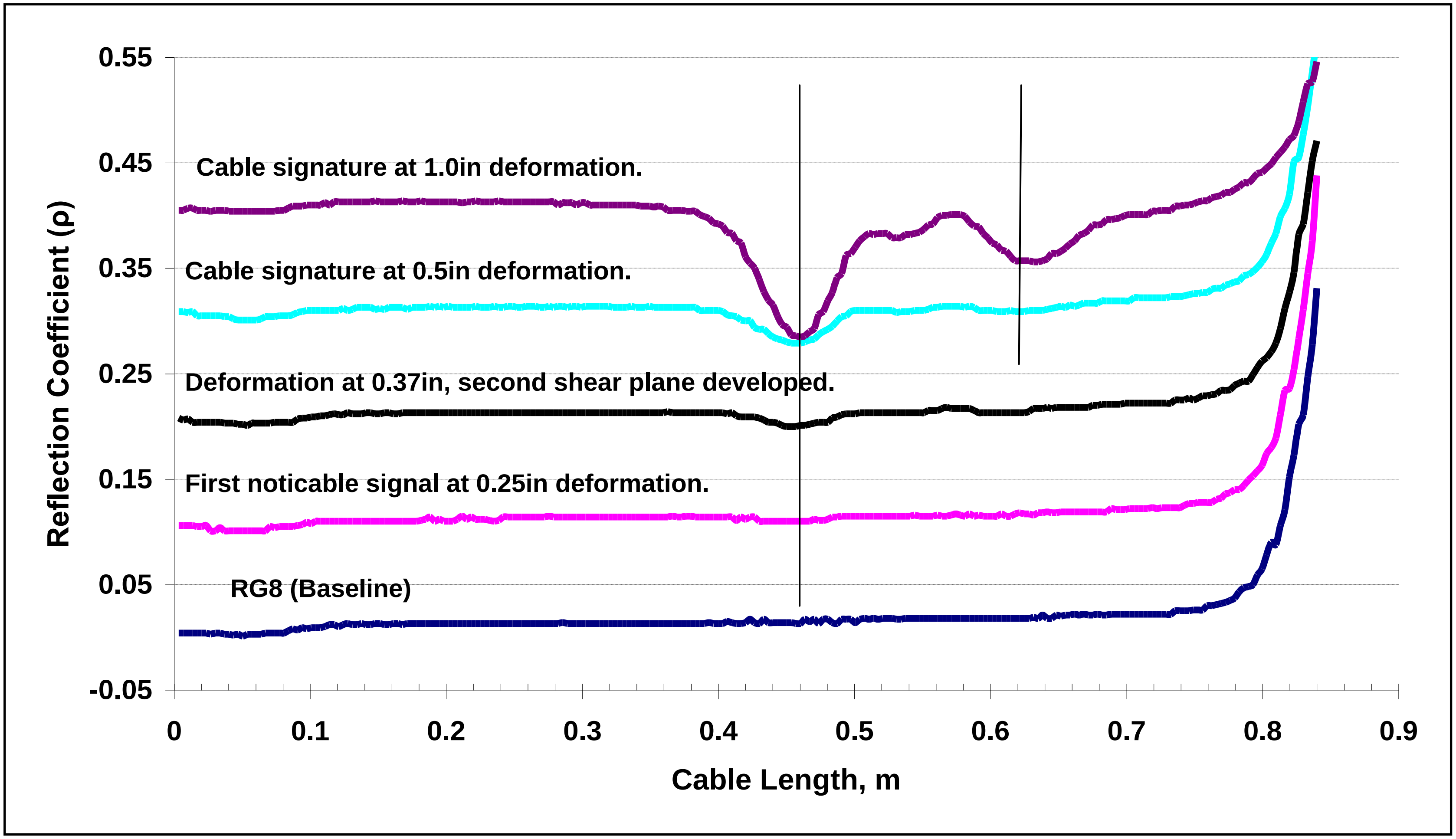


Figure 4.3: Summary of waveforms for laboratory shear testing results for RG8 cable.

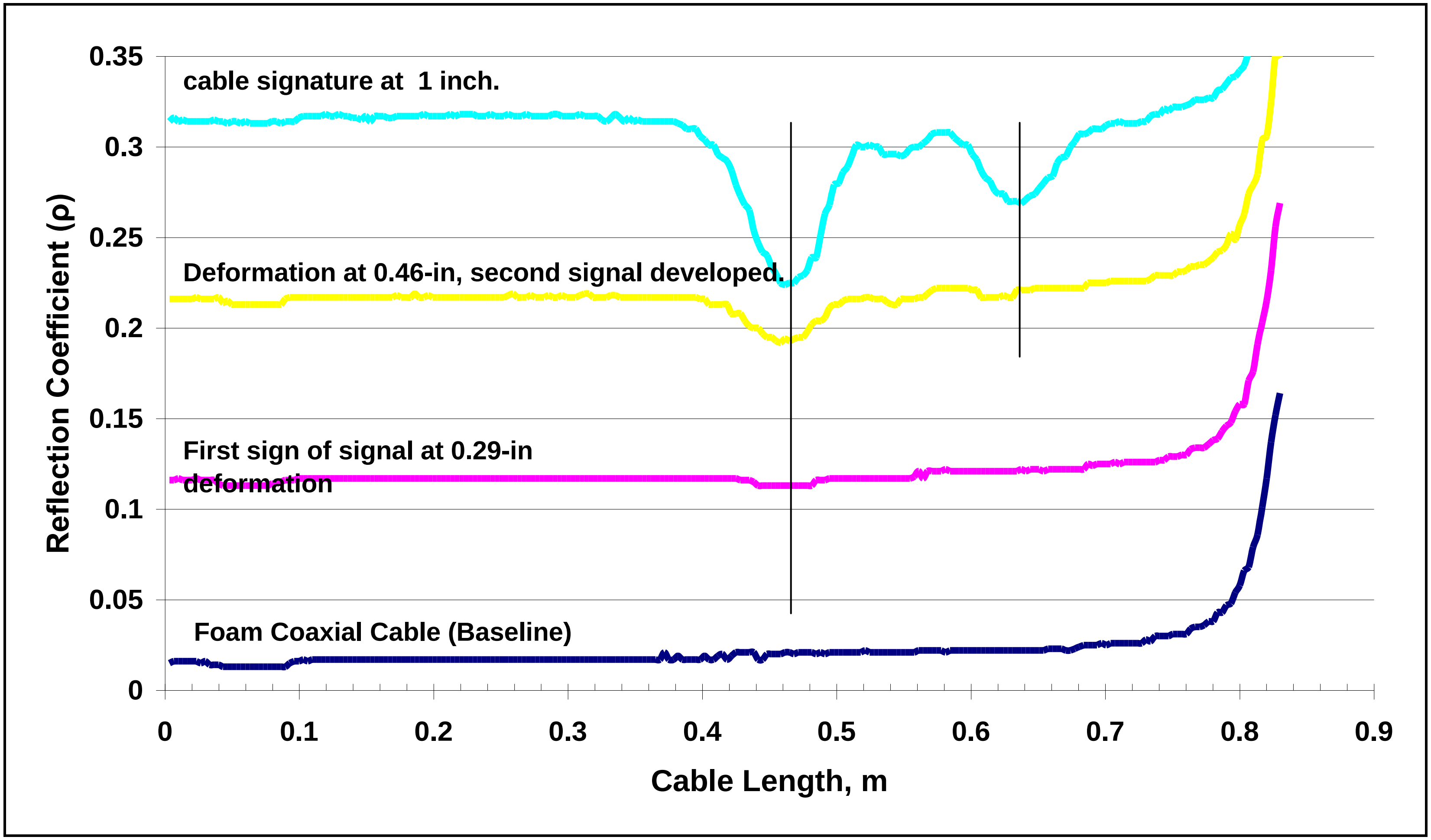


Figure 4.4: Summary of waveforms for laboratory shear testing results for rigid aluminum - foam dielectric cable.

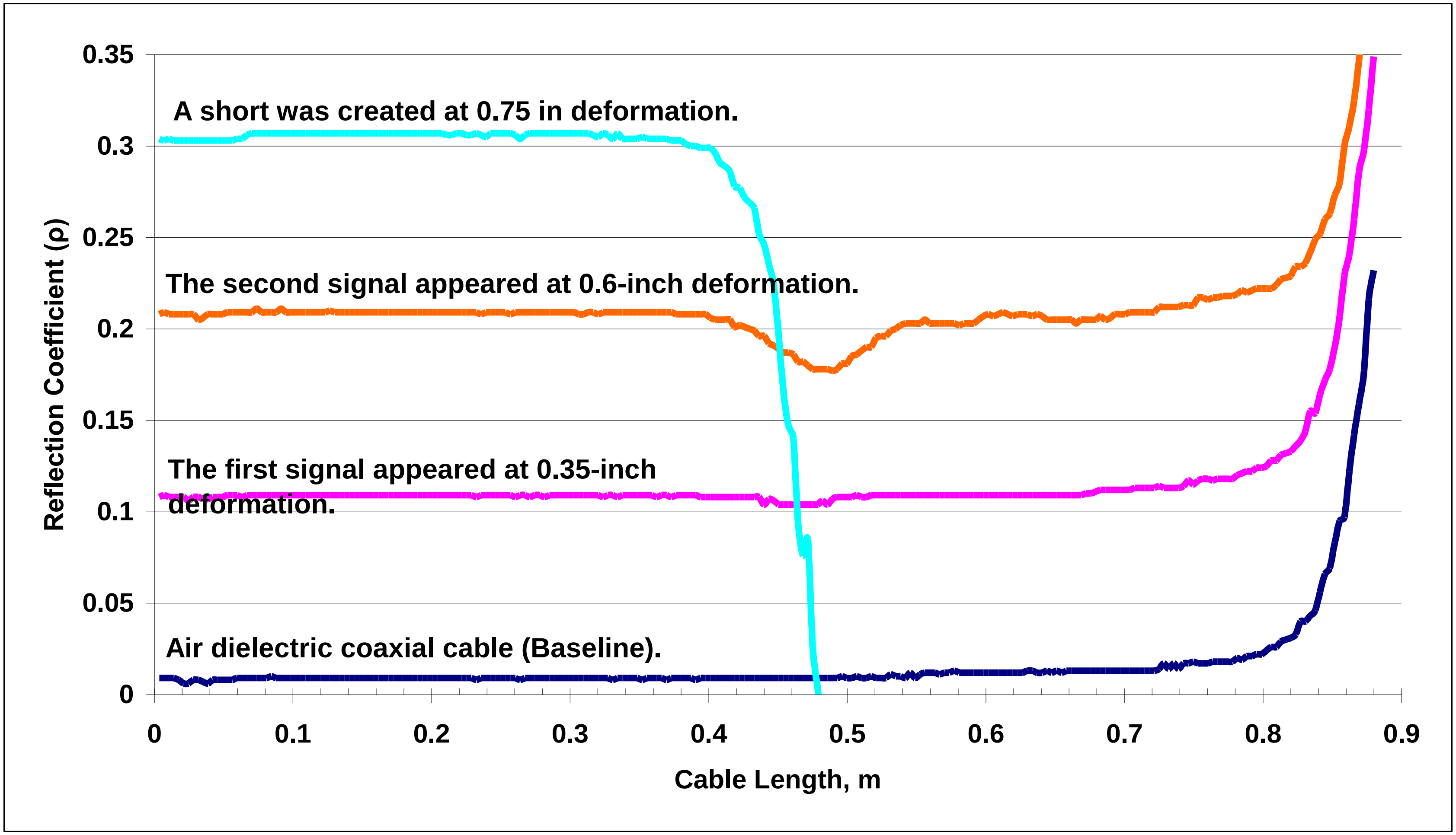


Figure 4.5: Summary of waveforms for laboratory shear testing results for rigid copper-air dielectric cable.

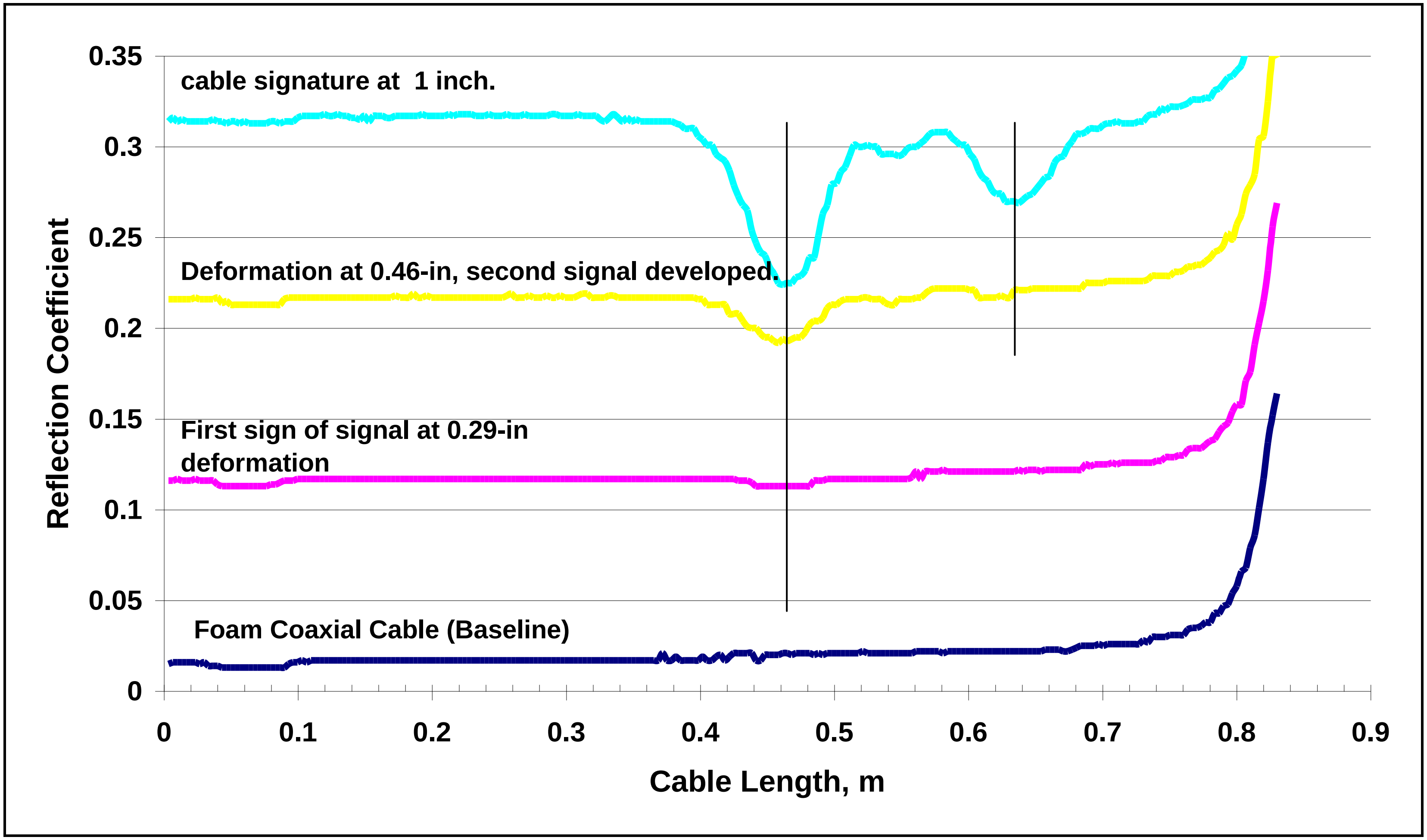


Figure 4.6: Summary of waveforms for laboratory shear testing results for RG58 cable

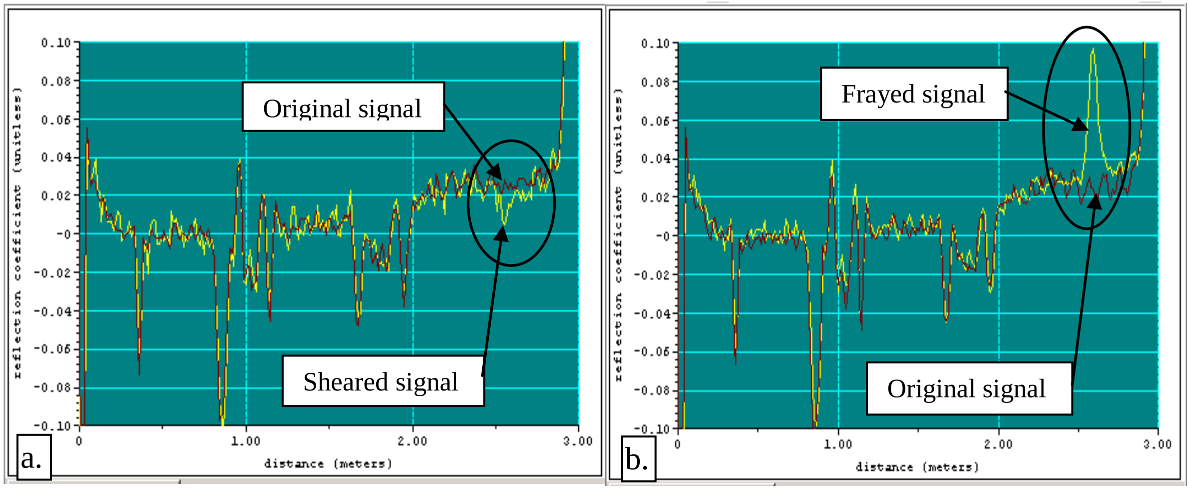


Figure 4.7: Comparison of waveforms for cable shear and outer conductor fraying. (a) The negative signal spike represents an RG58 cable under pure shear deformation. (b) The positive signal spike represents a condition where 75 percent of the RG58 cable's outer conductor was removed.

4.1.1 Correlation between Reflection Coefficient and Displacement

An analysis was conducted to quantify changes of the reflection coefficient as a function of displacement. Figures 4.8 to 4.11 show the reflection coefficient (ρ) versus the magnitude of displacement for all cable types tested. A linear best fit line was used to provide a mathematical correlation of this relationship for each cable.

The relationship of displacement to changes of the reflection coefficient can be predicted using the equations shown on the graphs, with the slope of the line being the cable sensitivity. The laboratory study suggests that RG8 and foam dielectric cables have a nearly linear relationship between their reflection coefficients and displacement over the entire range of displacements measured, once the threshold displacement was achieved. In contrast, the air-dielectric cable exhibited a different result. The air dielectric cable had a linear relationship between its reflection coefficient and displacement from the threshold displacement of 0.27 inches up to 0.57 inches. At deformations beyond 0.57 inches the reflection coefficient increased exponentially until a complete short was encountered at approximately 0.74 inches. The linear portion of this relationship was used to represent the cable testing results and to define an equation to predict the relationship between the reflection coefficient and displacement. Finally, as illustrated in Figure 4.11, it was not possible to develop a relationship between shear displacement and reflection coefficient for the RG58 cable because of the fraying of the outer conductor. Correlating the magnitude of the reflection coefficient to displacement was unsuccessful for the RG58 cable.

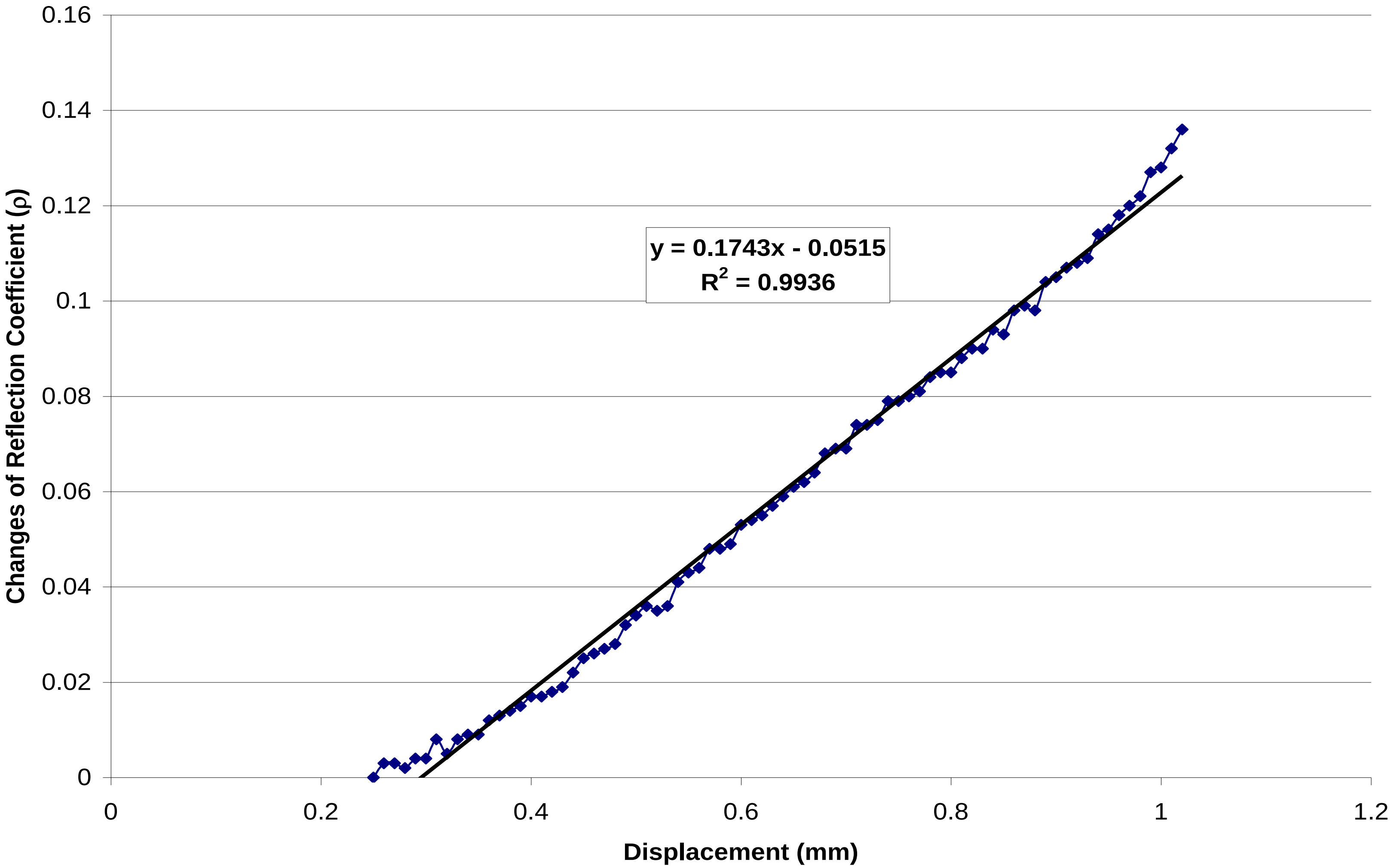


Figure 4.8: Changes of reflection coefficient versus displacement of RG8 cable.

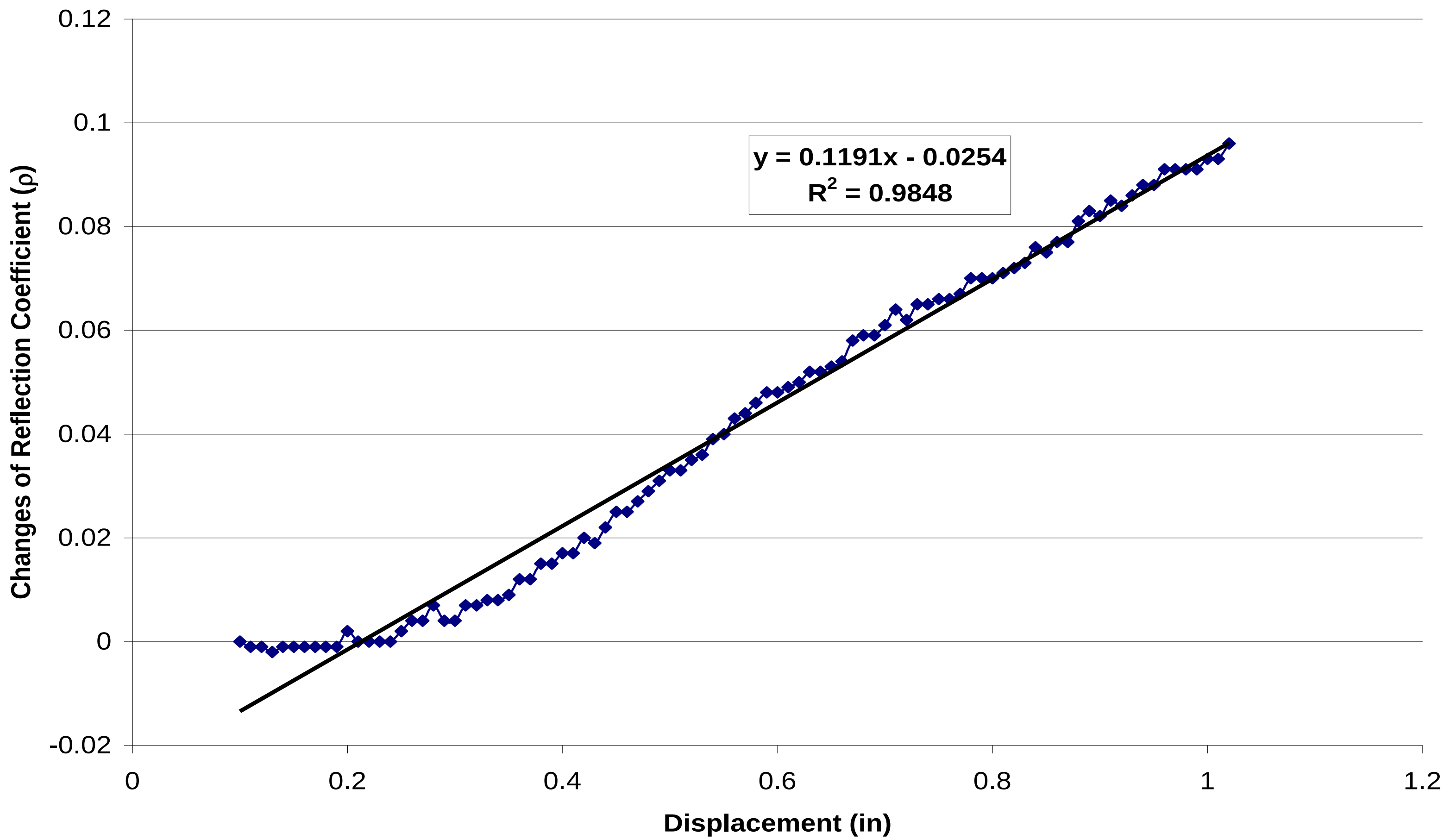


Figure 4.9: Changes of reflection coefficient versus displacement of foam dielectric cable.

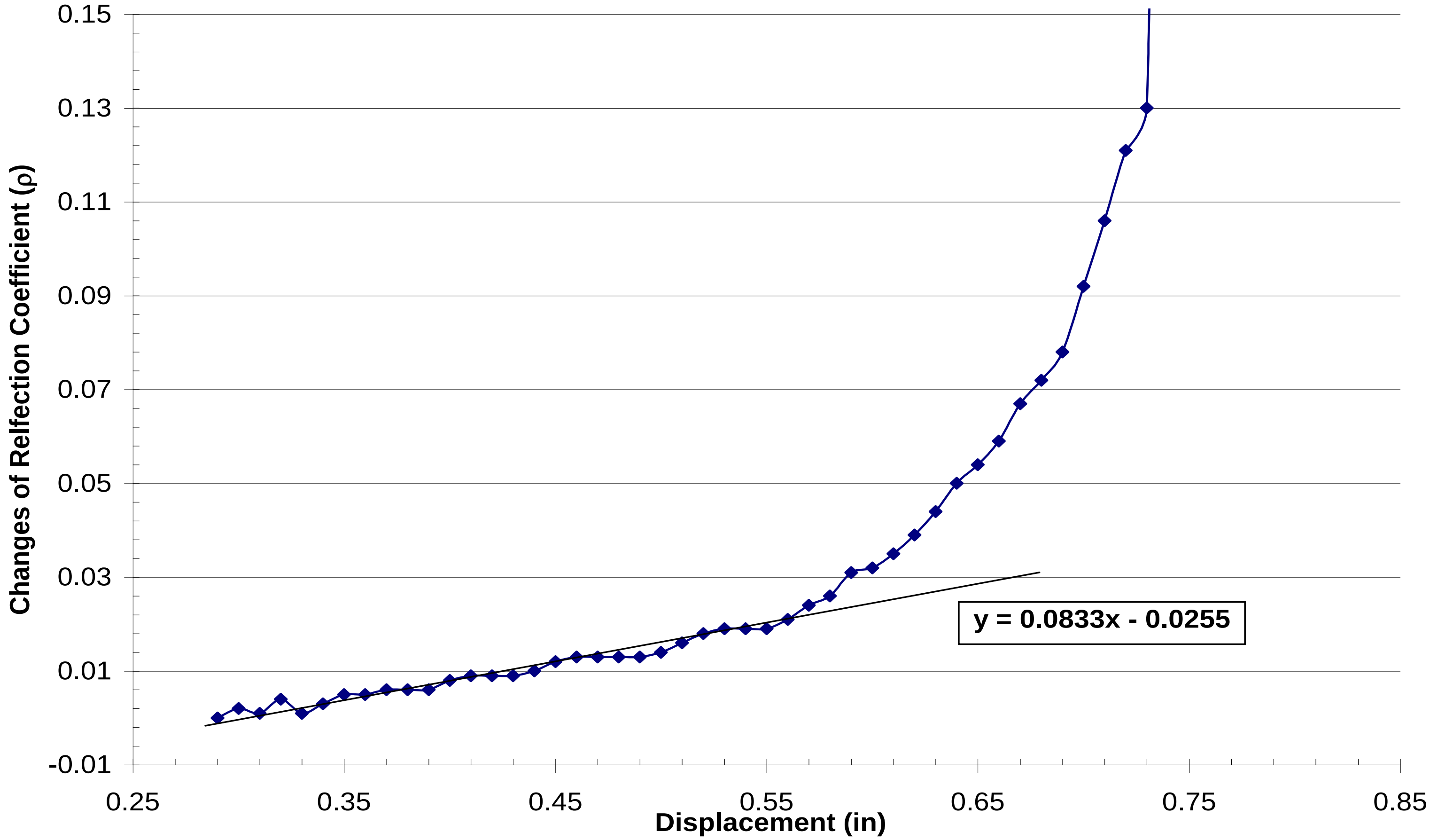


Figure 4.10: Changes in reflection coefficient versus displacement for rigid copper-air dielectric cable.

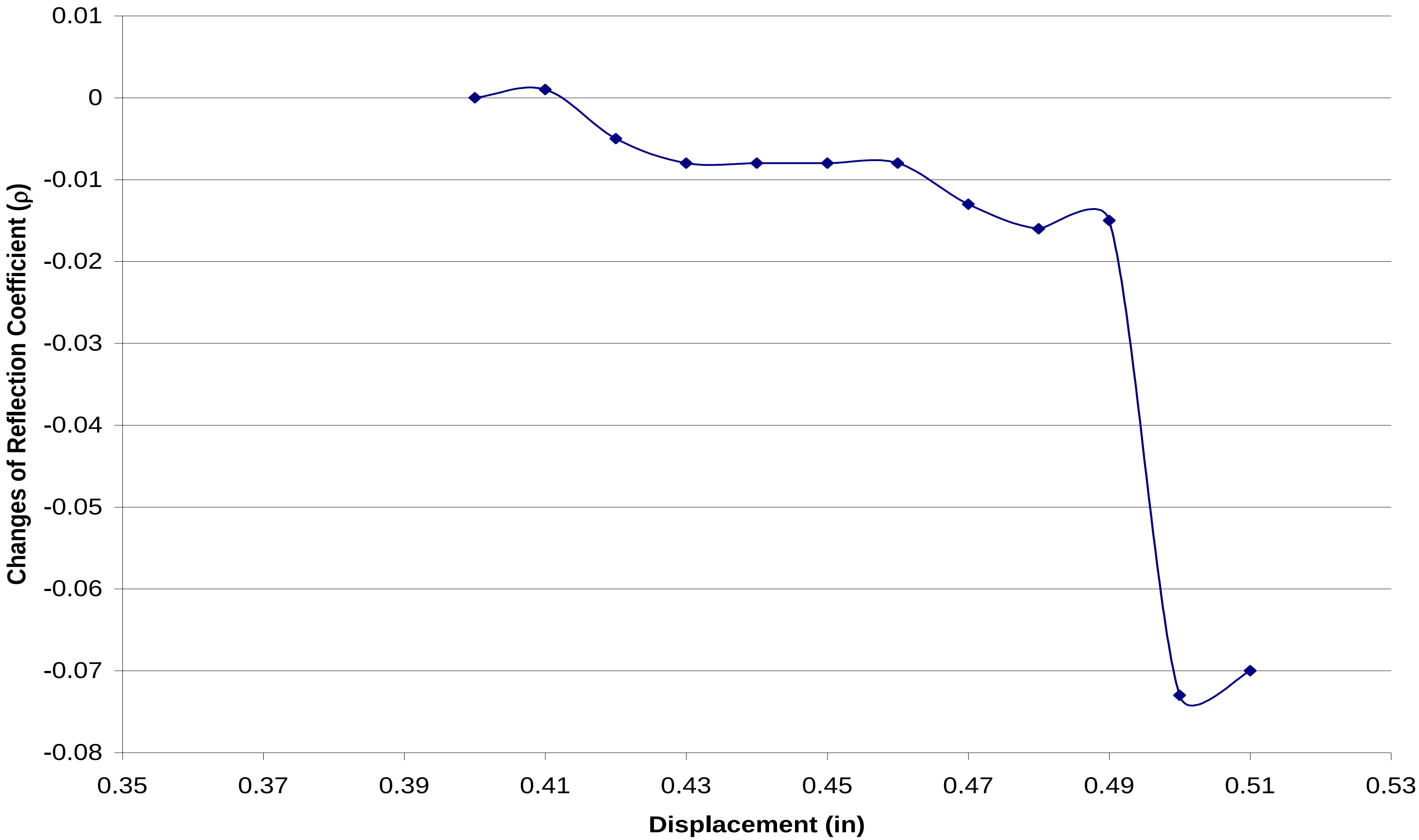


Figure 4.11: Changes in reflection coefficient versus displacement for RG58 cable.

4.1.2 Cable Sensitivity

Cable sensitivity has a direct influence on the cable signal. A more sensitive cable is a better probe for monitoring slope movements, especially on a site with soft soil. A sensitive cable is capable of capturing small movements, which in turn will allow the operator to have an earlier awareness of slope movement. Early awareness will in turn allow for more immediate and possibly cheaper remediation measures to be taken.

Based on the graphical analysis in Section 4.1.1, the coaxial cables are sorted according to their sensitivity level in Table 4.1. Sensitivity of the coaxial cables was defined as the slope of the linear portion of the reflection coefficient to displacement curves as illustrated in Figures 4.8 to 4.11. The sensitivity of a cable can also be defined as the amount of displacement needed for the first noticeable reflection spike to occur. The results of the laboratory testing in this study suggest that the RG8 cable is the most sensitive to deformation of those cables tested. It is closely followed by the foam dielectric and air dielectric cables. The results from the RG58 cable testing were inconclusive. As a result of this laboratory study, RG8 cables were selected as the primary TDR cable probes for the later phases of this study.

Table 4.1: Summary of cable sensitivities for coaxial cables used in this study

Cable Type	First noticeable spike occurred at displacement of	Slope on the Reflection vs. deformation graph (Sensitivity)	Cable completely shear off at
RG8	6-mm (0.25in)	0.1743	No shear off at termination
Foam Dielectric	7-mm (0.29in)	0.1191	No shear off at termination
Air Dielectric	9-mm (0.35in)	0.0833	19-mm (0.74in)
RG58	11-mm (0.43in)	Inconclusive	13-mm (0.51in)

4.2 Field Testing Results

This section summarizes the testing results for all field monitoring stations, starting with the first TDR station installation at MM46 on I-540 and concluding with the last installed station on US Highway 167 near Batesville, Arkansas. The results are presented in two separate sections beginning with the stations that had no significant recorded movement, followed by stations which did show significant recorded movement.

4.2.1 Stations without Significant Recorded Movement

4.2.1.1 Station MM46

The true movement for this slope was monitored using three inclinometer casings positioned in the middle of the test area as illustrated in Figure 4.13. The intent of this study was to compare the readings from the 12 TDR cables to the readings of the inclinometer probes, to establish a relationship between movement and reflection coefficients. Unfortunately this was not possible at this site based on the collected data. A review of the inclinometer data for this station indicates the slope was creeping very slowly. The greatest recorded movement for this station, based on inclinometer readings, was 17 millimeters (0.63 inches) over a monitoring period of more than two and a half years. Figure 4.15 shows the results for the middle inclinometer casing, labeled as Hole #2 in Figure 4.13, which had a total depth of 2.4 meters (7.87 feet). The greatest displacement for this casing occurred at a depth of 0.6 meter below the ground surface. The other inclinometer casing that was located in the upper portion of the slope, Hole #1, had a maximum recorded movement of 9 millimeter (0.35 inch), as indicated in Figure 4.14. The displacement patterns from these two inclinometers indicates a relatively well defined shear zone at a depth of about 2 meters near the top of the slope and a less well defined failure near the middle of the slope at approximately 1 meter. The deformation at mid-slope appears to be more rotational in nature rather that translational. The lower inclinometer casing, (Hole#3), located at the toe of the slope, was abandoned because it became apparent during early monitoring that it did not have a sufficient anchorage to provide reliable readings.

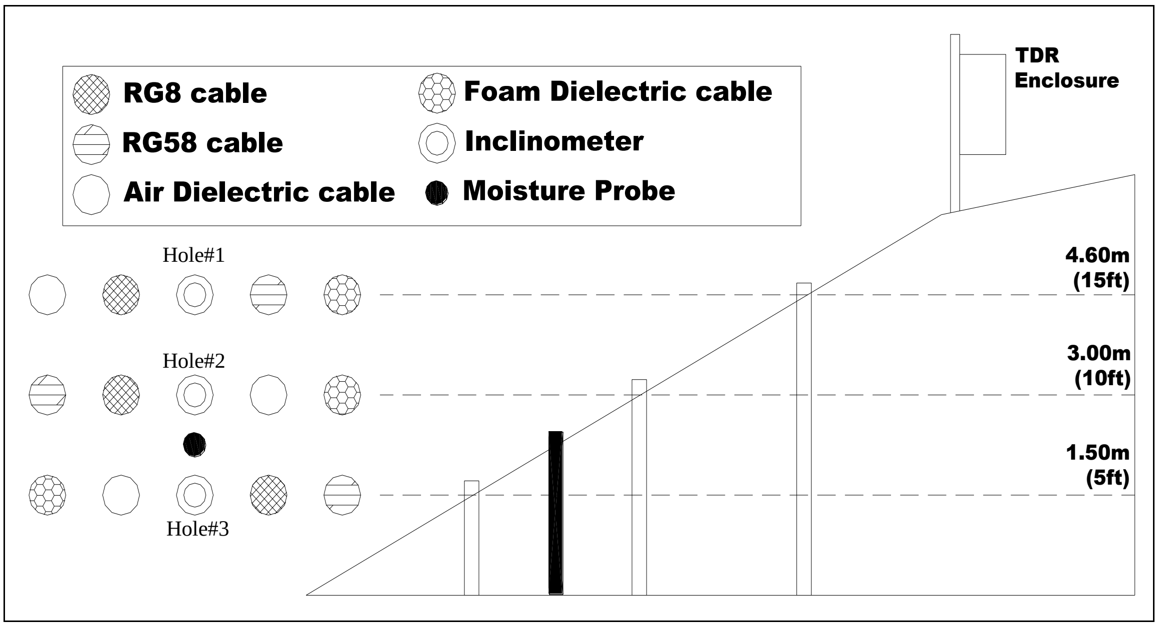


Figure 4.13: TDR cables and Inclinometer casings layout for the Mile Marker 46 site.

Even though the maximum displacements recorded by the inclinometer at this station exceeded the laboratory threshold to produce a reflection spike in the RG8, foam dielectric, and air dielectric cables, none of them exhibited any reflections at the plane of movement defined by the inclinometers. It was hypothesized that this anomalous result was partially the result of the slow movement rate of the slope, which may have retarded the formation of a reflection spike. Most of the cables tend to relax as time passes and the reflection spike fades away when the shear distortion in the cable dissipates. Another possible reason that no reflection spikes were observed was that the shearing action in the slope was not confined to a localized plane as in the laboratory test, but it was spread out across a shear zone. Therefore, the shear on the cables was not well defined. Another conclusion that was drawn from the results from this station is that the high density of the large diameter grouted boreholes for cable and inclinometer installations over a relatively small area served to reinforce the slope and retard movements. This conclusion is based on the fact that well defined tension cracks developed in the slope immediately adjacent to the monitored area. These cracks extended across the upper and middle portions of the slope and terminated within the instrumented area of the site.

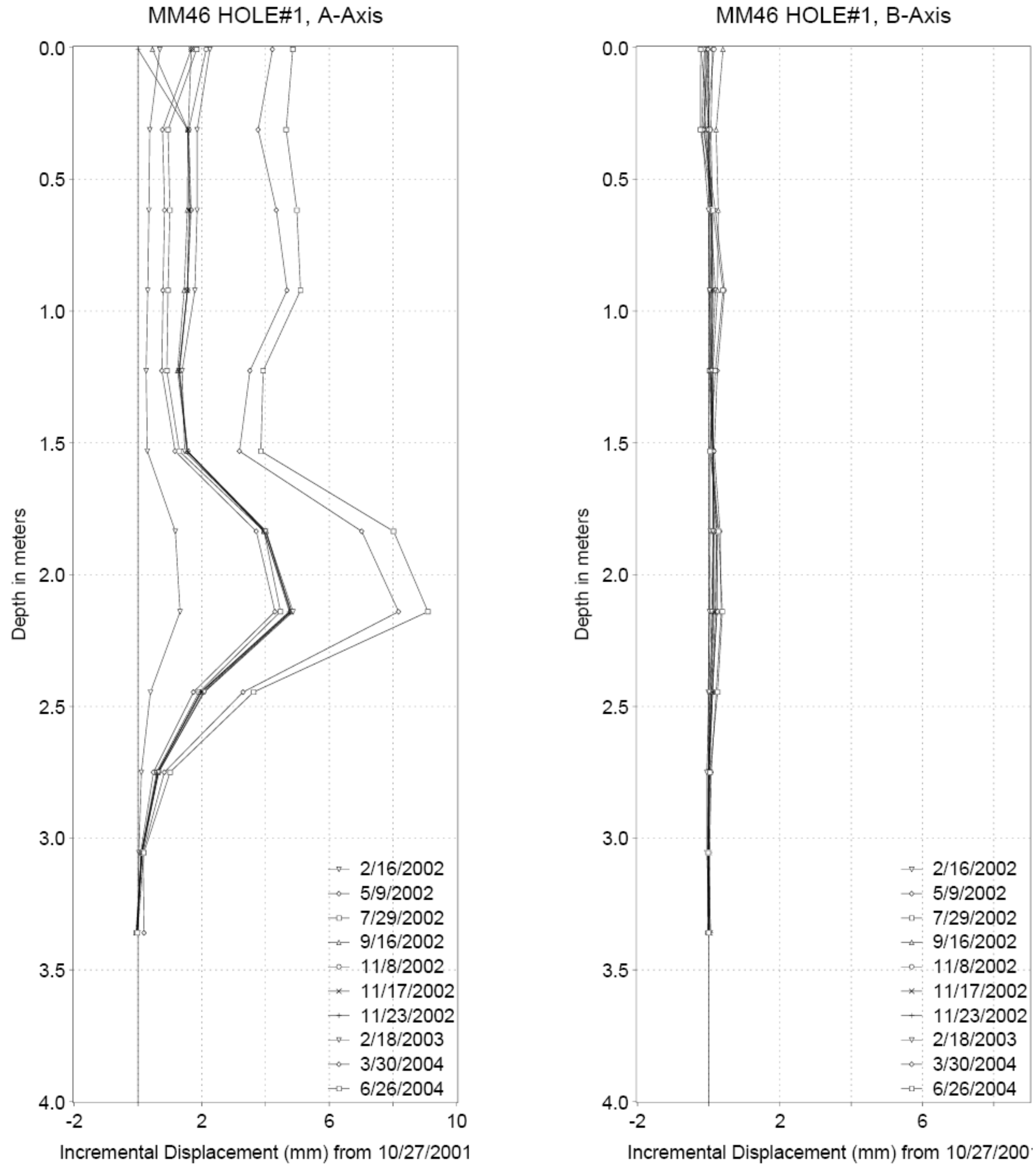


Figure 4.14: Summary of inclinometer monitoring result for Hole#1 at MM46 (Top Row)

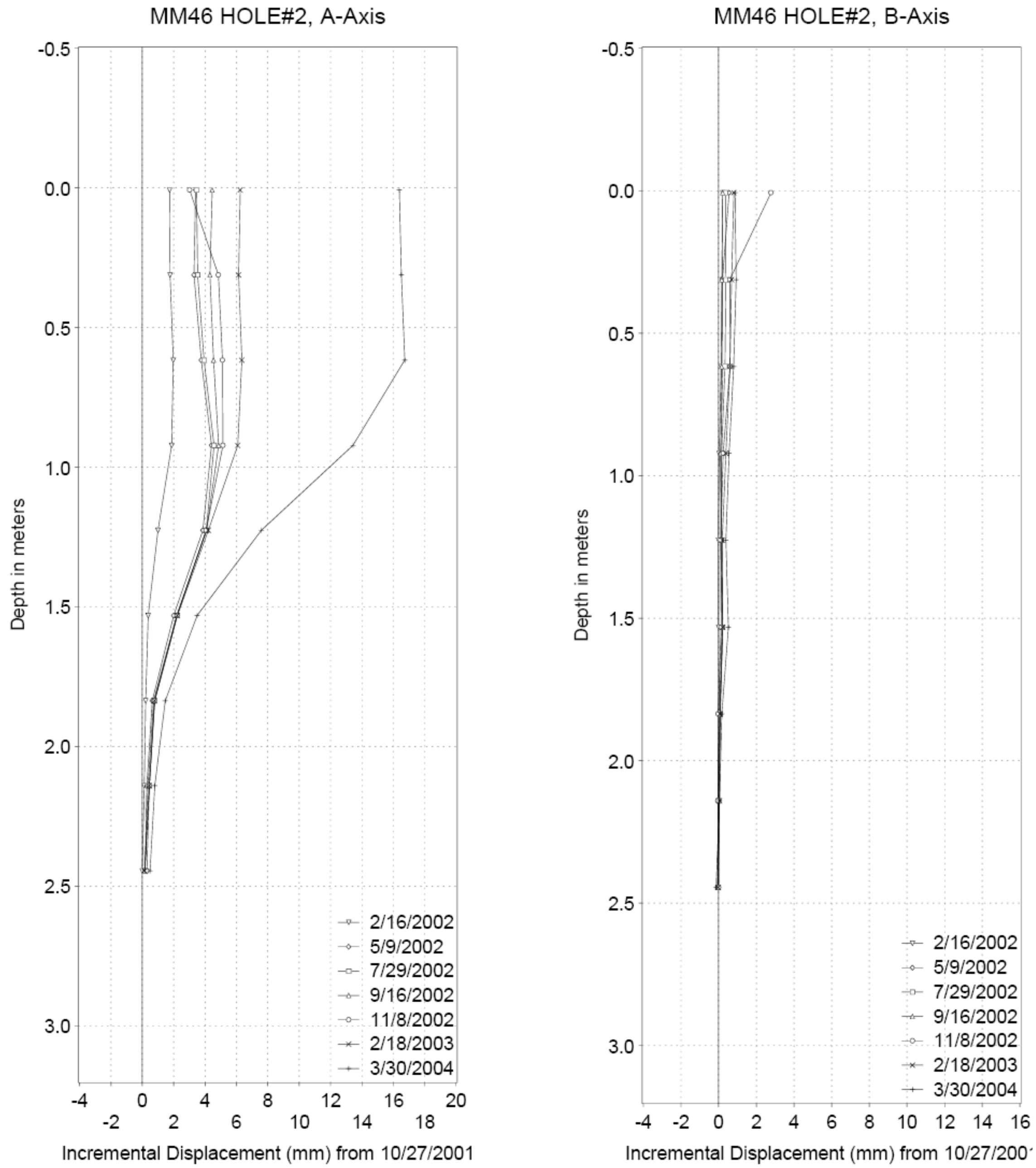


Figure 4.15: Summary of inclinometer monitoring result for Hole#2 at MM46 (Middle Row)

4.2.1.2 Station at Ozark

This station was installed at the request of the Arkansas Highway and Transportation Department. As shown in Figure 4.16, the slope is immediately to the north of the west bound lanes of Interstate 40 near mile marker 35 (MM35). This slope had been creeping for many years, requiring maintenance crews to periodically resurface the pavement in order to eliminate the dip that formed as a result of the slide movement. This installation was made immediately after a roadway surface repair and significant improvements in upslope drainage were made. Immediately after the repair, a horizontal surface crack formed across the top of a section of the slope where fresh fill material had been added during the repair. It was feared that this additional overburden material had exacerbated the slope instability problem. Three coaxial cables (two-RG8 and one-RG58) and two inclinometer casings were installed downhill from the crack to monitor the slope movement.

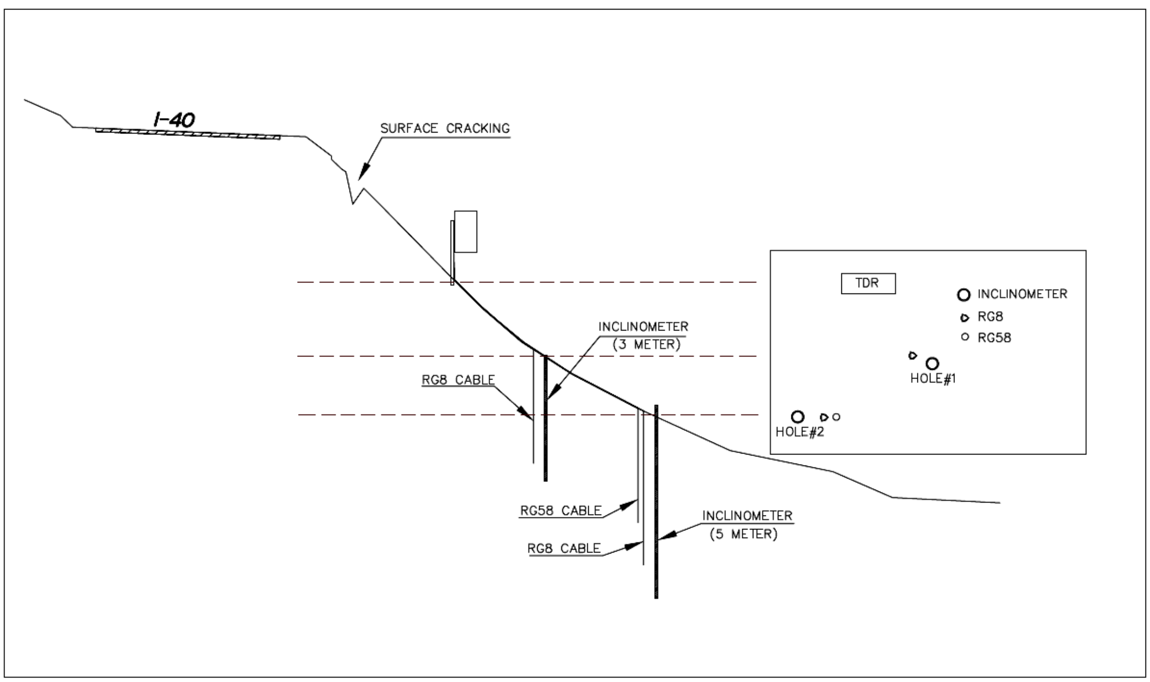


Figure 4.16: TDR cables and inclinometer casing layout for the Ozark site

The depth of the cables and inclinometer casings ranged from 2.74 meters (9 feet) to 6.1 meters (20 feet). The relative shallow depths of the boreholes were the result of the inability of the drilling crew to penetrate a very hard layer of material at the termination depth. As shown in Figure 4.17, a total movement of only 1.9 millimeter (0.08 inch) was recorded in the upper, (Hole #1), inclinometer casing over a monitoring period of eight months. The recorded movement was near the top of the casing, and much of it was for the portion of the casing that was above ground. The recorded movements below the ground surface were unlikely to have been the result of any localized shear in the slope, and were clearly not sufficient to produce a reflection spike in the coaxial cables, or possibly not even enough to break the grout around the cables. As a result of the very small movements observed, the monitoring results at this location did not produce useful information for this study.

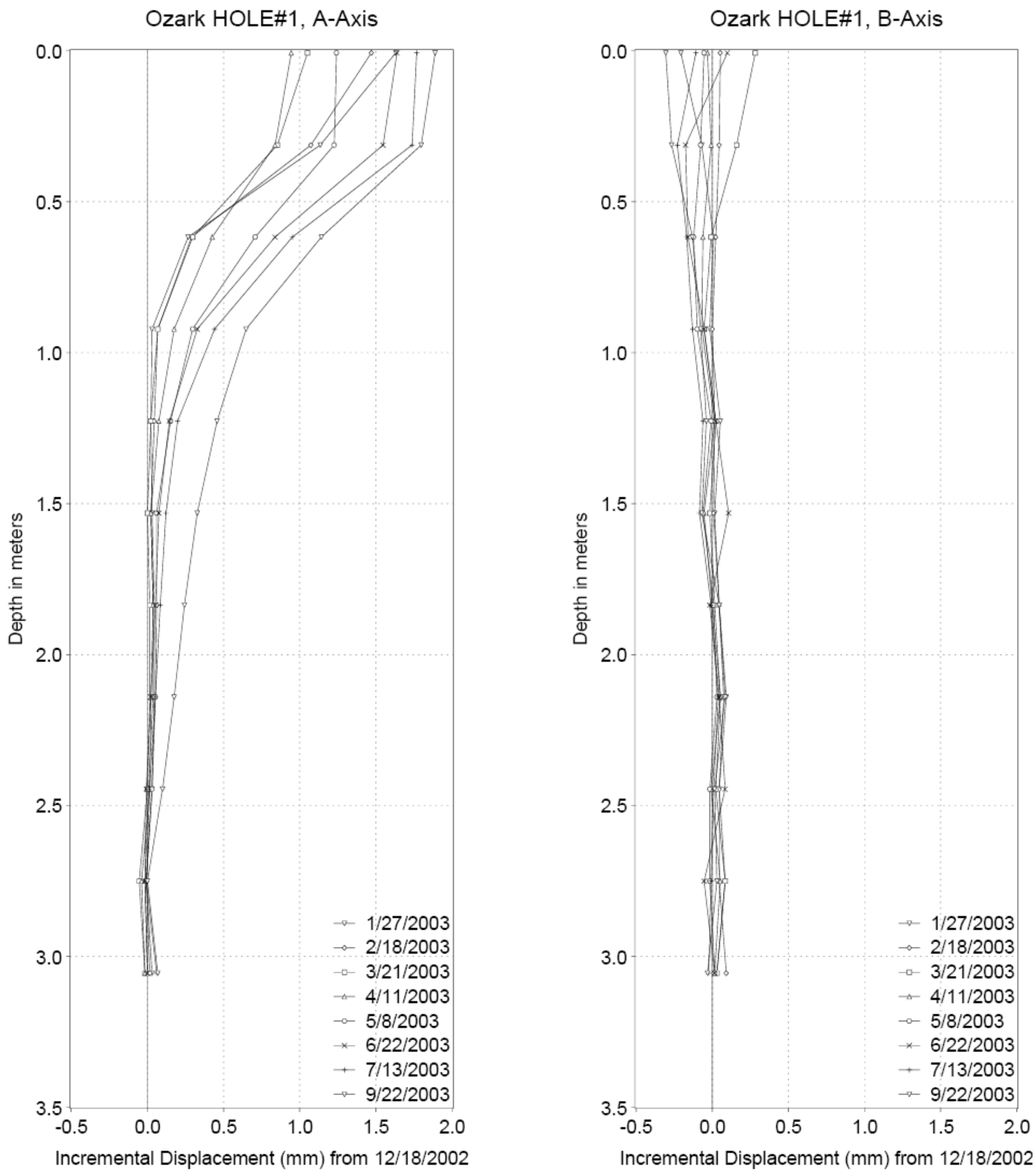


Figure 4.17: Summary of inclinometer monitoring results for the upper casing (Hole#1) at the Ozark Station

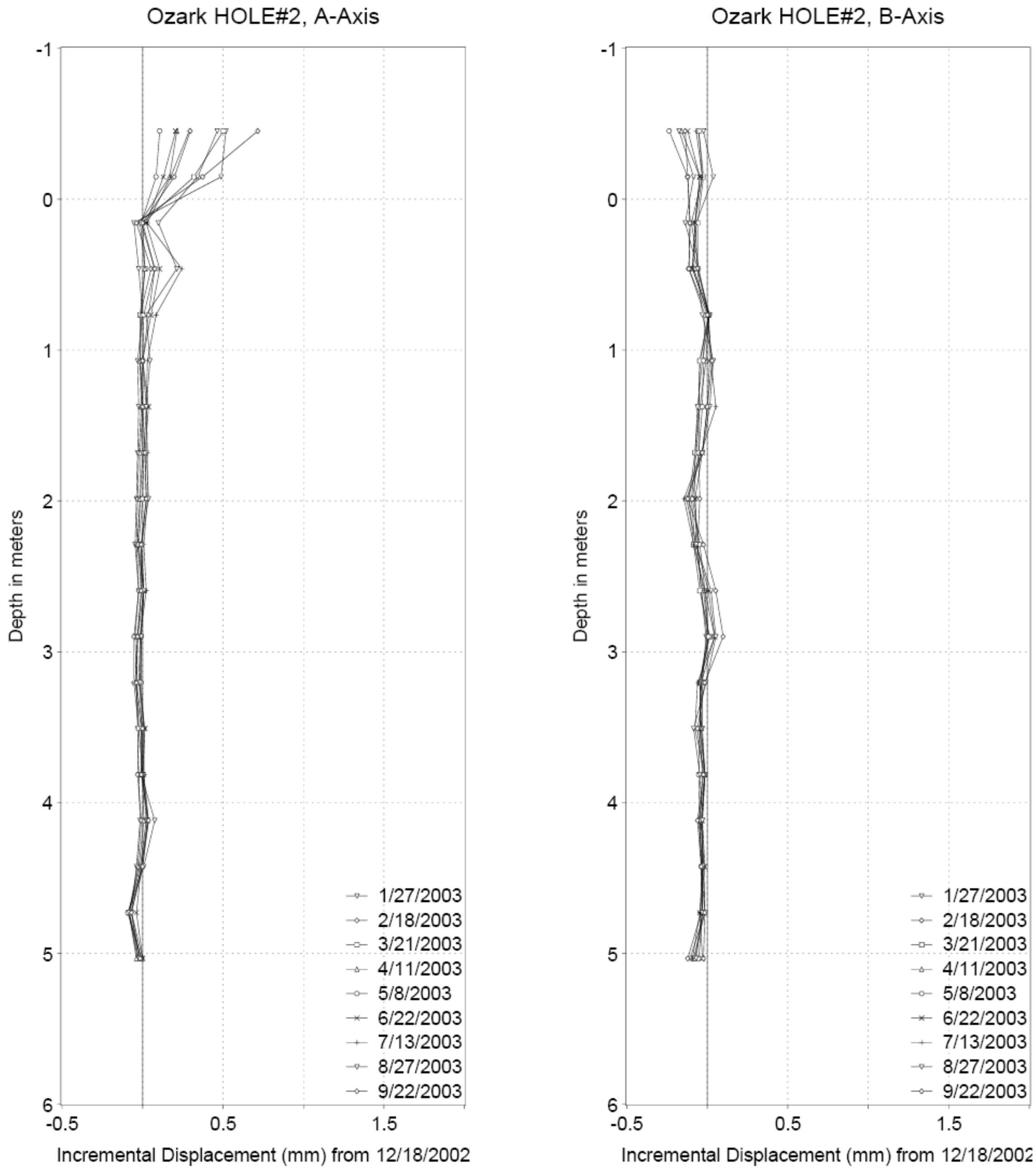


Figure 4.18: Summary of inclinometer monitoring results for the lower casing (Hole#2) at the Ozark Station

4.2.2 Stations with Significant Recorded Movement

4.2.2.1 Station MM50

The installation layout for this site is illustrated in Figure 4.19. In total, 9 cables, one moisture probe and 2 inclinometer casings were installed at this station. As explained in Chapter 3, the grout strength for the first installation of 5 cables was determined to be too weak to create significant distortion in the cables. Therefore, a second round of 4 cables was installed with stronger grout. An additional multiplexer was also used to accommodate the additional cables. Two of these four cables eventually detected movements, while no movement was detected by the original five cables. Figures 4.20 to Figure 4.26 illustrate the monitoring results from the TDR cables and inclinometer casings at this station. All of these figures are intended to give an overview of the subsurface activities during the monitoring period.

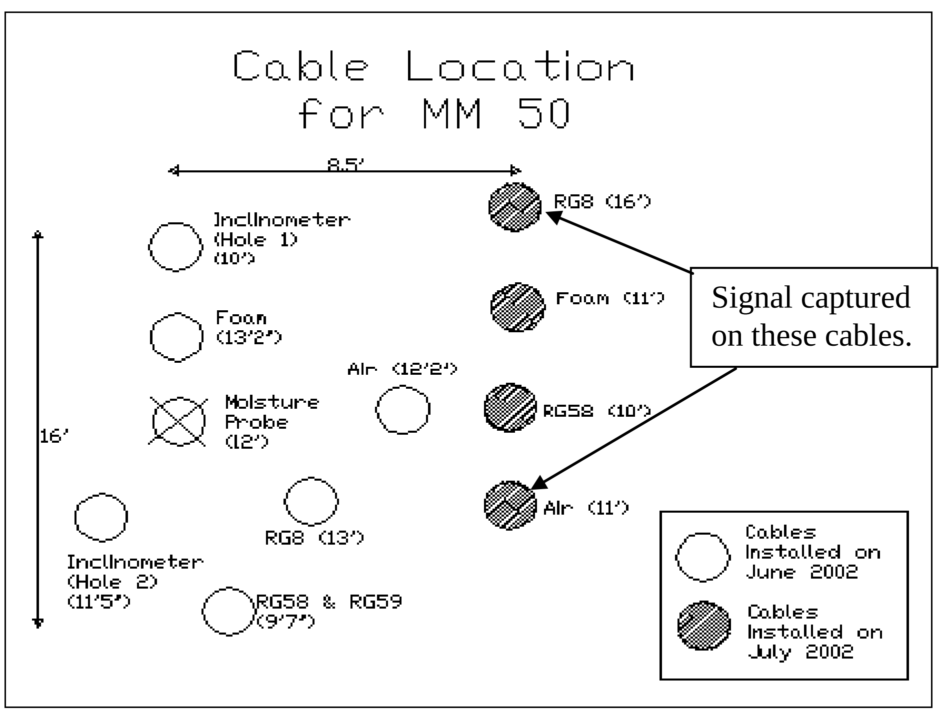


Figure 4.19: Cables and inclinometer casings installation layout on MM50.

Figure 4.22 illustrates the development of a broad, poorly defined, shear zone with peak shear intensity at about 0.7 m below the ground surface for the upper inclinometer casing while Figure 4.23 illustrates a more clearly defined shear zone at about 1.0 m below the ground surface for the lower casing. This movement developed over a period of almost 2 years, extending from July of 2002 to March of 2004. Figure 4.24 and 4.25 present the inclinometer data in the classical cumulative displacement format. These figures are included for completeness, but are not analyzed because they cannot show the location of maximum shearing intensity like the incremental displacement graphs can. According to these figures, the total displacement at the top of the casing for Hole#1 was 89 millimeters and 78 millimeter for Hole#2. Figure 4.24 shows a plot of the maximum incremental movement recorded from the inclinometer casings as a function of time. Both inclinometer casings at this station recorded 6 to 7 millimeters (~0.27 inch) of displacement by the 46th day (7/22/02) after installation. This amount of movement was the minimum displacement (threshold displacement) required in the laboratory to produce a reflection spike in the waveform of the TDR cables. However, no spikes were observed in any of the TDR cables on this date. Subsequent inclinometer data showed shearing continued to increase at the same depth at both locations and caused further displacement with time. The maximum incremental displacements were recorded on 3/30/04, and were 23 millimeters for the upper casing (Hole #1) and 25.5 millimeters for the lower casing, Hole#2. The displacement pattern illustrated in Figure 4.26 indicates that the rate of movement for both inclinometer casings at MM50 was consistent, even though they were located 14 feet apart. Figure 4.26 shows a slow displacement rate from October 2002 to February 2003 and again from

October 2003 to February 2004. In contrast, the slope movement rate was higher from June 2002 to October 2002 and from February 2003 to October 2003. These results suggest the possibility that slope movement is related to weather. Based on the weather record provided by weather.com, April through June are the average wettest months in Northwest Arkansas. This wet period correlates with high slope movement rates that were observed during the spring and summer periods. In essence, the high moisture content in the soil reduces soil its strength and concurrently increases its unit weight which leads to greater slope instability and movement. The final few recordings of inclinometer casing movement in the spring of 2004 showed that displacements increased at an accelerating rate, while at the same time a tension crack developed upslope from the lower inclinometer casing, (Hole#2).

A TDR waveform was selected from each month of monitoring and compiled into an Excel® spreadsheet. The graphs of these compilations are presented in Figures 4.20 and 4.21 for the RG8 and air dielectric cables respectively where each waveform is separated by 0.02 rho for ease in visualization. These two cables, from the second installation with strong grout, were the only two cables to exhibit any reflection spikes due to slope movement. Reflection spikes for both cables were first recorded in August of 2003. At this time the maximum deformation recorded by both inclinometers was about 15 mm, which was about twice the threshold deformation necessary to produce a reflection spike in the laboratory experiment reported in a previous section of this chapter.

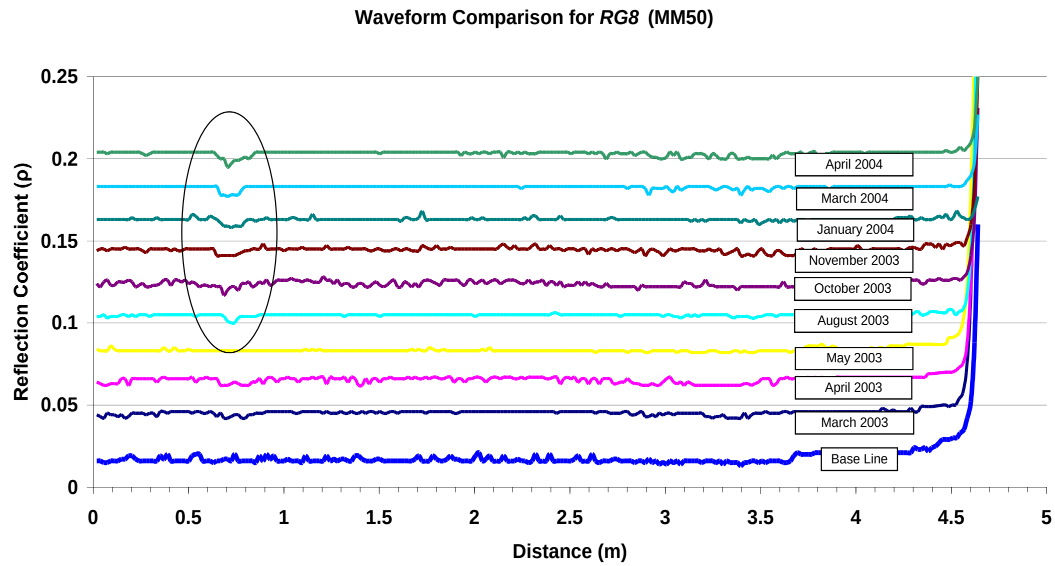


Figure 4.20: Summary of TDR testing results for RG8 cable at station MM50

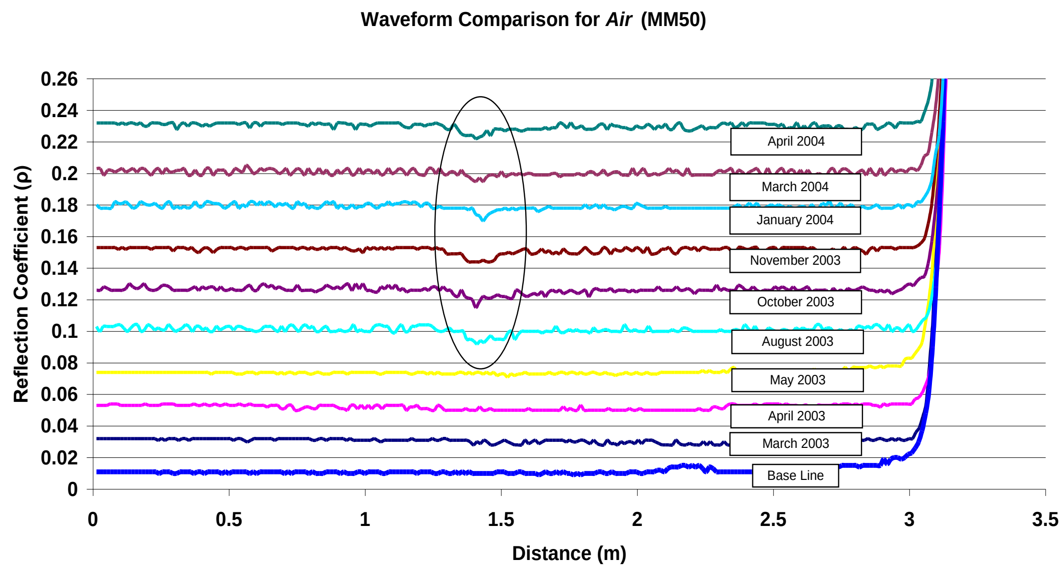


Figure 4.21: Summary of TDR testing results for rigid copper-air dielectric cable at station MM50

The RG8 cable was located 8.5 feet away from the upper inclinometer, (Hole#1), but they were at the same transverse elevation on the slope. The depth of the recorded reflection spike in the RG8 cable waveform was 0.7 meter (2.30 feet) below the ground surface. This result agreed with the shear location reported by the upper inclinometer casing, at Hole#1, as illustrated in Figure 4.22. The reflection spike signal captured by the air-dielectric cable indicated that shear was occurring at 1.4 meter (4.59 feet) below the ground surface. The location of this spike signal does not match with the depth of shear plane captured by either the inclinometer casing at MM50. The actual reason for this difference is unknown; however the following refers to a partial analysis of this result:

1) This cable was located about 10 feet away from lower inclinometer casing and 14 feet away from the upper inclinometer casing (Figure 4.19). The actual shape of the shear plane is unknown. However, the inclinometer results indicated the shear plane was closer to surface on Hole#1 than on Hole#2.

2) Any changes in soil properties between the inclinometer casing locations and the cable location could affect the location of the shearing surface.

3) Other cable probes installed between the Air dielectric cable and the inclinometers casings might form a localized reinforcement and change the shape of shear plane.

4) The number of multiplexers and the length of the transmittal cables connecting TDR probe to the TDR unit play an important role on cable sensitivity. The laboratory results proved that the cable sensitivity is inversely proportional with the cable length. Multiplexers, connectors, and deformation in cable reduce the signal strength as it is transmitted through the cable.

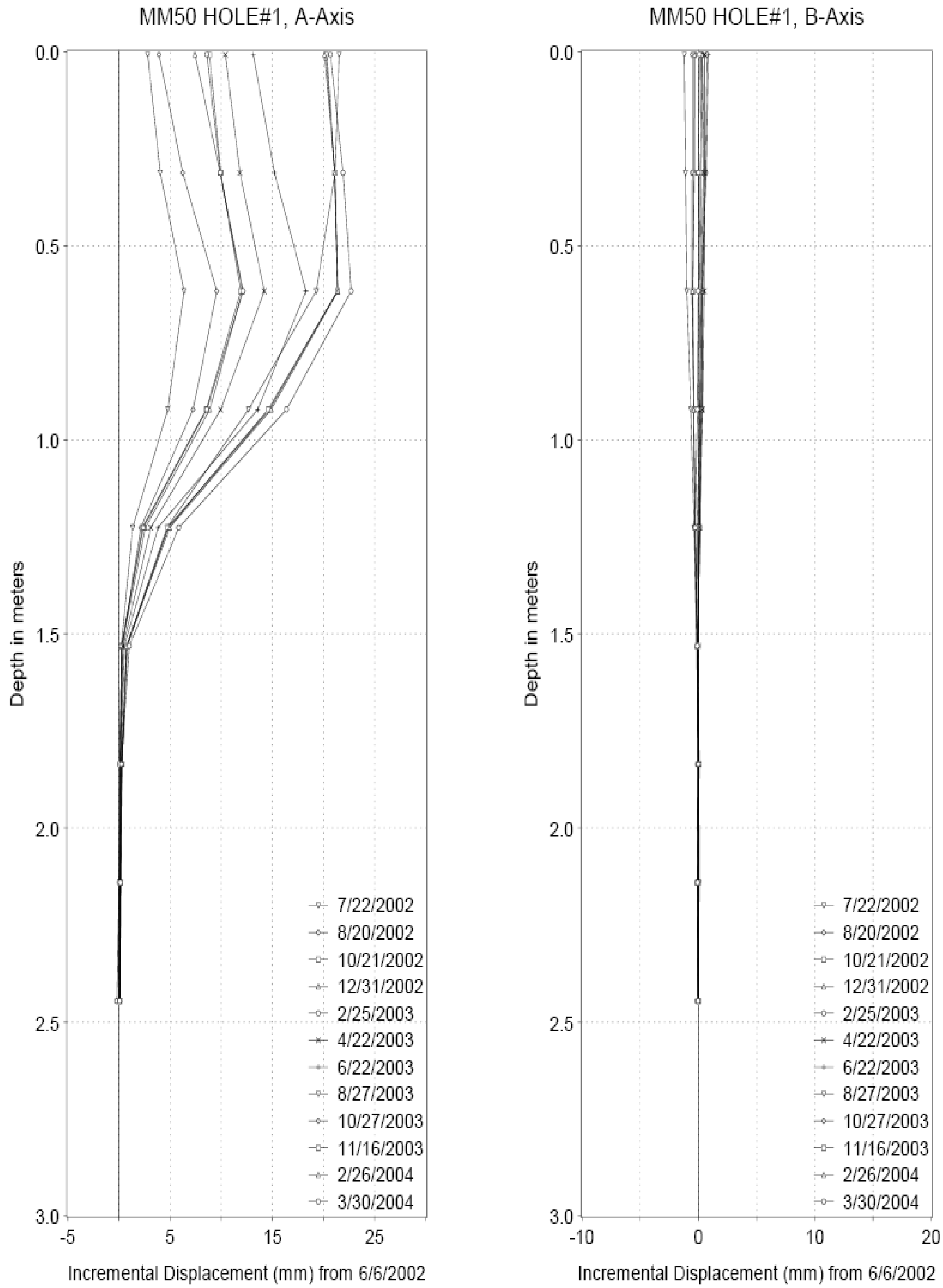


Figure 4.22: Summary of inclinometer monitoring results for the upper inclinometer casing at Station MM50 (Hole #1) - incremental displacement

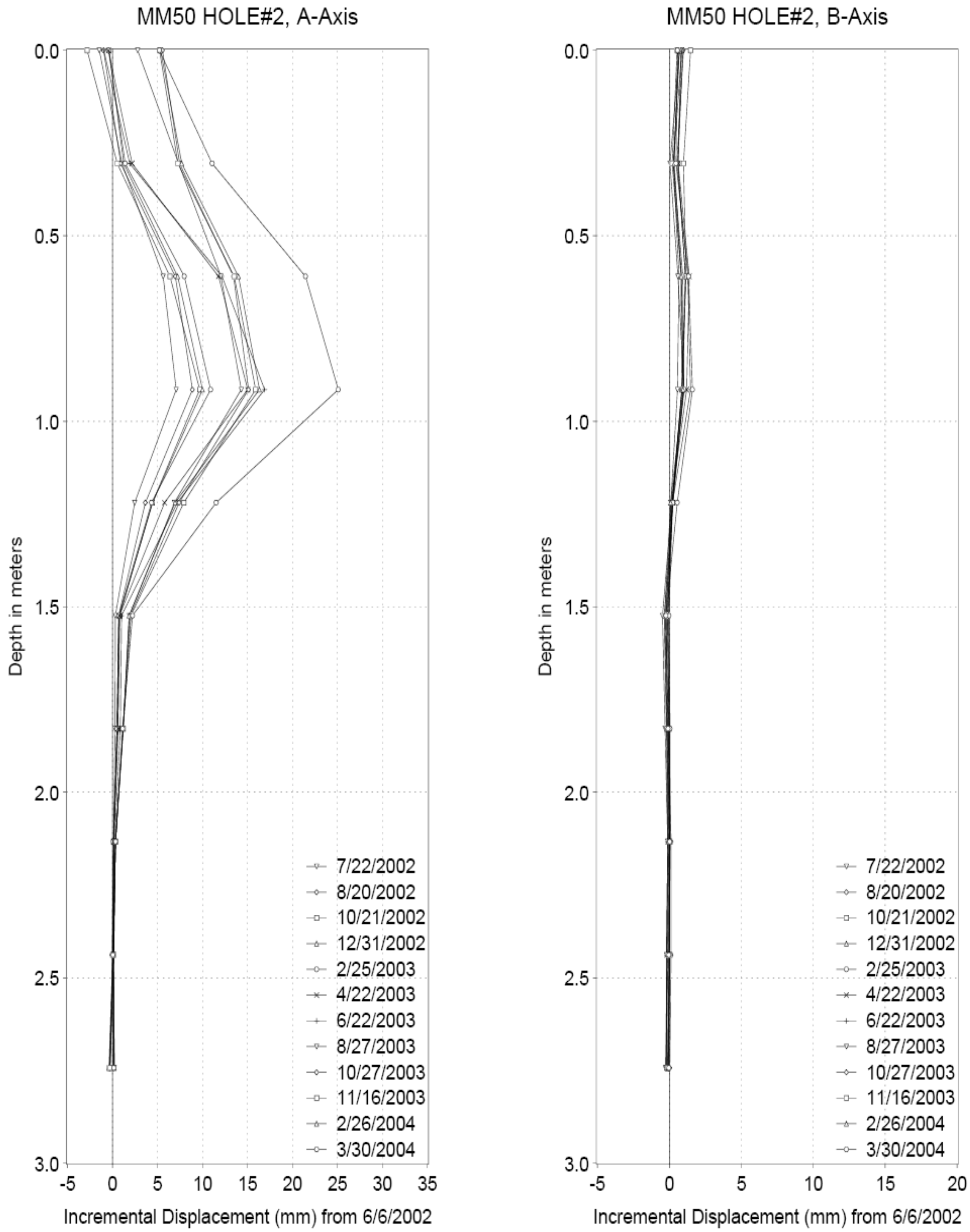


Figure 4.23: Summary of inclinometer monitoring results for the lower inclinometer casing at Station MM50 (Hole#2) – incremental displacement

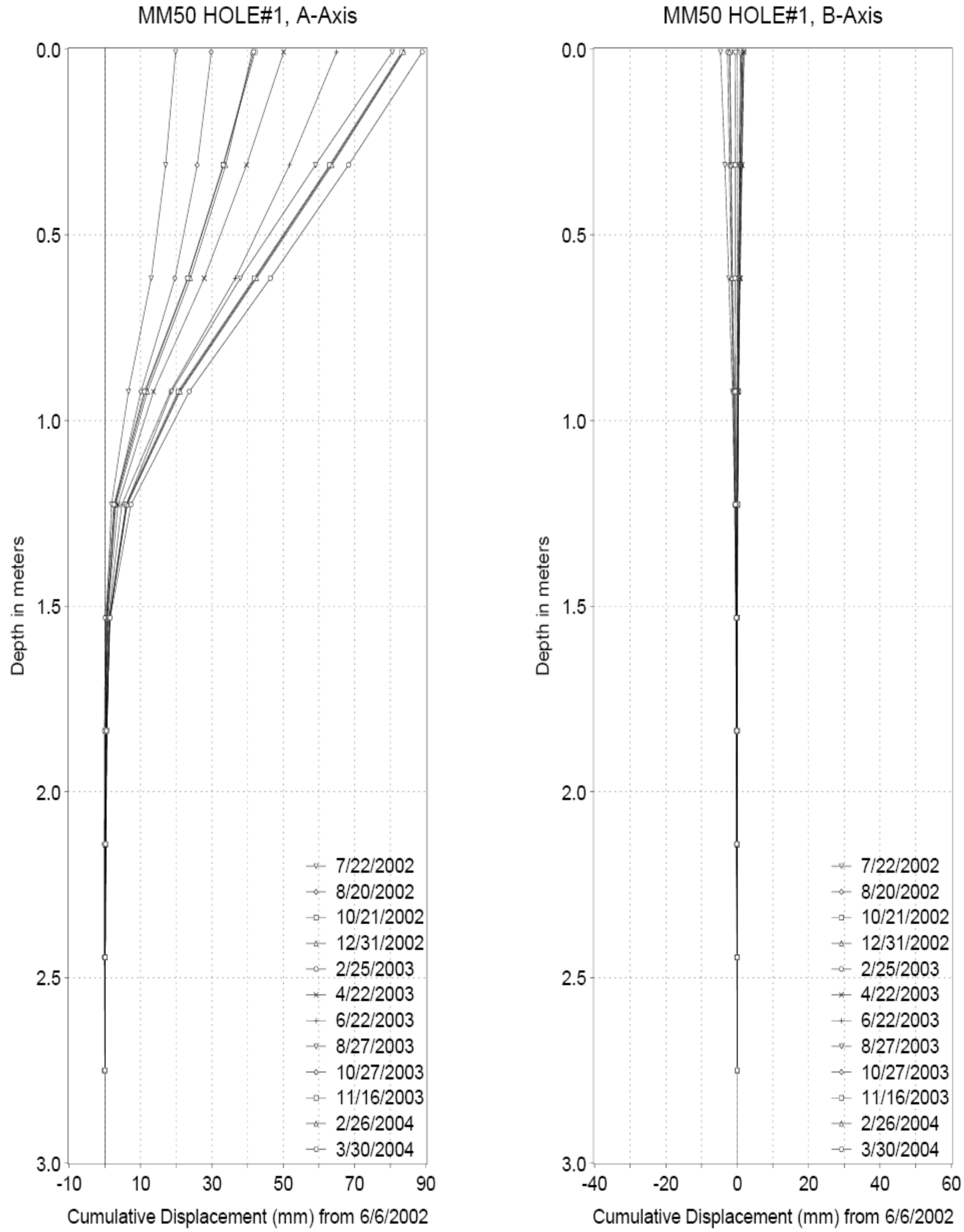


Figure 4.24: Summary of inclinometer monitoring results for the upper inclinometer casing at Station MM50 (Hole#1) – cumulative displacement

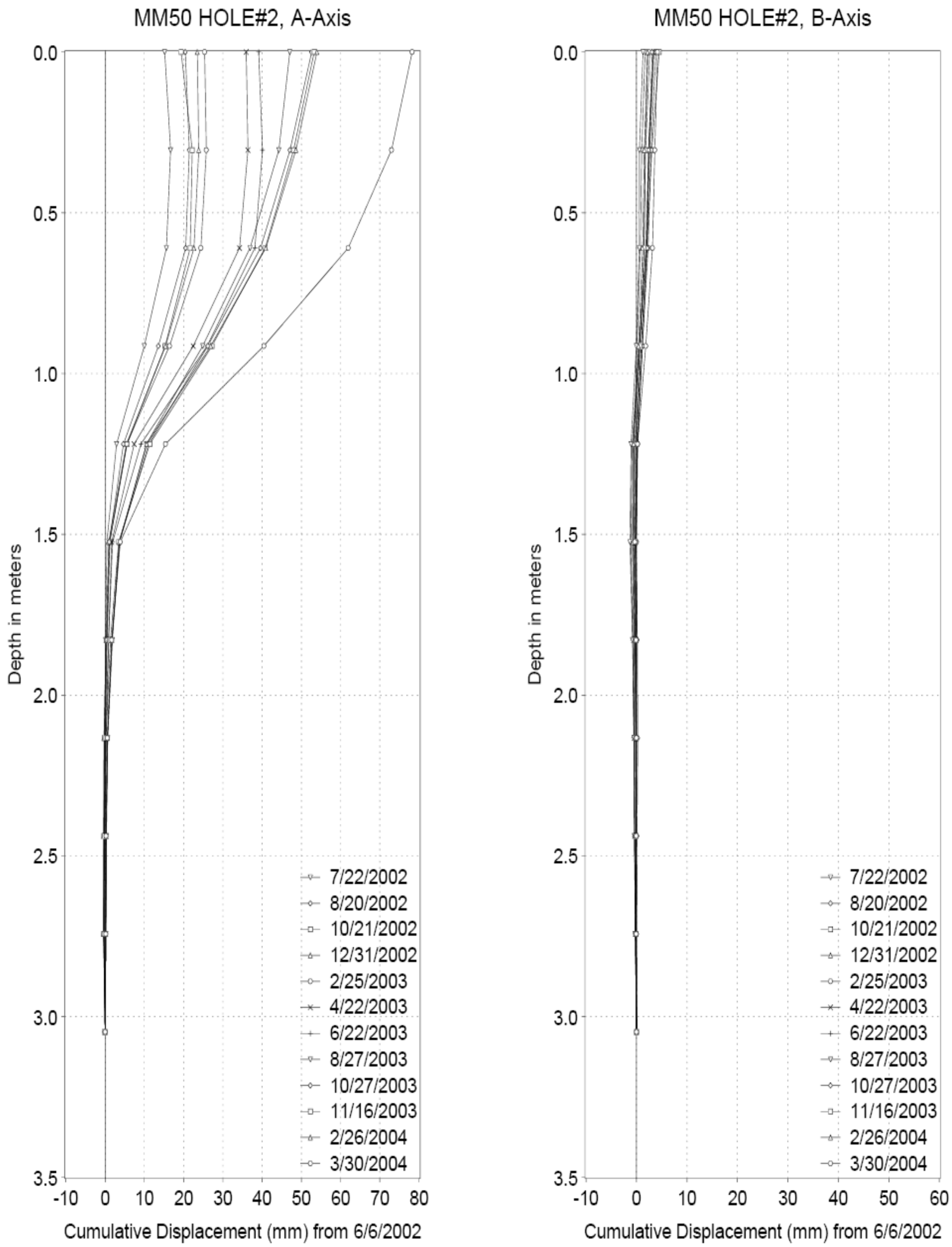


Figure 4.25: Summary of inclinometer monitoring results for the lower inclinometer casing at Station MM50 (Hole#2) – cumulative displacement

The incremental displacement graphs for upper and lower casings display some rotational movement of the soil in addition to translation along a shear plane. This is especially true for the inclinometer reading for the upper casing. The graphs for the upper casing do not display a well defined shear plane; rather the top 1 meter block of soil seems to have slid progressively from the surface down to a partially defined shear plane. This pattern of shearing happened only when the slope failure was very shallow (1 meter or less below surface). However, a shear plane did develop in the slope at MM50 as evidenced by the bulging shape of the inclinometer logs for incremental displacement in Figures 4.22 and 4.23, and the movement was eventually large enough to fracture the grout column of the TDR cables an produce a reflected signal.

Figure 4.26 indicates the slope movement had surpassed the threshold movement of 6mm (0.25 inch), which was the amount required to produce a reflection in the TDR waveform in the laboratory, by September of 2002. However, the reflection spikes for the RG8 and air dielectric cables did not become noticeable until August of 2003 when the displacement was approximately 15 mm in both cables. This amount of deformation was approximately twice that required in the lab to produce the first noticeable reflection spike in the TDR waveform. Some of the reasons for these differences may be explained by the following hypotheses:

1) Laboratory tests were run under very controlled conditions. In the lab the shearing plane was confined to a 3 mm zone in the cable and 25 mm of shearing distortion took place in under one hour. In the field this shearing took place over the length of nearly a meter and the distortion took nearly two years. The controlled conditions of the laboratory produced a much higher distortional flux

in the cable than observed in the field. In addition, there was no time allowed for relaxation of the cable distortion in the lab compared to the very long time available for relaxation in the field.

2) Signal attenuation due to cable length and multiple connections would cause some loss in signal strength during signal transmission. The length of cable used in the laboratory tests from the TDR pulse generator to the location of the first shear plane was approximately 10 feet. In the field, this distance was from 40 feet to 80.feet. In addition, the signal pulses had to be transmitted through one or two extra multiplexers and possibly one or more additional connectors before reaching the shear zone in the field, while there was only one multiplexer and one connector in the lab testing. All of these issues would have increased signal attenuation in the field and flattened the reflection spikes.

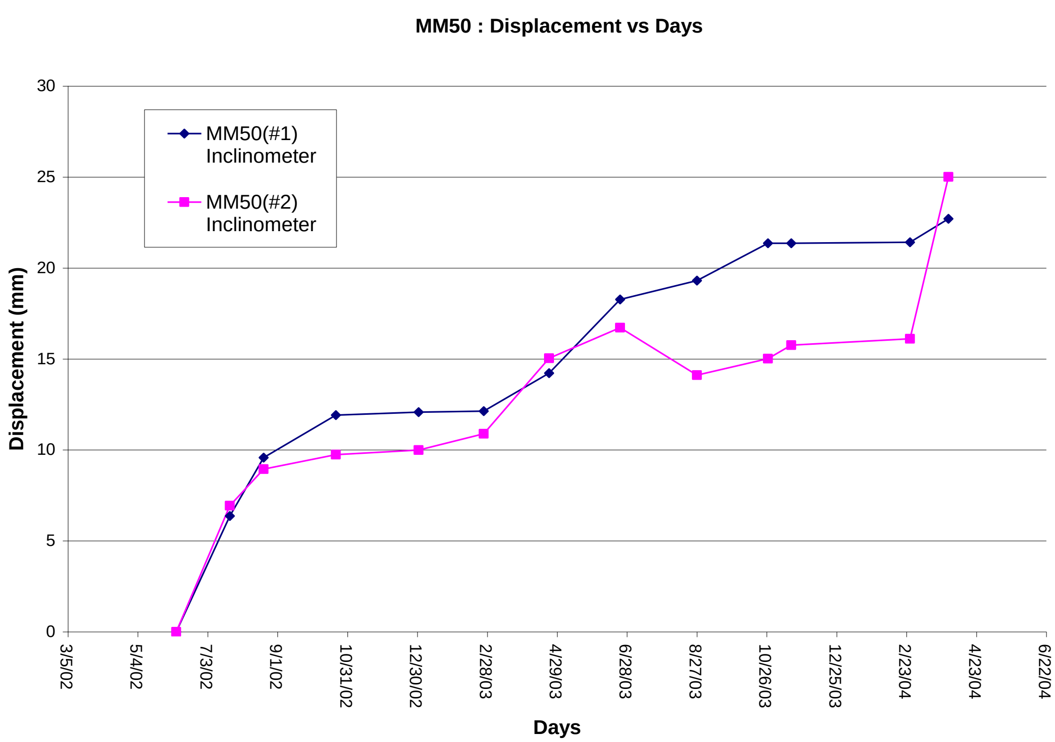


Figure 4.26: Displacement versus time for inclinometer casings on MM50.

4.2.2.2 Station at Batesville

Among all of the TDR stations installed during this study, the Batesville Station provided the most significant results. Within 6 months of their installation, all installed TDR cables and inclinometer casings produced definitive readings. Figure 4.27 shows the monitoring station layout and the stratigraphy of the site.

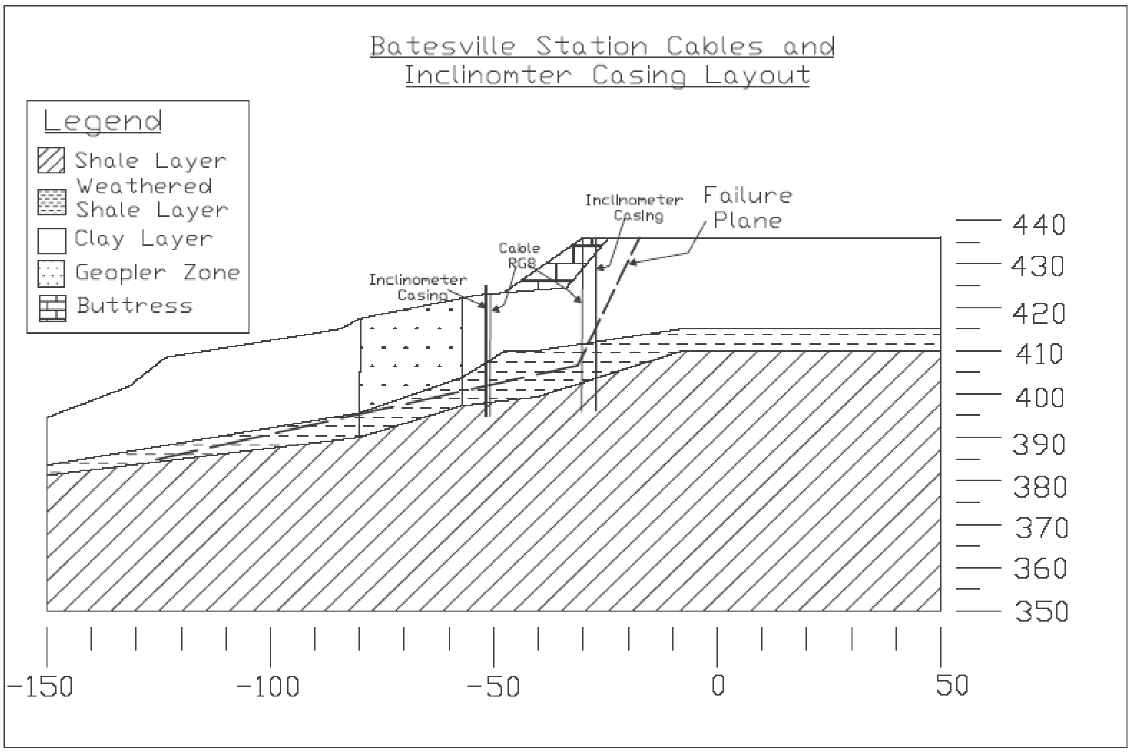


Figure 4.27: Batesville station soil profile and installations layout.

Figures 4.28 and Figure 4.29 provide a summary of the inclinometer monitoring data for this site. The upper inclinometer casing was located on the shoulder of the road, and is referred to as Batesville Hole#1. This casing exhibited a maximum incremental deflection of 64 millimeters (2.51inch) at 6.9 meters (22.64 feet) below the surface on 10/24/2003. The second casing, located approximately mid way along the assumed failure surface of the slope instability was referred to as Batesville Hole#2. A maximum displacement of 38 millimeter (1.48 inch) was observed in this casing at a depth of 6 meters (19.69 feet) on 8/12/2003. The monitoring of Batesville Hole#2 was terminated on this date due to excessive bending or possible shearing of the casing at the 6 meter depth. This dislocation actually prevented the inclinometer probe from passing through the entire casing, thus making it impossible to log the hole beyond the 6 meter depth.

In comparison to the inclinometer monitoring results from MM50, the Batesville slope had a deeper and a much more well defined shear plane. As illustrated in Figures 4.28 and 4.29, the rotation seen at MM50 was not observed at this site in either of the incremental displacement plots. The results from both inclinometer probes provided a clear picture of the shear plane locations. However, some minor differences were observed in the sliding patterns recorded by the two inclinometer casings. The incremental displacement graph for the upper casing, Batesville Hole#1, clearly shows a sharp spike, indicating a single, well defined shearing plane. Conversely, the incremental displacement graph representing Batesville Hole#2 shows that displacement of the inclinometer casing was caused by multiple shearing planes throughout a one to two meter zone.

To better illustrate the rate of movement of the slope, the maximum incremental deflections from both inclinometers are plotted against time in Figure 4.30. These graphs indicate that both inclinometer casings were experiencing the same amount of slope movements during the first 50 days of monitoring. Data collected after May 2003 indicated that the displacement near the toe of the slope (Hole#2) was increasing at a faster rate than at the crest of the slope (Hole#1). This can be concluded from the fact that the gap between the two plots in Figure 4.30 is becoming larger with time. The plot for Hole #2 stops at 132 days, when the last data logging occurred for that casing. Logging for Hole#1 continued for another 7 months and was terminated in December of 2003, when the contractor performing slope remediation forced the termination of the monitoring program. Plots for both inclinometers exhibit the classical acceleration of displacement with time, predicting that a catastrophic slope failure was immanent.

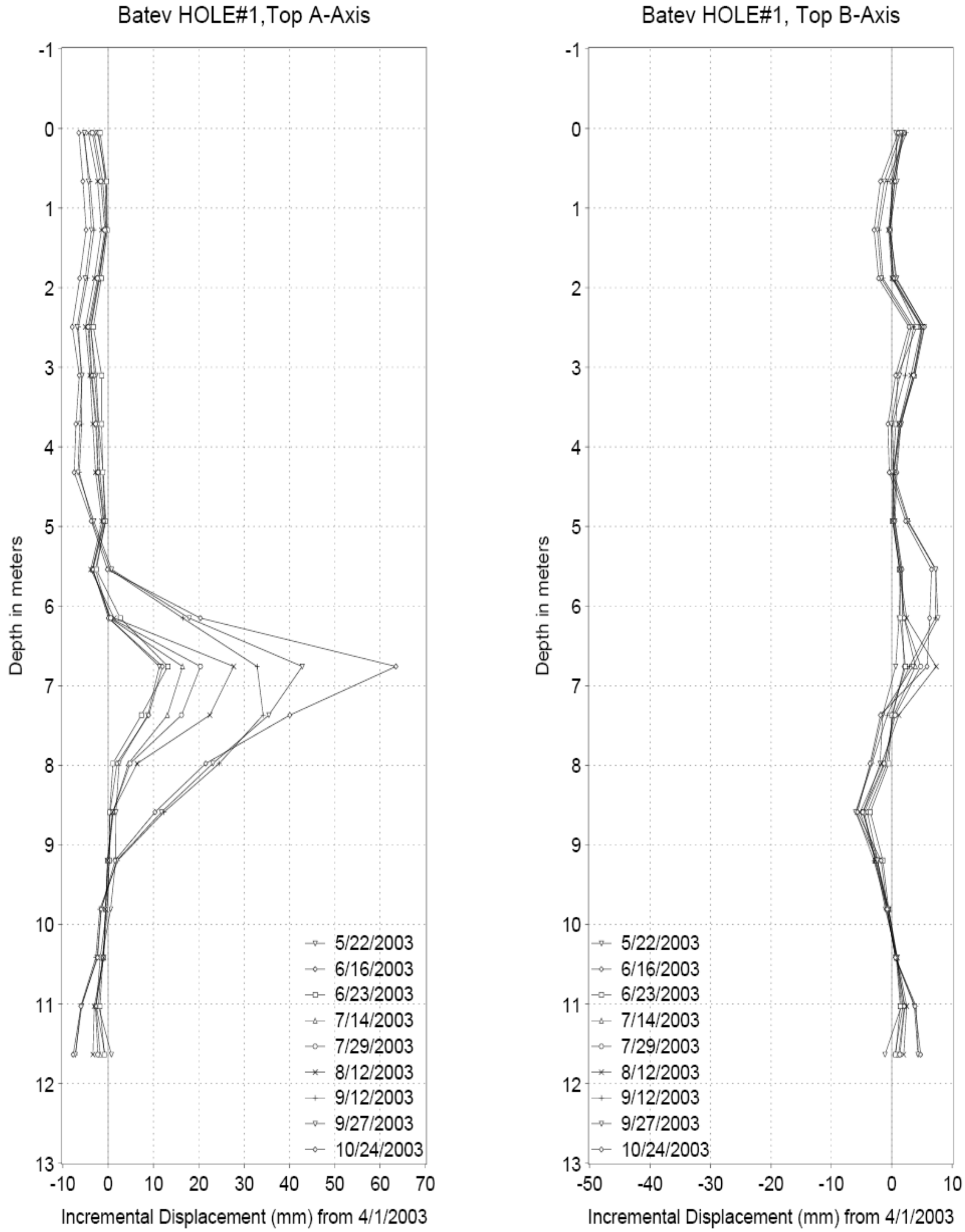


Figure 4.28: Summary of inclinometer testing results for the upper borehole at the Batesville Station Hole#1 (Upper Casing)

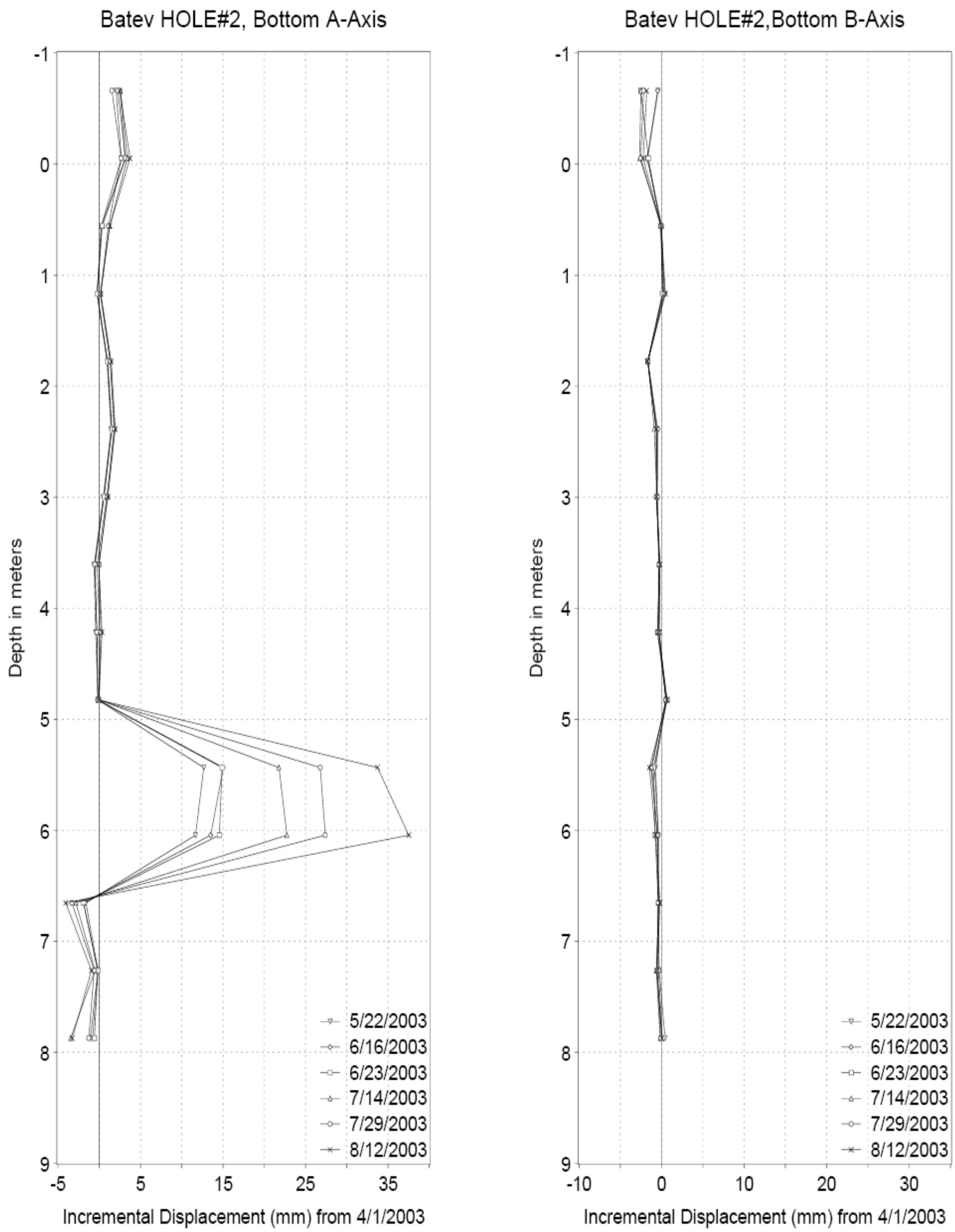


Figure 4.29: Summary of inclinometer readings for the lower casing at the Batesville Station –Hole#2 (Lower Casing)

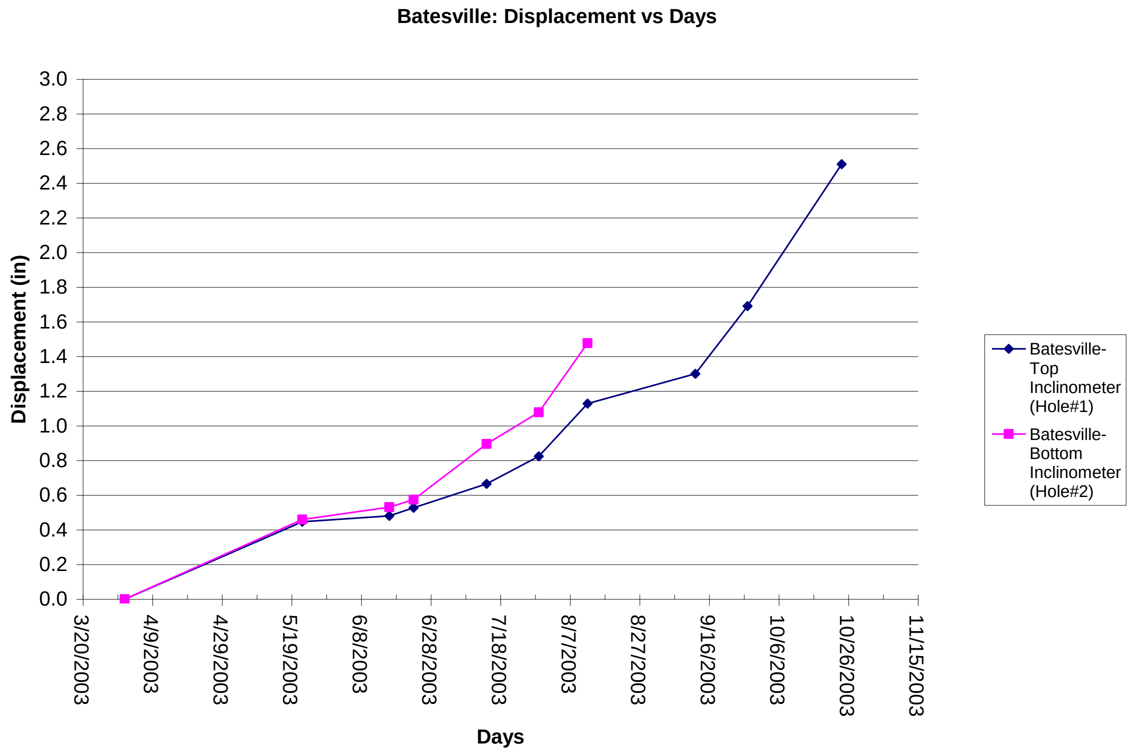


Figure 4.30: Displacement versus time for the inclinometer casings at the Batesville monitoring station

Figures 4.31 and 4.32 illustrate the results of the inclinometer monitoring as cumulative displacement. Inspection of these two figures shows that soil movement in the vicinity of the lower casing could be represented as block movement above the shearing plane. It is clear from Figure 4.32 that all of the soil above the shearing plane was moving at the same rate as evidenced by the vertical plots of displacement with depth. For the upper casing this was not the case. Soil near the shear plane moved at a faster rate than soil near the top of the casing as evidenced by the cumulative displacement plots tending back to zero near the surface of the ground. It is possible that the pavement system may have strengthened the upper layers and retarded surface movements in the vicinity of the upper casing, which would account for the differences in the movements recorded.

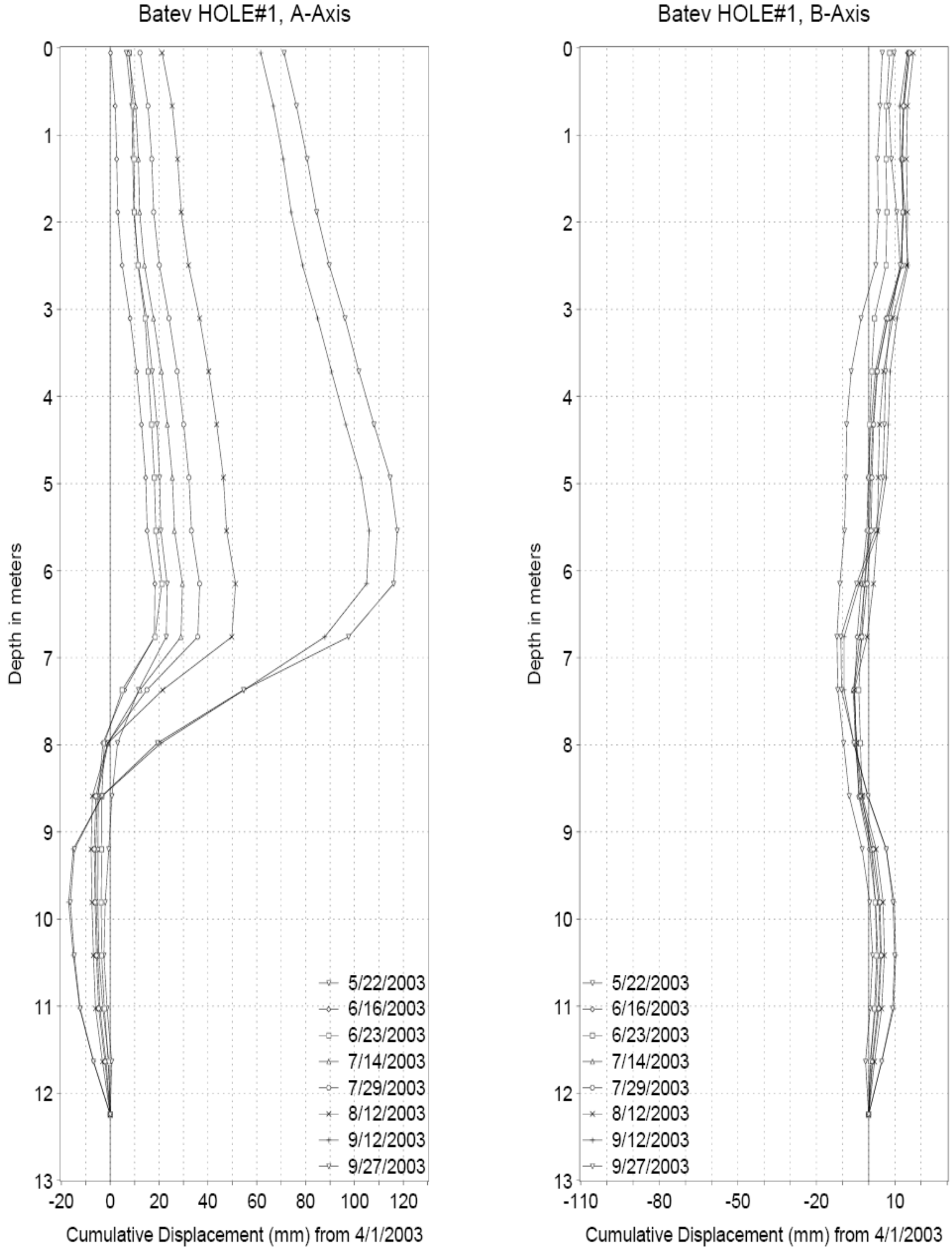


Figure 4.31 Summary of inclinometer monitoring for the upper casing at the Batesville Station, Hole#1– cumulative displacement

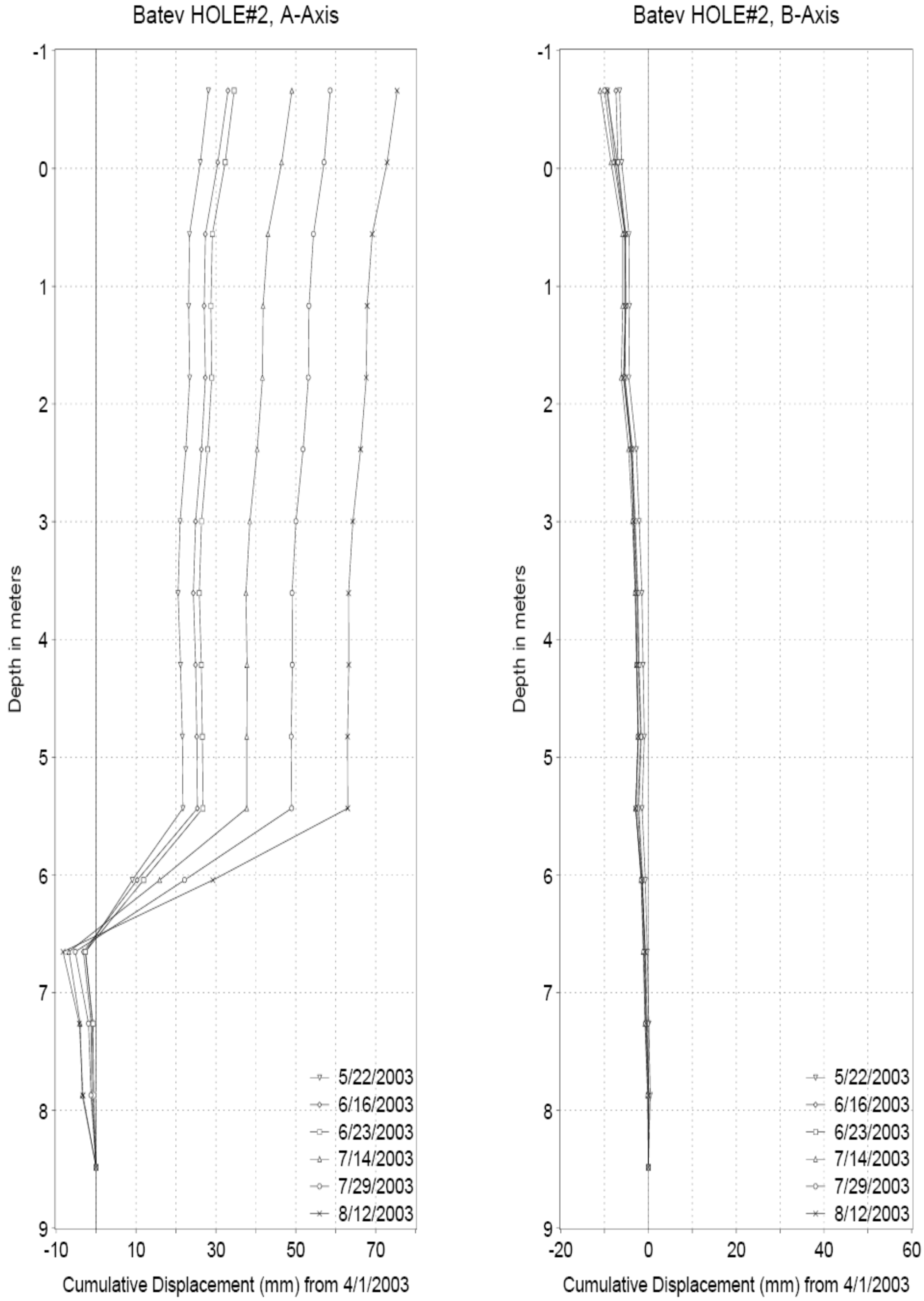


Figure 4.32: Summary of inclinometer monitoring for the lower casing at the Batesville Station Hole#2 (Bottom) – cumulative displacement

Figures 4.33 and 4.35 provide a summary of the TDR cable waveforms for the upper and lower cable locations for this station. A piece of coaxial cable that was retrieved from a previous monitoring station was reused for this station. The result of reusing this cable can be seen in Figure 4.33, where the baseline waveform for this RG8 cable has a cyclic "wiggle" at an interval of approximately 1.5m. It is believed that this "wiggle" in the signal was caused by improper storage and unrolling of the cable which created minor kinks when it was laid out. Nonetheless, this cable still indicated a well defined reflection spike at a depth of 7.9 meters (feet) below the ground surface as shown in Figure 4.33. The magnified section of the waveforms, illustrated in Figure 4.34, helps the user to better compare the changes of the signal spike from 0 rho to 0.029 rho.

Even though the location of the upper TDR cable and the upper inclinometer casing were just 3.4 feet apart, the shear plane indicated by these two devices had a difference in elevation of nearly a meter (3.28 feet). Originally it was believed that the location of the shear plane indicated by the TDR cable was in error. However, the difference was proven correct when a back analysis of the slope failure was conducted. A plausible failure mode for this slope was a sliding block failure along the strong underlying shale. By projecting an active wedge from the indicated upper scarp in the roadway down to the lower failure surface along the shale, the failure plane passed through the zone where the monitoring borehole was located at a 45 degree angle. This would have accounted for the observed difference in elevation in the shearing surface between the two recording devices. The shear surface used in the back analysis of slope stability was illustrated in Figure 4.27.

A reflection spike was observed at 5.8 meters below the ground surface in the lower TDR cable. This reading matched the elevation of the inclinometer results obtained from the lower casing, which was located 5 feet away along the same transverse plane as the TDR cable. Again, these observations confirmed the assumed failure surface used by the AHTD in their back analysis of the failure. Even though the lower inclinometer casing had exhibited a large displacement, as illustrated in Figure 4.29, the corresponding TDR cable exhibited only a minor change in its reflection coefficient at that location. The actual reason for the weak signal on TDR cable is unknown. However, it is possible that a loose connection in the system could have caused major attenuation of the signal, or the multiple shearing planes indicated by the inclinometer reading may have smeared the distortion so that a clearly defined spike could not be developed. Because of the remoteness of the site it was not possible to visit it frequently to determine the root cause of this problem. However, some observations can be made about this signal. Unlike the sharp spike of the Batesville upper cable, the reflection spike for the Batesville lower cable is elongated, as indicated in Figure 4.35. In fact, it mimics the shape of the incremental displacement curve for the inclinometer data shown in Figure 4.29. This may indicate that the shear in this area was not confined to a single surface but rather extended over a zone and definitive cracking of the grout column was probably not confined to one location. This, in turn may have resulted in some cable tension in the shear zone which would have tended to produce a positive rather than negative spike which might have counteracted a negative spike caused by to shear.

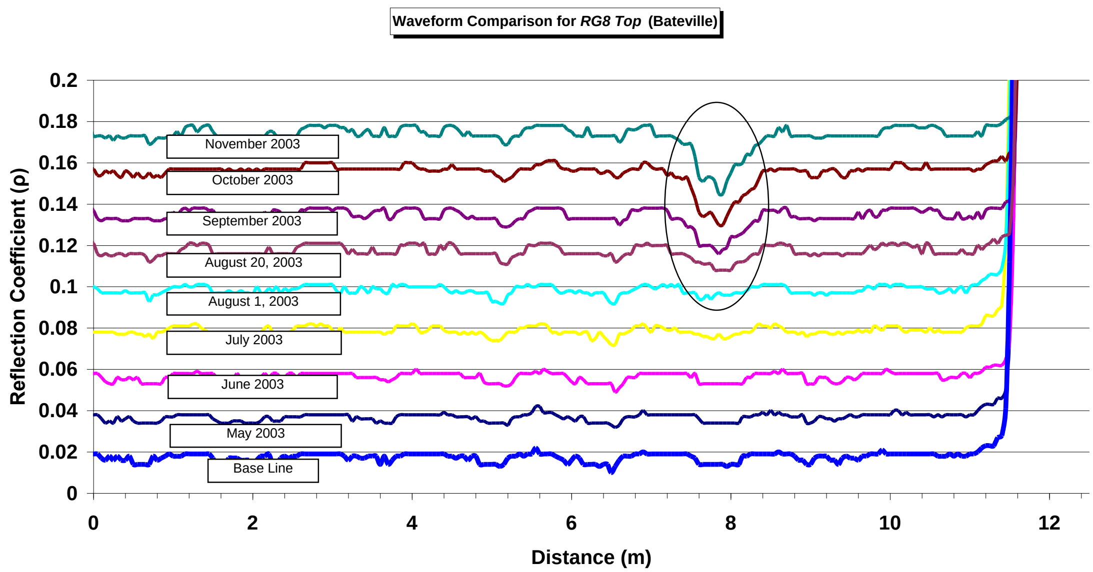


Figure 4.33: Summary of TDR testing results for the upper RG8 cable at the Batesville Station (Upper Cable).

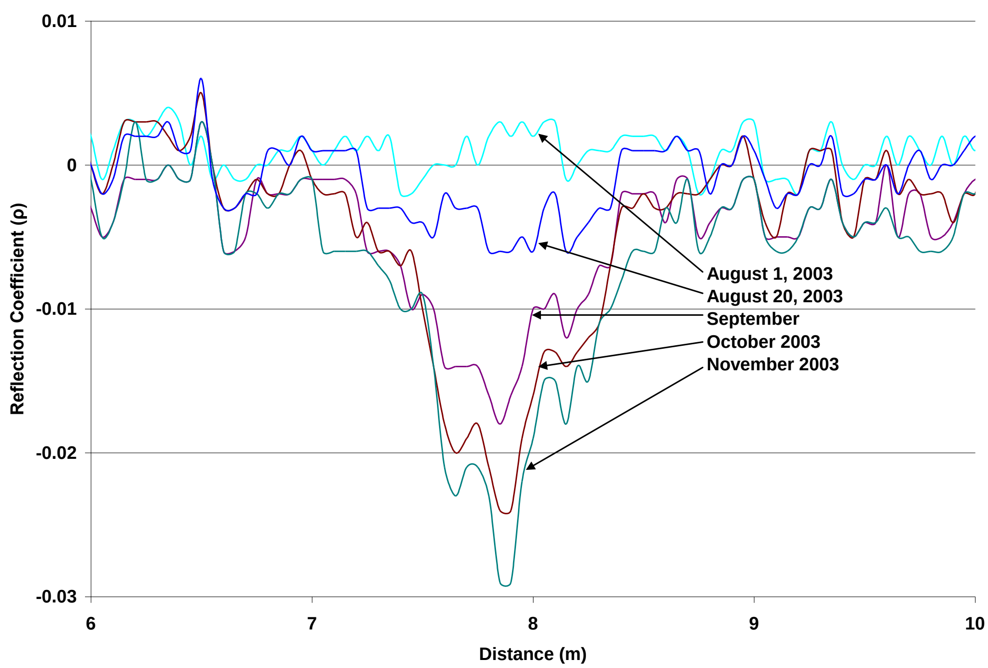


Figure 4.34: Enlarged waveform for RG8 cable on the road shoulder.

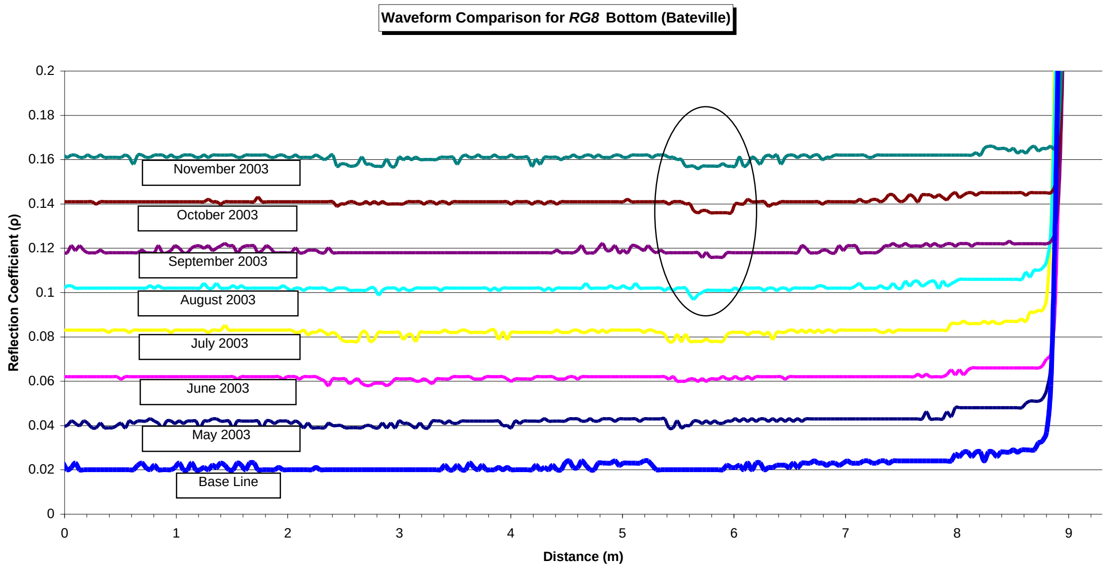


Figure 4.35: Summary of TDR testing result for the lower RG8 cable at the Batesville Station (Lower Cable).

4.3 Correlation of TDR Reflection Coefficients and Displacements from Inclinometer Readings

Slope monitoring by TDR is a method that can be fully automated to obtain results at a low cost relative to other techniques. These two features make it a viable option for long term monitoring. However the method does have disadvantages. The most important drawback for this method is that there is no well defined relationship between the TDR reflection coefficient and actual slope displacement. The results from the laboratory work and field monitoring during this study have provided valuable data for creating a correlation between these two measurements.

4.3.1 Correlation for MM 50

The correlation presented in this section is between the RG8 cable and the upper inclinometer casing (Hole#1). This cable and casing pair was selected for the correlation analysis because they were located approximately 8.5 feet apart along the same transverse plane, and, as illustrated in Figures 4.20 and Figure 4.25, both measuring devices indicated that the shearing surface was located at the same depth (0.7 meter below the surface). Illustrated in Figure 4.36 is the relationship between incremental displacements, measured with a probe inclinometer, to changes in the reflection coefficient for the RG8 cable. The TDR reflection spike was first noted at the end of August 2003 after the cable was temporary disconnected from the automated data collection system. As a result of the intermittent cable readings the spike was believed to have developed sometime between June and August of 2003. The incremental displacement of the inclinometer casing along the shearing surface was 0.7 inch when a spike in the TDR signal was first noticed. The monitoring results between August 2003 and March 2004 show that the TDR reflection coefficient at the location of the shearing surface increased in direct proportion to the inclinometer displacement. A linear best fit line was drawn to define the linear relationship of the TDR reflection coefficients and the inclinometer casing displacement. As illustrated in Figure 4.36, the slope of this relationship, which is a measure of cable sensitivity, is 0.0148,

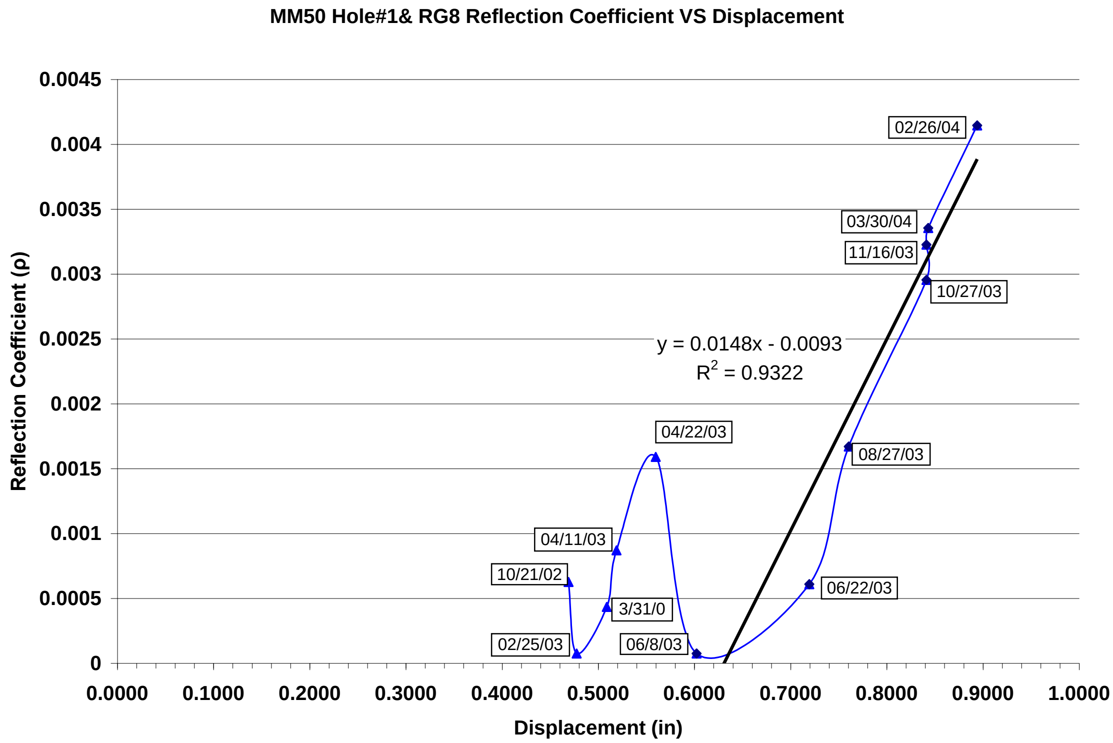


Figure 36: Comparison of changes in reflection coefficient with displacement for the upper inclinometer casing and RG8 cable probe at MM50.

4.3.2 Correlation for Batesville

The results of TDR and the inclinometer comparison for the Batesville upper location are presented in Figure 4.37. As indicated in Figure 4.37, the data points between 5/22/03 to 8/12/03 show only displacements measured by the inclinometer but no reflection activity in the TDR signal. The first spike for this RG8 cable was recorded on 9/4/03 but it could not be used for this data correlation because the inclinometer logging did not take place until 9/12/03. The last three sets of data in Figure 4.37, which match inclinometer and TDR result for the same day, show gradual increases in the reflection coefficient versus displacement. A best fit line was created in this plot to estimate a linear relationship between the reflection coefficient and displacement.

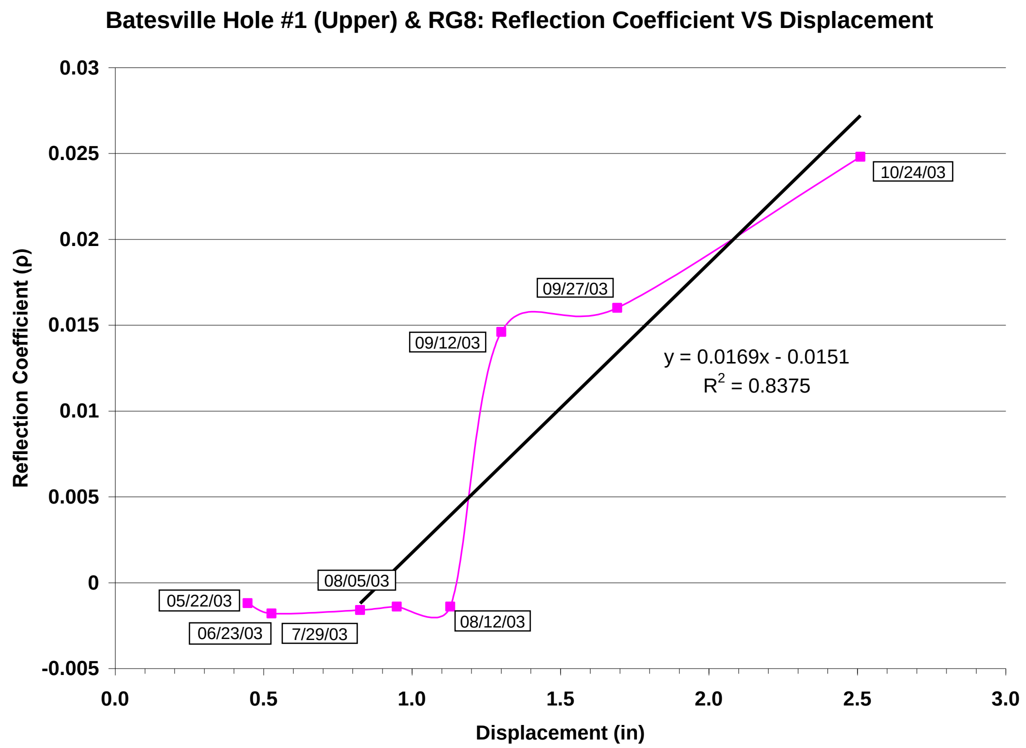


Figure 4.37: Correlation between changes in reflection coefficients with displacement of field data at Batesville.

4.3.3 Generalized Relationship between Displacement and Reflection Coefficient

In order to develop a generalized relationship between displacement and reflection coefficient both sets of the field data as well as the laboratory data for the RG8 cable were analyzed. Those data are summarized in Table 4.2, along with the operating parameters of each individual TDR monitoring system.

Table 4.2 Summary of RG8 Cable Properties on Laboratory, MM50, and Batesville

Station	Transmission Cable Length m (ft)	Probe Length m (ft)	Number of Multiplexers	Number of Connectors	Threshold Displacement (in)	Cable Sensitivity
Laboratory	5.4 (17.7)	0.84 (2.8)	0	1	0.25	0.1743
MM50	18.4 (60.3)	4.64 (15.2)	2	1	0.7	0.0148
Batesville	48.3 (158.5)	12 (39.4)	1	2	1.18	0.0169

One measure of cable probe efficiency is the displacement required to observe a discernable spike in the cable probe waveform. This displacement is termed the threshold displacement. Laboratory testing indicated that the first noticeable spike in the waveform for the RG8 cable probe was developed at a displacement of 0.25 inch. However, the threshold displacement required to observe a spike in the waveform in the field for the RG8 cable was 0.76 and 1.12 inch for MM50 and Batesville respectively. One of the major differences between different test setups was the length of transmittal cable between the TDR unit and the cable probe. It is believed that cable length and number of connections in the TDR system have the most impact on the threshold displacement required to observe a spike in the cable probe waveform. Figure 4.38 illustrates this concept, the shear displacement required for the RG8 cable to develop an initial signal increases with the length of the transmittal cable. Similarly, Figure 4.39 illustrates that the cable sensitivity, decreases with the length of the transmittal cable.

Another measure of TDR probe efficiency is termed cable sensitivity which is the magnitude of the reflection coefficient as a function of displacement, once the threshold displacement has been achieved. A plot of reflection coefficient versus measured displacement can be used to determine cable sensitivity. The slope of a straight line fitted through the data is defined as the cable sensitivity, expressed in rho/in for this study. From Figure 4.36 and 4.37 the cable sensitivity was determined to be 0.0148 rho/in for MM50 and 0.0169 rho/in for Batesville, respectively. The sensitivity for the laboratory testing on RG8 was 0.1743 rho/in, as illustrated in Figure 4.8. Figure 4.39 portrays cable sensitivity as a function of cable length. Ideally a straight line would be used to fit this data, but a power function has a much higher correlation coefficient. In addition to cable length, the number of connectors and multiplexers in the system has a distinct affect on signal attenuation. By assuming that a multiplexer adds approximately 30 ft and a connector adds 10 ft to apparent cable length for RG8 cable, a straight line could be used as a trend line when fitting data for threshold displacement versus cable length. This relationship is illustrated in Figure 4.38 and the straight line fit for the adjusted cable length has a correlation coefficient greater that. 0.99. Using this same methodology, cable sensitivity versus apparent cable length can be fit with a straight line with a correlation coefficient of 0.77 as illustrated in Figure 4.39. Of course further testing is required to determine exactly how multiplexers and connectors affect cable sensitivity.

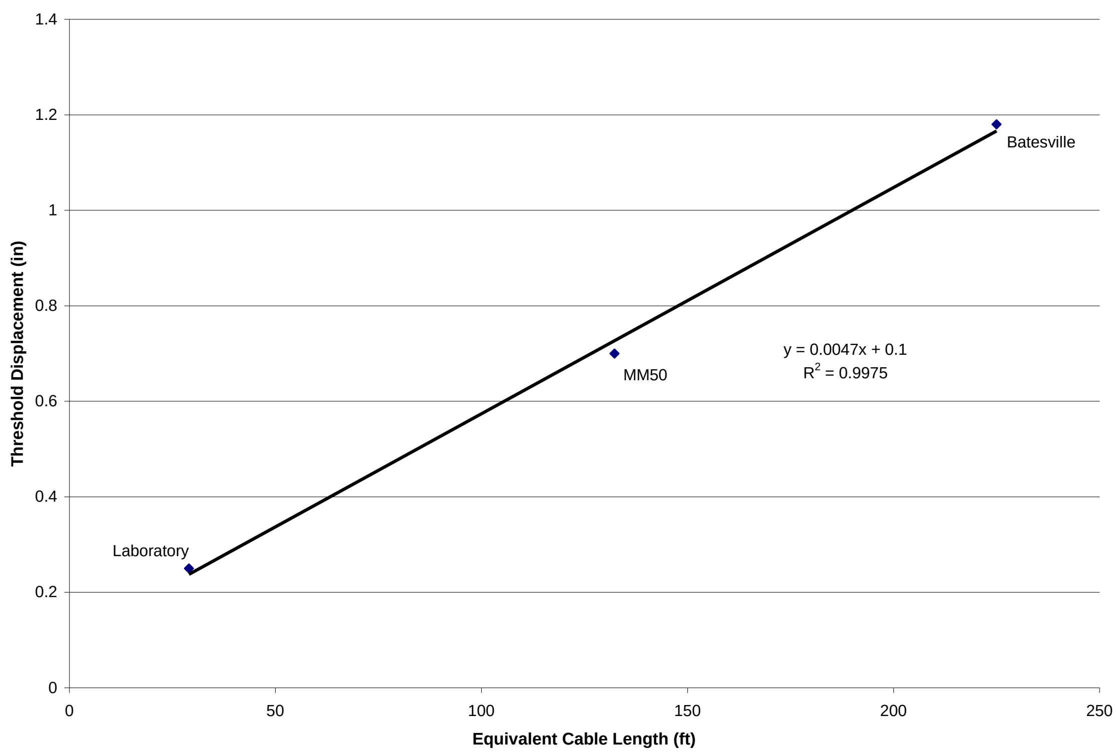


Figure 4.38: Threshold displacement versus cable length.

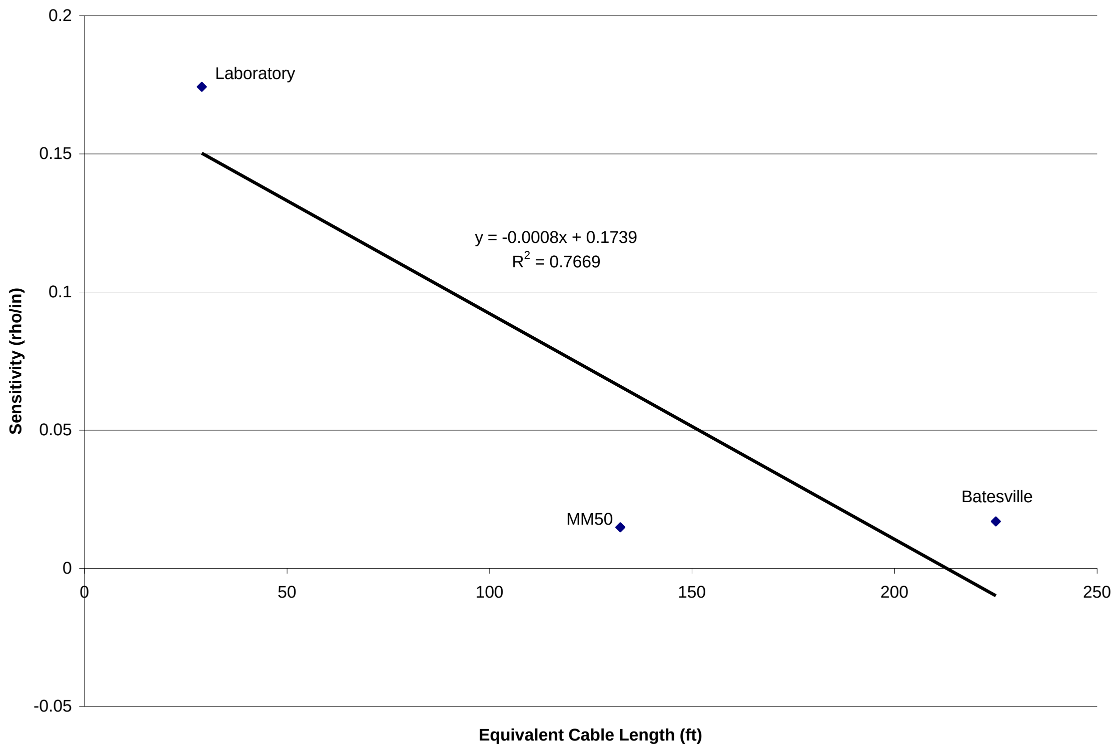


Figure 4.39: RG8 cable sensitivity versus equivalent cable length.

By extrapolation from the data presented in Figures 4.38 and 4.39 one can create a prediction model that will relate a cable probe's refection coefficient to the true displacement of a soil or rock mass along a failure surface. Equation 4-1 can be used to obtain an estimate of this movement (d) along the shearing plane once a spike in the probe's waveform is observed.

$$\delta = a + xb + \frac{\rho}{(c - d \times x)} \qquad 4\text{-}1$$

Where:

δ = Displacement (inches)

a = y-intercept of threshold displacement versus apparent cable length (= 0.1 in for RG8 cable used in this study).

b = slope of threshold displacement versus cable length (= 0.0047 for RG8 cable used in this study.)

x = apparent cable length between the TDR pulser-receiver and the fault in the cable probe (feet)

c = y- intercept of cable sensitivity versus cable length. (= 0.174 for RG8 cable used in this study)

d = slope of cable sensitivity versus cable length (= 0.0008 for RG8 cable used in this study.

ρ = reflection coefficient of the TDR cable probe, rho

Chapter 5

Conclusions and Recommendations

This study investigated Time Domain Reflectometry (TDR) and Slope Inclinometer technology as applied to the monitoring of slope stability at four different installations around the State of Arkansas. The studies were aimed at discovering the relationship between TDR reflection coefficient and soil mass movement. The focus of the study was on the sensitivity of coaxial cables to shearing distortion. An attempt was made to quantify the magnitude of displacement along a shearing plane based on the magnitude of the TDR reflection coefficient.

Extensive descriptions of study locations, cables employed, grout placement, equipment used, as well as data analysis are included in this report. First, the installation locations were identified for suitability of study and slope movements were expected. Second, instrumentation integration and methods to acquire data manually and remotely were described in detail to prove the effectiveness of the TDR system implementation for slope stability monitoring. Automated TDR systems were made possible by programmable data logging equipment and wireless communication instruments. Lastly, the research results for both inclinometer and TDR systems concluded that both technologies are useful for detecting slope movements. Special attention was devoted to data analyses in an attempt to determine the TDR cable's localized shear response. Most of the analysis effort was devoted to establishing the relationship between TDR reflection coefficients and the magnitude of shear displacement by correlating the results of inclinometer readings and TDR waveforms. Based upon these measurements and observations, the following conclusions and recommendations are made:

5.1 Conclusions

- Slope inclinometers are much more sensitive to gradual or small slope movements when compared to TDR systems. While inclinometer equipment is capable of detecting very small movements, it is much more labor intensive than automated TDR systems.
- TDR systems can successfully incorporate remote and autonomous data acquisition. With this feature, human intervention can be minimized allowing for the installation of TDR stations in locations that are far away from the polling station.
- TDR systems responded better to localize shearing planes that are common with deep seated failures.
- TDR systems cannot report slope movement until a threshold displacement is achieved. This displacement varied from site to site but appears to be related to the length of the cable in the system and possibly to the number of connectors and multiplexers in the system.
- Correlations between inclinometer displacement and TDR reflection coefficients indicate that they are directly proportional. However this relationship was not constant between sites and again appeared to be related to the length of the cable in the system.
- Based on laboratory and field studies RG-8 coaxial cable appeared to be the most cost effective and efficient cable for use in TDR studies.
- The magnitude of displacement along a shearing surface can be estimated with the prediction equation developed in this study.

5.2 Lesson Learned

- Precautionary steps should be taken when storing TDR cables to avoid kinking of the cables. If old TDR cable is being reused, the waveform of the TDR cable should be checked before installation to insure it possesses a stable baseline waveform.
- The length of aboveground transmission cables and the use of multiple connectors and multiplexers should be minimized to reduce signal attenuation.
- Daily data acquisition for TDR is essential for the measurement of slope movements and to obtain a complete history of the cable deformation.
- Ground water level and the soil moisture content have a great effect on slope stability. These data should be collected in conjunction TDR cable probe data to create a complete picture of slope stability. Moisture data can also be measured using TDR techniques.
- The TDR cable probe which is paired with an inclinometer casing should be installed as close as practical and in the same transverse plane to ease data comparison and to avoid different soil properties and failure surface geometries.

5.3 Recommendations

The viability of using TDR techniques to measure movements of unstable soil masses has been proven in this study. However, only 4 out of 26 cables installed in this study recorded slope movement activities even though the adjacent inclinometers recorded small but finite slope movements. While it is hypothesized that the reduction of cable sensitivity was caused by the length of cable and the number of connector and multiplexer used in a TDR installation, more laboratory testing should be conducted to quantify their affects on signal attenuation. It is recommended that coaxial cables with varying length to mimic typical field installations be used in laboratory testing to determine the effect of cable length along with the effect of the number of connectors and multiplexers on signal attenuation. Laboratory studies on these parameters will allow the variable to be controlled in such a fashion so that better relations between reflection coefficient and shear displacement can be developed.

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APPENDIX A

TDR Automated Data logging Programming

```
{CR10X}
;Testing Program for Bateville (5/21/03)
;
*Table 1 Program
  01: 60        Execution Interval (seconds)
;______________________________________________
;Turn on the cell phone at 11:35 for 20 minutes.

1:  If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 695      Interval (same units as above)
 3: 47       Set Port 7 High

2:  If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 715      Interval (same units as above)
 3: 57       Set Port 7 Low
;______________________________________________
;Cables probe testing.

3:  If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 180      Interval (same units as above)
 3: 30       Then Do

4:  Do (P86)
 1: 45       Set Port 5 High
;______________________________________________

;Batt Voltage

5:  Batt Voltage (P10)
 1: 1        Loc [ Batt      ]

6:  Internal Temperature (P17)
 1: 2        Loc [ Temp      ]
;______________________________________________
;
;Get waveform for RG8, 103(Top)

7:  TDR100 Measurement (P119)
 1: 00       SDM Address
 2: 1        Waveform
 3: 1001     MMMP Mux & Probe Selection
 4: 4        Waveform Averaging
 5: 0.85     Vp
 6: 250      Points
 7: 19.63    Cable Length (meters)
 8: 10.47    Window Length (meters)
 9: 0.0      Probe Length (meters)
10: 0.0      Probe Offset (meters)
11: 4        Loc [ RG8a_1    ]
12: 1.0      Mult
13: 0.0      Offset
```

Instruction Description
Execution Sequence
Instruction Number
Parameter
Program Execution
Testing Instruction

```
;Set port 5 low

8:  Do (P86)
 1: 55       Set Port 5 Low
;_______________________________________________
;
;Output Batery Voltage

9:  Do (P86)
 1: 10       Set Output Flag High (Flag 0)

10:  Set Active Storage Area (P80)
 1: 1        Final Storage Area 1
 2: 100      Array ID

11:  Real Time (P77)
 1: 1220     Year,Day,Hour/Minute (midnight = 2400)

12:  Sample (P70)
 1: 2        Reps
 2: 1        Loc [ Batt      ]

;_______________________________________________
;
;Output RG8 Waveform 103
13:  Do (P86)
 1: 10       Set Output Flag High (Flag 0)

14:  Set Active Storage Area (P80)
 1: 1        Final Storage Area 1
 2: 101      Array ID

15:  Real Time (P77)
 1: 1220     Year,Day,Hour/Minute (midnight = 2400)

16:  Sample (P70)
 1: 259      Reps
 2: 4        Loc [ RG8a_1    ]
;_______________________________________________

17:  End (P95)

*Table 2 Program
  02: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines

End Program
```

Output Instruction

TDR Alarm Programming

```
;Waveform Alarm Testing
22:  Spatial Minimum (P50)
 1: 230      Swath
 2: 13       First Loc [ Air_11    ]
 3: 263      Min Loc [ Min      ]

23:  If (X<=>F) (P89)
 1: 263      X Loc [ Min       ]
 2: 3        >=
 3: 0.01     F
 4: 45       Set Port 5 Low

24:  If (X<=>F) (P89)
 1: 263      X Loc [ Min       ]
 2: 4        <
 3: 0.009    F
 4: 55       Set Port 5 High

;Dialing Properties
25:  Initiate Telecommunications (P97)
 1: 22       Phone Modem/9600 Baud
 2: 2        Disable when User Flag 2 is High
 3: 75       Seconds Call Time Limit
 4: 120      Seconds Before Fast Retry
 5: 2        Fast Retries
 6: 5        Minutes before Slow Retry
 7: 265      Failures Loc [ Failure   ]
 8: 151      Call-back ID

;Dialing Number
26:  Extended Parameters (P63)
 1: 1        Option
 2: 4        Option
 3: 7        Option
 4: 9        Option
 5: 5        Option
 6: 7        Option
 7: 5        Option
 8: 5        Option

27:  Extended Parameters (P63)
 1: 8        Option
 2: 4        Option
```

3: 2	Option
4: 13	Option
5: 00	Option
6: 00	Option
7: 00	Option
8: 00	Option