Inclinometer – Time Domain Reflectometry Comparative Study

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Ohio Research Institute for Transportation and Environment

Prepared in cooperation with the Ohio Department of Transportation and the U.S. Department Transportation, Federal Highway Administration

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16. Abstract
Four pairs of inclinometers and time domain reflectometry (TDR) cables were set up to make a side-by-side comparison of the performance of these systems in detecting slippage of soils in the shoulders of State Route 124 and State Route 338 in Meigs County, Ohio, within 50 feet (15 m) of the Ohio River. The soil consisted of sandy silt, silt, and clay on top of sedimentary rock. Borings were located 3-6 ft (1-2 m) from the edge of the pavement on the shoulder of the road at two locations on each road, with a TDR and an inclinometer located 3-5 ft (1-1.7 m) apart. Borings extended 10 ft (3.3 m) into the bedrock. Sixteen monthly readings were taken.

At all four locations, the inclinometers detected shearing at depths ranging from 16 ft (4.9 m) to 40 ft (12.2 m). All of the detected shears were also identified by the TDR cables to within 1 ft (0.3 m). Water leakage occurred at shear locations on two TDR cables, preventing further monitoring below that depth on each; one inclinometer was also deformed beyond use at the same depth as the corresponding TDR cable water leakage.

The cost for materials and casing for a single inclinometer installation is $484, versus $316 for a TDR, a reduction of 34.71%. The data acquisition and analysis equipment costs are $11,245 and $5,110 respectively, for a reduction of 54.56%. The total savings for a TDR system is 53.74%. For an additional $3105, remote monitoring of TDR installations can be added, eliminating the need for site visits until the cable becomes damaged; the TDR system savings even with the remote monitoring are still 27.27% over the inclinometer. Labor time costs for initial installation are comparable at 8-12 hours, while the reading time is reduced from 10-30 minutes for an inclinometer to 1 minute for a TDR system. TDR cables also have the advantage that they can be extended to a safer or more accessible point for reading.

17. Key Words
Inclinometer, inclinometry, time domain reflectometry, soil condition monitoring, landslide, soil slippage

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INCLINOMETER - TIME DOMAIN REFLECTOMETRY COMPARATIVE STUDY

FINAL REPORT

December 2004

Prepared in cooperation with the Ohio Department of Transportation and The U.S. Department of Transportation, Federal Highway Administration

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CHAPTER 1: INTRODUCTION

Slope stability is an ever-present issue in hilly or mountainous terrains with clay rich soil, constructed embankments, fluctuating temperatures and/or changing soil moisture conditions. Landslides constitute a major geologic hazard; occurring in all 50 states [1]. Accurate determination of the shear plane depth in a landslide is needed to devise an effective remediation plan.

The term landslide is the most common and universally accepted currency as the general term for slope movements. Slope movement can be divided into falls, topples, slides, lateral spreads and flows [2]. Sliding is one of the most common types of mass movement. Slides are characterized by shear displacement along one or several shear planes [3]. The types of slope movement investigated in this study are rotational and translational slides. Case, of the Wyoming State Geological Survey Geologic Hazards Section [3], describes the different types of landslides. He writes "In a rotational slide, the surface of rupture is concave upward, and the mass rotates along the concave shear surface. Rotational slides are usually called slumps, and they can occur in bedrock, debris, or earth."

Figure 1.1 shows a diagram of a typical rotational slide. Additionally, "In a translational slide, the surface of rupture is a planar or gently undulatory surface." [3]

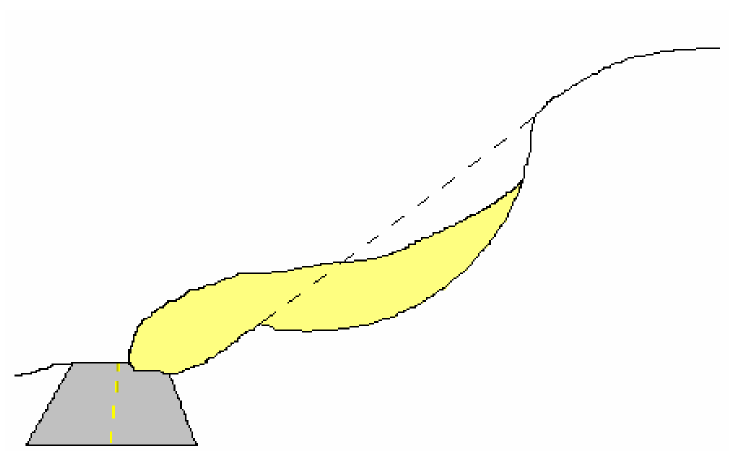


Figure 1.1 - Diagram of Rotational Slide

1.1 Lateral Earth Movement Detection

Slope inclinometer probing, the conventional method for slope movement analysis, has a number of drawbacks. This method is costly to install and monitor, and becomes ineffective in measuring large lateral deflections. An economical alternative to slope inclinometers for monitoring slopes is electrical Time Domain Reflectometry (TDR). The cables used to implement TDR in slope studies are inexpensive, simple to install, and provide long-term monitoring of slope movement. Measurements take only seconds, a large contrast to the traditional time intensive 'cable pull' process of inclinometer probing.

To study and compare the two methods, inclinometers and TDR cables were installed side-by-side at two separate landslide locations. The effectiveness of the TDR method and the correlation of localized shear plane depths between the two techniques were investigated.

1.1.1 Inclinometers

Inclinometers are traditionally used to monitor horizontal subsurface deformation in landslide areas and embankments. The components of an inclinometer system are the inclinometer casing, an inclinometer probe, a control cable, and a readout unit. The Slope Inclinometer Digitilt™ Inclinometer Probe Manual outlines the basics of the inclinometer method:

> "Inclinometer casings are typically installed in a near vertical borehole that passes through a zone of suspected movement. The bottom of the casing is anchored in stable ground and serves as a reference. The inclinometer probe is used to survey the casing and establish its initial position. The probe is lowered to the bottom of the

casing and an inclination reading is taken. Additional readings are made as the probe is raised incrementally to the top of the casing. Ground movement causes the casing to move from its initial position to a new position. The rate, depth and magnitude of this displacement are calculated by comparing data from the initial survey to data from subsequent surveys. The inclinometer probe does not measure displacement directly. Instead, it measures the tilt of the casing. The amount of tilt measured is then converted to a lateral distance from the measurement interval. Deviation at one interval is called incremental deviation. The sum of incremental deviations is the cumulative deviation." [4]

Figure 1.2 shows the principle of inclinometer operation. Changes in deviation are called displacements. Movement of the casing can be identified through analyzing the cumulative displacement.

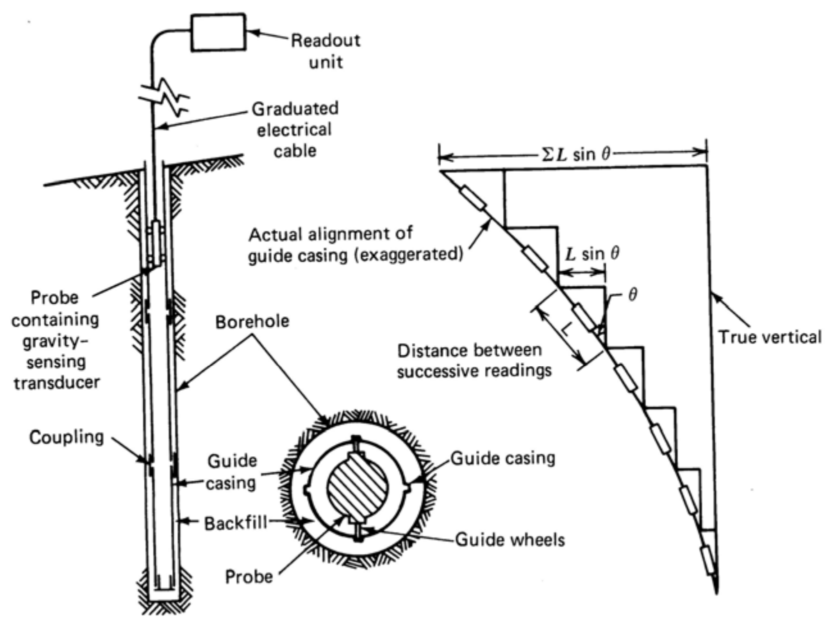


Figure 1.2 – Principle of Inclinometer Operation

From *Geotechnical Instrumentation for Monitoring Field Performance,* Dunnicliff [5]

Several disadvantages arise when using an inclinometer to monitor lateral subsurface earth movement. One concern is that “the casing may be too stiff to conform with soil deformation along thin transverse shear bands in soft soils” [6]. Another limitation occurs when “deformation at a shallow but distinct shear zone prevents passage of the probe to deeper sections and precludes measurement altogether” [6]. Other factors affecting the precision of inclinometer data include: “precision of gravity-sensing transducer, design and condition of wheel assembly, casing alignment, casing diameter, borehole backfilling procedure, spiraling of casing, depth interval between reading positions, temperature effects, and handling of the probe.” [5]

1.1.2 TDR Method

TDR, is a technology that has been employed for a variety of uses. Since the 1930’s, TDR has been used for examining electrical properties of cables and transmission lines, and measuring the electrical properties of organic liquids [7]. More recently, TDR has been utilized in monitoring slope movement to locate shear planes in localized shear failures. To monitor slope movement, coaxial cables are grouted in boreholes and analyzed with a cable tester [8]. TDR uses an electronic voltage pulse that is reflected like radar from a damaged location in a coaxial cable. Figure 1.3 shows the principle of the TDR method. Slope movement can be identified by comparing changes in successive cable traces [8].

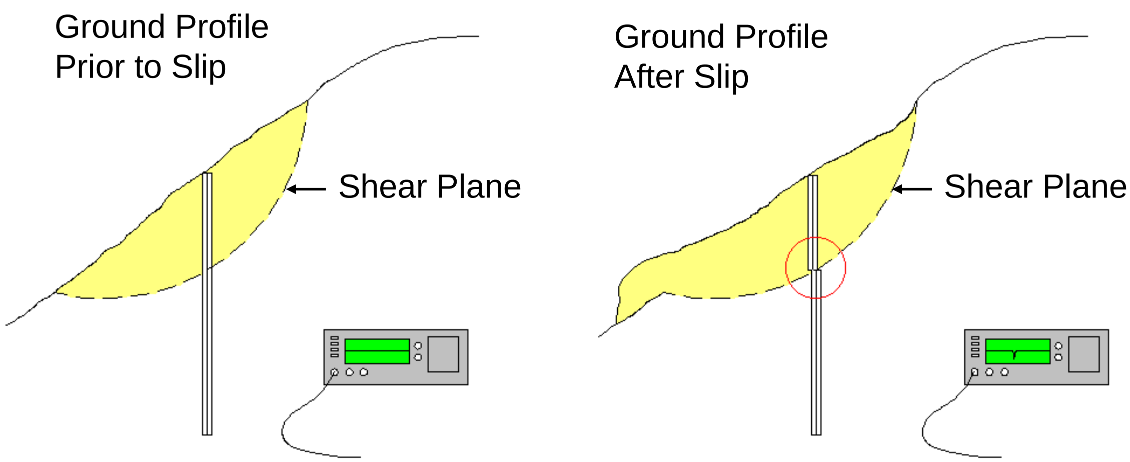


Figure 1.3 - Principle of the TDR Method

Coaxial cables are composed of a center metallic conductor surrounded by an insulating material, a metallic outer conductor surrounding the insulation, and a protective jacket. Figure 1.4 shows the components of a coaxial cable. Kane describes the role of the coaxial cables in TDR method:

> "Each cable has a characteristic impedance determined by its material composition and construction. If the cable is deformed, the distance between the inner and outer conductor changes. It is this change that causes a difference in the impedance, and a resulting reflection of the voltage pulse." [8]

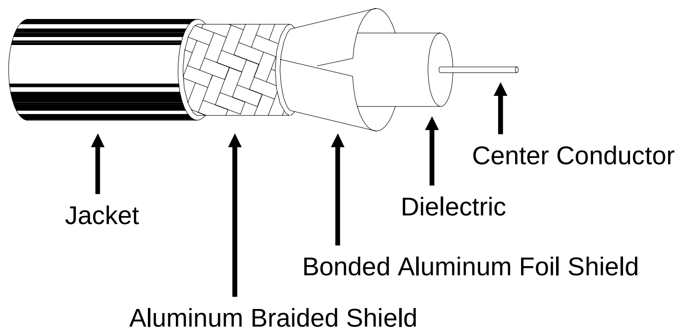


Figure 1.4 - Coaxial Cable Diagram

TDR operates by sending a “wavefront” of energy through a cable at nearly the speed of light [9]. Kane states, “Electrical energy travels at the speed of light in a vacuum, but travels somewhat slower in a cable. This is called the velocity of propagation.” [8] “Under normal conditions, cable impedance is fairly constant" [9]. As the wavefront encounters “variations” in the cable’s physical characteristics, the “impedance of the cable changes at the point of damage,” and part of the wavefront is reflected back to the source. [9] “When the propagation velocity of a particular cable is known, the time travel of the reflected pulse can be used to determine the distance to any cable reflection.” [8] “Cable variations or permutations are affected by the physical distance between the two conductors and the insulating material between the conductors, referred to as the dielectric.” [9]

1.2 Objectives

The main objective of this research was to complete a side-by-side comparison of TDR and slope inclinometer probing to identify shear planes. In addition to comparing the two methodologies on the technical basis of accuracy and dependability, other objectives for this study included a comparison on the practical basis of cost and relative ease of installation and data collection.

1.3 Organization of Report

- Chapter 2 provides an outline of the geology of the region and a review of relevant literature on the TDR method.
- Chapter 3 describes the test site, instrument preparation and installation of the inclinometers and TDR cables, soil profiles obtained during drilling, and the data acquisition methods.
- Chapter 4 discusses determination of shear plane depth from the two methods, the results of the field-data, and the comparison of the two methods for identifying the depth to a shear plane.
- Chapter 5 details the cost of materials and instrumentation components used and the ease of use of the two methods.
- Chapter 6 presents the conclusions and recommendations of the study.

CHAPTER 2: LITERATURE REVIEW

The geology of the test region was studied and summarized. A literature review was completed to understand and evaluate the state-of-the-art technology for the TDR method. Applicable research to this study is outlined in the following chapter.

2.1 Geology of Test Region

The test sites are located in southeastern Ohio, in the Ohio River valley. From Brockmans's *Physiographic Regions Map of Ohio*, the test sites are within the Marietta Plateau [10]. According to Brockman, distinguishing characteristics of the Marietta Plateau are; "mostly fine-grained rocks, red shales and red soils... , landslides common; remnants of ancient lacustrine clay-filled Teays drainage system." Brockman defined the geology of the area as "Pennsylvanian-age Upper Conemaugh Group through Permian-age Dunkard Group, cyclic sequences of red and gray shales and siltstones, sandstones, limestones and coals." The Pennsylvanian age, 325-286 million years ago, was described by Ohio Department of Natural Resources Division of Geological Survey:

> "Ohio in Pennsylvanian time was a relatively flat coastal-plain swamp in equatorial latitudes. Fluctuations in sea level resulted in alternating terrestrial, freshwater, and marine deposits." [11]

The Permian age, 286-248 million years ago, was described by Ohio Department of Natural Resources Division of Geological Survey:

> "In early Permian time, southeastern Ohio was a coastal-plain swamp. Ohio lay about 5° north of the Equator. The swamp eventually was filled by influx of deltaic sand and mud. Later Permian time was characterized by uplift and erosion." [11]

The test sites are located in a landslide-prone “redbed” area. Figure 2.1 shows the distribution of landslide-prone redbeds in Ohio. Redbeds are “red-colored sedimentary rocks” [12]. Hansen, from the Ohio Department of Natural Resources Division of Geological Survey, states that:

> “The most slide-prone rocks in eastern Ohio are red mudstones ("red beds") of Pennsylvanian and Permian age. These rocks tend to lose strength when they become wet, forming rotational slumps or earthflows.” [13]

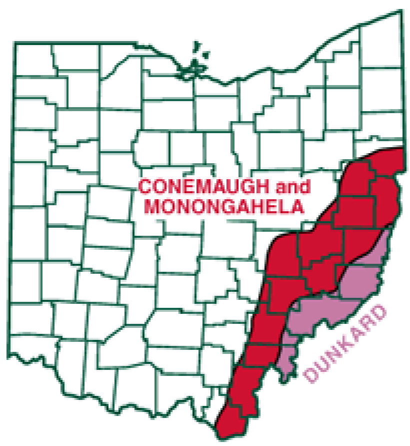


Figure 2.1 - Distribution of Landslide-prone Roadbeds in Ohio

(Image from Richard M. DeLong, Ohio Department of Natural Resources Division of Geological Survey [12])

The soil regions of the test sites are “Gilpin – Upshur-Lowell – Guernsey,” according to the *Soil Regions of Ohio* map by the Ohio Department of Natural Resources [14]. These soil series consist of moderately to very deep well drained soils. The Gilpin series were “formed in residuum of nearly horizontal interbedded shale, siltstone, and some sandstone of the Allegheny Plateau.” [15] The Lowell series were “formed in residuum of limestone interbedded with thin layers of shale on upland ridgetops and sideslopes." [16]

Landslide activity in eastern Ohio was investigated by Fisher in his article, *The Geology of Eastern Ohio with Relation to Slope Movements* [17]. He states,

> "The upper Pennsylvanian and Permian cyclothermic sedimentary rocks of the Ohio river valley are especially subject to downslope movements. ... Earthflows and rotational slumps are the most common types of slope failures..."

Fisher further remarks that the Upper Ohio River Valley area ranks third behind the Pacific Coast and the northern Rocky Mountains south to the Colorado Rockies in terms of "troublesome and dangerous downslope movements".

2.2 TDR to Monitor Slope Movement

Since its early use in the 1930's to locate faults in transmission lines, TDR has been employed increasingly as a means to monitor soil and rock slope movement, mostly in northern California. Presently, many articles have been published on TDR and its application to locating shear planes.

Anderson and Welch investigated five case histories in Nevada and California of TDR applied in the geotechnical/geologic field to detect movement and locate shear planes in rock or soil slopes in their article, *Practical Applications of Time Domain Reflectometry (TDR) to Monitor and Analyze Soil and Rock Slopes* [9]. The case histories took place from 1996 to 1999 and cover a range of applications which include an open pit rock slope, a small rock slope, two embankment/levees over soft/loose soil, and a native soil slope. They found that economical RG-59 cable (@ $0.35/m) can be used for non critical or shallow applications where it is desired to simply locate the shear plane of a slide. Their experience has shown that hard Portland cement grout mix will make the cable sensitive to smaller movements and will even work in soft soil conditions where simple shear plane location is desired. Overall they found TDR to be a valuable, economical tool in accessing and analyzing soil and rock slopes. They concluded that the most notable limitation of the TDR method is in detecting the exact magnitude of movement.

Kane, Beck and Hughes also found RG-59/U to be an economical cable suitable for TDR monitoring. In their article, *Applications of Time Domain Reflectometry to Landslide and Slope Monitoring* [18], they note that it suffers from signal attenuation and is not recommended for deep holes, in excess of 33 meters, or long term monitoring. They determined the cable to be good for routine landslide investigations and accurately determining locations of slide planes.

Dowding and O'Connor provided information from their experience with TDR in their article, *Comparison of TDR and Inclinometers for Slope Monitoring* [19]. According to Dowding and O'Connor, when monitoring to detect narrow shear zones in soils, it is best to use small ratios of hole-to-cable diameter. Solid aluminum coaxial cables can be installed in deformed inclinometer casings to allow continued monitoring. The results of installing and monitoring coaxial cables installed in deformed inclinometer casing indicate that the technique is effective whether the casing has been installed in rock or soil.

Kane has investigated and experimented with TDR in numerous applications in California. Kane elaborates on his findings in the FHWA Report, *Development of a Time Domain Reflectometry System to Monitor Landslide Activity* [20]. Kane found that one can differentiate between shear and tensile cable failures:

> "In shear failures a voltage spike of short wavelength is recorded. The wavelength increases in direct proportion to shear deformation. A distinct negative spike occurs just before failure. After failure, a permanent positive reflection is recorded. In tensile failures the wavelength reflection is a subtle trough-like voltage signal that increases in length as the cable is further deformed."

Figure 2.2 and Figure 2.3 show the shear and tensile cable failure traces Kane observed during laboratory tests.

Figure 2.2 – Cable Shear Failure

(Reproduced from Kane, *Development of a Time Domain Reflectometry System to Monitor Landslide Activity*, Figure 2-2a [20])

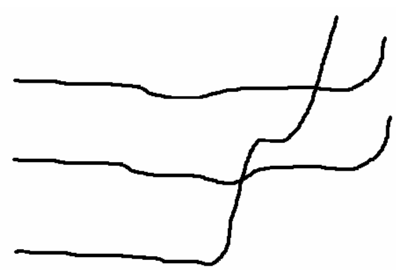


Figure 2.3 – Cable Tensile Failure

(Reproduced from Kane, *Development of a Time Domain Reflectometry System to Monitor Landslide Activity*, Figure 2-2b [20])

Kane notes that grout surrounding the TDR cables in the boreholes should approximate the soil in strength and stiffness. Grout must be stiff enough to stabilize the borehole, but compliant enough not to affect the movement of the soil mass. From his experience and research, Kane has found that a jacketed cable will fail at approximately 27.7 mm (1.1 in) of horizontal movement. The cable used by Kane for the California installation was RG-59/U (Belden). Additionally, in their article, *Instrumentation Practice for Slope Monitoring* [21], Kane and Beck note that in TDR, the cable must be deformed before movement can be located. Simple bending of the cable, without damage, will not indicate movement.

In another article, Kane provides insight into the preparation and installation of TDR cables. The article, *Monitoring Slope Movement with Time Domain Reflectometry* [8], instructs one to prepare cables by:

> "... cutting the down-hole cable ends square, sealing the ends with liquid electrical 'tape', and slipping a tight fitting rubber or plastic boot over the end. The connection should be wrapped securely with electrical tape to prevent water infiltration. The inner and outer conductors should not be allowed to contact each other. ... Cables are installed by weighting the end of the cable and lowering the cable end to the bottom of the hole. The cable may also be pushed down the hole, especially when installing in hollow stem auger or casing. Cables installed in this manner in dense grout may float out of the hole and may need restrained until grout sets. The grouts used were 10% bentonite/90% cement slurry or 100% cement."

In their article, *Measurement of Localized Failure Planes in Soil with Time Domain Reflectometry* [22], Dowding and Pierce found that a dielectric material with low shear strength and stiffness is necessary to produce a deformable cable. They recommend the use of polystyrene foam, not polyethylene. Polystyrene foam has a shear strength and stiffness of 4 kPa and 280 kPa respectively. Solid polystyrene foam has a shear strength and stiffness of 870 kPa and 36 GPa respectively. Weak soil has a shear strength of less than 1 MPa and a modulus of under 100 MPa. The grout should have physical properties similar to soil. Grout shear strength and stiffness should equal the soil shear strength and stiffness.

O'Connor described the operating principle of TDR in his book, *GeoMeasurement by Pulsing TDR Cables and Probes* [6]:

"The TDR unit generates a fast rise time step function. The step propagates through the sampling receiver and through the transmission line under test. ... This scan is displayed as a reflection coefficient (i.e., ratio of reflected to transmitted voltage). The time delay between a transmitted pulse and the reflection from a cable fault to change in capacitance uniquely determines the fault location. Additional information can be obtained by analyzing the sign, length, and amplitude of the reflection coefficient signatures which define the type and severity of every cable fault."

O'Connor's research indicated that use of an appropriately compliant cable/grout system should allow measurement of shear zones as thin as 5 mm. This detectable thickness is approximately 1/120 that possible with an inclinometer.

1.3 TDR/Inclinometer Comparison

Dowding and O'Connor compared slope inclinometer and TDR responses for a number of cases in their paper *Comparison of TDR and Inclinometers for Slope Monitoring* [19]. The responses indicated that:

> "...both technologies provide useful information; TDR technology is especially sensitive to localized shear so it is the most responsive to concentrated shear strain. On the other hand, slope inclinometers are especially sensitive to gradual changes in inclination so they are most responsive in soils undergoing general shear. TDR technology will also respond to abrupt changes in shear strain at the boundaries of a thick shear band."

The case histories presented involved monitoring movement in soil and rock slopes and embankments as well as retrofitting deformed inclinometer casing with coaxial cables. Grout strength should be: "(1) low enough to fail before bearing capacity of the surrounding soil is reached, and (2) high enough to deform the cable it encapsulates." Due to the behavior of inclinometer casings and TDR cables, they have found that the thinner the localized shear zone, the greater the TDR response and the smaller the slope inclinometer response. Their results indicate that both technologies provide useful information. They state, "Their differences do not imply that either technology is more correct; rather the two techniques respond optimally under different conditions."

Dowding, Dussud, Kane & O'Connor elaborated on the TDR soil deformation monitoring method and presented technical details to installation and analysis in, *Monitoring Deformation in Rock and Soil with TDR Sensor Cables* [23]. They stated that TDR sensor cables provide another instrument to supplement and/or verify subsurface deformation measured by inclinometers. One approach that they adopted:

> "combined the technologies by installing TDR cables and inclinometers in separate holes and remotely interrogating TDR cables using and automated data acquisition system connected to a phone or radio modem. When the TDR cable indicates that movement has occurred, an independent measurement is then made by profiling the inclinometer casing."

Lessons learned by the team included ensuring the top-of-hole connectors are moisture proofed and placed in a locked protective cover, installing cables in dedicated boreholes, and using RG/U cables kept below 50 meters to minimize attenuation and noise.

O'Connor found that TDR has several other advantages over inclinometers. In his book, *GeoMeasurement by Pulsing TDR Cables and Probes* [6], he stated the most important advantage is complete automation of data acquisition. Multiplexing allows multiple cables to be monitored from electronics installed at a central location. These advantages show that compliant cable grout systems may be deployed for remote, early detection of subsurface movements in any number of situations using TDR.

Dowding, Cole, and Pierce evaluated the TDR and inclinometer methods in their article, *Detection of Shearing in Soft Soils with Compliantly Grouted TDR Cables* [24]. They stated that "monitoring shear deformation within soil by TDR cable technology offers an opportunity to detect thin localized shear zones and to remotely monitor site response." The 60 cm resolution of inclinometers "limits their resolution of thin or localized shear bands even when readings are taken at a fraction of the wheel base." They state "installation of specially designed coaxial cables in soil now presents an opportunity to search for thin, localized zones."

From the reviewed research it was seen that the side-by-side installation of inclinometers and TDR cables would provide useful information in further evaluating the TDR method for slope movement analysis. To date, the TDR method had not been implemented in southeastern Ohio. Since the analysis of the TDR method at the test sites would be conducted with borings less than 50 meters, RG-59/U coaxial cable would be an economical choice.

CHAPTER 3: EXPERIMENTAL SETUP AND PROCEDURE

The slope movement test sites were located along State Route 124 and State Route 338 in Meigs County, Ohio. Figure 3.1 shows the vicinity map of the test sites. These sites were selected by the Ohio Research Institute for Transportation and the Environment (ORITE) and the Ohio Department of Transportation (ODOT) for their ongoing soil movement. SR 124 and SR 338 are two lane asphalt pavement roads that run parallel to the Ohio River. Many sections of the roads are located less than 50 feet (15.2 m) from the river's edge. The road surface elevation is less than 25 feet (7.6 m) above the water surface at normal flow. These roads are constantly in need of repair and reconstruction as the soil below them sinks and slides toward the river. Every few months ODOT fills new dips in the asphalt pavement with cold patch to keep the road passable. The slopes along the river are continually eroded away by the river; removing lateral support and further weakening the slopes [25]. Many places along the road have collapsed into the river and have been fully reconstructed with stabilized rock embankments. Figure 3.2 shows a stabilized rock embankment adjacent to the SR 338 site. The road also experiences heavy truck traffic, which contributes to the rapid deterioration of the road.

Four pairs of Time Domain Reflectometry (TDR) cables and slope inclinometer casings were installed at two test sites. The test sites, State Route 124 – Mile marker 46.86 and State Route 334 Mile marker 20.92, had two TDR cables and two inclinometer casings installed at each site.

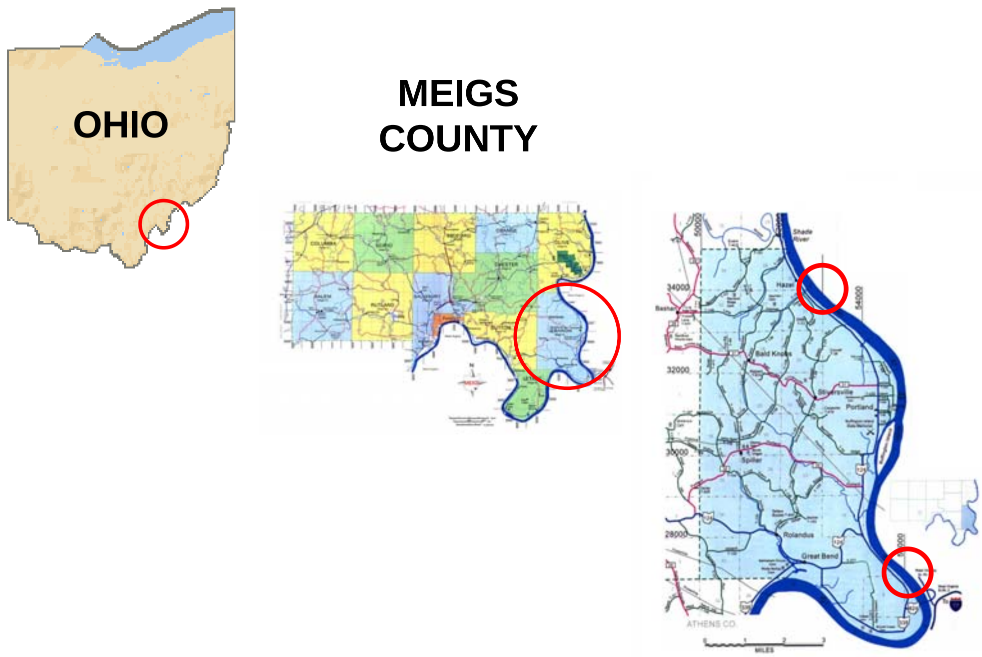


Figure 3.1 - Map of Test Sites

Figure 3.2 - Stabilized Rock Embankment along MEG 338

3.1 Experimental Setup

The instrumentation map of the test sites can be seen in Figure 3.3. The TDR cables and slope inclinometer borings were located between three to six feet from the edge of pavement, in the shoulder of the road. This configuration was chosen to allow room for positioning the drill rig and protection of the instrumentation from traffic. The cable and casings caps were installed level with the ground surface to prevent damage during mowing. The TDR cables and inclinometer casings were located approximately three to five feet apart to ensure that an accurate comparison could be made without soil disturbance affecting the instrumentation readings.

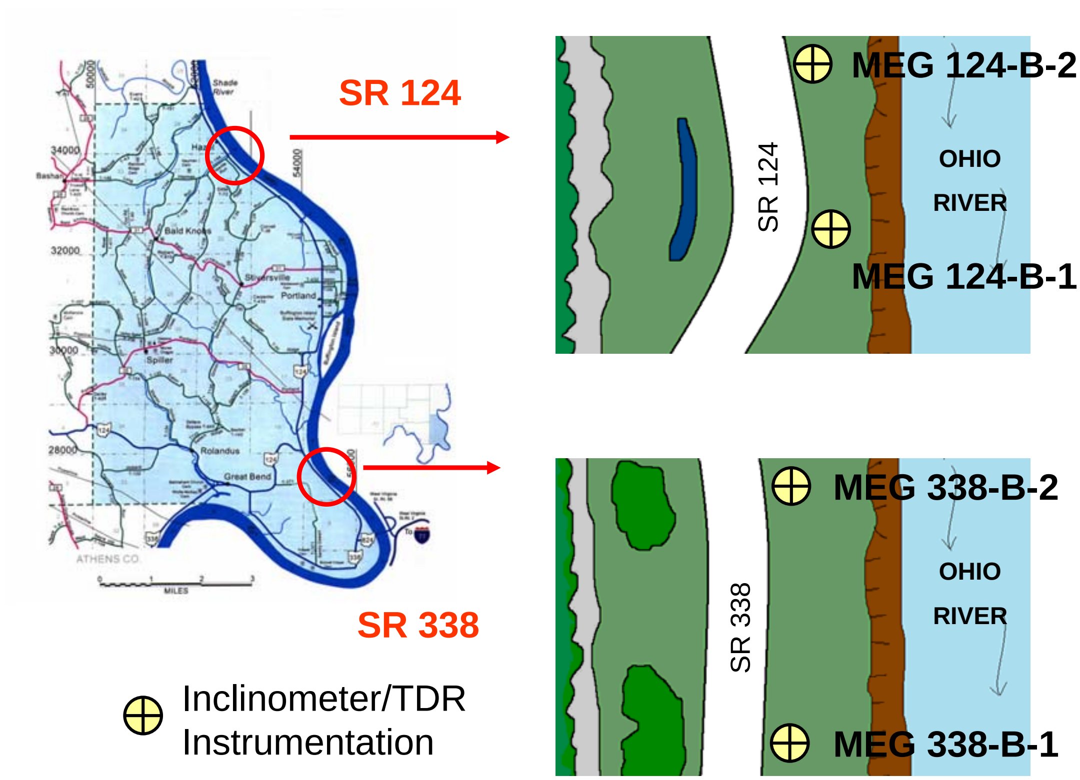


Figure 3.3 - Detail Map of Test Sites

Figure 3.4 shows the installation of instrumentation at the MEG-338 site. The picture shows the vicinity of the test site to the Ohio River.

Figure 3.4 - Installation of Instrumentation at MEG-338 Site

Figure 3.5 shows an overall view of the MEG-124 site. The dip in the road is clearly evident. This location was experiencing lateral subsurface soil movement and road deterioration. The alignment of this section of road was originally straight, but it has shifted towards the river and sunk many feet over the years.

Figure 3.6 shows the installation of instrumentation at the MEG-124 site. At the time of installation, over ten nineteen of asphalt had been placed at this location to fill the dip and keep the road passable.

Figure 3.5 - General View of MEG-124 Site

Figure 3.6 - Installation of Instrumentation at MEG-124 Site

3.2 Instrumentation Preparation

The instrumentation selected for the study was prepared in the laboratory. The necessary materials were purchased and assembled if needed. The full materials list used in the inclinometer and TDR installation can be found in Section 0.

3.2.1 Inclinometer Preparation

The inclinometer casings selected for this research were PVC RST 2.75 inch (6.99cm) outer diameter glue and snap casings. The casings required no laboratory preparation other than purchase of the casings and ABS cement. The casing thickness was 0.25 inches (0.64cm). The casings were grooved to allow for two axis readings. The casing characteristics are outlined in Table 3.1.

Table 3.1 - Inclinometer Casing Characteristics

Description	RST Glue & Snap Inclinometer Casing
Glue & Snap Coupling O.D.	2.75 in. (70 mm)
Casing Outer Diameter	2.75 in. (70 mm)
Casing Inner Diameter	2.32 in. (59 mm)
Casing Section Length	10 ft. (3 m)
Casing Weight	.85 lbs/ft. (1.27 kg.m)
Material	ABS Plastic
Groove Spiral	<0.3 deg./10ft. (<.005 Rad/3 m)

3.2.2 TDR Cables

The coaxial cable selected for these sites was Belden Precision Video Type RG-59/U. This cable has an outer diameter of 0.199 inches (5.50 mm) and a nominal velocity of propagation of 84%. As stated in Section1.1.2, the velocity of propagation is the speed at which an electrical signal travels in relation to the speed of light. This means electrical energy travels at 84% the speed of light in this cable. The cable characteristics can be found in Table 3.2.

Table 3.2 - TDR Cable Characteristics

Description	Belden Precision Video RG-59/U Type
Trade No.	1506A
UL NEC Type	NEC CMP
CSA Cert.	CSA CXC FT 4 FT 6
Standard Lengths / Std. Unit Lbs. ea.	500 ft (152.4m)/16.5 lb (7.49kg)
	1000 ft (304.8m)/37.7lb (17.12kg)
AWG (stranding)	20 (solid) .032 bare copper
[Diameter in Inches]	9.9Ω/M’
Nominal D.C.R.	32.5Ω/km
Insulation &	Foamed FEP Teflon
Nominal Core O.D.	.135 in (3.4 mm)
Nominal O.D.	.199 in (5.05 mm)
No. of Shields &	Duofoil +95% tinned copper braid
	100% shield coverage
Material Nom. D.C.R.	3.2Ω/M’ 10.5Ω/km
Nominal Impedance	75 Ω
Nominal Velocity of Propagation	84%
Nominal Capacitance	16.1 pF/ft.
	1 / .29
Nominal Attenuation: MHz / db.100 ft.	10 / 1.05
(30.5 m)	50 / 1.80
	100 / 2.70
	200 / 3.80
	400 / 5.50
	700 / 7.20
	900 / 8.30
	1000 / 9.40

Following the procedure outlined by Kane in *Monitoring Slope Movement with Time Domain Reflectometry* [8], the cables were first prepared by cutting the down-hole end square and sealing it with three layers of liquid electrical tape. Polyplefin shrink fit end caps were fastened to the down-hole end to prevent water infiltration. Additional liquid electrical tape was applied after affixing the end caps. Care was taken to ensure that the outer and inner conductors did not contact each other. The cables were cut to a length of 70 ft (21 m) and marked with colored electrical tape at 5 ft (1.5 m) intervals to allow for accurate depth measurements during installation. The cables were cut with at least an additional 20 ft (6.1 m) of cable to allow for installation through 10 ft (3.0m) lengths of 1.5 in (3.8 cm) PVC pipe sections. A BNC connector was soldered to the top-end of the cables in the field after installation.

3.3 Instrumentation Installation

The installation of the TDR cables and slope inclinometer casings began on September 26th, 2002 and was completed on October 8th, 2002. The drilling work was performed by the Ohio Department of Transportation (ODOT) Soil Foundations drilling crew. The inclinometer and cable borings were drilled with a trailer mounted soil auger. A detailed soil profile was developed in the boring process. The standard penetration test was conducted at two foot intervals to a depth of 25 ft (7.6 m) and 5 ft (1.5 m) intervals beyond the 25 ft (7.6 m) depth. Soil samples were taken for moisture content analysis and soil classification in the ODOT Soils lab. The soil samples were taken every 2 ft (0.6 m) to a depth of 25 ft (7.6 m) and every 5 ft (1.5 m) thereafter. Upon reaching bedrock, the auger bit was replaced with a three inch diameter diamond tipped core barrel. The core barrel allowed for removal of five foot sections of the underlying sandstone. The borings were drilled ten feet into the sandstone to allow the inclinometer casings and TDR cables to be anchored in the bedrock. The stone cores were taken to the ODOT lab by the ODOT Soil Foundations crew. Figure 3.7 shows a sample of the rock cores collected. The Field Data can be found in APPENDIX D – Field Data.

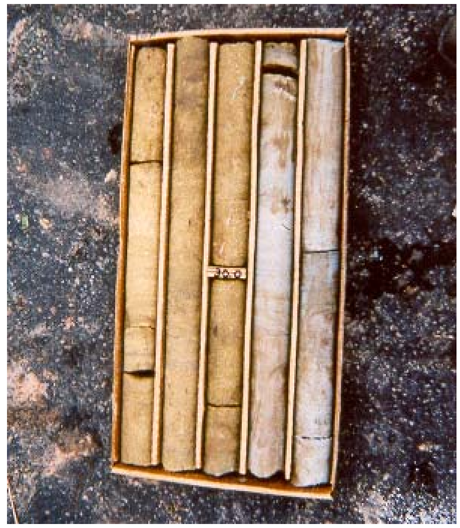


Figure 3.7 - Typical Stone Material Encountered at Test Sites

3.3.1 Inclinometers

Six and one-quarter inch outer diameter auger bits were used to create the borings for the 2.75” (6.99 cm) outer diameter RST slope inclinometer casings. The inclinometer casings employed for these sites were RST glue and snap casings in 10 ft (3.0 m) sections. The casings required a thin coating of ABS 771 cement at the snap lock connectors. The casing sections were connected together as they were lowered through the hollow core of the auger into the boring. The A-Axes of the casings were oriented towards the direction of assumed movement, as shown in Figure 3.8. The B-Axes were perpendicular to the direction of assumed movement. The casings were filled with water to counteract the buoyancy of the plastic tubing in the uncured grout. The auger sections were then pulled out of the boring, ensuring that no twisting of the casing occurred. The grout was mixed and pumped into the bottom of the boring through 1.5 in (3.8 cm) diameter PVC tubing. The grout mixture used was one batch (3.65 ft^3 (0.103 m^3)) equals one 94 lb (43 kg) bag Portland cement, half a 50 lb (23 kg) bag Bentonite, and 30 gal (113 l) water. This is the typical grout used for inclinometer installations by the ODOT Soil Foundations and Drilling Crew. Keeping the full length of the 30 ft (9.1 m) plus water filled casing in the grout filled boring required the assistance of several crew members. The casing was centered in the boring and the drilling auger was set on top of the casing while the grout set overnight. After overnight setting of the grout, additional grout was added to the boring if needed. Finally, a 6 in (15 cm) diameter PVC tube with a screw cap was affixed over the casing top and set in place with quick setting cement. Figure 3.9 shows a diagram of the inclinometer installation.

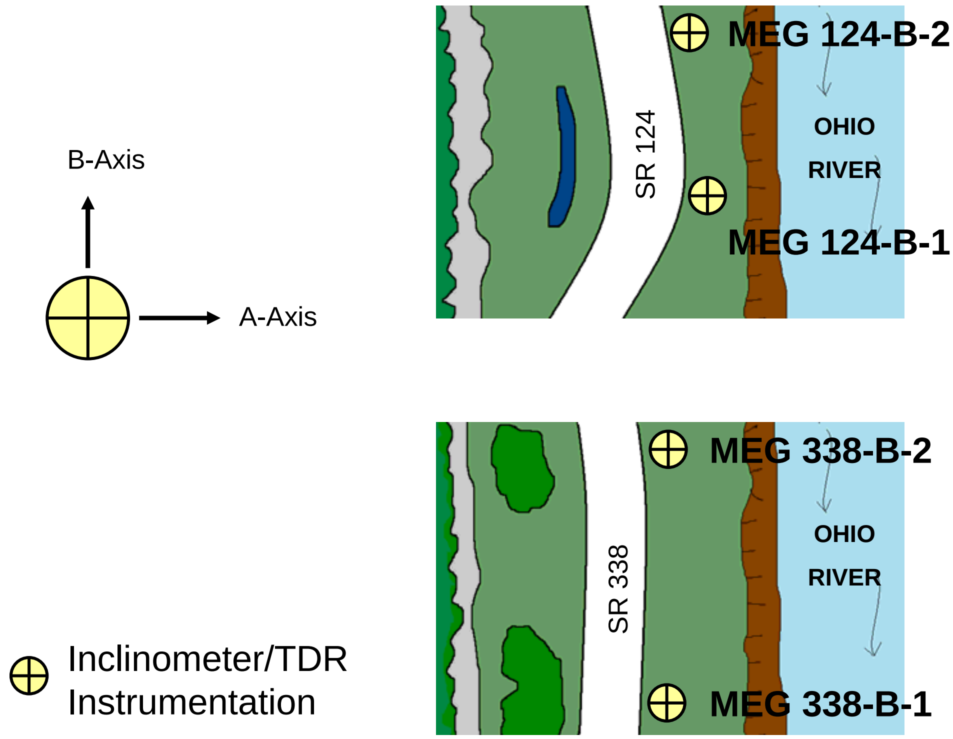


Figure 3.8 – Axis Orientation of Inclinometer Casings

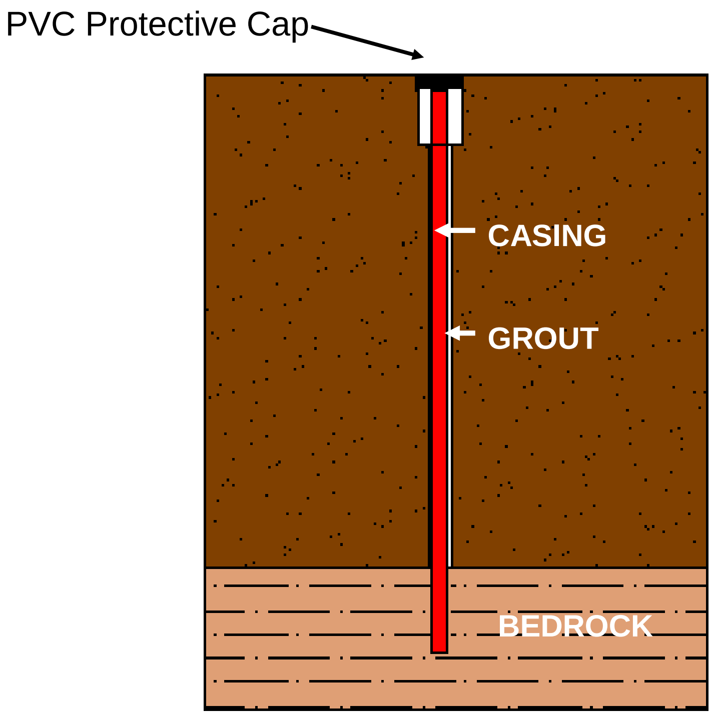


Figure 3.9 – Inclinometer Installation Diagram

3.3.2 TDR Cables

The TDR cables used have a diameter less than ¼” (6.4 mm) and require only a small boring. Small diameter auger bits were not available at installation; therefore the same 6 ¼ in. (15.9 cm) outer diameter auger bits used for the inclinometers were used for drilling the TDR cable borings.

The TDR cables were installed using ten foot sections of 1 in (2.5 cm) diameter end-threaded grey PVC tubing. The cable end was inserted into the tubing section and then weighted with lead sinkers. The weights were attached to the cable with duct tape. The cable ends were weighted to keep the cable from floating in the uncured grout. The weight kept the cable taut while the grout set. The cable was fed through the tubing as more sections were attached and it was lowered through the hollow core of the auger to the bottom of the boring. Once the boring bottom was reached and the cable end was securely located in bedrock, the auger sections were carefully raised from around the cable and 1.5 in (3.8 cm) PVC pipe. Sections of the PVC tubing were then raised and unattached while the cable was held securely at the top of the boring. An additional twenty feet of cable above the boring was necessary to remove tubing sections and hold the cable. When all tubing sections were removed, the cable was centered in the boring and held taut while grout was pumped in to the boring. The same grout mixture was used for the Inclinometers and the TDR Cables. After overnight setting of the grout, additional grout was added to the boring if needed. Once the grout stiffened, a 4 in (10 cm) diameter PVC tube with a screw cap was affixed over the cable and set with quick setting cement. The cable was cut with additional cable at the top of the ground surface. This allowed room to setup instrumentation for data acquisition. A BNC connector was then soldered to the cable end. Figure 3.10 shows a diagram of the TDR installation.

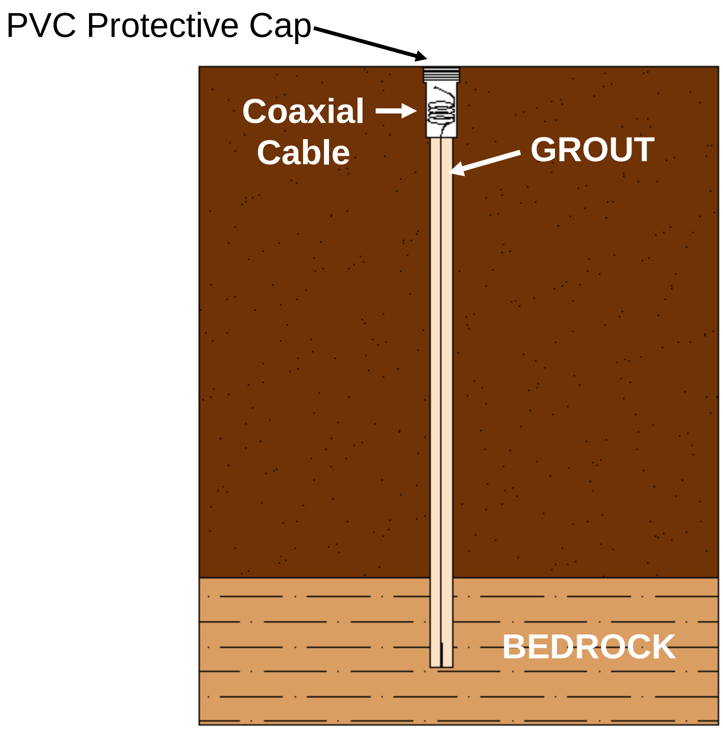


Figure 3.10 – TDR Installation Diagram

Figure 3.11 shows a photograph taken during the installation of a TDR cable after installation of an adjacent inclinometer casing at the MEG-338 site.

Figure 3.11 - Drilling TDR Boring Adjacent to Inclinometer Installation at MEG-338 Site

Figure 3.12 shows the installation of a TDR cables using the 1.5 in (3.8 cm) PVC pipe. Figure 3.13 shows the completed installation of an inclinometer and TDR cable. The protective PVC caps have been set in place with quick-setting cement.

Figure 3.12 - Installation of TDR Cable Using 1.5 in (3.8 cm) Diameter PVC Pipe

Figure 3.13 - Completed Installation of Inclinometer and TDR Cable

3.4 Soil Profiles of the Test Sites

Detailed soil profiles of the test sites were developed during drilling for the inclinometer casings by the ODOT Soils Laboratory. The boring logs and field data are attached in APPENDIX C – Boring Logs and APPENDIX D – Field Data. The soils encountered in the borings were sandy silt, silt and clay. The bedrock encountered was sedimentary rock; sandstone, siltstone and mudstone. Table 3.3 lists the depth to bedrock encountered at the test sites. Figure 3.14 shows the initial gravimetric soil moisture content with depth at the test sites.

Table 3.3 - Depth to Bedrock

Test Site	Depth to Bedrock
MEG 338-B-1	25' (7.6 m)
MEG 338-B-2	25' (7.6 m)
MEG 124-B-1	35' (10.7 m)
MEG 124-B-2	37.5' (11.4 m)

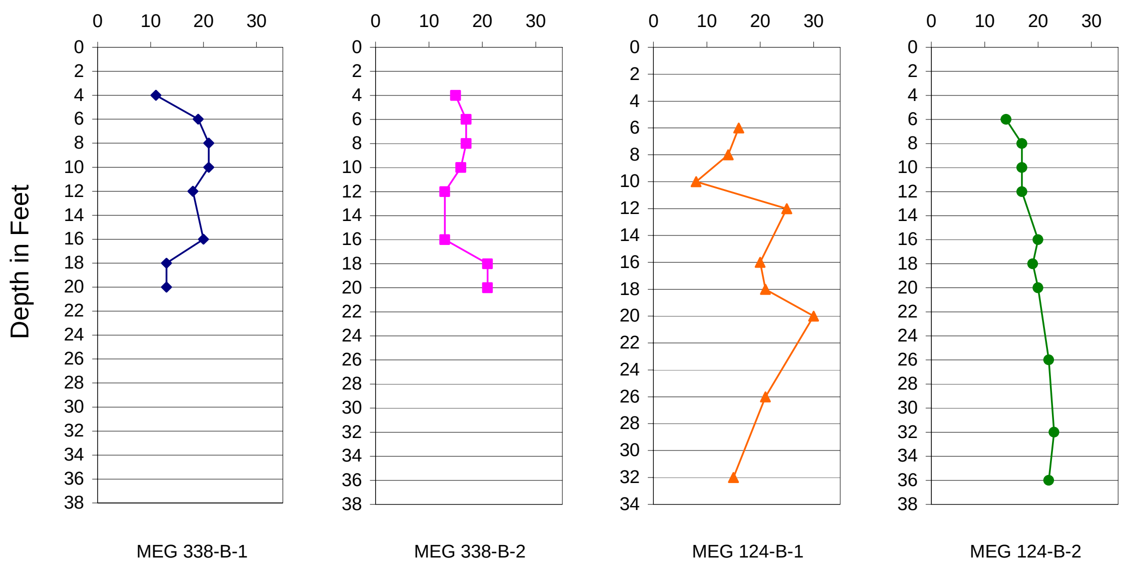


Figure 3.14 – Gravimetric Soil Moisture Content from Soil Boring Laboratory Analysis (1 ft = 0.3048 m)

Figure 3.15 shows the standard penetration number, N with depth and the rock quality designation, RQD of the cores at the test sites. From Table 3.4 it can be seen that the rock cores removed at MEG 338-B-1, MEG 338-B-2, and MEG 124-B-1 all were good quality. Three cores were obtained for MEG 124-B-2. The shallowest cores were very poor and poor quality. The third core was fair quality.

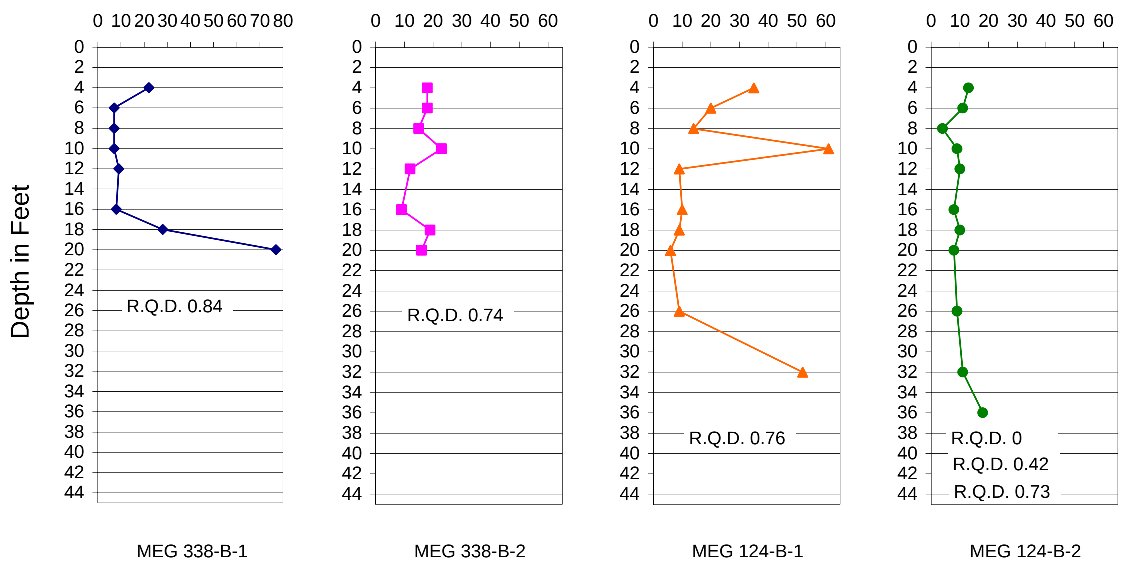


Figure 3.15 – Standard Penetration Number, N, and RQD from Boring Logs (1 ft = 0.3048 m)

Table 3.4 – Qualitative Description of Rocks Based on RQD

(From B.M. Das, *Principles of Geotechnical Engineering*, 4th Edition, pp.668 [26])

RQD	Rock Quality
1-0.9	Excellent
0.9-0.75	Good
0.75-0.5	Fair
0.5-0.25	Poor
0.25-0	Very Poor

The N values varied greatly for the four sites. Table 3.5 shows the N values with depth. Table 3.6 shows the approximate correlation of standard penetration number and consistency of clay soils.

Table 3.5 – Standard Penetration Number, N with Depth (1 ft = 0.3048 m)

Depth (ft)	MEG 338-B-1	MEG 338-B-2	MEG 124-B-1	MEG 124-B-2
0				
2				
4	22	18	35	13
6	7	18	20	11
8	7	15	14	4
10	7	23	61	9
12	9	12	9	10
14				
16	8	9	10	8
18	28	19	9	10
20	77	16	6	8
22				
24				
26			9	9
28				
30				
32			52	11
34				
36				18

Table 3.6 – Approximate Correlation of Standard Penetration Number and Consistency of Clay

(From B.M. Das, *Principles of Geotechnical Engineering*, 4th Edition, pp.654 [26])

Standard penetration Number, N	Consistency
0	
	Very soft
2	
	Soft
4	
	Medium Stiff
8	
	Stiff
16	
	Very stiff
32	
>32	Hard

The soil profile at MEG 338-B-1 ranges from stiff to hard. There is a very stiff soil layer near the ground surface underlain by softer layers. The final layer encountered was hard. At MEG 338-B-2 there were several very stiff soil layers above weaker stiff layers. At the bottom of the profile was more very stiff soil. MEG 124-B-1 was a layered profile of hard and stiff soils. Asphalt was encountered to a depth of 19 feet. MEG 124-B-2 was the most consistent profile with the soil ranging from medium stiff to very stiff. Additionally, the water elevation encountered during drilling was recorded at a depth of 20 ft (6.1 m) for MEG 124-B-1 and 30 feet for MEG 124-B-2.

3.5 Data Acquisition

The initial TDR cables and slope inclinometer readings were taken on September 16, 2002. After initial calibration readings, the inclinometers and TDR cables were read monthly. A total of 16 readings, including the baseline readings on September 16, 2002, were taken. The data obtained from the readings was shared between the Ohio Department of Transportation and the Ohio Research Institute for Transportation and the Environment, Ohio University.

3.5.1 Inclinometer Readings

The Inclinometers were read by ODOT personnel using the Slope Indicator Company Digitilt® system. The system, shown in Figure 3.16, used a portable probe containing a gravity-sensing transducer, a portable readout unit for power supply and indication of probe inclination and a graduated electrical cable linking the probe to the readout unit. The probe read both the A axis and B axis simultaneously, but two readings, 180-degrees apart were taken and the readings were averaged for each axis. The traces of cumulative displacement were provided. The rate and depth of movement were also provided in monthly reports from the ODOT Office of Geotechnical Engineering. Figure 3.17 shows a photograph taken during an inclinometer reading by ODOT. The Inclinometer traces are located in APPENDIX A – Inclinometer Readings.

Figure 3.16 – Slope Indicator Company Digitilt® System

(Images from http://www.slopeindicator.com/instruments/inclin-intro.html and http://www.slopeindicator.com/instruments/readout-datamate.html)

Figure 3.17 - Inclinometer Reading by ODOT

3.5.2 TDR Cable Readings

The TDR cables were read manually using the setup shown in Figure 3.18. The TDR cables were connected to a Campbell Scientific TDR100 unit. An external 12V sealed rechargeable lead-acid battery was used to power the TDR100. The TDR100 does not have a built-in display, therefore the Windows software PCTDR100 was used to read the TDR traces. PCTDR100 required a connection from the serial communications port of the computer to the serial port of the TDR100. The traces were stored in .wfd and ASCII format and can be found in APPENDIX B – TDR Traces. A sample trace from the PCTDR100 software taken in the laboratory is shown in Figure 3.19. Table 3.7 details the TDR100 performance specifications.

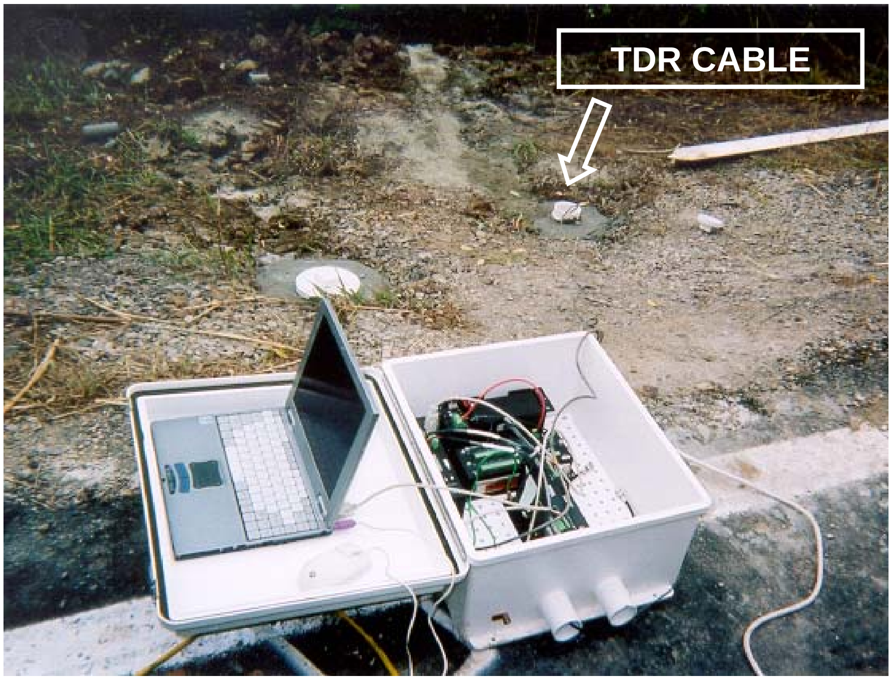


Figure 3.18 - TDR Data Acquisition Setup

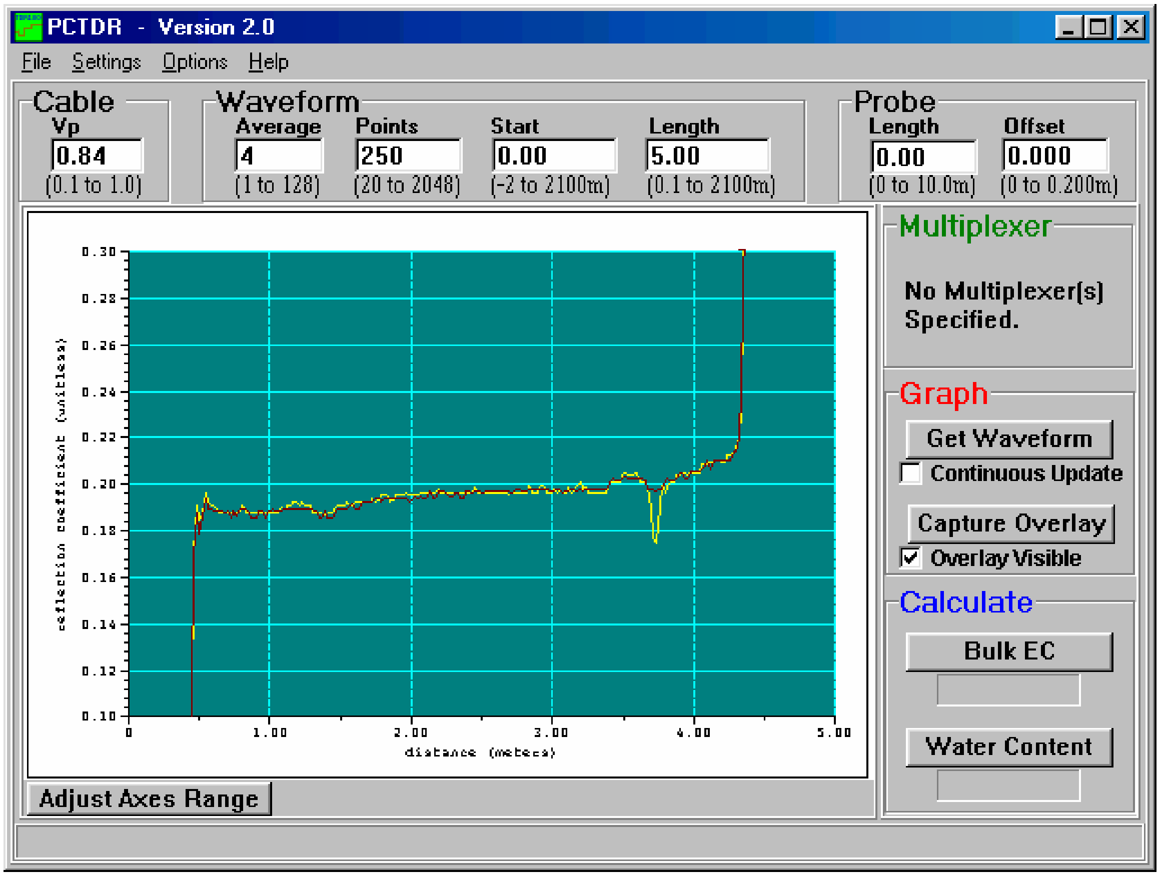


Figure 3.19 – Sample Laboratory PCTDR100 Trace

Table 3.7 - TDR100 Performance Specifications

TDR100	Specifications
Pulse Generator Output	250 mV into 50 ohms
Output Impedance	50 ohms ± 1%
Time Response of Combined Pulse Generator and Sampling Circuit	≤ 250 picoseconds
Pulse Length	14 microseconds
Maximum Cable Length	2100 meters @ Vp = 1
Timing Resolution	12.2 picoseconds
Waveform Sampling	20 to 2048 waveform values over chosen length
Waveform Averaging	1 to 128
Electrostatic Discharge Protection	Internal clamping
Power Supply	12 volt, 300 milliamps maximum
Temperature Range	-25°C to 50°C

CHAPTER 4: DETERMINATION OF SHEAR PLANE DEPTH

Reduction of the data obtained from the inclinometers and TDR cables was necessary to determine the shear plane depth. Two distinct methods were used to determine the shear plane depth.

4.1 Inclinometers

The ODOT Office of Geotechnical Engineering was responsible for reading and analyzing the inclinometer data. Monthly reports outlining depth and rate of movement and the inclinometer cumulative displacement plots were provided to Ohio University. The inclinometer readings obtained during the monitoring period can be found in APPENDIX A – Inclinometer Readings. A sample of the raw inclinometer data before analysis can be found in APPENDIX E – Sample Data for Inclinometer Reading.

4.2 TDR Cables

The TDR data was processed with Microsoft Excel. The PCTDR100 program used to acquire the TDR traces provides a plot of the trace in .wfd format; however the ASCII files are necessary for data processing. A sample PCTDR trace can be seen in Figure 3.19. The ASCII files were imported into Microsoft Excel. A sample ASCII data file for a TDR trace can be found in APPENDIX F - ASCII Data File Format for TDR Traces. Excel was chosen for this application for its simplicity, since only four cables were analyzed each month. For the processing of multiple cables, other programs such as

Matlab or a custom Visual Basic application would be more efficient. The TDR traces obtained over the monitoring period can be found in APPENDIX B.

To read the TDR cables, a pulse waveform is transmitted through the coaxial cable. If the pulse encounters a change in the impedance of the cable, it is reflected. The reflected signal is divided by the transmitted signal to determine the reflection coefficient. Kane elaborates on the reflection coefficients for various cable impedances:

> "If the reflected voltage equals the transmitted voltage, the reflection coefficient is +1 and the cable is broken. If the opposite occurs, and the cable is shorted, all the energy will be returned by way of the ground, and the reflection coefficient will be -1. If the cable has a change of impedance, the reflection coefficient will be between -1 and +1. If the pulse experiences a decrease in impedance, the reflection coefficient will be negative. If the pulse experiences a higher impedance the reflection coefficient will be positive." [20]

A kink or shear of the cable will reduce the cable impedance. Extension of the cable will increase the impedance.

The depth of movement is determined from the TDR trace. Any deformations in the TDR cable will appear in the TDR trace. A shear or kinking of the cable will appear as a small negative spike in the TDR trace. Complete shearing of the cable will appear as an open circuit in the TDR cable. The signature traces for these deformations can be seen in Figure 4.1 and Figure 4.2. Once a cable has been deformed, it may longer protected from water intrusion and the cable trace can deteriorate rapidly. Figure 4.3 shows the effect of water intrusion into the cable end. This water intrusion into the cable end can be seen as a decreasing incremental step in the depth of the cable end in the monthly readings. Additionally, if the BNC cable connector is submerged, water intrusion can damage the top end of the cable and the traces are compromised.

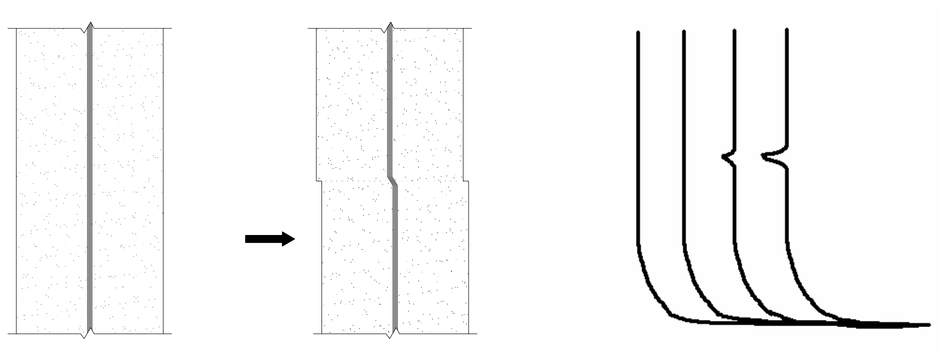


Figure 4.1 - Characteristic Trace for Shearing or Kinking of TDR Cable

(Reproduced from Kane, *Development of a Time Domain Reflectometry System to Monitor Landslide Activity*, Figure 2-2a [20])

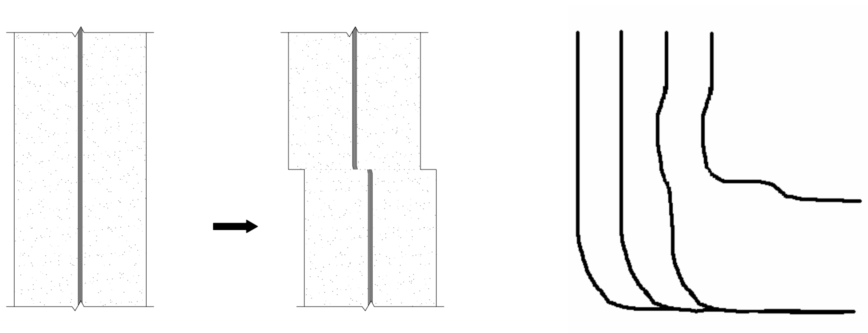


Figure 4.2 - Characteristic Trace for Extension Failure of TDR Cable

(Reproduced from Kane, *Development of a Time Domain Reflectometry System to Monitor Landslide Activity*, Figure 2-2a [20])

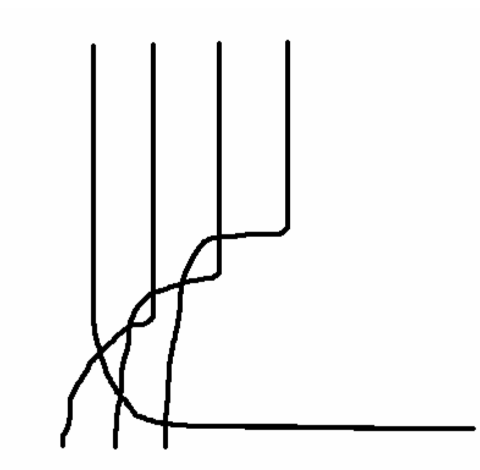


Figure 4.3 – Observed TDR Trace for Cable Experiencing Water Intrusion

4.3 Monitoring Results

After 16 months of monthly monitoring, the study showed a clear correlation in detection of the shear planes between the TDR cables and the slope inclinometers. The TDR traces and final inclinometer cumulative displacement plots are shown on the following pages. The depth of movement for the inclinometers was determined by the

Ohio Department of Transportation. The observed depth of lateral movement by the inclinometers is highlighted in the TDR traces.

Figure 4.4 and Figure 4.5 show the monthly TDR cable readings and the last inclinometer reading for MEG 338-B-1. The MEG 338-B-1 cable experienced cable deformation at a depth of 16 ft (4.9 m) and cable shear at a depth of 38 ft (11.6 m). The cable deformation at 38 ft (11.6 m) allowed water to infiltrate the end of the cable. The water damage in the cable can be seen in the monthly traces as an incrementally decreasing depth to the cable end. The inclinometer detected the shear plane at a depth of 16 ft (4.9 m). The movement at the 16 ft (4.9 m) depth is located within a red silt and clay layer. The medium stiff soil at this depth is underlain by a very stiff layer. The detected movement is along the interface of the two layers.

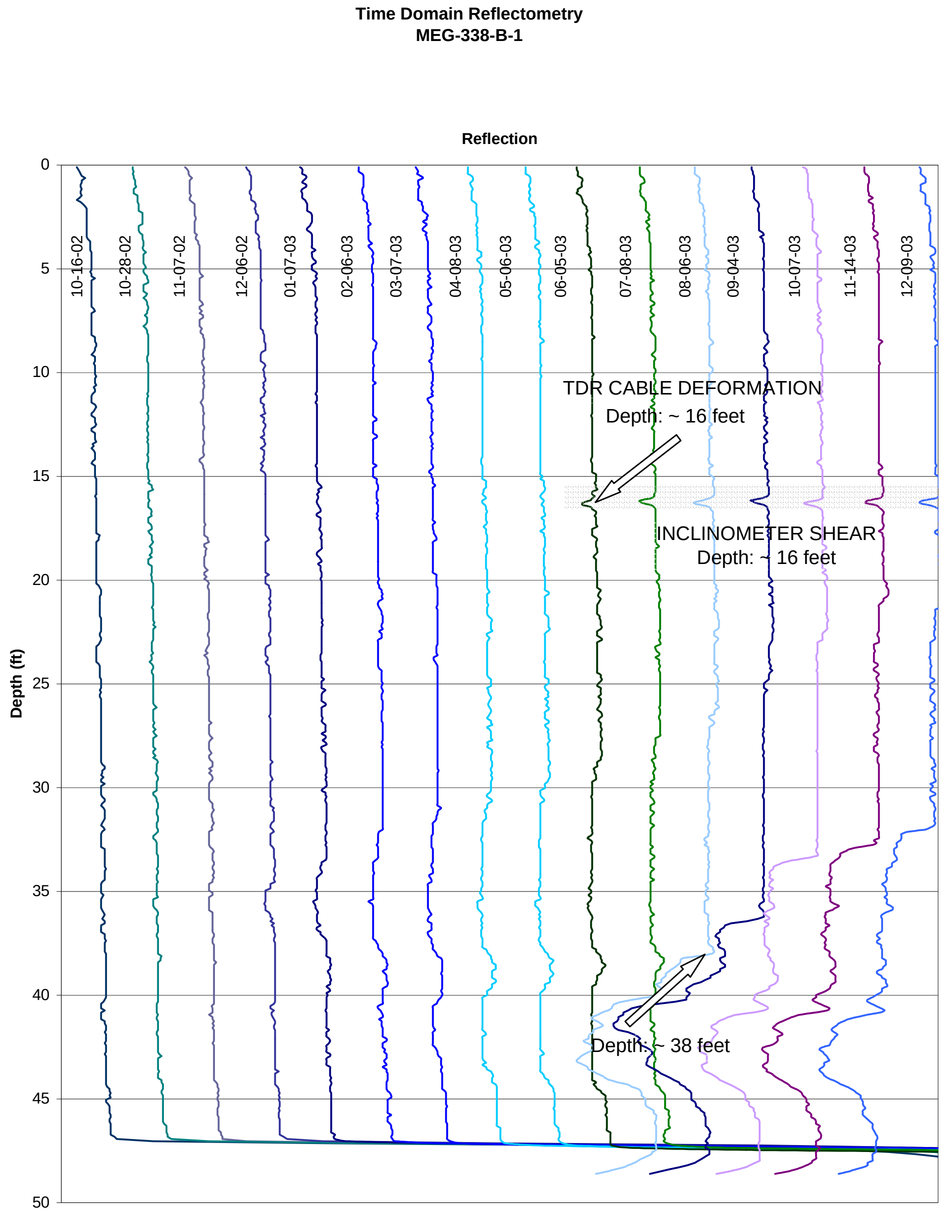
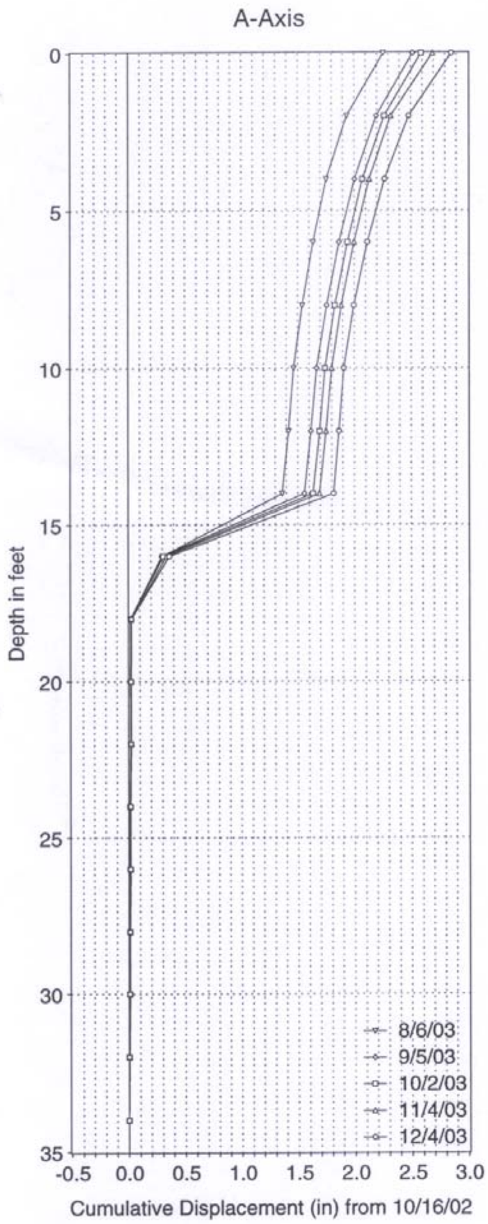
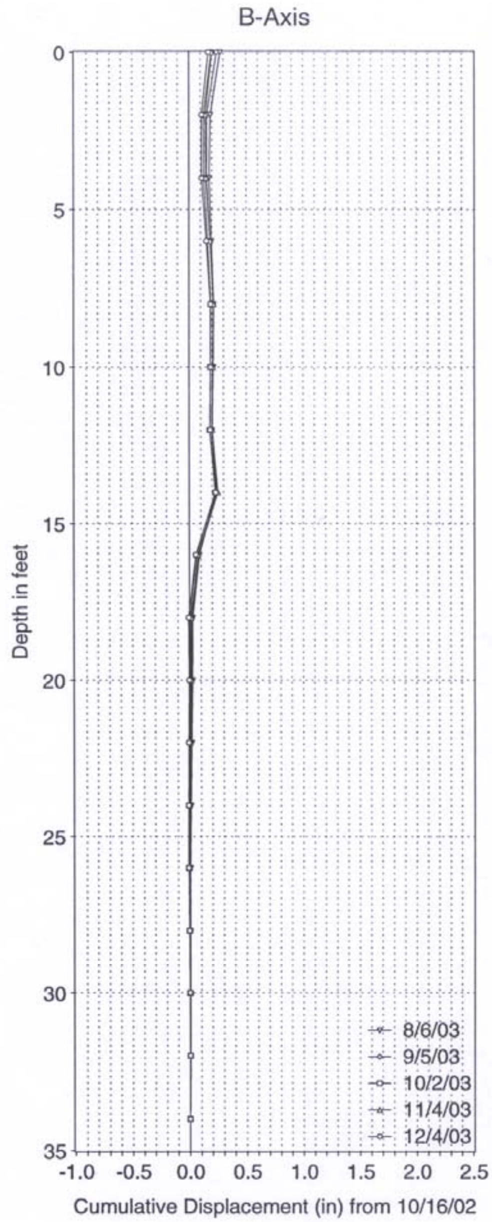


Figure 4.4 – MEG 338-B-1 TDR Cable and Inclinometer Monthly Reading Results (1 ft = 0.3048 m)





MEG-338-20.92

Slope Inclinometer Installation B-1

A-axis in direction of assumed movement

Figure 4.5 – MEG-338-B-1 Inclinometer Reading (1 ft =0.3048 m, 1 in = 2.54 cm)

Figure 4.6 and Figure 4.7 show the monthly TDR cable readings and the last inclinometer reading for MEG 338-B-2. The MEG 338-B-2 cable experienced cable deformation at a depth of 18 ft (5.4 m). The cable connector at the top-end of the cable was damaged due to standing water in the PVC protective cap. The water damage is evident in the September through December traces. The inclinometer detected the shear plane at a depth of 18 ft (5.4 m) and the casing failed completely at a depth of 17 ft (5.2 m). The inclinometer casing at this site experienced an unusual negative cumulative displacement at the top end of the casing. The detected movement is in a red, gravelly sandy silt located at the interface between a medium stiff layer and a very stiff soil layer. The detected movement here is also along the interface of the two layers.

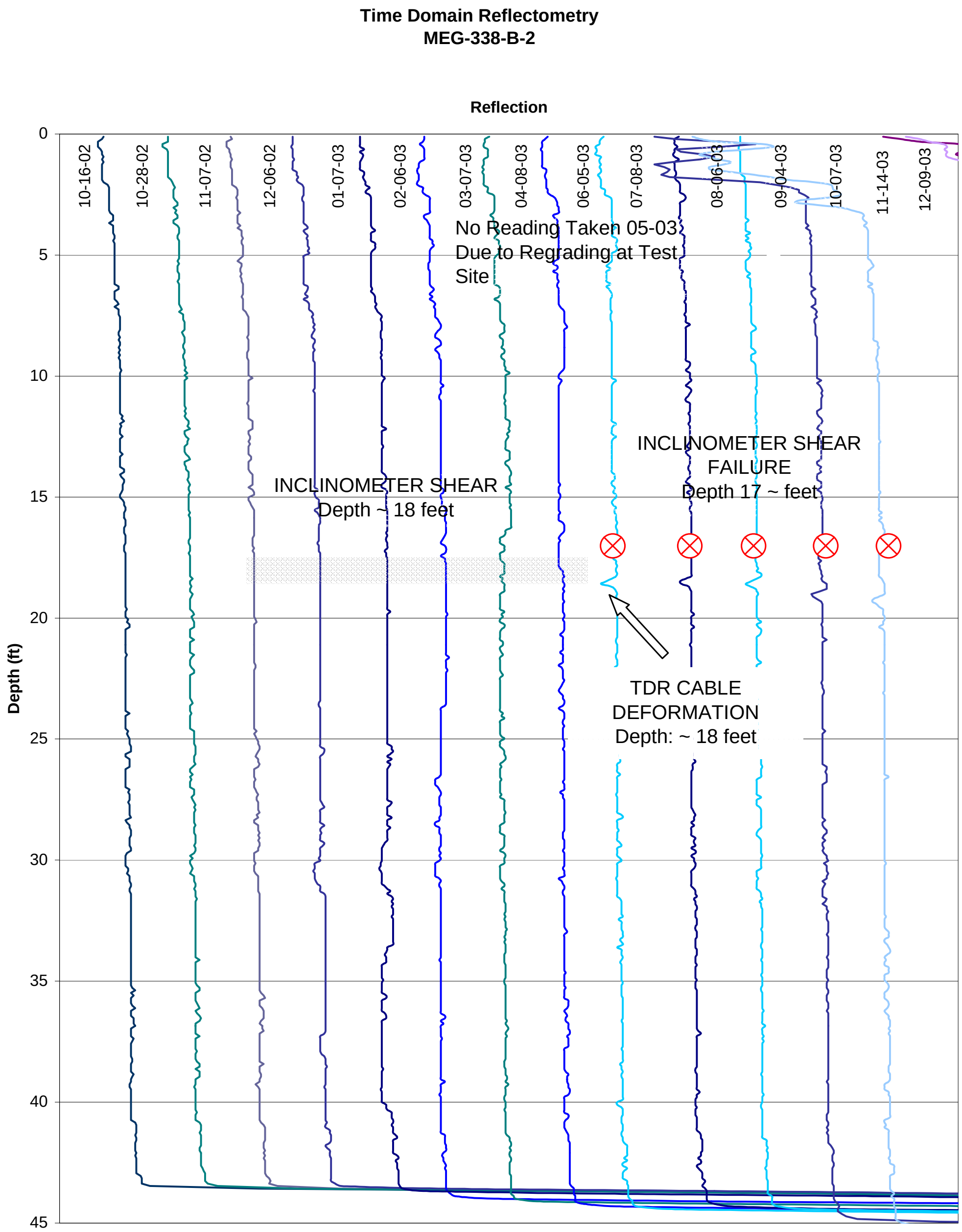
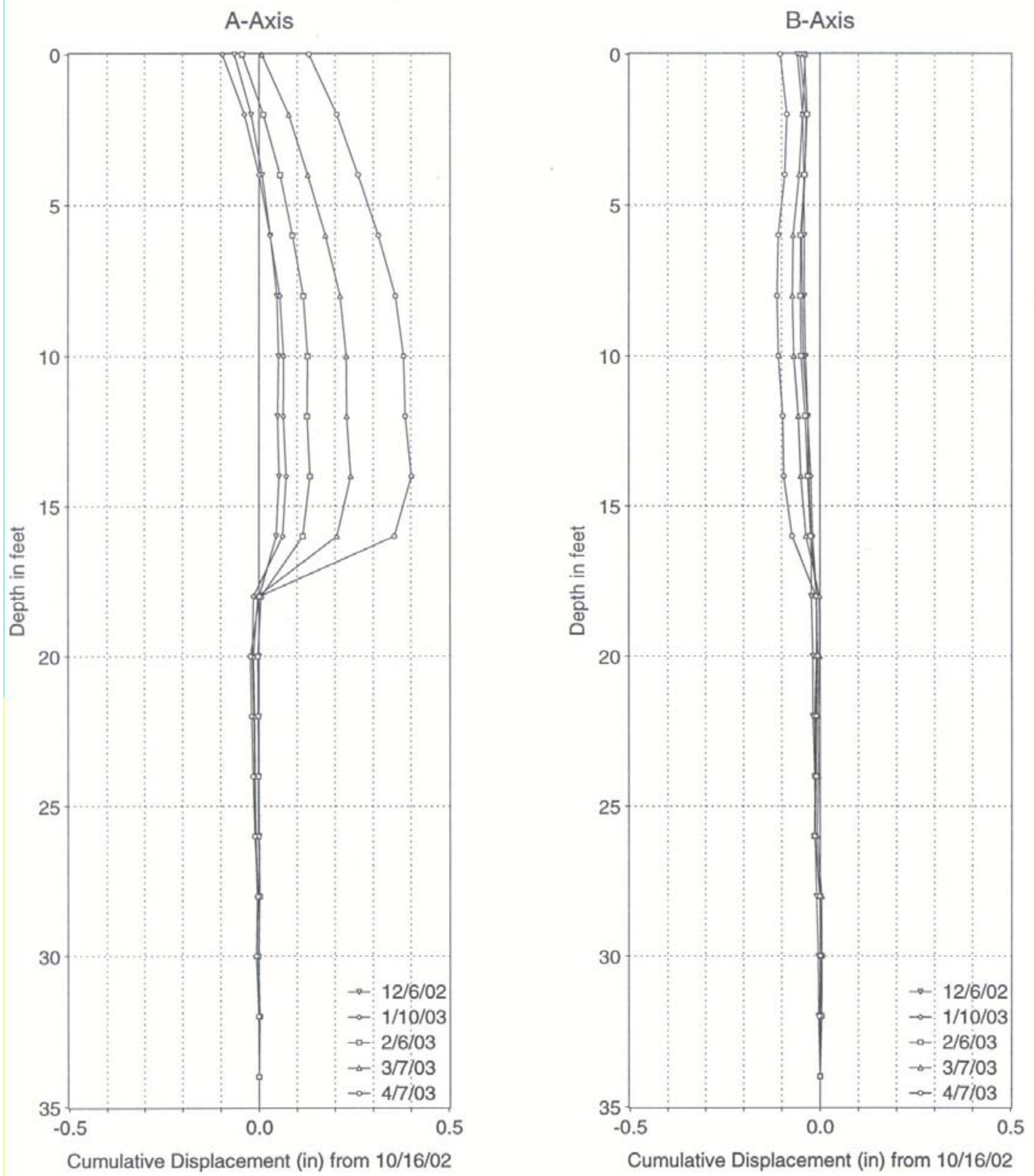


Figure 4.6 - MEG 338-B-2 TDR Cable and Inclinometer Monthly Reading Results (1 ft = 0.3048 m)

(⊗ Indicates inclinometer casing deformed beyond use)



MEG-338-20.92

Slope Inclinometer Installation B-2

A-axis in direction of assumed movement

Figure 4.7 – MEG-338-B-2 Inclinometer Reading (1 ft = 0.3048 m, 1 in = 2.54 cm)

Figure 4.8 and Figure 4.9 show the monthly TDR cable readings and the last inclinometer reading for MEG 124-B-1. The MEG 124-B-1 cable experienced cable shear at a depth of 31 ft (9.4 m). An initial deformation of the cable was detected at a depth of 42 ft (12.8 m), but the cable was sheared at the 31 ft (9.4 m) depth the following month so further monitoring of the 42 ft (12.8 m) depth shear plane was not possible. The damaged cable experienced water intrusion which can be seen in the monthly traces as an incrementally decreasing depth to the cable end. The inclinometer detected a shear plane and deformed beyond use at a depth of 30 ft (9.1 m). The movement at this depth is located within a red silt and clay layer. The stiff soil at this depth is underlain by a significantly harder layer. The detected movement is along the interface of the two layers, just above the bedrock.

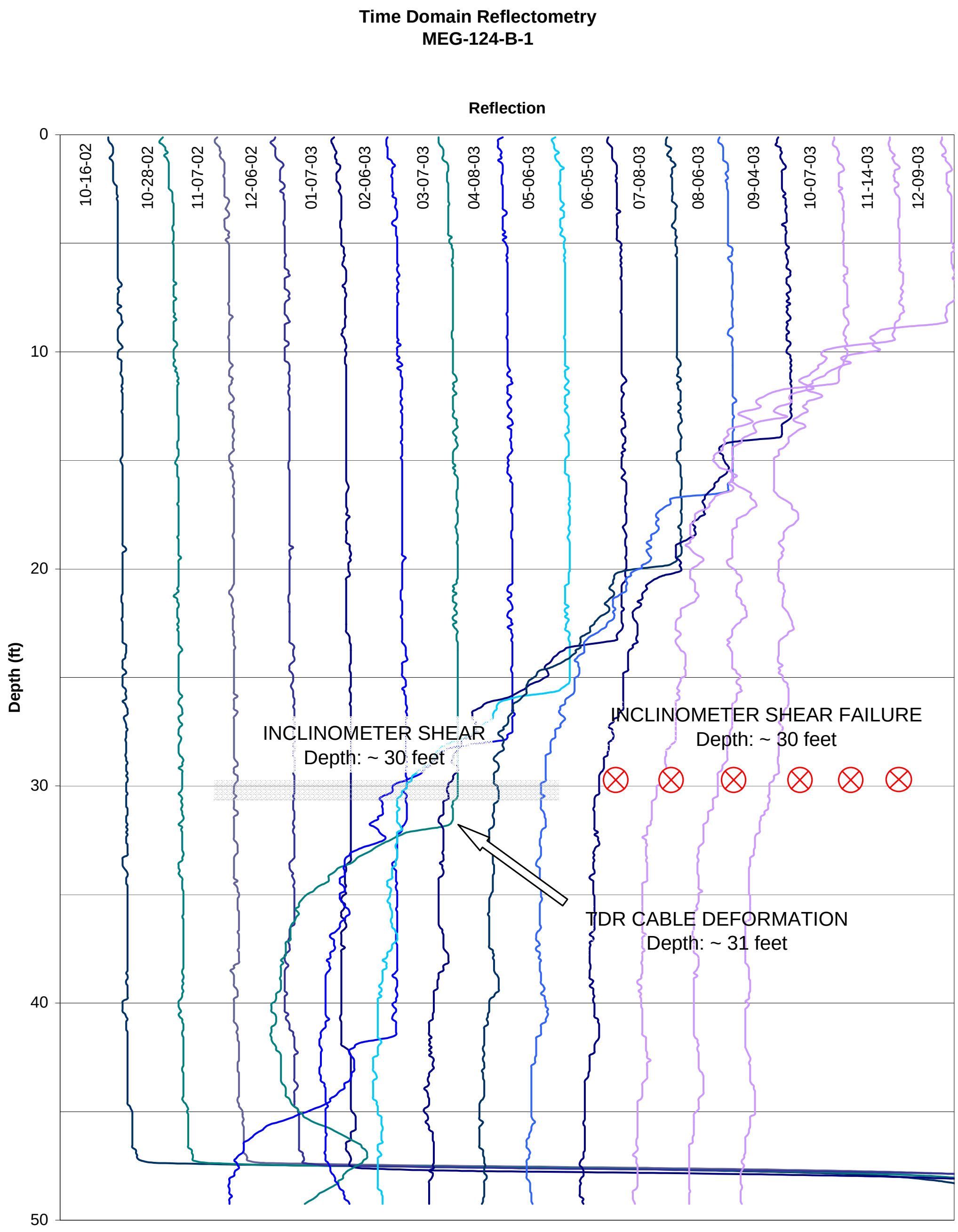
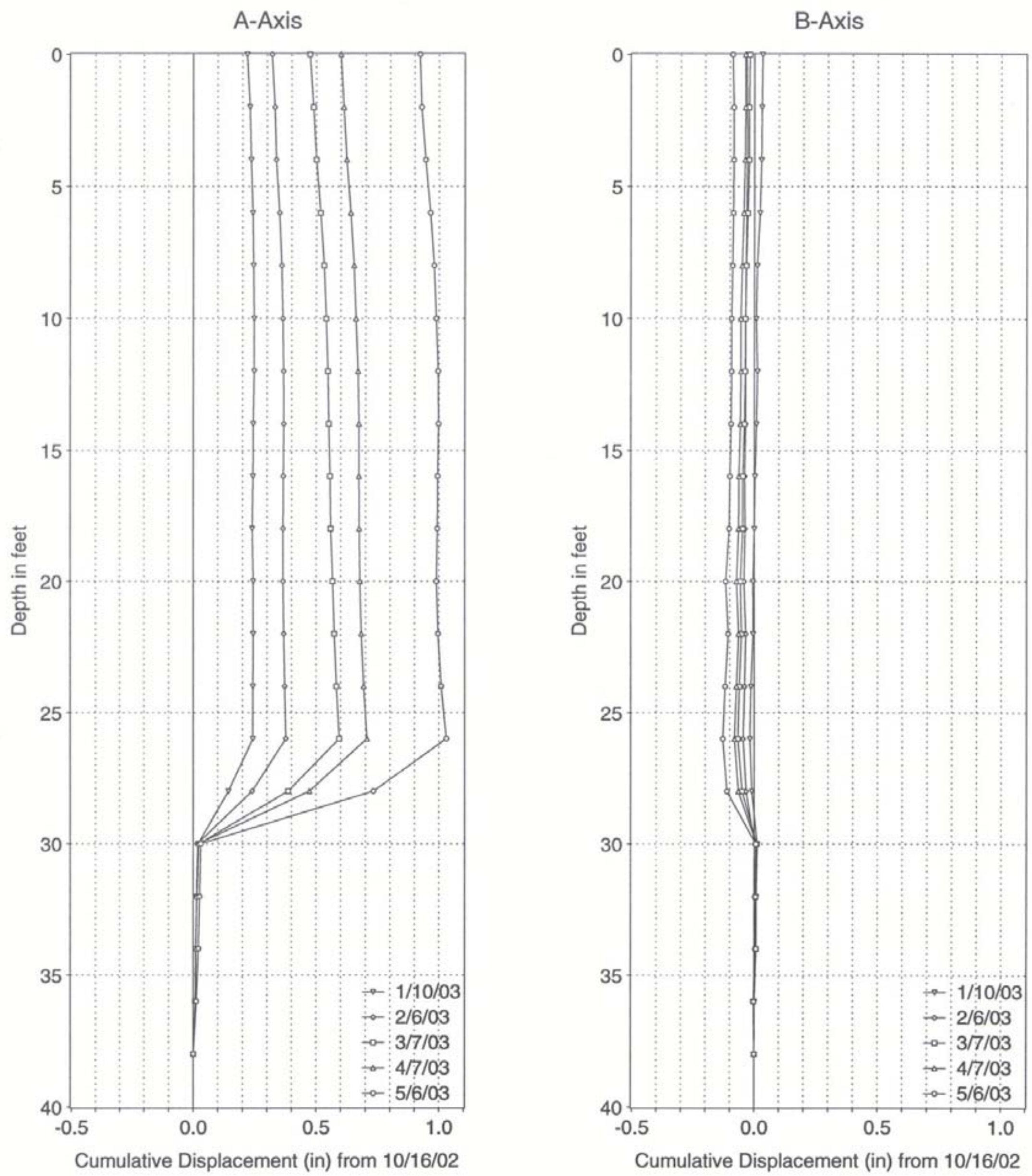


Figure 4.8 - MEG 124-B-1 TDR Cable and Inclinometer Monthly Reading Results (1 ft = 0.3048 m)

(⊗ Indicates inclinometer casing deformed beyond use)



MEG-124-46.86
Slope Inclinometer Installation B-1

A-axis in direction of assumed movement

Figure 4.9 – MEG-124-B-1 Inclinometer Reading (1 ft = 0.3048 m, 1 in = 2.54 cm)

Figure 4.10 and Figure 4.11 show the monthly TDR cable readings and the last inclinometer reading for MEG 124-B-2. The MEG 124-B-2 cable experienced cable deformation at a depth of 41 ft (12.5 m). The cable also experienced water intrusion at the damaged cable end. The inclinometer detected a shear plane at a depth of 40 ft (12.2. m). The movement is located within the bedrock, in a grey siltstone layer with a RQD of 0. The layer below is also a grey siltstone but has an RQD of 42. The detected movement is at the interface of the weak grey siltstone and stronger grey siltstone layer below.

Time Domain Reflectometry
MEG-124-B-2

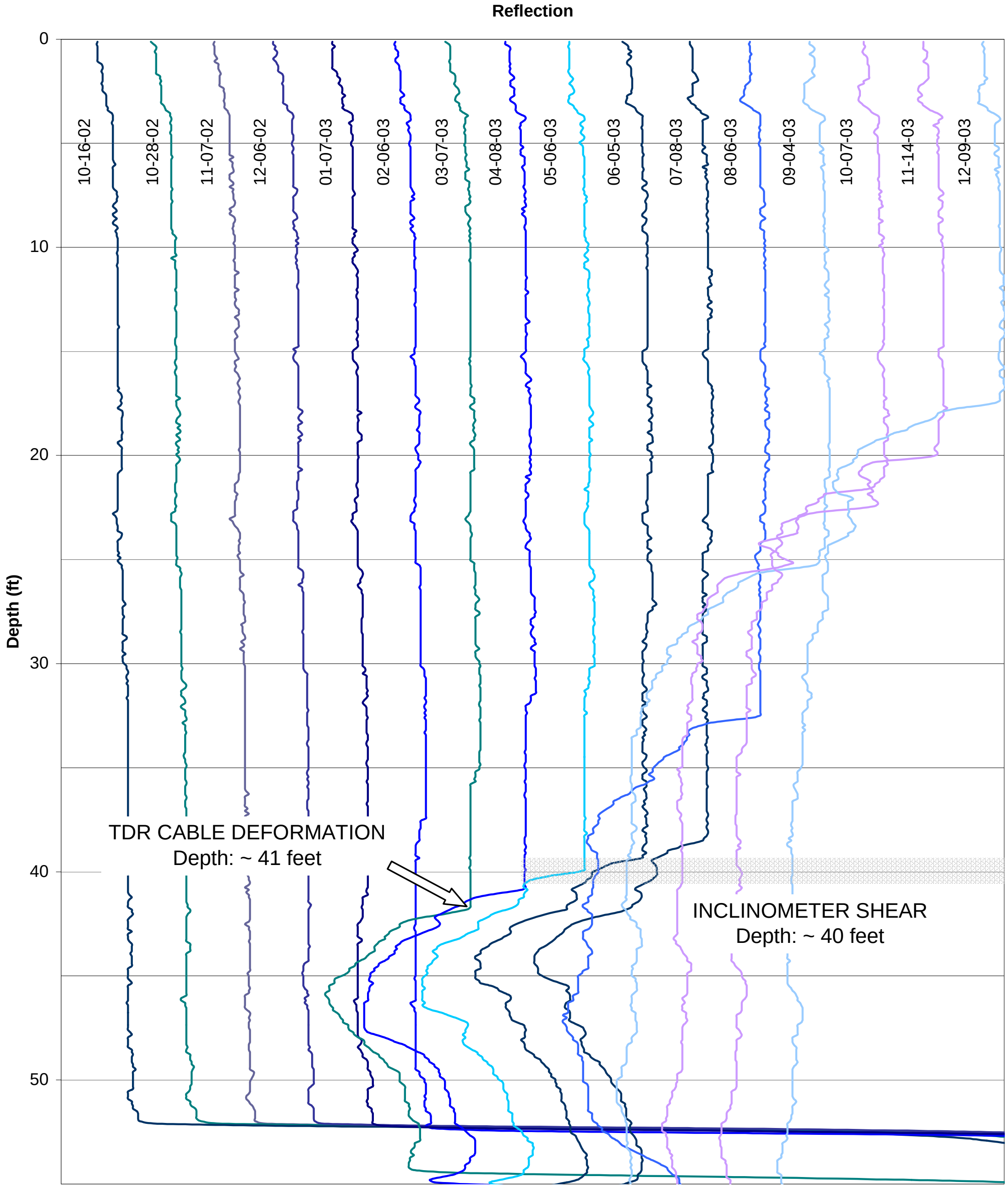
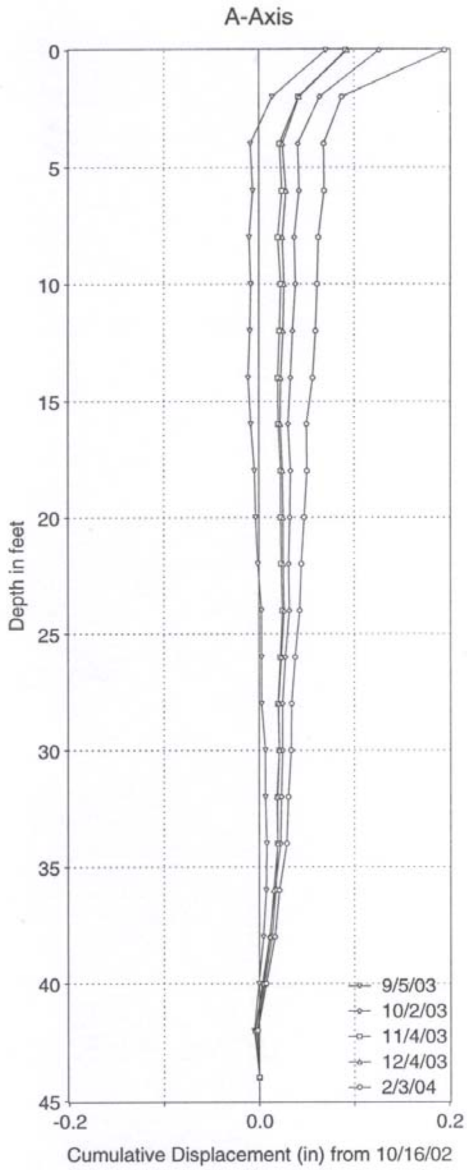
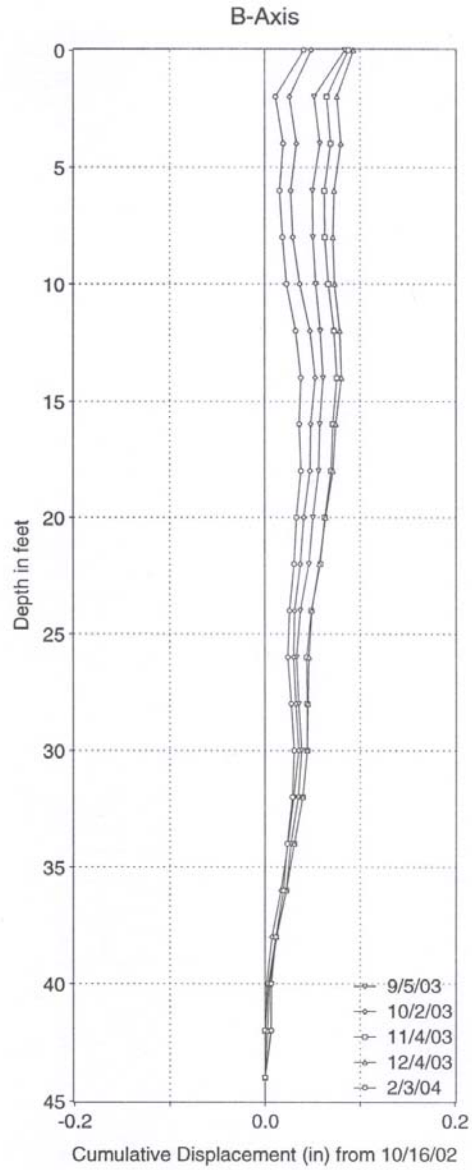


Figure 4.10 - MEG 124-B-2 TDR Cable and Inclinometer Monthly Reading Results (1 ft = 0.3048 m)





MEG-124-46.86

Slope Inclinometer Installation B-2

A-axis in direction of assumed movement

Figure 4.11 – MEG-124-B-2 Inclinometer Reading (1 ft = 0.3048 m, 1 in = 2.54 cm)

4.4 Advanced TDR Analysis

In addition to visual interpretation of the raw TDR traces, signal processing techniques were explored with the aim of extracting positive indications of slope movement from the TDR data earlier than was possible via visual inspection of the traces. Since small impedance changes are difficult to discern with the naked eye from a plot of reflectance versus depth at different times, this analysis applied signal processing techniques that emphasize contrast between invariance and small variations in the signal with respect to both time (e.g., testing date) and space (e.g., reflection origin). This process consisted of noise filtering, time differentiation, and spatial differentiation. This signal processing train was followed by development of a metric we dubbed the "Failure Indicator," that emphasizes variation in the temporal-spatial derivative of the noise-filtered data.

4.4.1 Noise Filtering

First, noise was removed from each TDR trace using a low-pass filtering technique that affords neighboring samples a logarithmically decreasing influence on the filtered value relative to distance from it. This low-pass filter weights adjacent samples by the following function:

$$x'_i = k\, x'_{i-1} + (1-k)\, x_i$$

where k is the filter constant between 0 and 1, i is the ordinal of the sample number (in this case with respect to distance along the cable, which equates with time of TDR signal refection), x_i is the unfiltered value of sample i, and x'_i and x'_{i-1} are the filtered values at i and i-1.

The filter was applied bi-directionally to the raw data, and the results of filtering in each direction were averaged, as per the following formulae, where x'_1 and x'_2 are the filtered values in each direction, and x' is the final result.

$$x'_{i,1} = k\, x'_{i-1,1} + (1\text{-}k)\, x_i$$

$$x'_{i,2} = k\, x'_{i+1,2} + (1\text{-}k)\, x_i$$

$$x'_i = 0.5(x'_{i,1} + x'_{i,2})$$

The filter constant, k, was adjusted until maximum contrast (or signal-to-noise ratio, SNR) was achieved in the final slope failure metric, which turned out to be a function of the first derivative of TDR signal with respect to time and distance. We found the optimal filter constant to be k=0.90. The plot in Figure 4.12 illustrates the effect of this filter on a TDR trace obtained from installation A on January 7, 2003.

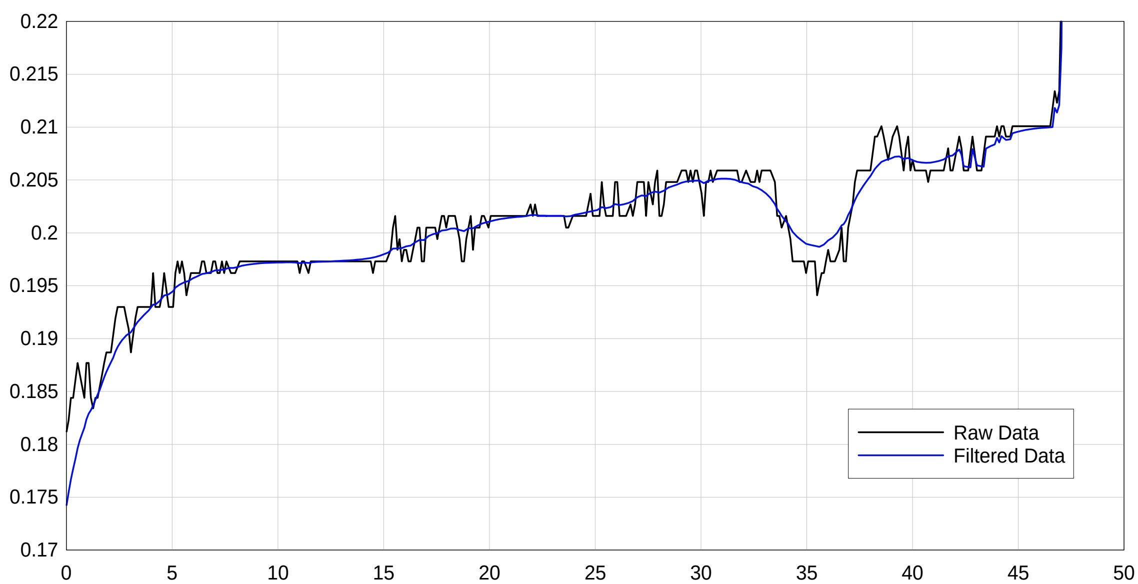


Figure 4.12. Example of noise filter applied to data collected from installation A (338-B-1) on January 7, 2003.

4.4.2 Temporal Differentiation

The time derivative of each TDR trace was then computed by backward differencing with the trace taken previously. Traces in this study had been acquired approximately every month for seventeen months. We utilized a time derivative to minimize the effect of long-term drift on our ability to discriminate changes in time, and to construct a signal from which we could discern changes in rate of cable deformation over time. Central differencing in time, though more accurate than backward differencing, was avoided because the objective was to identify slope failure at the earliest possible date. Future data must be considered unavailable to a method intended real-time interpretation.

4.4.3 Spatial Differentiation

Just as the time derivative was taken to emphasize small signal changes over time, a spatial derivative was then taken to emphasize small changes with respect to position along the TDR cable. For this derivative, a 3rd order central difference was chosen. The criterion for this choice was the finding that small cable deformations at the onset of slope failure were typically expressed in at least four adjacent samples of the TDR trace, whereas variations due to noise were higher frequency. The 3rd order central difference therefore provided the best SNR for detecting the onset of slope failure.

Figure 4.13 and Figure 4.14 are two views of the data obtained from installation C, also known as 124-B-1, after signal processing to obtain the derivative with respect to time and distance along the cable. The first figure shows processed traces from all months. Interesting to note is that the successive data clearly show the migration of upper boundary of soil failure zone with respect to depth as failure progresses. By further analyzing these data, it may be possible to infer quantities of material mobilized or other information about the failure, possibly including intrinsic properties of the soils involved, useful for stabilization design.

Apparent from Figure 4.13, is that useful data are still being obtained at least to up to 15 months following installation of the TDR monitoring infrastructure, whereas the slope indicator installation at this location had been rendered unusable by shear failure after only 8 months. Similar circumstances prevailed at the remaining three monitoring locations.

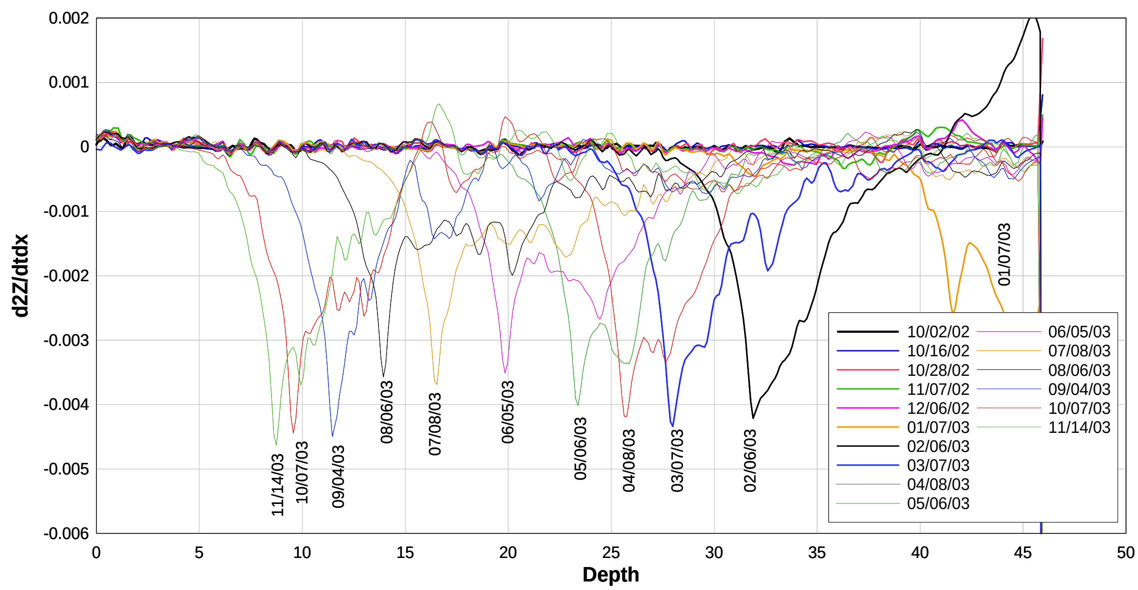


Figure 4.13. Derivative of TDR signal with respect to time and distance along the cable at installation C (124-B-1) (1 ft = 0.3048 m).

Figure 4.14 shows the first four traces of the same data as Figure 4.13 at an exaggerated scale vertical scale to illustrate how early in time a slope failure can be discerned from the processed TDR data. In Figure 4.14, it is apparent that significant cable deformation has occurred at approximately 38 ft (11.6 m) deep by November 7, 2002. This date is just 36 days after the first trace was taken, October 2, 2002. Furthermore, the flat spot in the data between 34 ft (10.4 m) and 38 ft (11.6 m) suggest the hypothesis that the cable was already under strain in this depth range when the

October 2 readings were obtained, as axial tension on the cable would tend to produce such a result by reducing small cable deformations that were present in the installation from the start.

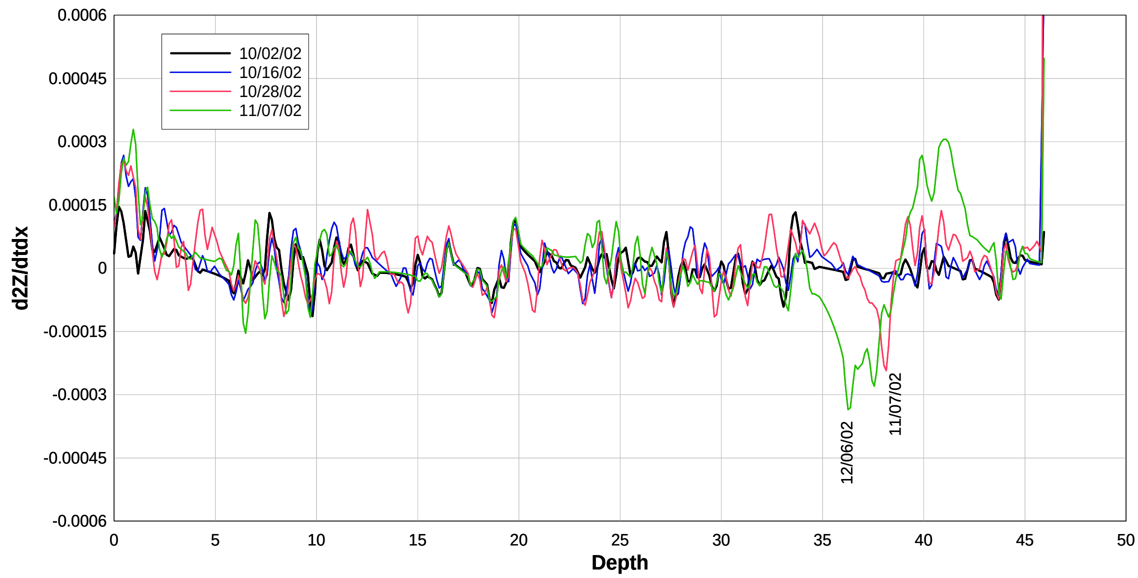


Figure 4.14. Derivative of TDR signal with respect to time and distance along the cable at installation C (124-B-1) (1 ft = 0.3048 m).

4.4.4 Movement Indicator

To better detect the onset of a slope failure by comparison of a varying TDR signal against some threshold value, we developed a metric that results from taking the absolute value of the negative portion of the derivative of the TDR signal with respect to time and distance along the cable. In other words, the devised metric is the negative portion of the temporal-spatial derivative, rectified. This metric, which we called the Failure Indicator, is shown for boreholes A, B, C, and D (338-B-1, 338-B-2, 124-B-1, and 124-B-2) in Figures Figure 4.15 through Figure 4.18. Each figure clearly shows when, and at what depth, a significant increase in the Failure Indicator emerges from the data. Typically, a value above 0.00018 stands out as significant. The mode of initial cable deformation detected by the Failure Indicator appears to correspond to Kane's description of tensile strain on the cable. The Failure Indicator detects the upper edge of the strained region, so the depth at which the peaks occur does not representative the center of the movement. The center of movement, or shear plane, would be indicated by the zero crossing between positive and negative peaks in the temporal-spatial derivative of reflectance, as shown at a depth of 38 ft (11.6 m) in Figure 4.14. The Failure Indicator in this case will peak at 35 ft (10.7 m).

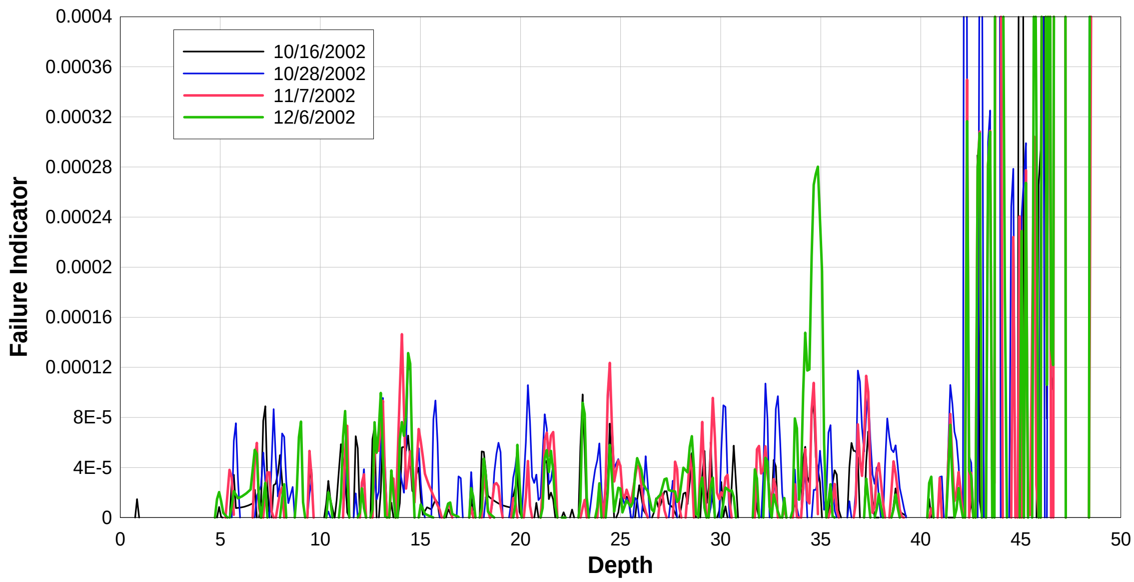


Figure 4.15. Failure Indicator versus depth at installation A (338-B-1) through December 6, 2002, 81 days following baseline reading, showing movement at 35 ft (10.7 m) deep (1 ft = 0.3048 m).

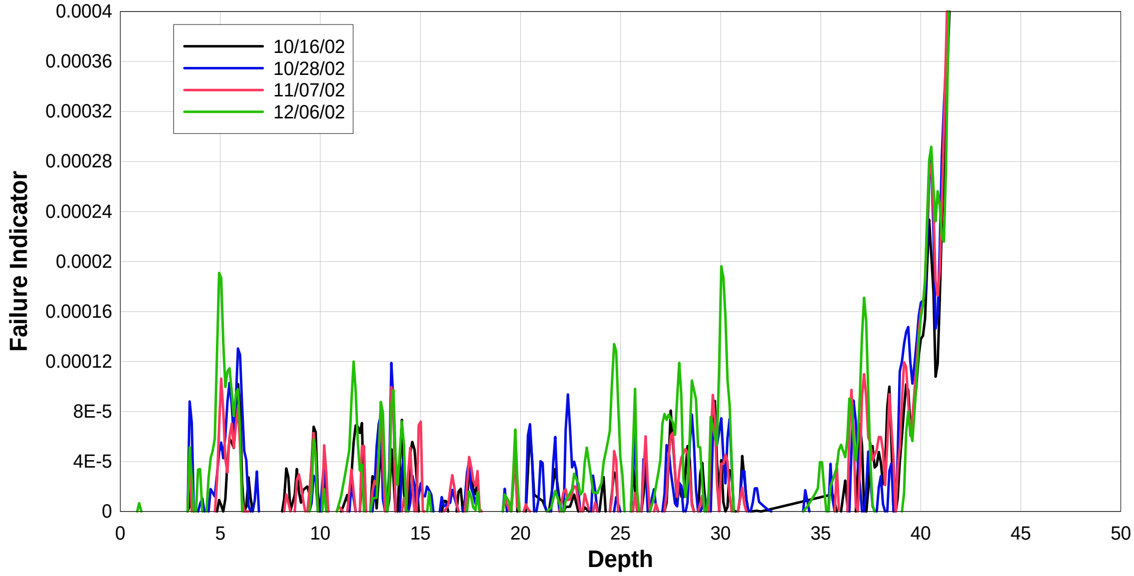


Figure 4.16. Failure Indicator versus depth at installation B (338-B-2) through December 6, 2002, 81 days following baseline reading, showing movement at 5 ft (1.5 m) and 30 ft (9.1 m) deep (1 ft = 0.3048 m).

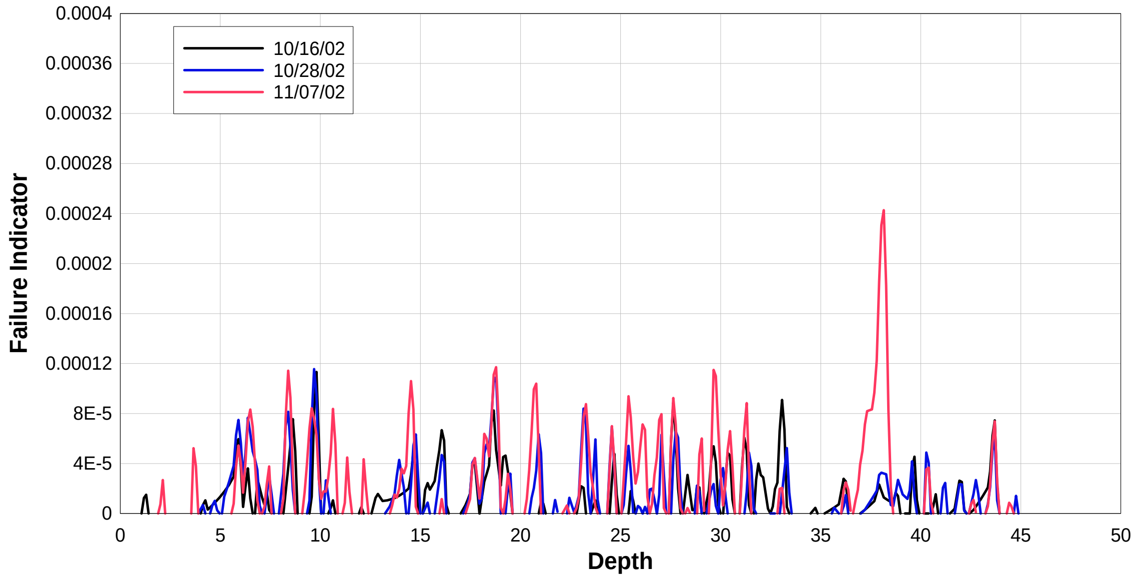


Figure 4.17. Failure Indicator versus depth at installation C (124-B-1) through November 7, 2002, 52 days following baseline reading, showing movement at 38 ft (11.6 m) deep (1 ft =0.3048 m).

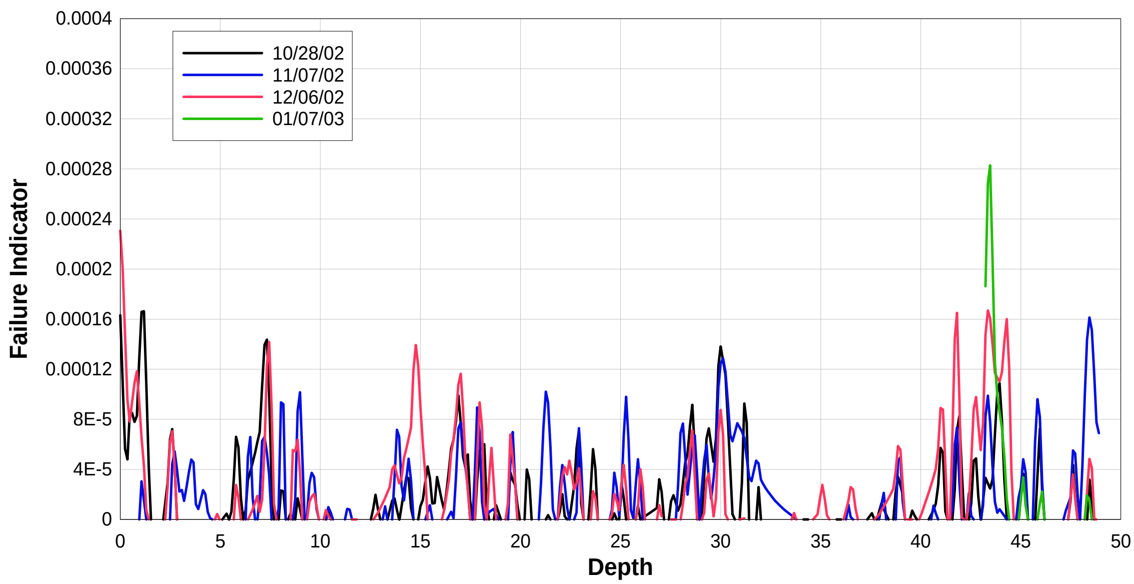


Figure 4.18. Failure Indicator versus depth at installation D (124-B-2) through January 7, 2003, 103 days following baseline reading, showing movement at 43 ft (13.1 m) deep (1 ft = 0.3048 m).

Since the processing performed did not explicitly account for time between traces or sample spacing along the cable, changes to these quantities would impact the value of the Failure Indicator at which soil movement should be considered apparent.

Interesting to note is that in most of the plots above, peaks in the failure indicator at multiple depths can be seen to recur month after month at the same depth. Since this indicator includes a time derivative, the recurrence of the same peaks over several months is an indication of sustained shear movement at each recurring peak location. We have only chosen in this analysis to ignore peaks below a certain threshold for the purposes of discriminating them from non-recurrent peaks of similar magnitude, which may be attributable to random error. With further processing, a metric that accounts for peak persistence may be developed to reliably provide even earlier detection of slope failure.

4.5 Comparison

Table 4.1 shows the earliest detected movement for the inclinometers, the raw (unprocessed) TDR cable traces, and the processed TDR results.

Table 4.1 - Earliest Detection of Movement – TDR Cables & Inclinometers

Borehole	Inclinometer	Raw TDR Date	Processed TDR Date
	Date:Depth	Date:Depth	Date:Depth
MEG 338-B-1	06/03:16' (4.9 m)	06/03:16' (4.9 m) 08/03:38' (11.6 m)	12/02:35' (10.7 m)
MEG 338-B-2	11/02:18' (5.5 m)	06/03:18' (5.5 m)	12/02:5' (1.5 m) 12/02:30' (9.1 m)
MEG 124-B-1	11/02:30' (9.1 m)	02/03:42' (12.8 m) 03/03:31' (9.4 m)	11/02:38' (11.6 m)
MEG 124-B-2	04/03:40' (12.2 m)	03/03:41' (12.5 m)	01/03:43' (13.1 m)

Table 4.2 shows the depth of movement and corresponding reading date for the two methods. Depth of movement is defined as the recognizable zone of lateral deformation. From this table it can be seen that the inclinometer detected movement before unprocessed TDR data at MEG 338-B-2 and MEG 124-B-1, but the processed

TDR data indicated movement well before unprocessed TDR in all cases, but later than slope inclinometer only at MEG 338-B-2.

Table 4.2 - Depth of Movement and Date of Detection Comparison

DATE	338-B-1			338-B-2			124-B-1			124-B-2		
	INCL	raw TDR	proc TDR	INCL	raw TDR	proc TDR	INCL	raw TDR	proc TDR	INCL	raw TDR	proc TDR
10/02												
11/02				18’			30’		38'			
12/02			35'	18’		5,30'	30’		38'			
01/03			35'	18’		5,30'	30’		38'			43'
02/03			35'	18’		5,30'	30’	42’	38'			43'
03/03			35'	18’		5,30'	30’	31’	38'		41’	43'
04/03			35'	18’		5,30'	30’	31’	38'		41’	43'
05/03			35'	18’		5,30'	30’	31’	38'		41’	43'
06/03	16’	16’	35'	X 17’	18’	5,30'	X 30’	31’	38'		41’	43'
07/03	16’	16’	35'	X 17’	18’	5,30'	X 30’	31’	38'	40’	41’	43'
08/03	16’	16,38’	35'	X 17’	18’	5,30'	X 30’	31’	38'	40’	41’	43'
09/03	16’	16,38’	35'	X 17’	18’	5,30'	X 30’	31’	38'	40’	41’	43'
10/03	16’	16,38’	35'	X 17’	18’	5,30'	X 30’	31’	38'	40’	41’	43'
11/03	15’	16,38’	35'	X 17’	18’	5,30'	X 30’	31’	38'	40’	41’	43'
12/03	15’	16,38’	35'	X 17’	18’	5,30'	X 30’	31’	38'	40’	41’	43'

Depth of Movement in Feet (1 foot = 0.3048 meters)

X Indicates Shear Failure of Inclinometer Casing

The monthly climatic data from the National Oceanic and Atmospheric Administration (NOAA) [27] for the monitoring period can be found in Table 4.3. Figure 4.19 and Figure 4.20 plot the monthly precipitation and temperature from NOAA for Ohio during the monitoring period.

Table 4.3 – Ohio Climatic Data from NOAA [27] (1 in =2.54 cm)

Month	Precipitation (in)	Temperature (°F)
October 2002	3.09	52.0
November 2002	3.04	40.4
December 2002	2.79	30.9
January 2003	1.67	21.8
February 2003	3.00	25.6
March 2003	2.16	41.2
April 2003	2.62	52.2
May 2003	6.89	59.6
June 2003	4.11	66.2
July 2003	6.67	71.9

August 2003	5.13	72.6
September 2003	5.94	62.7
October 2003	2.38	51.8
November 2003	3.63	46.1
December 2003	2.60	32.8

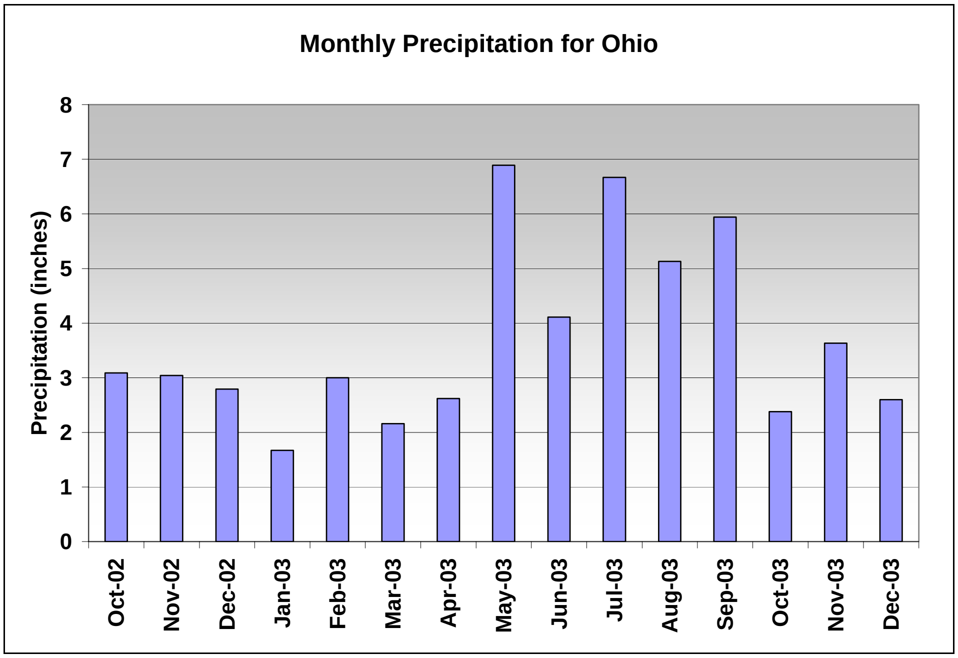


Figure 4.19 – Ohio Monthly Precipitation from NOAA [27] (1 in = 2.54 cm)

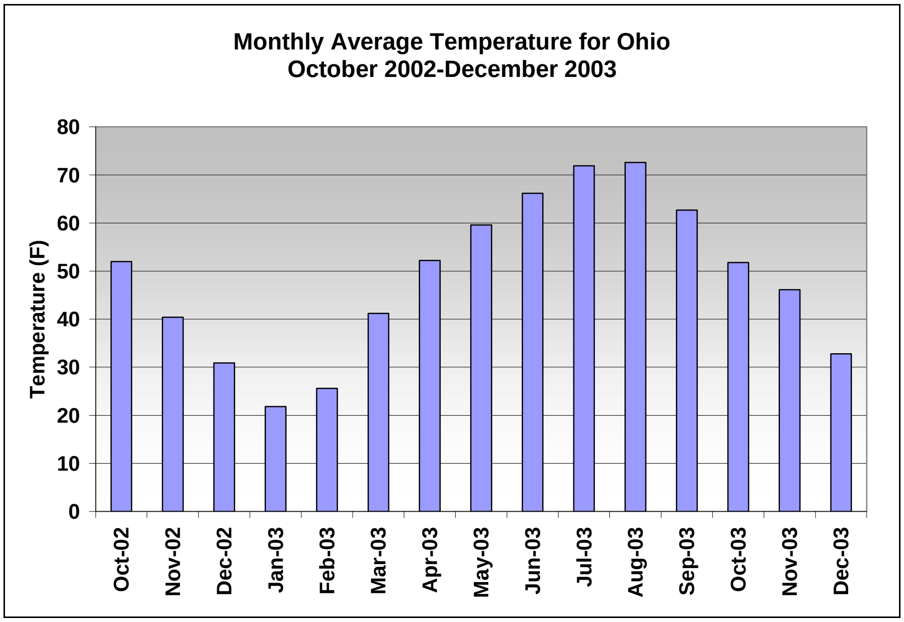


Figure 4.20 – Ohio Monthly Temperature from NOAA [27]

Landslides can have several causes, such as rainfall, snowmelt and rapid drawdown. Rainfall decreases the strength of soil. In *Geology for Engineers and Environmental Scientists* [25], Kehew states:

"Rainfall causes a rise in the water table within the soil and increases the pore pressure throughout the [soil]. ... After rainfall, the effective stress decreases because of the increase in pore pressure. [The] strength of the soil along a potential failure plane is therefore lower."

Snowmelt and rapid drawdown also decrease the strength of soil. According to TRB Special Report 247:

> "Rapid melting of a snowpack caused by sudden warming spells or by rain falling on snow can add water to hillside soils. ... Snowmelt may also recharge shallow fractured bedrock and raise pore-water pressures beneath shallow soils, thus triggering landslides. ... The sudden lowering of the water level (rapid drawdown)

against a slope can trigger landslides on the banks of lakes, reservoirs, canals, and rivers. Rapid drawdown can occur when a river drops following a flood stage... Unless pore pressures within the slope adjacent to the falling water level can dissipate quickly, the slope is subjected to higher shear stresses and potential instability. ... Thick uniform deposits of low-permeability clays and silts are particularly susceptible to land sliding triggered by rapid drawdown." [28]

The climatic NOAA data was compared to the detected movement to help determine why the slopes experienced movement. The TDR cables at the MEG-124 site first experienced cable deformation in February and March of 2003. January and February 2003 had an average monthly temperature below freezing, whereas March 2003 had an average monthly temperature well above freezing. The detected slope movement may have been caused by an increase in water infiltration and pore pressures from the soil thawing after the freezing temperatures in January and February. The TDR cables at the MEG-338 site first experienced cable deformation in June 2003. The readings were taken at the beginning of June, just after nearly seven inches of precipitation fell in the previous month. The heavy rain may have saturated the soil and led to the slope movement. Additionally, the river elevation may have risen and fallen quickly within the month of May. The water in the clay soil at the site may not have been able to dissipate quickly enough and therefore contributed to the decrease in soil strength.

4.6 Reliability

The TDR cables and inclinometers detected the shear planes at nearly the same depth at all test locations. The depth of movement detected for the two methods was within one foot for all test sites. The depth of movement was easily determined by the TDR method. Water intrusion in the cable end from shear damage caused some cable traces to deteriorate. Shearing of the cable may damage the cable and affect the traces, but unlike inclinometer casing shear failure, cable shear does not put any additional equipment at risk. Inclinometer casing shear requires skilled data acquisition operators to ensure the inclinometer probe does not become stuck in the deformed casing.

There was only one instance where readings were unable to be taken due to site access restrictions. Regrading at the MEG 338-B-2 site prohibited the reading of the inclinometers and cables in May 2003. The cable and inclinometer were unburied and readings resumed the following month. Flooding at the MEG 124 site prevented the crews from accessing the instrumentation in January 2004, however at the time there was only one readable inclinometer remaining at the site.

CHAPTER 5: COST ANALYSIS

The objectives of the study included a comparison of the TDR cables and inclinometers not only on their performance for detecting shear planes, but also on the basis of cost, ease of installation and ease of data collection. Detailed logs were kept during installation and monthly readings to allow comparison of time allocated to each task.

5.1 Itemized Materials

The materials used in the installation of the TDR cables and inclinometers were recorded. Table 5.1 shows the materials used and their cost for the inclinometer casings installation. Table 5.2 shows the materials used and their cost for the TDR cables installation. The total cost for all materials for the four inclinometer casings installation was $1936 and the cost for the four TDR cables was $1264.

Table 5.1 - Materials for Inclinometer Installation

Material	Cost
25 – 10 ft sections RST Glue & Snap Inclinometer Casings and Casing Top & Bottom Caps	$1478
4 – PVC Protective Top Casings	$48
Portland Cement	$104
Bentonite	$95
ABS 771 Cement	$10
Miscellaneous items	$201
Total Cost	$1936

Table 5.2 - Materials for TDR Cable Installation

Material	Cost
500 ft Belden RG59/U Coaxial Cable	$575
4 – BNC Connectors	$8
3M Scotchkote Electrical Coating	$25
Coaxial Cable Stripping Tool	$58
4 – PVC Protective Top Casings	$40
Portland Cement	$140
Bentonite	$115
Miscellaneous items	$303
Total Cost	$1264

The material cost per 40 foot depth for the inclinometers and TDR cables were $484 and $316 respectively, as seen in Table 5.3.

Table 5.3 - Materials Cost per 40 ft (12.2 m) Depth Installation

Materials per 40 ft (12.2 m) Depth	Cost
Inclinometer Casing	$484
TDR Cable	$316

The materials used in the installation are only part of the total cost. The data acquisition systems used to read the cables and casings are outlined in Table 5.4. The price of the TDR equipment is less than half the price of the inclinometer equipment. The TDR system also has the option of remote monitoring. Table 5.5 details the components needed to set up remote data acquisition.

Table 5.4 - Data Acquisition and Analysis Equipment

Equipment	Price
Slope Indicator Digitilt Inclinometer Probe	$5200
Probe Cable (200 ft (61 m)) + Connector	$2250
Slope Indicator Digitilt DataMate	$2900
Slope Indicator DigiPro Software (3 Users)	$895
Inclinometer Total	**$11,245**
Campbell Scientific TDR100 Unit + PCTDR Software	$3650
12V Battery + Charger	$260
Laptop (Connect to TDR100)	$1200
TDR Total	**$5110**

Table 5.5 –Components for TDR Remote Monitoring Setup

System Components	Price
Campbell Scientific TDR100 Unit + PCTDR Software	$3650
Campbell Scientific CR10X Datalogger	$1200
Campbell Scientific SDMX50 Multiplexer	$460
12V Battery + Charger	$260
Fiberglass 16”x18” Reinforced Enclosure	$400
Cellular Telephone Package	$650
Telephone Modem	$395
Laptop (Connect to TDR100)	$1200
TDR Total	$8215
Monthly Cellular access must also be provided	

Campbell Scientific component prices from 2002 U.S. Price List, Campbell Scientific, Inc.

It is important to note that the inclinometer system components are carried with the crew and used at many sites. For remote monitoring of TDR cables, the system components must be left on site. The cost of the on-site components for remote monitoring are approximately $7015 (Remote monitoring total setup minus the cost of the laptop). However, multiplexing allows for the analysis of many cables at one site, thereby decreasing the cost per cable. If ten cables are installed and connected to one TDR remote setup, the price per cable is reduced to approximately $825.

5.2 Ease of Installation and Data Collection

For this study, the inclinometers and TDR cables were both installed in 6 ¼ inch diameter borings using a hollow core soil auger. As was seen in the previous section, there is not a significant economical advantage of TDR cables over inclinometers in the installation process and materials. Both methods require the use of a skilled drilling crew for boring and soil analysis. The advantage of TDR is in the speed of data acquisition. The readings take less than a minute and can be easily automated and read remotely as was detailed in Table 5.5. Table 5.6 shows the labor comparison for the two methods. Both take 8-12 hours to drill the boring, collect soil samples, and install the casing or cable. The benefit is in the time saved by the data acquisition crew.

Table 5.6 - Labor Comparison for TDR Cables and Inclinometers

Item	Time
Time to Drill 40 foot boring and Install Inclinometer Casing	8 - 12 hours
Time to Drill 40 foot boring and Install TDR Cable	8 – 12 hours
Time to Read 2-Axes 40 foot Inclinometer Casing On-site	10 – 30 minutes
Time to Read 40 foot TDR Cable On-site	1 minute

If the TDR cables are installed and read remotely, the data acquisition crew only needs to visit the site at installation to setup the system. All other readings will be taken while sitting in the office. This is a significant reduction in the time required for data acquisition since the crew does not have to travel to the site to take readings Remote readings also ensure the safety of the crew if the cables have to be installed in an unstable or difficult to access site.

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CHAPTER 6: CONCLUSIONS & RECOMMENDATIONS

After sixteen months of monthly monitoring, the study showed a clear correlation in detection of the shear planes between the TDR cables and the slope inclinometers. The unprocessed TDR and inclinometers detected the shear planes at nearly the same depth at all test locations. The depth of movement detected for the two methods was within one foot for all test sites. The processed TDR detected movement at slightly different depths because the processing method emphasized the edge of the strained region rather than the middle. Alternative processing schemes can be easily devised to indicate the middle of the cable strain region corresponding to the soil shear plane.

Although the unprocessed TDR data cannot provide exact rate of movement, further processing potentially can. The TDR system can be more economical than slope inclinometer probing for basic identification of shear plane depth in slope movement analysis installations.

The coaxial cable for the TDR method costs less than inclinometer casing. TDR readings take less than a minute and can be easily automated and read remotely. Multiplexing cables in automated remote reading setups allows for analysis of many TDR cables at one site. This is a significant reduction in the time required for data acquisition since the crew does not have to travel to the site to take readings. Additionally, TDR cables can be extended to a convenient safer location away from the boring if necessary and slope movement can be determined immediately during data collection rather than waiting for data analysis in the office.

Identifying the location of shear planes with TDR cables is relatively straight forward, however, determining the magnitude of movement along them is not. The ability to interpret TDR monitoring data can be greatly improved by application of carefully selected signal processing techniques. In this case, taking the temporal-spatial derivative of noise-filtered TDR traces proved effective at elucidating slope failure earlier than visual inspection of raw data could discern.

TDR continued to provide useful monitoring capability long (several months) after nearby slope inclinometer installations had failed, but damage to the protective coating of the TDR cable can allow water intrusion, which changes the electrical properties of the cable making traces difficult to interpret.

By further analyzing TDR monitoring data, it may be possible to infer quantities of material mobilized or other information about a slope failure, possibly including intrinsic properties of the soils involved, useful for stabilization design

6.1 Recommendations

It is recommended to use smaller diameter auger bits for TDR cable installation, preferably under 3 in (7.6 cm). The 6¼ in (15.9 cm) bits were oversized for the small 0.2 in (5.1 mm) diameter coaxial cables. Additionally, ensuring the top-of-hole cable connectors are not submerged will increase the life span of the cable.

Since the signal processing chain applied here to processed TDR data was both sampling-interval dependent and time difference dependent, further experimentation and analysis are recommended to develop a more independent technique for detecting slope failure.

Further study is recommended to develop methods for inferring additional information and properties using TDR.

Further cost-benefit analysis of TDR versus slope inclinometer monitoring should consider low cost alternatives to drilling, such as direct push technology, for installing the TDR cable. Unlike slope inclinometer monitoring, the installation of TDR infrastructure does not necessarily require boring equipment, and combining TDR cable emplacement with Cone Penetration Testing (CPT) would be an efficient method for obtaining in-situ soil parameters as well.

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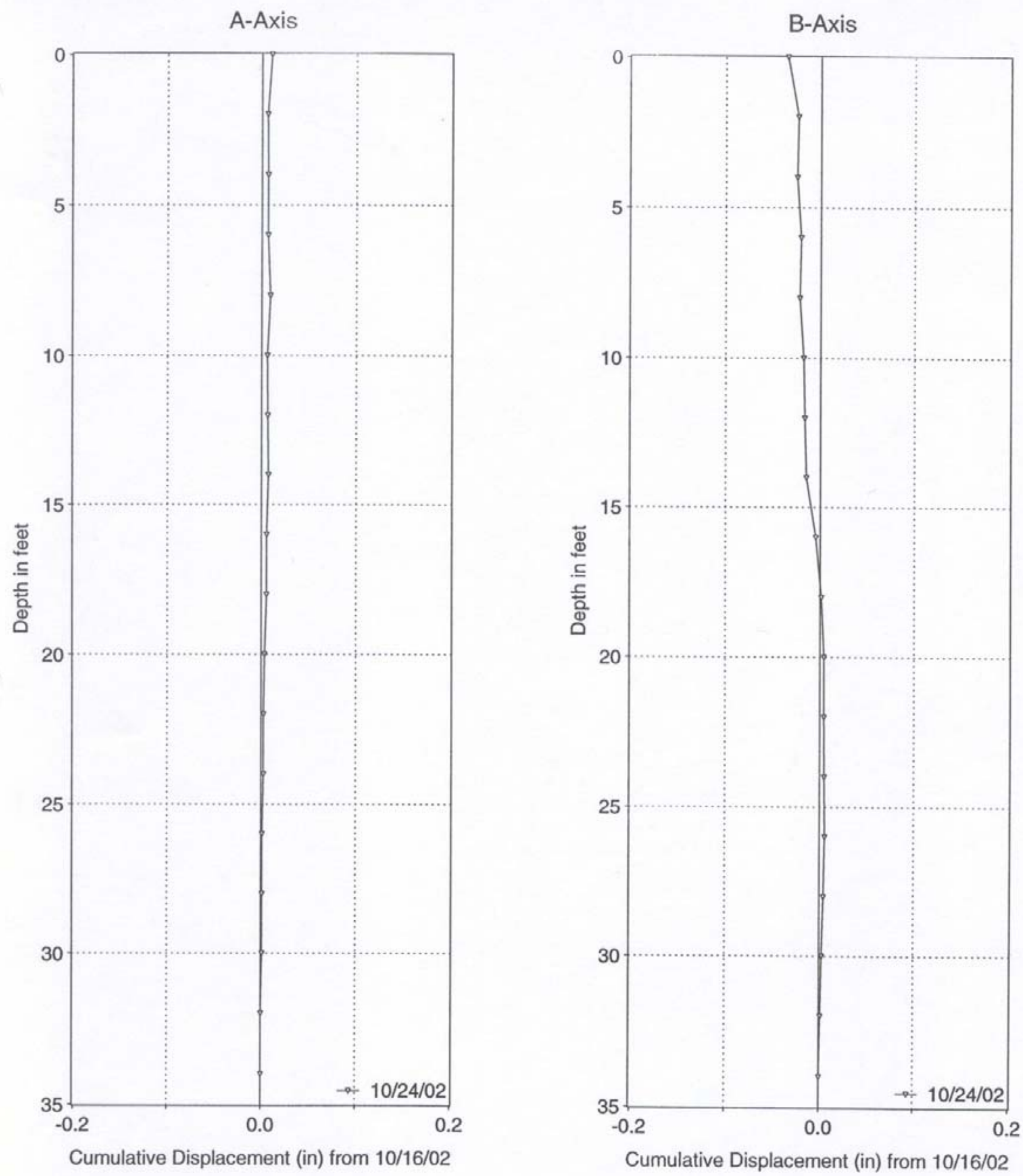
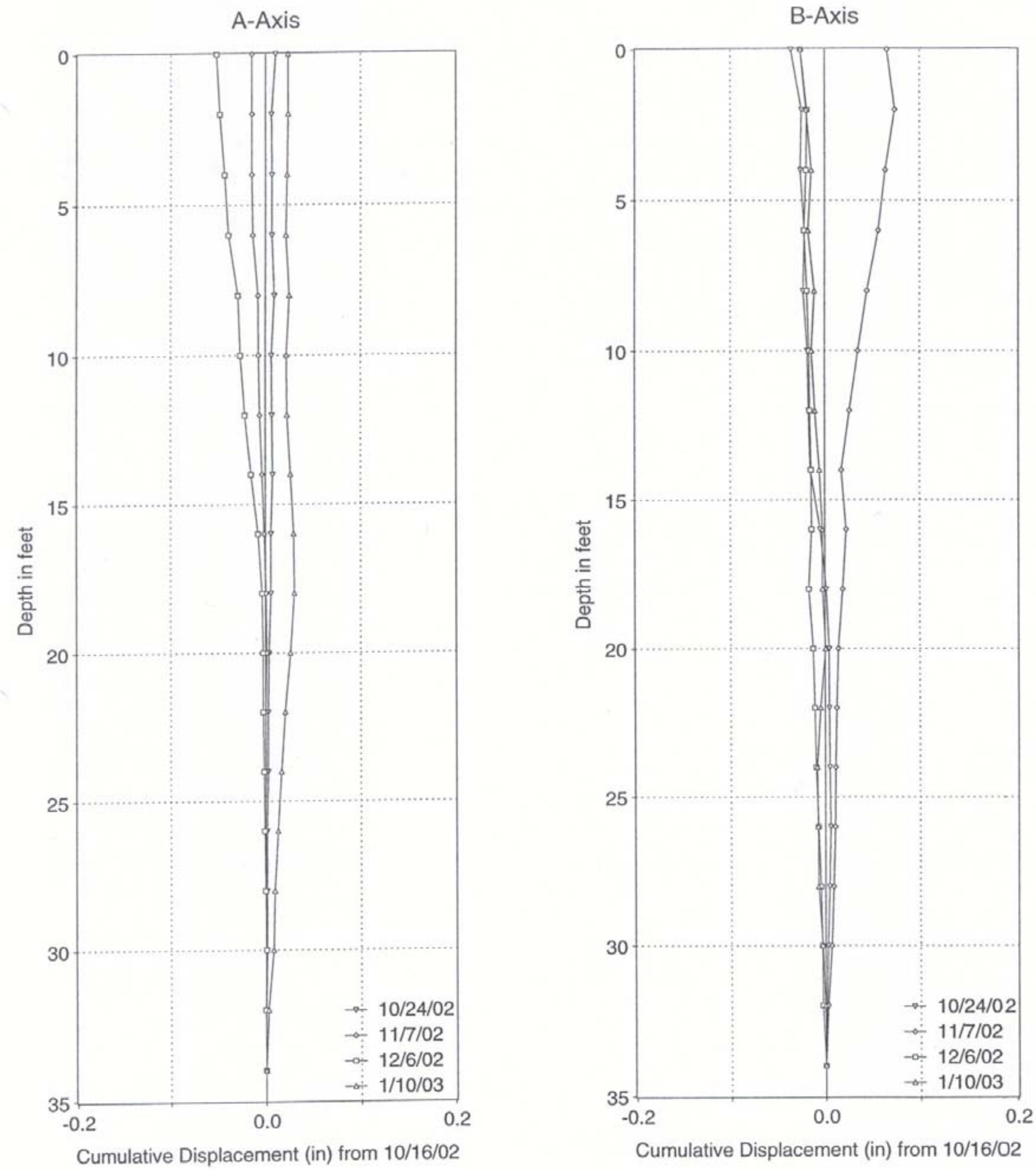
APPENDIX A – Inclinometer Readings



MEG-338-20.92
Slope Inclinometer Installation B-1

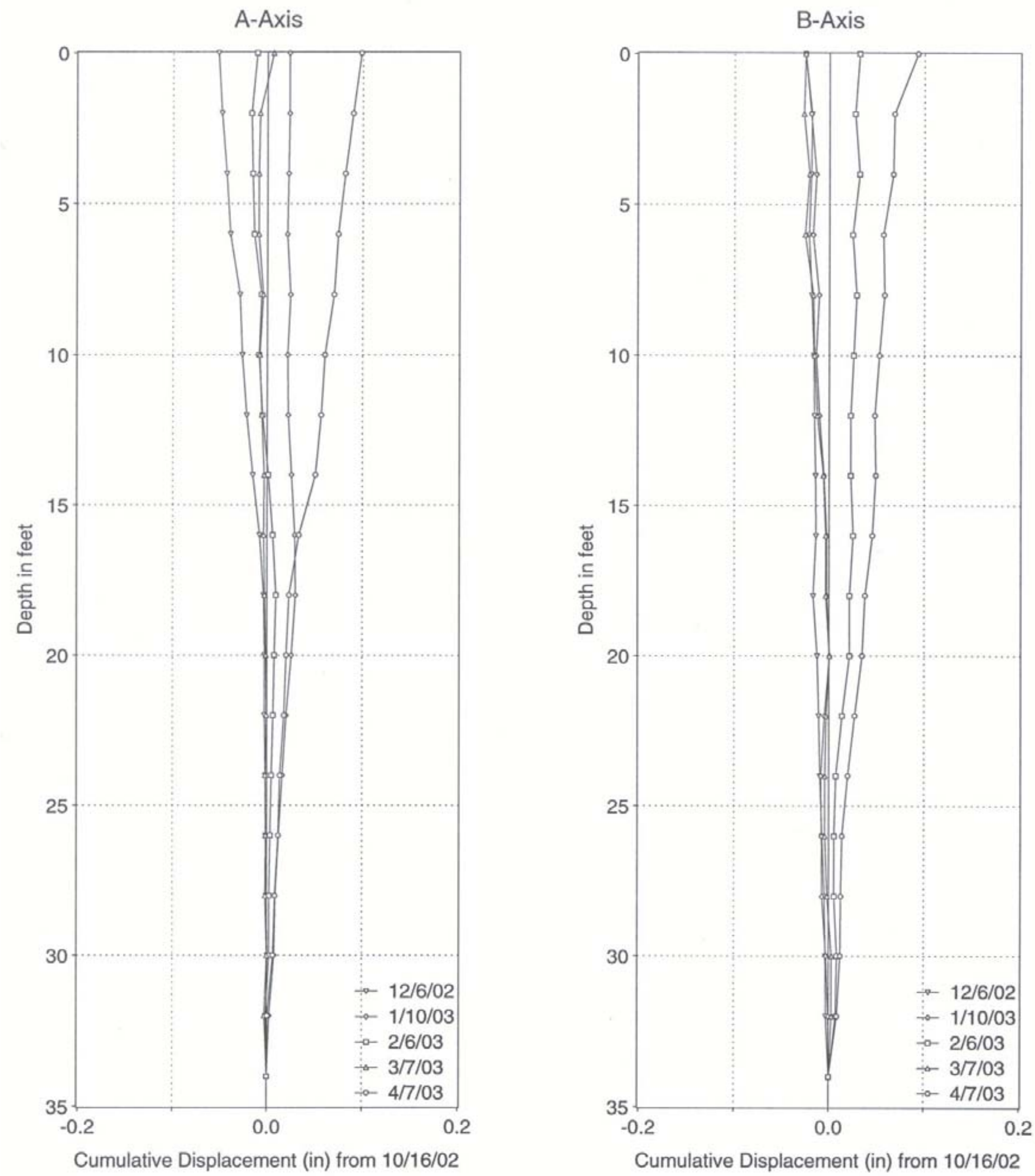
A-axis in direction of assumed movement



MEG-338-20.92

Slope Inclinometer Installation B-1

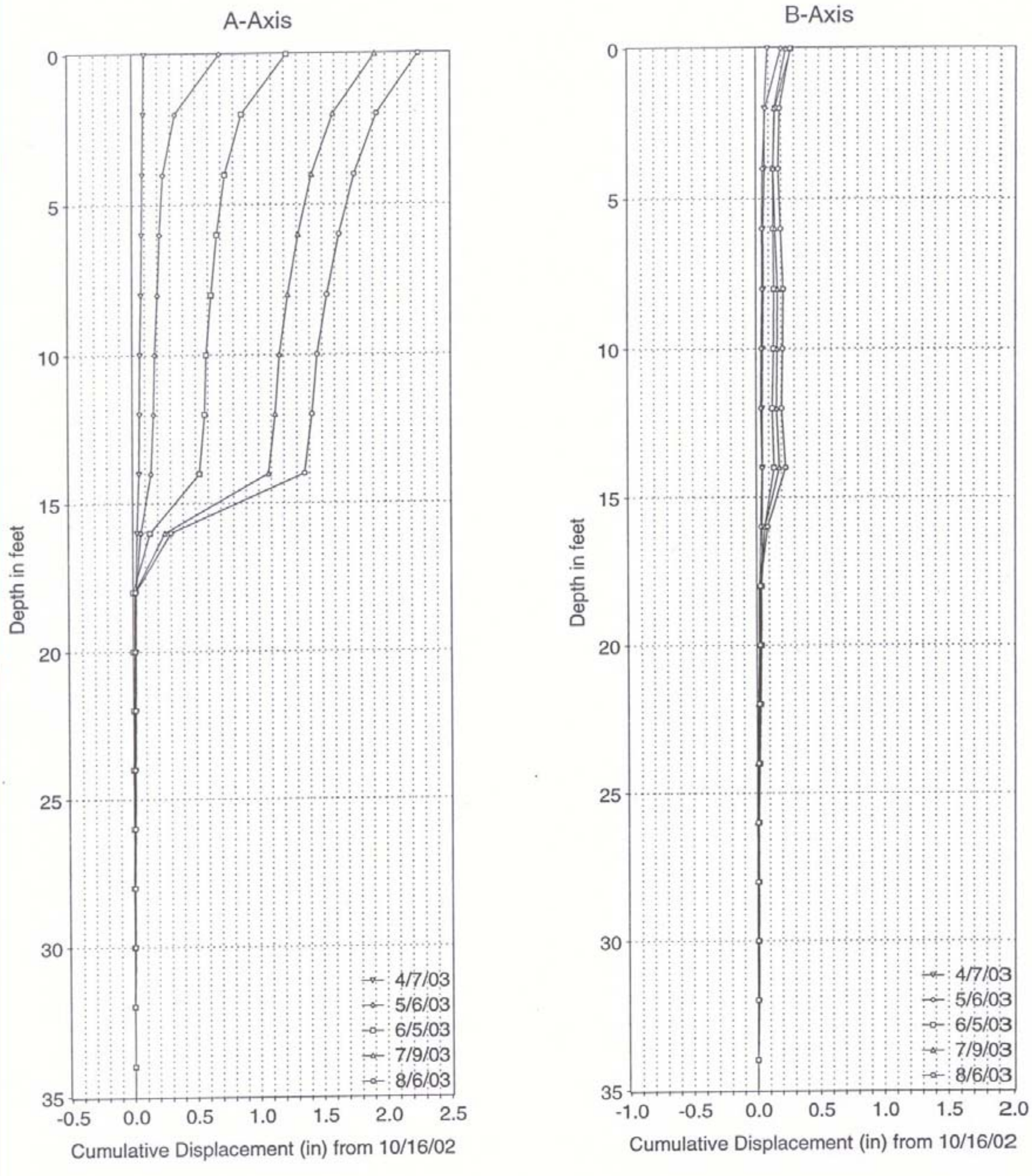
A-axis in direction of assumed movement



MEG-338-20.92

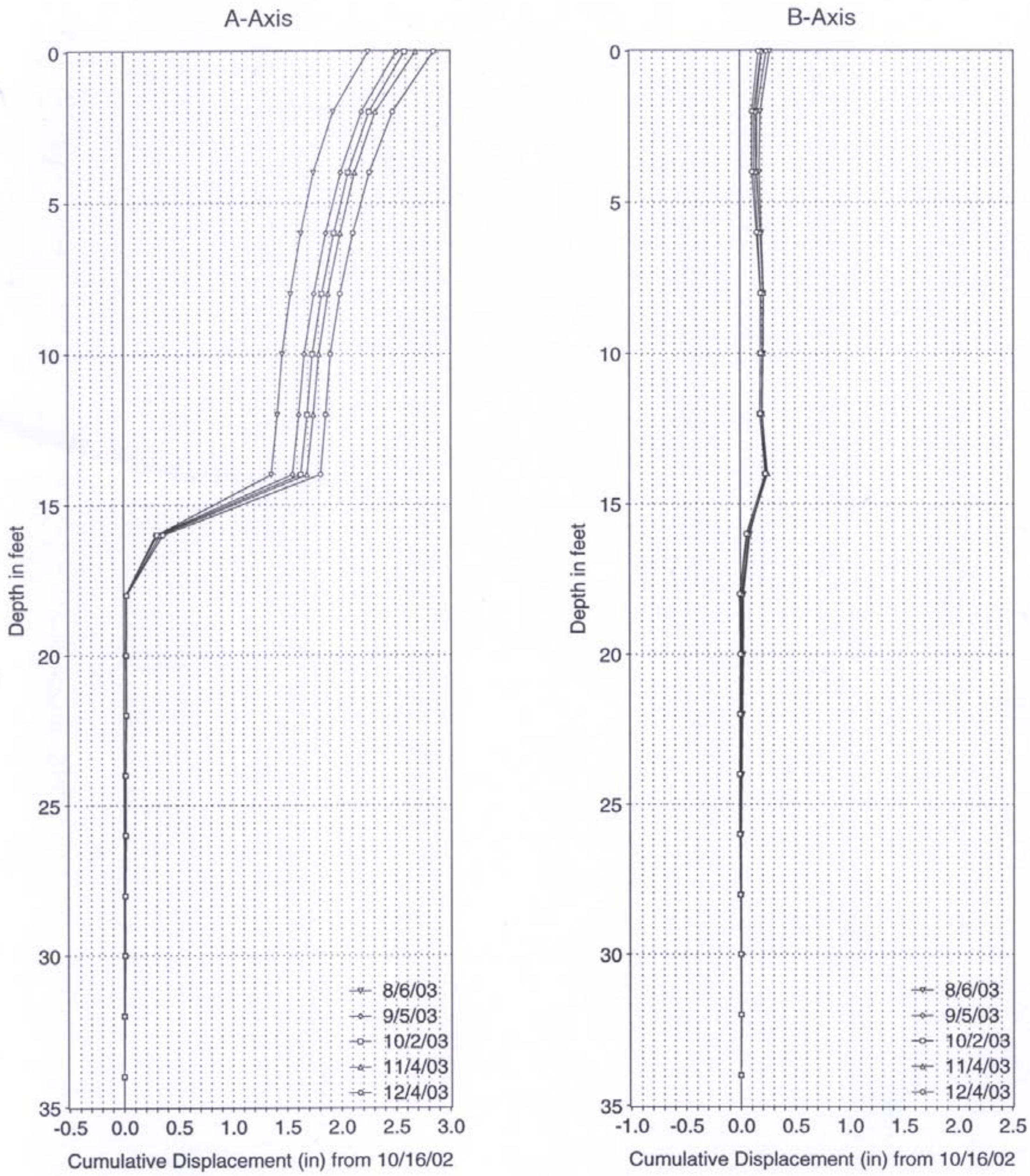
Slope Inclinometer Installation B-1

A-axis in direction of assumed movement



MEG-338-20.92
Slope Inclinometer Installation B-1

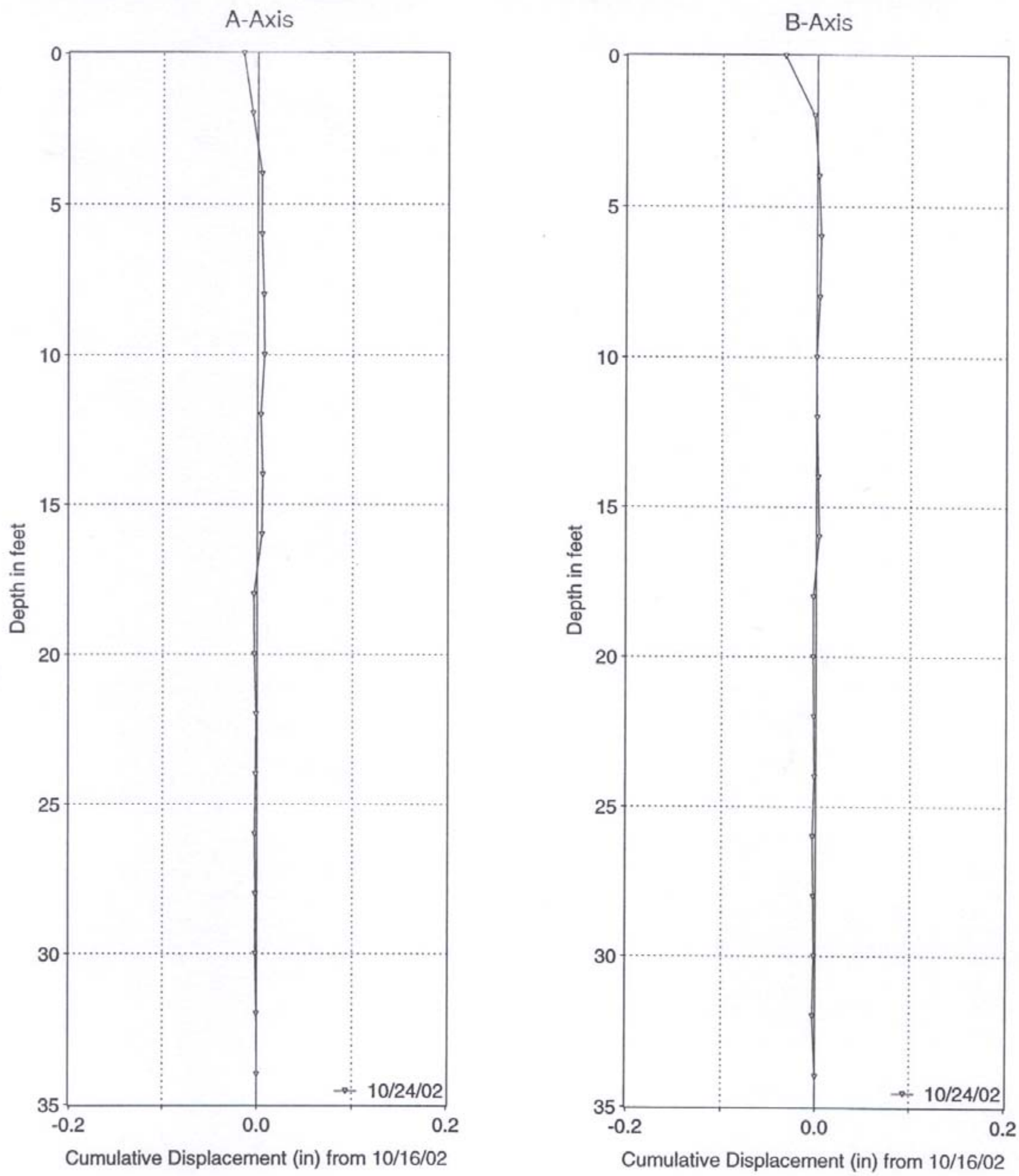
A-axis in direction of assumed movement



MEG-338-20.92

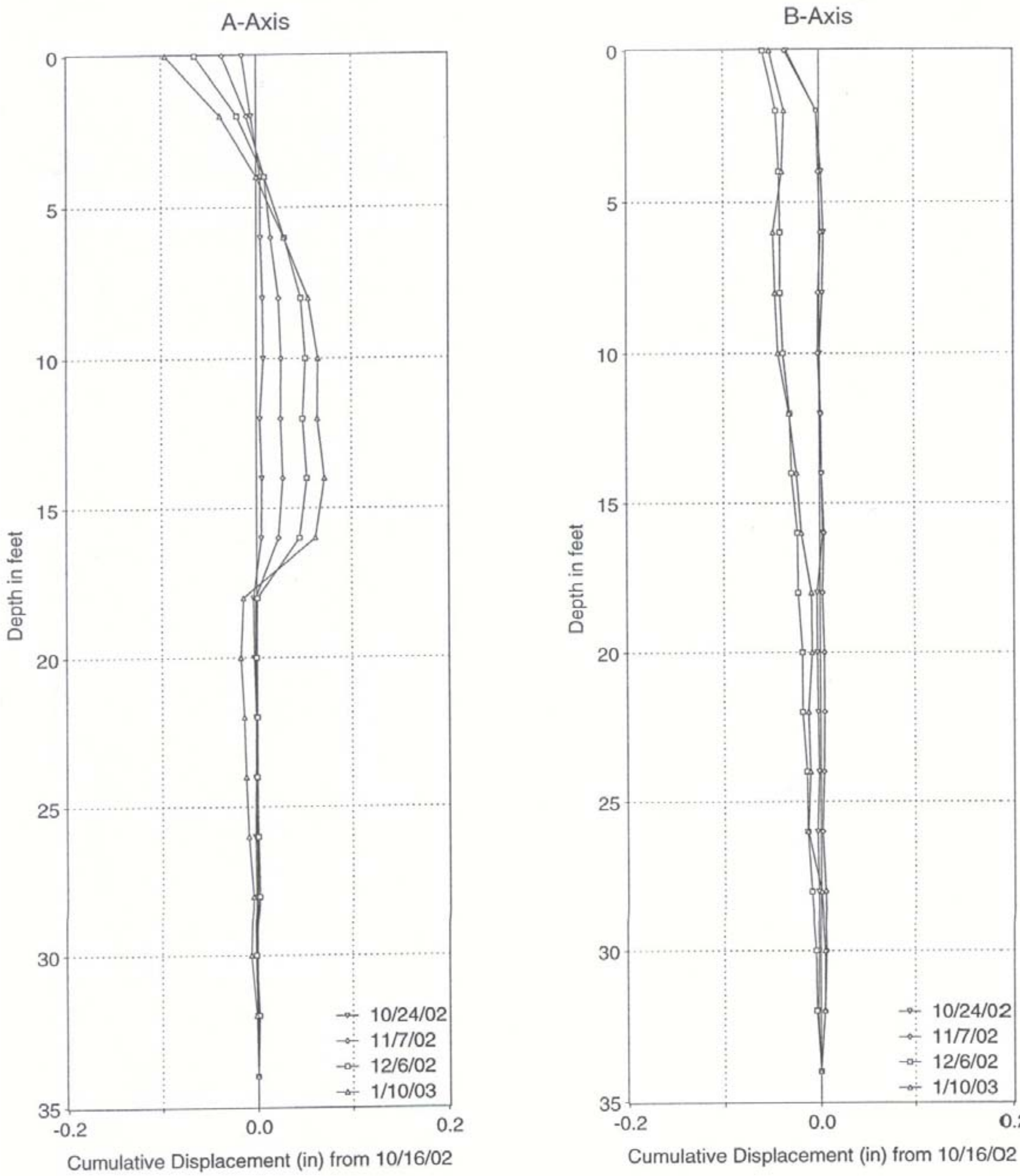
Slope Inclinometer Installation B-1

A-axis in direction of assumed movement



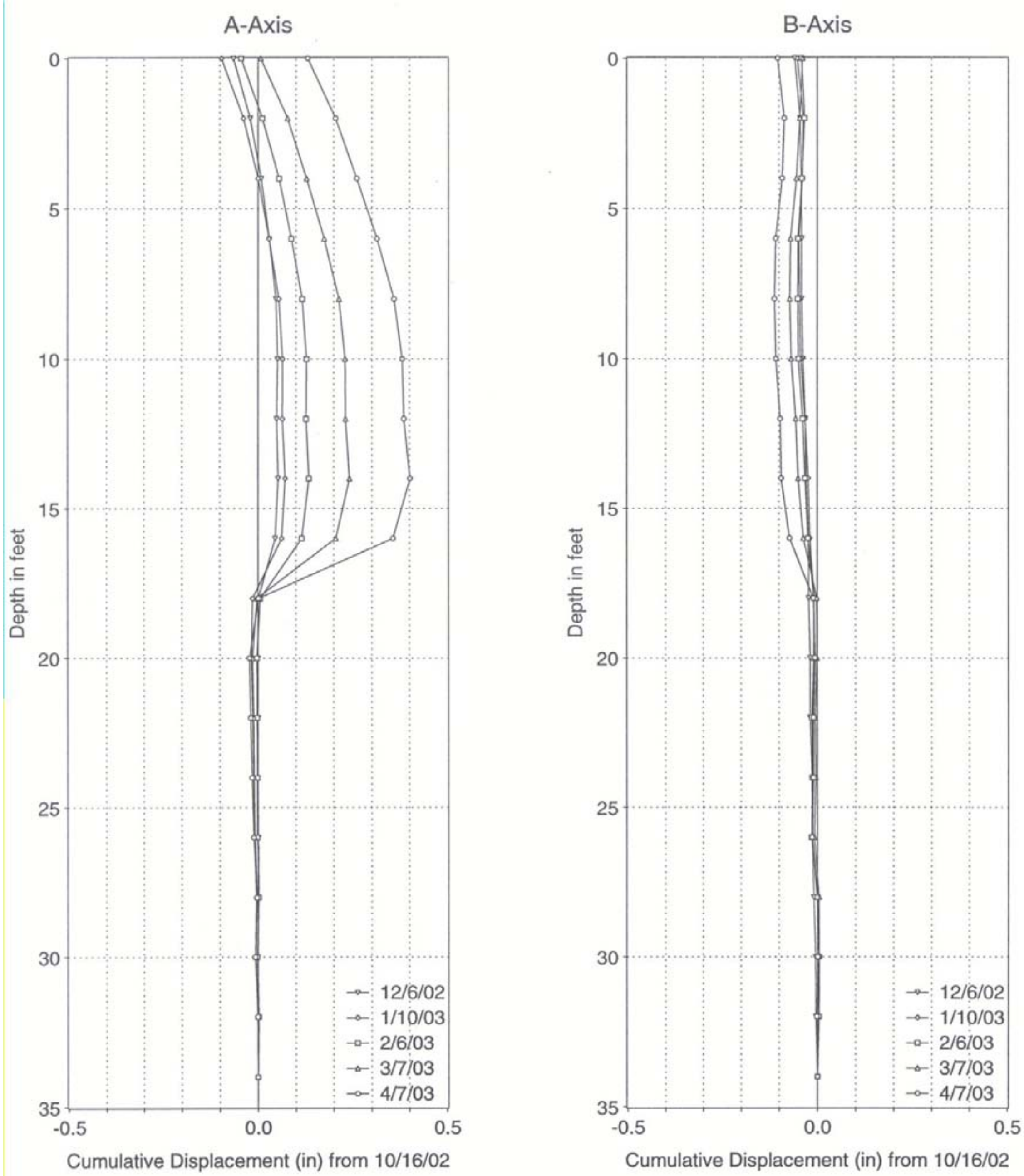
MEG-338-20.92
Slope Inclinometer Installation B-2

A-axis in direction of assumed movement



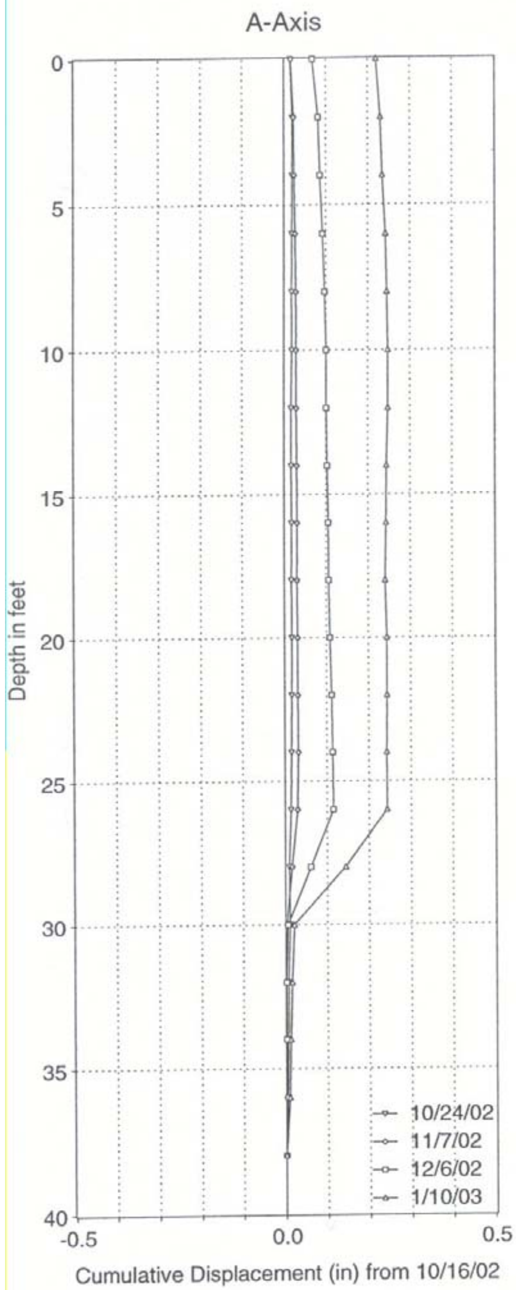
MEG-338-20.92
Slope Inclinometer Installation B-2

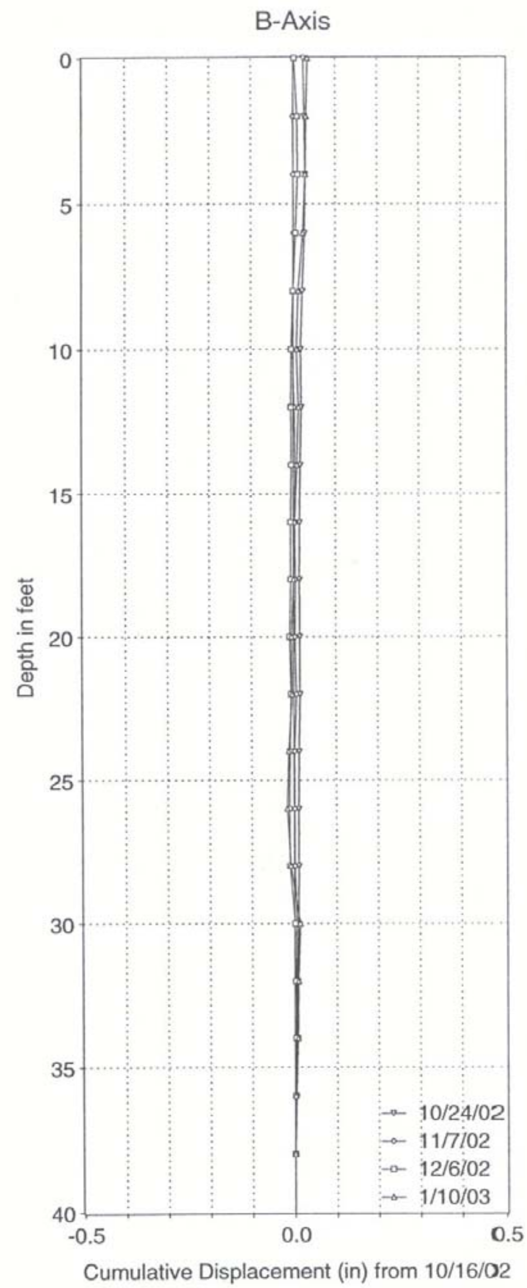
A-axis in direction of assumed movement



MEG-338-20.92
Slope Inclinometer Installation B-2

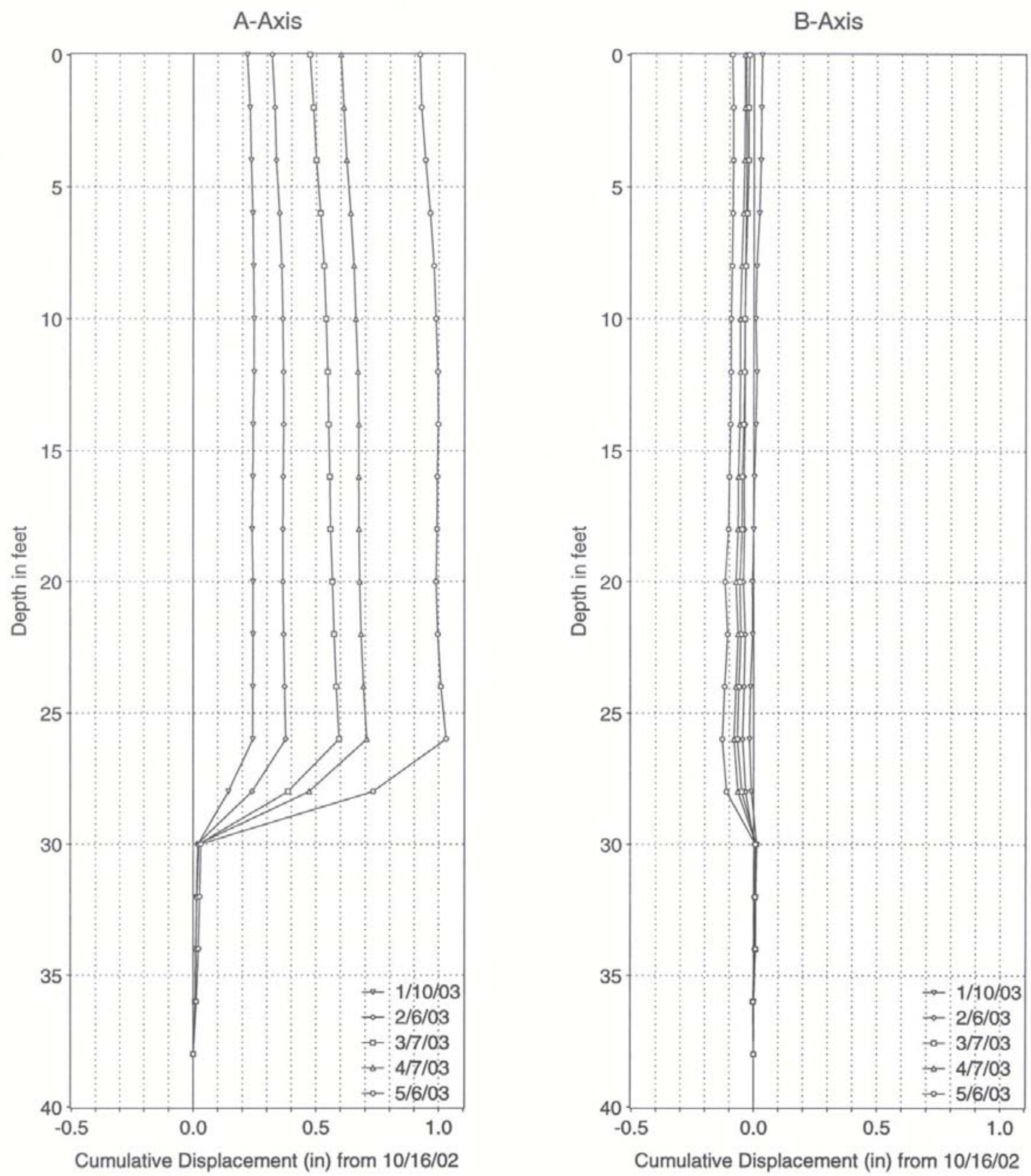
A-axis in direction of assumed movement





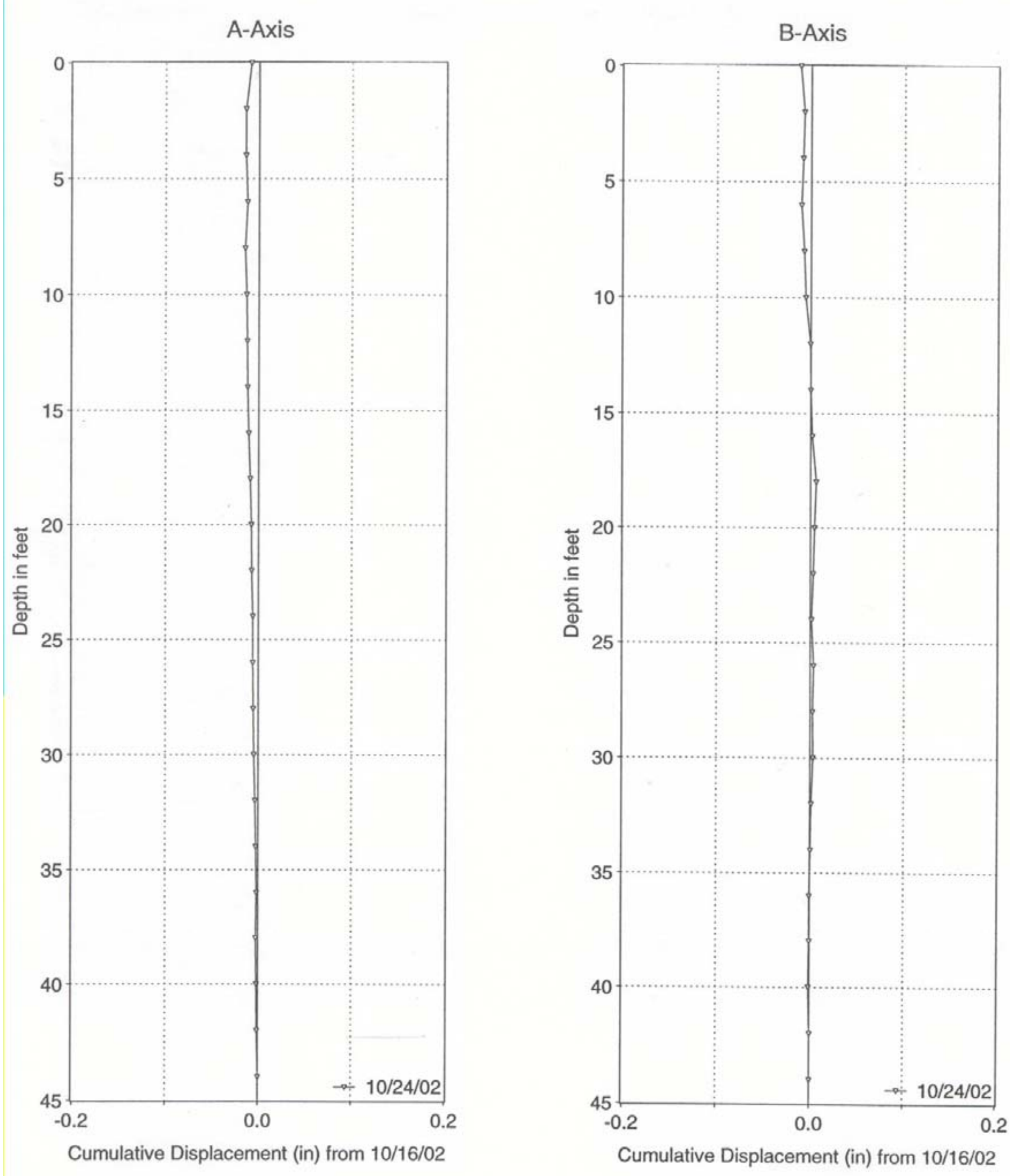
MEG-124-46.86
Slope Inclinometer Installation B-1

A-axis in direction of assumed movement



MEG-124-46.86
Slope Inclinometer Installation B-1

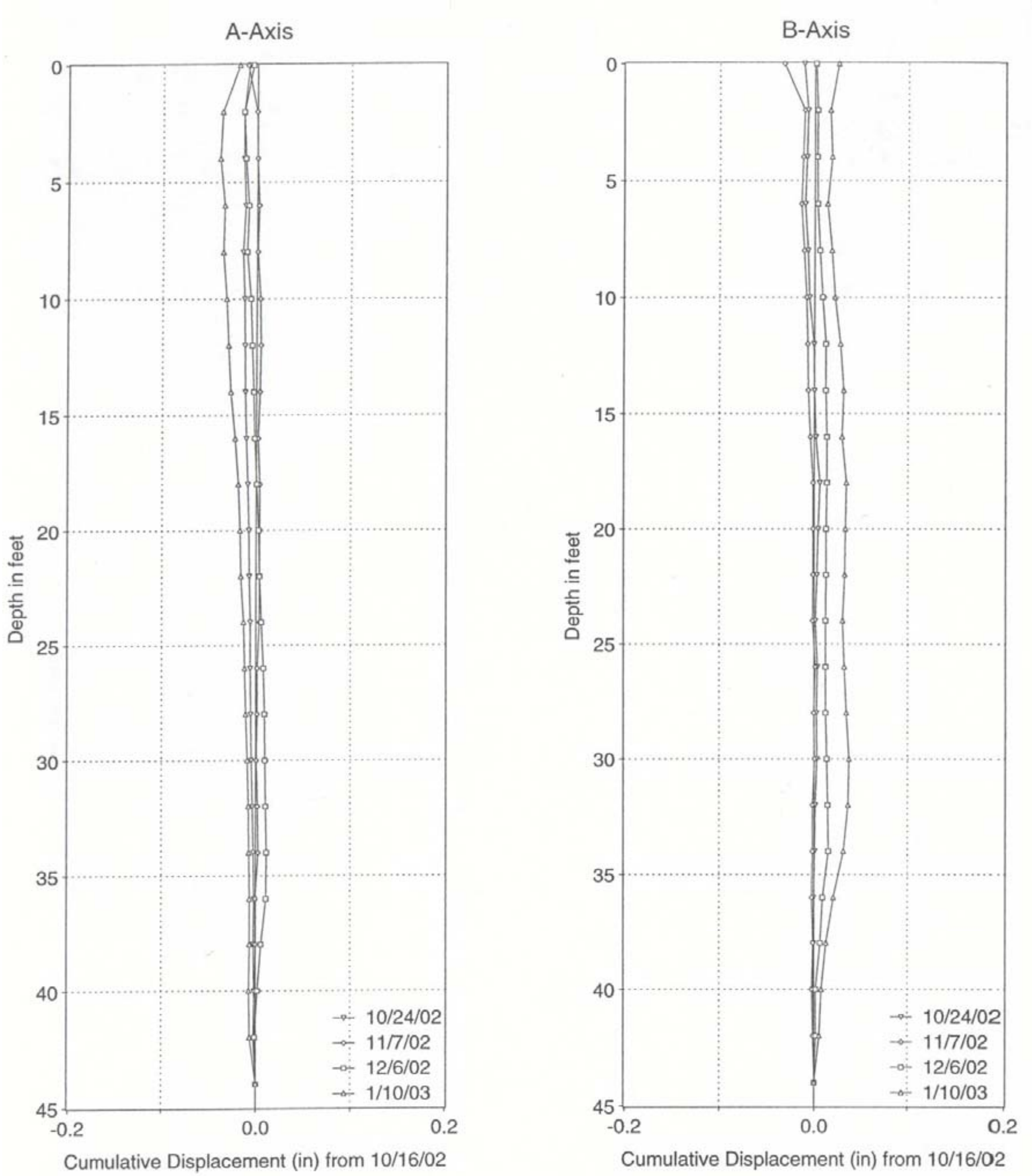
A-axis in direction of assumed movement



MEG-124-46.86

Slope Inclinometer Installation B-2

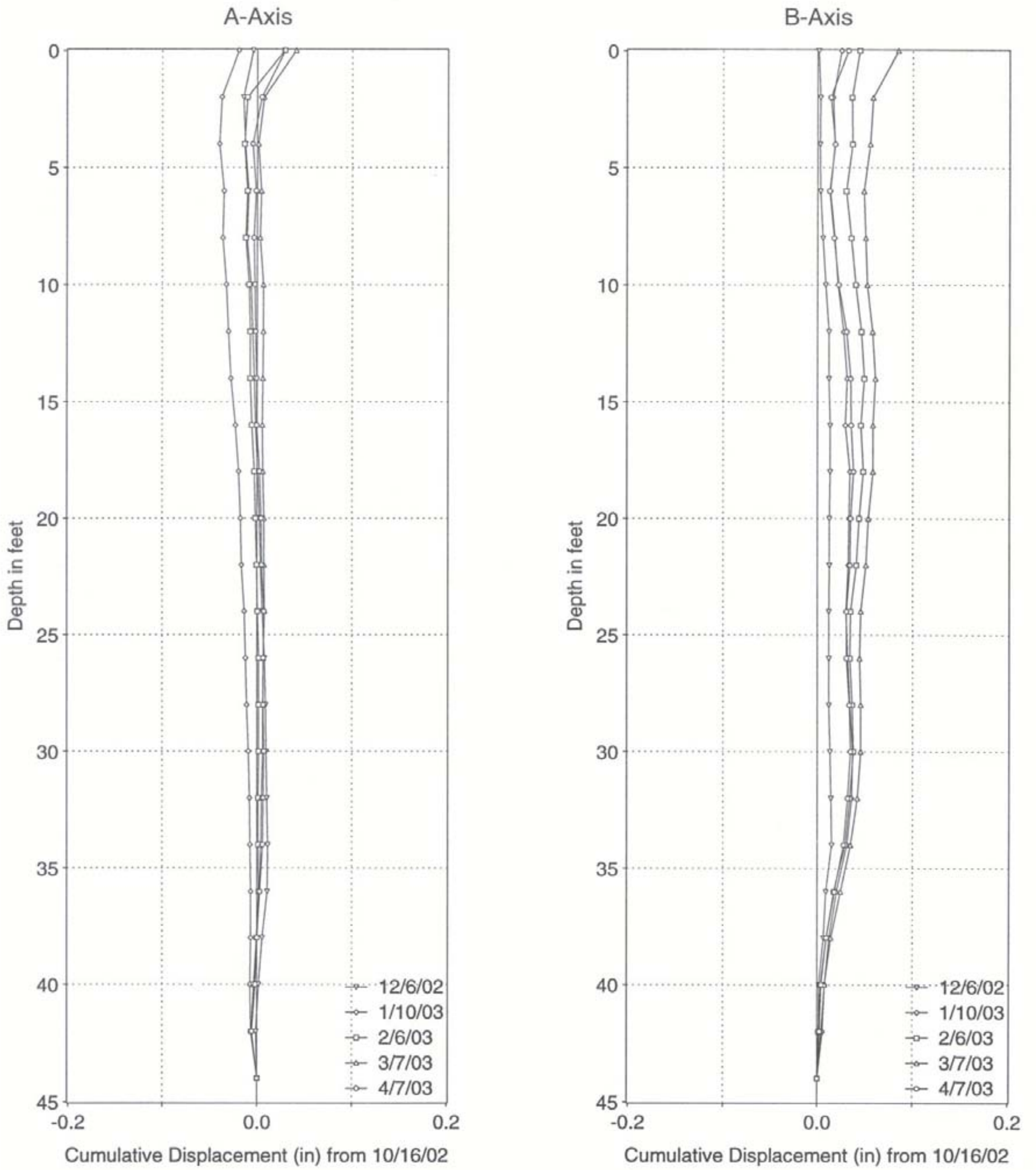
A-axis in direction of assumed movement



MEG-124-46.86

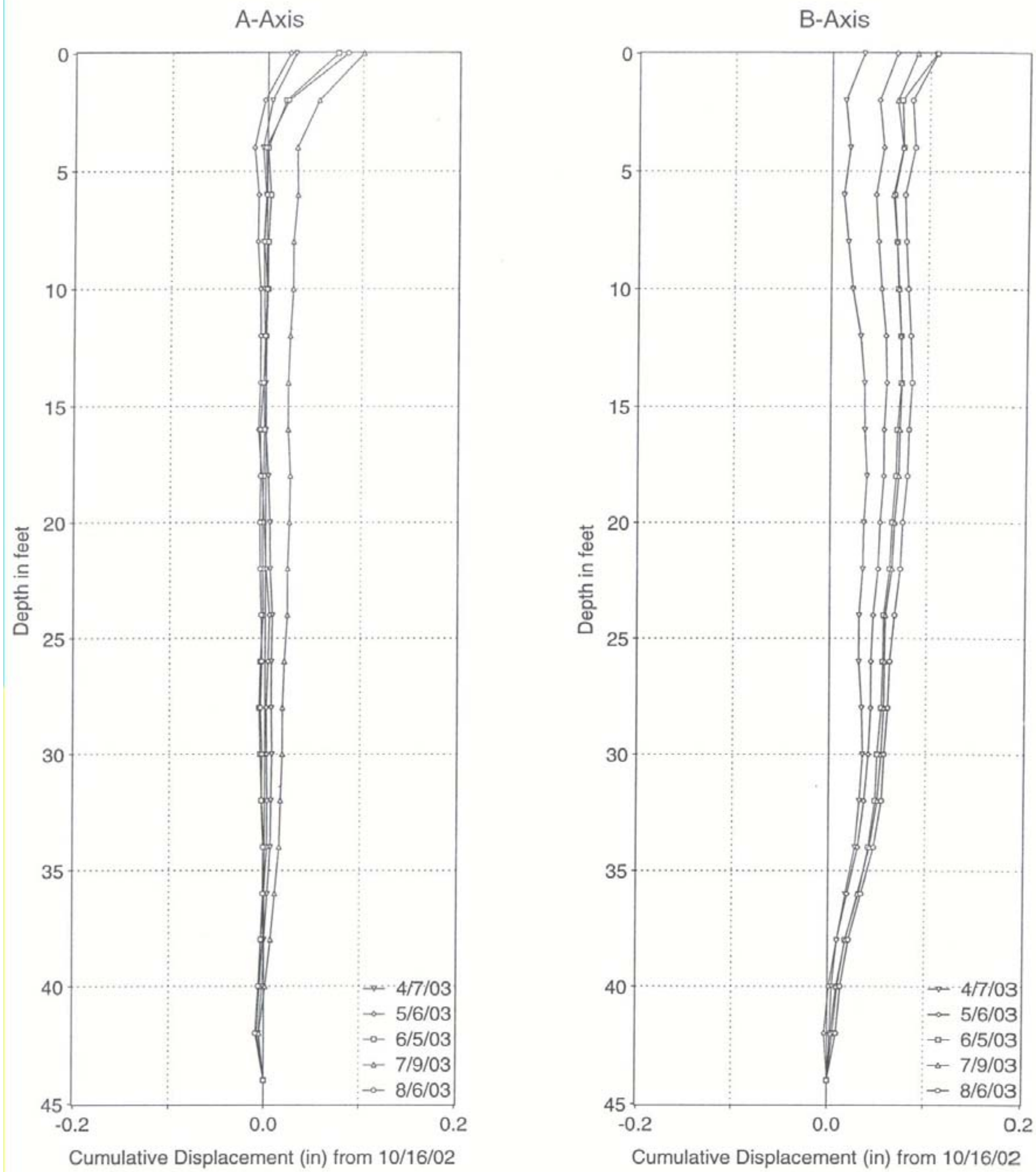
Slope Inclinometer Installation B-2

A-axis in direction of assumed movement



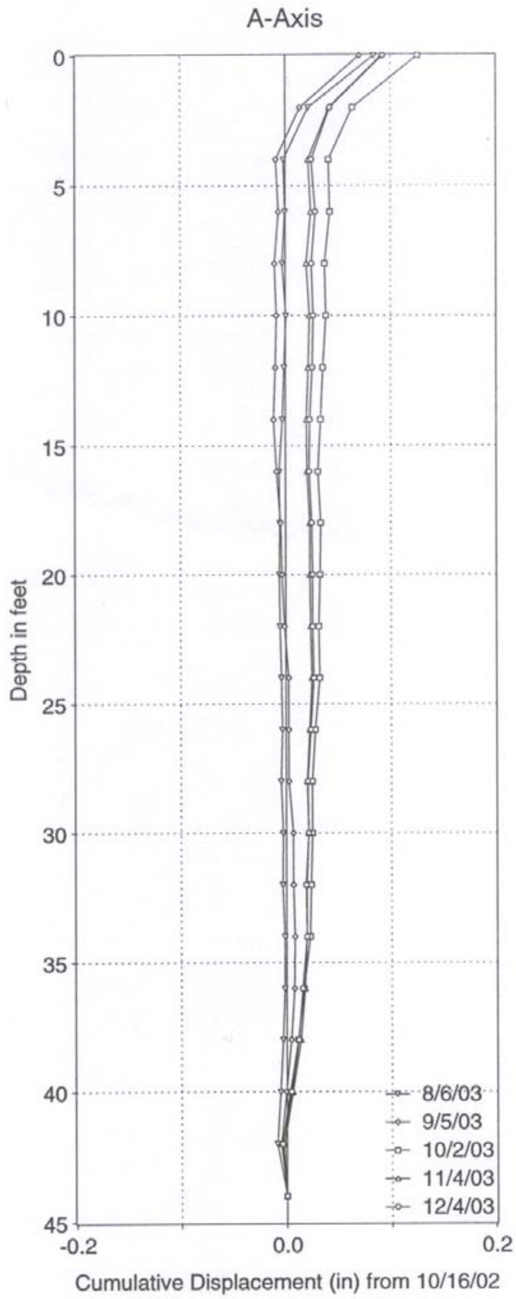
MEG-124-46.86
Slope Inclinometer Installation B-2

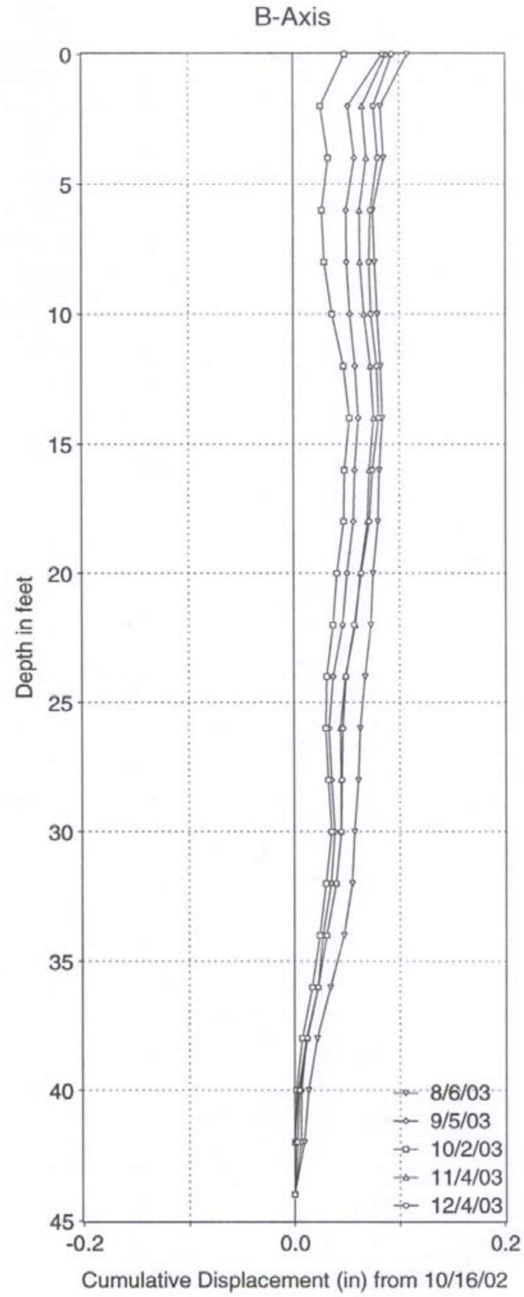
A-axis in direction of assumed movement



MEG-124-46.86
Slope Inclinometer Installation B-2

A-axis in direction of assumed movement

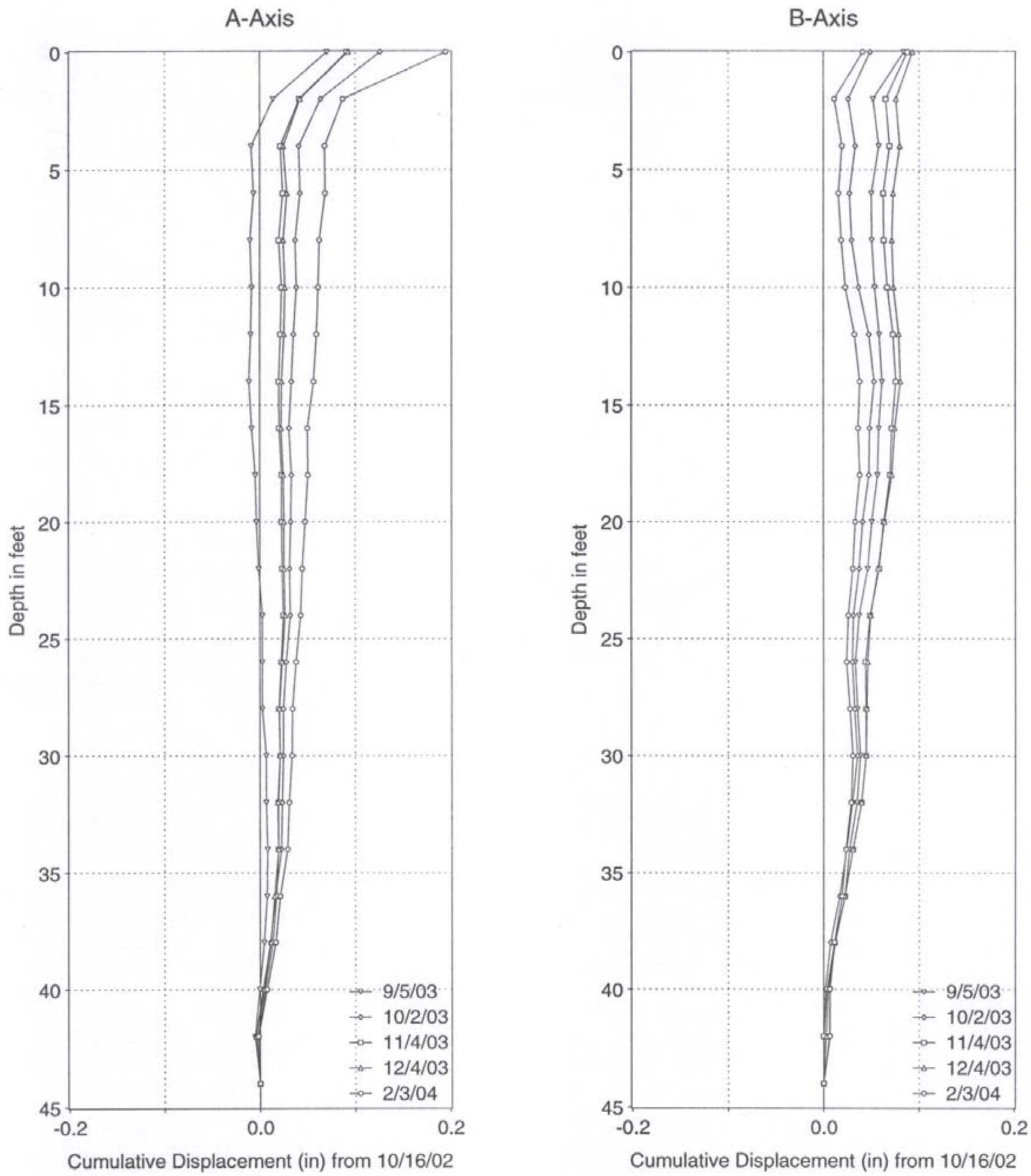




MEG-124-46.86

Slope Inclinometer Installation B-2

A-axis in direction of assumed movement

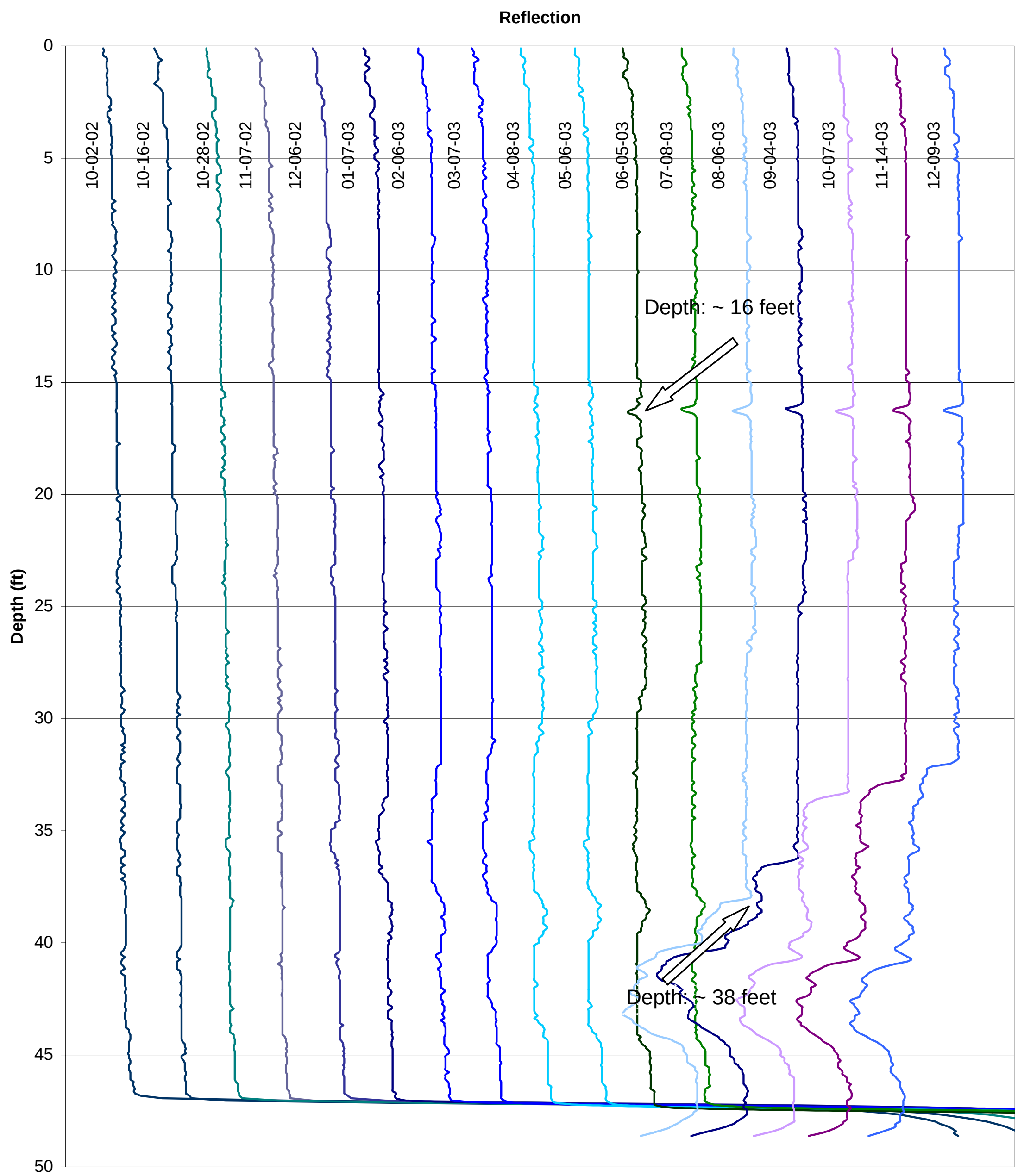


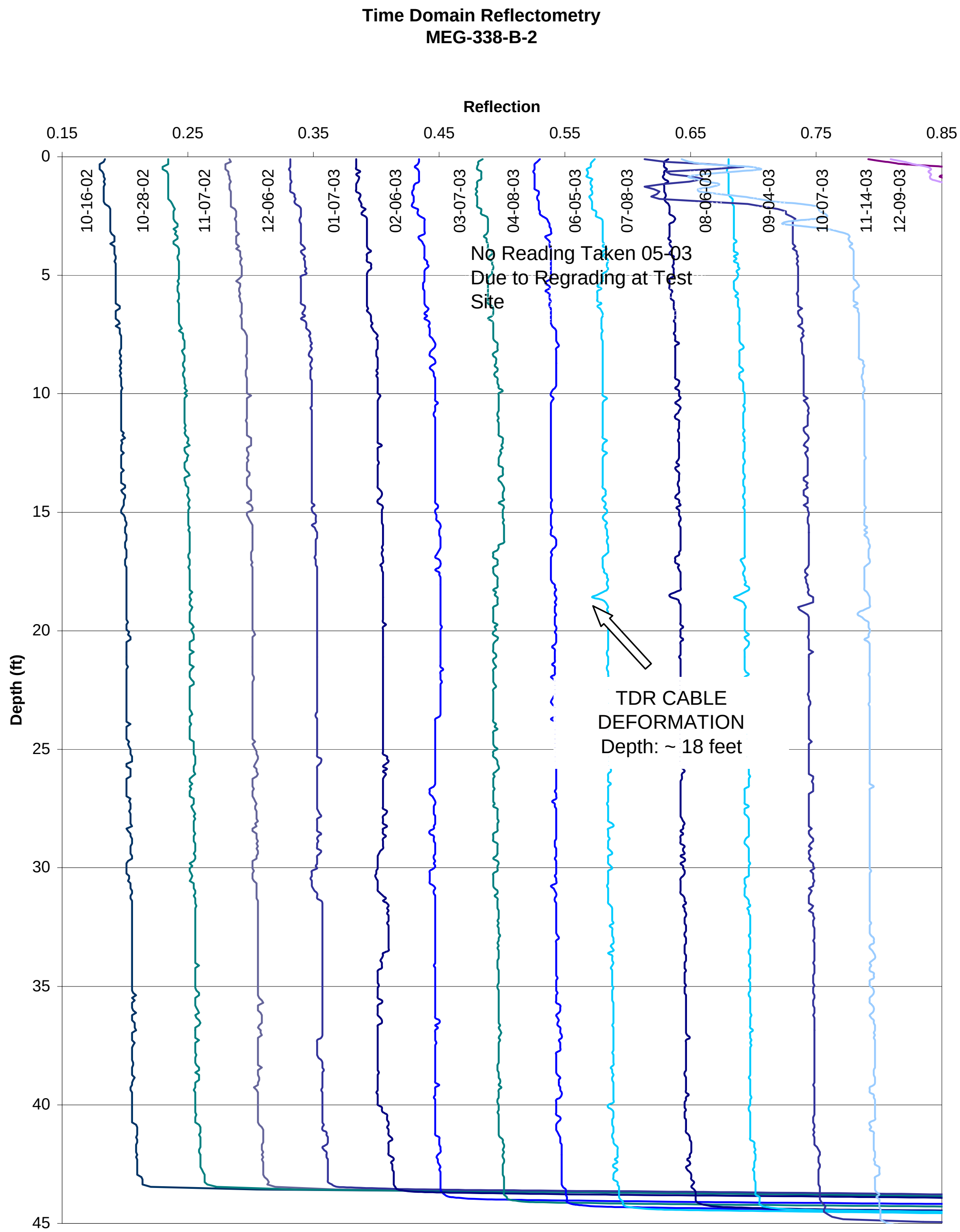
MEG-124-46.86
Slope Inclinometer Installation B-2

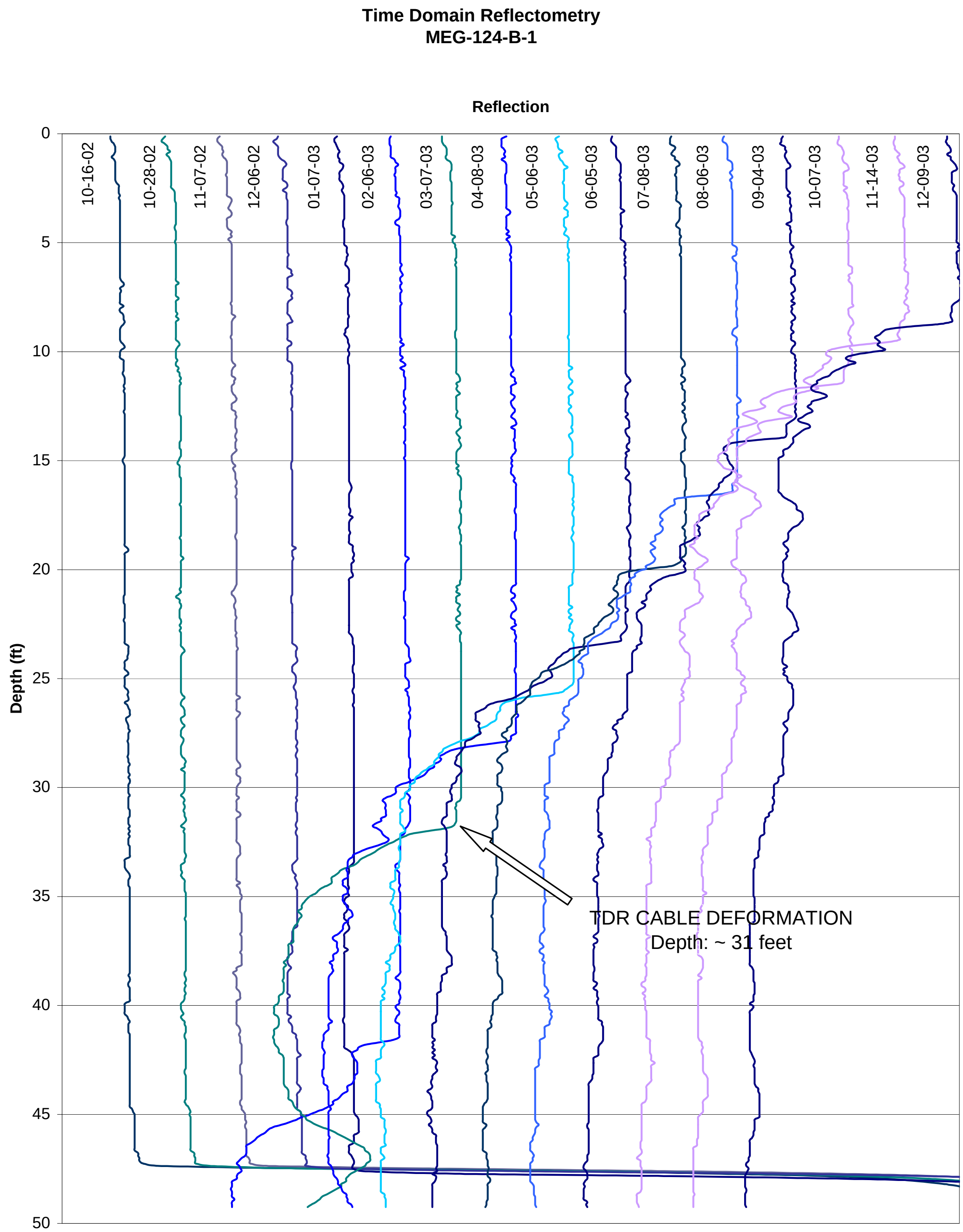
A-axis in direction of assumed movement

APPENDIX B – TDR Traces

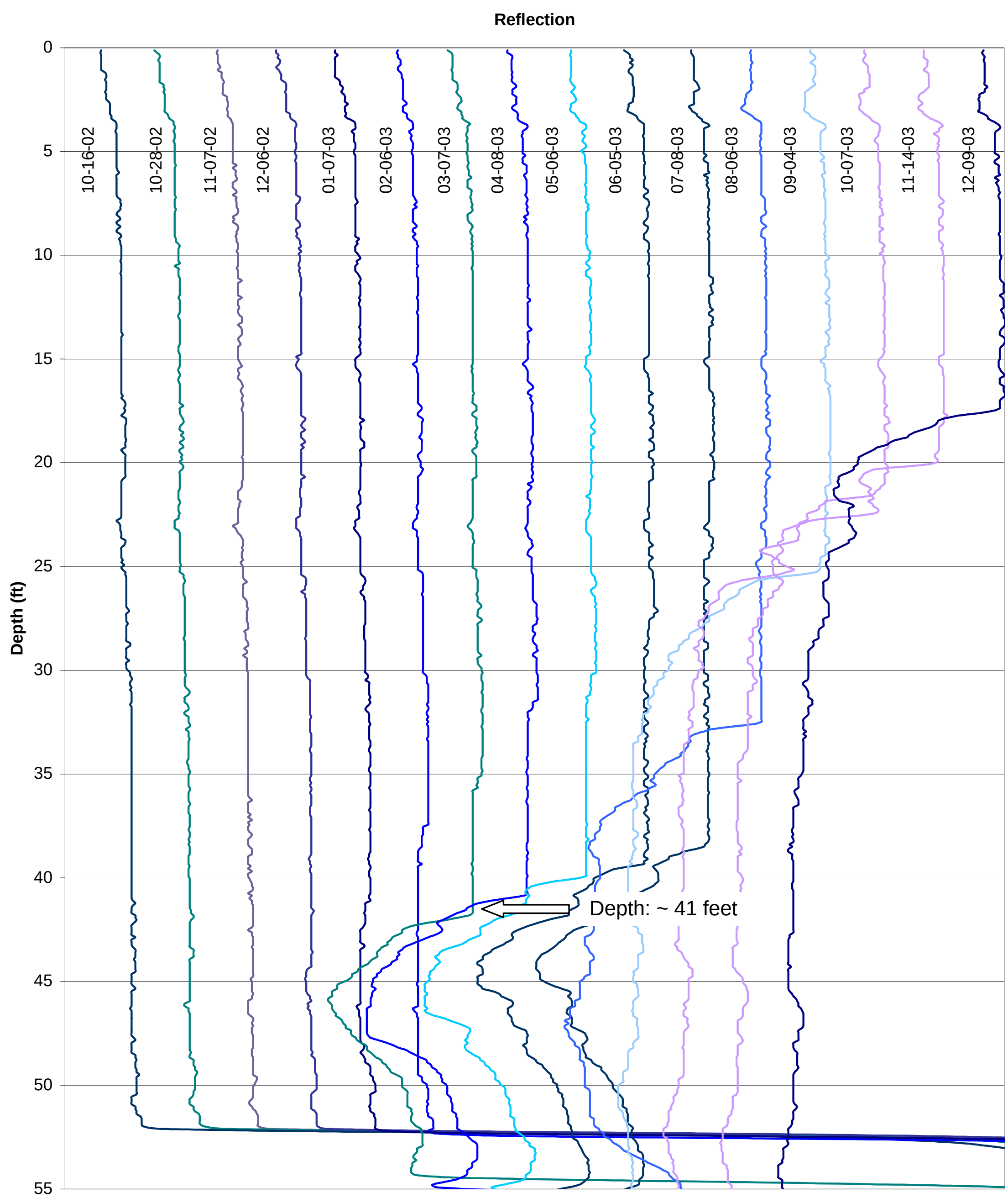
Time Domain Reflectometry
MEG-338-B-1




Time Domain Reflectometry
MEG-338-B-2
Reflection
0.15
0.25
0.35
0.45
0.55
0.65
0.75
0.85
Depth (ft)
0
5
10
15
20
25
30
35
40
45
10-16-02
10-28-02
11-07-02
12-06-02
01-07-03
02-06-03
03-07-03
04-08-03
06-05-03
07-08-03
08-06-03
09-04-03
10-07-03
11-14-03
12-09-03
No Reading Taken 05-03 Due to Regrading at Test Site
TDR CABLE DEFORMATION Depth: ~ 18 feet


Time Domain Reflectometry
MEG-124-B-1
Reflection
Depth (ft)
0
5
10
15
20
25
30
35
40
45
50
10-16-02
10-28-02
11-07-02
12-06-02
01-07-03
02-06-03
03-07-03
04-08-03
05-06-03
06-05-03
07-08-03
08-06-03
09-04-03
10-07-03
11-14-03
12-09-03
TDR CABLE DEFORMATION
Depth: ~ 31 feet

Time Domain Reflectometry
MEG-124-B-2



APPENDIX C – Boring Logs

State of Ohio
Department of Transportation
Office of Geotechnical Engineering

LOG OF BORING

Date Started 9/25/02 Sampler: Type SS Dia. ______ Water Elev. - Project Identification: MEIGS
Date completed 9/25/02 Approx. MED-338-20.92
Boring No. B-1• Station & Offset 95+40, 16' RT. Surface Elev. 579.5' LANDSLIDE SLOPE INCLINOMETER

Elev. 579.5	Depth 0	Std. Pen./ R.O.D.	Rec. ft	Loss ft	Description	Sample No.	% Agg	% C.S.	% F.S.	% Silt	% Clay	L.L.	P.I.	W.C.	ODOT Class
579.0		AUGERED			SOD AND TOPSOIL	-	-	-	-	-	-	-	-	-	VISUAL
577.0	2														
	4	6/10/12			RED SILTY SANDY GRAVEL	1	43	15	14	15	13	NP	NP	11	A-2-4
574.5	6	3/3/4			RED SANDY CLAY WITH STONE FRAGMENTS	2	9	7	8	31	45	38	15	19	A-6a
572.0	8	2/3/4			RED SILT AND CLAY WITH STONE FRAGMENTS	3	0	4	6	34	56	39	15	21	A-6a
569.5	10														
	12	2/3/4			RED SILT AND CLAY	4	0	3	5	37	55	37	13	21	A-6a
567.0	14	3/3/6			RED SILT AND CLAY	5	0	4	6	38	52	39	14	18	A-6a
564.5	16	2/3/5			RED SILT AND CLAY WITH STONE FRAGMENTS	6	9	4	6	37	44	37	14	20	A-6a
562.0	18	12/12/16			RED GRAVELLY SANDY SILT	7	16	11	18	28	27	NP	NP	13	A-4a
559.5	20														
	22	11/12/65			RED SILTY GRAVELLY SAND	8	15	23	25	21	16	NP	NP	13	A-4a
	24				TOP OF ROCK										
554.5		50(0.1)			BROWN, MEDIUM-GRAINED, FRIABLE SANDSTONE	9								4	VISUAL
554.4	26														
	28														
	30	84	4.9	0.0	SANDSTONE, BROWN, GRAY IN THE BOTTOM HALF, HARD, SLIGHTLY FELDSPATHIC, MEDIUM-GRAINED, MEDIUM-BEDDED, SLIGHTLY JOINTED IN A FEW PLACES. NO CORE LOSS. R.O.D. IS 84										
	32														
	34														
544.5					BOTTOM OF BORING										

Particle Sizes: Agg= >2.00mm, Coarse Sand= 2.00-0.42mm, Fine Sand= 0.42-0.074mm, Silt= 0.074-0.005mm, Clay= <0.005mm

Form TE-15L Revised 9/95

• NOTE SLOPE INCLINOMETER TUBING WAS INSTALLED IN THIS HOLE TO 35.0' FEET DEEP. FURTHERMORE, AN ADJACENT 35.0' DEEP HOLE WAS DRILLED AT STA. 95+38, 16' RT. AND TDR CABLE WAS INSTALLED IN IT.

State of Ohio
Department of Transportation
Office of Geotechnical Engineering

(2/2)

LOG OF BORING

Date Started 9/30/02 Sampler: Type SS Dia. ____ Water Elev. - Project Identification: MEIGS
Date completed 9/30/02 Approx. MED-338-20.92
Boring No. B-2 • Station & Offset 98+04, 19' RT. Surface Elev. 579.5' LANDSLIDE SLOPE INCLINOMETER

Elev.	Depth	Std. Pen./ R.Q.D.	Rec. ft	Loss ft	Description	Sample No.	% Agg	% C.S.	% F.S.	% Silt	% Clay	L.L.	P.I.	W.C.	ODOT Class
579.5	0						Physical Characteristics								
579.0		AUGERED			TOPSOIL	-	-	-	-	-	-	-	-	-	VISUAL
577.0	2														
574.5	4	8/8/10			RED SILTY CLAY WITH STONE FRAGMENTS	10	0	8	11	36	45	39	16	15	A-6b
572.0	6	9/9/9			RED SANDY CLAY WITH STONE FRAGMENTS	11	10	9	11	33	37	40	16	17	A-6b
569.5	8	7/7/8			RED SANDY GRAVELLY CLAY	12	19	9	8	30	34	35	11	17	A-6a
567.0	10														
	12	11/11/12			RED SILTY SANDY GRAVEL	13	44	12	8	19	17	NP	NP	16	A-4a
564.5	14	6/5/7			RED SILTY GRAVELLY SAND	14	23	23	16	17	21	32	9	13	A-4a
562.0	16	7/4/5			RED GRAVELLY SANDY CLAY	15	19	12	13	26	30	34	14	13	A-6a
559.5	18	8/11/8			RED GRAVELLY SANDY SILT	16	16	15	26	23	20	NP	NP	21	A-4a
	20														
	22	7/8/8			RED GRAVELLY SANDY SILT	17	19	9	20	31	21	NP	NP	21	A-4a
	24				TOP OF ROCK										
554.5		50(0.2)			BROWN FRIABLE SANDSTONE	18	-	-	-	-	-	-	-	8	VISUAL
554.2	26														
	28														
	30	74	4.9	0.1	SANDSTONE, BROWN IN THE UPPER PORTION, GRAY BELOW, FIRM, SLIGHTLY FELDSPATHIC, MEDIUM-GRAINED, THIN-BEDDED, IN THE TOP 2.0', MEDIUM-BEDDDED BELOW, JOINTED NEAR THE TOP. CORE LOSS 1% R.Q.D. IS 74										
	32														
	34														
544.5					BOTTOM OF BORING										

Particle Sizes: Agg= >2.00mm, Coarse Sand= 2.00-0.42mm, Fine Sand= 0.42-0.074mm, Silt= 0.074-0.005mm, Clay= <0.005mm

Form TE-15(Revised 9/95

• NOTE SLOPE INCLINOMETER TUBING WAS INSTALLED IN THIS HOLE TO 35.0' FEET DEEP, FURTHERMORE, AN ADJACENT 35.0' DEEP HOLE WAS DRILLED AT STA. 98+01, 18' RT. AND TDR CABLE WAS INSTALLED IN IT.

Date Started 10/1/02 Sampler: Type SS Dia. ______ Water Elev. 470.5' Project Identification: MEIGS
Date completed 10/2/02 Approx. MEG-124-46.86
Boring No. B-1 * Station & Offset 92+59, 14' RT. Surface Elev. 480.5' LANDSLIDE SLOPE INCLINOMETER

Elev.	Depth	Std. Pen./ R.O.D.	Rec. ft	Loss ft	Description	Sample No.	Physical Characteristics % Agg	% C.S.	% F.S.	% Silt	% Clay	L.L.	P.I.	W.C.	ODOT Class
480.5	0														
479.5	2	AUGERED			GRAVEL AND SAND (BERM MATL.)	-	-	-	-	-	-	-	-	-	VISUAL
478.0	4	20/21/14			ASPHALT	1	-	-	-	-	-	-	-	7	VISUAL
475.5	6	11/14/6			RED SILTY GRAVELLY SAND WITH ASPHALT	2	35	16	20	18	11	NP	NP	16	A-2-4
473.0	8	8/8/6			RED SILTY SANDY GRAVEL WITH ASPHALT	3	50	19	16	9	6	NP	NP	14	A-1-b
470.5	10														
468.0	12	17/29/32			CRUMBLY WET ASPHALT	4	-	-	-	-	-	-	-	8	VISUAL
465.5	14	3/5/4			RED GRAVELLY SANDY CLAY	5	17	7	13	26	37	34	17	25	A-6b
463.0	16	12/5/5			RED SILTY CLAY WITH ASPHALT	6	-	-	-	-	-	-	-	20	VISUAL
460.5	18–20	3/4/5			GRAY SANDY SILT WITH ASPHALT	7	13	3	21	39	24	NP	NP	21	A-4a
	22	2/3/3			GRAY SANDY SILT	8	0	2	29	43	26	NP	NP	30	A-4a
455.5	24–28	3/3/6			GRAY SANDY SILT	9	0	2	22	48	28	28	5	21	A-4a
450.5	30–34	12/22/30			RED SILT AND CLAY	10	0	3	3	36	58	41	12	15	A-7-6
445.5	36	50(0.3)			TOP OF ROCK — RED SOFT MUDSTONE	11								8	VISUAL
444.0	38	76	3.0	0.0	SILTSTONE, DARK GRAY TO BLACK, FIRM, CARBONACEOUS, WITH CALCAREOUS NODULES AT THE BOTTOM, JOINTED AT THE TOP AND BOTTOM. NO CORE LOSS. R.O.D. IS 76										
441.0					BOTTOM OF BORING										

Particle Sizes: Agg= >2.00mm, Coarse Sand= 2.00-0.42mm, Fine Sand= 0.42-0.074mm, Silt= 0.074-0.005mm, Clay= <0.005mm

Form TE-15, Revised 9/95

* NOTE: SLOPE INCLINOMETER TUBING WAS INSTALLED IN THIS HOLE TO 39.5' FEET DEEP, FURTHERMORE AN ADJACENT 40.0' DEEP HOLE WAS DRILLED AT STA. 92+50, 14' RT. AND TDR CABLE WAS INSTALLED IN IT.

State of Ohio
Department of Transportation
Office of Geotechnical Engineering

(2/2)

LOG OF BORING

Date Started 10/7/02 Sampler: Type SS Dia. ______ Water Elev. 451.0' Project Identification: MEIGS
Date completed 10/7/02 Approx. MEG-124-46.86
Boring No. B-2 • Station & Offset 95+34, 17' RT. Surface Elev. 481.0' LANDSLIDE SLOPE INCLINOMETER

Elev.	Depth	Std. Pen./ R.O.D.	Rec. ft	Loss ft	Description	Sample No.	% Agg	% C.S.	% F.S.	% Silt	% Clay	L.L.	P.I.	W.C.	ODOT Class
481.0	0														
478.5	2				FILL MATERIAL										
476.0	4	5/6/7			BROWN SILTY SAND	12	0	1	61	26	12	NP	NP	-	A-4a
473.5	6	5/5/6			BROWN SANDY SILT	13	6	2	44	30	18	NP	NP	14	A-4a
471.0	8 / 10	1/2/2			BROWN SANDY SILT	14	0	2	38	34	26	NP	NP	17	A-4a
468.5	12	2/4/5			BROWN SANDY SILT	15	0	0	46	34	20	NP	NP	17	A-4a
466.0	14	3/5/5			BROWN SANDY SILT	16	0	0	43	33	24	NP	NP	17	A-4a
463.5	16 / 18	2/3/5			BROWN SANDY SILT	17	0	0	39	35	26	NP	NP	20	A-4a
461.0	20	2/4/6			BROWN SANDY SILT	18	0	0	36	38	26	NP	NP	19	A-4a
	22	2/3/5			BROWN SANDY SILT	19	0	0	39	39	22	NP	NP	20	A-4a
456.0	24 / 26 / 28	2/4/5			BROWN SANDY SILT	20	0	0	36	41	23	NP	NP	22	A-4a
451.0	30 / 32	3/5/6			BROWN AND GRAY SANDY SILT	21	0	0	30	48	22	NP	NP	23	A-4a
446.0	34 / 36				TOP OF ROCK										
443.5	38	4/6/12			GRAY SANDY SILT	22	0	4	29	33	24	NP	NP	22	A-4a
441.0	40	0	2.3	0.2	SILTSTONE, GRAY TO BLACK, FIRM, CARBONACEOUS, W/NUMEROUS CALCAREOUS NODULES, THIN-BEDDED, WITH SCATTERED CLAY SEAMS, BROKEN AND JOINTED AT THE TOP, JOINTED AT THE BOTTOM. CORE LOSS 8 % R.O.D. IS 0										
438.4	42	42	5.0	0.0	SILTSTONE, DARK GRAY TO BLACK, FIRM, CARBONACEOUS, WITH CALCAREOUS NODULES AT THE BOTTOM, JOINTED AT THE TOP, BROKEN AND JOINTED AT THE BOTTOM. NO CORE LOSS. R.O.D. IS 42										
436.0	44	73			SANDSTONE, GRAY, FIRM TO HARD, FINE-GRAINED, MEDIUM-BEDDED, WITH THIN CLAY SEAMS AT THE BOTTOM; GRADING TO BLACK SILTSTONE (CONTAINING CALCAREOUS NODULES) AT THE BOTTOM. NO CORE LOSS. R.O.D. IS 73										

BOTTOM OF BORING

Particle Sizes: Agg= >2.00mm, Coarse Sand= 2.00-0.42mm, Fine Sand= 0.42-0.074mm, Silt= 0.074-0.005mm, Clay= <0.005mm

Form TE-115 Revised 9/95

• NOTE: SLOPE INCLINOMETER TUBING WAS INSTALLED IN THIS HOLE TO 45.0' FEET DEEP, FURTHERMORE, AN ADJACENT 45.0' FEET DEEP HOLE WAS DRILLED AT STA. 95+37, 17' RT. AND TDR CABLE WAS INSTALLED IN IT.

111

APPENDIX D – Field Data

FIELD DATA - SOIL LOG

Project Code:

Project Identification: MEG. 338 - 20.92 (Co., Rt., Br.No./Sec.No.)

Station: + Offset: . Order Code: 0 1

Location No. B1 Over: SLOPE

Pier-Abut. INDICATOR

Started: 9-25-02 Equipment: B53

Completed: 9-25-02 Water Level:

Depth Feet	Samples	Elevation	Description
0			6" TOPSOIL + SOD
			RED CLAY W/ SAND + GRAVEL
	①		2.5 - 4.0 B 6-10-12
5			RED SILTY CLAY W/ STN. FRAGS
	②		5.0 - 6.5 B 3-3-4
			RED SILTY CLAY W/ STN. FRAGS
	③		7.5 - 9.0 B 2-3-4
10			RED SILTY CLAY
	④		10.0 - 11.5 B 2-3-4
			RED. CLAY W/ STN. FRAGS
	⑤		12.5 - 14.0 B 3-3-6
15			RED CLAY W/ STN. FRAGS
	⑥		15.0 - 16.5 B 2-3-5
			RED CLAY W/ SANDSTNE FRAGS
	⑦		17.5 - 19.0 B 12-12-16
20			RED CLAY W/ SAND + SND. STN. FRAGS
	⑧		20.0 - 21.5 B 11-12-65
			BRN. SANDSTONE
25	⑨		25.0 - 25.1 B 50

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25		
		PUT CORE BARREL IN AT 25.1
30		GOOD BRN. SANDSTONE
		25.1 - 30.0 CORED REC. 4.9
		GOOD BRN. SANDSTONE TO
35		GOOD GREY SANDSTONE
		30.0 - 35.0 CORED REC. 5.0
		PLACED 35.0 OF SLOPE IND.
		PIPE IN THIS HOLE AND
		GROUTED IT IN.
40		E.O.B. 35.0
	B/A	A SECOND HOLE WAS DRILLED
		BESIDE THIS HOLE AND A
		WIRE SLOPE IND. WAS PLACED
45		PLACED IN THIS HOLE.
		THESE HOLES WERE DRILLED
		APPROX 460' WEST OF THE 21
50		MILE MARKER AND 16' RT
	B/A	NO SAMPLES WERE TAKEN ON
		THIS HOLE HOLE WAS CORED
55		AND CARE WAS PLACED
		OVER THE HILL.
		LISA OF THE UNIVERISITY SAID
		STA. + OFFSETS WOULD BE
60		LOCATED LATER.

Remarks: DRILLER CAREY

Party: SABO

Chief of Party: MELEISH

FIELD DATA - SOIL LOG

Project Code:

Project Identification: MEG. 338 - 20.92 (Co., Rt., Br.No./Sec.No.)

Station: + Offset: , Order Code: 0 1

Location No. B2 Over: SLOPE

Pier-Abut. INDICATOR PIPE

Started: 9-30-02 Equipment: B53

Completed: 9-30-02 Water Level: DRY BEFORE CORING

Depth Feet	Samples	Elevation	Description
0			0.5' TOPSOIL
			RED CLAY W/ STN. FRAGS
	(10)		2.5 - 4.0 B 8-8-10
5			RED CLAY W/ STN. FRAGS
	(11)		5.0 - 6.5 B 9-9-9
			RED CLAY W/ STN. FRAGS
	(12)		7.5 - 9.0 B 7-7-8
10			RED CLAY W/ STN. FRAGS
	(13)		10.0 - 11.5' B 11-11-12
			RED CLAY W/ STN. FRAGS
	(14)		12.5 - 14.0 B 6-5-7
15			RED CLAY W/ STN. FRAGS
	(15)		15.0 - 16.5' B 7-4-5
			RED CLAY W/ SAND + STN. FRAGS
	(16)		17.5 - 19.0 B 8-11-8
20			RED CLAY W/ STN. FRAGS (MOIST)
	(17)		20.0 - 21.5' B 7-8-8
			WEAK BRN. SANDSTONE
25	(18)		25.0 - 25.2 B 50

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Depth Feet	Samples	Elevation	Description
25			
30			GOOD BRN. SANDSTONE
			25.2 - 30.0 CORED REC. 4.8
35			GOOD GREY SANDSTONE
			30.0 - 35.0 CORED REC. 4.9
40			PUT 36.0 OF PIPE IN HOLE
			AND GROUTED HOLE
45			E.O.B 36.0
50			
55			THIS HOLE WAS DRILLED
			196' WEST OF THE 21 MILE
			MARKER 19' RT. OF CL
60			

Remarks:

Party: SABO, CAREY

Chief of Party: McLeish

FIELD DATA - SOIL LOG

Project Code:

Project Identification: MEG. 124 - 46.86 (Co., Rt., Br.No./Sec.No.)

Station: +   **Offset:** .   **Order Code:** 01

Location No. B1   **Over:** SLOPE

Pier-Abut. INDICATOR (PIPE)

Started: 10-1-02   **Equipment:** B53

Completed: 10-2-02   **Water Level:** ~10.0

741 WEST M.M. 47

Depth Feet	Samples	Elevation	Description
0			1.5 GRAVEL + SAND (BERM)
			ASPHALT
	1		2.5 - 4.0 B20-21-14
5			ASPHALT TO RED CLAY W/ STN. FRAGS
	2		5.0 - 6.5 B11-14-6
			RED CLAY W/ STN. FRAGS + ASPHALT
	3		7.5 - 9.0 B8-8-6
10			ASPHALT (WET)
	4		10.0 - 11.5 B17-29-32
			RED CLAY W/ STN. FRAGS
	5		12.5 - 14.0 B3-5-4
15			ASPHALT + RED CLAY
	6		15.0 - 16.5 B12-5-5
			GREY SILTY CLAY + ASPHALT
	7		17.5 - 19.0 B3-4-5
20			GREY SILTY CLAY
	8		20.0 - 21.5 B2-3-3
			GREY SILTY CLAY
25	9		25.0 - 26.5 B3-3-6
30			RED CLAY
	10		30.0 - 31.5 B12-22-38
35			RED SHALEY CLAY
	11		35.0 - 35.3 B50
			AUGERED TO 36.5' HIT HARD GREY
			SHALE.
			PUT CORE BARREL IN AT 36.5'
40		GOOD	GREY SANDY SHALE
			36.5 - 39.5 CORRO REC. 3.0
45			PUT 4 SECTIONS OF PIPE
			IN HOLE AND GROUTED
			6" OF PIPE STICKING OUT
50			OF GROUND
			E.O.B. 39.5'
			HOLE WAS DRILLED APPROX.
			741' WEST OF MILE MARKER
55			47 14' RIGHT OF ℄
60			

Remarks:

Party: CAREY SADD

Chief of Party: McLAISH

Form TE-6
DOT-Revised 1/92

FIELD DATA - SOIL LOG

Project Code:

Project Identification: MEG. 124- 46.86 (Co., Rt., Br.No./Sec.No.)

Station: + | Offset: . | Order Code: 01

Location No. B2 | Over: SLOPE

Pier-Abut. INDICATOR PIPE

Started: 10-7-02 | Equipment: B53

Completed: 10-7-02 | Water Level: -30.0 BEFORE CORING

SLOPE INCLINOMETER

Depth Feet	Samples	Elevation	Description
0			DRILLED ON FILL
	12		BRN. SNDY CLAY 2.5-4.0 B5-6-7
5	13		BRN. SNDY CLAY 5.0-6.5 B3-5-6
	14		BRN. SNDY SILTY CLAY 7.5-9.0 B1-2-2
10	15		BRN. SNDY SILTY CLAY 10.0-11.5 B2-4-5
	16		BRN. SNDY SILTY CLAY 12.5-14.0 B3-5-5
15	17		BRN. SILTY CLAY 15.0-16.5 B2-3-5
	18		BRN. SILTY CLAY 17.5-19.0 B2-4-6
20	19		BRN. SILTY CLAY 20.0-21.5 B2-3-5
25	20		BRN. SILTY CLAY 25.0-26.5 B2-4-5
30	21		TUBE WET AT 30.0 BRN. + GREY SILTY CLAY 30.0-31.5 B3-5-6
35	22		GREY SILTY CLAY TO SHALE FRAGS 35.0-36.5 B4-6-12 AUGERED TO 37.5
40			PUT CORE BARREL IN AT 37.5 GREY SHALE 37.5-40.0 CORED REC 2.3
45			GREY SNDY SHALE 40.0-45.0 CORED REC. 5.0
50			PLACED 45.0 OF PIPE IN HOLE AND GROUTED IT IN.
55			E.O.B. 45.0
			HOLE WAS DRILLED 466' WEST OF MILE MARKER 47 17' RT OF CL
60			

Remarks: DRILLER CAREY

Party: SABO

Chief of Party: McLEISH

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Form TE-4
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APPENDIX E – Sample Data for Inclinometer Reading

B2.00

TIME = 08:14:27 16 Oct 2002
DIGITILT/SPIRAL = D
ENGLISH/METRIC = E
HOLE # = B2
PROJECT = MEG124
JOB DESC = Slope Failure
DIR CODE = A0
PROBE SER # = 26123B
OPERATOR = ABC
START DEPTH = 43
END DEPTH = 1
INCREMENT = 2
INSTR CONST = 20000
ROTATIONAL CORR A = 0.0000
ROTATIONAL CORR B = 0.0000
SENSITIVITY FACTOR A = +0
SENSITIVITY FACTOR B = +0

+1.0	A0	-193	B0	184
	A180	178	B180	-206
+3.0	A0	-175	B0	179
	A180	160	B180	-199
+5.0	A0	-168	B0	165
	A180	155	B180	-195
+7.0	A0	-152	B0	179
	A180	139	B180	-201
+9.0	A0	-123	B0	179
	A180	112	B180	-205
+11.0	A0	-102	B0	178
	A180	90	B180	-199
+13.0	A0	-114	B0	150
	A180	101	B180	-175
+15.0	A0	-185	B0	158
	A180	175	B180	-179
+17.0	A0	-236	B0	191
	A180	224	B180	-206
+19.0	A0	-230	B0	187
	A180	219	B180	-203
+21.0	A0	-249	B0	202
	A180	238	B180	-218
+23.0	A0	-281	B0	214
	A180	268	B180	-224
+25.0	A0	-336	B0	278
	A180	324	B180	-303
+27.0	A0	-371	B0	297
	A180	359	B180	-311
+29.0	A0	-378	B0	283
	A180	367	B180	-298
+31.0	A0	-402	B0	270
	A180	391	B180	-282

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B2.00

+33.0	A0	-413	B0	283
	A180	400	B180	-294
+35.0	A0	-479	B0	322
	A180	470	B180	-336
+37.0	A0	-528	B0	364
	A180	517	B180	-376
+39.0	A0	-511	B0	405
	A180	499	B180	-417
+41.0	A0	-511	B0	407
	A180	499	B180	-421
+43.0	A0	-498	B0	417
	A180	486	B180	-429

APPENDIX F - ASCII Data File Format for TDR Traces

4	Waveform Averaging
0.8400	Velocity of Propagation
500	Number of Points in Waveform
0.0000	Start of Displayed Waveform in meters
16.0000	Length of Display Window in meters
0.0000	Probe Length in meters
0.0000	Probe Offset in meters
0.0000	Constant
-0.3437	Start of Waveform Reflection

Coefficients

-0.1915 .
0.0270 .
0.0259 .
0.0238 .
0.0163 .
0.0109 .
0.0045 .
0.0045 .
. . .
. . .
. . 500 Data Points for
Reflection
. . Coefficient
. . .
. . .
0.9396 .
0.9536 .
0.9664 .

0.9771	.
0.9836	.
0.9900	.
0.9953	.
1.0007	.
1.0018	End of Waveform Reflection Coefficients