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TIME DOMAIN REFLECTOMETRY AS A ROCK MASS MONITORING TECHNIQUE

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Abstract. This paper describes the practices and methods used in a study of Time Domain Reflectometry (TDR) as an inexpensive deformation monitoring tool in underground excavations at the Waste Isolation Pilot Plant (WIPP). The WIPP is being developed near Carlsbad, New Mexico, for the disposal of transuranic nuclear wastes in bedded salt 655 m (2 150 ft) below the surface. Data collected from WIPP geomechanical monitoring are used to characterize conditions, confirm design assumptions, and understand and predict the performance of the deep salt excavation. The geomechanical monitoring program encompasses numerous geomechanical monitoring techniques ranging from inspection of observation boreholes to advanced radar surveys. In 1989 TDR was introduced as a monitoring tool with the installation of 12.7 mm (0.5 in) diameter TDR cables in the underground excavations. In 1993, a new TDR system was installed in a separate location. Based on experience with the previous installation, enhancements were implemented into the new TDR system that: 1.) extended the period of performance by increasing cable diameter to 22.2 mm (0.875 in), 2.) increased accuracy in locating areas of deformation by aligning cables with nearby observation boreholes, and 3.) improved data acquisition and analyses using a standard laptop computer, eliminating the chart recorder previously used. In summary, the results of a correlation between the TDR signatures to nearby observation boreholes and geomechanical instrumentation will be presented.

Introduction

The Waste Isolation Pilot Plant (WIPP) is being developed near Carlsbad, New Mexico, for the disposal of transuranic nuclear waste in excavations in bedded evaporite deposits 655 m (2 150 ft) below the surface. WIPP was authorized by Congress in 1979 under Public Law 96-164 to provide "...a research and development facility to demonstrate the safe disposal of radioactive wastes resulting from the defense activities and programs of the United States exempt from regulation by the Nulear Regulatory Commision" (DOE, 1992). To fulfill this mission, the U. S. Department of Energy (DOE) is constructing a full-scale facility to demonstrate both technical and operational principles of the permanent isolation of transuranic waste. The facility is also designed for in-situ studies and experiments in salt. One of these experiments includes the use of Time Domain Reflectometry (TDR) as a rock mass monitoring tool.

Geologically, the facility excavations are located in the Permian Salado Formation, a thick sequence of bedded evaporite deposits. The formation is composed predominantly of halite containing minor amounts of clay, anhydrite, and polyhalite. The facility horizon lies within a thick unit of halite intercalated with thinner beds of anhydrite and clay, as shown in Figure 1. Anhydrite "a" is approximately 21 cm (8 in) thick and occurs about 4 m (13 ft) above the roof in most excavations. Anhydrite "b", is underlain by clay G, is approximately 6 cm (2.4 in) thick and occurs about 2 m (7 ft) into the roof.

These clay layers located in the roof can have a significant impact on the geomechanical performance of the excavations because they provide surfaces along which slip and separation may occur. It is the goal of TDR monitoring at the WIPP to locate and quantify shear and lateral displacement occurring at these clay layers.

The use of TDR as a rock mass monitoring tool was derived from its use in locating and evaluating breaks in transmission lines by observing reflected waveforms. In TDR rock mass monitoring, movements caused by

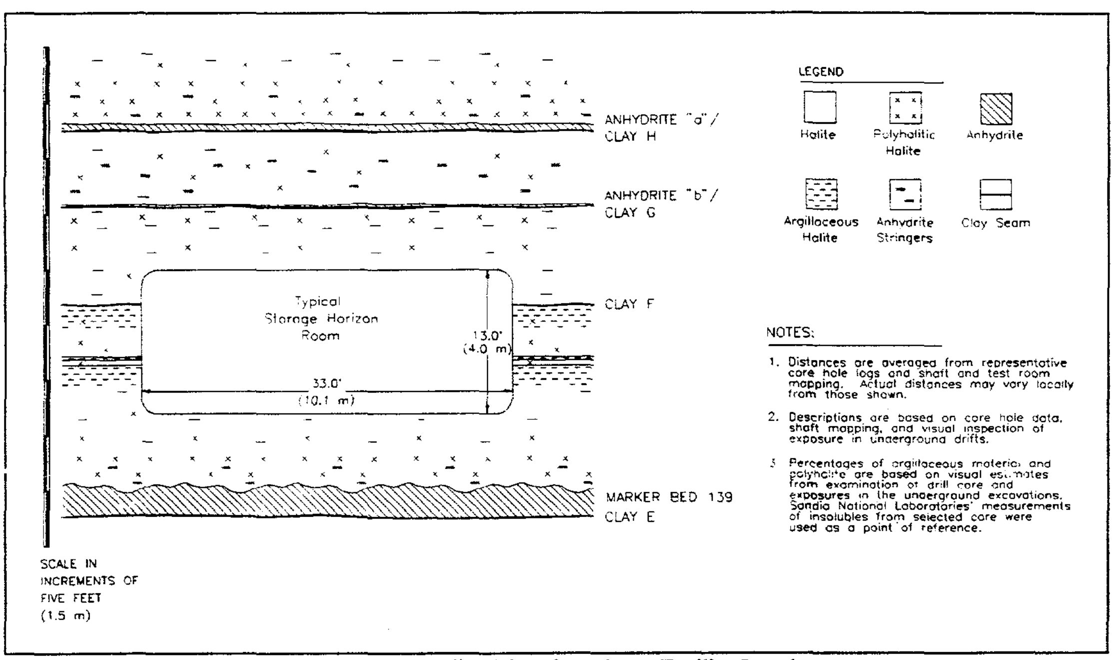

Figure 1. Generalized Stratigraphy at Facility Level

shear and lateral rock displacement deform the grouted coaxial cable which in turn produces changes in the reflected waveforms. As reported by Dowding, Su, and O'Connor (1989), physical changes to the coaxial cable induce changes to the electrical characteristics of the cable. Four common physical changes to the coaxial cable are described below and shown in Figure 2. They include:

1.) cable abrasion or partial hole in the outer conductor, which increases inductance of the coaxial cable and is indicated on the reflected waveform as a positive spike,

2.) a reduction in the outer diameter of the cable such as a cable crimp, which increases capacitance and produces a local negative spike in the reflected waveform,

3.) poor splicing, corroded connectors, or a severed cable which causes an increase in resistance and produces increased reflected voltage for downline portions of the cable; and

4.) water within the coaxial cable causes a reduction in impedance that produces an increased reflected voltage in the affected section.

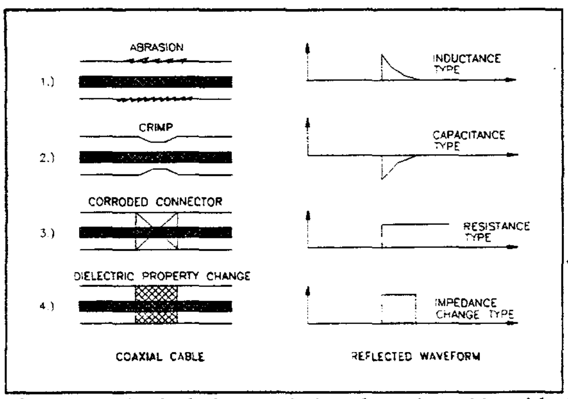

Figure 2. Physical changes induced on the cable with the corresponding reflected waveform.

TDR INSTALLATION

Fourteen coaxial cables in three arrays were installed in a newly excavated room in Febuary 1994. Array No. 1 consists of three roof cables, Array No. 2 consists of three roof cables, three floor cables, and two rib cables. Array No. 3 consists of three roof cables. Cables located in the roof were grouted into boreholes that were 4.6 m (15 ft) long and 7.6 cm (3 in) in diameter in order to penetrate both clay seams. Cables installed in the ribs were also grouted into 4.6 m (15 ft) long, 7.6 cm (3 in) diameter boreholes. Floor cables were grouted into the holes 3.0 m (10 ft) long and 7.6 cm (3 in) in diameter. In addition, each borehole contains a 30.5 cm (12 in) long, 15.2 cm (6 in) diameter collar to allow access to the cable for reading while preventing the cable from extruding out of the borehole.

The coaxial cables are 22.2 mm (0.875 in) in diameter, copper corrugated cables with a copper hollow tube center conductor, an extruded spiral polyethylene dielectric and a polyethylene jacket. Prior to installation, the cables were crimped at 0.61 m (2 ft) intervals which serve as refererence crimps and sealed at both ends to prevent grout from entering the cable during installation (Figure 3). After crimping, the cables were inserted into

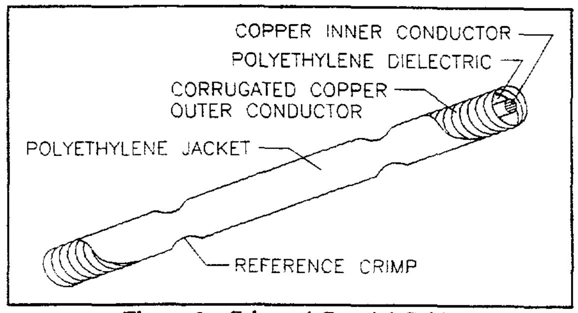

Figure 3. Crimped Coaxial Cable

the borehole along with a vent tube. The borehole was sealed and grout pumped into the borehole until grout exited the vent tube as shown in Figure 4.

Each array of TDR cables was installed near an existing roof extensometer, roof to floor convergence point, and observation borehole. All data collected from these instruments were manually collected in order to quantify and correlate to TDR data.

The extensometers are located in the roof and monitor bed separation across the clay seams. The convergence points are used to determine roof to floor closure and the observation boreholes are used to determine shear displacement at the clay seams. Figure 5 shows a planview layout of the instrument and TDR cable locations in the room.

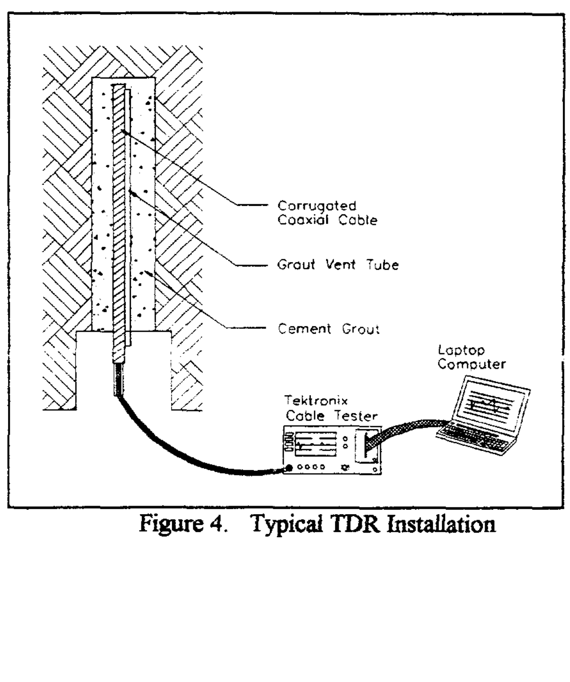

Figure 4. Typical TDR Installation

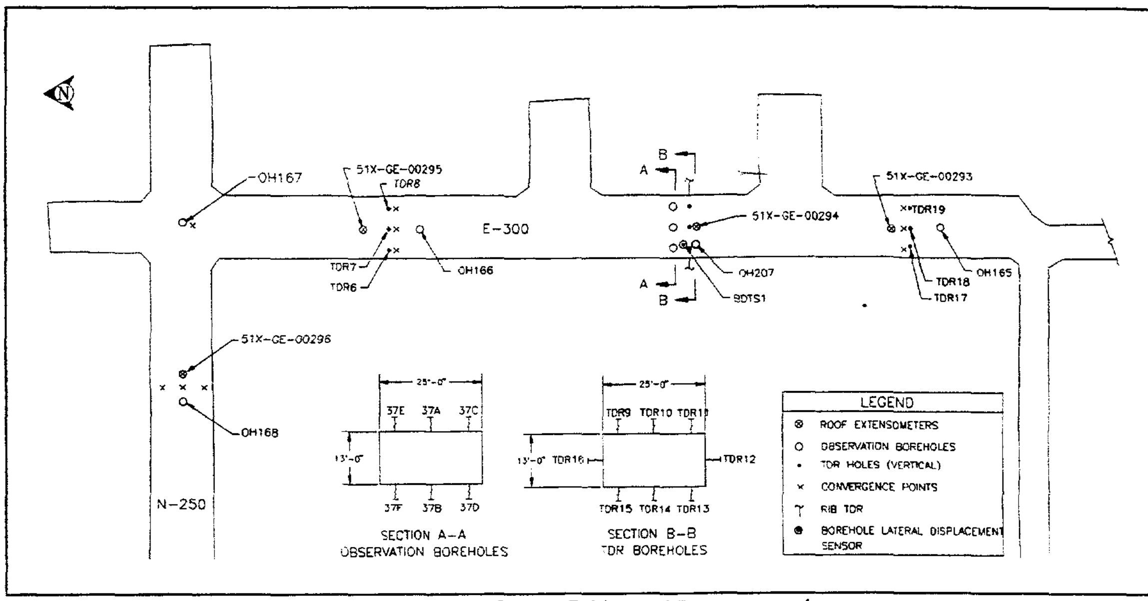

Figure 5. Layout of TDR Cables and Instrumentation

TDR DATA ANALYSES

In the field, TDR cables are read using a Tektronix Reflectometer that downloads the data to a standard laptop computer as shown in Figure 4. The data is then entered onto a spreadsheet that enables the user to determine more accurately the location and magnitude or the reflection coefficient of the peaks and valleys indicated on the waveforms (Figure 6). The reflection coefficient of the peaks and valleys are measured in units of millirhos, which is the ratio of the voltage applied to the cable divided by the voltage reflected back from the cable due to cable breaks or an impedance mismatch.

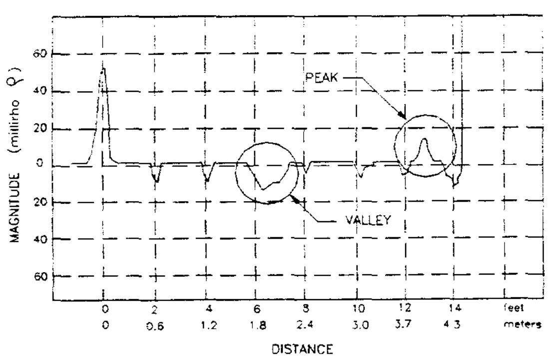

Figure 6. Waveform of Crimped TDR Cable

The reflection coefficient of the peaks on the waveform is then converted to displacement in centimeters (inches).

Through a series of shear tests performed by New Mexico Institute of Mining and Technology (Aimone-Martin et al., 1994), equation (1) was derived as the relationship between shear displacement and reflection coefficient.

$$y = a + \frac{b}{1 + e^{-(\frac{x-c}{d})}} \qquad \text{Equation (1)}$$

where
a = -75.07
b = 487.83
c = 0.2691
d = 0.156
x = shear displacement in centimeters (inches)
y = reflection coefficient (millirhos)

Since shear displacement was known and reflection coefficient unknown in equation (1), it was manipulated to solve for shear displacement as depicted in equation (2).

$$x = -d * \ln\left[\frac{b}{(y-a)} - 1\right] + c \qquad \text{Equation (2)}$$

By using equation (2) reflection coefficient of increasing valleys depicted on the waveforms was converted to shear displacement for correlation to nearby instruments.

For purposes of this paper, correlation will only focus on shear displacement since no indication of movement has occurred thus far on cables located in the roof at room centerline which would be compared to nearby roof extensometers.

The TDR cables were installed on March 3, 1994 and data collection began on March 10, 1994. Immediately after installation, TDR17 was lost completely due to grout in the cable, leaving only thirteen cables for monitoring. Over time, as shear deformation began to occur, crimps in the form of valleys began to appear on the waveforms at locations where clay G was found in nearby observation boreholes. Shear deformation was first noticed in cables located in the roof along the ribs. This occurrence corresponds to patterns of stratigraphic offsetting found in observation boreholes of the existing Excavation Effects Program (Francke and Terrill, 1993). Through the Excavation Effects Program, surveys of observation boreholes have found that significant shear displacement develop at clay seams near excavations. In most cases, the beds nearer to the excavation move towards the centerline of the excavation. The shear displacement is usually symmetrical around the centerline of the room, with the greatest shear displacement magnitude near the ribs (Figure 7).

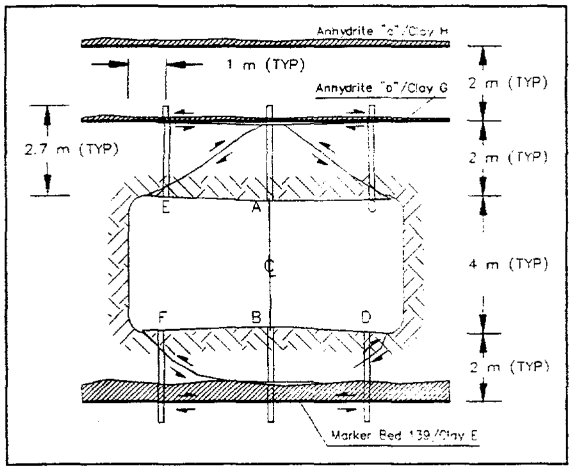

Figure 7. Typical Deformation Patterns Around Underground Openings at the WIPP (Francke and Terrill, 1993)

Figure 8 shows the waveforms over time of TDR9 located along the west rib at midroom. As shown, shear deformation began to appear approximately three months after installation on June 16, 1994. The crimp continued to increase through October 10, 1995, 586 days after installation, when the signal indicated a complete break in the cable at approximately two meters (6.5 ft) into the back. Total shear displacement recorded on TDR9 one day prior to the complete break was 1.3 cm (0.51 in) which translates into a shear displacement rate of 1.7 cm/yr (0.67 in/yr). This corresponds to the shear displacement rate recorded from a nearby observation borehole with a rate of 1.6 cm/yr (0.63 in/yr). Data also correspond to a nearby borehole transducer which recorded a rate of 1.5 cm/yr (0.60 in/yr). In addition, all three instruments, TDR9, observation borehole, and borehole transducer identified shear deformation occurring at clay G, two meters (6.5 ft) into the back.

The remaining four roof cables located along the rib continued to be monitored through complete break of the cable with the exception of TDR8.

On June 16, 1994 moisture was found on TDR8, located along the east rib. Readings continued to be collected as shown in Figure 9 and over time, clarity in magnitude of the crimps decreased due to moisture in the cable. However, location of shear deformation along clay G remained evident at approximately 2.3 meters (7.5 ft) into the back which corresponds to data collected from a nearby borehole that recorded clay G and shear displacement at 2.4 meters (7.75 ft). On August 26, 1995, 541 days after installation, TDR8 indicated a infinite flatline waveform, evidence of change in impedance caused by moisture in the cable as described by Dowding, Su, and O'Connor (1989).

The TDR cables located down centerline of the room (TDR 7, TDR10, TDR18) showed no indication of shear deformation or separation therefore, a comparison to nearby extensometers and observation boreholes could not be performed. The two cables installed in the rib (TDR 12, TDR16) also showed no signs of shear deformation or separation in the waveform, however, moisture was found on TDR 16 located in the west rib. Over time the moisture evaporated and the cable resumed its initial waveform.

TDR cables located in the floor continued to be monitored. TDR13 located along the east rib has indicated shear at approximately three meters (10 ft) into the floor. In July 1995, TDR14 was filled with water and monitoring discontinued. TDR15 located along the west rib remains intact and shows no sign of shear displacement as monitoring continues.

Table 1 summarizes the data collected from TDR cables and nearby instrumentation.

TABLE 1

	Area of Shear Displacement on TDR Cable (meters)	TDR Shear Displacement Rate (cm/yr)	Extensometer Expansion Rate Across Clay "G" (cm/yr)	O/B Shear Displacement Rate (cm/yr)	Transducer Displacement Rate (cm/yr)
TDR6	2.4	3.3		0.0	
TDR7	no shear	0.0	0.63	0.0	
TDR8	2.4	cable wet		hole blocked	
TDR9	2.0	1.7		1.6	1.5
TDR10	no shear	0.0	0.25	0.6	
TDR11	2.0	0.4		1.5	
TDR17	n/a	damaged		0.9	
TDR18	no shear	0.0	0.20	0.4	
TDR19	1.8	1.1		1.5	

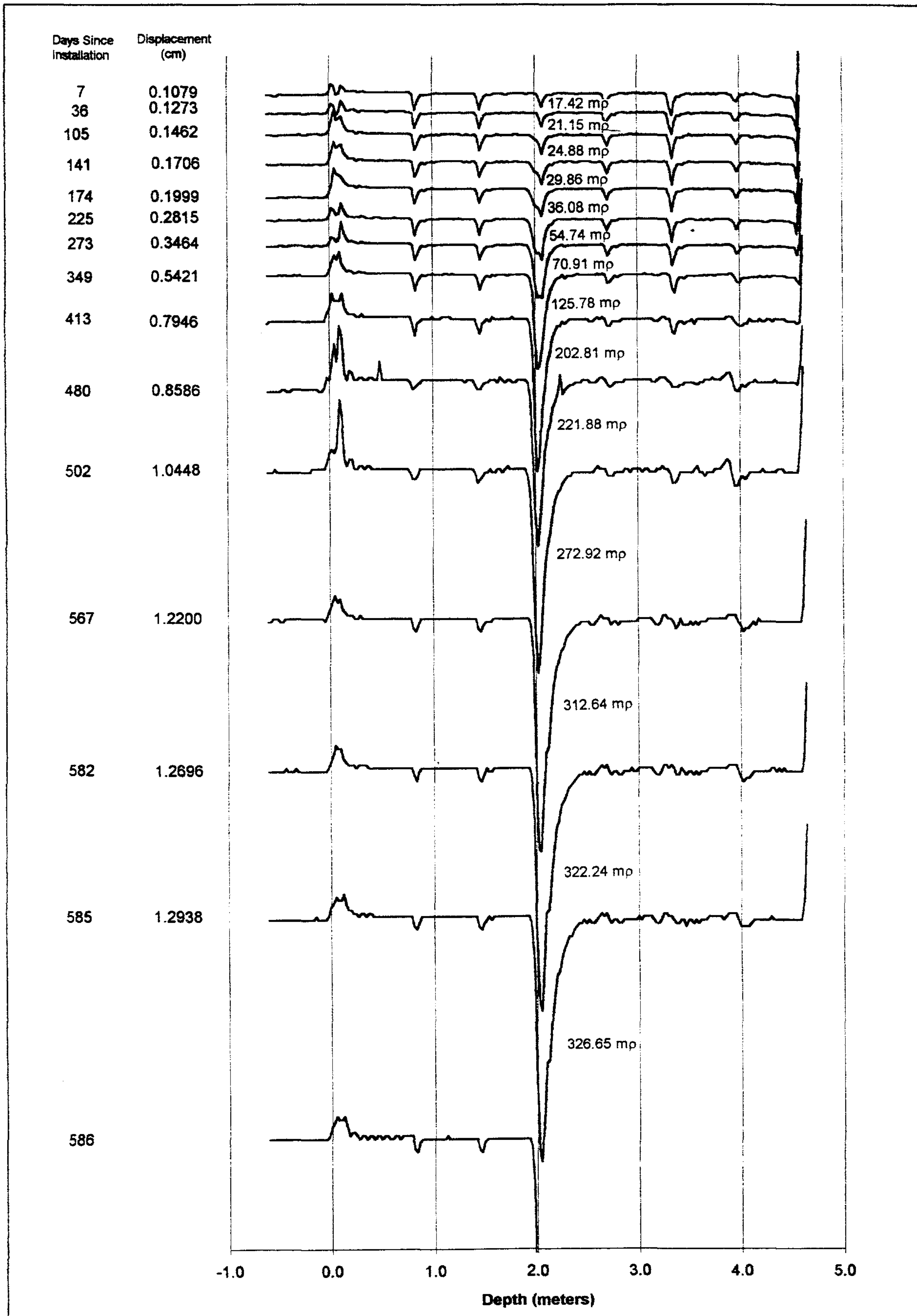

Figure 8. TDR9 Waveforms Over Time

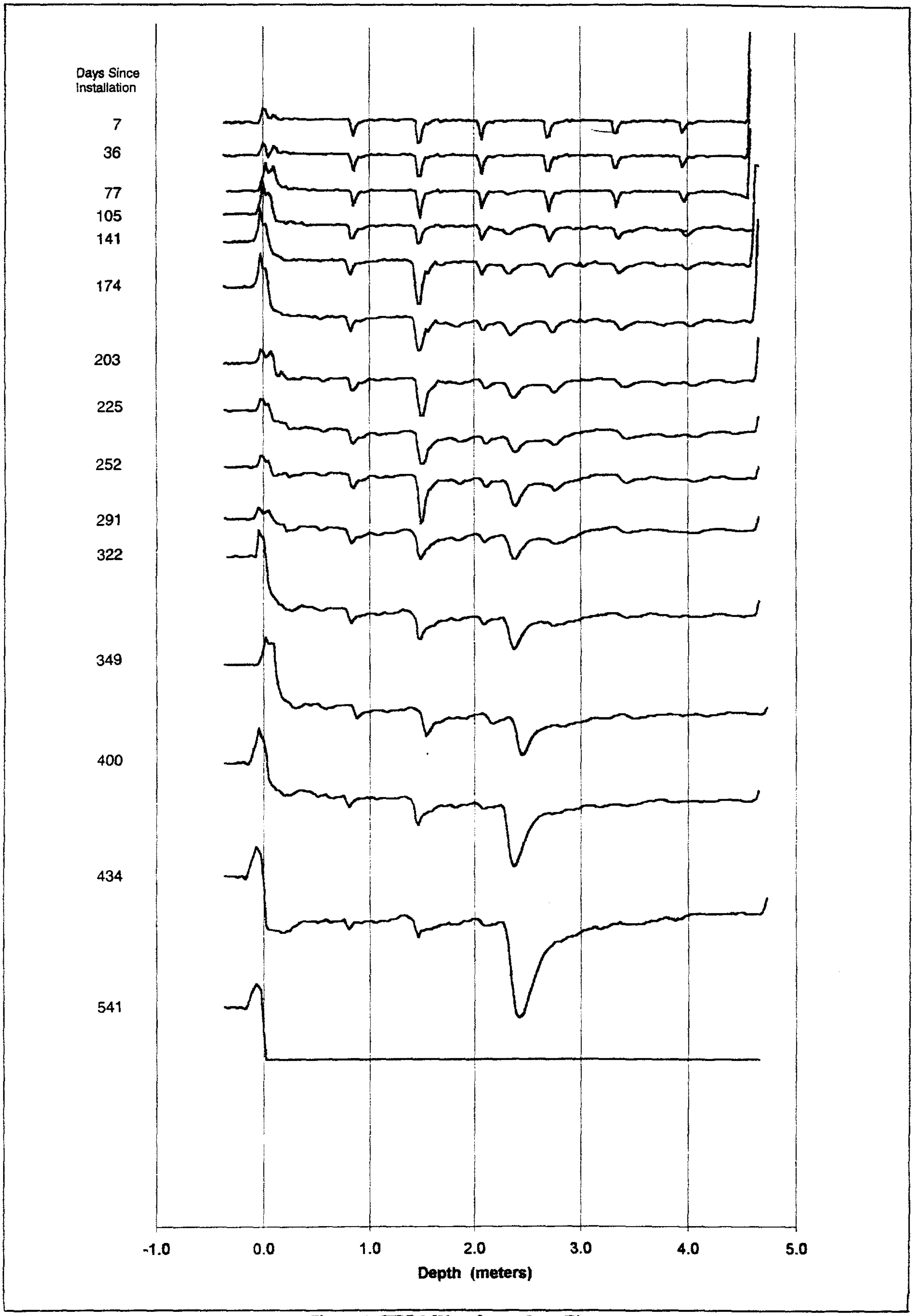

Figure 9. TDR8 Waveforms Over Time

Summary

Due to the patterns of stratigraphic offsetting around the underground openings, only six TDR cables located along the ribs showed signs of shear deformation. Moisture was found on two cables causing damage to one cable (TDR8) and a complete loss of the second cable (TDR17). In addition, delayed drilling of two observation boreholes did not provide sufficient time for shear displacement to be observed for this reporting period. Due to the moisture and delayed drilling, only two TDR cables (TDR9 and TDR19) were available for a correlation of shear displacement rates to nearby instruments.

Shear displacement rates from TDR9 correlated very well with rates from a nearby observation borehole and borehole transducer. TDR19 also correlated well with a nearby observation borehole.

Although moisture was observed in TDR8, continued monitoring enabled the area of shear deformation to be located. In addition, moisture observed on TDR16 evaporated, allowing the cable to return to its initial state. Therefore, monitoring should continue on cables which have been affected by moisture but, caution should be taken when placing a quantitative value on the occurring shear displacement.

In addition to correlation of shear displacement rates, TDR confirmed the patterns of stratigraphic offsetting observed by the Excavation Effects Program. This confirmation is evident by the fact that shear displacement occurred in roof cables located along the ribs, whereas those located along room centerline indicate no evidence of shear deformation. Continued monitoring of cables located along room centerline, will enable the development of stratigraphic separation to be observed as deformation propagates from the ribs to excavation centerline reaching the overlying clay seam. This will also provide a comparison of bed separation to nearby roof extensometers.

Overall, time domain reflectometry has proven to be an effective, simple, and inexpensive tool for monitoring rock mass movement in underground excavations.

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