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TDR MONITORING AS A COMPONENT OF SUBSIDENCE RISK ASSESSMENT OVER ABANDONED MINES

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ABSTRACT

In situations where important structures are located over subsurface cavities, decision makers need a quantitative measure of the likelihood of subsidence occurring. A state-of-the-art sensor has been developed based on the principle of time domain reflectometry (TDR). It has been used to monitor stability of crown pillars over abandoned gold mines in Nova Scotia and Ontario as well as strata movements over abandoned coal mines in Illinois and Ohio. Coaxial cables are grouted into a rock mass which is expected to cave. Rock movement deforms the cable and produces changes in TDR pulse reflection signatures. This technology has been advanced such that it is possible to not only locate but also characterize and quantify rock mass displacements by analyzing changes in these signatures. The remote monitoring capability available with TDR provides many benefits including: 1) the ability to interrogate cables as frequently as desired which has minimized data loss prior to cable "failure", and 2) data is acquired in digital form so it can be analyzed in real time. An example case is presented in which automated TDR monitoring was an integral part of the site selection process for a new school building.

KEYWORDS

Time Domain Reflectometry • TDR • Field Instrumentation • Subsidence • Abandoned Mines • Displacements • Groundwater • Stiffness • Discontinuities

INTRODUCTION

When openings are excavated in a rock or soil mass, stresses may exceed the in situ strength resulting in displacements as unstable blocks move. Coaxial cables can be grouted into a rock mass, as shown in Figure 1, to monitor such displacements. Prior to installation, the cable is crimped to provide reference reflections at known physical locations along the cable. After crimping, the cable is lowered down a borehole and bonded to the surrounding rock with an expansive cement grout that is tremied into the hole. At locations where progressive rock movement is sufficient to fracture the grout, cable deformation occurs that can be monitored with a time domain reflectometry (TDR) cable tester (Dowding *et al.* 1988,1989). Significant developments have emerged in the interpretation of TDR signatures with respect to quantifying changes in reflection magnitude and wavelength. These developments make it possible to distinguish cable shear from cable extension. In addition, hardware and software are commercially available that allow remote, automated monitoring (Campbell Scientific 1991; Tektronix 1989).

Illinois Mine Subsidence Insurance Fund

The Illinois Mine Subsidence Insurance Fund (IMSIF) was created on September 1, 1979 by the Illinois General Assembly (IMSIF 1987) to provide compensation to property owners, through a reinsurance mechanism, against expensive structural repairs for damage caused by mine subsidence. Despite the potential risk, little effort has been made to prevent development over abandoned coal mines or to adopt building codes to minimize damage in subsidence-prone areas. There is currently little application of alternative designs that would lessen expensive abatement and minimize subsidence impacts over abandoned mines.

Houses, schools, churches, commercial buildings, and regional shopping centers continue to be built over mines that have the potential to cause subsidence of the surface and damage to these structures. Development of undermined areas has continued for several reasons (Stache 1996): (1) many areas were developed years ago when the mines were active and the towns had already expanded extensively over the mined areas, (2) the extent of the mine workings were not realized when the areas were developed, (3) the entire abandoned mine may not cause surface subsidence; if mine subsidence occurs, it may be limited to localized failures, (4) it is not possible to accurately predict when an abandoned mine may fail and/or (5) there may be significant liability involved if a landowner was denied the opportunity to develop land based on the possibility that the land may someday subside resulting in structural or environmental damages.

Structural damage may be caused by a variety of earth movements unrelated to mine subsidence (e.g., shrinkage and swelling of expansive soils). Therefore, claims for damage caused by subsidence must be verified by an investigative team. The structure is monitored using survey techniques until it has stabilized. Only then are repairs completed. Surveys to evaluate mine subsidence may span several years.

TDR Monitoring Over Abandoned Mines

The pits, sags, and troughs that develop on the surface over abandoned underground mines are the ultimate result of subsurface strata movements. Subsidence characterization over abandoned room-and-pillar mines remains relatively undeveloped due to a lack of understanding regarding time-dependent rock mass behavior at mine level and within the overburden. In the case of important structures located over abandoned mines, it is not enough to say that subsidence is imminent. A means must be provided to detect strata movements and quantify the rate at which they are occurring so that appropriate measures can be taken to mitigate damage. TDR monitoring of cables embedded in strata overlying abandoned mines provides a means of locating and quantifying subsurface deformation which is a precursor to surface subsidence.

The remote, automated monitoring capability provided by TDR is particularly attractive. While surveying is done by a two-person crew once every six months, TDR monitoring is done automatically on a daily basis which reduces costs and provides a continuous time history of subsurface movements. By virtue of this continuous record, it is possible to identify trends and precursors to surface movements resulting in a more complete approach. A variety of locations in which TDR has been used to monitor movement over abandoned mines is listed in Table 1. Note that this approach is tailored to monitoring localized occurrence of subsidence beneath important structures. GIS technology (Treworgy , Hindman 1991; Stache 1996) must be used to integrate the data acquired by TDR and survey monitoring into an assessment of mine-wide subsidence risk.

EXAMPLE CASE

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Coal mining was active within Collinsville, Illinois from 1870 to 1964 and the area is underlain by a network of mine openings. Support for the overlying rock is provided by pillars and blocks of coal that have begun to fail or possibly punch into the underlying claystone floor. As a result of deep failures within the abandoned mines, there have been occurrences of localized surface subsidence throughout the city. Movement of the overlying rock, and ultimately the surface, have subjected structures, streets, and utilities to strains and stresses that have caused damage.

The Dorris Elementary School has been undergoing damage due to subsidence since 1989 (Gibson , Schottel 1990) and the School Board needed information to determine a location for a new building. One of the sites under consideration was the athletic field north of the existing building (Figure 2) which would make it possible to keep the school in its current neighborhood. A second site was an athletic field adjacent to another school several blocks away. Subsurface investigations, which included the installation of TDR monitoring cables, were done at both sites. Results of monitoring at the first site are summarized in this paper.

Installation and Remote Monitoring

Cables were installed at three locations (TDR1, TDR2 and TDR3 in Figures 2 and 3) to maximize the value of data received and to maximize the likelihood of detecting subsurface movements before subsidence occurred at the surface. The locations were selected based on the following criteria: 1) historical subsidence data (O'Connor *et al*. 1996b), 2) proposed location for a new school, 3) subsidence currently developing northeast of Dorris School, and 4) mine geometry. It was originally planned that all holes would penetrate mine entries in the area of high extraction ratio (TDR3) and in the area proposed for a new building (TDR1 and TDR2), but this was accomplished only at TDR2.

The mines are approximately 60 m below the surface, overlain by 30 m of glacial material and 30 m of Pennsylvanian Age rock (Figure 3). The glacial material consists of 10 m of loess overlying silty clay till and sandy stream deposits. The topmost rock stratum at a depth of 30 m is a claystone that has altered to a silty clay of high plasticity. This altered zone is approximately 8 m thick and washed out easily during drilling.

After drilling, sampling, and camera inspection of mine level conditions was completed in each hole, a contractor-designed plug was placed to seal the bottom. A 22.2 mm diameter CommScope cable was crimped then grouted into the hole as described earlier, and the as-built conditions are summarized in Figure 3. The cables do not extend to mine level due to problems encountered during installation. In particular, the weathered claystone continually squeezed and plugged the holes. In hole TDR3, it was necessary to install the cable and grout tube through the wireline casing.

At the surface, lead wires were connected to each of the three coaxial cables and brought to a central location where a utility pole was installed (Figure 4). A TDR data acquisition system (Campbell Scientific 1991) was installed on this pole within enclosures. The lead wires were connected to a multiplexer which was connected to a Tektronix 1502B TDR cable tester which in turn was connected to a storage module and modem. The datalogger was programmed to turn on the cable tester, interrogate each cable, store data in the storage module, and then turn off the cable tester. Data is downloaded from the storage module via a phone line (Figure 4).

Subsurface Displacements and Surface Subsidence

Representative data for TDR3 are shown in Figures 5 and 6. The histogram of stiffness versus depth in

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Figure 5 was produced using a technique developed by Siekmeier *et al*. 1992 to estimate the stiffness of each rock stratum based on its rock mass classification. The significant features are the two stiffer limestone strata. The upper one is about 1.2 m thick, and the lower one is 6 to 7 m thick. This lower unit forms the immediate mine roof. No fractures were observed in cores obtained in these strata.

The change in TDR waveforms at a depth of 42 m (Figure 5) is characteristic of cable shear and tensile deformation. The time history of reflection magnitude is plotted in Figure 6b where an increase in magnitude is associated with shear deformation and a decrease is associated with tensile deformation (Dowding *et al*. 1988). The periods of deformation can be conveniently identified by the rate of change in reflection magnitude as summarized in Table 2. During the period from April 1995 to August 1996 when the cables experienced tension, probably due to strata separation, surface subsidence of 7 to 20 mm occurred as shown in Figure 6a. When the mode of cable deformation is predominately shear, it is possible to convert TDR reflection magnitude to shear displacement (Dowding , Huang 1994; O'Connor , Zimmerly 1991). In this case, the predominant mode has been tensile deformation so a correlation with the magnitude of surface subsidence is not possible although a correlation with rate of movement will be possible as more survey data becomes available.

Similar cable deformation has occurred at location TDR2 not only at a depth of 42 m but also at a depth of 40 m. This deformation is occurring at the location of clay seams above and below a fractured shale (Figure 3) which is less stiff than adjacent strata. This is consistent with findings in studies conducted over high extraction coal mines in Illinois (O'Connor *et al*. 1996a). These studies as well as those conducted by others (Bauer *et al*. 1991) have found that cable deformation occurs along discontinuities between strata which differ greatly in stiffness.

Water levels

When the mine entries were encountered in TDR2 and TDR3, gas was exhausted continuously. Furthermore, when an inspection was made with the downhole camera, it was found that the mine is flooded and the measured water level is shown in Figure 3. The ends of the coaxial cables were not sealed prior to installation and water has been penetrating the polyethylene dielectric. The maximum height of water penetration in TDR3 is consistent with the water level measured in the mine. The maximum height of water penetration in TDR2 appears to be related with the fractured shale stratum. The height and rate of water penetration in the two cables are independent. This implies that the fractured shale aquifer is confined by the clay seams and not in communication with the mine.

It is suspected that ongoing subsidence at the Dorris site is a complex process of pillar punching, stress transfer between pillars, and time-dependent changes of water pressure within the mine. Unfortunately, it is not likely that water will drain from the polyethylene foam in response to a decrease in water pressure. Such monitoring would require the use of air-dielectric coaxial cable installed in observation wells as described by Dowding *et al*. 1996. Changes in water pressure could conceivably be precursors to subsidence as was the case in Streator, Illinois (USEPA 1981) and near Cambridge, Ohio (Willard 1995).

CONCLUSION

TDR technology makes it possible to do automated, remote monitoring of changes in subsurface conditions over abandoned mines. This monitoring was one component of the subsidence risk assessment performed during site selection for a new school building. At one site, subsurface strata separation and shearing occurred intermittently during the period from April 1995 to June 1996 along horizontal discontinuities represented by clay seams and a fractured shale stratum which are less stiff than adjacent

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strata. Surface subsidence, which is a consequence of these subsurface movements, was verified by periodic survey measurements. Based partly on the results of this monitoring program, it was apparent that this site was experiencing subsidence that would be a chronic problem. The School Board was able to justify to faculty, students and parents that this site was not a viable location for the new school building and the alternative site was selected.

Acknowledgments

The assessment of historical data, field work and outreach activities performed during this study could only have been accomplished by a team of dedicated professionals. Mr. Robert Gibson and Mr. Bruce Schottel of the Illinois Abandoned Mined Land Reclamation Council provided historical subsidence data, critical review of interpretations, the downhole camera, and immeasurable assistance in use of the camera. Mr. Steve Danner and Mr. Joe Robertson of the IMSIF provided historical subsidence data, critical review of interpretations, and continued surface survey data acquisition. Mr. Dennis Craft, Administrative Assistant of Collinsville Unit School District No. 10, and Mr. Lannie Altenberger, Maintenance Supervisor, provided critical support during all phases of the field work. John Siekmeier, Larry Powell and Mark Chandler of the U. S. Bureau of Mines (USBM), Minneapolis performed critical tasks during drilling and camera inspection at the Dorris School. Jay Fouquette (USBM) aided during installation of lead cables at the Dorris School. Finally, it is imperative to acknowledge the efforts of Jan Stache (USBM) in planning and execution of all community outreach activities with the assistance of Sean Killen (USBM).

FIGURES

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Paper 230, Figure 1.

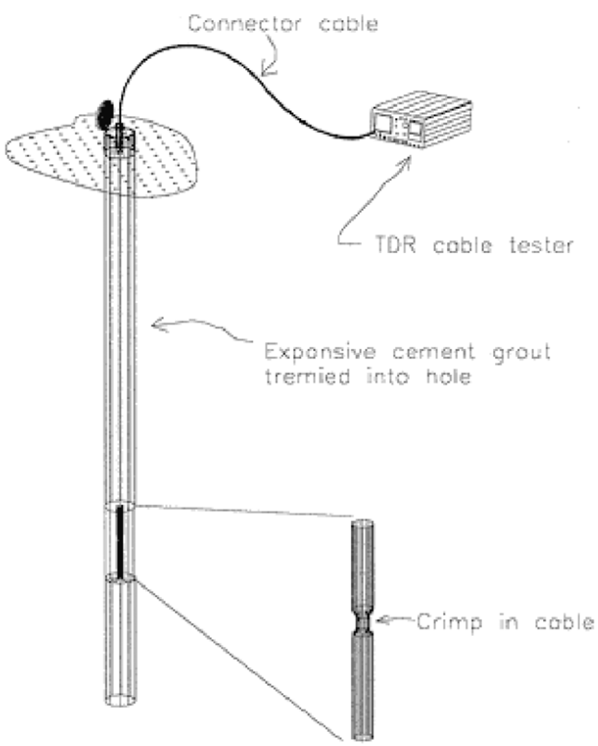

Figure 1. Schematic of TDR installation.

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Paper 230, Figure 2.

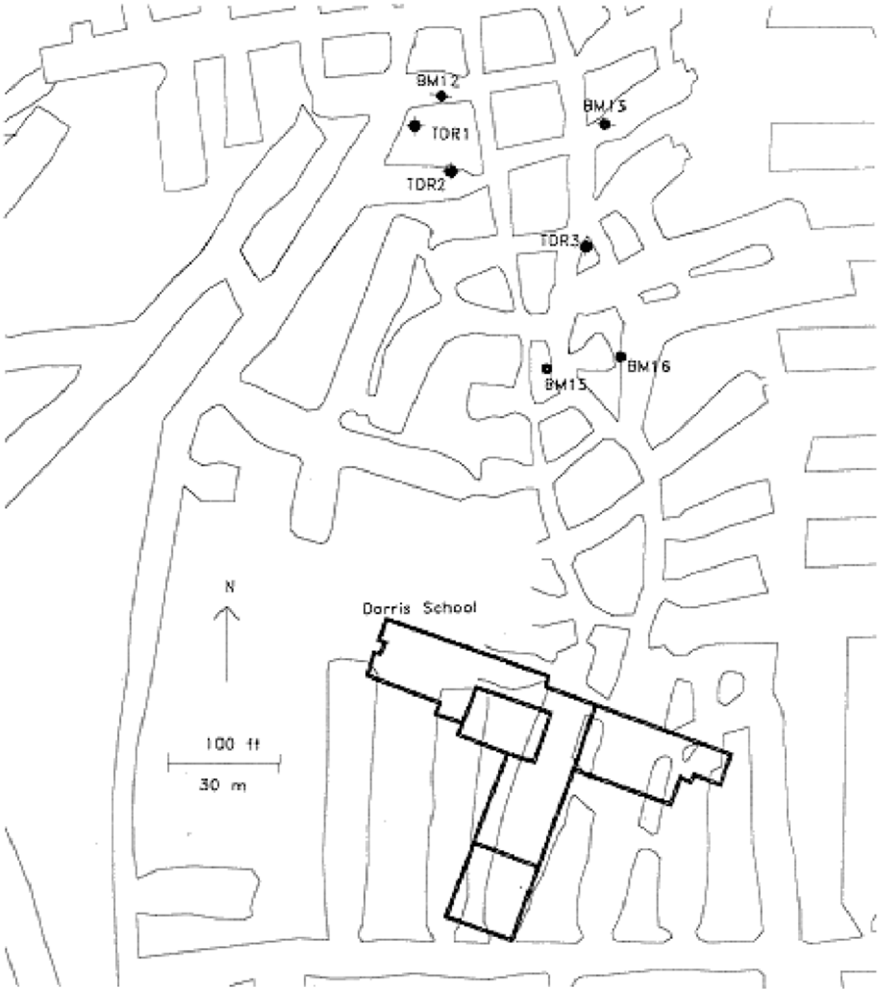

Figure 2. Locations of cables, benchmarks and structure overlain on mine map.

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Paper 230, Figure 3.

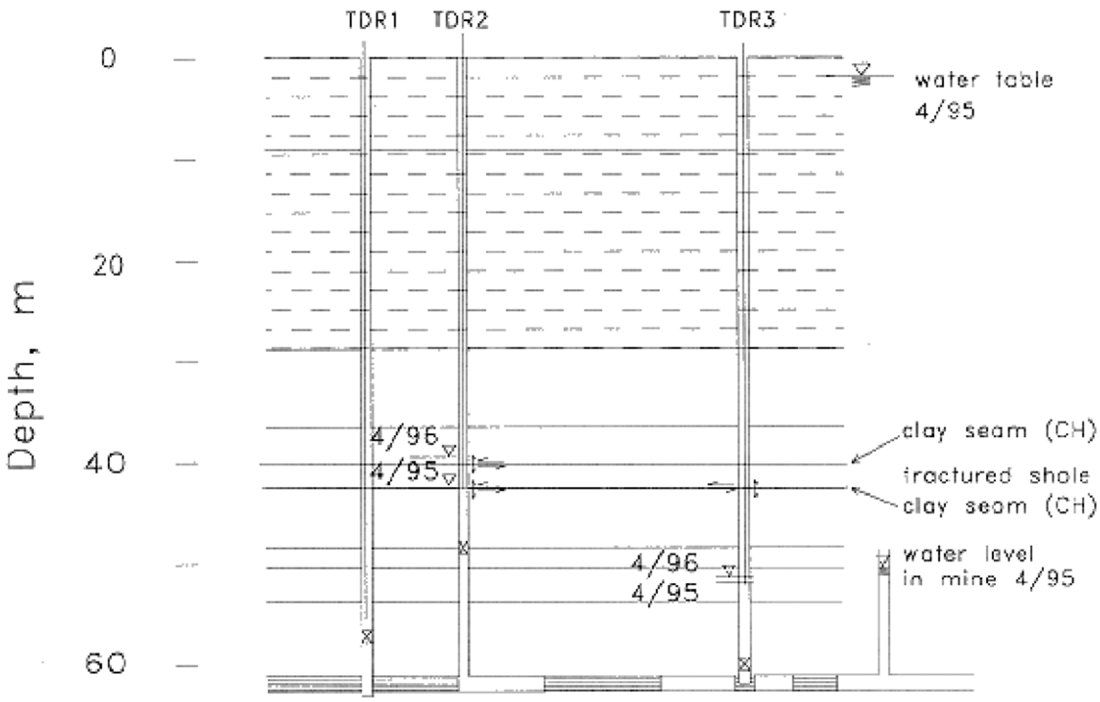

Figure 3. Subsurface conditions and TDR monitoring cable locations. Water levels in TDR2 and TDR3 are the maximum height of water penetration in the coaxial cable foam dielectric.

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Paper 230, Figure 4.

Figure 4. TDR data acquisition system. Cable tester, data logger and modem are in the upper enclosure; multiplexer is in the lower enclosure; system is powered by a deep cycle battery that is trickle-charged by the solar panel.

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Paper 230, Figure 5.

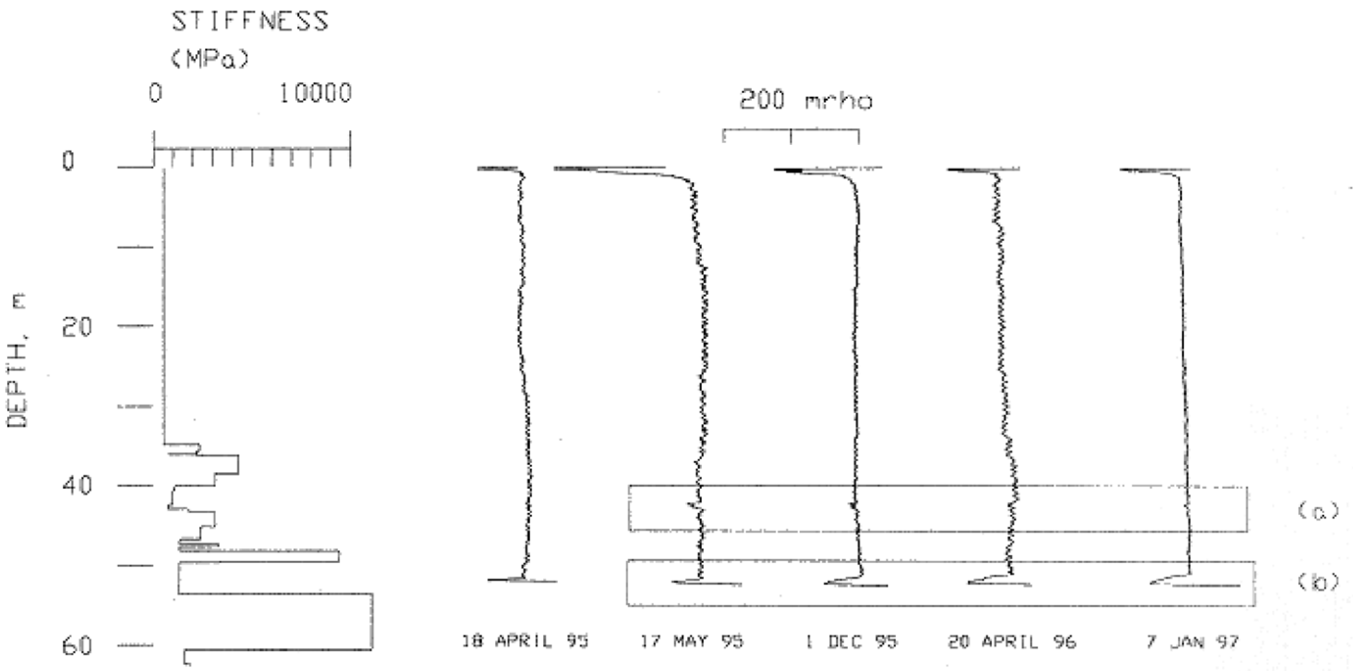

Figure 5. Waveforms acquired at TDR3. The reflection (a) at a depth of 42 m is associated with deformation along a clay seam at the bottom of a fractured shale stratum. The reflection (b) is associated with the water interface rising within the cable.

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Paper 230, Figure 6.

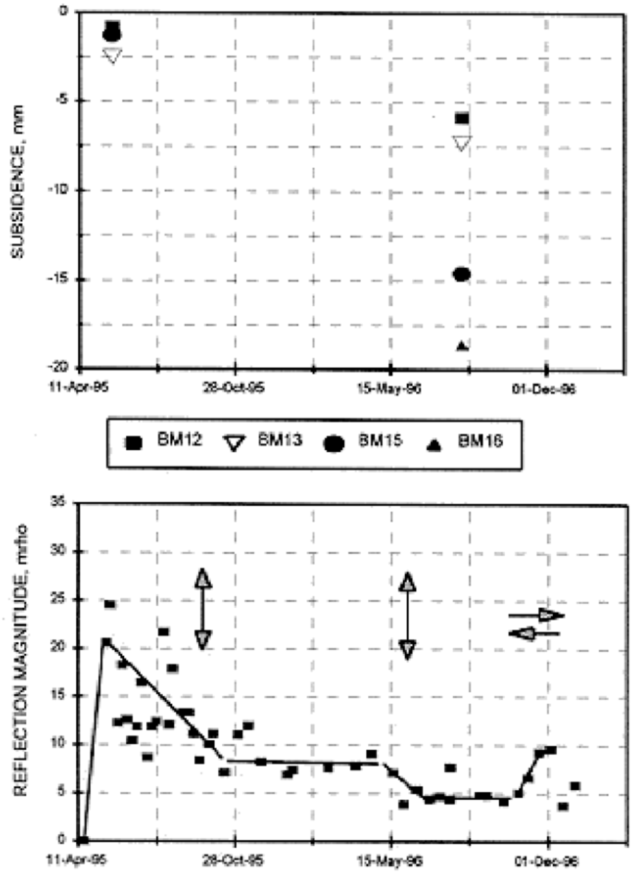

Figure 6. Time history of surface subsidence and subsurface behavior. *A,* surface subsidence; *B,* cable deformation at a depth of 42 m.

TABLES

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Paper 230, Table 1.

Table 1.-Locations where TDR has been used to monitor subsidence over abandoned mines.

Location	Date Installed	Number of Holes	Hole Dip, degrees	Cable Length, m	Cable Type	Abandoned Mine Type	Reference
KY	Feb-82	8	90	55	A[1]	coal mine	Dowding (1983)
Collinsville, IL	May-89	1	90	43	B[2]	coal mine	Bauer et al (1991)
Goldenville, NS	May-91	8	35 to 50	7 to 26	B	gold mine	Hill (1993)
Cobalt, ON	Mar-92	9	40 to 87	5 to 23	B	gold mine	Charette (1993a,b)
Timmons, ON	Jul-92	15	40 to 60	9 to 29	B	gold mine	Aston and Charette (1993)
Collinsville, IL	Mar-95	5	90	61	C[3]	coal mine	O'Connor (1995)
Cambridge, OH	Jan-96	6	90	12 to 15	C	coal mine	

[1]A RG8AU, 12.7 mm, braided copper, Radio Shack, Chicago, IL

[2]B FXA12-50, 12.7 mm, solid aluminum, Cablewave Systems, New Haven, CT

[3]C P3 75-875 CA, 19.05 mm, solid aluminum, CommScope, Catawba, NC

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Paper 230, Table 2.

Table 2.-TDR reflection magnitude and rate of change at a depth of 42 m in TDR3.

Date	TDR reflection magnitude (mrho)	Difference (mrho)	Rate (mrho/month)	Interpretation
17 May 95	20.59			
		-12.36	-1.9	tension
1 Dec 95	8.23			
		0.82	0.2	stable
20 April 96	9.05			
		-4.66	-1.9	tension
3 July 96	4.39			
		0.64	0.2	stable
25 Oct 96	5.03			
		4.2	4.8	shear
20 Nov 96	9.23			

criterion: rate < -1 mrho/month — tensile deformation
rate > 1 mrho/month — shear deformation

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