EFFECTS OF UNDERMINING INTERSTATE ROUTE 70
SOUTH STRABANE TOWNSHIP
WASHINGTON COUNTY, PENNSYLVANIA

NOVEMBER 1999 TO OCTOBER 2000

The Pennsylvania Department of Environmental Protection (PADEP), Bureau of Mining & Reclamation contracted GeoTDR, Inc. under Service Purchase Contract No. 3500016513 effective June 1, 2001. The scope or work was to prepare a report summarizing the effects of undermining a 1.5-mile segment of Interstate Route 70 in South Strabane Township, Washington County, Pennsylvania over the period from November 1999 to October 2000. This report summarizes the effects of undermining along I-70, historical background on this issue, and the cost effectiveness of measures taken by the Pennsylvania Department of Transportation (PennDoT) to ensure the safety of the traveling public.

1.0 INTRODUCTION

The project location on I-70 east of Washington, PA is shown on Figure 1 and Photo 1. The Eighty-Four Mining Company extracted coal from two panels at a depth of 559 to 651 ft (170 to 198 m) beneath I-70 using the longwall mining technique. This high extraction technique involved removal of two large blocks of coal approximately 1000 ft wide, 6000 to 8700 ft long, and 6 ft thick. Figure 2 (map in pocket) shows a plan view of the highway, stationing and limits of underground coal mine panels. The northern panel (3 South LW Panel) was mined between November 22, 1999 and March 2, 2000 and averaged 70 ft (18 m) of advance per day (Appendix A). 4 South LW Panel was mined between March 9, 2000 and October 16, 2000 and averaged 40 ft/day (12 m/day).

Under Pennsylvania law, mining companies must allow surface owners to purchase subjacent support. If the Commonwealth wants to use the surface in a way that would require the underlying coal be left in place for support, the coal owner may petition for appointment of a State Mining Commission to determine how much, if any, of the coal it owns must be left in place. Proceedings during the period 1962-1965 resulted in determinations that the coal owners did not have to leave any coal in place. The Commission rulings were that the amount the Commonwealth would have to pay to leave the coal in place would likely exceed the cost of any subsequent damage.

PennDoT Engineering District 12 assumed responsibility for precautionary measures as I-70 was undermined and repairs after mining was completed. To ensure the safety of the traveling public, PennDoT took several precautions including temporary support of an overpass, reduction of speed limits, provision for lane closures and detours, visual monitoring patrols, and real time monitoring of ground movement with a call back alarm capability. Innovative monitoring of ground deformation was accomplished with Time Domain Reflectometry (TDR) to interrogate coaxial cables installed in seven deep holes, and an array of thirty-two tiltmeters installed along the highway shoulder. Surface monitoring was also conducted with Global Positioning System (GPS) measurements at more than five hundred locations. The tiltmeters were connected to a remote data acquisition system that automatically recorded and stored measurements. When specified tilt values were exceeded, the system initiated a phone call to key PennDOT personnel who then monitored tiltmeter measurements in real time via a phone line connection. Based on this information they could alert other agencies if necessary, and intensify visual reconnaissance to determine if lane closures were necessary.

The roadway was only marginally impacted as 3 South LW Panel was mined since chain pillars along the south edge of this longwall panel support the road as shown in Figure 2. However, the roadway crosses over the centerline of 4 South LW Panel at two locations and the response was significantly different when this panel was mined. As a consequence of the small subsidence or differential settlement over chain pillars, the buried culverts and overpass along the undermined section of I-70 were not subjected to damaging tilts or strains. However, the pavement was subjected to transient tensile strains that caused longitudinal cracks to develop between lanes. Residual compressive strains near the edge of Panel 4 South caused transverse compression bumps to develop. Temporary lane closures were required as the cracks were filled and bumps were milled down to level the road surface.

The total cost for precautionary measures and repairs was $2,153,370 which is equivalent to $484,993 in 1962 dollars assuming an interest rate of 4% over the period 1962-1999. In order to purchase support in 1962, it is estimated that the Commonwealth would have needed to buy at least 2,207,650 tons of coal. Conceivably, this coal could have been purchased in 1962 at a price of $0.49 per ton so the cost would have been $1,081,749. It is more probable that the Commonwealth would have purchased support in 1999 but this would require a purchase of 5,617,920 tons at a cost of $40,449,024. Consequently, the amount the Commonwealth would have had to pay for support exceeded the cost of precautionary measures and repairs.

Based on an analysis of accident reports for periods before, during, and after undermining, it is concluded that neither mining nor precautionary measures contributed to accidents. In particular, analysis of accident records for the period from Nov 1999 to Oct 2000, when I-70 was being affected by undermining, indicate that no accidents involved collision with temporary construction barriers.

1.1 Scope of this Report

The Department of Environmental Protection, Bureau of Mining and Reclamation contracted with GeoTDR to prepare a summary report documenting the effects of undermining a 1.5-mile segment of Interstate 70 in Washington County, Pennsylvania. The scope of this work include the following tasks:

1. Gather information describing the transportation structures present within the subsided segment of Interstate 70 (SR0070-0214-0000 to SR0070-0230-0000).
2. Obtain information from the 1962 State Mining Commission ruling that governed the undermining of the subject road segment.

3. Gather information regarding road damages and subsidence effects from the Pennsylvania Department of Transportation (PennDoT).
4. Gather information on precautionary measures (bridge supports, lane restrictions, detour provisions, observation patrols, etc.) employed by PennDoT.
5. Gather information on ground movements and measured subsidence from PennDoT and GeoTDR.
6. Obtain Eighty-Four Mining Company's and West Virginia University's subsidence predictions for the affected road segment, or predict the magnitude of probable subsidence using a suitable modeling technique.
7. Determine the costs incurred by the Commonwealth in monitoring the road, taking precautionary measures and repairing damaged road segments.
8. Check PennDoT records for reports of accidents that occurred as a result of subsidence effects or PennDoT traffic diversions.
9. Calculate the cost PennDoT would have incurred in purchasing coal support for the subsided road segment in 1962 and convert that amount to present dollars.
10. Compare the amount of money PennDoT spent for monitoring, precautionary measures, road repair and accident liability to the present value of the amount PennDoT would have spent to purchase coal support for the road segment in 1962.
11. Assess the accuracy of subsidence prediction techniques by comparing predicted and measured subsidence.

1.2 Information Sources

GeoTDR was actively involved in the design and installation of the instrumentation and analysis of data. The data was supplied to GeoTDR as mining progressed. Correspondence with PennDoT and Earth Inc. provided supplementary information and GeoTDR personnel made site visits periodically during and after mining. Subsequent to completion of mining, PennDoT supplied computer disks with all available measurements and digital photographs. When this Service Contract was awarded, GeoTDR contacted PennDoT to obtain additional information that they graciously supplied. The sources and type of information collected are as follows:

1. GeoTDR, Inc, Westerville, OH (formerly of Apple Valley, MN)
    - Summary spreadsheets and plots
    - AutoCAD drawings
    - Data analyses and interpretation
    - Photographs

2. PennDoT Engineering District 12, Uniontown, PA
    - GPS survey measurement updates
    - Tiltmeter measurement updates
    - TDR measurement updates
    - AutoCAD drawings
        - Subsidence prediction
        - Mine map

        - Roads
        - Drainage
    - State Mining Commission Ruling documents
    - Photographs
    - Accident record database
    - Inventory of transportation structures
    - Cost data
    - Aerial photographs
    - Topographic maps
    - Updates on mine face locations

3. Christine Davis Consultants
    - Washington County Prothonotary's Office
    - Washington County Recorder of Deeds Office
    - Allegheny County Law Library
    - Office of General Counsel of PADEP, Pittsburgh
        - Court records
        - State Mining Commission procedures
        - State Mining Commission Ruling documents
        - Enabling legislation

4. West Virginia University, Department of Mining Engineering
    - Comprehensive and Integrated Subsidence Prediction Model

5. Other sources are provided in the list of references (Section 10.0)

1.3 Acknowledgements

This report is the result of contributions by many individuals. GeoTDR would like to acknowledge the gracious contributions of PennDot Engineering District 12, in particular, Mr.Ronald Clark, Mr. David Whitlatch, Mr. Roy Painter, Mr. Chris Sleighter, and Mr. Robert Hoone. Ms. Mindy See and Ms. Christine Davis of Christine Davis Consultants Inc. compiled documentation on the 1962 State Mining Commission rulings. Mr. Michael Sydlik and Mr. Patrick Brown of Earth Inc. were responsible for management of the drilling and contracts for installation of the monitoring system. Mr. Michael Bodnar of the McMurray District Mining Office of the Pennsylvania Department of Environmental Protection (PADEP) provided technical support during project planning and was actively involved in visual monitoring. Mr. Joseph Stock and Ms. Cathie Nichols of Geotechnical Consultants Inc. were instrumental in managing the compilation of information and drawings that appear in this report. Dr. Kevin O'Connor was the project manager for GeoTDR Inc. and Mr. Harold Miller was the Contract Manager for the PADEP.

2.0 LONGWALL MINING AND SUBSIDENCE

The 5.6 ft (1.7 m) average thickness Pittsburgh coal seam shown in Figures 2 and 5 was being mined 559 to 651 ft (170 to 198 m) below the highway by the longwall mining method. This mining technique involved use of moveable roof supports which made it possible to excavate an entire block of coal 1065 ft (324 m) wide and 8700 ft (2650 m) long as shown in Figure 2. A shearer moved across the full width of a panel making a cut about 3 ft (1 m) deep and loaded the coal onto a conveyor that transported it to another loading point. Hydraulic roof supports were advanced behind the shearer so the mine roof and overlying rock fractured and collapsed into the void behind the supports. Caving and fracturing propagated up through the overlying rock mass as shown in Figure 5.

With this loss of support, subsidence of the overlying rock mass was a certainty and the ground surface ultimately deformed into a trough with maximum subsidence of 3 to 5 ft (1.0 to 1.5 m) as shown by the transverse profile in Figures 3, 5, and 11. Around the margins of this trough, differential vertical movement of the surface caused tilt, and differential tilt caused curvature. This curvature caused tensile and compressive strains. Curvature-induced strains caused both general and, occasionally abrupt, deformation of the pavement.

3.0 PAST EXPERIENCE AND PRECAUTIONARY MEASURES

Other sections of interstate highways in this region have been undermined in the past. They include a section of I-70 east of the Route 519 exit, another section just east of the present mining area, and four sections on I-79, near the Ruff Creek interchange in Greene County. There are nine longwall operations in this part of the State, so PennDoT has considerable experience with regard to expected roadway damage. However, each situation involves unique geology and geometry. For example, longwall mining in 1998 caused SR 136 to buckle and heave. That road (Figure 1) from Washington, PA to the town of Eighty-Four, PA had been closed for repairs nearly a dozen times over the last several years. Mine subsidence also caused power lines along the road to sag and the poles that support them to list sideways, some severely (Hopey, 2000).

Eighty-Four Mining Company had to prepare a mine plan and subsidence prediction prior to mining. When it became apparent that the section of I-70 shown in Figure 2 was going to be undermined using high extraction techniques, PennDoT recognized the likelihood of damage occurring to the pavement and to structures that could shut down the highway. The integrity of the overpass shown in Photo 2 was already questionable, past experience had taught PennDOT that the pavement would subside and crack, and there was concern about tilt affecting the hydraulic performance of reinforced concrete box culverts underlying the highway. While it would be possible to make repairs after mining was completed, the immediate need was to ensure the safety of the driving public as the highway was undermined.

3.1 Proactive versus Reactive Precautionary Measures

The plan of action developed by PennDoT was multifaceted with the primary objective being protection of the driving public. Proactive components of the plan included increased support for the single-span overpass shown in Photo 2, dismantling of the overhead sign structure shown in Photo 1, installation of an alarm system, and visual monitoring. As summarized in Appendix G reactive components of the plan included reducing the speed limit to 40 mph (57 km/h), lane closures, and provisions to detour traffic in case closure of all lanes was deemed necessary. The alarm system consisted of an array of tiltmeters along the highway (Figure 2 and Appendix C) connected to a remote data acquisition system for automated monitoring. Complementing the tiltmeters were more than five hundred points where survey measurements (Appendix A) were taken periodically, and an array of TDR monitoring cables (Appendix B) that were grouted into deep drill holes to monitor precursor movement within the rock mass overlying the mine.

3.2 Instrumentation

The instrumentation system was developed by Ron Clark of PennDoT District 12 to provide real time monitoring and to provide quantitative information about ground response to supplement PennDoT's experience and its database of visual observations and survey measurements. The locations, precision and range requirements for instrumentation were determined on the basis of the mine layout shown in Figure 2 and the anticipated subsidence profile (Tandanand and Powell, 1991) shown in Figures 5 and 11. A comparison of anticipated (i.e., predicted) subsidence and measured subsidence is included in Sections 4.0 and 5.0.

Precursor subsurface deformation was monitored by grouting coaxial cables into holes drilled from the surface to within 150 ft (46 m) of the coal seam as shown in Figure 5 and Photo B.1 (in Appendix B). The cables were interrogated using TDR (O'Connor and Dowding, 1999). It was originally planned to install cables at seven locations where the highway intersects the edges of the mine panels, but four holes (TDR-1, TDR-3, TDR-4, and TDR-5) were moved closer to the centerlines of the panels to increase sensitivity to precursor movement ahead of the advancing mine face.

Biaxial tiltmeters shown in Figure C.1 (Appendix C) were installed along the roadway shoulder at a spacing of 200 ft (60 m) beginning at the location where I-70 intersects 4 South LW Panel as shown in Figure 2. The x-axis was oriented perpendicular to the longwall panel centerline (N30E) and the y-axis was oriented parallel to the centerline (N60W). These two components of tilt are discussed in Section 4.2.

Extensive GPS measurements were made by PennDoT to monitor surface subsidence. In addition to the thirty-two tiltmeter locations and three of the TDR hole locations, periodic measurements were made at over five hundred points in the following fifteen groups:

BL East	26 points
BL West	86 points
Bridge 1	16 points at bridge over Zediker Station Rd (Photo 2)
Bridge 2	18 points at bridge over Zediker Station Rd (Photo 2)
Centerline	99 points along centerline of I-70 (Photo1)
Cross Section	8 points
Eastbound	75 points along eastbound lanes of I-70
Grid 1	16 points at strain grid no. 1 (Figure D.2)
Grid 2	16 points at strain grid no. 2 (Figure D.2)
Grid 3	16 points at strain grid no. 3 (Figure 2 and Figure D.2)
Iron Pins	32 points along I-70
TDR	3 points at TDR surface locations (Figure 2)
Tiltmeters	32 points at tiltmeter surface casings (Figure 2)
Westbound	75 points along westbound lanes of I-70
Zed Rd CL	11 points along Zediker Station Road centerline

These points were located along I-70 and along Zediker Station Road that passes beneath the highway. As indicated by the list of dates in Table A.3 (Appendix A), the measurements were made periodically to monitor the magnitude of vertical movement. Differential vertical movement between adjacent points along I-70 was used to verify the tiltmeter measurements. Furthermore, the survey network included three 30 ft by 30 ft (9 m by 9 m) grids which were established to measure surface strain using a technique presented by van der Merwe (1989). The location of one grid is shown in Figure 2, and the others are shown in Figure D.2.

3.3 Alarm System and Visual Monitoring

A critical requirement for the monitoring system was an automatic, datalogger-initiated capability to alert PennDOT personnel in the event that anticipated movement was exceeded. Automation was accomplished by connecting the tiltmeters to a remote data acquisition system controlled by a Campbell Scientific CR10X data logger (Appendix C). This data acquisition system could be connected to eight tiltmeters at one time then moved as mining progressed so the greatest distance from any tiltmeter to the system would be no greater than 1000 ft (300 m). Four locations for the monitoring system were selected and utility poles were installed to have power and a phone line available at each location (Photo C.7). Initially, the electronics were mounted on a utility pole but, in order to make the system more mobile, the system was placed in a steel enclosure that could be carried by two people and loaded into a pickup truck (Photo C.8).

It was originally estimated that the maximum tilt would be 0.016 ft/ft (0.92 arc-degree, or ratio of vertical to horizontal V:H = 1:62.5). Based on experience published in the subsidence engineering literature for residential structures, an initial alarm level of 0.002 ft/ft (0.12 arc-degree or V:H = 1:500) was established (Geddes and Cooper, 1962; Holla, 1988; Marino, 1985; Stacey and Bell, 1999, O'Connor, 1990). Whenever this tilt value was exceeded, the datalogger initiated a phone call to PennDoT personnel on duty 24 hours a day. The alarm value was incrementally increased as personnel gained experience with the system.

Once the datalogger-initiated phone call was made to key personnel informing them which tiltmeter had exceeded the limit, they would monitor tiltmeter measurements in real time via a phone line. Based on this information, they could make a decision about alerting other agencies and increasing the frequency of visual monitoring to determine if lane closures were warranted.

4.0 SUBSIDENCE EFFECTS - MEASUREMENTS AND OBSERVED DAMAGES

The angle of draw shown in Figure 3 represents a mathematical model of the limits of movement within the overburden and on the ground surface. Conventional experience is based on vertical movement, so the angle of draw concept is consistent with intuition. However, there are other modes of deformation, especially subsurface movement within the overburden, that are precursors of surface subsidence and not consistent with intuition.

Based on TDR measurements that have been made over several longwall mines, it is known that, in fact, vertical movement is only one component of the actual behavior. TDR measurements have made it possible monitor shear deformation within the overburden. This is represented in Figure 4 by the horizontal double-headed arrows intersecting vertical cables within the overburden. Based on TDR measurements it is known that this deformation not only occurs as a precursor in advance of mining but also occurs well beyond the limits of surface subsidence.

On the surface, in addition to vertical subsidence, other components of deformation are tilt, curvature and horizontal strain. The following discussion considers measured values of these components and the damage that was observed. Section 5.0 presents a comparison with predicted values.

4.1 Overburden Response

When the overlying rock collapses into the mined-out void, a large amount of energy is transmitted throughout the overburden. It travels as compressive stresses and shear stresses that propagate away from the collapsing rock in all directions. When the shear stress at any location is greater than the shear strength of the rock mass at that location, fracture and slip occur. Typically, the weakest component of shear strength is the resistance to slip along discontinuities such as joints and bedding planes. This type of localized shearing was detected and measured using TDR.

Details of the TDR cable installation are presented in Appendix B, but basically it involved drilling holes from the surface to within 150 ft of the coal seam, placing coaxial cable in the hole and grouting it to the rock mass with cement grout. The cables were then periodically interrogated with a TDR cable tester that sent a voltage pulse along the cable and reflections occurred at each location where the cable was deformed. Each reflection appears as a spike in the TDR record shown in Figure 6.

The overburden response was consistent with behavior observed at other sites where TDR has been used to monitor subsurface deformation over longwall coal mines (O'Connor et at, 1996). Deformation was concentrated at "significant horizontal discontinuities" which are bedding planes between strata with a large difference in strata stiffness (Appendix K). This is represented graphically in Figure 6 by the stiffness histogram and was evident in all the TDR cables. Deformations were consistently concentrated at specific discontinuities in specific strata. (Appendix K, Table K.4).

In addition to identifying rock mass characteristics that controlled overburden response, the TDR measurements made it possible to quantify the magnitude and rate of movement at each depth. The magnitude of each reflection (i.e., each spike in the record) was proportional to the magnitude of cable deformation at that depth (O'Connor and Dowding, 1999). This deformation magnitude is plotted versus distance to the mine face for representative depths in Figure 7, where distance is negative as the mine face was approaching a cable location and positive as the face moved past the cable. Note that the deformation did not begin simultaneously at all depths. Also, when the shear deformation at a particular depth was great enough to sever the cable, it was not possible to detect any continuing movement below that depth.

The plot in Figure 7 illustrates that deformation was occurring within the overburden over 1000 ft in front of the mine face. Furthermore, the waveform for May 1, 2000 in Figure 6 shows that movement had occurred at location TDR4 during mining of Panel 3 South that was more than 443 ft north of the cable location. This indicates the lateral extent of the influence of mining, and a summary for all TDR cables is presented in Figure 8. The data points indicate locations within the overburden where shear deformation was detected using TDR. Precursor movement occurred ahead of the mine face, and outside the edges of the panel being mined.

It is important to emphasize that the precursor movement is shear deformation along discontinuities within the rock mass. This behavior is not taken into consideration with angle of draw concept shown in Figures 3 and 4 which only accounts for the lateral extent of vertical subsidence on the ground surface. For purposes of comparison in Figure 8, a line representing an angle of draw of 30 degrees is superimposed to illustrate that subsurface movement occurs well beyond the limits of mining and surface movement.

The magnitude of movement, and the number of discontinuities along which deformation occurred, increased within 60 ft of active mining (Figures 7 and 8). Then, as the mine face advanced past a location, the immediate roof collapsed into the mined-out void and the process of shearing and caving progressed up through the overburden as shown in Figure 5. Ultimately, this process resulted in vertical and horizontal deformation of the ground surface as discussed below.

4.2 Surface Tilt and Curvature

The primary purpose for installing biaxial tiltmeters every 200 feet along I-70 over the undermined area was to provide real time monitoring of surface movement and an alarm system to warn when movements were exceeding anticipated magnitudes. These anticipated magnitudes were computed using a profile function model as discussed in Section 5.0, but it is important to appreciate that tilt is actually vector with a magnitude and direction. Both the magnitude and direction varied as a location was undermined. It was necessary to measure two perpendicular components - one is parallel to the longitudinal axis of the longwall panel (Figure 4) and the other is transverse to the longwall panel (Figure 3). The magnitude and time history of each component was controlled by the location of the tiltmeter with respect to the edge of the longwall panel.

As subsidence occurs, the ground surface deforms into the shape of a trough that elongates as the mine face advances. Around the margins of the trough the surface slopes down over the edges of the longwall panel. Along the margin over the advancing mine face, there are transient effects similar to a wave on the ocean as shown in Figure 4. A person standing at a location over the center of the longwall panel will feel themselves being lowered as the ground subsides and the wave moves past. Furthermore, if you watch a utility pole in time lapse animation, you will observe that it is not only lowered but it also tilts. If the pole is located over the centerline of a longwall panel in which the face is advancing from west to east as shown in Figure 4, the top of the pole will tilt toward the west as it is undermined. The tilt will increase in magnitude and then decrease as the mine face advances past that location. The tilt magnitude is a function of time (i.e., the mine face location), and the pole may actually become vertical again.

The variation in surface deformation over the undermined area is evident in the time histories of each tiltmeter as mining progressed along Panel 4 South. As shown by the y-axis time histories (Figure 9 and Appendix C), tilting began as the face moved underneath a location, reached a peak value, and then decreased to a final value close to 0.0 arc-degree after the face was well past the location as the rock mass approached equilibrium.

At locations close to the edge of the panel, tilt is residual as shown in Figure 3, Figure 5 and Photo 3. As shown by the x-axis time histories in Figure 9, tilting in this direction began as the face moved beneath a location and then increased to a residual value as the surface subsided and reached equilibrium.

The transient and residual tilt magnitude depended on the location with respect to the edge of the panel. For locations more than 100 feet inside the panel footprint there was a maximum transient tilt (Figure 10 and Figures C.12 - C.16). For locations from 100 to 300 feet from the edge of the panel, there was a maximum residual tilt (Figure 10 and Figures C.10 - C.15). For locations within 100 feet of the panel rib there was very little tilt (Figure 10, Figures C.1 - C.9). The transient and residual tilt measurements summarized in Table 1 further illustrate the variation along I-70 where it crossed the width of Panel 4 South.

Another important concept is the difference in tilt between adjacent locations. For example, consider a row of utility poles located along the centerline of the longwall panel as shown in Figure 4. The two poles over the mine face are tilted so their tops are farther apart than their bottoms, and a wire suspended between these poles would be stretched (i.e., experience tensile strain). The two poles near the bottom of the subsidence trough are tilted so their tops are closer than their bottoms and a pipe suspended between these poles would be compressed (i.e., experience compressive strain). The difference in tilt between points along a profile is the curvature. This is plotted along the profile in Figure 3 and Figure 5 and is the cause of strain on the ground surface.

Curvature of the ground surface is the variation in tilt between adjacent locations. If there is a short distance from the location of "zero" subsidence to the point of maximum subsidence, there will be a high curvature strain. As the distance between these points increases, the curvature decreases. Consider the distances shown in Figure 3 between a) the point of "zero" surface subsidence and the inflection point, and b) the inflection point and the point of maximum subsidence, S_{max}. As these distances decrease, the curvature strain increases.

4.3 Surface Strain

As a consequence of differential tilt, the ground surface, pavement and structures were subjected to curvature. Humping curvature caused tensile strain while sagging curvature caused compressive strain. The anticipated final transverse strain profile is shown in Figure 5 with tensile strain being positive and compressive strain being negative. Superimposed on the profile are a) measurements from the strain grid (Figure D.2) and b) values computed from the differential tilt between adjacent tiltmeters. These computed values are also summarized in Table 2 to show that the largest residual strains occurred near the margins of the subsidence trough where there was the greatest difference in tilt.

It is more pertinent to consider the curvature and strain actually experienced by the highway. By resolving the tilt measurements into components parallel to the road centerline it is possible to compute an average curvature between adjacent tiltmeters. These computed transient strains are summarized in Table 2. They did not occur simultaneously along the road but sequentially over the period from May 5 to 15, 2000. Note that the transient strains over the center of the longwall panel were as large as the residual strains along margins of the subsidence trough. Furthermore, the maximum average tensile strain of 0.015 ft/ft should be considered a conservative estimate since it is likely that localized strains as great as 0.040 ft/ft may have occurred based on the maximum strain grid measurements shown in Figure D.2 and Figure 5.

Transient strains over the panel centerline dissipated as the mine face advanced, the surface approached final subsidence (Figure 4), and tilts decreased (Figure 9). However, residual strains along the margins of the subsidence trough were permanent. This difference was reflected in the highway's response to subsidence.

4.4 Structural Response and Damage

The maximum average compressive strain of 0.015 ft/ft occurred between tiltmeters TL23 and TL24 (I-70 STA 1238+00 to STA 1241+00), but the strain grid measurements (Appendix D, Figure D.2) indicate that local strains may have been on the order of 0.040 ft/ft. The tilt and curvature caused by subsidence are apparent in the pavement dip and guardrail sag along the southern edge of 4 South LW Panel as shown in Photo 3. During periods of reduced visibility (night, fog, rain, snow, etc.) it would not be apparent to drivers that there is such a dip in the road. This was one reason that PennDoT reduced the speed limit to 40 mph (67 km/h) over the section of I-70 affected by undermining. A list of damage that developed along I-70 is presented in Table 3, photographs are shown in Appendix H, an overall comparison with measurements is presented in Table 4, and particular details are discussed below.

4.4.1 Pavement Damage

A 12-mm-high compression bump developed in the highway near STA 1241+00 (Photo 4). This location corresponds with the maximum residual strain as indicated by the profile in Figure 5 and summary in Table 3. The bump occurred 19 days after this location had been undermined. After this bump occurred, PennDoT restricted traffic during the morning rush hour to one lane in each direction. Traffic was backed up while the hump was milled smooth then all four lanes of the highway were opened at 1:30 p.m. The state police, the Department of Environmental Protection and PennDoT continued to reduce the speed limit in the area to 40 mph (67 km/h), monitor the highway 24 hours/day, and make repairs as needed.

Transient tensile strains were apparent as both panels were mined. Cracking developed in the pavement between the traveling and passing lanes, and also between the traveling and breakdown lanes (Appendix H, Photos H.9 - H.12)

Pavement cracking also developed on Rankin Rd, Zediker Station Rd, and Porter Hill Rd. (Appendix H, Photos H.23 and H.24). These relatively thin flexible pavements were more susceptible to the transient strains. Compression bumps also developed on Zediker Station Road (S.R.1049) just south of I-70.

4.4.2 Transportation Structures

Transportation structures along the section of I-70 affected by mining (Appendix E) included buried box culverts at I-70 STA 1226+00, STA 217+50 and STA 230+25, and the overpass at STA 223+40. In Figure 2, it can be seen that all these structure are located over chain pillars which remained after mining. As discussed in Section 4.2, tilt magnitudes at these locations (TL-17 and TL-3 in Table 1) were small. Consequently, these structures were not subjected to damaging magnitudes of tilt or strain.

Precautions shown in Photo 2 that were taken to buttress the overpass at STA 223+40 were justifiable considering its preexisting condition. The abutment walls were cracked and there were gaps between the bridge deck slabs. Although the actual magnitude of tilt and strain at this location was below damaging magnitudes, this was not anticipated. A perspective is gained by considering the impact of transient strains observed at the railroad bridge over the centerline of Panel 4 South (Figure 2 and Appendix H, Photos H.21 and H.22). Cracks developed between, and through, blocks in the abutment walls.

5.0 COMPARISON OF PREDICTED AND MEASURED SURFACE SUBSIDENCE

Subsidence is the vertical component of displacement on the ground surface. Outside the margins of the longwall panel, there is no subsidence. Referring to the cross section in Figure 3, as you move along the surface from the point of "zero" subsidence toward the panel centerline you walk down a slope until you reach the point at which maximum subsidence has occurred. You have progressed along the surface, through the zone of tensile curvature, past the point of maximum tilt (i.e., the inflection point), and through the zone of compressive curvature.

Prediction of surface subsidence involves the use of mathematical models to compute the subsidence profile. Dr. Syd Peng of West Virginia University computed a subsidence prediction for Eighty-Four Mining Co. using CISPM2 (Peng and Luo, 1994) which is based on an influence function technique. This method assumes that extracting a tiny element of underground coal seam will cause the ground surface to subside into a shape described by a normal probability distribution. The surface point directly above the extracted element receives the most amount of influence. Coal seam elements offset from this location have less influence on that surface point. The final subsidence at this point on the surface is the summation of the influence of each element of the longwall panel.

GeoTDR performed an independent prediction of surface subsidence in order to estimate the anticipated magnitude of tilt. This estimate was needed to establish requirements for the tiltmeters and establish tilt values to be used in activating the call back alarm. This prediction was computed using the profile function technique summarized in Figure D.1 (Tandanand and Powell, 1991).

As discussed in Appendix D, it is possible to develop a variety of anticipated subsidence profiles using these mathematical models. A comparison of the predicted and measured subsidence is as follows:

a) Maximum subsidence along I-70 over the centerline of Panel 4 South(Figure 11 and Table D.2)

CISPM2	3.92 ft
Profile function	5.00 ft
Measured	4.58 ft

a) Subsidence along I-70 over the chain pillars between Panel 4 South and Panel 3 South (Figure 11 and Table D.2)

CISPM2	0.85 ft
Profile function	1.25 ft
Measured	0.50 ft

b) Location of the inflection point (Figure 3)

CISPM2	66 ft and 137 ft from edge of panel
Profile function	0 ft from edge of panel
Measured	165 ft from edge of panel

c) Maximum tilt (Table 1 and Figure 5)

CISPM2	0.012 ft/ft (0.69 arc-deg)
Profile function	0.015 ft/ft (0.86 arc-deg)
Measured	0.026 ft/ft (1.80 arc-deg)

The greater magnitude of the measured tilt is apparent in the steeper gradient in the measured subsidence profile. This is reflected as greater curvature and larger curvature strain than anticipated.

d) Maximum curvature strain (Table 2 and Figure 5)

CISPM2	+0.009 ft/ft tension	-0.009 ft/ft compression
Profile function	+0.007 ft/ft tension	-0.009 ft/ft compression
Measured	+0.012 ft/ft tension	-0.015 ft/ft compression

The average strains between tiltmeters were consistent with the anticipated values but transient strains, and even local strains, were greater than anticipated. A ramification of this is that the tiltmeters installed at a spacing of 200 feet along the highway were not able to detect development of localized strains such as those which caused the compression bump (Photo 4). The strain grid with survey monuments at a spacing of 10 ft detected local strains of as large as 0.040 ft/ft as shown in Figure 5 and Figure D.2.

The bottom line is that the mathematical techniques used to predict subsidence profiles are estimates based on the experience and engineering judgement of the user. However, by fitting the mathematical profiles to match the measured profiles, it is at least possible to develop a rational approach based on this database.

6.0 STATE MINING COMMISSION RULING

Geotechnical Consultants, Inc. retained Christine Davis Consultants, Inc. to conduct background research into various records and proceedings of the State Mining Commission conducted from 1962-1965. The complete report is given in Appendix F.

The State Mining Commission procedures were established by the Commonwealth pursuant to P.L. 1409 (Act of June 1, 1933), as amended and set forth at 52 P.S. 1501-1507

(Act). The Act applies only to lands owned by the Commonwealth. It provides for the establishment of a Commission or Commissions from time to time to hear claims of owners of mineral rights (typically coal) underlying the land owned by the Commonwealth. It is quite common in Pennsylvania to have separate owners for both the surface and underlying mineral rights (such as coal) on the same parcel of land. If the Commonwealth wants to use the surface of the land in a way that may require the underlying coal be left in place for support, such as building a highway, the owner of the coal may petition for appointment of a State Mining Commission to determine how much if any of the coal it owns must be left in place to provide support to the surface, and how much the Commonwealth should pay the owner for this coal.

The proceedings all resulted in a determination by the State Mining Commission that the owners of the coal, with minor exceptions, did not have to leave any coal in place. The Commission rulings were that the amount the Commonwealth would have to pay to leave the coal in place would likely exceed the cost of any subsequent damage done from any subsidence to the surface. The owners were thus essentially permitted to remove all the coal and were further relieved of any responsibility or liability for any damages to the surface such removal might entail.

A review of records in the Washington County Prothonotary’s Office revealed a number of inconsistencies and missing items in the records relating to the four proceedings. Specifically, the Prothonotary’s Office could only locate a file for No 67. While a file was located for No 182, the papers in it were for an unrelated proceeding filed at No 180 July Term 1965 AD. A subsequent search produced no papers or file for the proceeding at No 180 however. No files could be located for No 117 or No 182. The clerks in the Prothonotary’s Office explained that such missing files for proceedings over 35 years old are not that uncommon given the vagaries of and sometimes haphazard methods many counties follow in handling, moving and storing old records.

The materials furnished for No 117 contain what appears to be a signed Order of the State Mining Commission, dated July 12, 1962, relieving Consolidation Coal Company of any obligation to provide support for the section of I-70 (referred to as old LR 62088-62054) bounded by TR 533 (Porter Hill Rd), SR 1049 and PA 519 (referred to as old LR 62103 and old LR 62075, respectively). Based on the foregoing review, it appears that the proceedings at No 117 are most relevant to the section of I-70 that is the subject of this report. It is not clear, however, how the proceedings were finally resolved due to the inconsistencies between the materials provided and the Docket Book entries. The inability of the Washington County Prothonotary’s Office to locate any file in this proceeding further exacerbated the problem of resolving these discrepancies.

7.0 COST ANALYSIS

An important consideration in this situation is a comparison of: a) the cost that would have been incurred by the Commonwealth of Pennsylvania in 1962 to purchase subjacent support for I-70 by purchasing unmined coal, and b) the cost actually incurred for precautionary measures and repair of I-70 in 1999-2000. The following cost analysis was performed using available information and reasonable assumptions.

7.1 Cost to Purchase Support

Scenario 1: Purchase Support in 1962.

The volume of coal was estimated based on the tabulation in Appendix F. Exhibit 1, Item 2, No. 117, "Exhibit A" (Sta 210+00 to Sta 352+00 in Figure 2) and based on a discussion with PennDoT District 12 (Sta 1190+00 to Sta 1241+96 in Figure 2, plus acreage for I-70 / I-79 interchange).

Scenario 2: Purchase Support in 1999.

Eighty-Four Mining Company would allow the Commonwealth to purchase support. It is most probable that this would require purchasing all mineable coal in Panel 3 South, Panel 4 South and Panel 5 South.

Scenario 3: Hypothetical Minimum Support for Purposes of Comparison

Compute the minimum amount of coal required simply to provide support for the existing right of way over Panel 3 South and Panel 4 South. This estimate of the total tonnage should be considered hypothetical since the as-built right-of-way could not have been known in 1962. Furthermore, the mining company would need to isolate a much larger block of coal as wide as the longwall panels in 1999.

	Quantity	Cost (1962)	Cost (1999)
Scenario 1	2,207,650 tons	$1,081,749	N/A
Scenario 2	5,617,920 tons	N/A	$40,449,024
Scenario 3	1,049,000 tons	$514,010	$2,286,820

7.2 Costs for Precautionary Measures and Repairs

The costs incurred by PennDoT for precautionary measures and repairs are listed in Table 5 and summarized as follows:

Description	Cost
Precautionary measures	$924,369
Repairs	$1,229,000
Total	**$2,153,369**

Using a present worth analysis and assuming an average annual rate of 4% over the period from 1962 to 1999, it is estimated that the Commonwealth needed to invest

$$\$2,153,369 \ / \ (1 + 0.04)^{38} = \$484,993 \quad \text{in 1962}$$

in order to cover the cost for precautionary measures and repairs.

7.3 Cost Comparison

Based on the above cost data and assumptions, it appears that it was cost effective for the state to forego paying for support.

Option	1962 Scenario 1	1999 Scenario 2
Investment for support	$1,081,749	$40,449,024
Investment for precautionary measures and repairs	$484,993	$2,153,369

The most likely scenario is Scenario 2. Scenario 1 was not likely for two reasons:

A) high extraction longwall mining technology was not being used by the U.S. mining industry and the coal seam was at a depth greater that 300 feet, and

B) the Commonwealth was using bond issues to finance land acquisition and construction of the interstate highway which was estimated to be $3.6million in 1962.

Consequently, it was not considered necessary to purchase support that would have increased costs by $1.1million in 1962.

The obvious objective of expenditures in this situation was to ensure the safety of the traveling public and to ensure the flow of commercial traffic as I-70 was undermined. A viable comparison is the cost involved when stabilizing abandoned mines beneath interstate highways. These sites are more difficult to deal with than an active high-extraction coal mine since the mine works are not always mapped and the mines are close to the surface. The State of Ohio has typically spent $3.5 million to $5.0 million stabilizing portions of interstate highways.

8.0 SAFETY EVALUATION

PennDoT provided data that summarize accident reports for the following periods:

Description	Duration	Accidents	Fatalities	Accidents/ month
Two years prior to mining	24 months Dec 1997 to Nov 1999	15	0	0.63
Active mining	13 months Dec 1999 to Dec 2000	7	0	0.54
After Mining	3 months Jan 2001 to Mar 2001	2	0	0.67

As shown in Appendix I, these accidents can be grouped according to location along I-70 and the month in which they occurred. Based on this breakdown, as mining occurred over the period from 12/1/99 to 10/16/2001 there was no significant difference in either the distribution of locations or months in which accidents occurred when compared with period from 12/1/97 to 11/30/99 prior to mining.

A detailed breakdown including location with respect to the active mining and active construction is summarized as follows:

PA State Police Accident No.	Date	I-70 Location	Cause	Relative Mine Face Location (feet)[1]	Within Vicinity of Active Mining or Active Construction
0023850	2/13/00	236 + 50	Engine fire	+ 1080	No
0034866	3/01/00	289 + 30	Careless lane change	- 2503	No
0034984	3/13/00	213 + 30	Driver fell asleep	- 3770	No
0119429	5/19/00	238 + 15	High speed and poor weather conditions	- 2500	No
0099993[2]	8/21/00	242 + 25	Hit embankment	+ 920	No
0117966	9/28/00	320 + 59	Careless lane change	- 6200	No

Notes.

1. "- "indicates that the mine face hasn't reached the accident location, and "+" indicates the face is past the accident location
2. Record not in PA State Police file, and accident not reported by PennDoT inspectors.

All accidents occurred at locations more than 900 feet from active mining. Furthermore, accident records for the period 12/1/99 to 10/16/2001, when I-70 was being affected by mining, indicate that no accidents involved collision with temporary construction barriers. The nearest accident occurred at 1:30 am on 8/21/00 in Segment 0225. The summary presented in Appendix I shows that this location had a high frequency of accidents prior to mining. It is concluded that factors other than mining or construction activities were the cause of these accidents.

9.0 SUMMARY

The Department of Environmental Protection, Bureau of Mining and Reclamation contracted with GeoTDR to prepare a summary report documenting the effects of undermining a 1.5-mile segment of Interstate 70 in Washington County, Pennsylvania. Information was collected from a variety of sources, particularly the Pennsylvania Department of Transportation. This information included drawings, measurements, photographs, court documents, accident records, list of transportation structures, and cost data. Based on this information the following conclusions have been made.

9.1 State Mining Commission Rulings

During the period 1962-1965, a State Mining Commission was established to determine how much coal should be left in place to support I-70. The Commission ruled that the amount the Commonwealth would have to pay to leave the coal in place would likely exceed the cost of any subsequent damage due to subsidence of the ground surface. These rulings permitted the coal owners to remove all the coal and were further relieved of any responsibility or liability for damages to the surface.

It should be noted that the longwall panel layout was conducive to protection of structures along I-70. The longwall panels and chain pillars were planned to maximize support for the highway.

9.2 Precautionary Measures

Precautionary measures were motivated by experience that PennDoT District 12 has had with subsidence and the resultant damage. Pavement cracking, residual bumps and sags, and tilting of utility poles are representative of the damage that has occurred along state highways due to longwall mining in this district. The prudent approach was to have a plan of action established to deal with the possibility that these effects might occur as I-70 was undermined.

The plan of action developed by PennDoT was multifaceted with the primary objective of protecting the traveling public. Proactive components of the plan included increased support for a single-span overpass, dismantling of overhead sign structures, installation of instrumentation and a call-back alarm system, and visual monitoring. Reactive components of the plan included reducing the speed limit to 40 mph, lane closures, and provisions to detour traffic in case closure of all lanes was deemed necessary.

9.3 Comparison with Predictions

Prior to mining, Eighty-Four Mining Co. (84MC) was required to develop a subsidence control plan as part of their mining permit. 84MC retained the services of Dr. Syd Peng to predict the subsidence profile that would develop along I-70 using an influence function model. Similarly, GeoTDR performed a subsidence prediction using a profile function model for purposes of specifying the sensitivity, range, and location of instrumentation. The predicted subsidence profiles differed from the actual measured subsidence. In particular the tilt (i.e., differential settlement) over the chain pillars was less than predicted. Furthermore, the locations where maximum residual strains occurred were farther from the edge of panel than anticipated, and the strain magnitude at these locations was greater than anticipated.

9.4 Subsidence Effects and Observed Damages

As a consequence of the small differential settlement and small strain that developed over chain pillars, the buried culverts and overpass along the undermined section of I-70 were not damaged.   However, at locations over 100 ft from the edge of the longwall panels, the pavement was subjected to transient tensile strains over the advancing mine face that caused longitudinal cracks to develop between lanes. Residual compressive strains at a location 200 ft from the edge of Panel 4 South caused transverse bumps to develop. In May 2000 and September 2000, temporary lane closures were required as the cracks were filled and bumps were milled down to level the road surface.

9.5 Cost Comparison

The total cost for precautionary measures and repairs was $2,153,370 which is equivalent to $484,993 in 1962 dollars assuming an interest rate of 4% over the period 1962-1999. In order to purchase support in 1962, it is estimated that the Commonwealth would have needed to buy at least 2,207,650 tons of coal. Conceivably, this coal could have been purchased in 1962 at a price of $0.49 per ton so the cost would have been $1,081,749. It is more probable that the Commonwealth would have purchased support in 1999 but this would require a purchase of 5,617,920 tons at a cost of $40,449,024. Consequently, the amount the Commonwealth would have had to pay for support exceeded the cost of precautionary measures and repairs.

9.6 Safety Evaluation

Based on an analysis of accident reports for periods before, during, and after undermining, it is concluded that the undermining and precautionary measures did not contribute to accidents. In particular, analysis of accident records for the period 12/1999 to 10/2000, when I-70 was being affected by undermining, indicate that no accidents involved collision with temporary construction barriers, and all accidents occurred at locations more than 900 feet from active mining. It is concluded that factors other than mining and construction activities were the cause of all these accidents.

Automated monitoring provided quantitative information upon which rational decisions could be made. It was possible to continuously monitor 1000 ft-long sections of I-

70 which made it possible to concentrate visual monitoring at critical locations when measurements exceeded selected action levels.

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