

## **Real Time Monitoring of Subsidence Along I-70 in Washington, Pennsylvania**

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Abstract. Two longwall coalmine panels were mined at a depth of approximately 156 m (510 ft) beneath I-70 east of Washington, Pennsylvania such that it crossed the width of one panel at two locations. The Pennsylvania Department of Transportation (PennDoT) assumed responsibility for real time monitoring of both ground deformation and changes in highway conditions.

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 along the highway shoulder. Surface monitoring was also conducted with global positioning system (GPS) measurements at more than one hundred locations. Tiltmeters were connected to a central remote data acquisition system that automatically recorded and stored measurements. When specified tilt values were detected, 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.

## **MOTIVATION BASED ON PAST EXPERIENCE**

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 or five 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 S. R. 136 to buckle and heave. That road 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 (1).

When it became apparent that the section of I-70 shown in Figure 1 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 Figure 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.

### **Coal Mining and Subsidence**

The 1.8 m (6 ft) thick Pittsburgh coal seam shown in Figure 3 was being mined 156 m (510 ft) below the highway by the longwall mining method. This mining technique involves use

of moveable roof supports to excavate an entire block of coal 332 m (1090 ft) wide and 2650 m (8700 ft) long as shown in Figure 1. A shearer moves across the full width of a panel making a cut about 1 m (3 ft) deep and loads the coal onto a conveyor that transports it to another loading point. Hydraulic roof supports are advanced behind the shearer and the mine roof and overlying rock fracture and collapse into the void behind the supports. Caving and fracturing propagate up through the overlying rock mass as shown in Figure 3.

With this loss of support, subsidence of the overlying rock mass is a certainty and the ground surface ultimately deforms into a trough with maximum subsidence of 1.0 to 1.5 m (3 to 5 ft) as shown by the transverse profile in Figure 3. Around the margins of this trough, differential vertical movement of the surface causes tilt, and curvature is caused by differential tilt. This curvature causes tensile and compressive strains. Slope and curvature of the surface impacts the line of sight of drivers. Curvature-induced strains cause both general and, occasionally abrupt, deformation of pavement and structures.

## **PLAN OF ACTION**

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 Figure 2, dismantling of overhead sign structures, installation of an alarm system, and visual monitoring. Reactive components of the plan included reducing the speed limit to 57 km/h (40 mph), 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 (at locations shown in Figure 1) connected to a central data acquisition system for automated monitoring. Complementing the tiltmeters were more than one

hundred points where survey measurements were taken weekly and an array of TDR monitoring cables that were grouted into deep drill holes to monitor precursor movement within the rock mass overlying the mine.

## **Instrumentation**

The instrumentation was installed to provide a real time monitoring system and to provide quantitative information about ground response to supplement PennDoT's experience and 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 1 and the anticipated subsidence profile (2) shown in Figure 3.

Precursor subsurface deformation was monitored by grouting coaxial cables shown in Figure 4 into holes drilled from the surface to within 46 m (150 ft) of the coal seam as shown in Figures 1 and 3. The cables were interrogated with Time Domain Reflectometry (TDR) (3). It was originally planned to install cables at seven locations where the highway intersects the edges of the mine panels, but four holes (TDR1, TDR3, TDR4, and TDR5) were moved closer to the centerlines of the panels to increase sensitivity to precursor movement ahead of the advancing mine face.

In order to maximize the sensitivity of TDR for monitoring cable deformation, it was not possible to use long lead cables (i.e., lead cable longer than 50 m). This restriction required that TDR waveforms be acquired with a laptop computer rather than the remote data acquisition system.

Biaxial tiltmeters shown in Figure 5 were installed along the roadway shoulder at a spacing of 60 m (200 ft) beginning at the location where it intersects Panel 4 South as shown in

Figure 1. The tiltmeters (Applied Geomechanics Little Dipper) have a resolution of 0.006 arc-degree and a range of +/-10 arc-degrees. Detachable fins allow the tiltmeters to be installed in slotted inclinometer casing that is grouted into a 150 mm diameter auger hole. The x-axis was oriented perpendicular to the longwall panel centerline (N30E) and the y-axis was oriented parallel to the centerline (N60W).

Extensive GPS measurements were made by PennDoT to monitor surface movement. In addition to the thirty-two tiltmeter locations and seven TDR hole locations, weekly measurements were made at over one hundred points along the highway and along the intersecting two-lane road that passes beneath I-70 as shown in Figure 2. Furthermore, the survey network included three 9 m by 9 m (30 ft by 30 ft) grids established to measure surface strain using a technique presented by van der Merwe (4). The location of one grid is shown in Figures 1 and 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 central data acquisition system controlled by a Campbell Scientific CR10X datalogger. 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 300 m (1000 ft). Four locations for the monitoring system were selected and utility poles were installed to have power and a phone line available at each location. Initially, the electronics were mounted on the utility

pole but, in order to make the system more mobile, all the electronics were placed in a steel enclosure that could be carried by two people and loaded into a pickup truck.

The datalogger would cycle over the eight tiltmeters being actively monitored once every fifteen minutes and store the measurements. It was originally estimated that the maximum tilt would be 0.016 m/m (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 m/m (0.12 arc-degree or V:H = 1:500) was established (6-9). 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 automatic, 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 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.

## **GROUND AND STRUCTURE RESPONSE**

The northern panel (3 South) was mined between November 22, 1999 and March 1, 2000 and averaged 30 m (100 ft) of advance per day. Panel 4 South was mined between March 3, 2000 and October 4, 2000 and averaged 15 m/day (50 ft/day). The roadway was only marginally impacted as Panel 3 South was mined since chain pillars along the south edge of this longwall panel support the road as shown in Figure 1. However, the roadway crosses over the centerline

of Panel 4 South at two locations and the response was significantly different when this panel was mined.

### **Overburden Response**

As the longwall face advanced, there was a continual redistribution of shear stresses with the surrounding rock mass, and movements occurred along discontinuities such as bedding planes that caused deformation of the coaxial cable. The spikes in the TDR signatures shown in Figure 6 developed at each location where the cable was being deformed. This deformation was concentrated at depths where there were large changes in strata stiffness (10) represented by the histogram on the left side of the figure. This behavior was evident in all the TDR cables. In spite of the fact that distances of 30 m to 1200 m separate the cables, deformations were concentrated at specific discontinuities in specific strata.

Precursor movement occurred ahead of the mine face and outside the edges of the panel being mined. For example, the TDR signature for 6/3/00 in Figure 6 shows that precursor movement was detected when the mine face was over 55 m from the cable. However, the waveform for 5/1/00 shows that movement had occurred even earlier due to mining of the previous mine panel (Panel 3 South) that was over 135 m north of the cable location. Typically, cables detected precursor movement 200 m from active mining but one cable detected movement as far as 365 m from active mining.

As the mine face advanced, 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 3. The rate at which this shearing and caving propagated was controlled by the rock mass discontinuities, and the process was tracked by interrogating the coaxial cables on a daily basis.

TDR reflection spikes such as those show in Figure 6 increased in magnitude as shearing deformation increased and the magnitude of the spike was converted to magnitude of deformation (3) as summarized in Figure 7. Precursor shear deformation was detected when the face was more than 200 m from the cable and the rate of deformation increased when the face was within 60 m (200 ft) of the cable.

### **Surface Tilt and Curvature**

While the primary purpose of the tilt measurements was to provide an automated monitoring and alarm system, the difference in slope between adjacent tiltmeters can be used to estimate curvature. The slope of the ground surface is a vector that changed in magnitude and direction as mining progressed and subsidence occurred, so the tiltmeters were oriented to measure slope components parallel and transverse to the longwall centerline. Measurements obtained along the highway from tiltmeters TL-17 to TL-3 (see Figure 1 for location) are summarized in Table 1 and the measured final transverse components are plotted in Figure 3 for comparison with the anticipated final transverse slope profile.

In a longitudinal cross section, the subsidence profile over the advancing mine face is transient and has a steeper slope than the final profile shown in Figure 3. As shown by the y-axis time history in Figure 8, 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. The peak and final longitudinal tilt measurements across the longwall panel are summarized in Table 1 to illustrate the much greater transient tilt and curvature experienced by the highway as it was undermined compared to the final equilibrium profile in Figure 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 3 with tensile strain being positive and compressive strain being negative. Superimposed on the profile are measurements from the strain grid and values computed from the differential tilt between adjacent tiltmeters. These computed values are also summarized in Table 2 to show that the largest final 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 estimate the maximum difference in slope between adjacent tiltmeters that occurred as the steep subsidence profile moved along with the mine face. These computed peak strains are summarized in Table 2. They did not occur simultaneously along the road but sequentially over the period from 5/5/00 to 5/15/00. Note that the transient peak strains, even over the center of the longwall panel, were as large as the final strains along margins of the subsidence trough. Furthermore, these strains should be considered average values since it is likely that localized strains as great as 0.04 may have occurred based on the maximum strain grid measurements shown in Figure 3.

Peak strains over the panel centerline were transient as demonstrated by the longitudinal time history in Figure 8b. However, final strains along the margins of the subsidence trough were permanent. This difference was reflected in the highway's response to subsidence.

## **Surface Subsidence, Structural Response, and Damage**

The tilt and curvature caused by subsidence are apparent in the pavement dip and guardrail sag along the southern edge of Panel 4 South as shown in Figure 9. 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 67 km/h (40 mph) over the section of I-70 shown in Figure 1.

A 12-mm-high compression bump developed in the highway at a location 44 m from the north edge of Panel 4 South as shown in Figures 1 and 10. This location corresponds with the maximum final strain as indicated by the profile in Figure 3 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 pm. The state police, the Department of Environmental Protection and PennDoT continued to reduce the speed limit in the area to 67 km/h (40 mph), monitor the highway 24 hours/day, and make repairs as needed.

Compression bumps also developed on S.R.1049 just south of the location shown in Figure 2.

## **CONCLUSIONS: WHAT WAS LEARNED?**

In addition to the measurements and responses summarized in Table 3, there were several lessons learned. For example, installation of the instrumentation required oversight by experienced personnel during the startup stage. After training, installation and data acquisition could be undertaken by PennDoT personnel.

TDR provided more sensitivity to precursor movement. A comparison of Figures 7 and 8 shows that the rate of subsurface movement increased when the face was within 60 m of a cable, but the tiltmeters did not detect surface movement until the mine face was directly beneath the tiltmeter.

Tiltmeter measurements proved to be reliable and cost effective for automated monitoring and for purposes of an alarm system. The actual damage was caused by strain but automated direct measurement of strain over long sections of highway would have been complex and expensive. Conceptually, it would be possible to create an alarm system based on strain values inferred from differential tilt measurements but this would require a more sophisticated algorithm. The approach used for this project was simpler and more cost effective.

Automated monitoring of the tiltmeters was expensive but off-the-shelf hardware made it possible to rotate the expensive electronics among several locations, which made it more cost effective. Automated monitoring provided quantitative information upon which rational decisions could be made. It was possible to continuously monitor a 300-m-long section of Interstate, and this made it possible to concentrate visual monitoring at critical locations when particular tiltmeters were showing measurements that approached and exceeded anticipated maximum values.

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**Table 1. Comparison of Final and Peak Tilt Measurements**

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

\*see Tandanand and Powell (2)

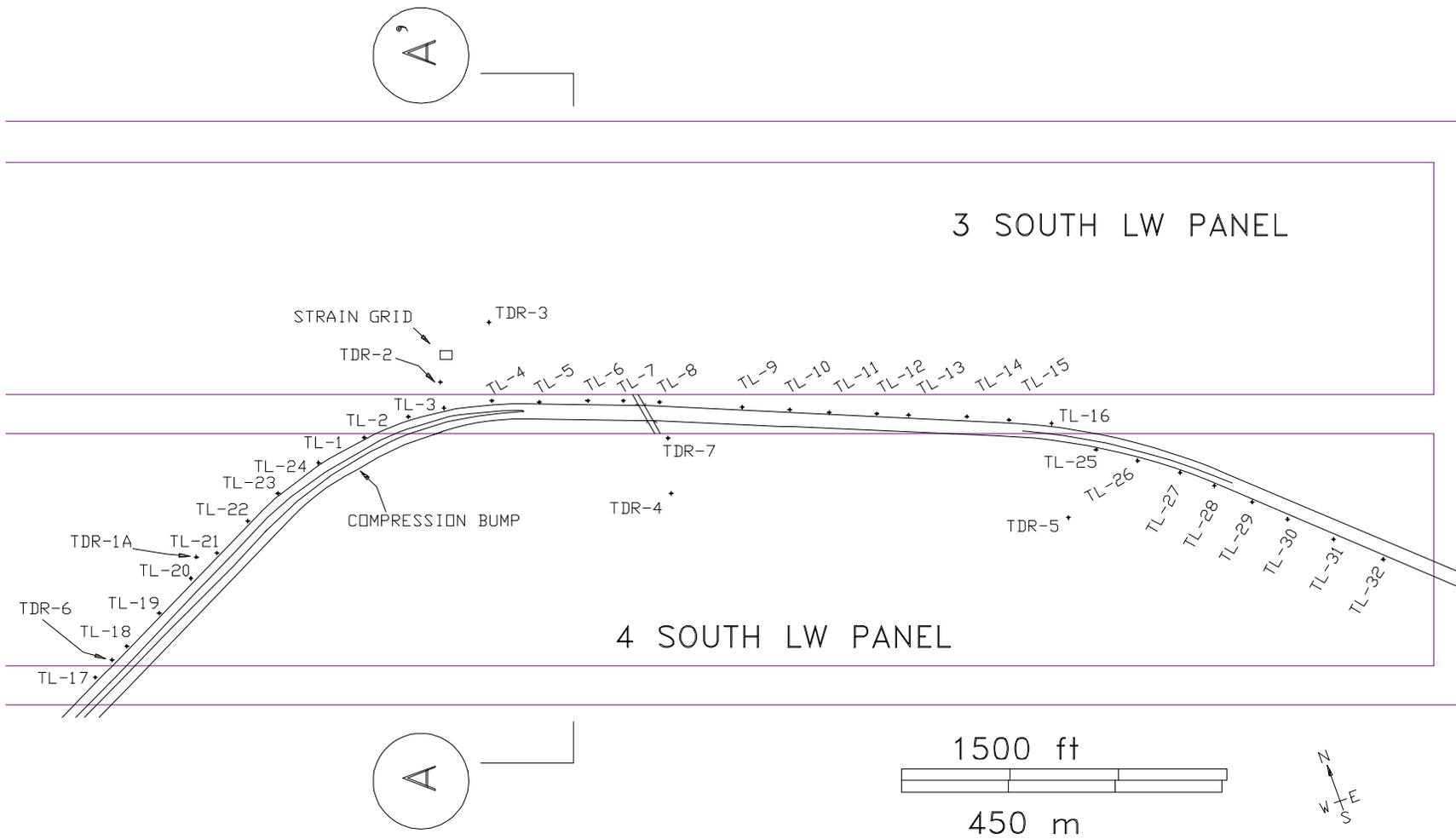
**Table 2. Comparison of Anticipated and Calculated Final and Peak Strains**

	<b>Final Strain Across Panel</b>		<b>Peak Strain</b>
	<b>Anticipated*</b>	<b>Measured**</b>	<b>Along Highway Measured**</b>
TL-17 to TL-18	-0.003	0.015	
TL-18 to TL-19	-0.009	-0.008	0.013
TL-19 to TL-20	0	-0.004	-0.009
TL-20 to TL-21	0	-0.002	0.012
TL-21 to TL-22	0	-0.001	-0.009
TL-22 to TL-23	0	-0.003	0.011
TL-23 to TL-24	-0.009	-0.015	0.011
TL-24 to TL-1	-0.006	0.011	0.009
TL-1 to TL-2	0.002	0.012	
TL-2 to TL-3	0.007	-0.001	

+ tensile strain  
 - compressive strain  
 \* see Tandanand and Powell (2)  
 \*\* calculated from differential tilt measurements

**Table 3. Summary of Measurements and Response**

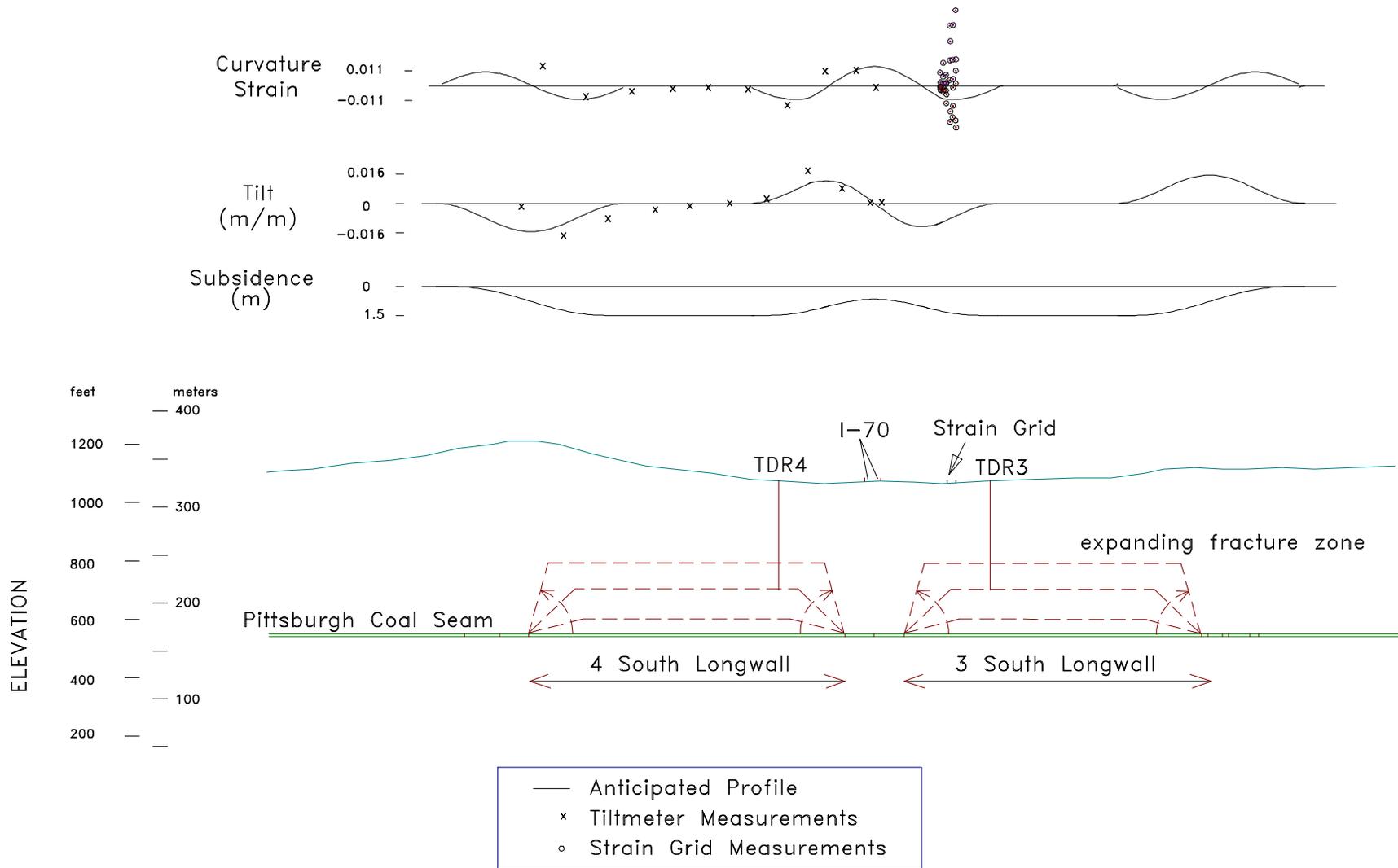
Subsurface Precursor Movement by TDR Cables	Movement detected more than 200 m in front of advancing mine face
	Deformation over Panel 4 South during previous mining of Panel 3 South indicated shearing over 200 m outside limits of panel
Surface Tilt	Initiated as mine face passed beneath a location
	Peak tilt was 0.03 m/m (1.8 arc-degree) Maximum final tilt was 0.01 m/m (0.6 arc-degree)
	Movement continued 450 m behind the mine face as the rock mass approached equilibrium
Differential Tilt and Curvature	Peak curvature was 0.004 m <sup>-1</sup> Maximum final curvature was 0.00012 m <sup>-1</sup>
Surface Strain	Peak computed strain was 1.0% Maximum computed final strain was 0.5% Maximum strain measured using GPS with grid was 0.5% to 4.0%
Structural Response	Abrupt development of compression bumps at location of maximum curvature strain
	Creep of pavement down slope as it was undermined
Actions Taken	Support for overpass
	Reduce speed limit to 67 km/h (40 mph)
	Periodic lane closures



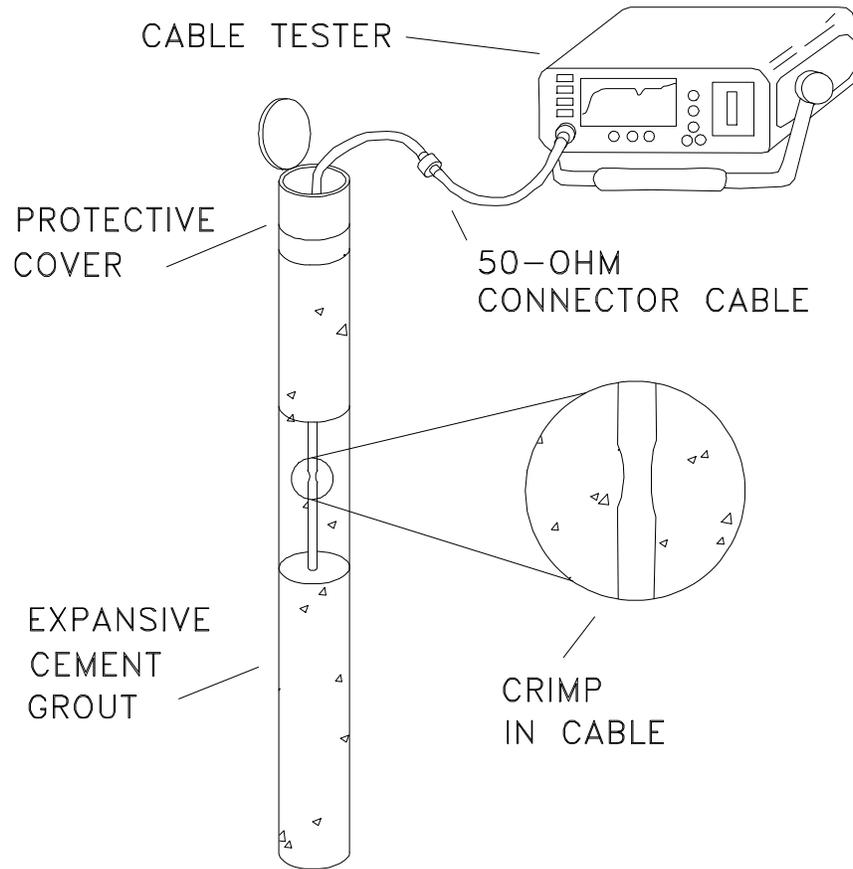
**Figure 1. Plan of highway, instrumentation, and longwall mine.**



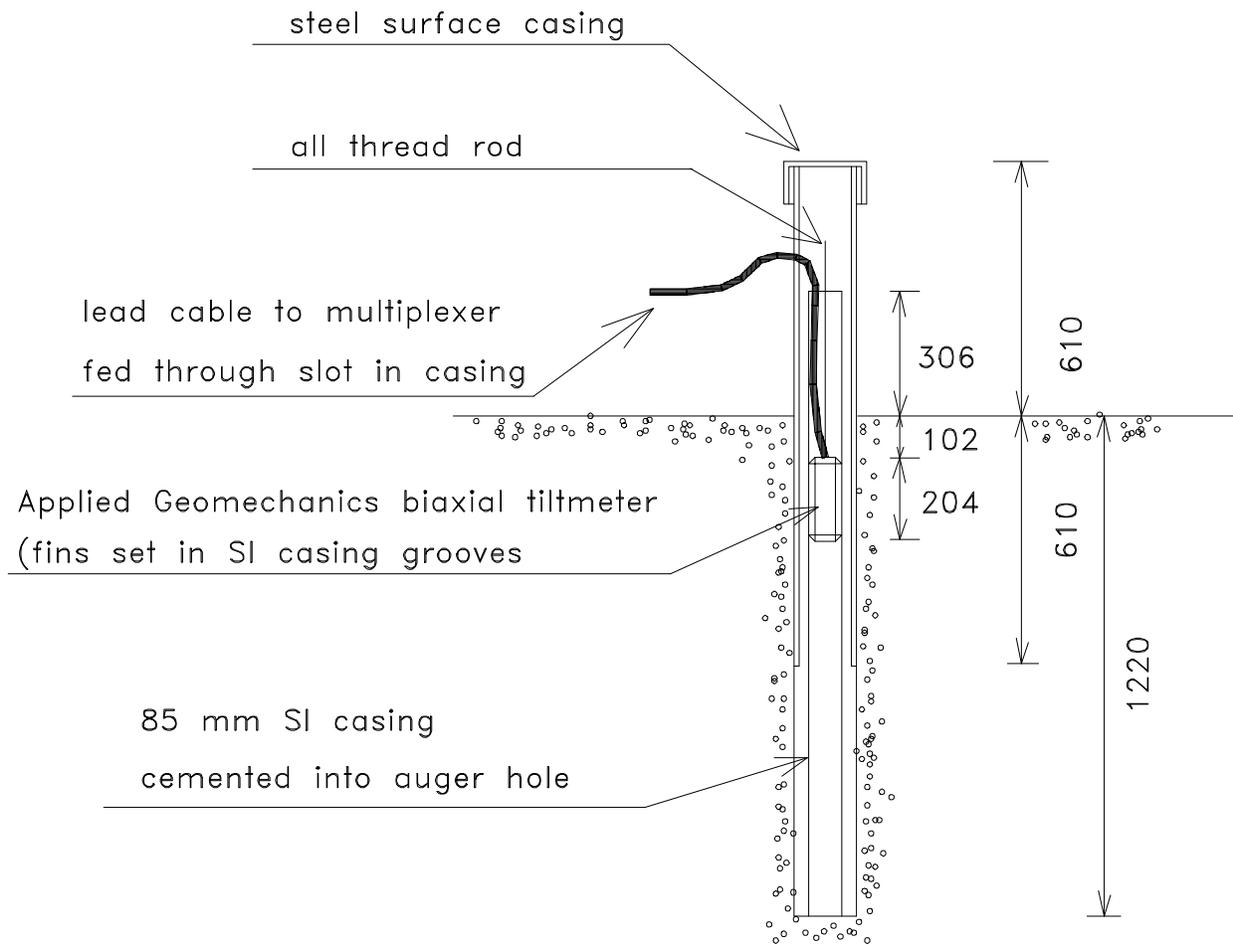
**Figure 2. View looking northeast at Zedeker Road overpass. The cast-in-place reinforced concrete blocks and wood cribbing were placed to provide additional support for the bridge deck. TDR-7 is located at the enclosure on the right side of the road.**



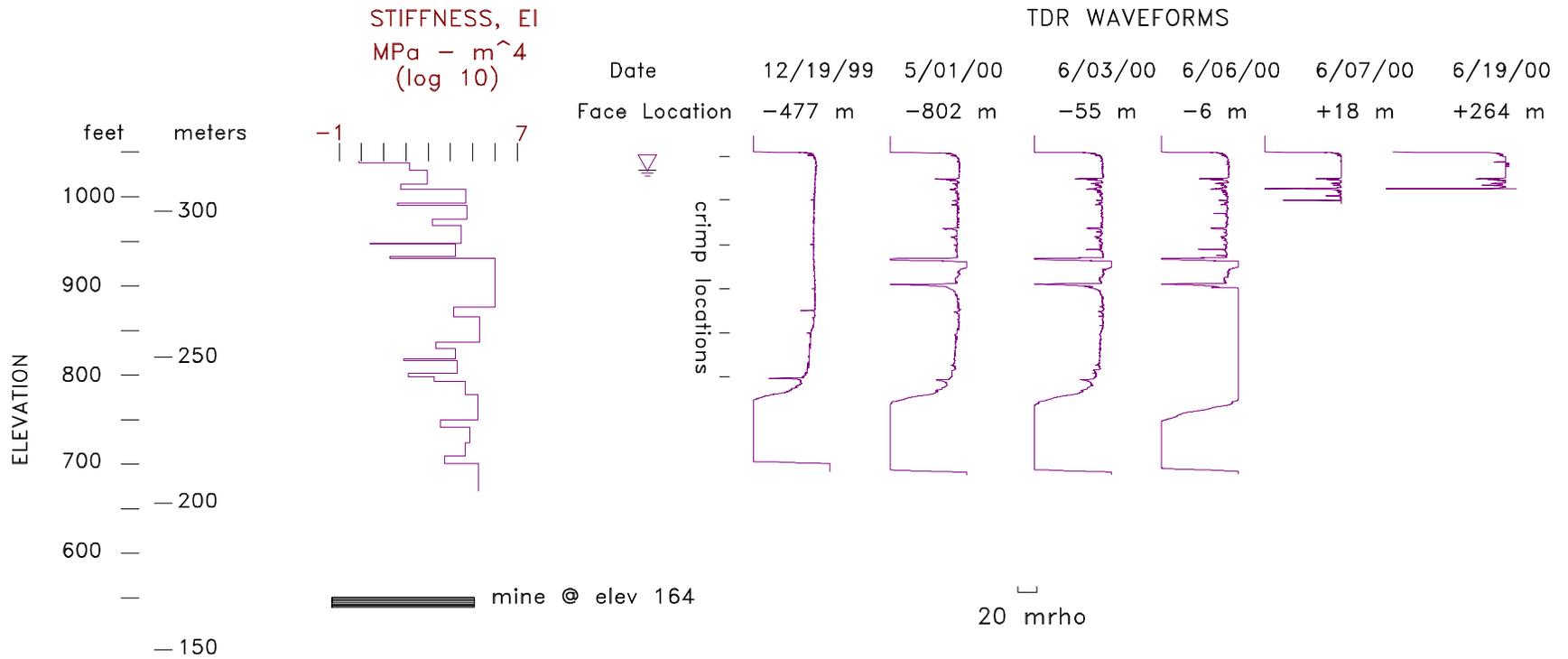
**Figure 3. Subsidence, tilt and curvature strain profiles along transverse cross section AA'. See Figure 1 for location. The solid lines are anticipated profiles and the dots are measured values. The fracture zone ultimately reached an equilibrium configuration**



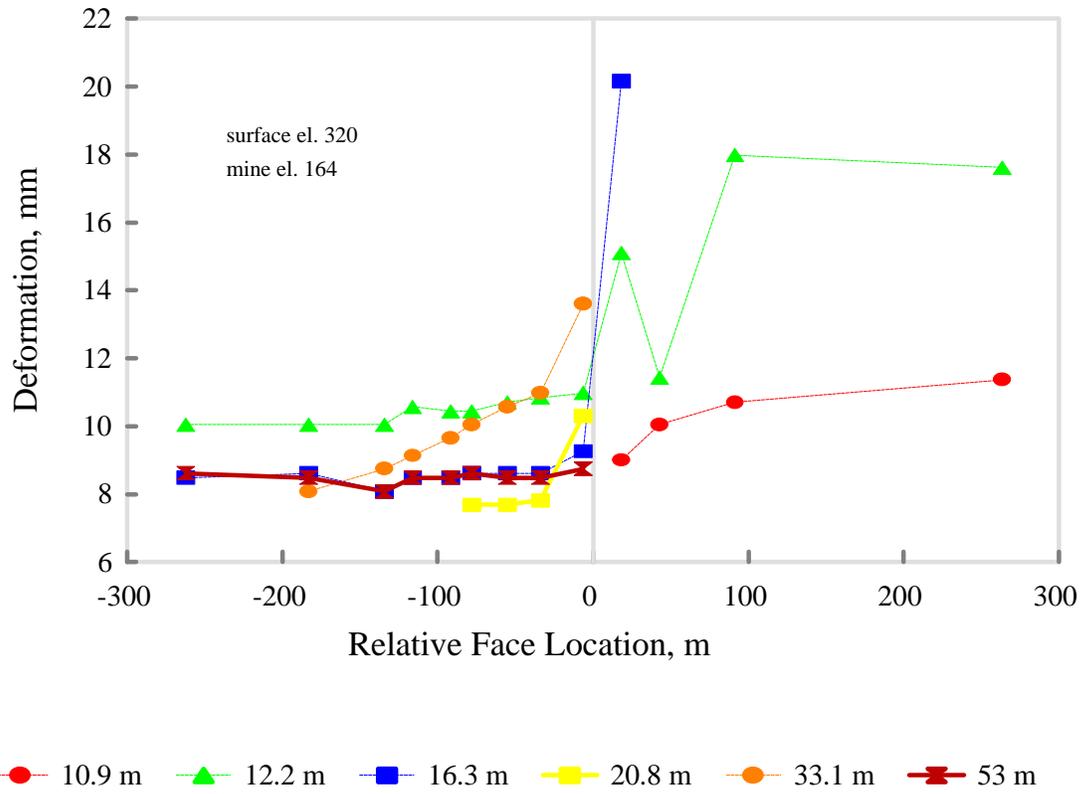
**Figure 4. Schematic of coaxial cable installation, and interrogation with a TDR cable tester.**



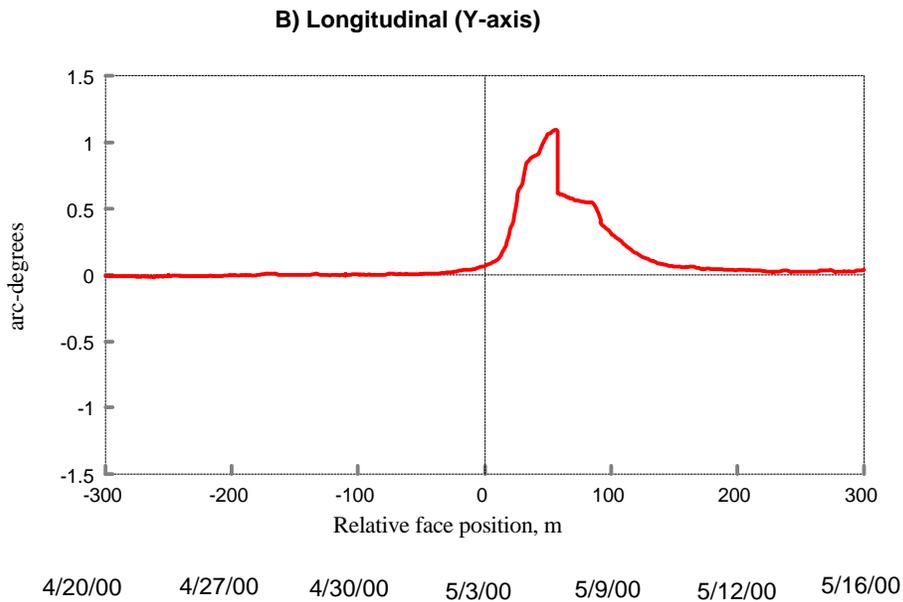
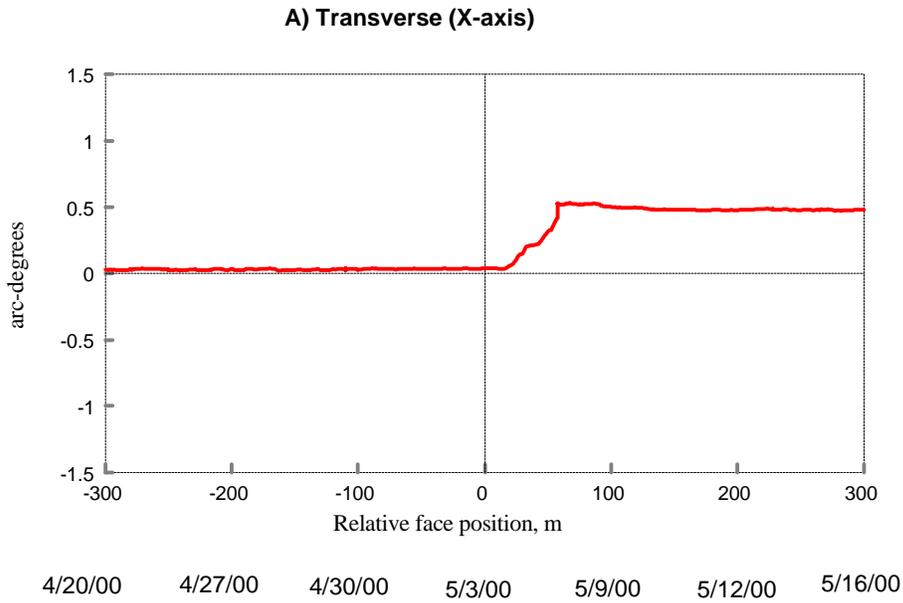
**Figure 5. Tiltmeter installation details with dimensions shown in millimeters.**



**Figure 6. TDR waveforms acquired at location TDR4. The TDR reflection spikes indicate where cable deformation occurred due to rock mass movement. They occurred at depths where there are stiffness discontinuities in the rock mass.**



**Figure 7. Time history of shear deformation in cable TDR4 at depths of 10.9 m, 12.2 m, 16.3 m, 20.8 m, 33.1 m, and 53 m.**



**Figure 8. History of tilt at location TL19 as the mine face advanced underneath this location; A, x-axis is transverse to the panel centerline and in the plane of Figure 3; B, y-axis is parallel to the panel longitudinal centerline and shows the steeper transient slope moving with the mine face.**



**Figure 9. Margin of final subsidence trough over the south edge of Panel 4 South. Note the guardrail in the right of the picture.**



**Figure 10. View looking northwest at the location where the 12 mm high compression bump developed. The asphalt was ground down to relevel the road surface.**

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