Overburden Deformation and Hydrologic Changes Due to Longwall Coal Mine Subsidence on the Illinois Basin

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ABSTRACT Subsidence-induced deformation and hydrologic changes were studied at two active longwall coal mines in Illinois using surveying and geotechnical monitoring. Surface subsidence characteristics fall into a range common to other Illinois longwall operations. Subsidence-induced water level fluctuations correlated with mining activity and the passing of the dynamic subsidence wave. Aquifer thickness and lateral extent affect these fluctuations. Bedrock water levels completely recovered at site 1 and partially recovered at site 2. Comparison of pre- and post-subsidence logs showed increased fracture frequency and decreased seismic velocities in the overburden at site 1. Deformation monitoring at site 2 showed only small vertical differential displacements within the overburden, suggesting a nearly uniform drop of the subsided rock mass and a caved zone extending less than 6 m above the mine. Mechanisms of overburden deformation observed at both sites include bedding separations and shear within incompetent formations.

INTRODUCTION

The purpose of this investigation is to characterize the surface expression, hydrologic impacts and overburden-deformation mechanisms of subsidence above active longwall coal mines in Illinois. Results from two mines are presented.

Site 1 is a 221-m deep operation in south-central Illinois. Site 1 was characterized before, during and after subsidence using core drilling, geophysical logging, surveying, in situ aquifer testing and geotechnical instrumentation monitoring.

Site 2 is a 122-m deep mine in southeastern Illinois. Investigations are still in progress, therefore only results from surveying and monitoring during subsidence are presented. Post-subsidence drilling and aquifer characterization at site 2 are planned.

SITE 1: 221-m DEEP LONGWALL OPERATION

Site 1 description

Site 1 is located in the flat to gently rolling farmland of south-central Illinois. The Herrin (No. 6) Coal seam, which is approximately three meters thick in this area, is
mined by the longwall method at a depth of 221 m. The overburden consists primarily of Pennsylvanian-age shales and siltstone overlain by six to eight meters of glacial drift. The aquifer monitored is a 26-m thick, laterally continuous argillaceous sandstone (Mt. Carmel Sandstone), located 21 m below the ground surface. Panel dimensions are 1524 m long by 183 m wide with 61 m between panels (double-chain pillars). Two adjacent east-west longwall panels were instrumented.

Site 1 monitoring program

Frost-protected survey monuments were installed 10.7 m apart (5% of depth of mining) in transverse and longitudinal lines over one panel to document dynamic and static surface subsidence and strain. Level surveys were performed using a WILD NA-2 with a micrometer; strain was measured with a tape extensometer.

Core holes were drilled before and after subsidence at the panel centerline. Both boreholes were inclined 10 degrees from vertical to intersect vertical joints and fractures. The pre-sub-sidence borehole was drilled to a depth of 214 m. Problems associated with loss of circulation prevented post-sub-sidence drilling below 158 m. Field description of drill cores included lithology, percent recovery, rock quality designation (RQD), and the fracture frequency of each 3.3-m core run. Geophysical logs including gamma ray, density and sonic velocity were run in the open boreholes.

Open-standpipe piezometers were installed in the glacial drift and the Mt. Carmel Sandstone aquifer to monitor the hydrogeologic effects of subsidence in these units. Drift and sandstone piezometers were positioned over the chain pillars, on the centerline and on the edge of the panel. Piezometric levels were monitored hourly using pressure transducers and data recorders.

The hydraulic conductivity of the sandstone aquifer was determined by in situ tests before and after subsidence. A pump test was conducted before and after undermining in a large-diameter well located at the panel centerline. Slug tests were performed in the piezometers before undermining and during active subsidence. Hydraulic injection tests were conducted in the pre- and post-sub-sidence inclined holes.

Time Domain Reflectometry (TDR) cables were used to document strain and fracture development in the overburden. Two 1.27-cm diameter unjacketed Cablewave System FXA 12-50 coaxial cables were grouted into deep boreholes at the center and edge of a panel. The cables were crimped at 6.1 m intervals to produce evenly-spaced signals that increase the resolution of distance measurements. Time domain reflectometry signals were monitored at regular intervals during and after subsidence. The mode of TDR cable deformation (shear or tension) was determined using the method of Dowding et al. (1988, 1989) and correlated with subsidence characteristics and lithology.

Site 1 results

Surface subsidence The transverse subsidence profile developed as mining progressed (Fig 1). Subsidence recorded at the center of the trough after one and one-half months was 1.89 m. Residual subsidence recorded after two years of monitoring is an additional 0.1 m for a total of 1.99 m. The ratio of maximum subsidence to extracted thickness at the transverse line of this panel is 0.69 or 69%. Subsidence of 0.40 m was observed over the chain pillars between the instrumented panel and the
previously-mined panel to the south. A 23-degree angle of draw was measured on the north side of the profile, where no previous mining had occurred.

Using static subsidence characteristics, maximum slope of 0.041 was calculated 38.16 m inside the edge of the panel (distance/depth ratio of 0.174). A maximum tensile strain of 0.0134 was measured 22.07 m inside the edge of the panel (distance/depth ratio of 0.101). The maximum surface compression is located 59.59 m inside the edge of the panel, which gives a distance/depth ratio of 0.272. These static subsidence characteristics at site 1 agree with values for the Illinois Basin published by Bauer & Hunt (1982).

**Geotechnical and geophysical logging** Figure 2 shows comparison of pre- and post-subsidence core logs. Core recovery was excellent before and after subsidence. Changes in the RQD of the respective cores was not unique to any particular lithology, but more a function of the position of mining-induced fracture zones within the overburden. Fracture frequency increased dramatically due to undermining (Fig 2).

A plot of changes in shear-wave velocity (Fig 2) shows four spikes that represent velocity decreases of 12 to 18%. These spikes directly correlate with coals and thin calcareous zones within the overburden. The general decrease of 1 to 10% in the shear-wave velocity throughout the rest of the overburden is the result of wave attenuation through a fractured medium filled with fluid.

**Water level response** Hydrographs from Mt. Carmel Sandstone-piezometers located on the centerline and chain pillars of the first panel are shown in Fig 3. Water levels declined as the mine face approached the instruments, reached maximum lows when tensile events passed, showed a temporary recovery spike as the maximum compressive strain passed, and then steadily recovered until passage of the mine face of

![Fig. 1 Transverse subsidence profile at site 1.](image-url)
FIG. 2 Comparison of pre- and post-subsidence logs from site 1 (Mehnert et al. 1990).
the adjacent panel. In each piezometer, maximum tensile events occurred when the mine face was 15 to 30 m past the instruments. Water levels from piezometers on the adjacent panel began to decrease when the approaching mine face was about 610 m away. Bedrock water levels recovered two or three months after undermining.

![Graph showing water level response at site 1](after Van Roosendaal et al. 1990).

Piezometric drops are caused by increased secondary porosity resulting from developing and opening fractures in the tensile part of the wave. Recovery occurs when the compressive part of the subsidence wave passes the piezometer, the fractures partially close and the cone of depression associated with the advancing longwall face (tensile event) moves away. The association between water-level fluctuations and dynamic-subsidence strains was also documented by Walker (1988).

Pre-subsidence hydraulic conductivities of $10^{-7}$ to $10^{-6}$ cm/s (shales), and $10^{-6}$ to $10^{-4}$ cm/s (sandstone) were measured by pump, slug and hydraulic injection tests. Post-subsidence values increased approximately two to three orders of magnitude for the shale and one order of magnitude for the Mt. Carmel Sandstone (Fig 2). The increase in hydraulic conductivity is attributed to mining-induced fracturing in the overburden (Booth et al. 1989). Drift water levels and local water-supply wells showed no appreciable change during mining.

Overburden deformation Figure 4 shows digitized TDR signals for the cable located at the panel edge. Each signal shows the crimps (every 6.1 m) and subsidence-induced changes in this cable for a particular mine-face position. Cable crimps and shear deformations produce sharp negative signals that increase in amplitude as deformation increases (see insert Fig 4). As shown in Fig 4, the cable located at the edge of the panel deformed in shear. Shear deformation occurred at interfaces between strong and weak lithologic layers or within weak layers such as claystones, to accommodate the bending deformation found near the edge of the panel. Shear signals increased in amplitude prior to cable failure, indicating the rate of deformation.
Terminal breaks in the cable progressed upward through the overburden as the mine face advanced. The cable at the centerline also showed shear deformation due to bending as the dynamic subsidence wave passed.

SITE 2: 122-m DEEP LONGWALL OPERATION

Site 2 description

Site 2 is located in the gently rolling farmland of southeastern Illinois, where topographic relief is 12 m. The overburden was monitored over a longwall mine working in the 1.7-m thick Herrin (No. 6) Coal seam at a depth of 122 m. Pennsylvanian-age shales and siltstones comprise the bulk of the bedrock overburden. The three to five meter thick Trivoli Sandstone aquifer, which is a medium-grained, slightly argillaceous and micaceous sandstone, is at a depth of 56.3 m. The Trivoli Sandstone has limited lateral extent at this site. Glacial deposits 24- to 27-m thick overlie the Pennsylvanian-age rocks. These glacial deposits consist of loess overlying glacial drift. Gravel is common at the base of the till.

One isolated east-west longwall panel was studied. The panel is 203.6-m wide by 2.4-km long. Double-chain pillars extend 61 m and 46 m from the north and south sides of the panel, respectively.

Site 2 monitoring program

Frost-protected survey monuments were installed 6.1 m apart (5% of mining depth) in transverse and longitudinal lines over the panel to document surface subsidence and
Overburden deformation and hydrologic changes

strain. Subsidence was monitored as described for site 1.

Piezometers were installed in a gravel unit at the base of the drift and in the Trivoli Sandstone. Drift and bedrock piezometers were positioned at the panel centerline, just inside the panel edge at the anticipated zone of maximum static tension, and over the chain pillars. Control piezometers were installed 206 m north of the panel edge. Water levels were monitored hourly using pressure transducers and data recorders.

A single 1.27-cm diameter TDR cable was installed in a 129.5-m deep borehole at the panel centerline. TDR monitoring was identical to the procedure followed at site 1.

Two six-anchor multi-position borehole rod extensometers (MPBX) were installed at the panel centerline to monitor vertical overburden deformation. The deep MPBX had grouted anchors every 6.1 m from 85.3 to 115.8 m, and at depths of 36.6 to 67.1 m for the shallow MPBX. Extensometers were measured and the elevation of the MPBX reference heads were surveyed three to four times daily during active subsidence.

Site 2 results

Surface subsidence Maximum subsidence measured at the center of the panel is 1.37 m. The ratio of maximum subsidence to extracted thickness is 69 percent.

An examination of the static subsidence profile gives a maximum tensile strain of 0.021 located 13.4 m inside the north edge of the panel (distance/depth ratio of 0.110). A maximum surface compressive strain of 0.0146 was measured 43.9 m inside the panel edge (distance/depth ratio of 0.360). The maximum slope of 0.0396 is located 31.7 m inside the south panel edge (distance/depth ratio of 0.26).

Water level response The water level response of two Trivoli Sandstone piezometers and one glacial drift piezometer is plotted in Figs 5 and 6. Trivoli Piezometer 2 (TP2) (Fig 5) is located 271 m from the transverse survey line at the panel centerline. Drift Piezometer 2 (DP2), and Trivoli Piezometer 3 (TP3) are on the transverse line and within the maximum static tensile zone at the panel side (Fig 6). In each figure, face positions are plotted relative to the location of the piezometers.

Water levels in the Trivoli wells began to decline when the mine face was about 457 m away and then partially recovered after subsidence occurred. Trivoli Piezometer 2 (Fig 5) experienced a rapid response because the face advance was continuous when it was undermined. Trivoli Piezometer 3 (Fig 6), however, showed a prolonged and irregular depression. The mine advance was slow and sporadic when these wells were undermined. Water levels partially recovered during periods of mine inactivity.

The water-level fluctuations of DP2 (Fig 6) are typical of all drift piezometers installed in the basal gravel regardless of position relative to the mine panel.

Overburden deformation Absolute anchor displacements for the shallow and deep MPBXs and surface subsidence are plotted against time in Fig 7. The largest relative displacement between any anchor and the reference head was 15 cm. The relative strains between anchors were less than one percent for all extensometers. The extensometers clearly show no evidence of large vertical differential displacements in the overburden to within 6.1 m of the mine roof. Therefore, the caved zone extends less than 6.1 m above the mine, or less than 3.3 times the mined height. The caved zone is within the values of two to eight times the mined height predicted by Peng & Chiang (1983). At the panel centerline the overburden rocks subsided as a fairly contiguous mass without caving or large bedding separations.
The TDR cable at the centerline deformed predominantly in shear. The cable showed subsurface movements about 61 m in advance of the moving face, agreeing with results presented by Dowding et al. (1989) from another Illinois longwall mine. Shear breaks correlate with weak lithologies and pre-existing joints. No clear correlation exists between the location of TDR cable deformation and the amount of differential strain between MPBX anchor positions. Cable deformation took place in the glacial drift as well as in the bedrock overburden.
CONCLUSIONS

(a) The surface expressions of longwall mining observed at these sites are typical of those experienced in the Illinois Basin.

(b) Piezometric levels in the overburden decreased as fractures developed due to the tensile portion of the dynamic (traveling) subsidence wave. Recovery began when the fractures closed due to the compression portion of the wave; the mine face advance carried away the cone of depression associated with the dynamic tensile event.

(c) At site 1 water levels in the shallow Mt. Carmel Sandstone aquifer recovered within two to three months. The thickness and lateral extent of this aquifer facilitated the rapid recharge to the newly created fractures. At site 2 water levels in the deep Trivoli Sandstone aquifer, however, have only partially recovered. This thin, discontinuous sandstone does not have sufficient storage capacity to recharge the fractures.

(d) Mining increased the bedrock hydraulic conductivities at site 1 by two to three orders of magnitude in the shale, and one order of magnitude for the Mt. Carmel Sandstone, producing improved aquifer characteristics.

(e) Fracture development in the overburden at site 1 was documented by a decrease in RQD and shear-wave velocity, and an increase in fracture frequency and hydraulic conductivity. Time domain reflectometry (TDR) signals indicated shear deformation between strong and weak lithologic layers near the panel edge.

(f) Bedrock deformation monitoring on the panel centerline at the shallower site 2 shows shear deformation 61 m in advance of the mine face and only minor differential vertical deformation. The overburden subsided as a contiguous rock mass with a caved zone within the size range predicted by Peng & Chiang (1983).
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REFERENCES


