

THE PRACTICAL APPLICATION OF SUBSIDENCE PREDICTION IN THE ILLINOIS COAL BASIN

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Abstract

The need for predicting mine subsidence derives from the damaging potential of the ground movements. The mining of coal underground can create vertical and horizontal movements at surface level, which are manifested as induced slopes, curvatures and strains. The slopes and strains damage surface or underground features, such as houses and buildings, power lines, pipelines, crops, or aquifers. Under present technological and economic conditions, subsidence prevention above longwall mines is not feasible. Nonetheless, it has been demonstrated, particularly in Europe, that surface subsidence can be predicted and controlled, thereby lessening the adverse effects of ground movements. With a reliable prediction technique available, subsidence can be predicted as part of the mining plan and, if environmentally or economically unacceptable situations are foreseen, remedial measures can be implemented. However, to be useful, the technique must be able to predict all of the components of subsidence as well as the damaging manifestations, i.e., vertical and horizontal movements, slopes, curvatures and strains. This paper presents research, conducted by the Bureau of Mines, on modifying the influence function method to predict subsidence of the ground surface. The application of the technique then is demonstrated for the prediction of pre-subsidence and post-subsidence shoreline contours around Rend Lake, IL, the prediction of induced slopes as it relates to crop or power line damage, and the prediction of curvature for the estimation of structural damage.

Introduction

The mining of coal underground can create vertical and horizontal movements at surface level, which are manifested as induced slopes, curvatures and strains (Shadbolt, 1978; Singh, 1978). These slopes and strains damage surface or underground features, such as houses and buildings, power lines, pipelines, crops, or aquifers. Under present technological and economic conditions, subsidence prevention above longwall mines is not feasible. Nonetheless, it has been demonstrated, particularly in Europe, that surface subsidence can be predicted and controlled, thereby lessening the adverse effects of ground movements (Kratzsch, 1983; Triplett, 1983). With a reliable prediction technique available, subsidence can be predicted as part of the mining plan and, if environmentally or economically unacceptable situations are foreseen, remedial measures can be implemented. However, to be useful, the technique must be able to predict all of the components of subsidence as well as the damaging manifestations, i.e., vertical and horizontal movements, slopes, curvatures and strains.

This paper presents research, conducted by the Bureau of Mines, on modifying the influence function method to predict subsidence of the

ground surface. The required functions have been determined for two case studies of subsidence above longwall coal panels in Illinois. However, the goal of subsidence engineering is not to predict subsidence, but to predict and mitigate subsidence damage. Therefore, the technique has been enhanced to calculate slope and curvature, and a method has been developed to predict strain using these curvatures and a simply measured site constant. The application of the technique then is demonstrated for the prediction of pre-subsidence and post-subsidence shoreline contours around Rend Lake, IL, the prediction of induced slopes as it relates to crop or power line damage, and the prediction of curvature for the estimation of potential structural damage.

Linear Equations in Cause and Effect

Linear equations frequently can be used to model physical problems in which the effects of several causes are to be superimposed. In these problems, a distribution of causes, $c(\xi)$, is assumed to exist over the volume, V , in a homogeneous region, \mathcal{R} , and the resultant distribution of effects, $e(x)$, is to be determined. The variables x and ξ are defined as representing position in space of any dimension within some interval in the region \mathcal{R} . Assuming superposition is valid, the total effect at a point x due to a distribution of causes within the entire region is (Hildebrand, 1965):

$$e(x) = \int_{\mathcal{R}} G(x, \xi) c(\xi) dV. \quad (1)$$

The function $G(x, \xi)$ is called the influence function of the problem and represents the effect at x due to a unit concentrated cause at ξ .

From these considerations, and the explanation of the procedure as given by Brauner (1973), the intensities previously used for subsidence prediction can be represented by a step function equal to one over the extracted area and equal to zero elsewhere. Employing a step function for the intensities may be appropriate under the conditions for which the influence function approach was first applied, that is, for stowed panels. However, the intensity function must be modified for caved panels (Triplett and Yurchak, 1990a). The total caving region can be represented in two dimensions by an intensity function which changes across the width of the panel, thereby incorporating such factors as the break angle of the immediate roof, incomplete convergence near the edge of the panel, and convergence of the entries adjacent to the mined panel. This function is similar to those assumed by other researchers when implementing corrections to the influence function approach (Berry and Sales, 1962; Kratzsch, 1983; Adamek and Jeran, 1985; Heasley and Saperstein, 1986). However, the inclusion of this function is not a correction; rather, Equation 1 requires that the intensities of the causes be represented by $c(\xi)$. The intensity functions shown in Figure 1 are given as a ratio of the maximum subsidence. Even though the intensities shown vary along one dimension, the function actually varies across both the width and length of the panel, and necessarily represents the geometry of the mining plan.

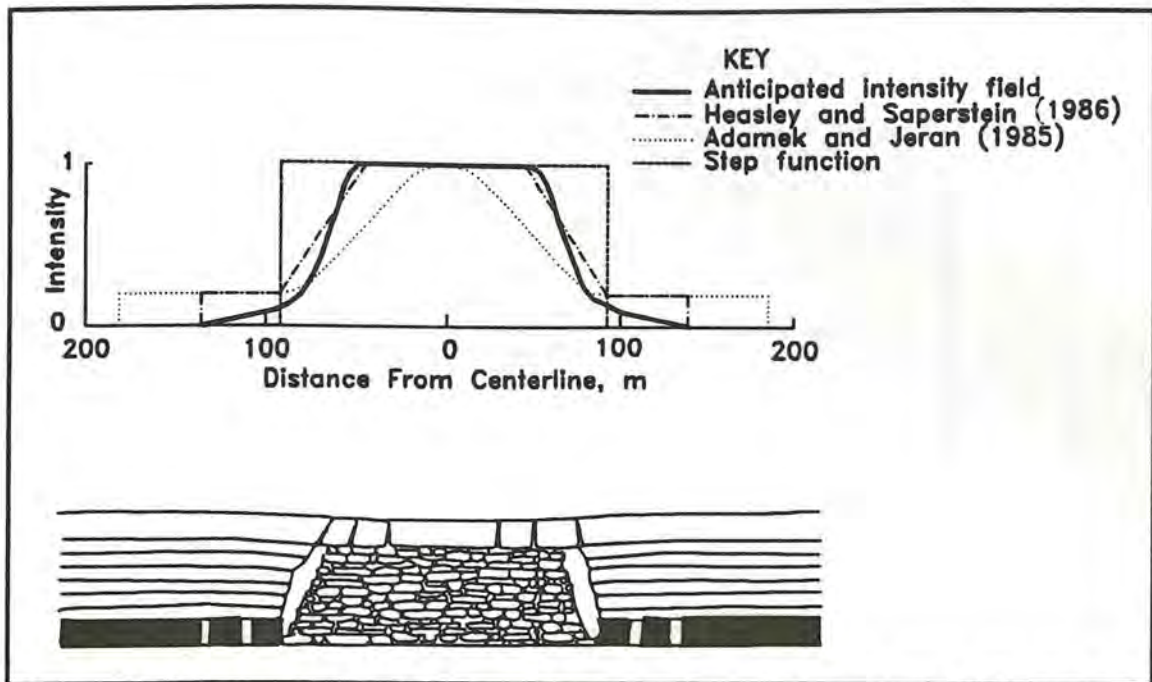


Figure 1 Various intensity functions for longwall caving (Triplet and Yurchak, 1990a)

Determining the Influence and Intensity Functions for a Longwall Panel

Field data from southern Illinois were used to demonstrate the influence function approach. In the first case study, a 850 ft wide and 625 ft deep panel was mined from west to east in the 8 ft thick Herrin #6 seam. In Figure 2, subsidence data above the longwall panel were matched using the influence function:

$$G(x_1, \xi_1, x_2, \xi_2) = \frac{nS_{\max}}{B^2} \exp \left[-n\pi \left(\frac{(x_1 - \xi_1)^2 + (x_2 - \xi_2)^2}{B^2} \right) \right] \quad (2)$$

with n equal to 3 (Triplet and Yurchak, 1990a). The corresponding intensity field was:

$$\begin{aligned}
 c(y) &= 0.00106y & y &= 0 \text{ to } 155 \\
 &= 0.91 - \{0.043 / (0.05 + 0.81e^{-0.085(297-y)})\} & y &= 155 \text{ to } 297 \\
 &= 0.86 + 0.00459(y-90.5) & y &= 155 \text{ to } 397 \\
 &= 1 & y &= 397 \text{ to centerline}
 \end{aligned} \quad (3)$$

where y in feet corresponds to the ξ_1 direction and is measured toward the panel centerline from the point of no convergence, found by matching the data to be 150 ft into the entries beside the edge of the panel. The radius of the influence function, B , consequently was 150 ft. This function is similar to that shown by the solid line in Figure 1. Assuming the validity of the intensity field, the caving characteristics within the extracted area close to the edge seem to be important, since the intensity function is small in this area. These characteristics may include the

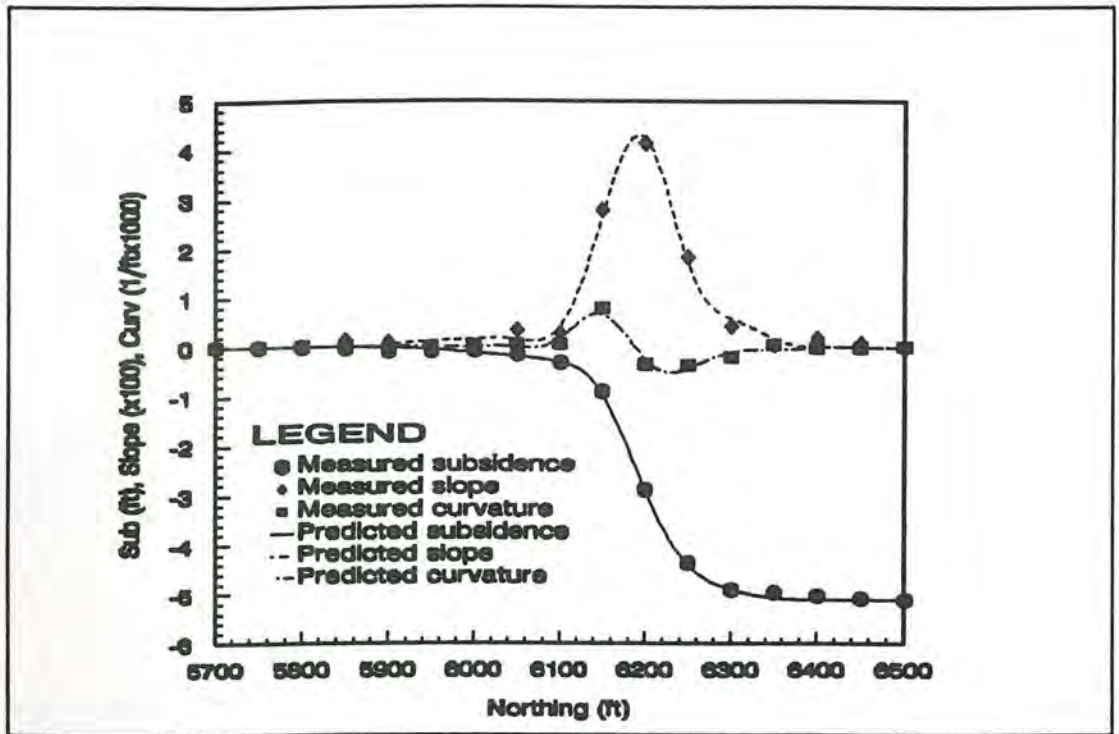


Figure 2 Measured and matched subsidence, slope and curvature for case study 1

shape of the caving zone and incomplete convergence near the edge. Also, the effect of chain pillar convergence is evident, since the intensity function is non-zero for some distance outside the edge of the panel.

The accuracy of this process is increased by matching the measured slope and curvature with the first and second partial derivatives of Equation 1. For example, the derivatives with respect to the northing, or x_1 , direction are:

$$\frac{\partial s(x_1, x_2)}{\partial x_1} = \int_{\mathbb{R}} \frac{\partial G(x_1, x_2, \xi_1, \xi_2)}{\partial x_1} c(\xi_1, \xi_2) d(\xi_1, \xi_2) \quad (4)$$

$$\frac{\partial^2 s(x_1, x_2)}{\partial x_1^2} = \int_{\mathbb{R}} \frac{\partial^2 G(x_1, x_2, \xi_1, \xi_2)}{\partial x_1^2} c(\xi_1, \xi_2) d(\xi_1, \xi_2) \quad (5)$$

where $s(x_1, x_2)$ is the subsidence at the surface. In these equations, ξ_1 and ξ_2 represent the northing and easting coordinates of a mine level point, and the above integrals are taken over the area in which intensities occur. Since x_1 and x_2 represent the northing and easting coordinates of a surface point, Equation 4 yields the slope and Equation 5 yields the curvature along a surface subsidence profile in the x_1 direction. If both the influence and intensity functions chosen to match

the measured subsidence are correct, then the slopes and curvatures given by Equations 4 and 5 should match the slopes and curvatures calculated along the measured profile. As a check, the first and second derivatives of the influence function were taken in the x_1 direction, and the predicted slopes and curvatures were compared with actual values produced by the derivatives of a fifth-order spline function fit to the subsidence data (Figure 2). The ability of these functions to predict the slopes and curvatures suggests that the functions are appropriate for this case study.

Figure 3 shows subsidence data of a second case study above another longwall panel in the same mine. The panel was 850 ft wide and 520 ft deep, with a mining height of about 7.5 ft. The subsidence data were matched using an influence function identical to that found for the first case study, except the radius of influence is decreased from 150 ft to 130 ft due to a shallower mining depth. The corresponding intensity field was:

$$\begin{aligned}
 c(y) &= 0.0007y && \text{for } y = 0 \text{ to } 141 \\
 c(y) &= .96 - (.028 / (.03 + .9e^{-198(283-y)})) && \text{for } y = 141 \text{ to } 283 \quad (6) \\
 c(y) &= .93 + .00244(y-86.3) && \text{for } y = 283 \text{ to } 377 \\
 c(y) &= 1 && \text{for } y = 377 \text{ to centerline}
 \end{aligned}$$

where y in feet is assumed to be 132.5 ft into the entries beside the edge of the panel. Again, the accuracy of the match was increased by comparing the slopes and curvatures as well as the subsidence (Figure 3).

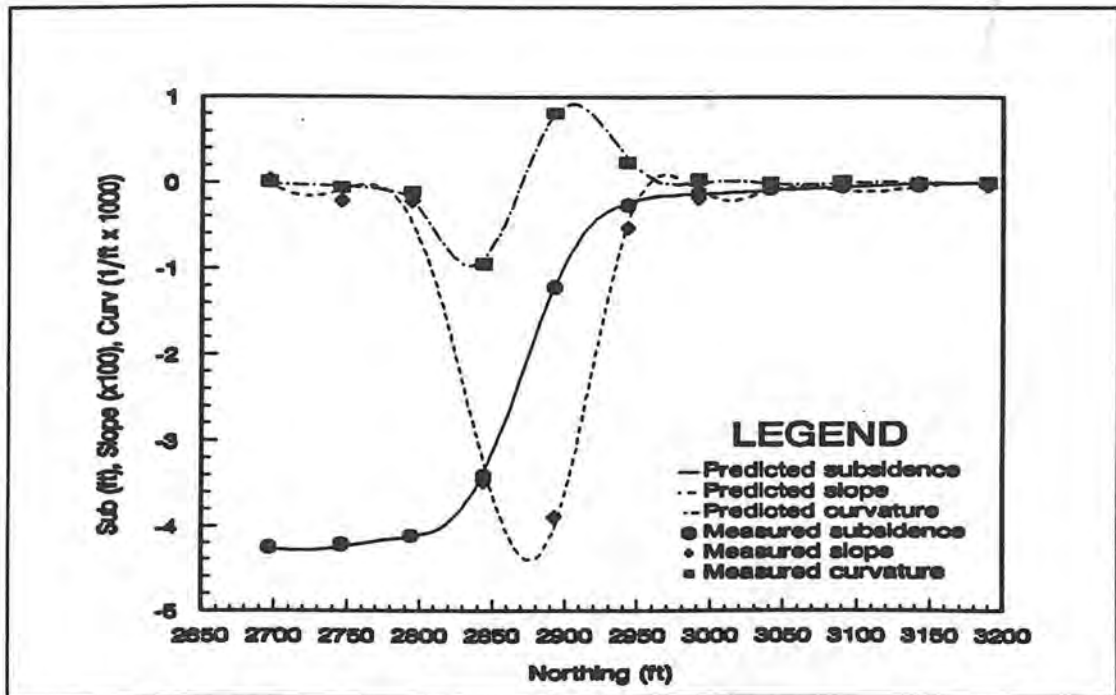


Figure 3 Measured and matched subsidence, slope and curvature for case study 2

The subsidence data was matched empirically for these case studies, with the intensities being a function of the geometry of the mine and time.

The difference in the intensity functions for these two case studies may be the result of the timing of the data collection. The subsidence profile for case study 2 was measured before the residual movements of the trough were completed; therefore, the profile is expected to change with time. However, the ability of the technique to match subsidence profiles for different times during and after undermining establishes the potential of including a time parameter in the calculations. This facility easily could be incorporated into the prediction program by including various intensity functions based on the mine geometry at any given time.

Application of Subsidence Prediction

As explained by Shadbolt (1978) and Singh (1978), damage to structures by subsidence is due to at least one of the following components:

Vertical displacement (subsidence) affects structures that depend on the retention of a given level, i.e., dams, water courses and drainage patterns, water tables, etc.

Differential subsidence (slope) affects all gradient-sensitive structures, in particular tall buildings, railroad tracks and highways, storage tanks and gravity drainage systems.

Differential slope (curvature) causes shear and bending stresses to all structures and its intensity is sufficient to produce substantial damage.

Horizontal strain is the major cause of structural damage, inducing tensile or shear cracks and buckling, which may cause distortion, fracture or failure.

Because of these different manifestations of subsidence, a prediction technique must produce not only the vertical displacements, but also the induced slopes and curvatures. Following are several examples which use the influence function technique to predict these quantities.

Vertical Displacement and Subsidence Contours

The results of subsidence prediction are most commonly given in the form of a subsidence profile over a single longwall panel. Even though this information may be valuable, the usefulness of the data is enhanced if the subsidence is predicted over a spatial area, particularly if post-subsidence contours are calculated from pre-subsidence contours and the predicted subsidence. An example of this capability is given by a case study around Rend Lake in southern Illinois. A longwall panel was being mined under the lake, and the coal company needed to predict the post-subsidence lakeshore contour. Figure 4 shows the panel layout. To predict the subsidence above this panel, the diverse geometries were represented by an intensity function which varied above the panel and was based on those previously described. The influence function in Equation 2 was used, with the area of influence being changed due to a change in depth. The southern edge is particularly complicated, and three zones were identified and modeled. The first zone was adjacent to a previously mined panel; therefore, only the additional subsidence from mining the new

panel had to be predicted. The second zone included the four-entry system in the chain pillars beyond the mined-out area, and the third zone included the three-entry system. Figure 5 shows the pre- and post-subsidence contours, with the 410 foot contour line representing the lakeshore.

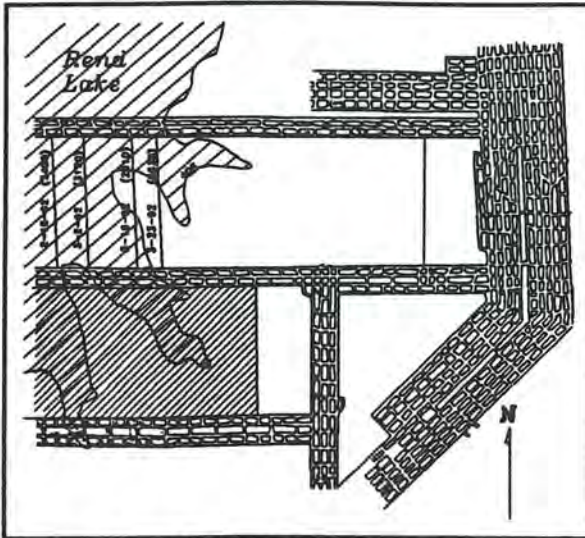


Figure 4 Plan of eastern end of longwall panel under Rend Lake

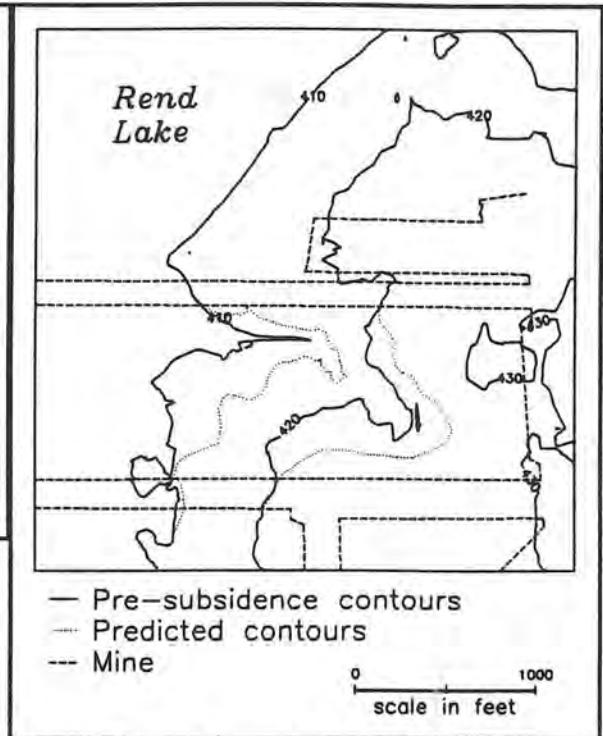


Figure 5 Pre- and post-subsidence contours of Rend Lake

Differential Subsidence, or Slope

As shown by the above example, the simple prediction of subsidence can be a valuable product. However, several researchers have demonstrated that, under certain conditions, slope is the prominent damaging manifestation of subsidence. The harmful effects of slope on high-tension power lines is described by van der Merwe (1992), while the impacts of slope on crop yield is given by Darmody et al (1988). Powell and Triplett (1988) and Kratzsch (1983) also defined tilt in a structure as a damage. Figure 6 shows two longwall panels in western Kentucky which are undermining farmland and high-tension power lines. In this case, induced slopes could damage crops or power lines directly, or could adversely affect drainage. Subsidence was predicted by representing the entire mine by a varying intensity function and using the influence function given in Equation 2, since the geology was nearly identical. Again, the area of influence being changed due to a change in depth. Figures 7a-b show the slopes for the northern 1/3 of the study area before mining, and after the mining of both panels. Because the subsidence and slopes could be predicted for any time, this example also demonstrates that the technique could be used for dynamic subsidence prediction. Figure 8 demonstrates the effect of subsidence on drainage by tracing the paths which water droplets would follow before and after subsidence, showing the potential for ponding after mining these panels.

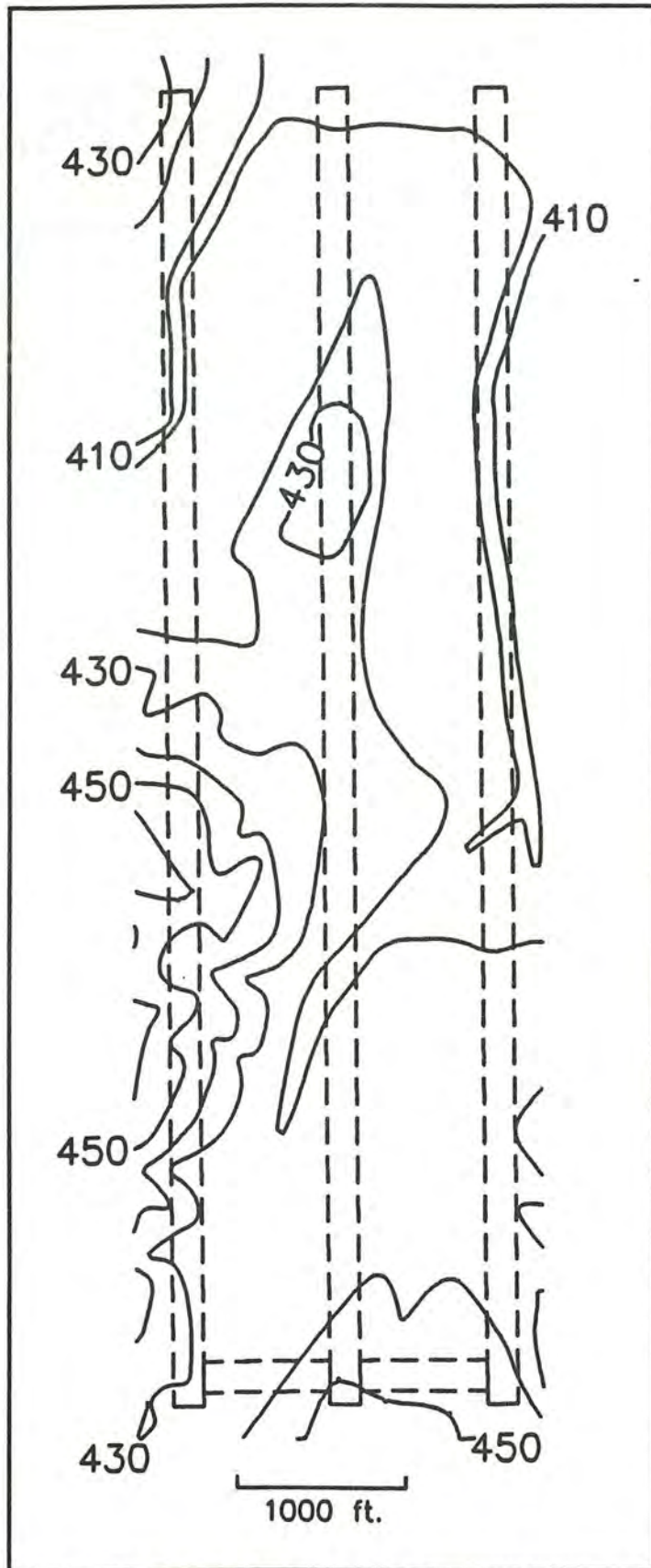


Figure 6 Panel layout for longwall mine in western Kentucky

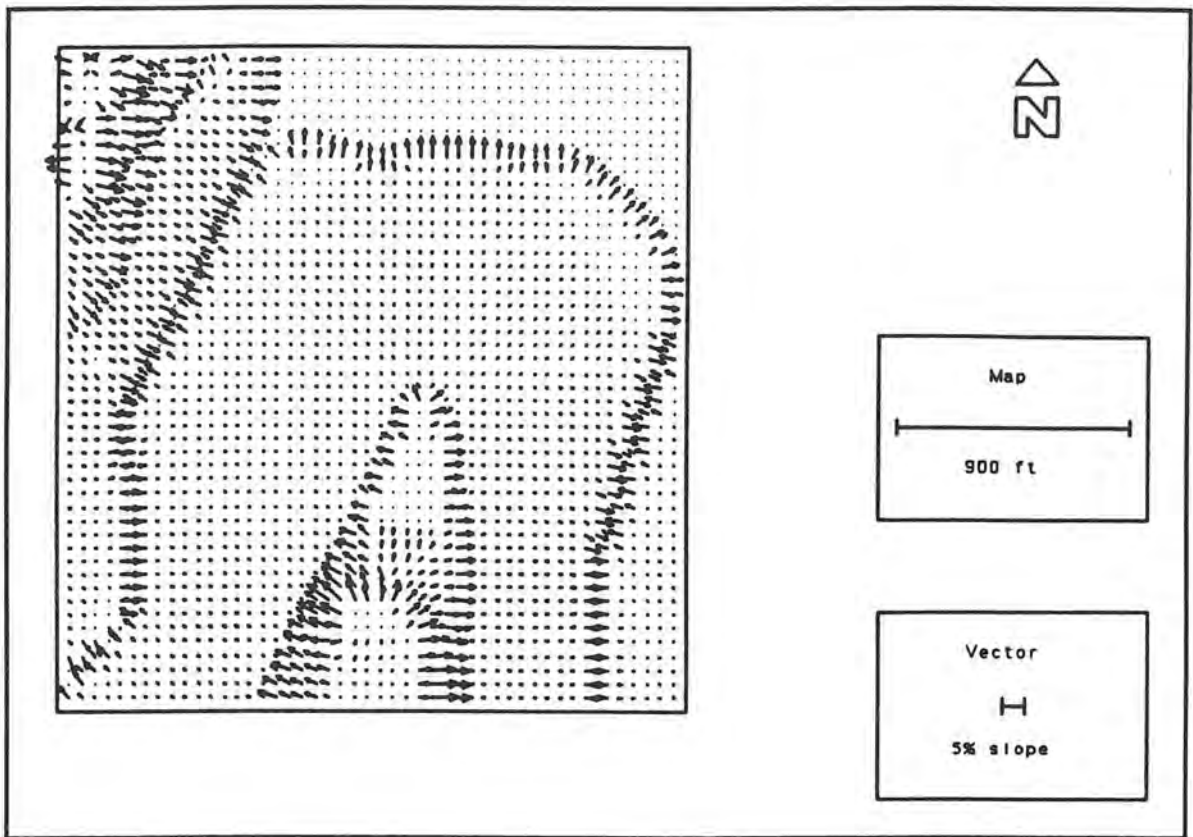


Figure 7a Pre-subsidence slope vectors

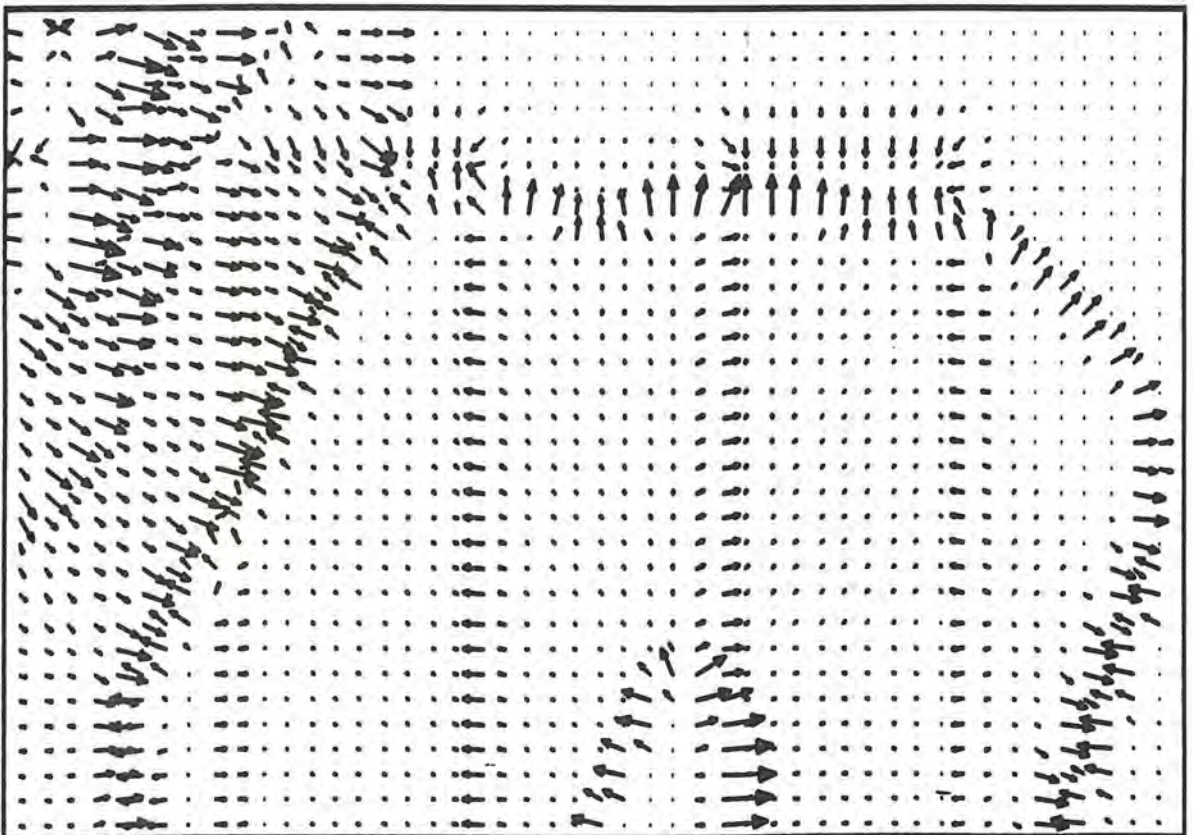


Figure 7b Detail of post-subsidence vectors after mining of both panels

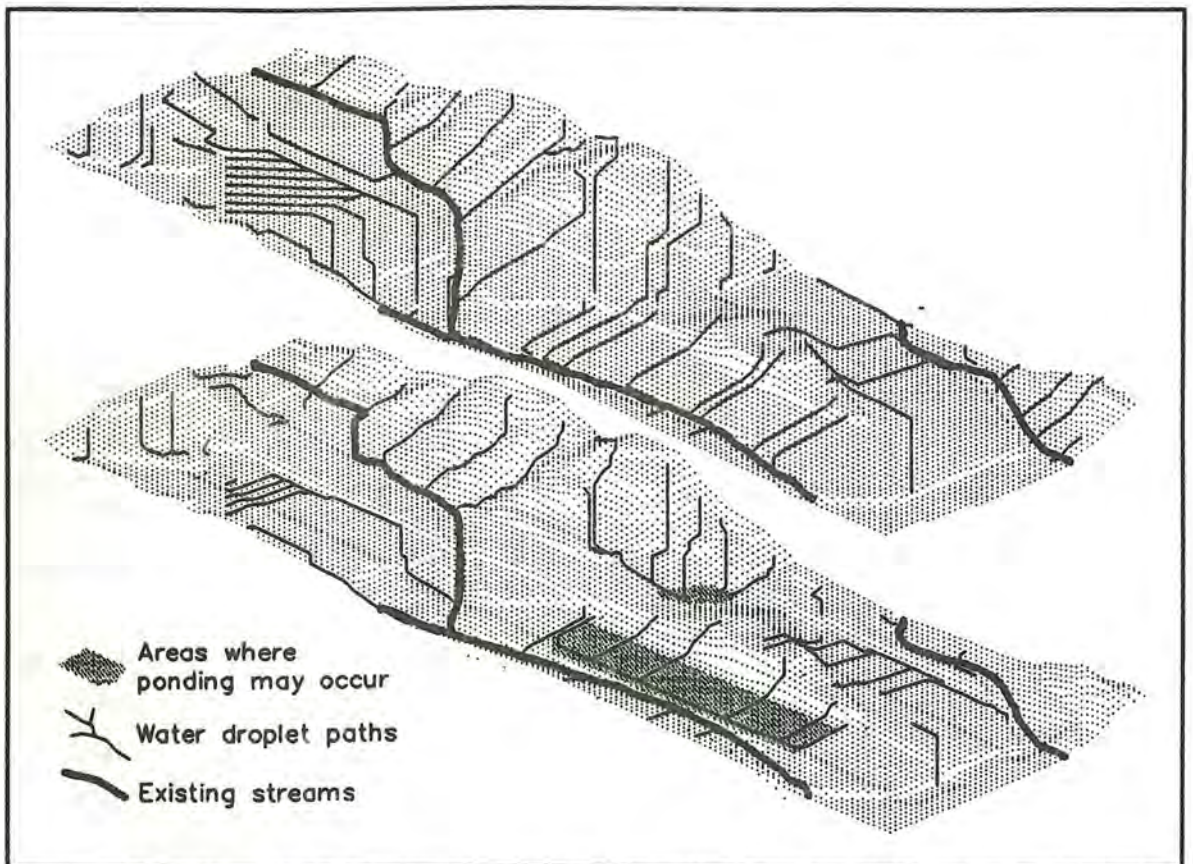


Figure 8 Water drainage patterns before (top) and after mining (bottom)

Differential Slope, or Curvature

Shadbolt (1978) and Singh (1978) described the impacts of curvature on structures. The harmful effects of curvature on various foundations also is described by Bennett et al (1992). An example of the value of curvature predictions can be given for the case study around Rend Lake shown in Figure 4. In this case, a levee was to be built to protect the land from inundation. Unfortunately, the Corps of Engineers could not design the levee in time to build the structure before undermining. However, the area was monitored and post subsidence contours will be compared to those predicted. Nevertheless, the case study can be used to demonstrate the use of subsidence prediction. The contours in Figure 6 could be used for siting the levee. However, this structure was to be constructed before undermining; therefore, the levee could be damaged by horizontal strain. Triplett et al (1992) showed that the strain from subsidence at one site in Illinois was due to bending. These findings have been duplicated in other areas of Illinois, particularly by Van Roosendaal, et al (1992). Thus, areas of high strain can be located by predicting areas of high curvature. Figure 9 shows the curvature profiles for cross-sections in the three different zones described earlier. Since the geometric conditions along the northern edge of the panel do not change, the curvatures are identical in all three zones. However, the curvatures do vary along the southern edge of the panel. Even though the maximum values of curvature are similar, the location of the maximum curvature does change, and should be considered when siting the levee.

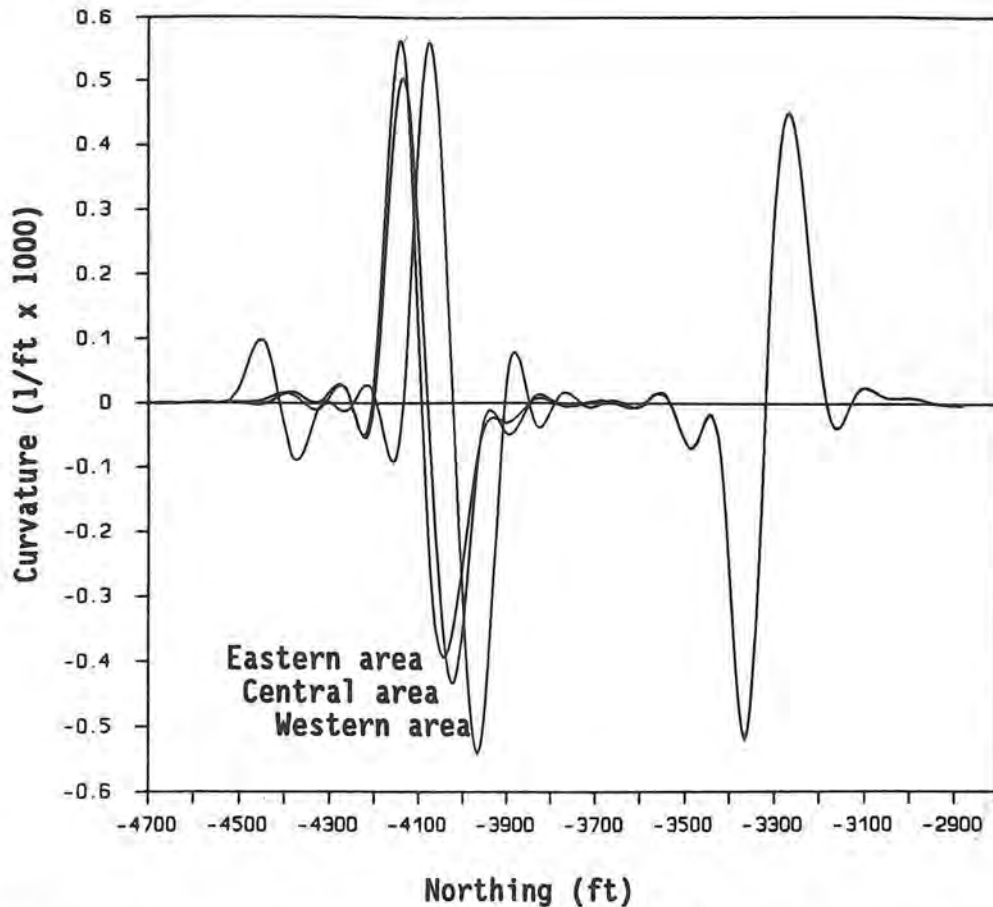


Figure 9 Curvature profiles for three different geometrical mining conditions

Conclusions

This paper presents research on modifying the influence function method to predict subsidence of the ground surface. The required functions were determined for two case studies of subsidence above longwall coal panels in Illinois. However, the goal of subsidence engineering is not to predict subsidence, but to predict and mitigate subsidence damage. Therefore, the technique was enhanced to calculate slope and curvature. Possible applications of the technique then were demonstrated for the prediction of pre-subsidence and post-subsidence shoreline contours around Rend Lake, with these predictions currently being verified by subsidence monitoring. Induced slopes above two adjacent longwall panels in western Kentucky were predicted to assess crop or power line damage, and the potential for ponding was identified. Finally prediction of curvature for the estimation of structural damage in siting of a levee was demonstrated.

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