SDPS for Windows: An Application for Subsidence Prediction, Optimum Mine Design and Environmental Control.

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Abstract

The impacts of underground mining on the surface are important mining and environmental considerations in the permission and planning of coal mining operations. As a result, the development of rigorous and well-accepted procedures for predicting ground movements and assessing mining impacts on surface structures and facilities is an important component of subsidence control. This task can be extremely complex due to the number and nature of the parameters affecting ground deformation induced by underground mining, as well as the interaction of geotechnical and structural factors determining the response of structures to such movements. In this paper different mining planning and subsidence control options are explored in order to select the optimum design for an underground coalmine. The analytical work is based on the latest version of the influence function formulation of the Surface Deformation Prediction System (SDPS). In its current format, the SDPS package exploits all the benefits of the MS Windows platform and has a direct interface to CAD software, thus facilitating input and output. The package also features advanced calibration routines to handle predictions over specific regions. Results for a specific case study will be presented to illustrate the application of this tool in subsidence damage assessment involving a significant number of surface structures.

Introduction

Surface subsidence is an important environmental consideration of active, as well as abandoned, mine operations. The damages attributed to this phenomenon include land settlement and fracturing, structural damage to surface building, disruption of ground water reservoirs, etc. The prediction of ground movements due to underground mining, the assessment of their impact on the surface and, finally, their control within acceptable environmental limits, are important considerations of underground coal mining.

The surface area above an underground excavation within which ground movements are significant and have the potential of causing damage to structures and facilities, is called the surface influence area. Since the subsidence profile diminishes to extremely small values far before it reaches the edge of the subsidence basin, it follows that this angle is of limited value in subsidence control (Peng 1992). Furthermore, the concept of "zero" subsidence is rather difficult to measure or implement. In many cases, the measurable level is defined by the accuracy of the surveying equipment. Modern total surveying stations can reach accuracies of at least 0.01 ft (0.12 in or 3 mm) for elevations. If such a cutoff value is adopted for defining the borderline of zero subsidence, then this value is independent of the seam thickness, and subsequently the subsidence factor, for a particular location. For example, a cutoff value of 0.01 ft for a 10-foot (3 m) thick panel is 0.1%m (where m is the seam or extraction thickness), whereas it is 0.2%m for a 5-foot (1.5 m) thick seam. Similarly, when the cutoff value is presented as a function of maximum subsidence Smax, which is a function of panel dimensions and overburden geology, then this may result in actual elevation sensitivities ranging from 0.02 to 0.005 ft (6.1 to 1.5 mm). In this respect, a better approach may be to define a minimum, "measurable", subsidence level as a reference point or even a "limit angle" defined as the angle between the vertical at the panel edge and the line connecting this edge to a surface point experiencing measurable vertical movement (Agioutantis and Karmis, 1998; Karmis *et al*, 1995).

Deformation Parameters as Related to Potential Damage

Damage to surface structures, especially buildings, is mainly caused by tilt, angular distortion (as related to differential settlement), bending (differential tilting) and horizontal strain, or a combination of these effects (Singh, 1992). Surface movements caused by underground mining are usually described by a number of characteristic indices, including: vertical displacement or subsidence, horizontal displacement or lateral movement, slope or tilt, horizontal strain, ground strain, and vertical curvature (Agioutantis and Karmis, 1998).

These ground movements have been utilized in a number of damage classification systems to develop damage criteria as a function of structure type. The National Coal Board (NCB, 1975) proposed one of the earliest and most widely used damage-scale classification systems. A study to develop established damage-limit values that correspond to various types of movements for different building categories was reported by Bhattacharya and Singh (1985). This classification scheme was based on extensive information collected in a number of countries. The results of this study were tabulated (Singh 1992) according to building categories, movement types and ranges of damage-limits. In addition, Karmis *et al*., 1995 reported a comparison of damage classification schemes utilizing horizontal strain and angular distortion.

The SDPS software

The latest version (version 5.2) of the Surface Deformation Prediction Software (SDPS) was developed specifically for the Microsoft Windows environment. One of the programs in this package implements the influence function method as described by Karmis *et al*, (1990a). This program can calculate a number of surface deformation indices given a digitized mine plan and the digitized surface topography. Calculations are based on several empirical relationships, developed through the statistical analysis of data from a number of case studies (VPI&SU 1987, Karmis *et al.* 1992), which include:

- A correlation of the maximum subsidence factor with the width-to-depth ratio of a panel and the percent hardrock (%HR) in the overburden
- A correlation of the distance of the inflection point from the rib of the panel, with respect to the width-to-depth ratio of the panel
- A regional value for the tangent of the influence angle (tanβ) and the radius of influence
- A regional value for the horizontal strain coefficient (Bs)

In effect, this implementation of the influence function method can model very complex mine layouts under variable surface terrain, and can calculate a number of deformation indices, including: subsidence, slope, horizontal strain and surface curvature, at any point on the surface or at any other elevation above the extracted seam (Karmis *et al.*, 1990b). Finally, it should be emphasized that the SDPS software has been tested extensively and has given excellent correlation between predicted and actual measured subsidence and horizontal strain values, for a number of case studies (VPI&SU, 1987; Karmis *et al.*, 1989).

Subsidence, by definition, is the vertical component of surface movement, while horizontal strain is defined as a two-dimensional tensor quantity for every surface point. Hence, the magnitude of strain is expressed by the principal strains developed though the following equation:

$$e_{1,2} = \frac{e_x + e_y}{2} \pm \frac{1}{2}\sqrt{(e_x - e_y)^2 + g_{xy}^2} \qquad (1)$$

where, e_x, e_y, $?_{xy}$ the strain components and e_1, e_2 the principal strains.

The value for maximum principal strain (positive or negative) is defined as the maximum of the principal strains at each point and can be calculated as follows:

If Abs(e1) >= Abs(e2) Then Em = e1; Else em = e2 (2)

It should be noted that most of the damage classification systems utilize the maximum horizontal strain (i.e., the maximum principal horizontal strain). The SDPS package can also calculate ground strains, which reflect the total surface deformation (horizontal and vertical components).

Description of Case Study

The concept of utilizing subsidence prediction for environmental control was applied to a case study involving underground mining over environmentally sensitive areas. More specifically this case study involves the prediction of ground movements due to high extraction of room and pillar panels under hilly surface terrain. The primary objective of the project was to identify possible damage to surface structures due to underground mining. The procedure to predict ground deformations was as follows:

- Extraction parcels were digitized for full extraction and high-extraction areas.
- Extraction thickness was assumed 5ft for all room-and-pillar panels. This is a conservative estimate since some of the panels have extraction thickness much less than 5 ft (1.5 m). In fact in some panels, extraction was stopped before reaching property line due to low coal conditions.
- An 85% extraction ratio was assumed for all room-and-pillar panels. This is again a conservative approach in the case of one room-and-pillar panel, where the pillars were not fully extracted at second mining but they where split.
- The edge effect incorporates the cantilevering of the overburden strata over the longwall gob to define the rate or slope of subsidence between the area of maximum subsidence in the center of the panel and point of

zero subsidence outside the panel. This edge effect correction was not used in any of the extraction panels. This is a conservative estimation, since the maximum influence for each panel is achieved.

- Extraction thickness was assumed 6 ft (1.8 m) for all longwall panels.
- Based on the analysis of the surveyed data the supercritical subsidence factor was set to 68%.
- Coal seam elevation ranges from 1180 ft (360 m) to 1210 ft (369 m)
- Surface elevations of the prediction area (over and outside the panels) range from 1280 to 2080 ft (390 to 634 m).
- A total of about 16000 prediction points was used to cover the whole area under investigation.
- The total number of extraction parcels was 18.
- An influence angle corresponding to 67 degrees was assumed for all panels.
- The default strain coefficient (Bs=0.35) was assumed for all panels.

The digitized mine plan was available as an AutoCad file (Figure 1). Subsequently, areas of similar extraction characteristics were grouped together and outlined using lightweight polylines (Figure 2). This was kept as a separate layer in the AutoCad file. Then, mine plan information was imported directly into SDPS

Figure 1: Partial image of all mine plan information

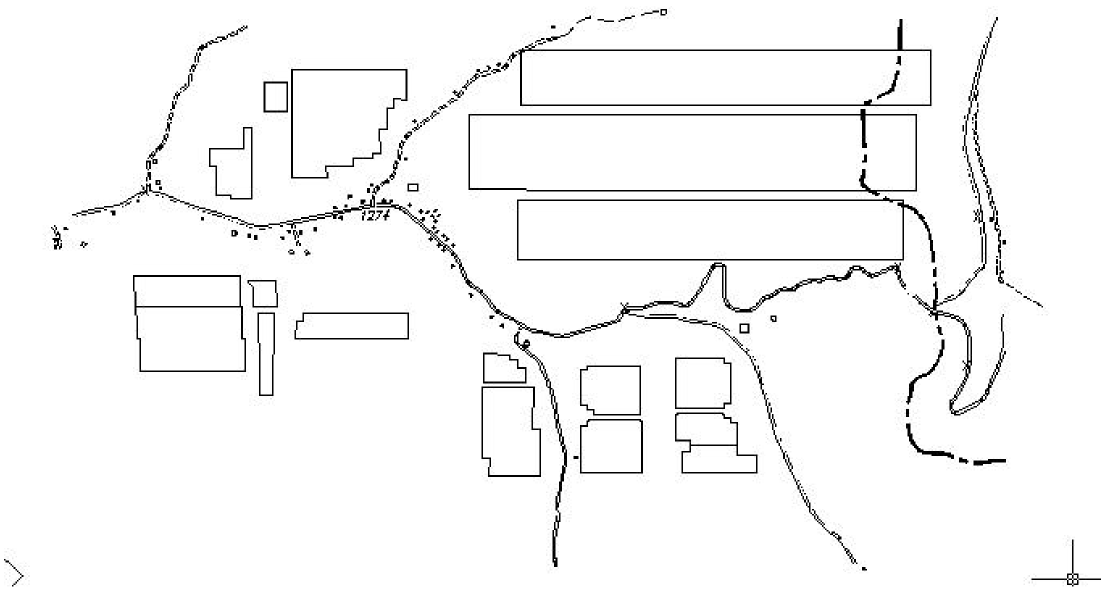

Figure 2: Simplified mine plan

(Figure 3). Surface points were then extracted from the topographic contours as digitized on the USGS map. This is also an automated procedure within SDPS. Average overburden properties (such as the influence angle and the strain coefficient) were assigned to the whole area, while an average extraction thickness was assigned to each panel shown on Figure 2.

Calibration of the SDPS Subsidence Model

Initially, the SDPS model was calibrated using surveyed subsidence data. This data was obtained from detailed subsidence studies of a nearby panel. The calibration procedure compares measured and predicted values for given surface points and the total error between the two values, i.e. the square of their difference, is calculated in all iterations. This procedure is repeated until the minimum error between measured and predicted subsidence has been obtained and the profiles of predicted and measured subsidence agree as closely as possible. The user should specify the range of parameters involved in the calibration (if such parameters are not know), such as the range of the supercritical subsidence factor (%), the range of the angle of influence (degrees), and the range of the edge effect (ft or m). To calibrate for strain, strain measurements should be available for the same points. The user has the option to calibrate for horizontal or ground (total) strains. For the aforementioned case study, the strain calibration was not executed due to the lack of strain data.

SDPS Subsidence Modeling and Discussion of Results

Surface deformations were calculated using SDPS version 5.2 for Windows. Vertical and horizontal movements as well as horizontal strains were calculated. Contours of these indices were created using Surfer 7 for Windows and subsequently superimposed on the area map. As expected, subsidence troughs develop around the high and full extraction areas. The 0.05 ft (0.6 in) subsidence contour (outer contour) is quite far from the surface structures in the area under investigation (Figure 4). Horizontal tensile strain contours reach a maximum value around the perimeter of the high extraction areas. The 0.5×10^{-3} tensile strain contour is the minimum tensile strain contour that was plotted and the figures clearly indicate that the surface structures in the study area are well away from significant tensile strain values (Figure 5).

As mentioned earlier, the impact of ground movements on surface structures and facilities is a function of the magnitude of those movements, the type of the structure and the location of the structure with respect to the mining workings. Surface disturbance may include changes in slope, curvature and vertical and horizontal displacements. As a result, in examining potential damages on surface structures, one must look for evidence of those movements on the

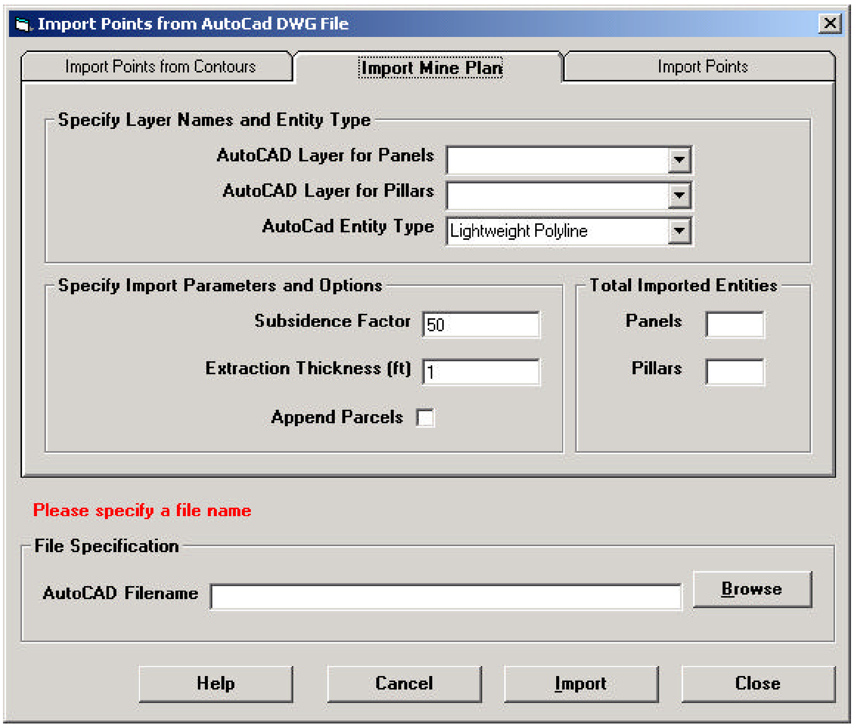

Figure 3: Importing mine plans and prediction points into SDPS

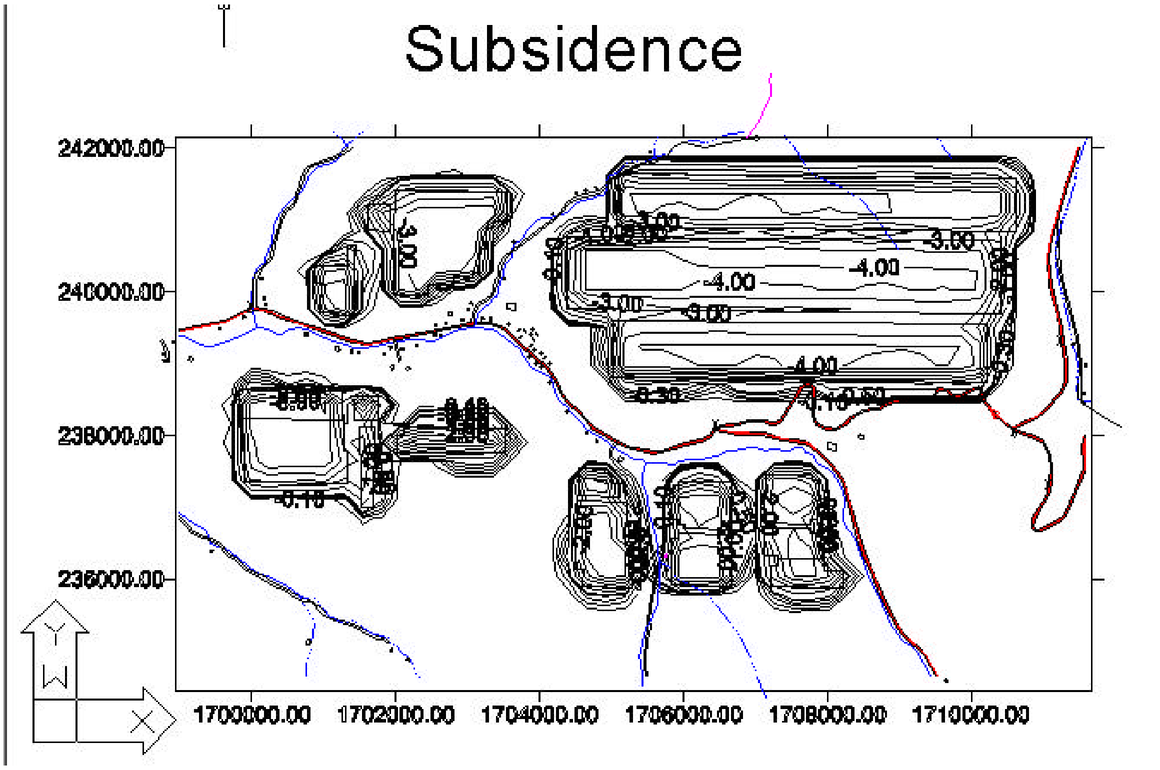

Figure 4. Subsidence contours superimposed on the study area

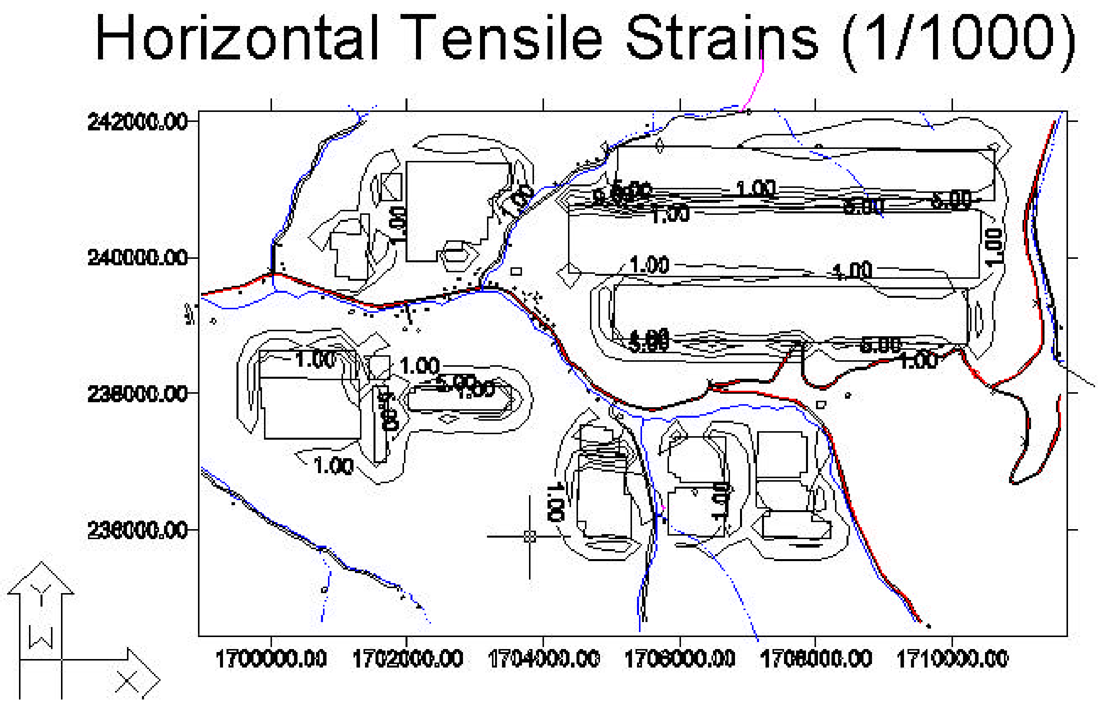

Figure 5. Horizontal strain contours superimposed on the study area

investigated structures and surrounding area. In addition, the manifestations of these movements will be different. For example, slope usually results in the tilting of a building, whereas curvature produces bending of foundation walls and cracks to masonry joints. Differential vertical and horizontal deformation can induce cracking of the structure and buckling of foundation and basement walls. In addition, a combination of those movements may result in twisting of walls and shearing of foundations. Furthermore, tension and compression zones, which are easy to predict, will have distinct impacts on the surface. Structures in the compression zone experience sagging and lateral compression.

In summary, the only way to ascertain mining induced damages is to adopt a holistic approach that can evaluate all potential damage modes and take into account all factors. For this particular case study, none of the surface structures experienced mining subsidence related damage, and, therefore, the mining plan adopted was considered optimum in terms of environmental control.

Conclusions

The results presented in this paper clearly demonstrate the ability of the SDPS package to predict regional subsidence characteristics, provided that local field data are available. The calculated ground deformation indices, i.e., subsidence and horizontal strain, can be correlated with established damage criteria, in order to determine potential impact of ground deformations to surface structures. In the case under investigation, subsidence and horizontal strain calculations and field investigations revealed that mining–induced movements, due to the underground workings of the mining operation, should not have any impact on the surface properties in proximity to the mining areas. These buildings were located at distances well away from the influence area of the mine workings and, consequently, at considerable distance from the expected threshold values of damage, in tension, compression or settlement, as predicted in the analysis. In addition, in assessing potential surface damages, one should consider not only the final deformation contours or profiles, but also the direction of mining and the propagation patterns of ground movements. Finally, the methodology presented in this paper can optimize the mine design processes, while achieving proper environmental management and control.

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