Enhancing Mine Subsidence Prediction and Control Methodologies

Michael Karmis, Stonie Barker Professor
Virginia Polytechnic Institute & State University
Blacksburg, VA

Zach Agioutantis, Professor
Technical University of Crete
Hania, Greece

Kevin Andrews, Graduate Research Assistant
Virginia Polytechnic Institute & State University
Blacksburg, VA

ABSTRACT

During the last 25 years, technological advancement and subsidence research have resulted in more accurate and diverse prediction capabilities. The work presented in this paper focuses on the development of integrated prediction capabilities for dynamic deformation indices and for strains over sloping terrain. In order to assist subsidence engineers with accurate prediction methodologies, the research also addresses the development and validation of techniques that can enable model calibration using alternative measured subsidence parameters such as horizontal or ground strain instead of the traditional vertical subsidence values.

This paper presents the basic concepts and validation of the above mentioned enhanced prediction and control methodologies, which are necessary for effective assessment and control of mining-induced subsidence, using examples and case studies. In addition, a risk assessment approach for evaluating landscape stability over mined areas is presented. The enhanced prediction methodologies have been incorporated into the Surface Deformation Prediction Software (SDPS) package.

INTRODUCTION

The impacts of mine subsidence due to underground mining are important environmental considerations in the permitting, planning, and monitoring of coal mining operations. Surface ground movements due to underground mining present significant problems that have the potential to create both mine permitting obstacles and hazardous surface conditions. Such ground movements may appear in many different forms on the surface, with varying impacts on nearby structures, roads, and hydrological regimes. As a result, the development of rigorous and well-accepted ground deformation prediction methodologies for assessing mining impacts on surface structures and facilities is an important issue for subsidence control. This task can be extremely complex because of the number and nature of the parameters affecting ground deformation induced by underground mining. Subsidence parameters, surface morphology, mine plan, coal structure characteristics, rate of mining, overburden lithology, and the type of surface facility to be protected must all be considered in the analysis.

Enhanced subsidence prediction techniques have been developed and subsequently validated using a combination of measured and theoretical case studies. This validation is made possible by developing new functions for the Surface Deformation Prediction Software (SDPS) package. This software package can address both surface deformations due to underground mining and mine stability issues. More information about SDPS can be found in VPI&SU (1987 & 2007), and Karmis et al. (1989, 1990 & 1992). The SDPS software has been tested extensively in numerous case studies (VPI&SU, 1987; Karmis et al., 1989; Newman et al., 2001, Agioutantis and Karmis, 2002; Karmis and Agioutantis, 2004) and is used widely by the mining industry and state and federal agencies for subsidence planning, prediction, and control.

The enhanced prediction and control methodologies developed through the current research include:

➢ Dynamic ground deformation prediction for longwall mining situations. This enables users to predict the development of ground deformations at any point with respect to the advancing longwall face using a few simple parameters.

➢ Strain as a reliable indicator of subsidence-related damage predictions. Strain is often considered one of the best indicators for subsidence-related damage predictions. The term horizontal strain denotes the strain calculated on a horizontal plane, while the term ground strain refers to strain calculations that take into account the slope of the surface. Ground strain calculations can be easily obtained for profiles since the ground slope along the profile is easily determined. Ground strain calculations are more realistic predictors of strains impacting a surface structure. An algorithm for ground strain calculations over a grid of surface points (flat or sloping) was developed in order to provide a better estimate of strains on surface structures.

➢ Model calibration relying on measured subsidence data. However, different regional parameters may be obtained when using other measured data such as horizontal or ground strain. An algorithm was developed to cross-correlate such predictions to ensure that calibration results using two different procedures are tied and considered as independent processes.

➢ Implementation of damage criteria based on the distribution of one specific ground deformation index, such as subsidence or strain. On many occasions worst case scenarios that would delineate potential damage areas based

on more than one damage criterion are needed. A procedure was developed to overlay threshold values based on accepted damage criteria for given prediction parameters.

ENHANCED SUBSIDENCE PREDICTION AND CONTROL METHODOLOGIES

The following sections provide the underlying principles and examples for the enhanced ground deformation prediction methodologies.

Prediction of Dynamic Subsidence Development

Dynamic subsidence differs from final subsidence in that it is the subsidence movements that occur as mining progresses toward, beneath, and past a point of interest on the surface. In contrast, static or final subsidence relates to the degree of subsidence that occurs at a particular point on the surface after the mining has passed that point and no further subsidence-related movements are expected to occur. The distinction between dynamic and static states of subsidence is very important because the distribution of strains, and therefore damage potential, for each condition is different. When evaluating an area to be undermined, it is important that field engineers assess the damage potential from both dynamic and static subsidence. The final, static subsidence trough that develops over a mined area will have permanent effects on the surface structures located near the edges of the subsidence basin due to tensional strains. Depending on the size and depth of the mine, an additional amount of area within the subsidence basin may be affected by compression. In the case of dynamic subsidence, the majority of surface area within the final subsidence basin will experience both tensile and compressive strains as mining progresses. Therefore, surface structures may be damaged by both tension and compression.

The methodology discussed by Jarosz, et al. (1990) has been incorporated into SDPS. It is based on the methodology proposed by Knothe (1953) that uses influence functions. The basic time-subsidence function proposed by Knothe (1953) calculates the transient subsidence at a point based on panel geometry, overburden depth, and a time coefficient:

$$\dot{S}(t) = c[S^f(t)\text{-}S(t)] \tag{1}$$

Where,
$S^f(t)$ = final subsidence
c = time coefficient
$S(t)$ = subsidence at time t,

Jarosz, et al. (1990) have implemented this methodology for advancing rectangular panels (i.e., longwall panels). This methodology assumes an equivalent panel boundary offset, d, which can be calculated by equation (2). The dynamic subsidence is calculated by reducing the final subsidence by the influence of the offset panel. Hence, the overall effect is that the higher the advance rate the greater the edge effect.

$$d = rc^2 / 2\pi v \tag{2}$$

Where,
r = radius of influence
c = time coefficient
v = rate of advance (extraction rate)

In addition, it is suggested based on back analysis, that the parameter c takes the value of c=0.075/day for the eastern Appalachian coalfields. This methodology provides a solution for the dynamic deformation indices for a rectangular longwall mine panel of constant width with one side advancing at a constant rate (Figure 1). This formulation has been tested using measured dynamic subsidence data from Pennsylvania and Illinois. Figure 2 shows a close match between the dynamic prediction of subsidence and measured data. The figure also includes the predicted final subsidence at the point and a vertical line approximating the location of the face when the main phase of subsidence is expected to be complete.
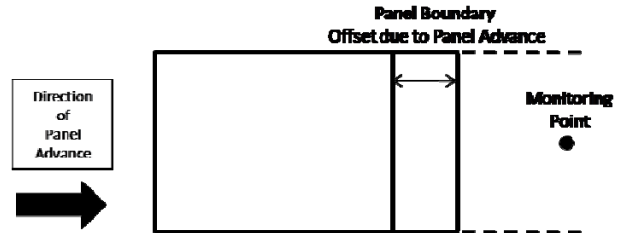

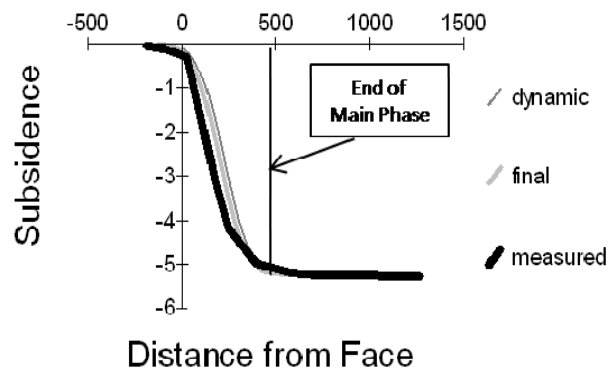**Figure 1. Basic layout for dynamic development prediction.**

Figure 2. Comparison of measured and predicted (dynamic and final) subsidence profiles at a point.

Ground Strain Calculations

A comparison of horizontal and ground strain definitions is shown in Figure 3. On horizontal surfaces, horizontal and ground strains should be almost identical. Often, prediction calculations of ground strain are performed along two-dimensional section lines. While consideration of ground strain along two-dimensional section lines throughout a study area can be helpful, ground strain on a surface grid is much more efficient for engineers needing to delineate areas most likely to experience damage. In addition, ground strains can be more closely related to measured movements.

An enhanced methodology has been developed by which strain at a surface point is evaluated by taking into account the effects of ground deformation on all adjacent points. This approach allows for the prediction of ground strain on each point irrespective of any profile lines that may be available for the study area. As a result, ground strain maps can be easily generated. Figure 4 presents the horizontal strain regions higher than $\pm 1.5 \times 10^{-3}$ (positive is tension and negative is compression) generated for a single rectangular panel extracted under a sloping surface. The surface slope has been set to a high angle (30 degrees) to generate

a more pronounced effect. The subsidence contour for 0.05 is also plotted for reference.
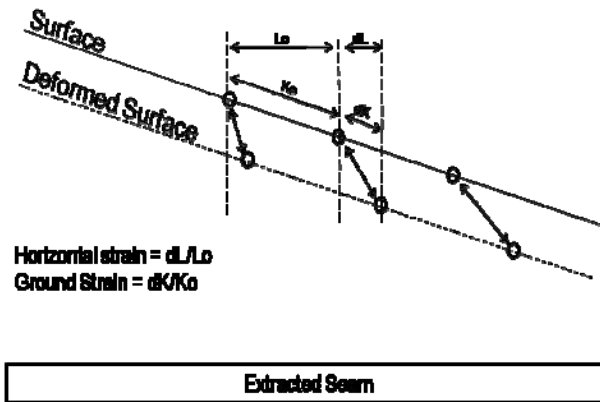

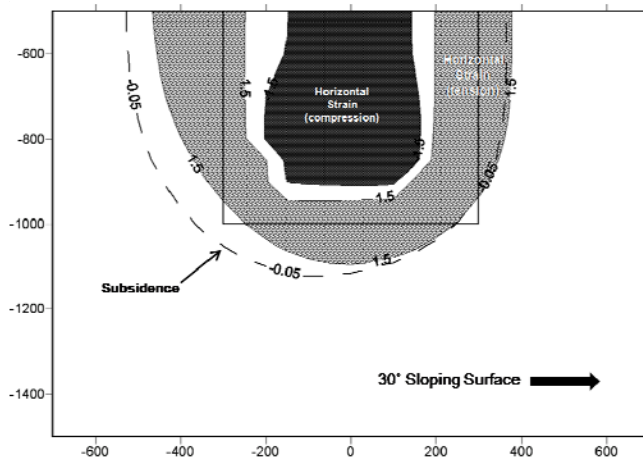**Figure 3. Comparison of horizontal and ground Strains.**

Figure 4. Contouring of predicted horizontal strain (solid line) and subsidence (dashed line) for 30˙ inclined surface. The mine panel is included as bold line.

In a similar fashion, Figure 5 presents the ground strain regions higher than ±1.5 x 10⁻³ as well as the 0.05 subsidence contour for the same example. By comparing Figures 4 and 5, it can easily be deduced that ground strains present a better approximation of the actual surface compressional and tensional regions.

Subsidence Model Calibration

Model calibration and determination of site-specific subsidence parameters is usually accomplished by a back-calculation using measured subsidence (vertical) data. Several hundred iterations are often required and computer programs such as SDPS are essential to perform this function. The iterative back-calculation of subsidence parameters is complete when calculated subsidence values and measured subsidence values are matched as closely as possible (minimum error index). The combination of subsidence parameters that produces the minimum error index is then used to determine the appropriate edge effect. The edge effect is adjusted until the slopes of the predicted and measured subsidence contours are coincidental. This procedure is repeated until the minimum error between measured and predicted subsidence has been obtained and the contours of predicted and measured subsidence agree as closely as possible.
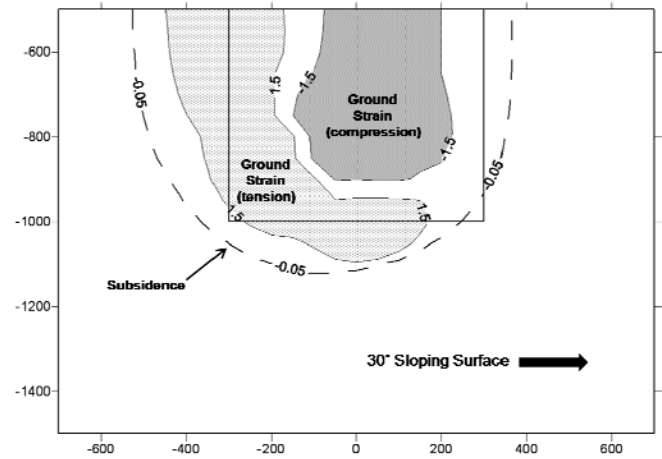
Figure 5. Contouring of predicted horizontal strain (solid line) and subsidence (dashed line) for 30˙ inclined surface. The mine panel is included as bold line.

The ability to evaluate the accuracy of a subsidence prediction model using various types of measured data greatly increases the quality of the model. The current research has evaluated the results of calibrating with measured ground strain or horizontal strain, in addition to vertical subsidence measurements. To perform the alternative calibrations, a new SDPS function was created. Figures 6 and 7 display the visual results of calibration using measured subsidence and ground strain, respectively. Predicted Line 1 in Figure 7 provides a better fit to the maximum strain values, but results to a higher percentile error for the entire profile compared to Line 2. In both cases the subsidence related parameters (i.e. influence angle, edge effect), do not change significantly. Table 1 provides a comparison of the calibrated subsidence parameters using both methods. As is evident in Table 1, the subsidence and ground strain calibration methods yield very similar results. The percentage error associated with the strain calibration reflects the difficulty of accurately measuring ground strains. However, strain calibration is an important utility for calculating the strain coefficient. In this case, strain calibration should be used in conjunction and complementary to subsidence calibration.

Figure 6. Calibration using measured and predicted subsidence.

Figure 7. Calibration using measured and predicted ground strain.

Table 1. Comparison of calibration parameters using subsidence and strain calibration.

Calibration Parameter	Calibration Based on Subsidence Data	Calibration Based on Strain Data (*)
Tangent of Influence Angle	3.0	3.0
Smax/m (%)	53%	45% (Line 1) 48% (Line 2)
Edge Effect Adjustment (ft)	167 ft	170% (Line 1) 168% (Line 2)
Overall Percent Error	13.2%	33.6% (Line 1) 22.3% (Line 2)

(*) Line 1 represents the best fit of the maximum strain values, as shown in Figure 7.

The previous example suggests that measured subsidence and strain data combined provide improved subsidence parameters for model calibration and subs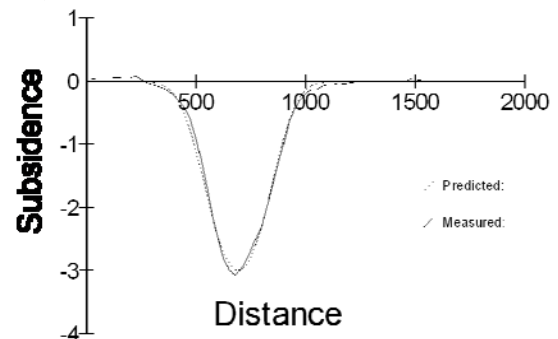equent use as a prediction tool. The capability of dual calibration provides a means to develop confidence in the approximated subsidence prediction parameters. Additionally, inconsistent calibrated parameter values serve as indicators of potential problems with measured data, special circumstances related to geologic environment, or other anomalies.

Risk Assessment Approach to Damage Criteria for Structures

The subject of developing damage criteria for surface structures and facilities is well discussed in the literature (Bhattacharya and Singh, 1985; Bruhn, et al., 1982), including the risk-based "damage" concept proposed by Karmis et al. (1994). In many cases, a risk analysis approach has been used successfully for planning and designing surface structures overlying previously mined areas or projected mine areas such as impoundment dams, waste disposal facilities and other surface structures. The first step in a risk analysis is to evaluate the stability of the underground working (i.e. pillars, roof, floor, etc), in order to determine the subsidence potential of each and every underground mining area. The second step is to calculate ground deformations using, in most cases, a worst case scenario of total collapse (Karmis and Agioutantis, 2004). Finally, risk areas may be identified by overlaying contours of deformation indices on surface facilities.

This research examines the capability and efficiency for carrying out a risk analysis approach using damage criteria by providing the means to establish equivalent ground deformation indices. By presenting deformation indices such as subsidence, slope, horizontal displacement, ground strain, and/or horizontal strain on a single easy-to-understand contour map, the mine planning engineer can observe relationships between deformation characteristics and damage threshold values. The result is efficient delineation of areas at risk to subsidence-related damage.

Figure 8 shows an actual case study of a proposed construction project to be located over an old room and pillar mine. In order to assess the potential impacts of underground mining to the planned surface facility, a worst case scenario was assumed for the room and pillar sections that had not been retreated.

Figure 8. Room and pillar mine under a planned surface facility (dark pillars have been extracted).

Figure 9 shows an overlay of predicted horizontal strain and ground strain contours. A threshold strain value of $\pm 1.5 \times 10^{-3}$ has been applied. The mine plan layout is simplified, showing the extracted room and pillar areas assumed in the worst case scenario. The generated map(s) may be easily manipulated to show different contoured values of both subsidence and slope or any other ground deformations indices. The contoured maps can be combined with maps of surface structures to provide a fast and easy assessment of potential damage problems (Figure 10).

Horiz. Strain - Maximum, Ground Strain

Figure 9. Map showing simplified mine plan overlain by predicted horizontal strain and ground strain contours.

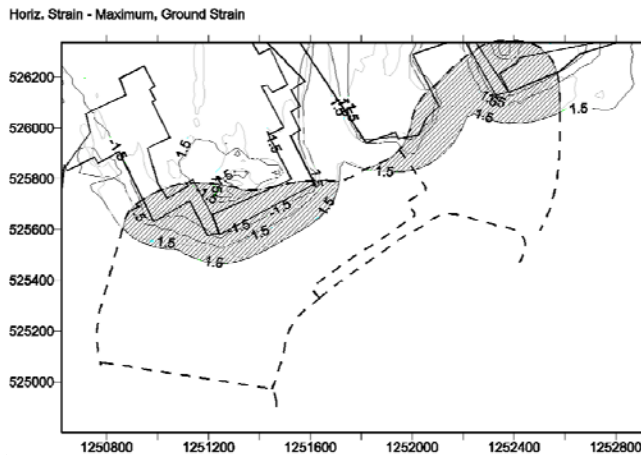Horiz. Strain - Maximum, Ground Strain

Figure 10. Map showing predicted high risk areas (shaded) based on overlapping of threshold strain contours and boundary of planned surface facility (dashed).

CONCLUSIONS

The results of the current research include the development, implementation, and validation of a number of enhanced methodologies associated with subsidence prediction. Validation of the methodologies was completed using a combination of measured and hypothetical subsidence data, and by incorporating the methodologies into SDPS. The improved subsidence techniques include dynamic subsidence development prediction, contouring of ground strain and other deformation parameters, diversified subsidence model calibration potential, and a risk-based methodology for assessing landscape stability.

Prediction of dynamic subsidence development facilitates the evaluation of not only the expected surface damage due to a final subsidence basin, but also the potential for structure damage from variable strain states during undermining. Measured dynamic subsidence data, when compared to dynamic subsidence predictions, confirm the validity of the enhanced methodology presented in this paper.

Ground strain, as compared to horizontal strain, is a more accurate predictor of damage-prone areas due to subsidence-induced tension and compression. This has been demonstrated via a new methodology that allows for contemporaneous contouring of multiple subsidence parameters. A hypothetical example demonstrates how threshold values for ground strain are easily and clearly represented by contouring, enabling correlation with expected horizontal strain and subsidence values. The contoured maps provide quick and accurate assessment of subsidence-induced conditions in both flat and steeply-sloping terrain.

Enhancement of SDPS calibration capabilities has resulted in the ability to calibrate models using either measured subsidence or measured strain (horizontal or ground). The diversified calibration techniques have been validated using measured case study data and are likely to provide more accurate models. They may also help to identify local geological anomalies or erroneous measured data.

The contouring of subsidence, ground strain, and other parameters aids the risk-based assessment approach to subsidence

-related damage that has been used successfully in case studies. A case study is presented to demonstrate how contour maps showing equivalent predicted subsidence and strain damage threshold values, as well as other parameters, can now be created and combined with maps of surface developments to determine high-risk areas.

The development and validation of state-of-the-art subsidence prediction methodology and implementation of such methodology into user-friendly programs such as SDPS are vitally important to the continued growth of the underground coal mining industry. Accurate prediction and assessment of potential problems associated with surface subsidence enables companies to avoid dangerous and expensive situations, allowing them to focus on production.

REFERENCES

1. **Agioutantis, Z., and M. Karmis,** 2002, «SDPS for Windows: An Application for Subsidence Prediction, Optimum Mine Design and Environmental Control», SWEMP, Cagliari, Italy, 6 p.

2. **Bhattacharya, S. and Singh, M.M.,** 1985, "Development of Subsidence Damage Criteria," Contract No. J5120121, O.S.M.RE, U.S. Dept. of the Interior, 195 p.

3. **Bruhn, R.W., McCann, W.S., Speck, R.C. and Gray, R.E.,** 1982, "Damage to Structures Above Underground Coal Mines in the Northern Appalachian Coalfield," Proc., 1st Int. Conf. on Stabi-lity in Underground Mining, Vancouver, Canada, pp. 1022-1042.

4. **Jarosz, A., M. Karmis, and A. Sroka,** 1990, «Subsidence Development with Time – Experiences from Longwall Operations in the Appalachian Coalfield», *International Journal of Mining and Geological Engineering*, Vol. 8, pp. 261-273.

5. **Karmis, M., A, Jarosz and Z. Agioutantis,** 1989, «Predicting Subsidence with a Computer», *Coal*, Vol. 26, No. 12, pp. 54-61.

6. **Karmis, M., C. Haycocks and Z. Agioutantis,** 1992, «The Prediction of Ground Movements caused by Mining», *Proceedings,* 3rd Workshop on Surface Subsidence due to Underground Mining, Morgantown, WV, pp. 1-9.

7. **Karmis, M., J. Mastoris, and Z. Agioutantis,** 1994, «An Investigation into the Potential of the "Damage Angle" Concept for Assessing the Impacts of Underground Mining on the Surface», Transactions, Society for Mining, Metallurgy and Exploration, Inc., Vol. 296, pp. 1883-1886.

8. **Karmis, M., Z. Agioutantis and A. Jarosz,** 1990, «Subsidence Prediction Techniques in the United States: A State-of-the-Art Review», Mineral Resources Engineering, Vol. 3, No. 3, pp. 197-210.

9. **Karmis, M. and Z. Agioutantis,** 2004, «A Risk Analysis Subsidence Approach for the Design of Coal Refuse Impoundments Overlying Mine Workings», 6 pages.

10. **Knothe, S.,** 1953, Wplyw czasu na ksztaltowanie się niecki osiadania, Archiwum Górnictwa i Hutnictwa, Tom 1, z.1. (In Polish)

135

11. **Newman, D, Z. Agioutantis, and M. Karmis,** 2001, «SDPS for Windows: An Integrated Approach to Ground Deformation Prediction», Proceedings of the 20th International Conference on Ground Control in Mining, Morgantown, WV, pp. 157-162.

12. **VPI&SU,** Department of Mining and Minerals Engineering, 1987, «Prediction of Ground Movements due to Underground Mining in the Eastern United States Coalfields», *Final report,* Contract No. J5140137, Office of Surface Mining, Reclamation and Enforcement, U.S. Department of Interior, Vols I, 205p, and II, 112p.

13. **VPI&SU,** Department of Mining and Minerals Engineering, 2007, «Surface Deformation Prediction System (version 5.5) - User's Manual», 140p.