Development of An Enhanced Methodology for Ground Movement Predictions Due to Longwall Mining in the Illinois Basin

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ABSTRACT

The Illinois Basin has an extensive history with the use of mechanized longwall mining dating back to the early 1970's. In recent times, technological advances have resulted in increased panel widths from 800 feet to over 1400 feet and daily panel advance rates have also increased significantly. The prediction and control of subsidence and surface deformation due to underground mining are important considerations in the permitting, planning, and monitoring of these coal mining operations. The prediction of mining-induced ground movements using the influence function method is a mature technology, well utilized in the Illinois basin, and widely used by researchers and planning engineers around the world. This paper utilizes subsidence data, recently measured in longwall operations in Illinois, to develop an updated ground movement prediction capability implemented by the Surface Deformation Prediction System (SDPS) software package.

INTRODUCTION

In recent years, overall Illinois production has increased primarily due to an increase in longwall mines and longwall productivity. Illinois has seen a rise in annual tonnage over the past five (5) years. The 2013 coal production approached 52 million tons, the highest annual production since 1994.

Historically, over 285 longwall panels have extracted coal and subsided more than 45,000 acres of land. Subsidence has impacted structures and infrastructure of all kinds and vast acreage of prime farmland. Predicting subsidence accurately in flat topography is an important part of evaluating potential impacts and a key element of mine permitting. Drainage restoration is a vital part of reclamation of subsidence.

As subsidence modeling tools and software became available, it became apparent that models developed primarily on Appalachia longwall subsidence data did not translate well to the Illinois basin. Illinois subsidence deformation parameters such as angle of draw were not being accurately predicted by the available models. Limited regional parameters for the Illinois basin were recently developed (Karmis et al, 2008) and are now frequently used by the industry to address permitting requirements. Still, further work is necessary to fully realize the potential and capabilities of tools such as SDPS.

In addition, since the development of the subsidence parameters for the Central US Coalfields, technological advances have resulted in increased panel widths from 800 feet to over 1400 feet. Daily panel advance rates have also increased significantly. It is believed that these technological advances have changed the resultant surface deformation parameters triggering the need to evaluate newer available surface subsidence data and adjust the modeling accordingly to better reflect the resultant surface subsidence trough and improve induced strain prediction.

COAL GEOLOGY AND RESERVES

Illinois Coal is part of the Eastern Region of the Interior Province, which also encompasses Indiana and Western Kentucky (Figure 1). This region is also referred to as the Illinois Basin, and coal seams were deposited during the Pennsylvanian (late Carboniferous), approximately 300 million year ago. During the Pennsylvanian, Illinois was located at, or near, the equator. Regular, repeating, glacial cycles, driven by earth orbit fluctuations, caused ice to wax and wane at the poles, sea level to rise and fall, and equatorial climates to oscillate between dominantly wet, and seasonally dry. Broad, low relief lowlands typified the landscape of Illinois and the continental interior.

During glacial episodes, ice formed at the poles, dropping sea level, and exposed the Illinois landscape. As polar ice masses increased in size, equatorial climate changed from seasonally dry to wet. Soils with seasonally dry characteristics initially formed on the exposed landscape. As climate became wetter the Illinois landscape became waterlogged and transitioned to forming peat swamps. As glacial intervals ended and polar ice melted back, equatorial climates become less wet, and sea level rose, drowning the peat swamps, resulting in black shales and limestone followed by thick gray shales and sandstones (which may downcut into underlying strata and coal seams) (Cecil, 2003). Over time these glacial oscillations repeated, the Illinois Basin slowly subsided, and a repeating sequence of coal bearing strata called cyclothems were deposited (Figure 2). These depositional conditions resulted in at least 50 named coal seams in Illinois, and well over 200 billion tons of coal in the ground. Approximately 36,800 square miles in Illinois are underlain by coal.

Figure 1. Extent of the Pennsylvanian System in the Illinois Basin (Korose, 2002).

The immediate floor of most Illinois coal mines is composed of clay-rich former soil (underclay, fire clay) that varies from 0 to several feet thick and is typically weak. Overlying strata usually consists of a few feet of fissile black shale, overlain by 0 to several feet of hard marine limestone, and in turn by tens of feet of silty shale to sandstone of varying consistency. In coal seams where large contemporaneous rivers flowed through the ancient peat swamps (Walshville River and Galatia River of the Herrin and Springfield coals respectively), the roof lithology is often different and variable. Coal seams near these ancient rivers are often missing the overlying fissile black shale and marine limestone completely and are instead covered by tidally laminated siltstone and sandstone 'stack rock', and sandstone. The 'stack rock' lithology has in the past proved to be problematic for mining, being difficult to bolt into and support, and prone to moisture sensitivity. At the same time, coal under 'stack rock' roof is tempting to extract due to it generally being thick and low in sulfur. The 'stack rock' facies changes in character away from the courses of these ancient rivers, transitioning to finer grain sizes, thinner beds, and erosional pod-like geometries towards the distal edges.

The complex depositional history of the region create unique and challenging mining conditions. Pillar punching and floor heave can be highly variable and unpredictable based on changes in immediate underclay thickness over short distances. Floors that become wetted or inundated can weaken resulting in localized pillar punching reducing void height in short periods of time. Weak roof rock can be difficult to control and is often intentionally cut and removed or unintentionally falls and is removed creating more unpredictable void heights, a key parameter in subsidence modeling.

COAL PRODUCTION IN ILLINOIS

Approximately 20 coal seams have been mined since the first recorded coal mining in 1810, however, the majority of historic production (90%) has been from the Herrin and Springfield coal. Current and future production will be predominantly from these two coals as well. All five (5) active longwall mines in Illinois extract from the Herrin Coal Seam.

The earliest coal mining was performed by underground mining methods. As surface mining methods and machinery improved, surface extracted coal reached approximately 50 percent of the total

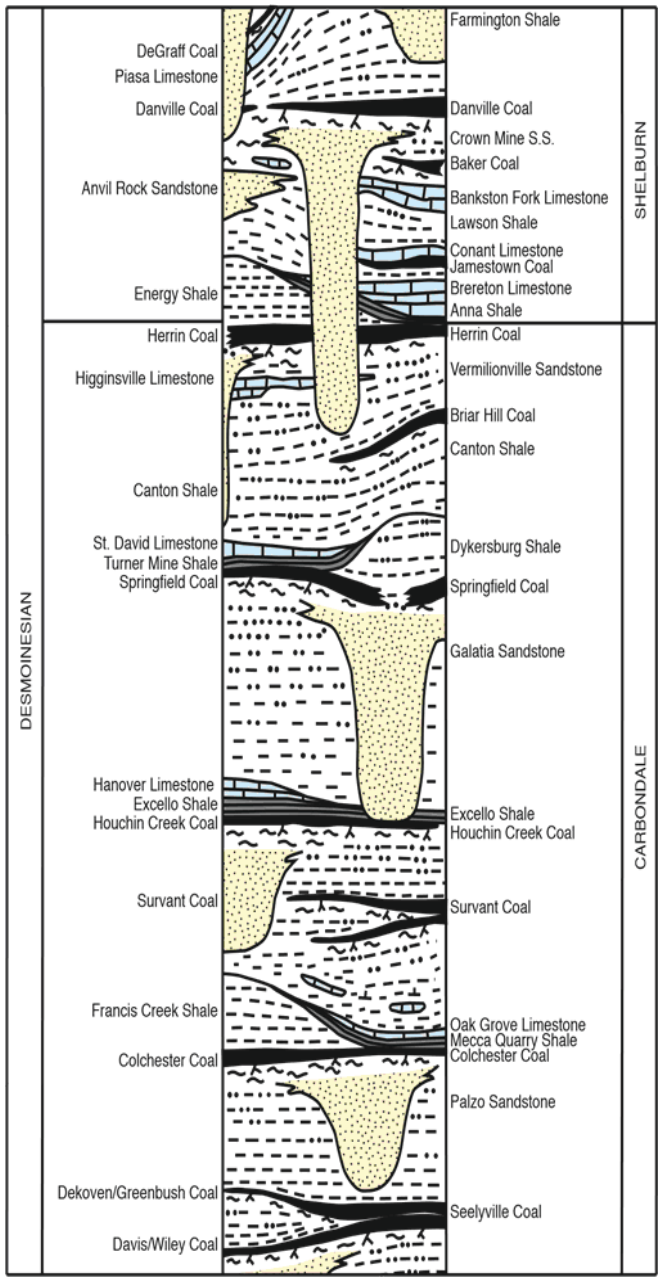

Figure 2. Generalized stratigraphic column of Pennsylvania coals in Illinois (modified from Nelson et al., 2011).

production in the 1960's. As surface minable coal along the basin rim were depleted, underground mining production again dominated. Today, approximately 89 percent of coal is produced by underground methods (Figure 3).

Annual production peaked in 1944 at approximately 74 million tons. Production dipped to record lows of 31 to 33 million tons from 2000 through 2007 as the impact of the Clean Air Act greatly reduced the demand for Illinois Basin high sulfur coal. Illinois has seen a recent surge in production (Figure 3) driven by market economics. Two main reasons contributed to this: a) new investments in longwall equipment and b) the fact that about half of the production is exported internationally. There has been a 51.2 percent increase in total annual tonnage over the past 5 years, primarily due to a surge in the use of longwall mining (Figure 4).

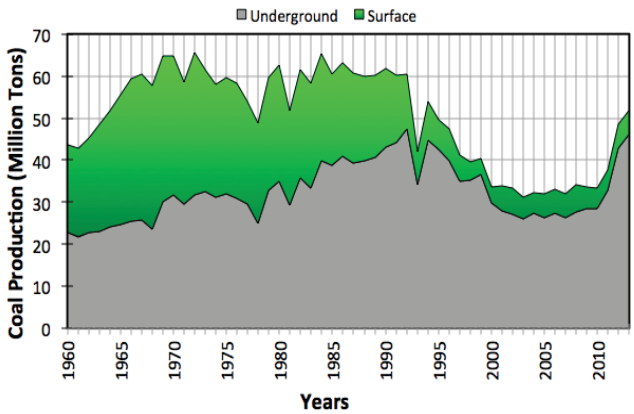

Figure 3. Total Illinois coal production since 1960 (IDNR 2013).

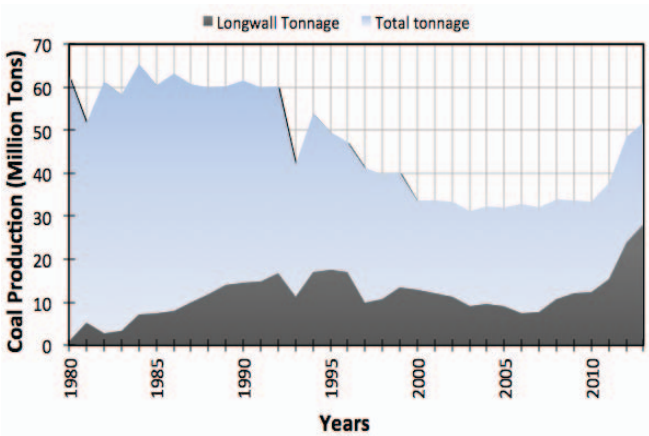

Figure 4. Illinois Longwall vs. total tonnage since 1980 (IDNR 2013).

IMPACTS OF LONGWALL SUBSIDENCE

Longwall mining and the resultant planned subsidence has affected numerous surface structures and facilities in the past 40 years. Homes, buildings, utilities, major pipelines, railroads and state highways have been impacted. The approach to dealing with subsidence damage minimization and mitigation of structures and infrastructure is handled similarly throughout the longwall areas of the country. Planning for subsidence of sensitive structures requires an understanding of the ground movements that will occur and the resultant induced strains.

What is unique to Illinois and longwall mining are the impacts to relatively flat surface lands and the resultant impediment of surface drainage. Farming is a major industry in Illinois with approximately 60 percent of the surface area of Illinois planted in either corn or soybean. The result of lowering the land surface though a series of adjacent longwall panels interrupted by the presence of chain pillars can leave a pronounced washer board effect on the surface. This can result in large areas of drainage impaired land. Water ponding areas can take a toll on farmland production by drowning crops and preventing farm machinery access until properly mitigated.

Illinois longwall mines are therefore required to provide existing contours and projected post subsidence contours typically at two (2) foot intervals. Areas of anticipated inundation are delineated and potential course of drainage restoration defined to demonstrate mitigation can be achieved. Mitigation is accomplished by deepening existing waterways and installation of new drainage courses. Subsurface drainage tiles that are impacted must be replaced, and in some instances supplemented with additional tiling, to achieve pre-subsidence drainage conditions.

Intermittent or perennial stream channels may require dredging downstream of the subsided area to reestablish pre-mining flow paths and prevent backup of water. This may also involve permitting through the Corps of Engineers in order to allow mitigation to occur within the banks of Corps jurisdictional streams. Accurate prediction of the resultant contours over a series of longwall panels provides the tools necessary to meet permitting requirements and assist in developing mitigation plans.

THE SDPS PACKAGE FOR GROUND DEFORMATION PREDICTION

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. A number of subsidence prediction techniques have been developed and subsequently validated using measured deformations (e.g. vertical and horizontal movements, ground strains, etc), over mined panels. 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.

The Surface Deformation Prediction System (SDPS) is a software package widely used by the US mining industry and state and federal agencies for subsidence planning, prediction, and control. It primarily utilizes the influence function method for subsidence prediction which is a well-established and accepted technique. The influence function methodology implemented in SDPS to calculate final surface deformations relies on a few subsidence engineering parameters, i.e., the angle of influence, the supercritical subsidence factor and the edge effect offset distance. Empirical relations are available that allow the estimation of the edge effect offset as a function of the width to depth ratio and the calculation of the supercritical subsidence factor as a function of the percent hardrock in the overburden. The edge effect is the offset of the location of the inflection point of the subsidence profile from the rib of the excavation.

Although this package was initially developed over 25 years ago as a result of an integrated research effort at VPI&SU (1987), it has been constantly updated with the incorporation of new analysis features (e.g. dynamic deformations, calibration routines, long-term stability calculations, etc) since then (Karmis et al. 1990a, 1990b & 1992, 2008; Jarosz et al. 1990). SDPS has evolved into a versatile prediction tool that can handle complex tasks, including multiple calibration routines, dynamic subsidence evaluation as well as an estimation of long-term subsidence effects under different scenarios (Karmis et al, 2008,). More recently (2013), the effect of sloping

terrain in the prediction of horizontal displacements has been incorporated allowing for accurate three dimensional predictions of deformation vectors over undermined areas in hilly or mountainous terrain. Furthermore, 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).

As subsidence modeling tools and software became available, it became apparent that models developed based primarily on Appalachia longwall subsidence data did not translate well to the Illinois basin. Illinois subsidence deformation parameters such as the angle of influence or the maximum subsidence factor were not accurately predicted by the available models. As a result, in 2008 a module was created within the Subsidence Deformation Prediction System (SDPS) (VPI&SU 1987, Agioutantis and Karmis 2013), to adapt the model to different conditions, i.e. central and western US coalfields. The case studies utilized in that research effort, however, were based on historical data which do not reflect current longwall practices in these areas.

INFLUENCE OF SOFT FLOOR CONDITIONS

In this paper, data from current longwall operations in the Illinois basin have been analyzed in an effort to more accurately estimate the subsidence engineering parameters needed for accurate predictions. An additional complication when analyzing data from Illinois basin operations is the influence of the weak floor as discussed previously. When the gate road pillars are loaded by the abutment loads created by the extraction in the two adjacent panels, the stresses transferred from the pillars to the floor may overcome the bearing capacity of the underclay (fire clay) immediate floor and, thus, pillars may sink or punch into the floor without failing. This mine level deformation will be promoted and accelerated under wet conditions.

Figure 5 presents the subsidence troughs generated due to mining of adjacent panels with and without gate road pillar punching. Pillar punching of the gate road pillars, when isolated (middle drawing Figure 5), effectively generates a smaller trough, but with potentially different subsidence characteristics than the troughs of the mined out panels, i.e. the corresponding influence angle and edge effect values may be different.

The technique of modelling a "pseudopanel" superimposed over the gateroad pillars in order to allow for pillar shrinkage due to pillar loading has been previously applied through the SDPS package (Hasenfus, 2013). This approach can successfully be utilized for direct subsidence calculations; however this technique can not be applied when using the SDPS calibration routines for multiple panels, where subsidence parameters are varied at mine level rather than at panel level.

To overcome this issue, the calibration routines in the SDPS package have been updated to handle different parameter requirements per panel. Thus, the mechanism of subsidence generation when pillars punch into the floor strata can be accommodated by assuming an "*equivalent extraction thickness*".

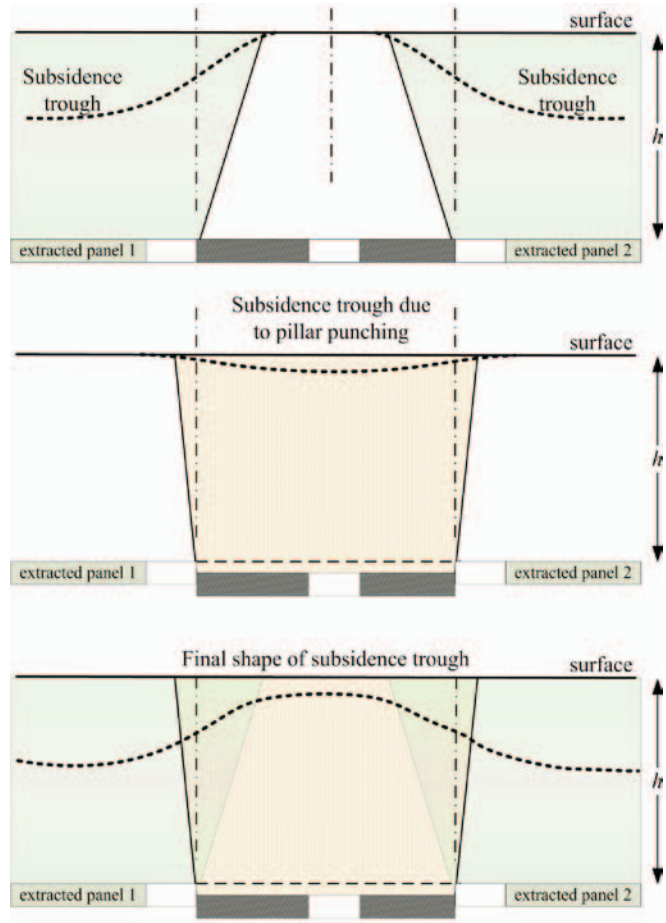

Figure 5. Equivalent subsidence trough due to gate road pillar punching (panel 1 and panel 2 are fully extracted).

This feature is optional and should be used only if the operator expects pillar punching or pillar shrinkage (reduced pillar size due to rib spall or rib rashing) in an area, or when investigating different ground movement scenarios.

ANALYSIS OF RECENT ILLINOIS BASIN CASE STUDIES

This investigation included the analysis of a number of monitoring lines (pin lines) spanning three separate coal mines. Typically, long wall operations collect survey data over the first two panels mined. The purpose of the monitoring is to define movements at the rib, at the panel corner and on the panel long axis. Furthermore a number of pin lines where located over the gate road pillars between two panels, thus movements could be monitored both when the first panel passed by and when both panels had been mined. Figure 6 shows a typical layout of monitoring lines over Mine A.

Mine A

One of the critical issues when collecting and processing data for subsidence engineering is to determine the actual extraction thickness. Boreholes provide the geological thickness of the deposit. In the case of high capacity longwall mines, it is very common to set the shearer to mine some roof and/or floor material for a number of reasons, such as enhanced productivity, adequate

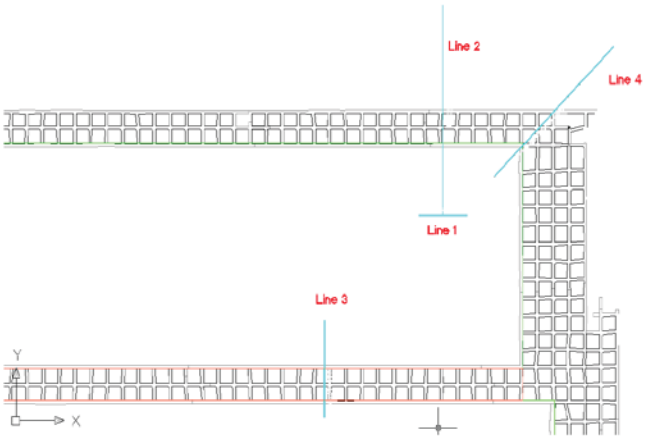

Figure 6. Typical layout of monitoring lines for Mine A.

roof stability at the face, etc. In addition, weak shale roof rock that typically falls onto the pan line chain conveyer and conveyed out also contributes to the actual extraction thickness and must be considered in the calculations. When predicting surface deformation due to underground mining, it is important to consider the actual extraction thickness and not the geologic thickness of the extracted seam, especially if the geologic thickness is variable.

The coal seam at the first mine operation (Mine A) lies about 550 feet deep. The seam thickness below the general location of the pin lines is about 6 feet. According to mine personnel, the extraction thickness for this mine varies between 7 and 7.5 feet. Panel widths are about 1300 feet including the width of the entries adjacent to the panels. The edge effect values predicted (Agioutantis and Karmis, 2013) for this width to depth ratio varies between 110 feet (conservative estimate) and 138 feet (average estimate). Figure 7 shows a typical range of influence angle values in the parametric analysis for site calibration for pin line 4. The procedure generates a set of prediction curves based on the parameter range specified by the user. The program then calculates the best fit between the calculated and the measured profile. The parameters used to generate this fitted profile are considered representative of the specific mine or regional location, i.e. the subsidence model is calibrated to the measured data for a particular location. It should be noted that fitted profiles representing the entire curve often do not necessarily fit data at or beyond the panel edge, because the best fit is calibrated for the entire range of data. Figure 8 shows a typical match between fitted and measured data for pin line 2.

Table 1 presents a summary of the analysis conducted using two different extraction thickness values. Note that pin line 1 is located along the longitudinal axis at the center of the panel and, therefore, is not affected by the edge effect offset. As expected, the variation in the assigned extraction thickness affects only the value of the calculated maximum subsidence factor. The best fit values for the edge effect and the tangent of the influence angle do not change. In all cases, the calculated edge effect value is between the minimum and maximum value of the edge effect as predicted by the methodology described in Agioutantis and Karmis (2013).

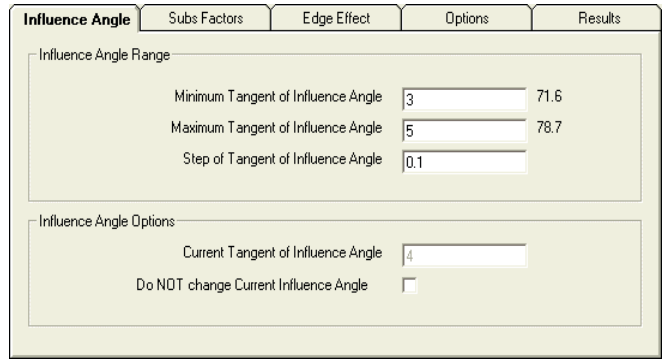

Figure 7. Specified range for the influence angle during calibration (screenshot from SDPS package).

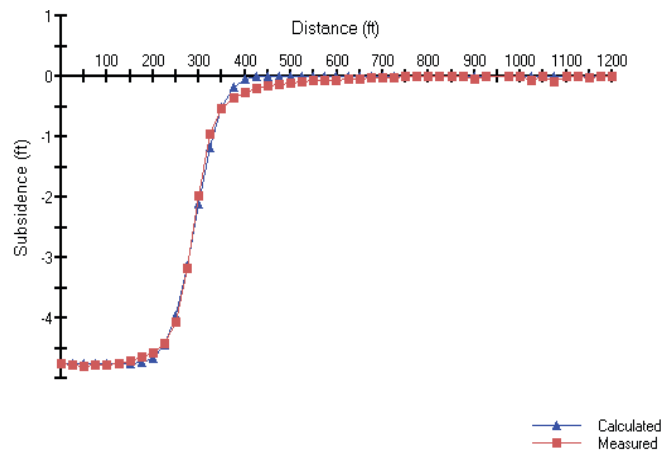

Figure 8. Measured and calculated data for best fit parameters (Mine A, Pin Line 2).

Mine B

The coal seam at the second mine operation (Mine B) is at a depth of about 530 feet. The extraction thickness at the general location of the pin lines is about 10 feet. Panel widths are over 1400 feet including the width of the adjacent entries. The edge effect values predicted for this width to depth ratio varies between 106 feet (conservative estimate) and 133 feet (average estimate).

Table 2 presents a summary of the analysis conducted for Mine B. Note that pin line 1 is located along the longitudinal axis at the center of the panel and, therefore, is not affected by the edge effect offset. Also, pin line 3 spans two panels and the same extraction thickness was assumed for both panels, although results indicate that this may not be the case as shown in Figure 10. In addition, results shown in Figure 10a do not include the effect of the pillars punching into the floor. By applying the procedure described previously (Figure 5), i.e. after defining an equivalent extraction area (pseudopanel) to allow for pillar punching and specifying different edge effect and influence angle values for this area. Figure 10b was generated as the best fit line between measured and calculated subsidence values.

Table 1. Site specific calibration results for Mine A.

					Values for best fit curve			
Operation	Pin Line	Extraction Thickness, m (feet)	Number of Contributing Panels	Predicted Edge Effect (feet) (*)	Tangent of Influence Angle	Smax/m percent (@)	Edge Effect (feet)	Percent Error (**)
Mine A	2	7	1	110 - 138	4.9	68	120	4.4
Mine A	4	7	1	110 - 138	5.2	78	130	22.4
Mine A	1	7.5	1	N/A	4.8	63	N/A (***)	0.88
Mine A	2	7.5	1	110 – 138	4.9	64	120	4.7
Mine A	4	7.5	1	110 – 138	5.2	74	130	22.2

(*) edge effect predicted by SDPS – conservative and average values
(@) supercritical subsidence factor
(**) percent of sum of differences between measured and calculated with respect to the sum of measured subsidence values
(***) Pin line is at supercritical conditions and is not affected by edge effect offset

Table 2. Site specific calibration results for Mine B.

					Values for best fit curve			
Operation	Pin Line	Extraction Thickness, m (feet)	Number of contributing Panels	Predicted Edge Effect (feet)	Tangent of Influence Angle	Smax/m (percent)	Edge Effect (feet)	Percent Error
Mine B	1	9	1	N/A	3	74	N/A	3.1
Mine B	2A	9	1	106 – 133	3	68	60	3.1
Mine B	4	9	1	106 – 133	2.9	80	70	3.9
Mine B	3	9, 9.5, (2.5) (*)	2	106 – 133	3.2	66	60	5.5

(*) pillar punching was simulated using an equivalent extraction thickness of 2.5 feet, a steep influence angle and no edge effect

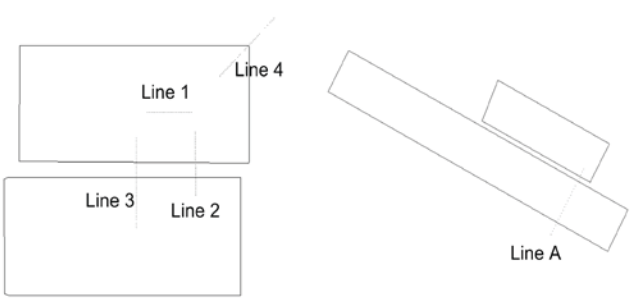

Figure 9. (a) Monitoring lines for Mine B (b) Monitoring line for Mine C.

Mine C

The coal seam at the third mine operation (Mine C) is at a depth of about 580 feet. The extraction thickness at the general location of the pin lines is about 6.3 feet. Panel widths are about 1350 feet including the width of the adjacent entries. The edge effect values predicted for this width to depth ratio varies between 116 feet (conservative estimate) and 145 feet (average estimate). The percent hardrock for this mine ranged from 15 to 19% between different boreholes. The predicted Smax/m based on this percent hardrock ranges between 69 and 72%.

Table 3 presents a summary of the analysis conducted for Mine C. The analysis includes points on one monitoring line spanning three adjacent panels. The analysis was performed by utilizing all the monitoring points or points over specific parts of the panels. The angle of influence remains pretty consistent, the edge effect value averages 70 feet which is below the values predicted for the particular panel geometry.

DISCUSSION OF RESULTS

Table 4 presents a summary of the average values for the subsidence engineering parameters estimated at each of the three sites. The average influence angle for Mine A is over 78 degrees, while the influence angle for the other mines is in the order of 72 degrees. The average value for Appalachia is about 67 degrees. The edge effect offset value for Mine A is between the average value (0.25 * depth) and the conservative value (0.20 * depth) as shown in Agioutantis and Karmis (2013). However, the edge effect values estimated for the other mines are about half of the recommended value. It should be noted that it would be important for accurate ground deformation calculations to determine whether the edge effect offset is affected by pillar punching or not.

Table 3. Site specific calibration results for Mine C.

						Values for best fit curve			
Operation	Pin Line	Extraction Thickness, m (feet)	Number of Panels	Predicted Smax/m (percent)	Predicted Edge Effect (feet)	Tangent of Influence Angle	Smax/m (percent)	Edge Effect (feet)	Percent Error
Mine C	1	6.33	2	69-72	116 – 145	3	70	70	9.5
Mine C	1A	6.33	2	69-72	116 – 145	3	70	75	6.8
Mine C	1B	6.33	1	69-72	116 – 145	3	70	65	1.6

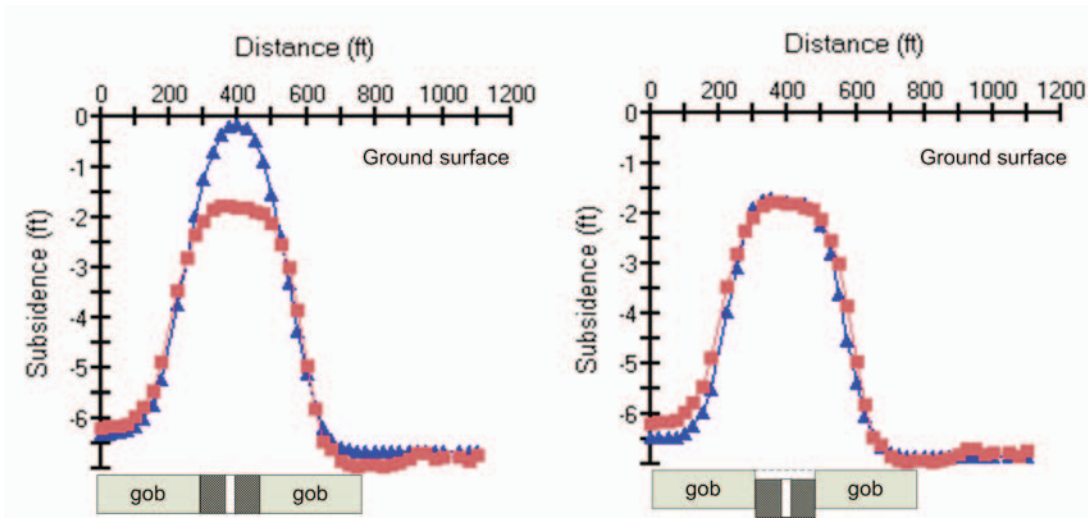

Figure 10. (a) Best fit between measured and calculated profiles assuming gate road pillars between panels are stable (b). Best fit line assuming an equivalent extraction area in the location of the gate road pillars (the blue lines show calculated values and the red lines show measured values).

Table 4. Summary of calibration results for all mines.

Site	Width (feet)	Depth (feet)	Extraction Thickness, m (feet)	Width/Depth Ratio	Smax/m (%)	Tangent of Influence Angle	Edge Effect (feet)
Mine A	1300	550	7 – 7.5	Supercritical	69	5	125
Mine B	1400	540	9 – 9.5	Supercritical	72	3	63
Mine C	1350	580	6.33	Supercritical	70	3	70

The roof of Mine A varies both vertically and laterally, in some cases by substantial amounts. Pod shaped lenses and wedges of gray shale that range from 2 to 20 feet thick and 10s to 100 feet in diameter are distributed throughout the mine. These gray shale pods are the erosional remains of a previously more extensive, and thicker deposit that emanated from peat-contemporaneous river channels that flowed through the peat swamp, and was subsequently removed during marine transgression over the peat swamp. Where the gray shale is eroded, marine black shale and limestone fill in the gaps between the pods. Both the marine black shale and limestone often thickens into these eroded gaps, increasing by as much as several feet. Because of this depositional history, roof lithology can potentially be quite variable over relatively short distances, changing in both thickness and height above the coal, and in cases of very large gray shale pods, both black shale and limestone can be completely absent. In short, this roof is best summarized as heterogeneous.

In contrast, the roof of Mine B is relatively uniform, consisting mainly of a few feet or less of marine black shale and approximately 3 feet of limestone. Minor local variation from these conditions can occur, but there is little deviation across the mine. Mine C follows suit with a uniform roof lithology consisting of black shale and limestone. In both cases the roof of Mine B and C is best summarized as homogeneous.

The floor in all three mines is similar, consisting of a clay rich, gray colored paleosol developed a few feet into silty parent material, with local variation in overall thickness.

It is possible that the greater percent errors and higher tangent of influence angle in Mine A versus Mine B and C are a result of the heterogeneous nature of the lithology of the roof in Mine A. The immediate roof lithology can affect caving characteristics, subsequent gob compaction and ultimately affect surface subsidence parameters. Therefore, variable roof conditions of limestone appearing and disappearing, and large gray shale pods shrinking and swelling, all within tens to a few hundred feet, might reasonably be expected to create variable model results. On the other hand, similar roof lithology thickness, and overall homogeneous roof in Mine B and C may explain the similar model results of Mine B and C.

CONCLUSIONS

In recent years, there has been an increase in longwall mines and longwall productivity in the Illinois coal basin. Since longwall mining will continue to impact large surface areas, the ability to accurately project subsidence profiles and induced strains is integral to the continued use of the longwall mining method. Coal companies and regulatory agencies require valid and accurate modeling tools to assist in predicting the potential impacts of planned subsidence. Accurately defining the limits and characteristics of planned subsidence will benefit both permitting and the efficient management of subsidence impacts.

In this work, subsidence data from current longwall mining in Illinois was analyzed in an effort to refine regional subsidence engineering parameters developed primarily for other coalfields. Special attention was paid to geologic influences such as weak floor in gate roads and the importance of using the best estimate of the actual extraction void as opposed to seam thickness.

The overall result is an improvement in the SDPS modeled profile fit with an option to consider pillar punching in the gate roads for more accurate subsidence simulation over a series of panels. Further work will be focused on the analysis of dynamic parameters and the analysis of ground strains for the same area.

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