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ABSTRACT

Subsidence, mining and site data has been collected over a number of longwall panels in the Illinois Basin. Using this data, empirical correlations are attempted to various subsidence parameters, including maximum vertical and horizontal displacement, subsidence slope and curvature and horizontal strain. Also, the corresponding locations of these various subsidence characteristics are correlated to the associated site conditions. An extensive list of definitions are provided for the various subsidence parameters utilized in the paper.

INTRODUCTION

A study was undertaken to assess empirical interrelationships of measured subsidence profile conditions with site and longwall mining conditions for the Illinois Coal Basin. Longwall mining involves the complete extraction of the coal contained in a large rectangular block or "panel" of coal. The rectangular longwall panel is "blocked out" by excavating passageways around its perimeter. Room-and-pillar mining is used to block out the panel. Excavation of the coal in the panel is an almost continuous operation. Working under the steel canopies of hydraulic, movable roof supports, a coal cutting machine runs back and forth along the "face" cutting coal during each pass. The cut coal spills into an armored chain conveyor running along the entire length of the face. This face conveyor dumps the coal onto belt conveyors for transport out of the mine. As the cutting machine passes each roof support, the support is moved closer to the newly cut face to prop up the exposed roof. The roof is allowed to collapse behind the supports as the face advances. Figure 1 is a schematic of the longwall mining method.

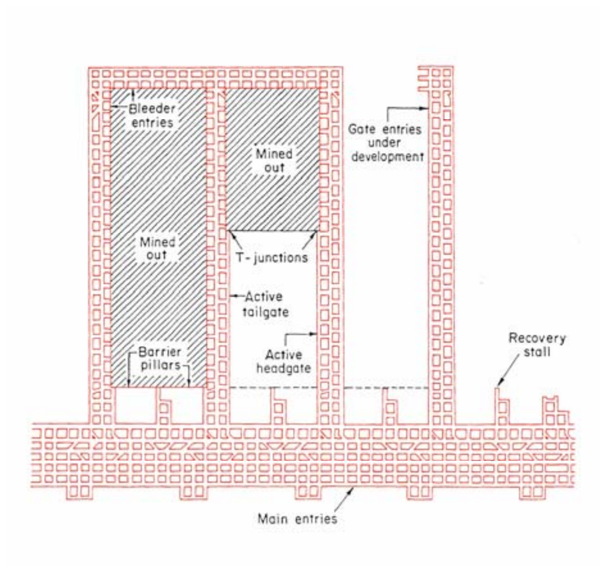

Fig. 1. Schematic of longwall mining technique (Marks, 1990)

SCOPE

A significant amount of longwall mining data was collected for several mines in the Illinois Basin. The data collected included subsidence related movements such as slope, curvature, horizontal movements, and horizontal strains in both transverse and longitudinal directions. In addition to the subsidence related data, -the associated site conditions such as mine depth, soil cover, rock cover, subsidence profile orientation relative to the panel, and coal height were also collected and summarized. Pertinent information for subsidence profiles of 7 longwall mines in the Illinois Basin were used to form the analyses performed, the subsidence data were augmented with non-IL case data.

DEFINITIONS

Subcritical, Critical and Supercritical Profile

For longwall mining, the subsidence profile curve has been categorized in terms of sub-critical, critical and supercritical as shown in Fig. 2 (Kratzsch, 1983). A subsidence profile curve that has maximum settlement less than the maximum value is called a "Sub-critical" profile and is characterized by the following equation that relates the width of the panel to the depth of coal seam:

$$P_w < 2D_c \tan \alpha \qquad (1)$$

Where:

P_w = width of panel, ft
D_c = depth of coal measure from the ground surface, ft
α = angle of profile development

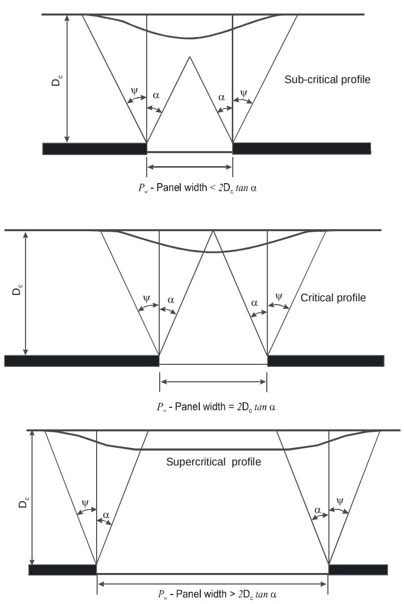

Fig. 2 Different subsidence profile types

A "Critical" profile curve indicates that subsidence has reached its maximum value at one point only at the center of the mined-out panel or when:

$$P_w = 2D_c \tan \alpha \qquad (2)$$

"Supercritical" profile curve refers to a subsidence curve measured to have a relatively flat zone of maximum statistical based relationships. Also, in some of the settlement. Flat curves occur where the panel is wide enough relative to the mine depth. The characteristic equation for supercritical profile is:

$$P_w > 2D_c \tan \alpha \qquad (3)$$

One other parameter that is frequently referred to in this paper is the horizontal distance from the point of zero subsidence to the point of maximum subsidence, or the subsidence profile width SPW. For a critical profile this is equal to the sum of the tangent of the angle of draw and the tangent of development angle times the coal depth (D_c) (see Fig. 2).

Ground Strain Characteristics

The characteristics of a subsidence trough over a longwall panel can be presented by profile curves showing the vertical displacement, slope and curvatures as shown in Fig. 3. The slope is the first derivative of the vertical displacement diagram and it increases from the edge of the panel, reaches a maximum value and flattens as it reaches the center of the mined-out panel. The maximum slope is found at the point of inflection. The slope of a certain curve was measured by the following expression (see Fig. 3):

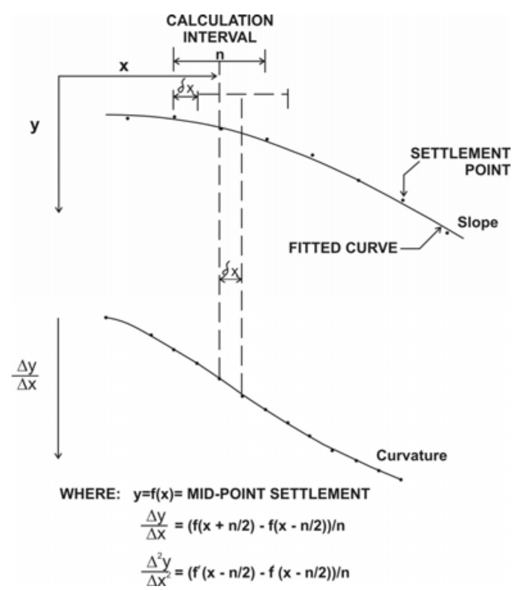

Fig. 3 Schematic of subsidence trough showing vertical movement, slope and curvature

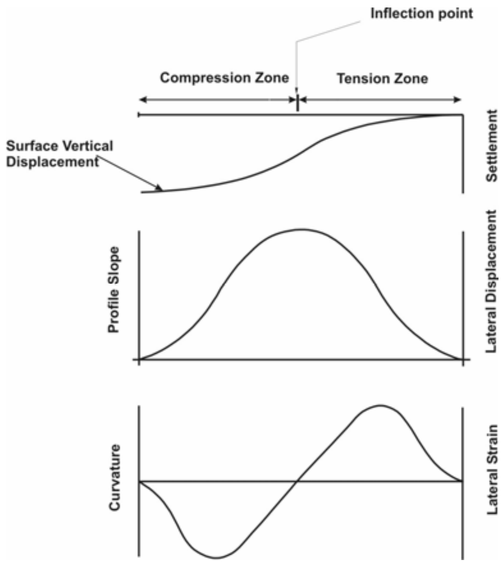

Fig.4 A Schematic showing tensile and compressive strain zones and correlation between different subsidence movement components

$$S' = \frac{\Delta y}{\Delta x} = \frac{f(x+\frac{n}{2}) - f(x-\frac{n}{2})}{n} \qquad (4)$$

where
n = interval length
S' = profile slope
Δy = change in vertical displacement
Δx = horizontal distance increment where Δy took place
$f(x+\frac{n}{2}) - f(x-\frac{n}{2})$ = the difference in vertical displacement as determined from the function describing the subsidence profile as determined at $(x+\frac{n}{2})$ and $(x-\frac{n}{2})$

The second derivative of the subsidence profile is approximately equal to the curvature. The curvature is the change of slope within a certain interval and is determined from the following equation (see Fig. 3):

$$S'' = \frac{\Delta^2 y}{\Delta x^2} = \frac{f'(x+\frac{n}{2}) - f'(x-\frac{n}{2})}{n} \qquad (5)$$

where
$f'(x+\frac{n}{2}) - f'(x-\frac{n}{2})$ = change of slope between $(x-\frac{n}{2})$ to $(x+\frac{n}{2})$

The point where the curvature changes from compression to tension is again the inflection point**.** In this paper the slope (S') is calculated at the midpoint of a chord with specific length. A chord length of 40 ft is used for determining different values that are listed in the tables. However, an additional analysis was done using a chord length of 10 ft to determine the slope and angle of distortion and this is presented in later sections of the paper. Similarly, the maximum curvature is calculated using Equation (5).

The lateral ground displacement profile empirically has the same pattern and is assumed proportional to the profile slope and therefore the lateral or horizontal strain along a section of profile can be approximated by the section curvature as shown in Fig. 4. The lateral strain is determined as the change in horizontal interval length over the original length. It is important to realize that all differential subsidence values (e.g. slope, curvature, horizontal strain, etc) are functions of the measurement interval and that they increase with smaller measurement intervals.

The subsidence profile is characterized by two distinct strain zones which are shown in Fig. 4. Compression strain results along the profile where the inward lateral ground movements decrease toward the center of subsidence trough. On the other hand, tensile strain results where the lateral ground movements increase toward the center of the subsidence trough. In this report the maximum curvature in the compression zone is called $S''_{max\ (comp)}$ and maximum tensile curvature is called $S''_{max(tens)}$. Location of $S''_{max\ (comp)}$ and $S''_{max(tens)}$ can be measured as their offsets from the edge of the panel and are denoted as OF_{cc} and OF_{tc}, respectively, which is illustrated in Fig. 5.

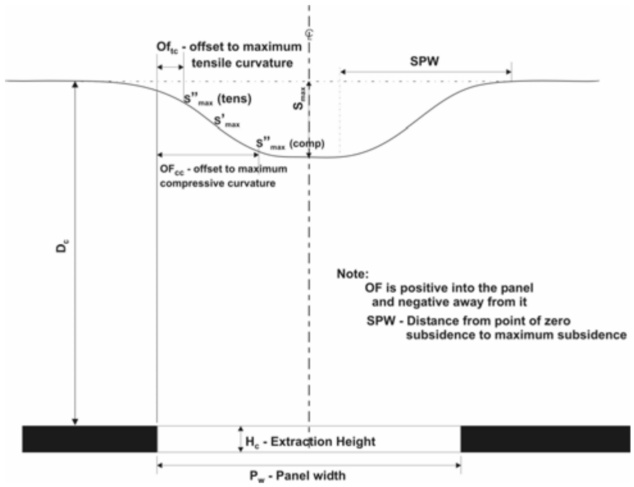

Fig. 5 Illustration of offsets to maximum Compressive and tensile curvatures

Other Profile Nomenclature

Figure 6 shows other profile nomenclature used in this paper, such as ribs, angle of draw, angle of break, draw zone, etc. It should be noted in this report that a subsidence profile curve across a panel will have two profiles extending from the vicinity of the ribs toward the middle of the trough forming one subsidence curve.

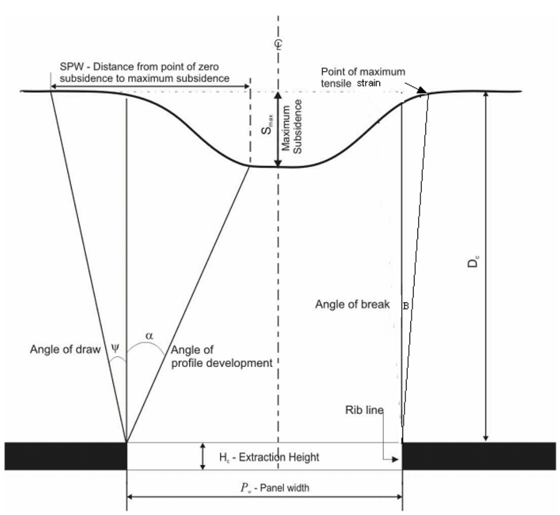

Fig. 6 A schematic of subsidence profile nomenclature

Also, depicted in Figure 6 is the Angle of Draw (Ψ) which is the angle measured from the edge of the panel to the point of zero subsidence and its horizontal projection at the ground surface is defined as the Draw Zone. The angle from the vertical at the edge of the collapsed workings to where tensile strain at the surface is the greatest is called Angle of Break (B).

Figure 7 shows the nomenclature for lateral or horizontal movements. The "H" refers to movements in the horizontal direction (lateral movement). So, H' is the horizontal strain for both tension and compression zones and OF_H is the offset from the rib to the point of maximum horizontal displacement.

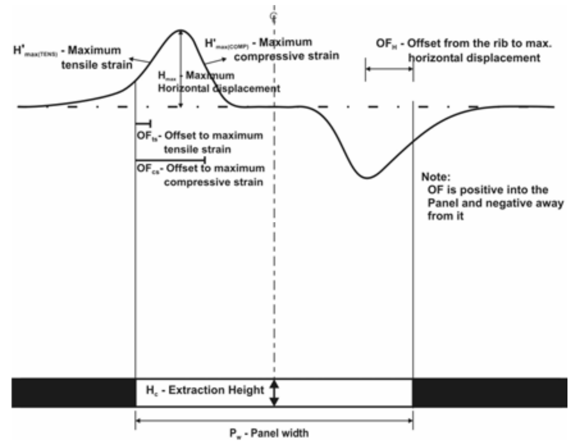

Fig. 7 Definition of the some nomenclature related to horizontal movement

Statistical Approach for Subsidence Movements. A statistical approach is used herein to determine the expected range of ground movement based on the associated site conditions. For subsidence-structure interaction analyses a statistical approach, which is based directly on actual field data, provides the most representative expected movements for the site conditions rather than some best fit subsidence profile generated from computer program. The use of readily available subsidence profile prediction codes are deemed too risky for subsidence-structure interaction because of the more general manner that the various subsidence characteristics are calculated and the level of sensitivity of many structures to such subsidence characteristics. Based on the statistical trends observed, statistical based subsidence profiles and areal maps can be generated to predict the locations and values of various horizontal and vertical movements induced by the subjacent longwall mining at the structure. This in turn can be used to assess the potential damage and necessary precautions or remediation measures.

Maximum Subsidence

For the case histories, the maximum subsidence values varied from 4.03 ft to 6.75 ft and the corresponding coal heights from 5.9 to 9 ft for the subsidence profiles in the Illinois Basin. The maximum subsidence can be correlated with the coal extraction height and the ratio of the panel width to depth of the coal seam. A scatter plot was developed incorporating all these parameters and is presented in Figure 8. The figure shows the relationship between Subsidence Factor (S_{max}/H_c) and P_w/D_c where S_{max} = maximum subsidence and H_c = thickness of coal seam (extraction height). It should be noted that in Figure 8 the extraction height is assumed to be the extraction height and therefore does not include any fallen roof material which may get conveyed out of the mine. This can explain why the Subsidence Factor for one point plotted out at about 0.95 in Figure 8.

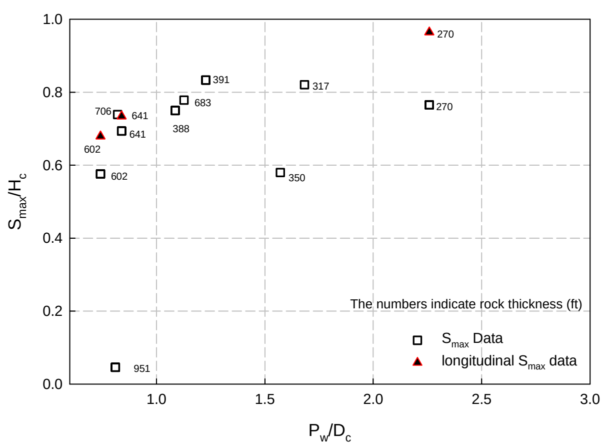

Fig. 8 A plot showing the relationship between S_{max}/H_c and P_w/D_c for transverse and Longitudinal subsidence data

Profile Width

As discussed earlier the distance from the point of zero subsidence to the point of maximum subsidence is defined as SPW. For a critical or supercritical profile this is equal to the sum of the tangent of Angle of Draw and Tangent of Development Angle multiplied by the depth to the coal layer. This is mathematically represented by the equation:

$$SPW = D_c\,(\tan \Psi + \tan \alpha) \qquad (6)$$

For the case histories the angle of draw (Ψ) varied between about 0º to 50º and the profile development angle (α varied between 17º and 31º. When evaluating SPW where a structure is located, the minimum, medium, and maximum values of SPW can be calculated. It should be noted, however, that the zero subsidence point was linearly extrapolated from definitive subsidence points at the end of the profile. The draw angles noted herein should not be confused with the relevant extent that the subsidence extends beyond the rib line when evaluating any effects from subsidence.

Maximum Slope and Curvature

As shown in Figs. 9 and 10 two plots of S_{max} against 2(SPW) S'_{max} and S_{max} against 4(SPW^2) S''_{max} were plotted to identify the range of measured slope and curvature. Much of the data used in this report was taken from Hunt, 1980, Bauer and Hunt, 1981, Marino, 1985, Marino and Bauer, 1989, and more recent data collected by MEA. It is important to point out that the plotted data also includes room and pillar mines in Illinois. The extraction ratio and the maximum subsidence for these cases mainly ranged from 50 to 87% and 0.5 to 5.2 ft, respectively.

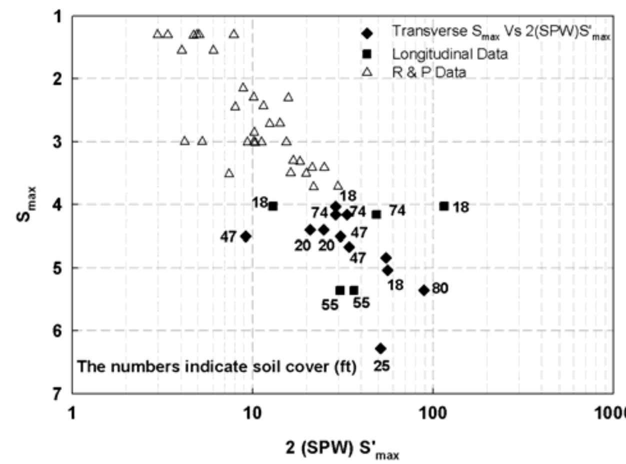

Fig. 9 A plot of S_{max} against 2(SPW)S'_{max} for both longitudinal and transverse longwall data and room-and-pillar data in the Illinois Basin

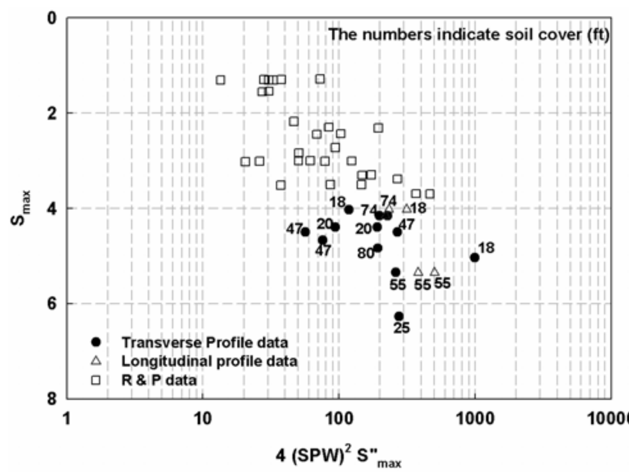

Fig. 10 A plot of S_{max} against 4(SPW^2) S''_{max} for both longitudinal and transverse longwall and room-and-pillar data in the Illinois Basin

Note that the maximum average curvature is the average of the maximum of the tensile and compressive curvatures for a profile. As can be seen in Figs. 9 and 10 the room-and-pillar data is an extension of the longwall trends. Figures 9 and 10 also show that for a given S_{max} and SPW a statistical variation in the measured maximum slope and average curvature can be about 3.5 and 4.5 times the lesser value in the main body of the data.

In addition to the determination of slope and curvature ranges, the locations of these permanent ground deformations relative to the structure are also needed for subsidence-structure analysis. There were a number of correlations that have been attempted with OF_{cc} (offset from the rib to maximum compressive curvature), OF_{tc} (offset from the rib to maximum tensile curvature), OF_{tc}-OF_{cc} and (OF_{tc} + OF_{cc})/2 with respect to various site conditions including P_w/D_c, R/D_c and (R-Sc)/Dc to investigate the effect of these factors on tension and compression maximum curvature locations. For an estimation of the location of S'_{max} with respect to the rib, (OF_{tc} + OF_{cc})/2 can be used. Correlations of (OF_{tc} + OF_{cc})/2 parameter with P_w/D_c, R/D_c and (R-SC)/Dc are given in Figs. 11 through 13, respectively. These plots do not show specific trends, nonetheless they can be used to get a range of values that can be used in the analysis. The parameter OF_{cc} - OF_{tc} represents the width of the profile between the points of maximum tensile and compressive curvatures. Figure 14 is a plot of the normalized offset difference $(\frac{OF_{cc}-OF_{tc}}{D_c})$ against $\frac{P_w}{D_c}$ utilizing data for transverse sections only. The figure shows that the normalized offset difference mostly lies within the range of –0.2 to –0.4. Figure 15 is similar to Fig. 14 but it utilizes data from both transverse and longitudinal sections with the normalized offset difference plotted against R/Sc. Figure 15 shows that the normalized offset difference ranges from –0.15 to –0.5.

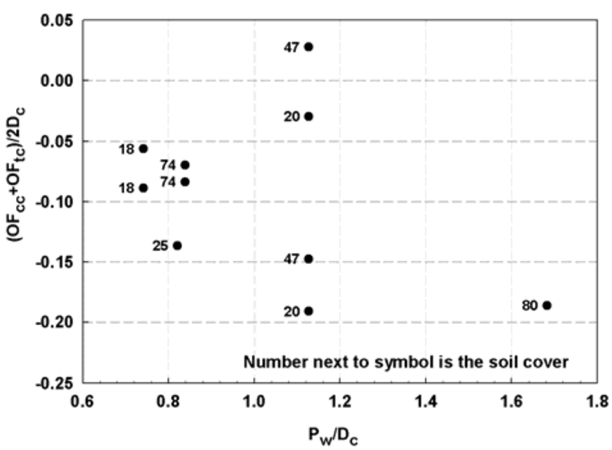

Fig. 11 $(\frac{OF_{cc}+OF_{tc}}{2D_c})$ *against* $\frac{P_w}{D_c}$ *using transverse data only*

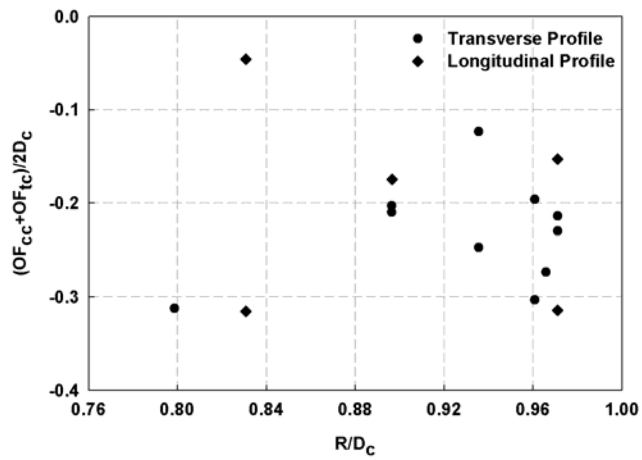

Fig. 12$(\frac{OF_{cc}+OF_{tc}}{2D_c})$ *against* $\frac{R}{D_c}$ *using longitudinal and transverse data*

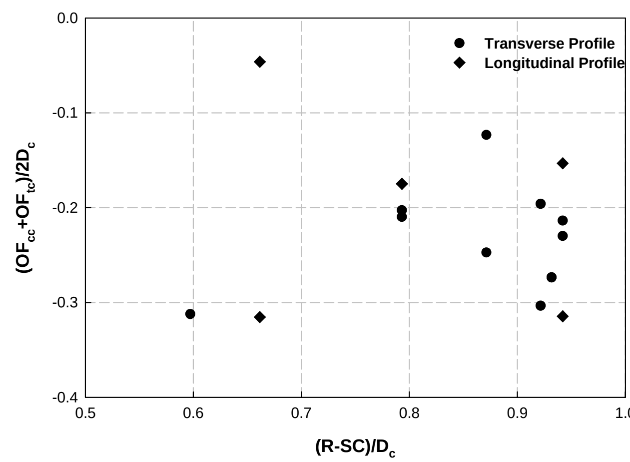

Fig. 13$(\frac{OF_{cc}+OF_{tc}}{2D_c})$ *against* $\frac{R-SC}{D_c}$ *using longitudinal and transverse data*

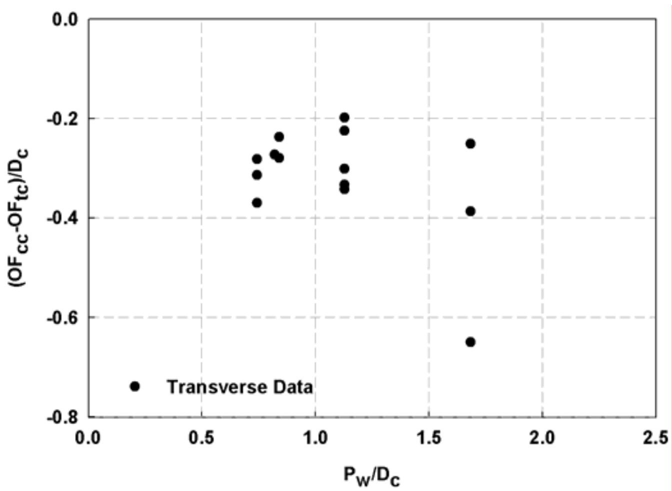

Fig. 14 $(\frac{OF_{cc}-OF_{tc}}{D_c})$ *against* $\frac{P_w}{D_c}$ *using transverse data only*

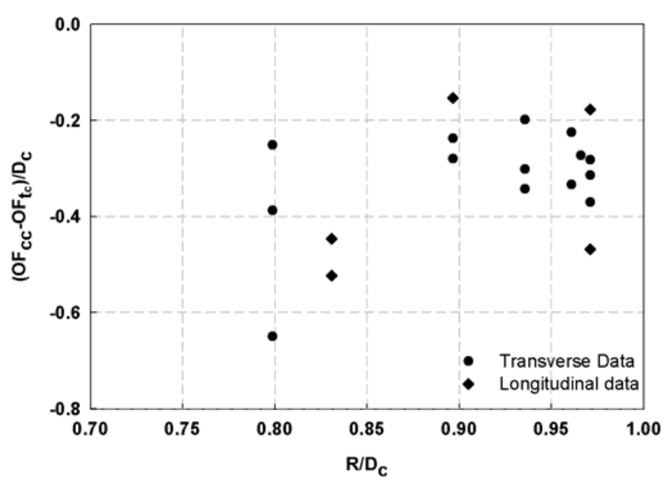

Fig. 15 $(\frac{OF_{cc}-OF_{tc}}{D_c})$ *Against* $\frac{R}{D_c}$ *using longitudinal and transverse data*

The effect of soil cover and rock thickness on the normalized offset difference was investigated by plotting it against $\frac{R-SC}{D_c}$ as shown in Figure 16. The plot shows an upward trend but of a wide band.

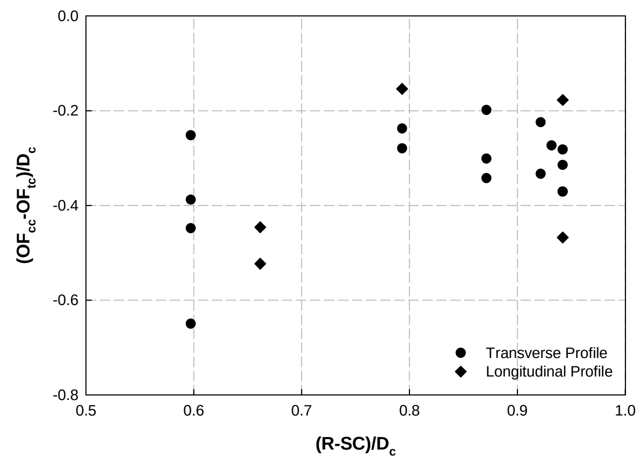

Fig. 16 $(\frac{OF_{cc}-OF_{tc}}{D_c})$ *against* $\frac{R-SC}{D_c}$ *using transverse and longitudinal data*

<u>Subsidence over Chain Pillars</u>

Subsidence over the centerline of the chain pillars (S_{cp}) was investigated for structures located over this area. The available subsidence data at the centerline of the chain pillar were normalized to the thickness of the coal seam (H_c) and then were plotted in Fig. 17 against the D_c/W_{cp}, where W_{cp} is the width of the chair pillar system. Due to the lack of subsidence data at the center of chain pillar, only four data points could be plotted in the figure.

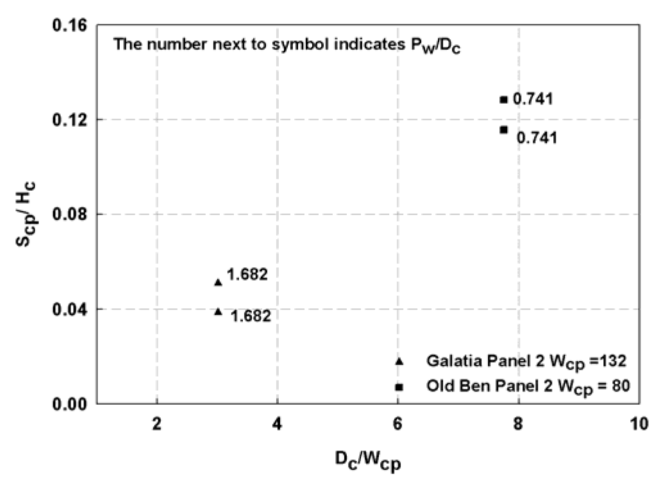

Fig. 17 S_{cp}/H_C *versus* D_c/W_{cp} *using Illinois longwall data US*

Horizontal Displacement and Strains

Because of limited amount of case data on subsidence induced horizontal displacement and strain assessment of statistical trends required augmenting these data with non-Illinois case data from the US and abroad. Figure 18 shows the relationship between the maximum horizontal strains in the tension zone ($H'_{max(tens)}$) and H_{max}/SPW. Figure 19 is similar to Fig. 18 but it is plotted for the compression zone horizontal strains. In both figures an apparent increase in H'_{max} with H_{max}/SPW exists, with a measured maximum tensile strain of 0.024 and maximum compressive strain of 0.021.

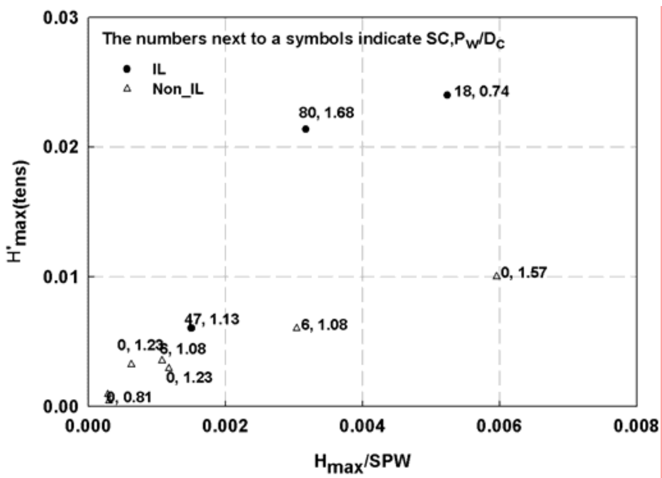

Fig. 18 Relationship between the maximum horizontal strains in the tension zone ($H'_{max(tens)}$) and H_{max}/SPW

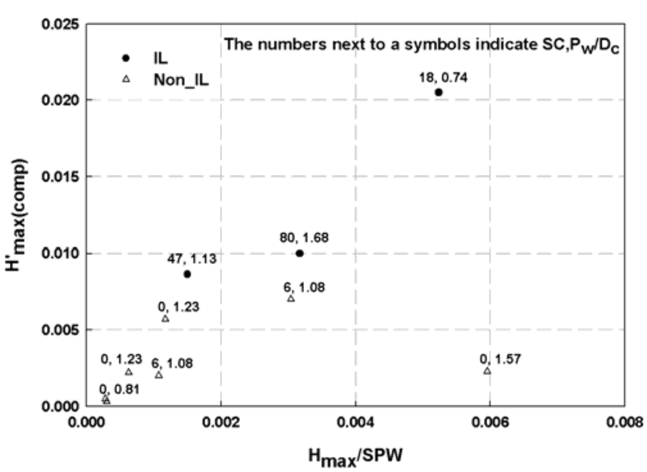

Fig. 19 Relationship between the maximum horizontal strains in the compression zone ($H'_{max(comp)}$) and H_{max}/SPW

The case data on horizontal movement was also used to estimate the offsets to maximum tensile and compressive strains by plotting the normalized offset of tensile strains (OF_{ts}/D_c) and compressive strains (OF_{cs}/D_c) against $(R\text{-}SC)/D_c$ as shown in Figs. 20 and 21. These plots show no trends but the OF_{ts}/D_c and OF_{cs}/D_c values determined from the case data range between 0.04 to -0.03 and -0.19 to 0.68, respectively. A second order plot of the ratio of H_{max}/S_{max} was attempted and showed a general decreasing trend with P_w/D_c (see Fig. 22). The range of H_{max}/S_{max} for the case data was from 0.09 to 0.62. The offset to the maximum horizontal displacement was plotted against R-SC with both parameter values normalized with respect to mine depth. For the data available the OF_H/D_c values ranged from –1.2 to -0.7 but no trend was found to exist (see Fig. 23)..

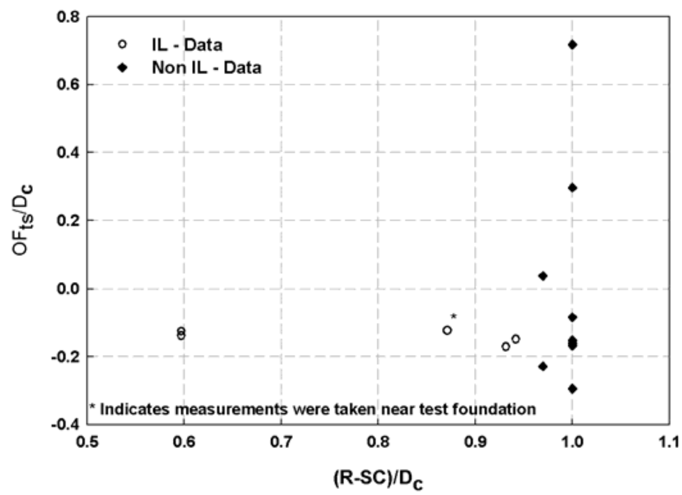

Fig. 20 Plot of OF_{ts}/D_c against $(R\text{-}SC)/D_c$

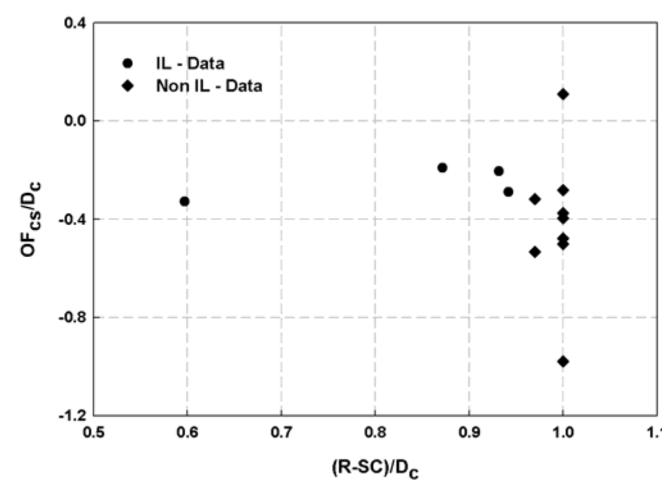

Fig. 21 Plot of OF_{cs}/D_c against $(R\text{-}SC)/D_c$

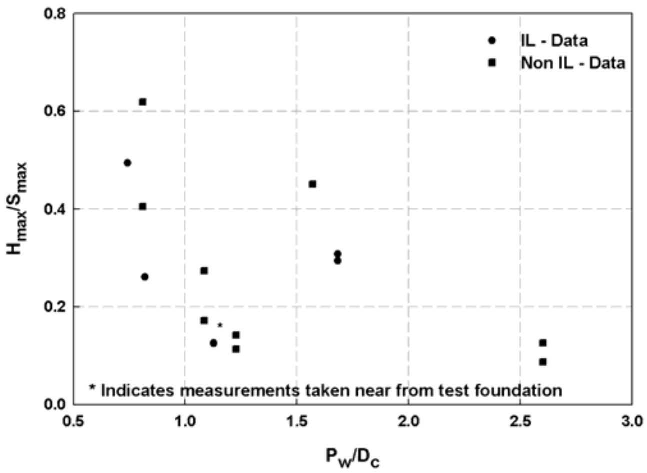

Fig. 22 H_{max}/S_{max} *versus* P_w/D_c

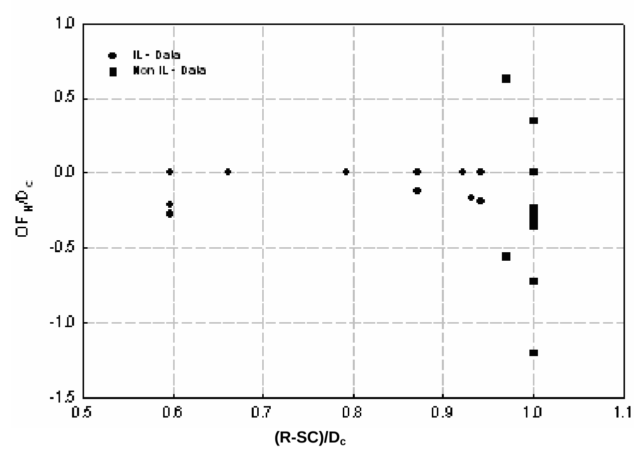

Fig. 23 (OF_H/D_c) *versus (R-SC)/Dc*

Subsidence Profile Construction

Statistical based profiles are developed using the information obtained from various relevant subsidence movement characteristics primarily from Illinois data and follow methodology used by Marino, 1997. For analysis of subsidence-structure interaction, profiles can be considered for the range of maximum slope and curvature, maximum horizontal displacement and strain, location, and width expected.

SUMMARY AND CONCLUSIONS

Using longwall data in the Illinois Coal Basin empirical correlations are provided in this paper. Important relationships are developed between site and mine conditions to the location and magnitude of a number of subsidence induced surface movements. Statistical plots were developed for longwall induced vertical displacement slope and curvature, as well as horizontal displacement and strain.

Determination of a statistical range of location and movement is the most appropriate method in evaluating subsidence-structure interaction prior to obtaining on-site subsidence data from longwalling. Use of subsidence prediction methods which provide one "best-fit" subsidence curve must in some fashion "average" the considered case history data. These "average" vertical and horizontal displacement curves are then differentiated to obtain other "averaged" ground distortion values. A statistical approach, however, focuses on direct correlations with the actual measured parameter values to obtain an actual range of values. For example, from the case data discussed herein shows that the maximum subsidence profile slope and curvature values were found to vary about 3.5 and 4.5 times, respectively, for a given maximum subsidence and subsidence width values.

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