THE SITING OF A PRISON COMPLEX ABOVE AN ABANDONED UNDERGROUND COAL MINE[1]

by

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Abstract. This paper discusses in detail the process undertaken to mitigate the effects of any future mine subsidence on prison structures proposed above old abandoned underground workings. The site for a proposed prison complex purchased by the State of Indiana was located in west-central Indiana and was undermined by an old abandoned room and pillar mine. The original plan for construction consisted of one phase. Based on a study of the mine map and subsurface verification of the extent of mining it was determined that all prison buildings and important structures could be placed above solid coal to the north. One masonry building, however, was located within the potential draw zone of mine works which still contained significant mine voids. Based on empirical data the subsidence potential was estimated and the building was accordingly designed to be mine subsidence resistant. It was decided that a phase two prison complex should be constructed adjacent to and just south of the Phase I complex. This complex would be directly above the underground workings. The first stage of design was to minimize subsidence potential by positioning the exposure of significant structures to the subjacent mining assuming the mine map was sufficiently accurate. Subsequently, an extensive subsurface investigation program was then undertaken to: 1. ascertain whether or not mine areas where buildings would be located were already collapsed and thus only nominal, if any, subsidence could occur in the future; and 2. verify the presence of solid coal areas within the mine as indicated on the mine map. Based on all the site information gathered subsidence profiles were developed from an empirical data base of subsidence events in the Illinois Coal Basin. As a result of this work many structures on the site required no or nominal subsidence considerations. For others that could be potentially affected by future subsidence movement, however, preliminary subsidence resistant designs were completed using the expected level of potential subsidence movement. The estimated costs to make each of these structure subsidence resistant was significant. Mine backfilling measures were taken at these structure locations.

Additional Key Words: Mine Subsidence, Subsidence profiles, Subsidence damage

Introduction

With little site specific subsidence data, prudent design assumes a worst case scenario. In other words random multiple mine subsidence events and the maximum possible magnitude of ground movement characteristics must be considered. A detailed investigation of the subsidence potential of a proposed construction site can, however, reduce the building costs significantly. As a result of such an investigation the subsidence potential for a specific structure can be reduced from the worst-case scenario to a lower risk level by limiting the range of subsidence movements,which are possible to a no risk of subsidence situation. Furthermore a subsidence potential investigation results in most accurately determining the most appropriate and cost-effective means of subsidence damage mitigation. This paper discusses a case history where site investigation of the subsidence potential was successfully used to obtain the best solution in mitigating any future damage from mine subsidence.

Background

A site in Carlisle, Indiana was selected by the State of Indiana for a prison complex. The prison is named the Wabash Valley Correctional Institution (WVCI). The main factors involved in the selection of this site were: 1. relatively low land purchase costs; 2. significant acreage; and 3. the politically advantageous location. One of the drawbacks to the site, however, was

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that it was undermined. History has shown that structures ill-prepared to handle mine subsidence perform very poorly and can result in abandonment of the structures (Marino, et al, 1982, and Marino and Funkhouser, 1986). Based on a preliminary subsidence investigation of the site it was determined despite the subsidence problems that the site could be cost-effectively developed providing that damage mitigation measures were taken (Marino, 1990A). At the time, only one prison complex was contemplated. This construction is called Phase I in this paper.

An investigation was conducted to determine the mine subsidence potential for the Phase I construction (Marino, 1991A). Based on this investigation it was found that only 2 of the 20 important Phase I structures could be significantly affected by subsidence movements (Marino 1991B and 1992.) From empirical data on subsidence, the possible ground movements at specific structure locations were estimated from which subsidence resistant design measures were determined.

After the Phase I construction the State decided to build a Phase II complex. The proposed Phase II construction is just south of the Phase I site (see Figure 1). Construction of proposed (Phase II) structures adjacent to pre-existing ones is apparently cost-effective as certain Phase I facilities can be mutually utilized (instead of having to construct certain new facilities at another location) and administrative cost per area will be lower.

The proposed Phase II construction presented a significantly more severe scenario than Phase I as much of this construction was planned over the recorded location of abandoned underground coal mine. A Phase II subsidence investigation was undertaken to reduce the subsidence potential from the worst case scenario at the proposed locations of "sensitive" structures mainly by: 1. Verification by subsurface exploration of significant solid coal areas shown on the map of mining beneath the site, and 2. Assessment by subsurface exploration of whether mined-out areas were collapsed or open. As a result of the investigation sufficient detail of the subsidence potential was determined for design of damage mitigation measures at the proposed structure locations.

Site Description

In Phase I there were 20 significant structures

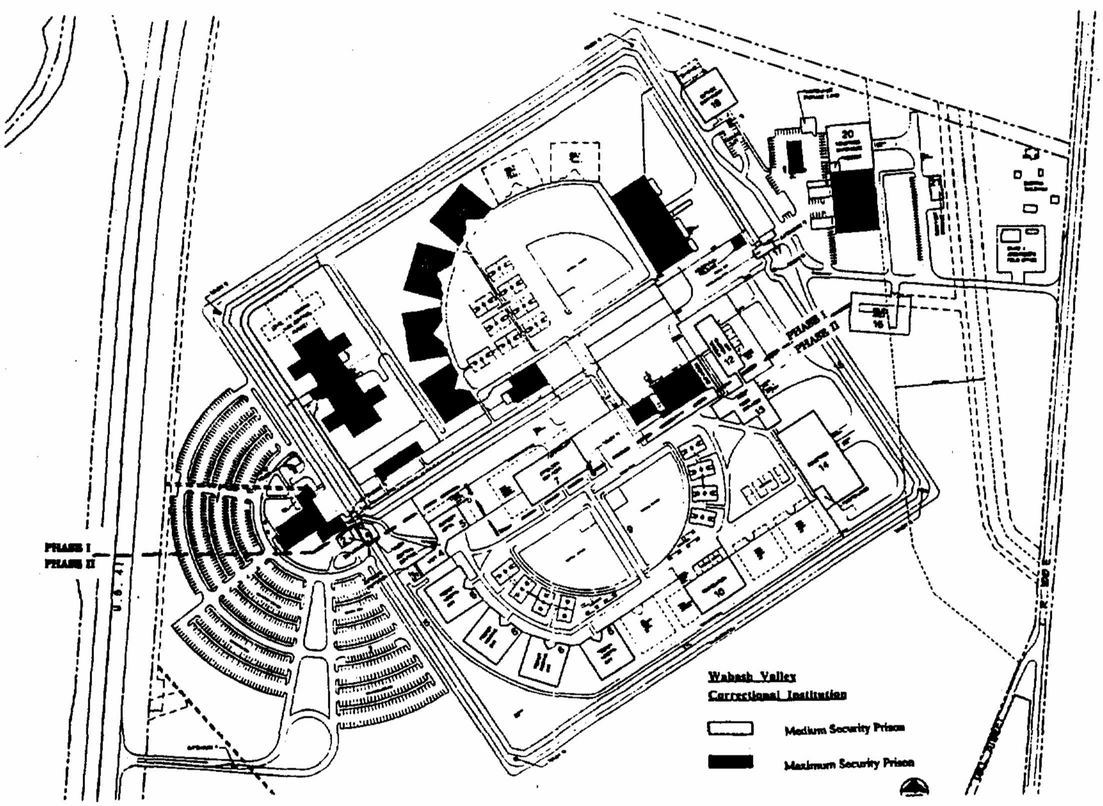

FIGURE 1. PHASE I AND PHASE II CONSTRUCTION OF PRISON COMPLEX.

constructed. Phase II construction at WVCI consisted of a total of 16 major structures. The Phase I and II structures consist of housing units, administrative buildings, recreational buildings, industries buildings, food service buildings, guard towers, and a radio tower (as well as other prison appurtenances). There are basically four building types that had to be considered on the site. These are as follows:

1. Low flexible steel structures with metal facing used primarily for storage and industrial functions.

2. Low one-story structures used for service areas such as food preparation and administration. These buildings would normally be masonry faced with higher degree of finish on the interior than Type 1.

3. Rigid multi-level living and administrative structures constructed of masonry and/or concrete.

4. Tower structures of steel frame.

Subsurface Exploration

Significant effort was expended in developing an exploration program in order to accomplish the goals of the subsidence investigation as stated earlier in the paper. The first step of the investigation was to determine the "shadow" areas of the important structures. "Shadow" areas are areas outlined by extending the planned limits of the building using a draw angle (in this case 30°) to mine level (see Figure 2). The purpose of determining these areas was to assess the actual area of the site requiring subsurface exploration. Using this criterion for Phase I an "east-west picket line" of drill holes with cross-borehole geophysics was proposed across the site. The geophysical method selected consisted of transmitting electromagnetic waves in the coal from one hole and receiving the wave in another. Mine voids are detected by a significant decrease in the received waves than otherwise expected. This method allowed hole spacing to be increased from about 30 ft to about 100 ft to over 200 ft. These borehole transmissions were conducted by RIMtech, Inc. using RIM℠ (Radio Imaging Method) technology for both the Phase I and Phase II work (List, et al, 1994).

The locations of all the holes drilled and all geophysical transmissions performed at the site are shown in Figure 3. For Phase I a total of 28 borings were drilled to depths greater than 300 ft and 23 cross-hole geophysical transmissions were done. To evaluate subsidence-related conditions for Phase II construction at WVCI a total of 39 boreholes over 300 ft were drilled through the mined-out coal seam, and 37 RIM surveys. Furthermore, a borehole TV camera operated by the U.S. Office of Surface Mining, Pittsburgh, PA was inserted into the four holes to assess in situ fracturing and voids in the overburden rocks and to view the immediate mine conditions. Most of the holes were drilled to establish areas of significant solid coal as noted in the mine map.

Geologic Conditions

A geologic column of the site is shown in Figure 4. As shown in Figure 4 the soils across the site are 35 to 70 ft deep and consist of lacustrine deposits over glacial drift. The rocks below the soil have been deposited in cyclotherms, and above the mined-out No. 5 (Springfield) Coal seam the No. 7, 6 and 5A Coals are present. As can be seen in Figure 4 the coal measure rock generally becomes finer grained with depth. Above the No. 7 (Danville) Coal fairly thick fine sandstone

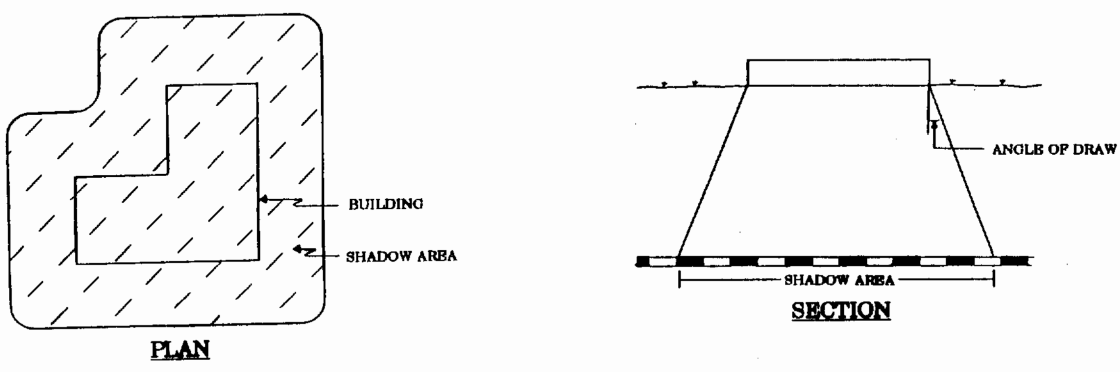

FIGURE 2. DETERMINATION OF A SHADOW AREA OF A BUILDING.

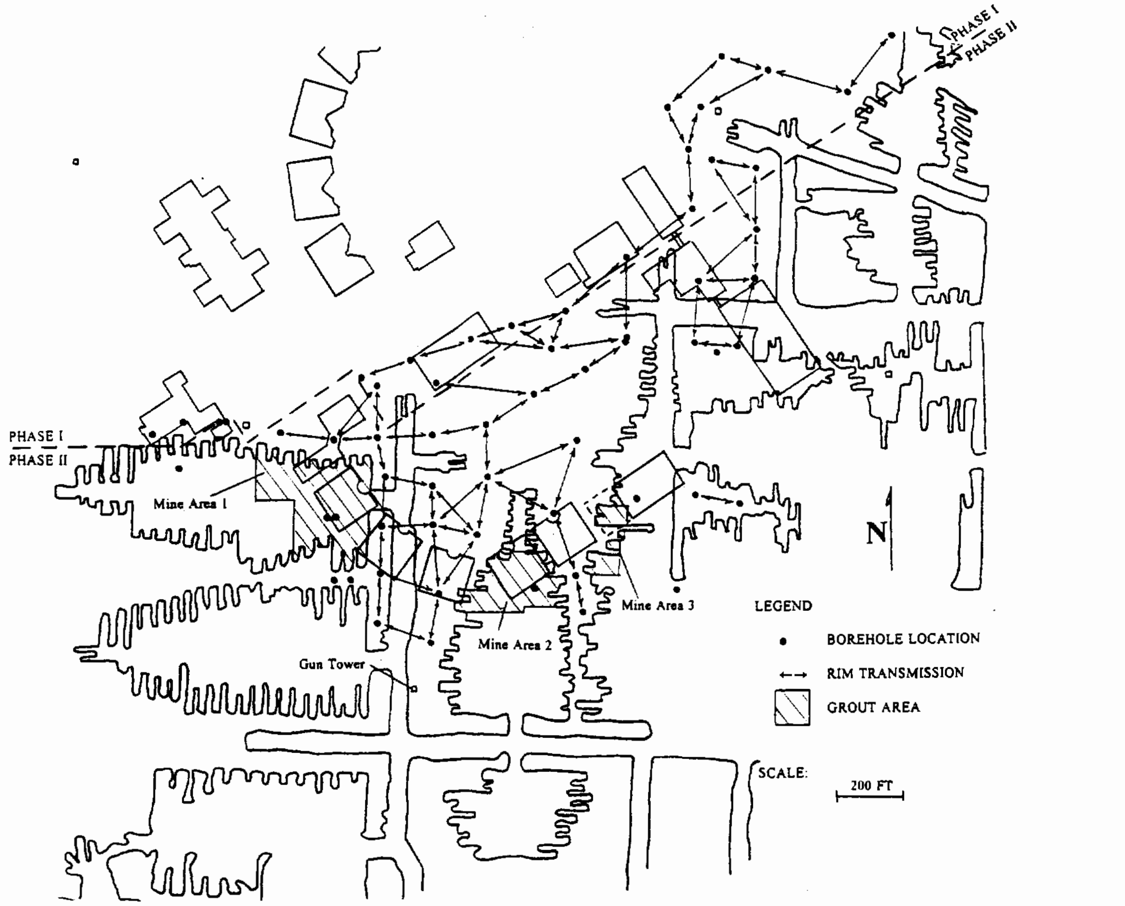

FIGURE 3. PLAN OF PRISON CONSTRUCTION WITH BOREHOLE LOCATIONS, RIM TRANSMISSIONS, AND MINING OUTLINE.

sequence the rock then becomes more shaly to the top of the mined-out No. 5 Coal. The No. 5 coal seam is present about 300 ft below the ground surface. Borehole water level measurements across the site indicate that the groundwater table is generally 5 ft to 10 ft below the ground surface. Water levels in cased holes which intersected the underlying mine working were found to be at approximately the same elevations as the ground water table.

Mining Conditions

The operation of the mine beneath the project site in the No. 5 coal seam appears to have begun in 1908 and was abandoned in 1928. About 800 ft south of the project site are the shafts where the mine air was vented and the mine personnel and coal tonnage were hoisted.

Based on the mine map the panel entries were generally 15 ft wide with 8-9 ft wide central pillars with 5 to 15 ft cross-cuts at varied spacing. Panel areas

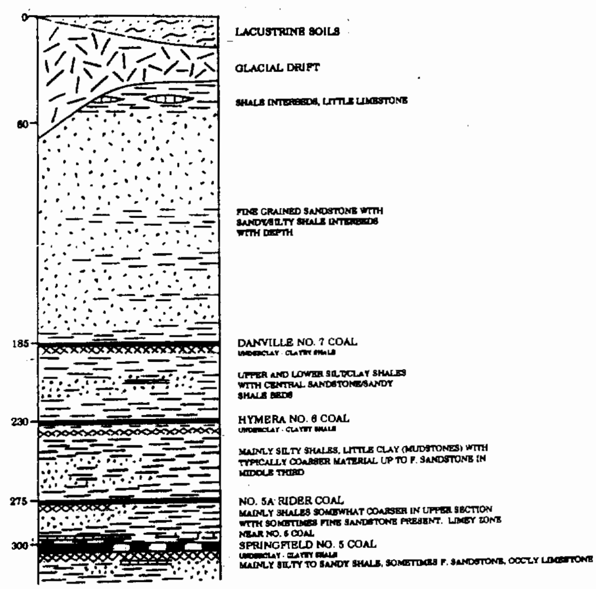

FIGURE 4. A GENERALIZED GEOLOGIC CROSS-SECTION.

beneath the project site have rooms which are 25 ft to 30 ft in width with fairly narrow 8-9 ft wide pillars that are butted adjacent to the entries. Cross-cuts in the panels are about 10 ft wide and have varied spacing. Production areas of the mine (adjacent panels with a central double entry system) are up to almost 400 ft wide but extend longitudinally up to 800 ft in length. These high extraction areas are found to have extraction rates from 68 to 75%. Based on the boring data the mine void height below the site ranged from 4.25 to 4.5 ft.

The mine appeared to be in differing states of stability. Areas were found that appeared to be presently stable, distressed, and collapsed. These conclusions were arrived at based on observations from the Phase I and Phase II drilling and the borehole camera results. Unfortunately, areas investigated which could subside and affect important project structures did not appear collapsed and could experience subsidence in the foreseeable future.

The most northwest mine panel located just south of the existing Central Administration Building Complex appears to be under distress. This is indicated by drilling information obtained in that area. In fact all major drill water losses that occurred in Phase I and II holes in the overburden where found in that area. In addition to encountering essentially open mine, uncollapsed mine workings were indicated in the borings by: 1. the lack of encountering voids or significant circulation loss above the immediate roof materials; 2. no apparent subsidence anomalies in the structural contours of the overburden coal or topography; and 3. reasonable mine void heights at expected elevations.

Mine subsidence results from instability at mine level which then propagates upwards until it reaches the surface. Because of the depth of the mine and the lack of aquifer conditions in the overburden rock, the possibility of surface subsidence from stoping of the roofs over rooms can be neglected. However, based on the information collected, the possibility of subsidence as a result of pillar or floor bearing capacity failure can not be eliminated. The coal measure of most concern is the floor underclay or clayey shale. In addition to time related strain softening or creep behavior of this material, core samples indicate they can continue to soften in the room as they are exposed to the mine water.

Somewhat offsetting the effect the mine water has on the floor is its fluid pressure at mine level. Based on open drill holes through the mine voids, hydraulic heads approximate the area hydrostatic levels. (The mine therefore appears to have essentially reached a state of hydraulic equilibrium.) A brief calculation indicates that the production pillar pressures are still on the order of 650 to 825 psi in production areas, surely enough to make failure possible.

Mine Verification Results

Much of the subsurface investigation effort was spent verifying the recorded areas of substantial coal or localized limits of mine. This was felt necessary as the possibility of inaccuracies in the mine plan recorded in 1928 existed due to the possibly additional mine extraction not mapped or from surveying errors. The effort expended on the mine verification investigation was based on reaching reasonable confidence level in the recorded outline of mining subjacent to certain proposed structures sensitive to ground movement. It was determined that if sufficient verification could be obtained for these structures substantial savings would result as the level of subsidence risk could be reduced.

The mine verification effort consisted of drilling a number of holes and performing RIM (Radio Imaging Method) cross-hole surveys in the No. 5 coal of the shadow areas of proposed building locations. In these shadow areas, areas of substantial coal as indicated on the mine map were investigated in order to project specific subsidence characteristics to the ground surface. Based on the drilling of these holes and cross-hole RIM transmissions between the holes the recorded outline of the mine map was found to be fairly accurate in the areas investigated. Two areas were identified by the RIM work, however, where geophysical anomalies indicated that the mining may have extended beyond the limits noted. It was later found through drilling during the construction phase that these anomalies were probably geologically related (Marino, et al, 1995).

Development of Subsidence Profiles

General Subsidence Characteristics

This section gives the background and methodology for development of the subsidence profiles for the proposed Phase I and II structures at WVCI. Because of the site conditions, the nature of the potential subsidence movements is of the sag variety. Sag-type subsidence consists of bowl-shaped depressions. In the Illinois Basin these depressions are usually greater than 300 ft and sometimes over 1,000 ft in diameter. Maximum settlements, in the central region of the sag, are typically found to be greater than 1 ft and less than 4 ft. An idealized subsidence profile over a panel of abandoned room-and-pillar workings is shown in Figure 5.

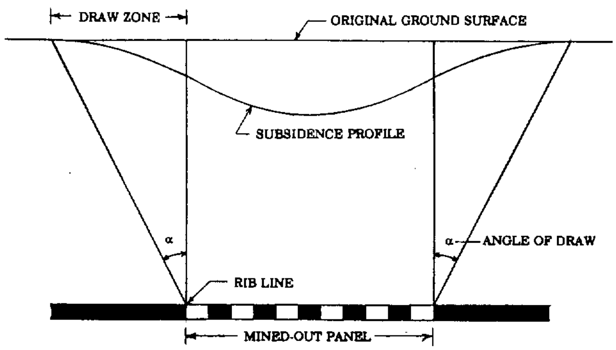

FIGURE 5. A SAG SUBSIDENCE PROFILE OVER A ROOM AND PILLAR PANEL.

The sag (or trough) characteristics are usually presented by profiles showing the vertical displacement, slope, and curvature (Figure 6). The slope is the first derivative of the vertical displacement diagram. For the typical range of profile slopes, the second derivative of the subsidence profile is approximately equal to the curvature.

As shown in Figure 6, the lateral ground displacement profiles has the same pattern and is empirically proportional to the profile slope (Brauner, 1973; Peng and Geng, 1983). Therefore lateral strain along a section of profile can then be empirically related to the section curvature since the section curvature is equal to the difference in slopes at the ends of the measurement interval divided by the interval length, (Brauner, 1973). The inflection point is where the curvature is zero (i.e. between the tension and compression zones).

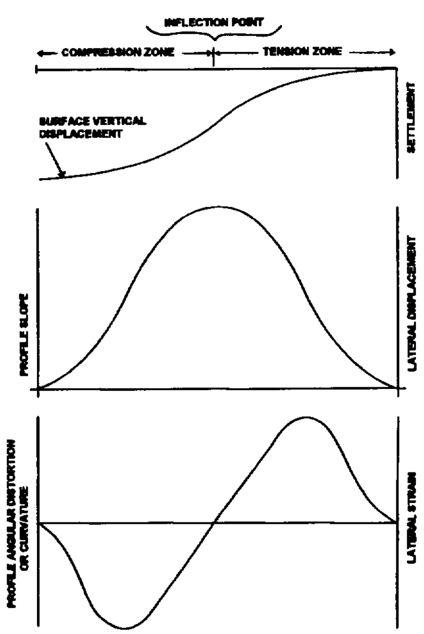

FIGURE 6. SUBSIDENCE PROFILE CHARACTERISTICS (MARINO, 1985).

Zones of tension and compression along the subsidence profile are also depicted in Figure 6. Ground compression along the subsidence profile is created by inward lateral ground displacements decreasing in the direction of the movement (toward the center of the sag). Whereas, extension results from the ground displacement increasing in the direction of movement. Reported absolute horizontal measurements are few, however, and are nearly impossible to determine for unplanned subsidence over abandoned mines since records can only be obtained after the movements have been noticed.

The plan configuration of the sag is mainly dependent on the shape of the failed mine area. Consequently, the outline in plan can range in shape from almost circular to elliptical to rectangular (trough-shaped). Also, the sag movements can remain fairly confined or can progress outward with time (see Figure 7). For the project site the sag will stay confined if sufficient coal exists to arrest the spread of failure, otherwise the outward progression of the sag may occur from the mine continuing to yield outward with time.

Separate, but adjacent and somewhat overlapping, subsidence events were another scenario that was considered at the prison site. Once a mine collapse occurs in an area, significant disturbance may be caused to nearby yet uncollapsed (possibly metastable) workings. Many times subsequent failures of adjacent areas of the mine (likened to a "domino" effect) then occurs, thus causing adjacent surface subsidences. These subsequent events have been noted days to a number of years after the initial subsidence event (Marino, 1990B).

<u>Empirical Correlations of Ground Movements</u>

Subsidence related measurements have been made over room-and-pillar mines in the Illinois Basin. With the use of such data empirical relationships have been developed which can be used to predict possible future subsidence in an uncollapsed mined-out area. Much of the data used in this study was taken from Hunt, 1980, Bauer and Hunt, 1982, Marino, 1985, Marino and Bauer, 1990, and more recent data in the author's file for this subsidence analysis.

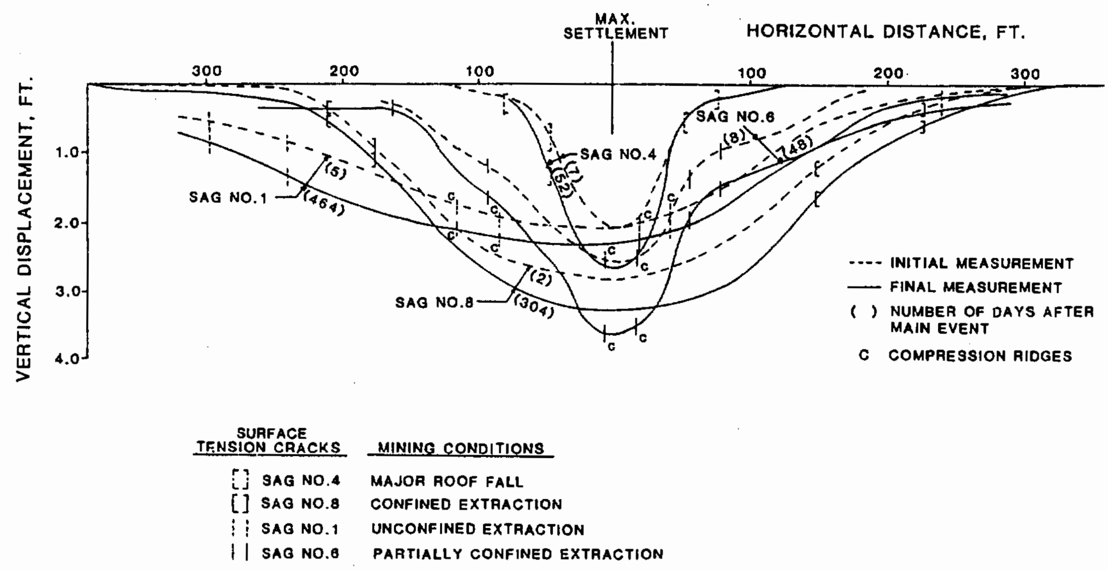

FIGURE 7. SUBSIDENCE PROFILES OF SAGS WITH SIGNIFICANTLY DIFFERENT PROPERTIES (MARINO AND CORDING, 1985).

Vertical Displacement Correlations

To adequately identify the various profile characteristics (as shown in Figure 6) these characteristics have been plotted against site conditions for cross-correlation. Probably the most basic, but most important, used to predict the subsidence potential is the one which determines the maximum subsidence. In Figure 8 is a plot of the modified subsidence factor versus the panel width to depth ratio. The maximum subsidence can be derived for the modified subsidence factor, SF′, which is defined as:

$$SF' = \frac{S_{max}}{He} \tag{1}$$

where S_{max} = maximum subsidence
H = extraction height
e = extraction ratio

Given the S_{max} value, the maximum profile curvature and maximum slope can be determined from empirical data given in Figure 9 and Figure 10,

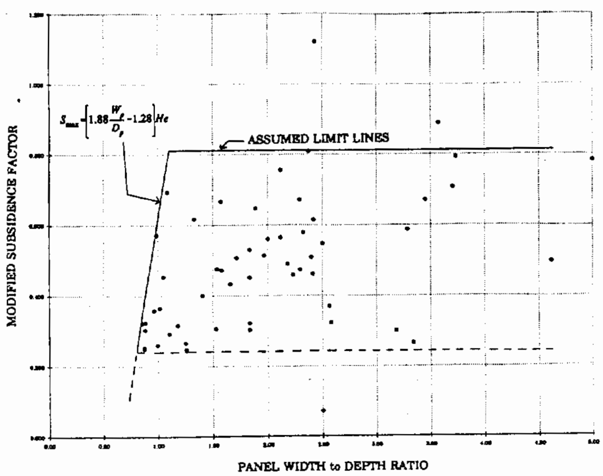

FIGURE 8. MODIFIED SUBSIDENCE FACTOR VERSUS THE PANEL WIDTH TO DEPTH RATIO FOR ROOM AND PILLAR MINES IN THE ILLINOIS BASIN.

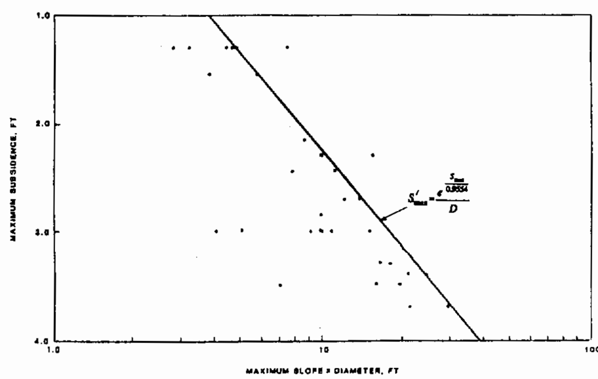

FIGURE 9. MAXIMUM PROFILE SLOPE TIMES SAG DIAMETER VERSUS MAXIMUM SUBSIDENCE FOR ROOM-AND-PILLAR MINES IN THE ILLINOIS BASIN.

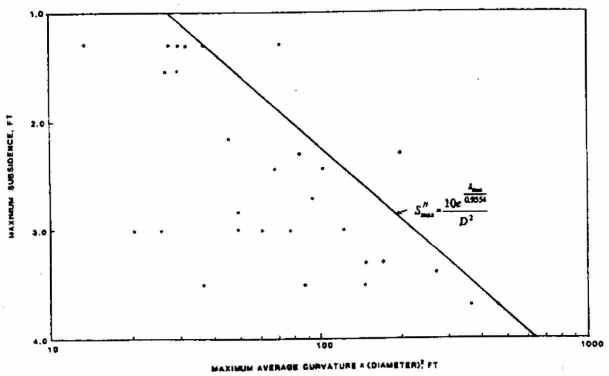

FIGURE 10. AVERAGE MAXIMUM CURVATURE TIMES THE SAG DIAMETER SQUARED VERSUS MAXIMUM SUBSIDENCE FOR ROOM-AND-PILLAR MINES IN THE ILLINOIS BASIN.

respectively. A measurement interval of 40 ft was used on a smooth line fitted to settlement points to determine the profile characteristics. This was done instead of calculating point to point derivatives to avoid measurement noise and to provide more realistic values for a structure. Note that in these correlations, maximum slope, S'_{max}, and curvature, S''_{max}, are multiplied by the diameter of the subsidence sag (or width), D, and D^2 respectively since they are also geometrically related to D as well as S_{max}. The maximum compressive and tensile curvatures are averaged in Figure 11. Overall, these curvatures have been found to be somewhat equal across a wider range of sag severity (see Figure 11). An estimate of the diameter of the sag can be assessed from expected angle of draw, α, (see Figure 5). From Bauer and Hunt, 1982, the angle of draw ranges from about 15° to 30°. The relationship of D and the profile shape to α and the angle of profile development, γ, is illustrated in Figure 12. As can be seen in this figure as the panel width increases at a given site a certain point is reached (i.e., $W_p = 2Dp \tan \gamma$) where no additional subsidence will occur and the profile becomes somewhat flat in the central region (Kratzsch, 1983). This panel widening tendency is exhibited in the Figure 8 with the essentially a horizontal band of case data when W_p/D_p is about greater than 1. Critical γ values from the lower and upper bound band lines on Figure 8 are 22° and 29°, respectively. Hunt, 1980 produced a statistical correlation indicating the relative position of various subsidence profile characteristics (see Figure 13). Based on Figure 13 the angle of profile development is generally larger than $\alpha \approx \gamma$ indicating generally broader curved profiles and therefore more gentle profiles. It is unknown, however, how the location of the maximum subsidence relative to the coal rib was measured. Also, the data in Figure 13 includes cases where $W_p < 2D_p \tan \gamma$.

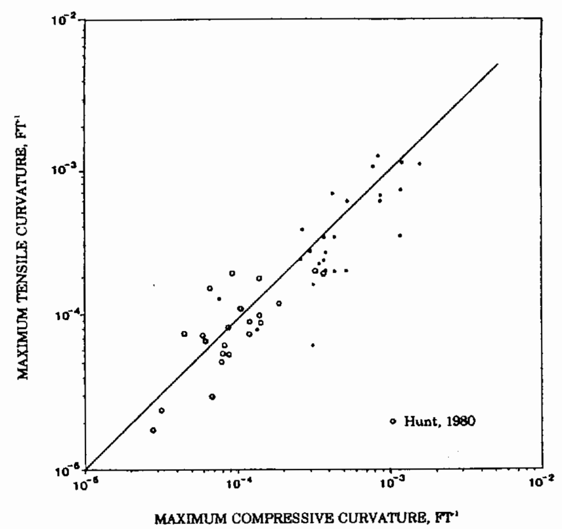

FIGURE 11. MAXIMUM TENSILE CURVATURE VERSUS MAXIMUM COMPRESSIVE CURVATURE FOR ROOM-AND-PILLAR MINES IN THE ILLINOIS BASIN.

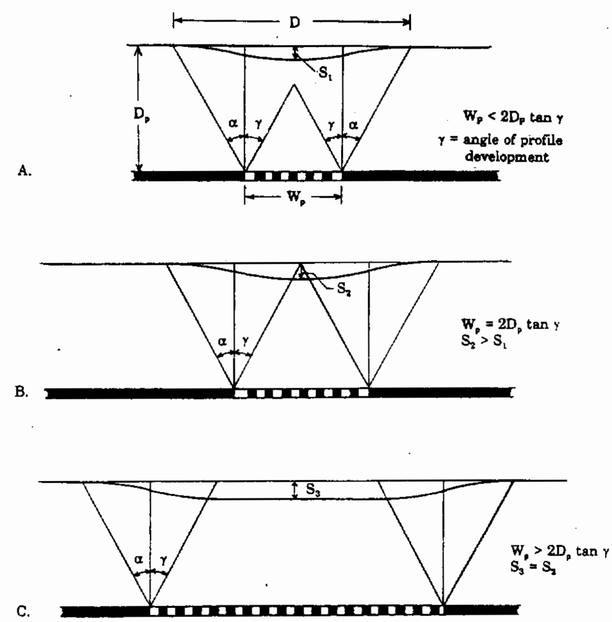

FIGURE 12. THE EFFECT OF WIDTH OF THE ROOM-AND-PILLAR PANEL ON SAG DIAMETER (OR WIDTH) AND PROFILE SHAPE.

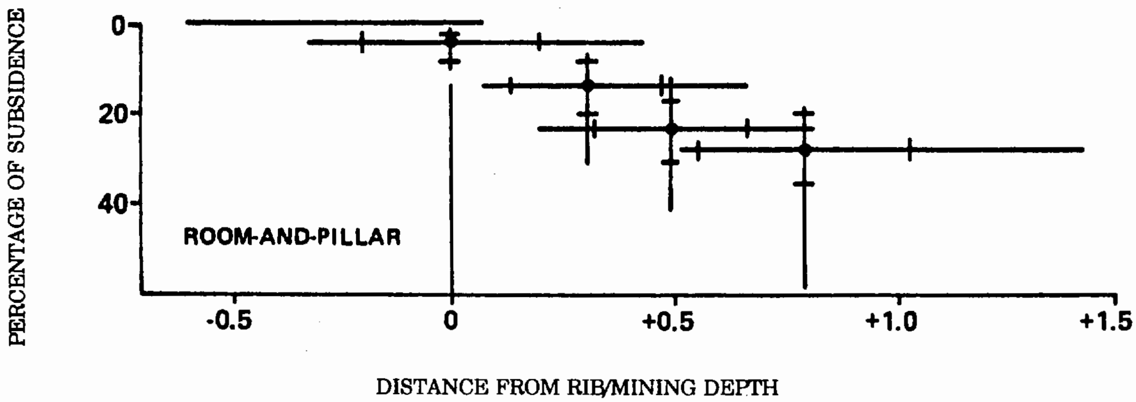

FIGURE 13. RELATIONSHIP BETWEEN MAGNITUDE OF SUBSIDENCE AND THE POSITIONS OF MAXIMUM: DRAW, TENSILE CURVATURE, SLOPE, COMPRESSIVE CURVATURE, AND SUBSIDENCE SHOWING THE MEAN, RANGE, AND STANDARD DEVIATION OF THE CASE DATA FOR ROOM-AND-PILLAR MINES (HUNT, 1980).

An important characteristic determined in Figure 13 is the relative position of the subsidence profile relative to the coal rib. Based on this case data the position maximum slope (or inflection point) can be 0.2 to 0.6 times the mine depth inside the rib (or and angle from vertical of 10° to 30° off the rib line).

Horizontal Displacement Correlations

Although it is difficult to obtain approximate vertical subsidence profiles from unexpected failures of room-and-pillar mines, horizontal displacement and strain data is even more scarce. Probably the most complete set of horizontal displacement data was collected over an abandoned mine in Danville IL (Marino and Devine, 1985). For this case the ratio of the maximum horizontal to vertical displacement was 0.45.

For longwall mining, where subsidence can be anticipated, empirical lateral displacement and strain relations have been developed. Table 1 shows ratios of maximum lateral displacement to maximum subsidence for various coal mining regions. Maximum lateral displacement values are used in profile precalculation methods. These methods predict lateral displacements by distributing the maximum displacement in proportion to the slope profile (Brauner, 1973, and Peng and Geng, 1983). The lateral strain can then be calculated for any interval along the predicted profile. Because the change in slope is proportionally equal to the change in lateral displacement over some interval, the curvature, S″, is empirically proportional to the ground strain. Empirical relationships have been developed between the curvature and horizontal strain (e.g., National Coal Board, 1975, and Bauer and Hunt, 1981).

Construction of Profiles

In order to construct the subsidence profiles for the various site conditions empirical correlations mentioned above are used. Each profile was drawn to fit the empirically derived profile conditions (e.g., maximum subsidence, maximum slope, maximum curvature, and profile width).

In estimating the maximum subsidence from Figure 8, limit lines are drawn including all but two of about sixty points. One of those points shows a subsidence greater than available void space. This may have resulted from inaccurate case data or from

TABLE 1 MAXIMUM LATERAL TO VERTICAL DISPLACEMENT RATIOS, V_{max}/S_{max}, FROM LONGWALL MINING

Location	V_{max}/S_{max}	Reference
U.S. Appalachian Field	0.3	Peng and Geng, 1983
Germany	0.35-0.45	Brauner, 1973
USSR	0.3-0.35	Brauner, 1973
France	0.4	Brauner, 1973
Great Britain	0.04-0.32	Breeds, 1976

(Averages: 0.22 all
0.15 limestone cases
0.24 others)

subsidence that was caused by a roof fall with flowing ground conditions. Ultimate bounding SF′ values appear to occur at about panel width to depth ratios of 1.11. This threshold corresponds to respective ratios observed for longwall mining in other coal regions (Whittaker and Reddish, 1989).

To estimate the maximum slope and curvature maximum probable bounding lines were drawn of Figures 9 and 10, respectively. Note for both scatter plots two points fall outside these limit lines. The position of these lines was thought to be reasonable because of: 1. the lay of the remaining data; 2. the conservative S_{max} predictions; and 3. minimum profile diameters are assumed in predicting the most severe profile conditions. The subsidence profile curves are also drawn assuming that the maximum hogging and sagging curvatures are equal as the overall trend shown in Figure 11 indicates.

Based on case data and above reasoning the following equations result.

Maximum Subsidence, S_{max} ft:

For $\frac{W_p}{D_p} \leq 0.8$:

$$S_{max} = 0.22He \tag{2}$$

For $0.8 \geq \frac{W_p}{D_p} \leq 1.15$:

$$S_{max} = \left[1.88\frac{W_p}{D_p} - 1.28\right]He \tag{3}$$

For $\frac{W_p}{D_p} \geq 1.11$:

$$S_{max} = 0.81He \tag{4}$$

where: W_p = width of panel
D_p = depth of panel
H = estimated extraction height of coal, ft
e = extraction ratio

Maximum Slope, S'_{max} :

$$S'_{max} = \frac{e^{\frac{S_{max}}{0.9554}}}{D} \tag{5}$$

where: D = width or diameter of sag

Maximum Hogging and Sagging Curvature, S''_{max}, ft^{-1}:

$$S''_{max} = \frac{10e^{\frac{S_{max}}{0.9554}}}{D^2} \tag{6}$$

The maximum horizontal movement is assumed to be equal to 0.45 times the maximum subsidence. This is the maximum ratio of maximum horizontal to vertical displacements reported and corresponds to only cases of abandoned mine measurements in Illinois. The horizontal displacement profile can be drawn by noting that the horizontal displacement profile has the approximate shape of the slope of the subsidence profile (see Figure 7).

3-D Characteristics

In plan the shape of the sag outline can be almost circular to elliptical. From the author's observation of subsidence in the Illinois Coal Basin the maximum diameter is usually no more than three times the minimum. This is shown on Figure 14. The 2-D

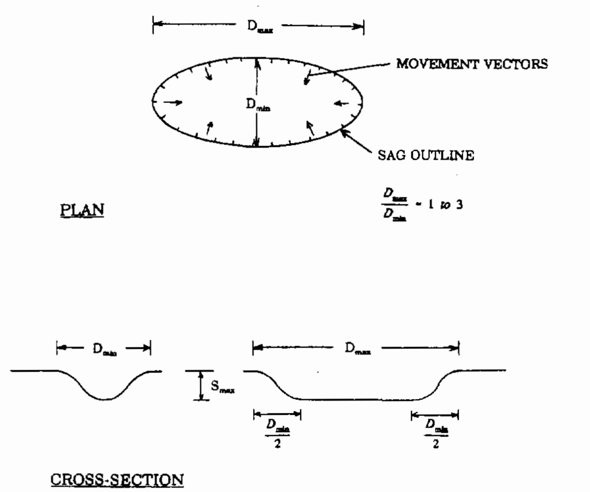

FIGURE 14. THREE-DIMENSIONAL SAG CONDITIONS.

condition is represented by a trough shape and also must be considered. As shown in Figure 14, except for the flat bottom section along D_{max}, the subsidence profiles can be assumed as identical. S_{max} and other profile characteristics are controlled, however, by the D_{min} direction.

Subsidence Potential at Project Structures

General

Based on the specific site conditions empirical subsidence data was used to determine the subsidence potential at proposed structure locations. The structures were investigated to reasonably determine the specific subsidence potential conditions where: 1. the potential damage levels from subsidence were not tolerable; and 2. the costs to effectively mitigate subsidence damage were high and very sensitive to the imposed level and character of the subsidence. The buildings evaluated for site specific subsidence characteristics were the recreation building, the housing units, custody admin-visit building, the administration building, and buildings for offender services and food services as well as a special housing unit. Based on the mine verification work discussed above, a number of investigated structure locations were found to have little or no risk of subsidence as sufficient unmined coal appeared to exist under these locations. These structures include all Phase I and II structures except for the administration building, offender and food services building, and some special housing units.

Site specific subsidence characteristics were not determined for some structures such as the gun towers, utilities, and the industries building (warehouse). For these structures it was more cost-effective to incorporate damage mitigation measures without investigating the site specific subsidence potential. A worst case subsidence scenario was provided for these structures.

For each of the subsidence-prone buildings specifically investigated a subsidence map and associated subsidence profiles have been prepared. Figure 15 illustrates the various elements on the subsidence maps. The main characteristic of these maps is the identification of areas of approximately the same subsidence conditions. These areas are blocked off and labelled $S_{max}(\#)$ and are called $S_{max}(\#)$ Zone.

With S_{max} Zones established, respective subsidence profiles can be developed. Minimum and maximum width profiles were constructed using angles of draw of 15° and 30°, respectively, and basically following the procedure given in the section entitled "Construction of Ground Movement Profiles". Consequently, the most abrupt and the most broad profiles were developed with the maximum probable subsidence, slope and curvature values. An example of these profiles developed are shown in Figures 16 and 17.

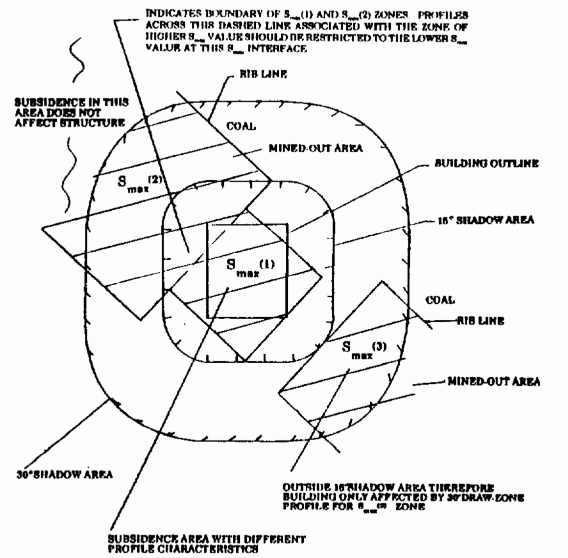

FIGURE 15. SUBSIDENCE MAP DEFINITIONS.

It should be noted that the rib lines marked on the subsidence maps determined the effective panel width, W_p, which was in turn used to determine S_{max} (see Figure 15). A rib line was drawn only where the mine indicated that a sufficiently wide area of coal was left to confine the subsidence (or mine collapse). Because this was a very important assumption in subsidence prediction all these areas were verified during the subsurface investigation discussed earlier in the paper.

One way of evaluating these coal areas may be to consider barrier pillar design formulas. Holland, 1973, presented various relationships which are used in designing the width of the barrier pillars. The pillar relationships are designed to prevent ingress or egress entries from being overridden by a major overburden collapse started in an adjacent mined-out area. A barrier pillar equation (presented by Holland) derived in the U.S. and used here to assess adequate coal width is:

$$W_B = 20 + 4H + 0.1d \qquad (7)$$

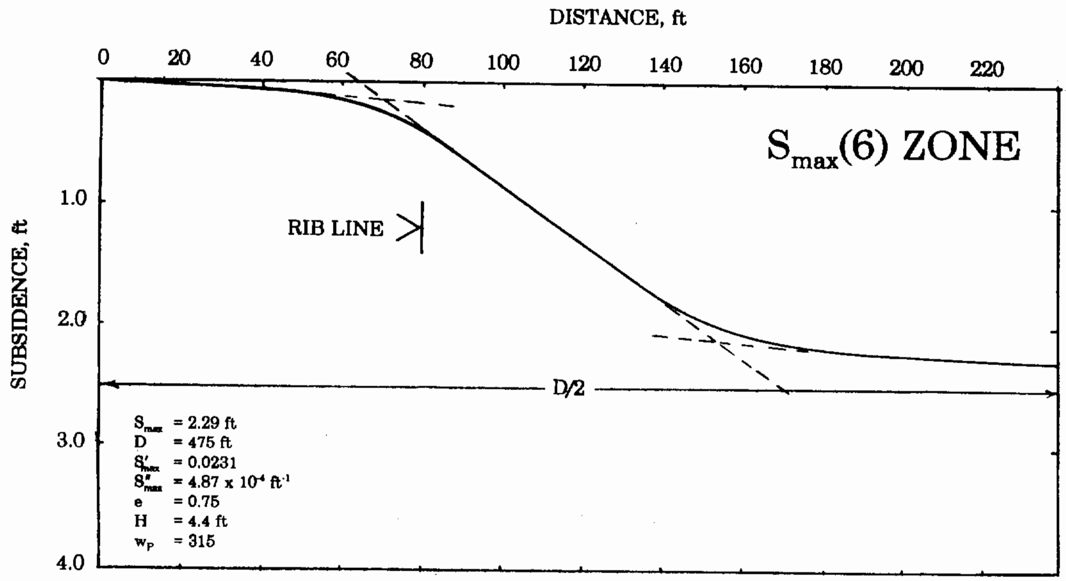

FIGURE 16. ESTIMATED SUBSIDENCE PROFILE FOR $S_{MAX}(6)$ ZONE WITH 15° DRAW ANGLE.

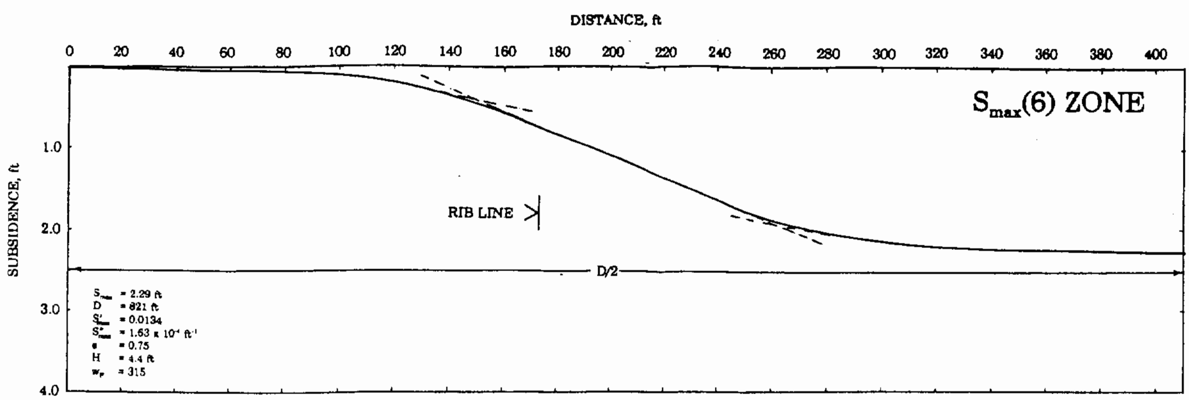

FIGURE 17. ESTIMATED SUBSIDENCE PROFILE FOR $S_{MAX}(6)$ ZONE WITH 30° DRAW ANGLE.

where: W_B = required barrier pillar width in feet
H = coal bed thickness in feet
d = coal bed depth in feet

These subsidence profiles were also applied to determine the horizontal movement conditions by: 1. taking the maximum lateral displacement V_{max} as 0.45 times S_{max} value, and 2. proportionating the lateral displacement based on the slope of the given subsidence profile. The horizontal displacement vector was assumed to approximate the direction of the slope of the subsidence sag.

The shape and sequence of sag events was also evaluated within S_{max} Zones. This is illustrated in Figure 18. Sags will be confined within the rib lines and will not significantly progress outward. The rib positions were marked on each subsidence profile (see Figures 16 and 17). The minimum diameter of the sag will run across the mined-out area between the two rib lines (see Figure 18). Based on the author's experience, the maximum diameter will be no more than 3 times the minimum.

Any random sequence of subsidence events was considered. The sequence which results in maximum stress conditions in the structure was determined. For example, maximum hogging may result when two adjacent events are considered causing a central "hump" under the structure (see Figure 19). Also, the ultimate subsidence condition should be evaluated where the entire mined-out area has collapsed (see Figure 18).

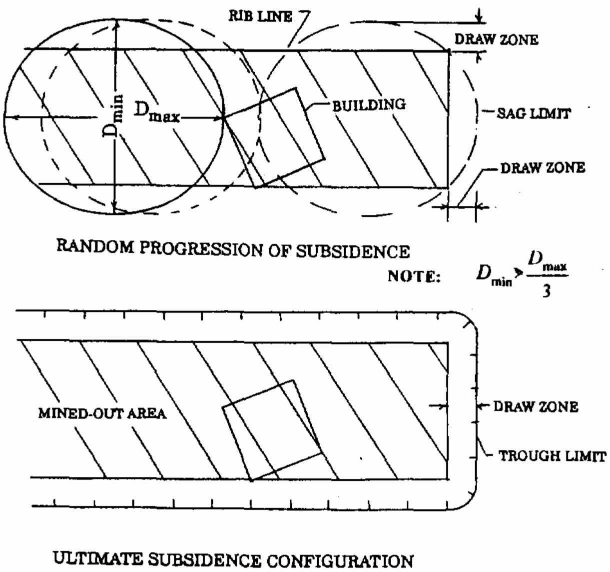

FIGURE 18. SAG SUBSIDENCE EVENTS CONFINED BY RIB LINES.

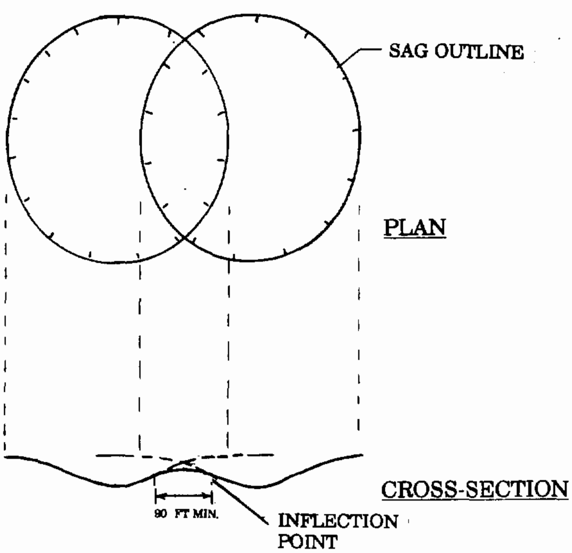

FIGURE 19. EXAMPLE OF SUPERPOSITION OF PROFILES OF TWO COINCIDENT SAGS.

Worst Case Condition

General

As discussed above, it was determined that for certain structures it was not cost-effective to investigate the site specific conditions controlling the magnitude and characteristics of the potential subsidence. For these structures where the mine workings were not reasonably verified in their respective shadow areas the worst case scenario was assumed. In other words under the worst case assumption the mine workings remain an undetermined factor, i. e., the sizes, shapes, as well as the sequences of potential areas of mine collapses.

For this site using the g_{min} and a_{min} the minimum sag diameter of 320 ft is calculated. This results in S_{max} =0.91 ft from assuming W_p =160 ft, H =5.0 ft (max. coal thickness encountered), and e =0.75. In Figure 20 overburden thickness is plotted against the average diameter of the subsidence for U.S. Coal fields (GAI Consultants, 1977). The empirical correlation shown indicated that for a depth, T, equal to 300 ft D =1 to 10 T. In other words considering a minimum sag diameter of 320 ft is consistent with this correlation.

The minimum diameter profile construction is shown on Figure 21. This profile may be most critical for certain small structures. On Figure 22 the worst most probable profile is given (for H =5.0 ft and e = 0.75). This profile is for sags of 505 ft or greater in width where the ultimate S_{max} has been reached. For sag diameters larger than the critical size the base of the profile is merely extended horizontally.

The maximum lateral displacement would be 0.41 ft and 1.50 ft for the minimum diameter and fully developed profiles, respectively. The lateral displacement profile would be proportioned to the subsidence slope profiles. Lateral surface displacement vectors point inward generally and can be assumed to be perpendicular to the crossing subsidence contour.

In building design for the worst-case scenario all possible positions of the sag under consideration should be evaluated. An illustration of this is shown in Figure 23. In addition to one sag occurring at a time, multi-events (with little time in between) should be considered. An example of superposition of events is shown in Figure 19. For analysis of sag superposition, it is not realistic to expect adjacent profile inflection points to be closer than 90 ft apart (assuming one row of pillars did not fail).

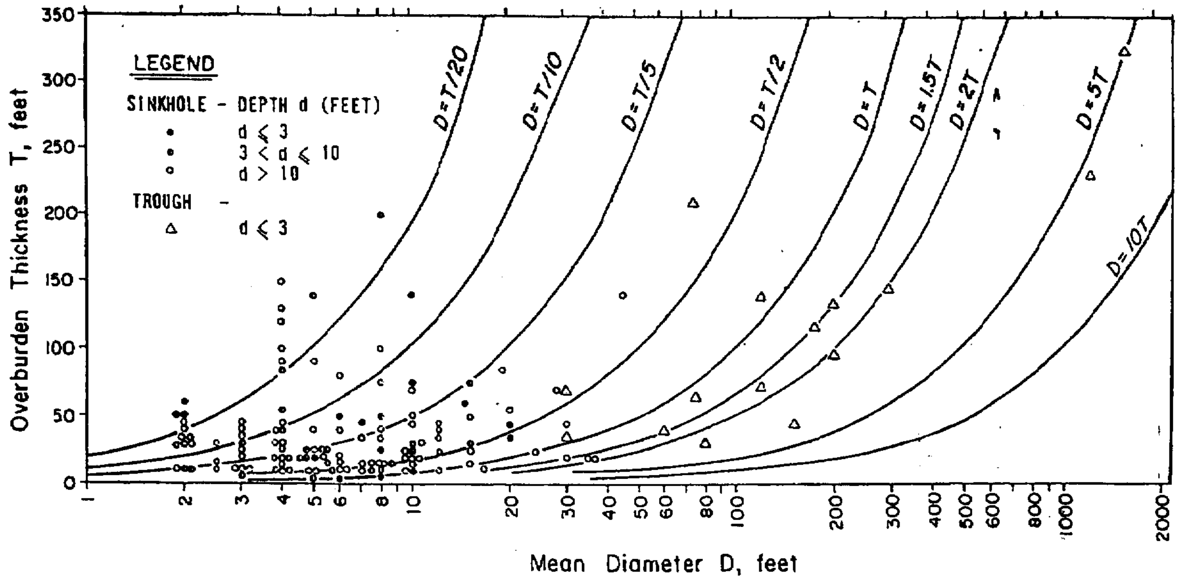

FIGURE 20. RELATIONSHIP OF DIAMETER AND DEPTH OF SUBSIDENCE FEATURE TO OVERBURDEN THICKNESS (GAI CONSULTANTS, 1977).

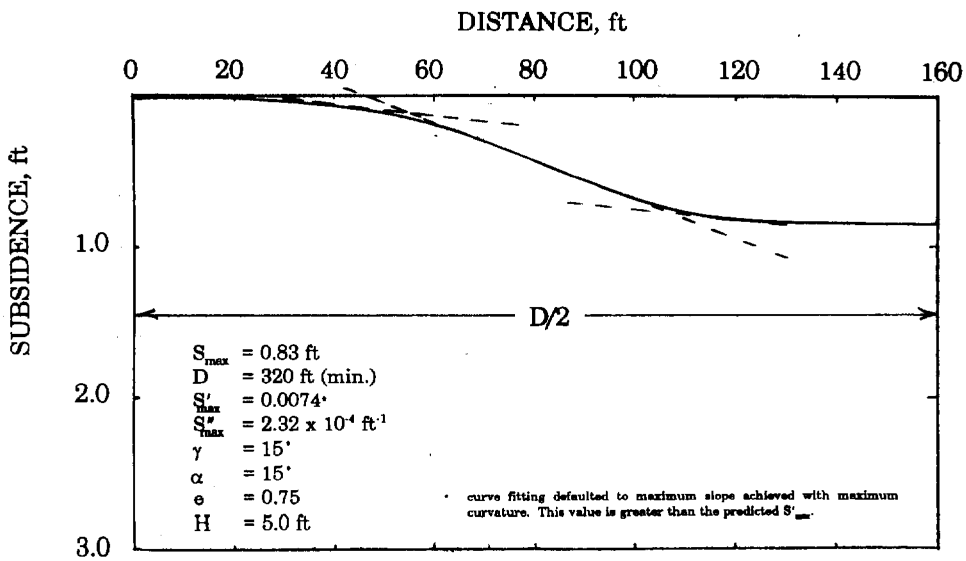

FIGURE 21. WORST-CASE PROFILE FOR MINIMUM DIAMETER.

Subsidence - Structure Interaction

Using the prepared subsidence maps as shown as in Figure 15 the potential range of ground movement which could affect for the structure in question was determined. In some cases the structure's exposure was limited to one-directional tensile subsidence movements and in other cases the host of movements possible were multi-directional and could be compressive and tensile in nature.

One structure, for example, in the outer portion of tension zone only was cost-effectively designed and constructed with a grade-beam like foundation (Marino, 1991C). Other structures evaluated with the use of subsidence maps required significant foundations in

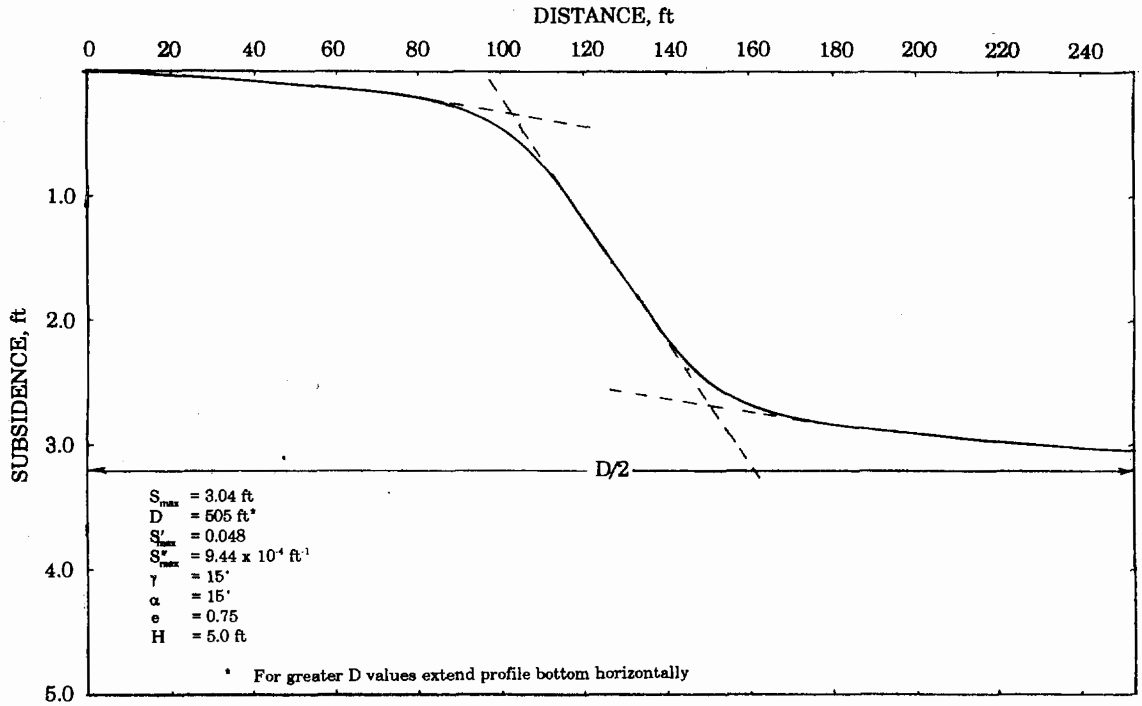

FIGURE 22. WORST-CASE FOR FULLY DEVELOPED PROFILE FOR D OF 505 FT OR GREATER.

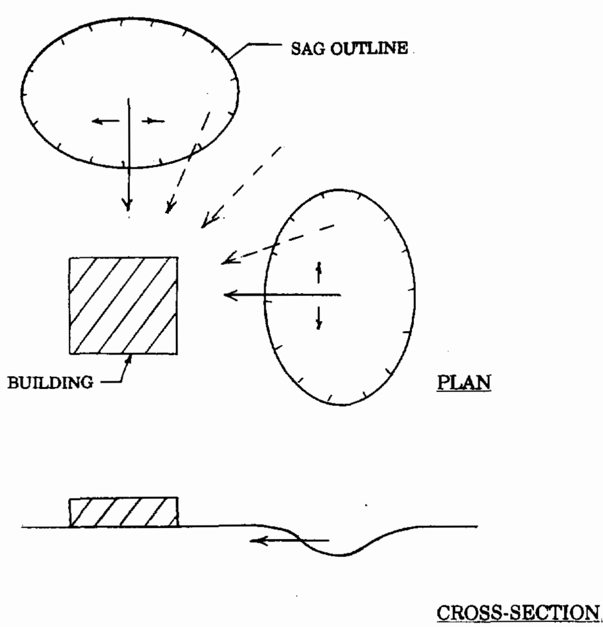

FIGURE 23. DIFFERENT RELATIVE POSITION SCENARIOS OF SAG TO BUILDING.

order to minimize the level of possible distortion to the superstructure. The buildings requiring significant foundations to resist subsidence were only present in the subsidence-proned Phase II construction. Because of the significant foundation cost for these Phase II structures it was determined that mine backfilling in the selected areas encompassing their respective shadow areas was the most cost-effective alternative (Marino et al, 1995). This solution resulted in great cost savings over the subsidence-resistant foundations. For certain buildings, such as warehouse-like structures, some subsidence damage was tolerated. Less costly subsidence mitigation measures, based on the worst case scenario, were taken into account in these buildings.

Conclusions

A large prison complex was constructed over abandoned mine works in Carlisle, Indiana. The complex involved a total of about 40 important structures. The present prison was constructed in two phases. To develop the site over the 300 ft deep old abandoned mine works a fairly detailed subsidence risk assessment was conducted for both phases of construction.

As a result of the subsidence risk assessments conducted the most cost-effective solution to mitigated subsidence damage was determined for each structure. The methodology used to estimate potential subsidence for each important structure is discussed in detail in the paper.

Many of the prison structures were found to have no little to no risk of subsidence while others could be exposed to limited to a wide range of subsidence movement characteristics. Based on the individual evaluations of the structure in question subsidence mitigation measures were taken. These measures ranged from foundation and superstructure treatments to mine backfilling depending on the structure and subsidence potential.

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