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Ground Movement Characteristics Above Mined Panels in Appalachia - An Empirical Approach

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SYNOPIS The growing recognition of mining subsidence and its effects has provoked numerous investigations into the modeling and prediction of this phenomenon. Through an analysis of case histories and examination of the various modeling techniques, it has become apparent that empirical studies currently represent the most realistic approach to this problem. However, the collection, analysis and interpretation of subsidence and strain data acquired from case studies presents substantial difficulties, due to varying monitoring techniques and methods of analysis. In this paper it is suggested that a prescribed monitoring program could eliminate these problems and ensure quality data by standardizing the measurement process. Such an effort may also increase the number of case studies available for analysis, allowing more intense investigations of subsidence prediction methods. Finally, some basic subsidence relationships developed from the established subsidence data bank on longwall and room and pillar mines in Appalachia are discussed in detail. These relationships may provide important information on the characteristics of ground movements above mined areas and thus greatly facilitate engineering design under these conditions.

INTRODUCTION

The current interest in mining subsidence and its effects in this country is a result of the migration of mining toward populous regions and the growing awareness of the damaging potential of this phenomenon. Subsidence studies have been undertaken in many coalfields around the world, yielding several subsidence prediction methods. However, through a review of the most prevalent of these techniques, it was found that none of the subsidence models satisfactorily represented the ground movements experienced in the Appalachian region. Consequently, to meet the need for accurate subsidence and strain prediction methods for the eastern United States, the development of empirical ground deformation models was attempted by a comprehensive analysis of case studies collected for that region.

In order to establish a substantial data bank for both longwall and room and pillar mining, revelant published information was collected, and in addition, coal companies were contacted to contribute any unpublished information that might be of interest to this study. The collected information was analytically and statistically treated to develop characteristic subsidence trends. During the data reduction process several problems were encountered involving the methods by which the measurements were taken and presented. Furthermore, the problems associated with the collected data emphasized the need for uniform and accurate measurement procedures.

This paper presents the most acceptable standards for ground deformation measurements based on the experience of the authors in reviewing numerous case studies. These standards are being tested in a systematic monitoring program which is currently being pursued above four mines in southwest Virginia. In addition, some basic subsidence relationships are described in detail for both longwall and room and pillar panels, with particular emphasis on predictive capabilities. Finally, the application of these relationships will be discussed in terms of improved engineering design.

COLLECTION OF CASE STUDIES

Three primary sources were considered during the development of the subsidence data bank for the eastern United States: literature, private industry and government agencies. An extensive literature survey was performed to gather all relevant publications, which allowed the collection of nine longwall and 35 room and pillar subsidence investigations. A number of case studies were also retrieved from private contacts with individual coal companies and government agencies, resulting in an additional 23 longwall and 25 room and pillar cases. This total of 32 longwall and 60 room and pillar case studies represents a substantial data bank for the eastern United States (Karmis et al., 1981(a); Karmis et al., 1981(b); Karmis et al., 1983).

Approximate geographic locations of the mines providing data for this research are shown in Figure 1. The regions are highlighted by shaded areas, instead of specific points, due to the proprietary nature of most of the information. Fourteen longwall studies were gathered from southern Pennsylvania, nine from northern West Virginia, four from eastern Ohio, two each from southern West Virginia and Alabama, and one from southwestern Virginia. The majority of the room and pillar studies were conducted in three Appalachian states: Pennsylvania, West Virginia and Alabama. The case studies collected from literature did not include all of the raw subsidence data, but in general, they did incorporate some or all of the following information: geographic locations, geometry and layout of the panels, subsidence monument plan, stratigraphic columns, surface contours, and data on the subsidence development and/or travelling profiles. Data gathered from industry included tables of the original displacement measurements.

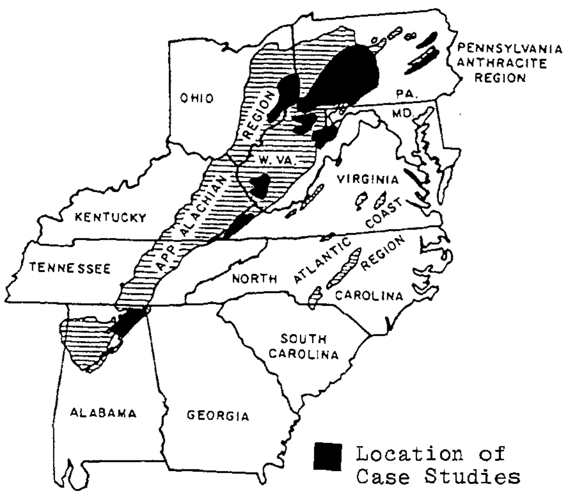

Figure 1. Location of Longwall and Room and Pillar Case Studies

Because most of the measurements were taken prior to this investigation, no guidelines could be placed on the procedures employed to obtain or record the displaced surface values. Therefore, whenever possible, interviews were conducted with mine personnel or the surveying companies responsible for monitoring to determine the survey procedures followed.

Since the influence of geologic parameters on subsidence was an important concept in the analysis, emphasis was also placed on the collection of lithologic and stratigraphic information as well as drill cores pertaining to the panel in question. The drill logs were analyzed to determine the seam depth and thicknesses of the individual strata. This information was then used in conjunction with statistical and analytical treatment of the subsidence surveys to develop surface deformation prediction models.

DEVELOPING THE SUBSIDENCE INFORMATION

During the analysis of the longwall and room and pillar subsidence data, several problems arose which hindered the data reduction procedure. These problems encompass both measurement and analysis methods and can present serious limitations on the success of an empirical subsidence study. Therefore, it is important that these complications are indentified and alleviated by a systematic data collection procedure.

A defined collection procedure would also remedy the most formidable data collection pitfall: general lack of knowledge of the basic fundamentals of subsidence engineering. The results of many diligent subsidence investigations have been constrained due to geometrical or time factors. For example, in several cases it was not possible to plot a transverse profile containing the largest vertical surface displacement due to the positioning of the monument lines too close to the panel boundaries. In other cases, the initial surveys were conducted after the stations were within the area of influence of the extraction, and in some instances the monitoring ceased before the profile reached full subsidence.

There were also certain surveys which measured subsidences in excess of that expected due to the influence of adjacent workings. The transverse profiles of two longwall panels influenced by old adjacent room and pillar workings are shown in Figure 2. In this diagram, the displaced surface points are seen to assume the standard shape of a subsidence curve, except that the measurements taken near to and above the ribsides of the two panels approach asymptotic conditions at 0.2 meters for the first panel and 0.4 meters for the second panel. The previously mined room and pillar sections appear to be causing the ground surface in these areas to be displaced.

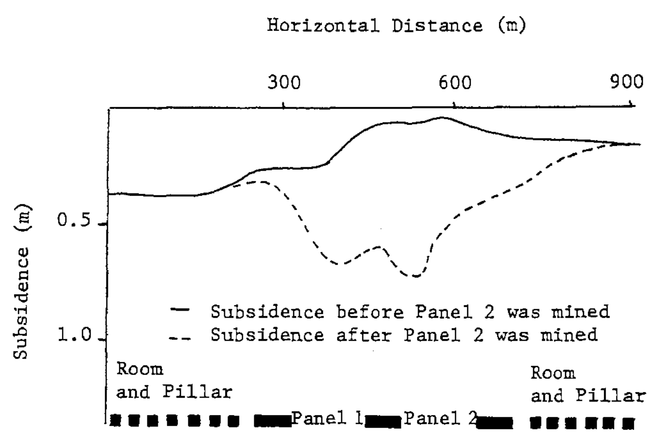

Figure 2. Transverse Profiles of a Case Study Showing the Influence of the Adjoining Room and Pillar Sections

Moreover, there were many case studies that had missing or inadequate data. For example, one particularly complex and time consuming task was defining the location of the face at the time of a certain survey. In a few case studies, only displacements around important structures were monitored, or survey lines were skewed across the panel by following roads or similar features. There were also cases where the spacing between monuments was too large and, therefore, the subsidence profile had to be approximated between stations.

The aforementioned problems were inherent in both the longwall and room and pillar data; however, the study of room and pillar subsidence also presents complications which are particular to that mining method. Whereas longwall mining may effect subsidence through both panel geometry and overburden geology, room and pillar operations include the effect of pillar size and geometry. Although pillar geometry can be quite simple and uniform, the unpredictable nature of pillar development and extraction can increase considerably the complexity of the problem. In order to develop a model of practical significance, it was necessary to make some assumptions and simplifications. For example, averaging of pillar sizes and locations may be necessary in order to form a uniform pillar size and distribution for empirical modeling. In addition, other factors such as depth of overburden, mine height, and panel width may be averaged when modeling subsidence profile parameters.

Aside from geology and geometry, other factors may also cause complications, including time parameters, prestress of overburden due to development, questionable extraction ratios, direction of mine development and extraction, and many more. To expand on one of these factors, the extraction ratios, it has been found that upon secondary extraction, accurate details of pillaring may not be available or easily assessed. Due to the instability of roof conditions during secondary extraction, initial mine designs may be altered. Once mining is complete, the remnant pillars or stumps are inaccessible and cannot be accurately surveyed, thus research can only assume these pillars to be as designed.

All of these deficiencies create serious problems on data analysis. However, it should be noted that company personnel are not completely familiar with the reduction, treatment and interpretation of subsidence data, particularly since this technology is just emerging for the eastern United States. This unfamiliarity should be expected and is the cause of many collection errors. For this reason all data must be carefully scrutinized to eliminate questionable data points and possible surveying errors.

In addition to data collection, the analysis of the subsidence information presents many intricacies. For example, in statistical analyses of a given area, it must be assumed that the data is both independent and uniformly distributed throughout the region. Obviously this is not the case, particularly in reference to the room and pillar panels. Although care was taken to use comparable mines and mine panels within this study, over 80% of the Appalachian room and pillar studies were located in southwestern Pennsylvania, specifically in the counties of Allegheny, Washington, Greene and Fayette. This is to be expected, considering the large urban population located in these undermined areas. Although such problems cannot be avoided in the data already collected, such local statistical biase should be considered and evaluated after the final analysis is complete.

The complications previously described present serious limitations on the extent to which subsidence information can be collected and analyzed. Furthermore, as with all data obtained for subsidence research, individual preference or biase is present throughout analysis. Many of the problems could be relieved, however, if a detailed systematic and standardized monitoring program were formulated. The standards set for minimal data acceptability and for the quality and clarity of that data should guide mining personnel in their measurement process and ensure quality information. This system should also allow for the measurement of horizontal displacements, thus augmenting the currently sparse strain data bank.

DEVELOPING A DISPLACEMENT MONITORING SYSTEM

The analysis and comparison of subsidence and strain data acquired from case studies present difficulties due to the different methods applied for selecting mine panels, instrumentation of those panels, monument setup and surveying procedure. A prescribed monitoring program could eliminate these difficulties by standardizing the measurement process. The quality of data would also be enhanced by the establishment of instrument and survey accuracy guidelines.

The best results from monitoring vertical movements would be obtained by using a precision level. However, trig-leveling may be efficiently applied if a highly accurate combination of theodolite and EDM is available. The EDM should have an accuracy of 6mm over the sight distance and the theodolite should have an accuracy of 0.6 seconds. The use of the theodolite in conjunction with the EDM also allows the concurrent measurement of horizontal displacements, thereby increasing the efficiency of the monitoring process.

The selection of monuments depends on the desired accuracy, available equipment, weather conditions and topography. Elaborate monuments consisting of long metal rods anchored with concrete to a depth of 60 cm under the frost line will give the most accurate results when measuring vertical movement. However, this type of monument usually is too expensive and requires a truck mounted drill for installation, thereby effectively preventing its use in mountainous terrain when a large number of stations is to be installed. As a result, the most practical alternative has been proved to be steel rods or pipes penetrating the ground to a depth of at least 30 cm beyond the frost line.

The survey monument layout is also a critical factor. The monuments are set on longitudinal and transverse lines above each panel which intersect near the panel center. The lines should be located outside the influence of the panel boundaries, a distance of at least 0.6 times the panel depth for eastern U.S.

conditions, and extend 0.8 times the depth beyond the edges of the extraction to ensure the determination of the angle of draw, with a set of reference points being established outside the area of influence. Following the guidelines suggested by the British National Coal Board (NCB, 1975), the spacing of the monuments should be approximately 0.05 times the depth to allow the accurate calculation of the distribution of horizontal strains along the monitoring lines. It should be noted, however, that distances of less than 7.5m between stations may result in large instrument errors.

When selecting mine panels for subsidence monitoring the width-to-depth ratio of the panel should be examined. For subcritical width-to-depth ratios (less than 1.2 for the Appalachian coalfields) the amount of subsidence measured will not represent the maximum subsidence to be expected for similar conditions and critical or supercritical extractions. Interaction among mine panels should also be examined. Typical situations include multiseam mining and the mining of adjacent panels in the same seam. Previous or simultaneous mining of contiguous seams will considrably affect the subsidence parameters, and when neighboring panels are mined, the position of the monitoring lines should be thoroughly examined. However, one advantage of the above situation does occur in the case of a subcritical panel. If the pillars between two adjacent panels are mined and the first panel is subcritical, continued monitoring of ground movement through the retreat of the second panel will yield both subcritical and critical profiles. This condition can prove useful for data comparison.

For the positioning of the monitoring lines a traverse should be run to tie the lines with mine coordinates. The tie for the direction of the monuments is important considering the length of the lines. Also, after the monuments and benchmarks have been installed, a traverse should be run well before mining to determine their exact original positions. The frequency of surveys as mining progresses depends on the depth of the mine and the rate of mining. The surveys should continue until ground movement has ceased, with six months after the termination of mining being a reasonable time limit.

The aforementioned standards were followed when designing a monitoring program for three room and pillar and one longwall panel in Southwest Virginia. An advanced surveying system was utilized, including a recording computer tacheometer and a set of reflecting rods with specially designed adaptors that can be attached to the monuments. The tacheometer has a coaxial telescope for simultaneous measurement of distance and direction. It includes a computer that corrects angle measurements using collimation and index corrections, calculates horizontal distances and coordinates, and performs other surveying functions. The accuracy of the instrument is 0.6" for angles and ± (5mm + 2ppm) for distances, with up to 440 lines of storage available for raw data or computed results.

The monuments consisted of one-inch diameter hot-roll steel rods in lengths of two or five feet. The rods were driven into the ground using a sledgehammer or a gasolined powered jackhammer. An adapter was used when installing the monuments to prevent mushrooming of the tops of the rods. Since the lines had been cleared of trees and brush prior to monument installation, the monitoring system allowed the efficient and accurate measurement of ground deformation.

BASIC EMPIRICAL SUBSIDENCE RELATIONSHIPS

Before subsidence prediction models can be developed several significant subsidence relationships must be ascertained, including the determination of the angle of draw, the critical width-to-depth ratio, the subsidence factor and the effect of the overburden geology. These characteristics are basic to both longwall and room and pillar subsidence and strain modeling.

One variable that has great significance in subsidence engineering is the angle of draw. The latter defines the limits of surface subsidence and fixes the value of the critical width-to-depth ratio. Figure 3 shows the plot of measured Appalachian longwall angles of draw as a function of the width-to-depth ratio of the panel. As can be seen, the average angle of draw for critical conditions is 31 degrees. This value suggests a critical width-to-depth ratio of 1.2, which agrees with Figure 3, where the line asymptotes at a ratio of approximately 1.2.

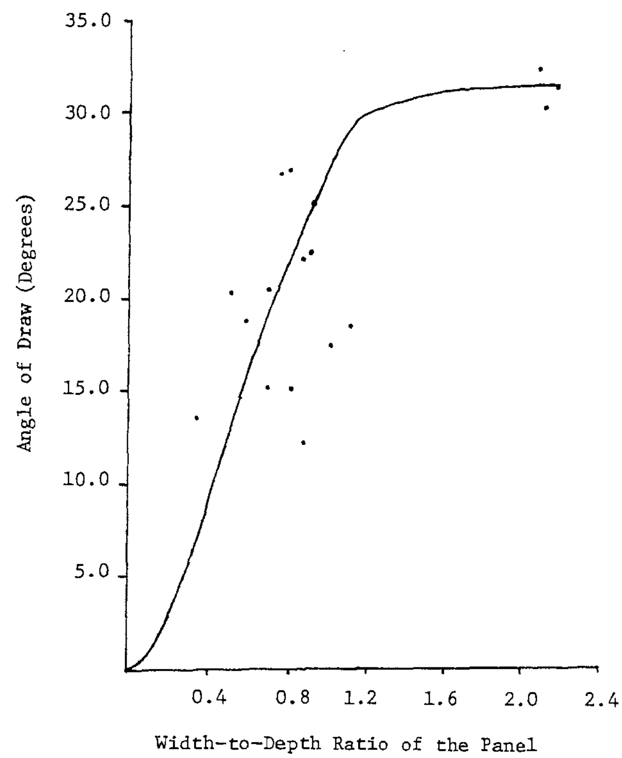

Figure 3. The Influence of the Width-to-Depth Ratio on the Angle of Draw

It was hypothesized that the geology of the overburden also influences the amount of subsidence. To determine the exact relationship, the subsidence factors for critical and supercritical longwall panels were plotted as a function of the percent of hardrock (sandstone and limestone) in the overburden. Only critical and supercritical panels were plotted in order to eliminate the effect of the width-to-depth ratio on the subsidence factor. From this plot, the linear relationship shown in Figure 4 was ascertained, with the amount of subsidence decreasing with increasing percent hardrock. Once this relationship was known, it was possible to present the maximum subsidence factor as a function of the percent hardrock and the width-to-depth ratio of the panel (Figure 5).

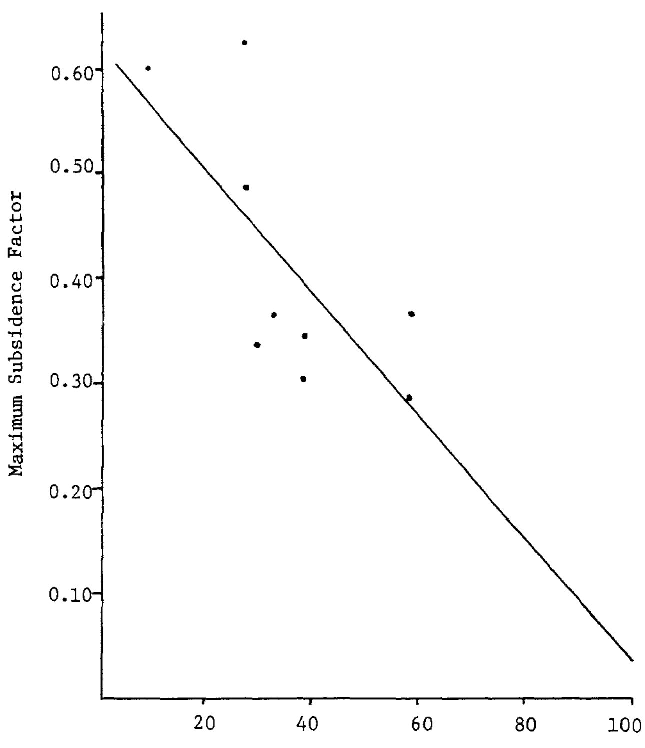

Figure 4. The Influence of Sandstone and Limestone in the Overburden on the Subsidence Factor for Critical and Supercritical Extractions

These subsidence relationships formed the basis of an Appalachian longwall subsidence prediction method (Karmis et al., 1983). They also represented the fundamentals from which a room and pillar model was developed. It was initially hypothesized that upper and lower bounds existed for room and pillar subsidence. The lower bound, it was assumed, would be related to the extracton ratio, such that at some extraction greater than zero the subsidence would be null. The upper bound hypothesis assumed that at some high exrtraction ratio the subsidence would approach longwall values.

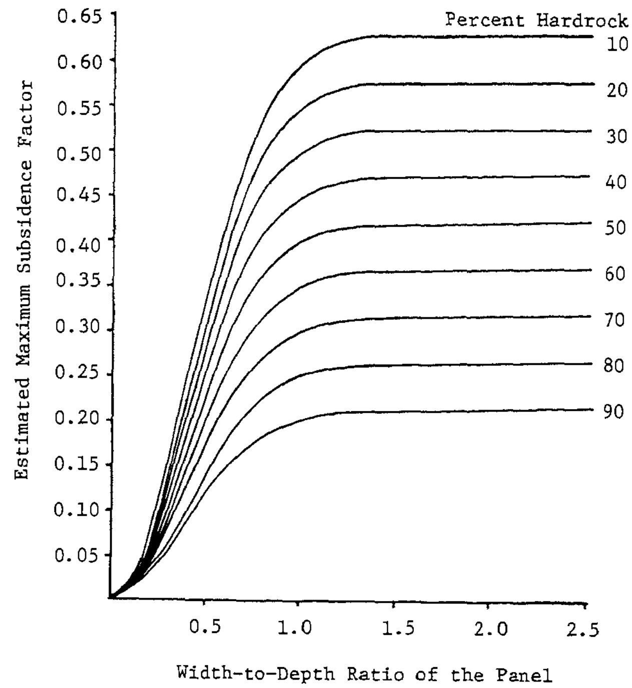

Figure 5. Determination of the Maximum Subsidence Factor from the Width-to-Depth Ratio and the Percent of Hardrock

To further substantiate the initial hypotheses, validation of existing empirical models within literature was undertaken. After careful consideration of the various models, that originally proposed by Wardell (1969) and adopted by Abel and Lee (1980) was found to be most representative of eastern U.S. conditions. An analysis of this method revealed a relationship between the maximum subsidence factor and an expression given by $(D/1 - R) \times (H/W_p)$, where D is the depth, R is the extraction ratio, H is the seam height and W_p is the pillar width. In order to better understand the mechanism behind this empirical model, further evaluation of the terminology is necessary. Inspection first shows that $D/(1 - R)$ is actually an expression of average pillar stress as given by the tributary area method. Furthermore, the term H/W_p can be considered as a dimensionless expression of pillar weakness, since pillar strength can be empirically related directly to W_p/H. In essence, therefore, the previous relationship can be viewed as an expression of stress divided by strength, or as an inverted safety factor for pillar design.

Further inspection of the correlation with the Wardell stress-strength factor revealed that, at high extraction ratios (i.e. upon pillar failure), the S_{max}/H correlation to both $D/(1 - R)$ and H/W_p diminished significantly. However, due to the correlation of S_{max}/H to $(1 - R)$ with high extraction data, the total stress-strength factor continued to relate with S_{max}/H, as shown in Figure 6. The logistics of this explanation are obvious. During and about pillar stability,

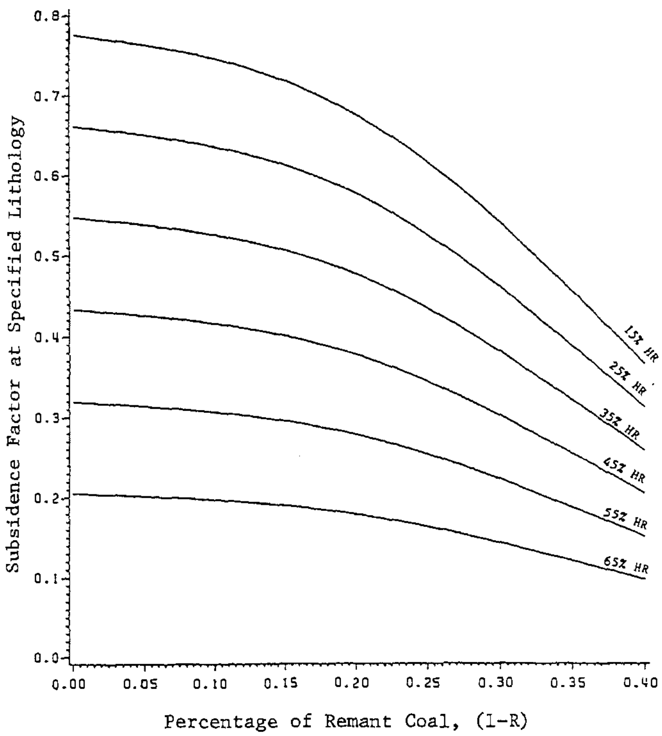

Figure 6. Effect of Extraction Ratio and Lithology on S_{max}: Supercritical Data Analysis

the subsidence can be correlated with pillar strength characteristics, presumably related to the amount of pillar yield. Upon failure, however, the stress-strength characteristics are no longer applicable, leaving (1 - R), or the percent of remnant coal, to be the only diminishing factor from S_{max} for a completely extracted panel.

This, therefore, led to the application of longwall (i.e. complete extraction) data into the previously restricted room and pillar empirical models. Utilyzing the assumption that at some high extraction ratio the maximum subsidence over partial extractions will approach S_{max}, longwall data was placed in the previous models for (1 - R) = 0. In order to fully utilize the longwall data, the geologic model for longwall subsidence was also incorporated. Despite the lack of quality geologic information, room and pillar studies showed that 70% of the data fell in a range of 35% ± 10% hardrock, with 35% being an average value. Using only those studies of trusted geology, between 25% and 45% hardrock, and the longwall data, the room and pillar models were adjusted to an average 35% hardrock. Subsequent relationships were then extrapolated using the longwall geologic model to correct for lithology. The lithologic adjustments of subsidence were not constant, however, due to the varying effect of geology, i.e. its influence is less pronounced for lower extraction ratios within room and pillar mining. The final models for supercritical panels relating the subsidence factor to both the extraction ratio and the stress-strength factor, for given lithologies, are shown in Figures 6 and 7.

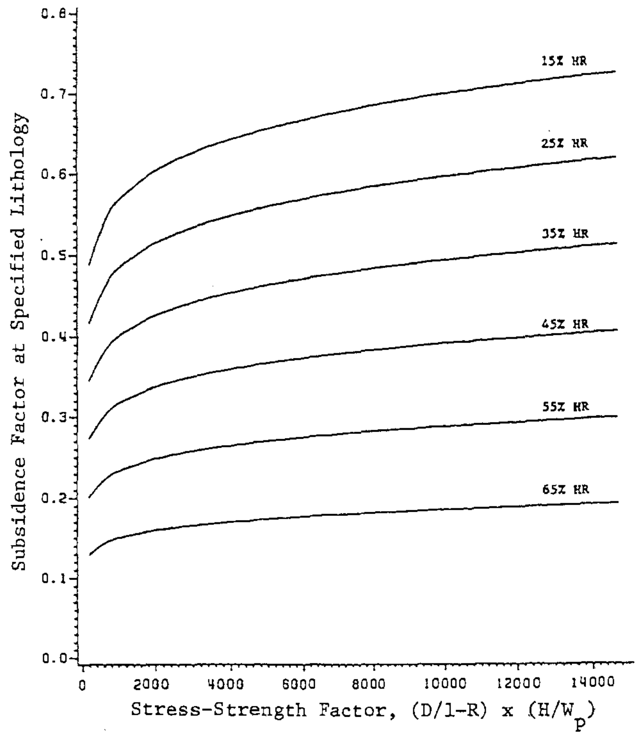

Figure 7. Effect of Pillar Stress-Strength and Lithology on S_{max}: Supercritical Data Analysis

CONCLUSIONS

The increased impact of subsidence damage in the eastern United States has provoked an intense interest in the mechanisms and manifestations of the phenomenon in this region. As a result, several subsidence prediction techniques have been developed to assist in minimizing the harmful effects of such surface deformations. In reviewing these methods, it is apparent that, irrespective of their limitations, empirical studies represent the most realistic approach to this complex problem.

The amount of data devoted to the formulation of the models pursued in this study was rather limited, thus placing certain restrictions on the application and verification of these techniques. Consequently, a substantial number of new case studies are needed to strengthen the established data bank and allow a more rigorous data treatment.

A systematic monitoring program would increase the number of case studies available for analysis. In addition, it would allow a more intense investigation of the subsidence relationships previously described and thus permit the reliable application of the subsidence prediction methods. The program should also prescribe the measurement of horizontal displacements, thereby expanding the minimal strain data currently available for the eastern United States. Moreover, the monitoring program should comply with established standards, in order to insure quality data.

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