

A STUDY OF LONGWALL SUBSIDENCE IN THE APPALACHIAN
COALFIELD

by

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INTRODUCTION

Mining subsidence is an important environmental phenomenon associated with most underground coal mining systems. The damage caused by this phenomenon ranges from land settlement to severe structural damage, and has been witnessed in rural as well as in urban areas. In fact, it is reported that in this country subsidence has had an adverse affect upon property in about 30 states (Singh, 1978).

In a recent study, the United States Bureau of Mines estimated that, in this country, over 2.0 million acres of land have been affected by mine subsidence, with an additional 1.5 to 2.4 million acres projected to become similarly damaged over the next 20 years (O'Rourke and Turner, 1981). In order to control this problem, the Surface Mining Reclamation and Control Act of 1977 has mandated that a subsidence plan be incorporated into every coal mine design (Office of Surface Mining, 1979). This action was taken in order to achieve the following objectives: (a) "to prevent subsidence from causing material damage or lessening the value or reasonably foreseeable use of the surface," (b) "to mitigate the effects of any material damage or diminution of

value or foreseeable use of lands," and (c) "to determine the degree of material damage or diminution of value or foreseeable use of the surface" (Office of Surface Mining, 1979).

Subsidence control is feasible within acceptable environmental levels given an accurate and practical method of subsidence prediction. The feasibility of subsidence control has been clearly demonstrated in many foreign coalfields, particularly in Europe where surface displacements can be predicted to a suggested accuracy of better than +20 percent.

In this country subsidence is rapidly gaining emphasis as an important problem of underground coal mining, especially because of an increased interest in longwall mining. Yet the art of subsidence prediction, and hence the control of subsidence, for both longwall and room-and-pillar mining systems is far from approaching maturity. It is necessary, therefore, to develop and apply prediction methods capable of providing mining operators accurate and flexible estimations of mining subsidence.

One limitation to the development of subsidence theories and prediction methods in this country is the lack of an appropriate data bank. Such an accumulation of subsidence data is necessary to establish regional subsidence characteristics and to validate the applicability of the various prediction methods.

During this research, a comprehensive effort was undertaken to establish a subsidence data bank consisting of published as well as unpublished case studies of mining subsidence. This effort was very successful, resulting in the collection of information pertaining to 34 longwall panels in Appalachia. The subsidence data were processed and analyzed to develop some basic relationships and trends of longwall subsidence in that region. Finally, this analysis was used to develop an empirical prediction method which can provide an accurate and practical tool of subsidence prediction in the Appalachian coalfield.

Chapter I

LITERATURE REVIEW

1.1 Subsidence Characteristics Over Longwall Panels

Although longwalls contribute to only a small percentage of the total United States coal production, this mining method has significantly increased in popularity since 1969 and continues to grow steadily (Von Schonfeldt et al, 1980). The longwall method of mining entails the removal of a long rectangular block of coal as shown in Figure 1.1.1, commonly referred to as a panel. As coal is mechanically removed from the longwall face, the immediate roof caves into the mined-out, or gob, area. Placing solid materials into the gob to prevent the meeting of the roof and floor, otherwise known as convergence, is termed packing or stowing.

Because a large tabular section of material is excavated during longwall mining, the resulting surface displacements are generally greater than those obtained with the room- and-pillar method of mining. The factors contributing to total subsidence, and the general shape assumed by the surface displacements overlying a longwall panel, have long been areas of interest for subsidence investigators.

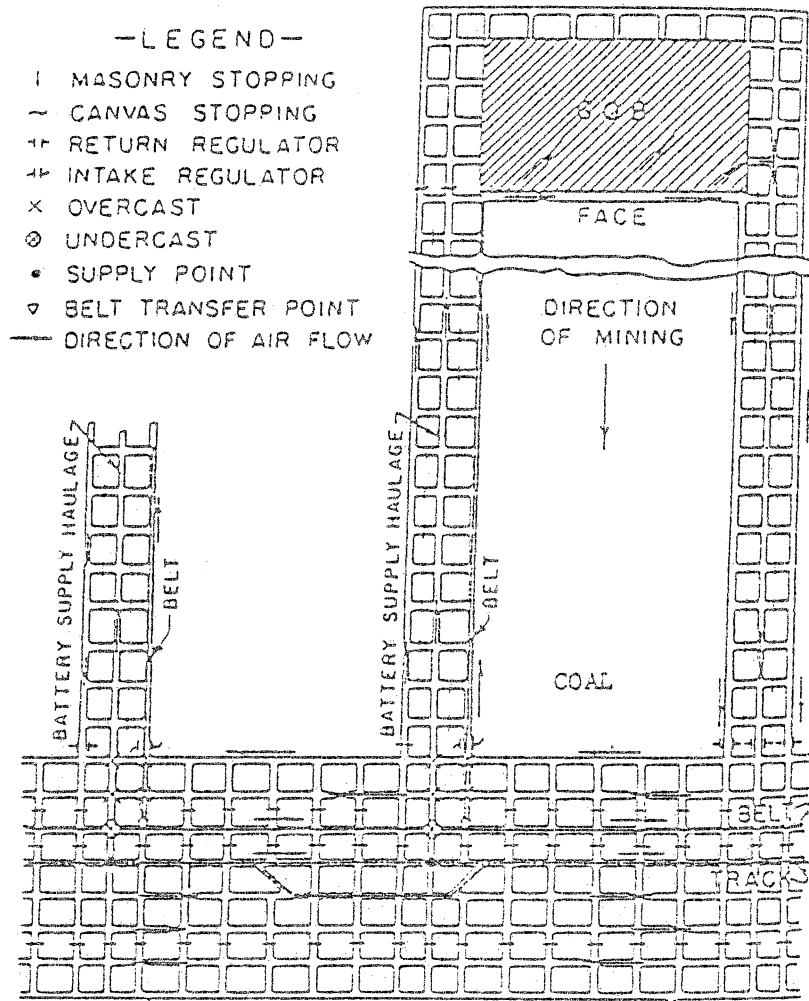


Figure 1.1.1 Plan of longwall mining method. Entries are driven by continuous miners (Cassidy, 1973).

- Trough Theory: One hypothesis introduced early in the 1900s and still widely accepted today is the trough theory of subsidence (Peng, 1978). By analyzing surface and underground measurements from European case studies, Dunrud (1976) revealed that surface displacements affect an area larger or smaller than the area extracted. Lehmann (1919) observed that the disturbed ground surface assumed a basin-like shape, as shown in Figure 1.1.2, within the limits of draw, for several mines located in the European coal districts (cited in Zwartendyk, 1971, pp. 85-86). Based on this observation, the trough theory was proposed. This theory assumes that the surface above a single horizontal opening settles in the general shape of a trough, with the maximum subsidence located near the center of the excavation and the magnitude of the displacement decreasing outward from the central point (Peng, 1978).

The angle of inclination between the edge of the workings and the lateral limit of subsidence at the surface has been termed the limit angle, or angle of draw. For European case studies, the limit angle is normally measured from the horizontal, and for mines in the United States and the United Kingdom, it is normally measured from the vertical. The angle measured from the horizontal, between the edge of the excavation and the point of maximum tension, is

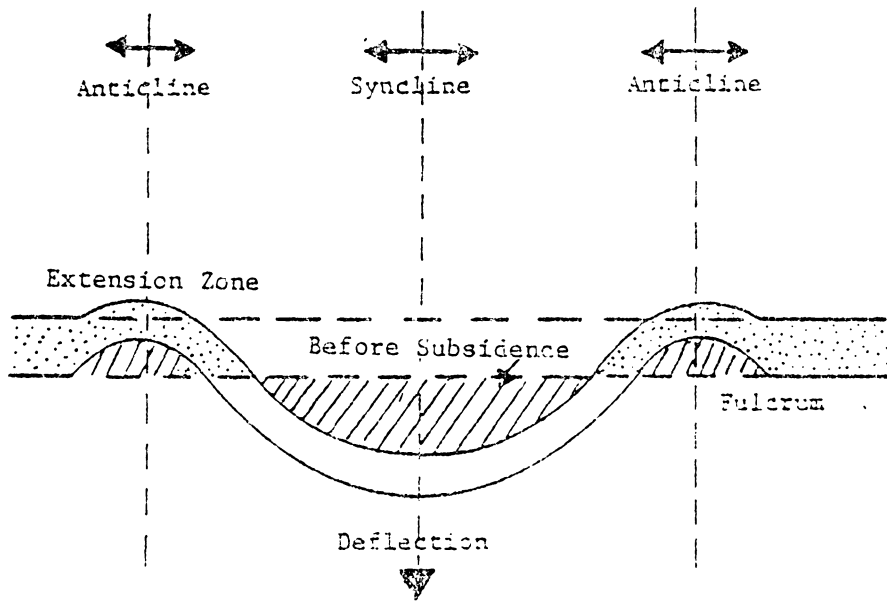


Figure 1.1.2 Lehmann's Theory (after WPI, 1981).

commonly known as the break or fracture angle (Singh et al, 1976). The value of this angle is generally larger than that observed for the limit angle. Figure 1.1.3 illustrates the location of the angle of draw.

Brauner (1973) described the limit angle to be indicative of "the limit of movements causing damages to structures, the limit of measurable movements, or the beginning of zero movement." He also suggested that the angle of draw is not an absolute rock characteristic, and neither does it qualify as a material parameter since it does not meet the elementary requirements of measurability and sole material-dependence. The limit angle has been found to vary with the thickness of the material removed, increasing with the volume of material excavated. It is difficult to assign a numerical value to the limit angle because determination of the exact location of a zero quantity at the surface is not always possible. Brauner has defined an indirect method of measuring the angle when there is uplift at the edge of the subsidence trough. Point a in Figure 1.1.4 illustrates the interpolated point of zero movement found with this type of analysis.

The fracture plane associated with the angle of break appears directly after active surface subsidence and remains fairly equal in orientation thereafter. As shown in

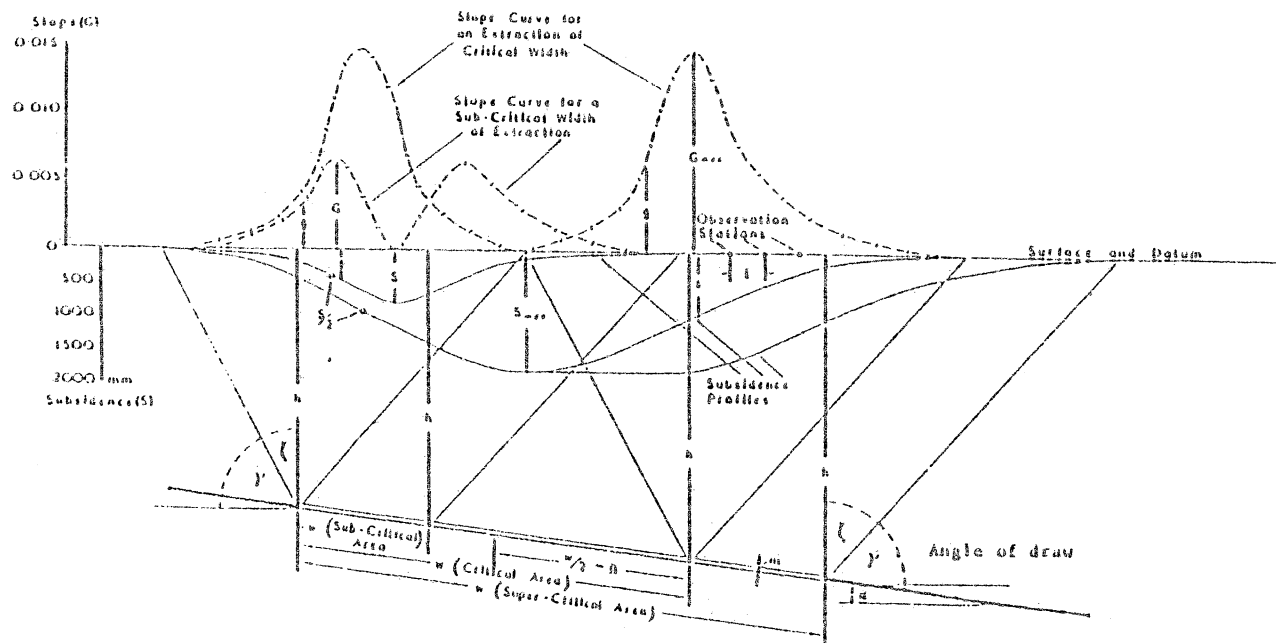


Figure 1.1.3 Typical section through workings, illustrating standard symbols for subsidence and slope (NCB, 1975).

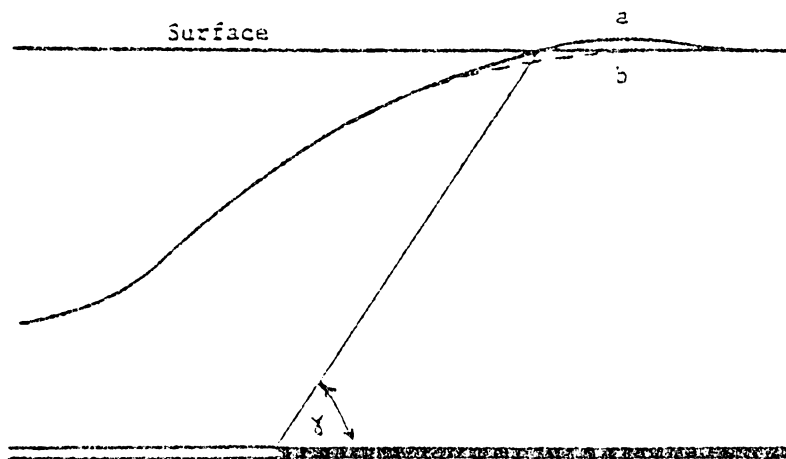


Figure 1.1.4 Definitions of the Limit Angle
(after Brauner, 1973)

Figure 1.1.5, this direction is generally towards the goaf. Because of limited laboratory observation and field measurements, information remains relatively scarce about the break angle (Singh et al, 1976). Pre-determination of this subsidence parameter would be particularly beneficial for coal mines in the vicinity of rivers, reservoirs, or surface structures.

- Caving: Movements of the overburden initiate from the immediate roof bed and progress upward, thus causing the strata above the opening to break and cave in (Singh et al, 1976). The zone of failure usually occurs in the shape of a dome, with the maximum height ranging from 30 to 50 times the height extracted (Peng and Cheng, 1980). Above this broken area the strata remains intact and will sag in a manner similar to that of a continuous beam. The sagging strata will eventually generate a trough-shaped subsidence profile. When the depth of the seam being mined is less than the height of the caved dome, a sink hole or holes will appear at the surface, without the formation of a trough. This phenomenon, often observed in shallow mines, should be considered during the analysis of field data; otherwise, the value of the maximum subsidence may appear to be distorted.

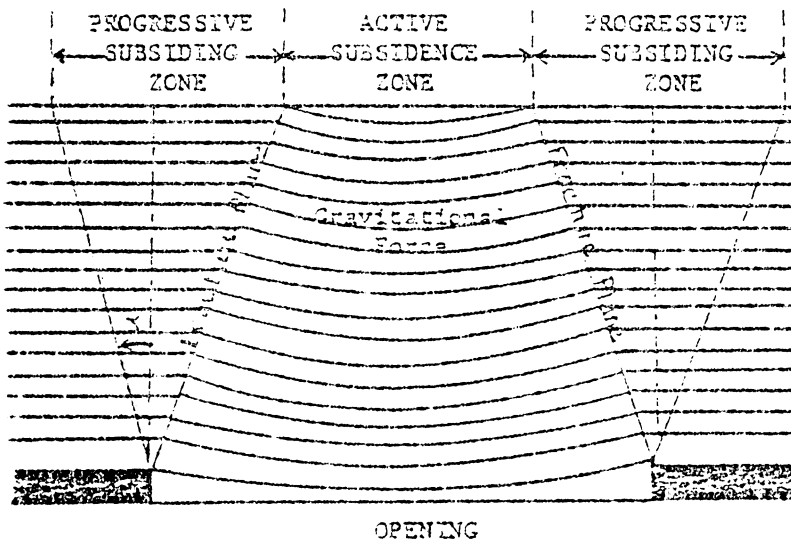


Figure 1.1.5 Strata movement in stratified formation (Singh et al, 1976).

- Modes of Displacement: Four modes of displacement possess the potential to cause surface and structural damage: (a) vertical displacement, (b) horizontal displacement, (c) tilt, and (d) curvature. Each of these forms of surface settlement may be explained from the concept of trough-shaped displacements (Dunrud, 1976). Observation of the displacement basin will show the rate of change of vertical settlement to approach maximum from the limit angle inward, and then approach zero in the midspan of the trough.

A subsidence trough generally forms with an outer zone of horizontal tensile strain surrounding an inner zone of horizontal compressive strain. If the maximum subsidence of the trough is critical, then the area surrounding this point becomes the third (and lowest) zone, where no horizontal strain exists (Panek, 1970). As the subsidence basin spreads outward with increasing extraction, surface structures above the panel are first subjected to a pulling and then to a squeezing effect as they pass through the transition zone. This phenomenon is illustrated in Figure 1.1.6. While the structure is subjected to a tensile strain, it is also exposed to an increasing tilt due to the slope of the ground surface.

Upward heaving or flexing is experienced by a structure as a result of curvature of the ground surface. An opposite

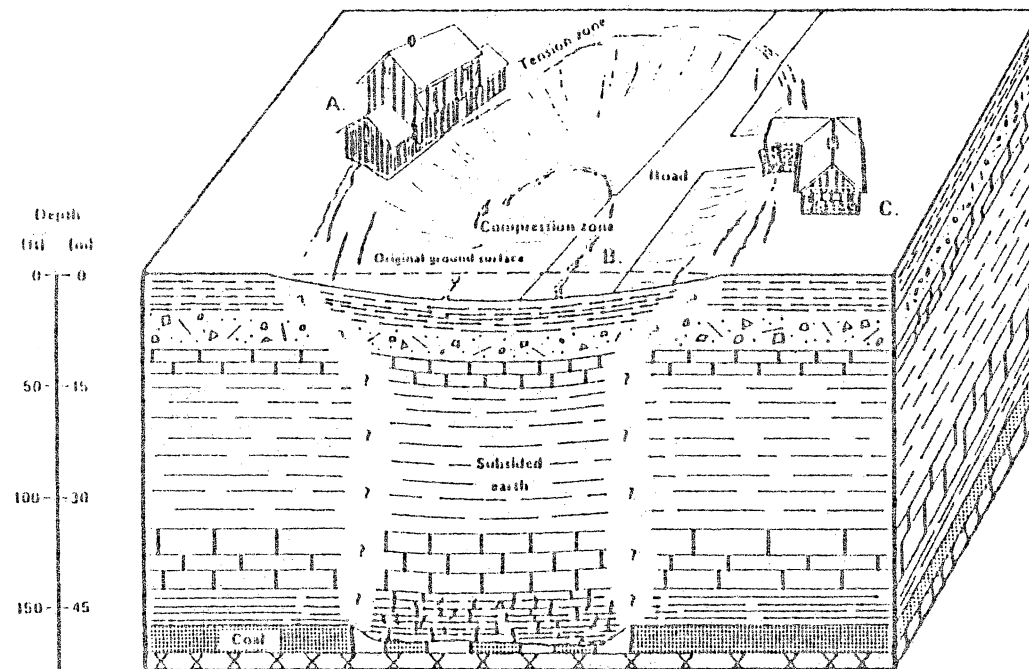


Figure 1.1.6 Block diagram of a typical subsidence sag event (DuMontelle et al, 1981)

- A. Wooden frame house in tension zone. Foundation has pulled apart and dropped away from the superstructure in one corner.
- B. Road in compression zone. Asphalt has buckled
- C. Brick house in tension zone. Walls, ceilings, and floors have cracked.

type of effect occurs when the structure is subjected to compressive strain. If a building settles uniformly, i.e. the vertical displacements vary uniformly along the subsidence trough, little damage will result. However, vertical settlements have been found to alter the grades of highways or railroad beds, to affect the flow of creeks and pipeline fluids, or to cause other complications (Panek, 1970).

Horizontal strains cause the failure or cracking of buildings that is often observed on the surface (Sinclair, 1963). The extent of the resulting damage is dependent upon a variety of design and environmental factors.

Curvature has a similar effect on surface structures, as do horizontal strains. The height of a building determines the extent of the resulting damage, with taller structures subject to more damage.

The instability of tall structures can generally be traced to the tilt of the ground surface. This type of deformation may cause heavy equipment to operate improperly or may interfere with the flow or drainage of materials from surface structures.

1.2 Factors Influencing Subsidence

Theoretically, a finite amount of subsidence may occur for a particular area of extraction. The maximum possible amount of surface settlement for an opening depends on several complexly associated elements that are often difficult to interpret. Although it is not easy to classify all of these parameters, most of them can be broadly categorized under one of the following headings:

- width and depth of the panel
- thickness of the extraction
- inclination of the seam
- method of extraction
- method and type of support utilized
- rate of advance or extraction
- influence of adjacent workings
- water-bearing strata
- topography
- geology (includes lithology, stratigraphy, etc.)

Shadbolt and Mabe (1968) classified these factors into three broad categories: (a) mining factors, (b) site factors, and (c) time factors. Whenever structural damage is involved, a fourth category, termed structural factors, should be incorporated into the subsidence analysis. Each of the parameters comprising these categories are described in the following sections. Before a thorough subsidence analysis is performed, it is necessary to understand the extent and influence of each of these elements on the surface displacements.

1.2.1 Mining Factors

Mining factors were the first subsidence parameters to be investigated because subsidence was initially considered to be only a function of the geometry of the excavation. British engineers developed a predictive method for displacement based on the input of geometrical parameters of the panel, such as width, height, and depth of the opening.

- Width and Depth : Three terms are commonly used to relate the width of an excavation to the amount of subsidence at the surface: critical,

sub-critical and super-critical widths. The maximum subsidence possible for an opening will not be achieved unless it is of critical dimensions. A critical profile is defined to possess maximum subsidence at one point--generally the central point. A subcritical profile exists when the panel width is not sufficient to produce full subsidence, and a supercritical profile is one which exhibits maximum subsidence along an area of the settlement trough.

A relationship exists between the depth of the excavation and the resulting surface displacement. A panel which is supercritical at a shallow depth may become critical at a greater depth, and could possibly reduce to subcritical if the depth is increased further (Peng and Cheng, 1980). The maximum possible subsidence for an opening will be attained only when the width-to-depth ratio of the panel is equal to or greater than twice the tangent of the limit angle. It is therefore necessary to correct panel dimensions to critical before a common basis may be established from which statistical analyses of subsidence case studies may be possible. The NCB (British National Coal

Board) has developed critical correction curves for their native mining conditions, which are included in the Subsidence Engineers' Handbook (NCB, 1975).

A subsidence curve is convex to a certain point and then it becomes concave. The location of the transition point is known as the point of inflection and has a subsidence value equivalent to half the maximum subsidence for that particular profile (NCB, 1975). The greater the curvature of the profile, the more pronounced will be the resulting damage to surface structures (Holland, 1973).

Various studies have been conducted to determine the effect of the panel width-to-depth ratio on the inflection point of the profile. The transition point is generally located over the solid coal when the extraction width is subcritical and over the gob when the panel is either critical or supercritical. The British found that for width-to-depth ratios of 0.25 or less, the transition point was located over the rib, whereas for width-to-depth ratios of 0.4, the inflection coincided with the ribsides. The larger ratios of

more than 1.4 possessed inflection points well inside the gob, corresponding to large degrees of curvature (NCB, 1975). However, exceptions were found with panels of small width-to-depth ratios and large angles of draw appearing to be critical, and with panels of large width-to-depth ratios and small limit angles being subcritical. Figure 1.2.1 illustrates the relationship between the inflection point and the width-to-depth ratio of a panel.

- Seam Thickness: While analyzing the works of Briggs and Menzel, Orchard (1957) found that a direct relationship between subsidence and depth is extremely variable, and that the amount of surface settlement is influenced by the extraction thickness and width-to-depth ratio of the panel. This relationship defines the full surface settlement for a critical panel to be:

$$S_{max} = m \cdot a$$

where,

m = seam thickness

a = subsidence factor

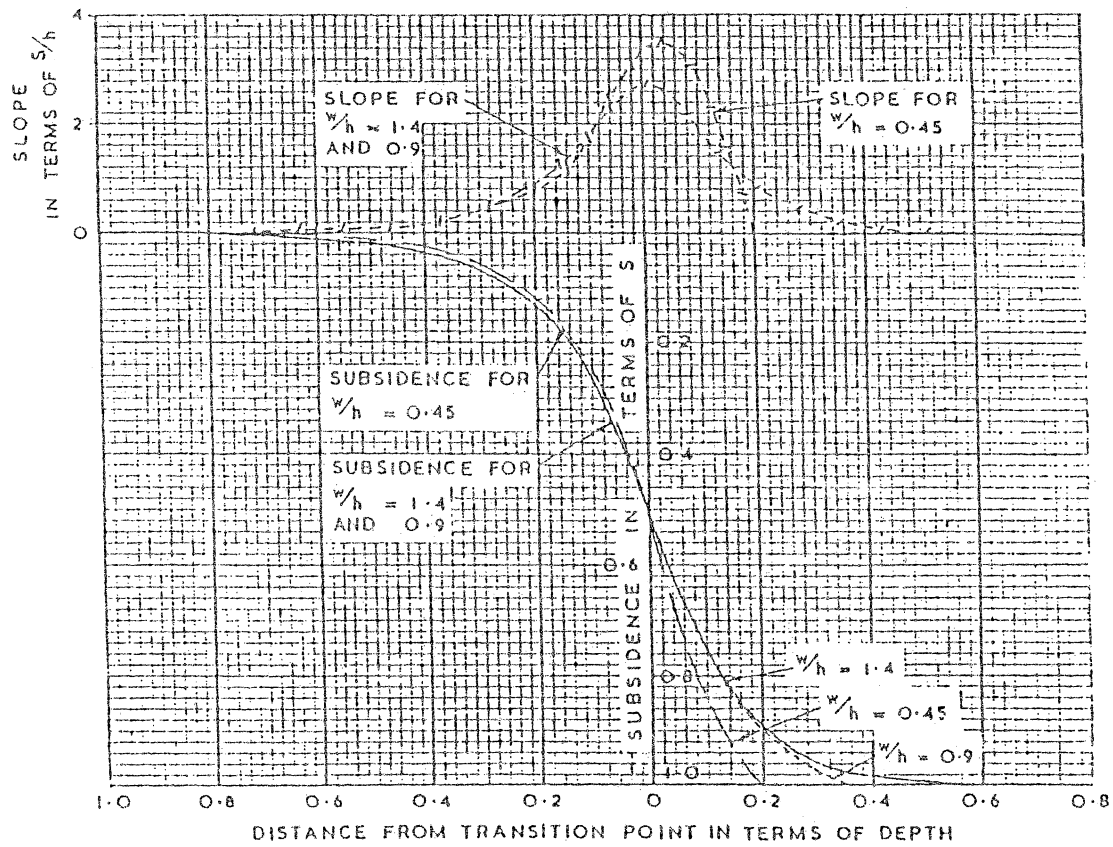


Figure 1.2.1 Typical Half Profiles and Slope Curves (NCB, 1975).

Table I contains the average subsidence factors observed for several continents. This chart, compiled by Brauner (1973), illustrates the effect of the mine support system on the surface settlements. The subsidence factors are shown to vary between 0.10 and 0.90, with close agreement demonstrated for all longwall systems (caving). Salamon (1964) discovered similar results for his study involving longwall mining, shown in Table II.

The graph illustrated in Figure 1.2.2 is a partial subsidence curve which was used by the NCB to obtain values of maximum subsidence for particular panel dimensions. Once again, the inhibiting effect of roof support on subsidence is illustrated. Approximately 50 percent less displacement will occur at the surface when stowing is employed. This type of support system is particularly effective where shallow workings are involved (VPI, 1981).

Whetton (1957) and Shulte (1957) have independently studied the amount of subsidence which may occur at the surface for various forms of roof support. Pneumatic stowing was found to produce

Table I
A COMPARISON OF SUBSIDENCE FACTORS
(After Brauner 1973)

Coalfield	Method of Packing	Subsidence Factor
British	Solid stowing	0.45
	Caving	0.90
Ruhr (Germany)	Pneumatic stowing	0.45
	Solid stowing	0.50
	Caving	0.90
North and Pas de Calais (France)	Hydraulic stowing	0.25 - 0.35
	Pneumatic stowing	0.45 - 0.55
	Caving	0.85 - 0.90
Upper Silesia	Hydraulic stowing	0.12
	Caving	0.70
U.S.S.R.		
Donets	Caving	0.60
Karaganda	Caving	0.70
Chelybinsk	Caving	0.90

Table II
 A COMPARISON OF SUBSIDENCE FACTORS
 (After Salamon 1964)

Method of Waste Control	Subsidence Factors		
	Germany	Poland	Hungary
Hydraulic stowing	-	0.12 - 0.20	0.25 - 0.5
Pneumatic stowing	0.45 - 0.55	0.25	-
Manual packing	0.50 - 0.60	0.40	-
Dummy road packing	0.58 - 0.85	0.55	-
Caving	0.85 - 0.95	0.70 - 0.80	0.8 - 0.98

TABLE III

Influence of Support System on Maximum Subsidence
 (After Schulte, 1957)

Method	Maximum Subsidence Factor
Hand packing	51.1 %
Centrifugal stowing	56.5
Pneumatic stowing	41.2

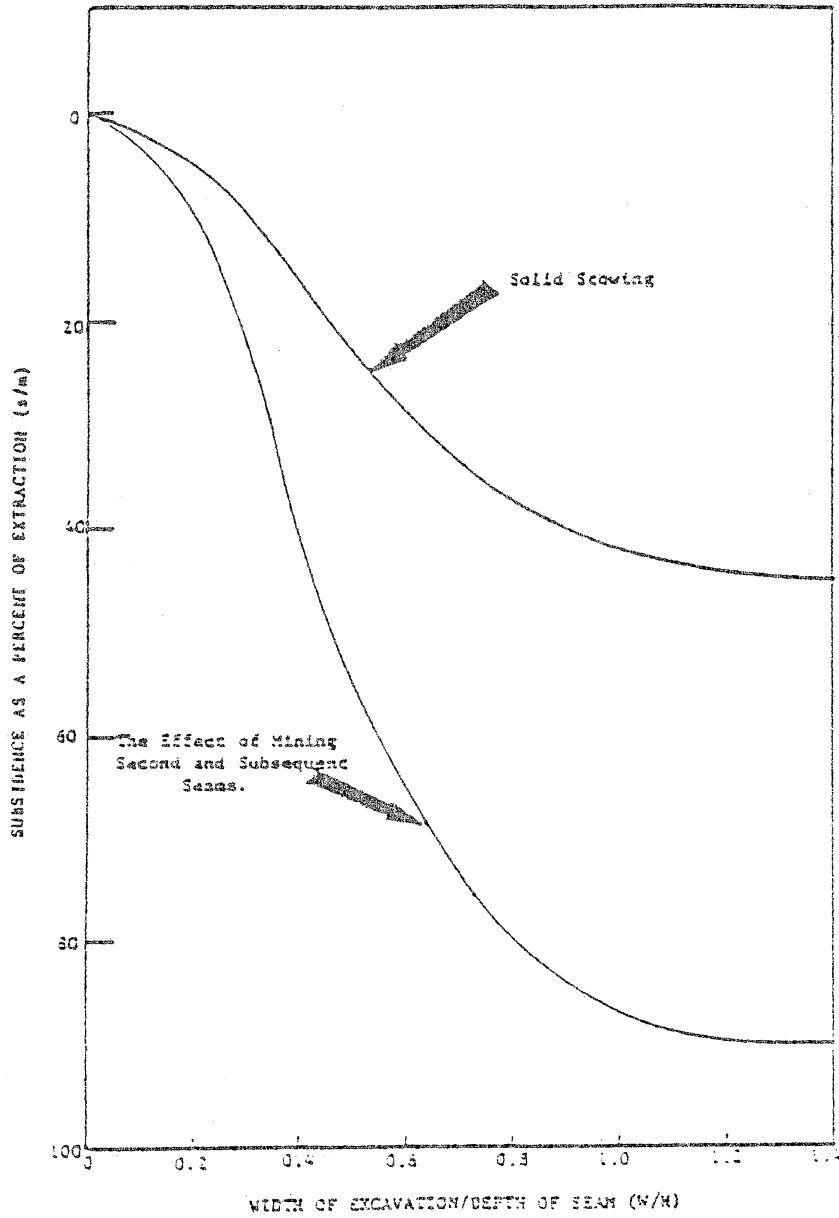


Figure 1.2.2 Relationship of subsidence to width/depth of working (NCB, 1975).

55 percent relief of subsidence at the surface while hand-packing produced only 40 percent (Whetton, 1957). Shulte averaged the values found for maximum subsidence of supported faces and published his findings, as shown in Table III.

Mining performed in a British virgin coalfield will generally induce maximum subsidence values of up to 80 percent of the extracted seam thickness, while workings of subsequent excavations may produce a total of 90 percent (VPI, 1981). This is usually true for mining panels which have advanced at least 1.4 times the depth of the seam, corresponding to an average limit angle of 35 degrees for the British coalfields. Angles ranging from 25-45 degrees have been suggested for these coalfields by other investigators. Orchard (1954) attributes these variations in the limit angle to the strength and hardness of the individual overburdens.

- Seam Inclination: The limits of subsidence are affected when mining is performed in an inclined seam. The subsidence trough becomes displaced toward the deeper edge of the excavation

and may become located outside of the dip edge of the opening (Peng, 1978). The limit angle will be smallest at the rise edge of the excavation and will increase toward the dip edge. The NCB has developed a graph which may be used to make appropriate adjustments to the angle of draw for seams steeper than 20 degrees (NCB, 1975). Full subsidence will no longer be located at the center of the opening, but will instead be located at a point normal to the center (Peng, 1978). Workings inclined 20 degrees or less will cause the profile to be displaced a distance determined by projection of normals from the seam to the surface. The effect of a slightly inclined seam on subsidence is shown in Figure 1.2.3a.

Bals (1932) suggested the formation of a double-sided subsidence trough when mining from an inclined seam and claimed that a correction graph based on this hypothesis is more accurate than other known methods. However, his theory is not applicable to non-elastic materials, nor is it supported by empirical data. The influence of a steeply inclined seam on subsidence, as seen by Bals, is shown in Figure 1.2.3b.

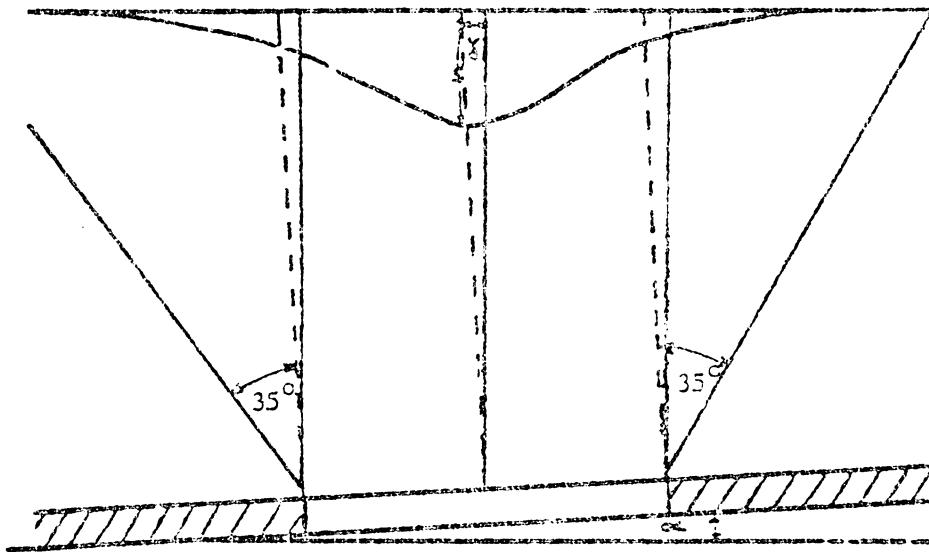


Figure 1.2.3a Subsidence Over a Slightly Inclined Seam ($< 1/15$)
(after Breeds, 1976)

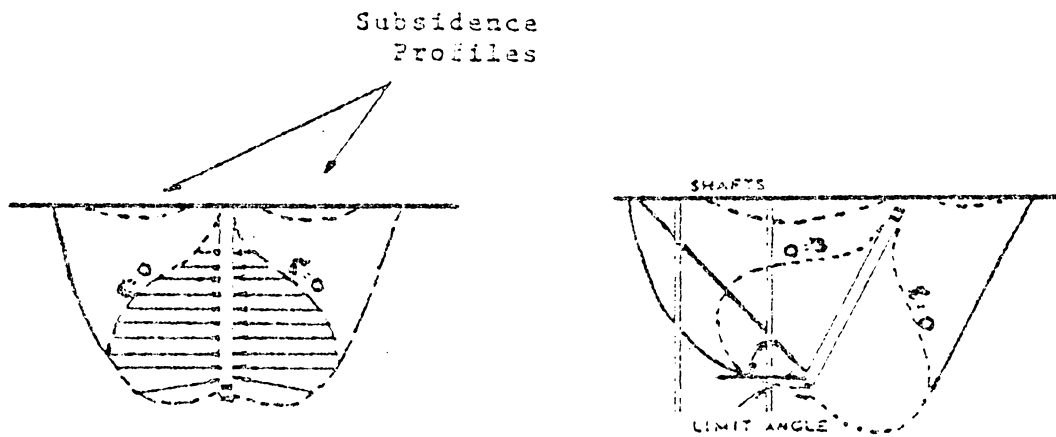


Figure 1.2.3b Diagram of Effect of Working in Steep Measures
(after Bais, 1967)

- Method of Extraction: The method of extraction employed in a mine will influence subsidence because extraction is directly related to the volume of material removed underground. As stated previously, mining methods which utilize caving, such as the longwall system, induce more subsidence than other methods. The maximum possible subsidence in room-and-pillar mining is believed to be proportional to the percentage of extraction employed above a threshold value, which has been determined to be 40 percent for the central United States, coal fields (O'Rourke and Turner, 1979).

Several mining methods, cited in literature, have been suggested to aid in the reduction of subsidence. For mining underneath developed areas, a panel and pillar method was successfully adopted in the United Kingdom. The pillars were mined by either longwall or room-and-pillar systems, with no backfilling performed in either case. This mining method was found to be successful in the stratified iron deposits of the Lorraine area of France (Zwartendyk, 1971).

The concept of harmonic mining was developed in the Netherlands by Grond (1947, cited in Zwartendyk, 1971, p. 19 2). During this process, more than one seam is mined in an orderly fashion. This method attempted to cancel the final vertical and horizontal strains produced from mining by strains produced from extractions in other areas. The major limitation was that it could only be employed with special equipment and under conditions not usually considered economically feasible.

- Rate of Face Advance: The rate of advance of a mining face has been found to affect the rate at which subsidence develops, but not the amount of total subsidence (Wardell and Webster, 1957). High rates of advance can lead to failure by fracture because of the time dependent and elastic failure mechanisms of intact rocks, whereas slower rates of advance may permit the occurrence of creep (Wardell, 1970).

1.2.2 Site Factors

Geotechnical factors, such as soil properties, rock properties, hydrogeology, and geologic discontinuities have an important effect on the extent of mining subsidence. The influence of the strata characteristics on the magnitude and development of the surface settlement has been an interesting, and somewhat controversial, subject to subsidence engineers. Numerous investigations have been conducted to study these ambiguous characteristics (O'Rourke and Turner, 1981).

In the United States coalfields, the typical stratigraphy of coal-bearing overburdens includes layers of shale, sandstone, and frequently limestone. It is difficult to determine the influence of each bed, because of the significant variations of their relative amounts, thicknesses, and competence. For example, shale has been noted to account for about three-fourths of the coal-bearing strata in England (Bell, 1975); on the other hand, approximately 70 percent of the strata over longwall panels near Wollongong, Australia are sandstones (Kapp, 1978). Tables IV and V present summaries of investigations conducted on the effects of the overlying strata on the measured subsidence and angle of draw. Stratigraphy is not the only controlling geologic property. The thicknesses of individual beds and their relative positions in the overburden, the strengths of the various rock materials, the bulking factors, and the bedding

Table IV.--Lithologies, mining conditions, and measured subsidence (supercritical condition)
(after Abel and Lee, 1980)

Location and Commodity	Lithologic percentages			Depth (m)	Mining height (m)	Extraction (percent)	Maximum subsidence (percent of mining height)	References
	In overburden							
	Shale	Sandstone	Limestone					
Pennsylvania coal.	50	22	28	90	1.7	81	40.0	Greenwald and others (1937).
Do-----	59	11	30	110	2.1	85	51.5	Haize and Greenwald (1939).
Do-----	70	11	9	100	1.6	90	50.0	Haize, Thomas, and Greenwald (1940).
Do-----	59	11	30	162	2.1	85	48.2	Haize, Thomas, and Greenwald (1941).
Do-----	59	11	30	91	2.1	85	46.3	Do.
New Mexico coal.	63	17	0	104	3.0	100	69.0	Abel and Gentry (1978).
Great Britain coal.	60	12	0	519	1.1	100	58.4	Sinclair (1950).
Do-----	63	29	0	793	1.0	100	65.2	Do.
Do-----	64	16	0	41	.6	100	84.0	Briggs and Ferguson (1933).
New Mexico uranium.	86	14	0	152	3.0	36	7.0	C. H. Parrish (written comm. 1979)
California borate.	17	83	0	118	42.1	100	73.9	Obert and Long (1962) ² .
Pennsylvania coal.	48	52	0	60	1.0	86	57.9	Hontz and Morris (1930).
Illinois coal.	71	17	12	130	1.1	100	61.2	Harbert and Rutledge (1927).
Do-----	57	38	5	152	2.4	69	34.8	Do.
Illinois shale.	64	4	12	119	7.6	51	15.2	Abel (1973), Fenix and Schssoon, Inc. (1972).
New Mexico potash.	40	(50 percent Salt Fm.)	10 ¹	105	3.0	95	58.0	Miller and Pearson (1958).

¹/Possibly subcritical, but presence of flat-bottomed subsidence trough indicates supercritical area.
²/Dolomite.

Table V - Angles of dip (from vertical) for mines in flat-bedded sedimentary rocks with respect to lithology of overburden (after Abel and Lee, 1980).

Location and Commodity	Lithologic percentages in overburden			Angle of dip (degrees)	Reference
	Shale ¹	Sandstone	Limestone		
Pennsylvania coal.	50	32	20	18.0	Greenwald and others (1937).
Do-----	78	13	9	24.0	Haize, Thomas, and Greenwald (1940).
Do-----	59	11	30	9.0	Haize and Greenwald (1939).
Great Britain coal.	12	88	0	0.0	English (1940).
New Mexico coal.	61	37	0	15.0	Abel and Gentry (1978).
Great Britain coal.	60	12	0	17.0	Stclair (1951).
Do-----	61	29	8	12.0	Do.
Do-----	61	16	0	29.0	Briggs and Ferguson (1933).
New Mexico uranium.	86	14	0	40.0	C. B. Parrish (written commun., 1979).
California borate.	17	83	0	0.0 (avg.)	Obert and Long (1962).
Pennsylvania coal.	48	52	0	18.0	Hontz and Norris (1910).
India coal.	25	75	0	11.0	Kumar and Singh (1971).
Do-----	23	77	0	21.0	Do.
Do-----	57	43	0	20.0	Do.
Do-----	17	62	0	18.0	Do.
Do-----	35	65	0	17.0	Do.
Do-----	35	65	0	17.0	Do.
Do-----	23	77	0	17.0	Do.
Do-----	12	60	0	27.0	Do.
Illinois coal.	71	17	12	8.5	Barbert and Rutledge (1927).
Do-----	57	18	5	0.0	Do.
Arizona copper.	0	0	100	12.0	Trischka (1934) ²

¹ Includes all argillaceous rocks.

² Fault bounded on all four sides. Therefore, not employed in statistical analysis.

cross-joint frequencies also affect the amount and form of the subsidence at the surface (Abel and Lee, 1980).

Abel and Lee (1980) performed statistical studies on the effect of various overburdens, overlying both stratified and non-stratified deposits, on surface subsidence. However, the authors did not distinguish between the different stratigraphies while performing their analyses. The results of the investigation were used to study the effect of the different percentages of shale, sandstone, and limestone in the overburden on the resultant surface subsidence. They concluded that the subsidence factor will usually increase as the amount of shale in the overburden increases, and that the presence of either sandstone or limestone will significantly reduce surface settlement. The relationship which exists between lithology and the angle of draw is difficult to determine because the percentages of shale, sandstone, or limestone, when considered singularly, are not good indicators (Abel and Lee, 1980). The angle of draw may not reach its normal limit if a fault is present in either type of overburden.

Peng and Cheng (1980) also found a correlation between the amount of sandstone in the overlying strata and the magnitude of the resulting subsidence factor. They suggested that the subsidence factor will decrease as the percentage

of sandstone in the overburden increases. The thicker sandstone strata are believed to offer mild resistance to caving and sag, as shown in Figure 1.2.4, limiting the propagation of crumbling strata in the overburden and also reducing the amount of surface settlement (Peng and Cheng, 1980).

Geology also refers to deformational parameters of the overlying strata. Crane (1931) found that faults, joints, and other planes of weakness have a definite influence on the angle of draw, the degree of influence depending on the dip, direction, and other characteristics.

It is important to understand the influence of geologic factors on surface displacement, because the subsidence trends observed for coalfields of different countries, as well as within the United States, have largely been attributed to geologic variations (Peng and Cheng, 1980). Consequently, the subsidence factors determined for one mine may not be applicable to another, unless the panel dimensions, geology, and other contributing factors are similar.

- Topography: The effect of topography or surface slope on subsidence is a recent area of investigation. Surface slope has not been determined to have a significant effect on surface settlement in the coalfields of the eastern United States, but it has been suggested to influence subsi-

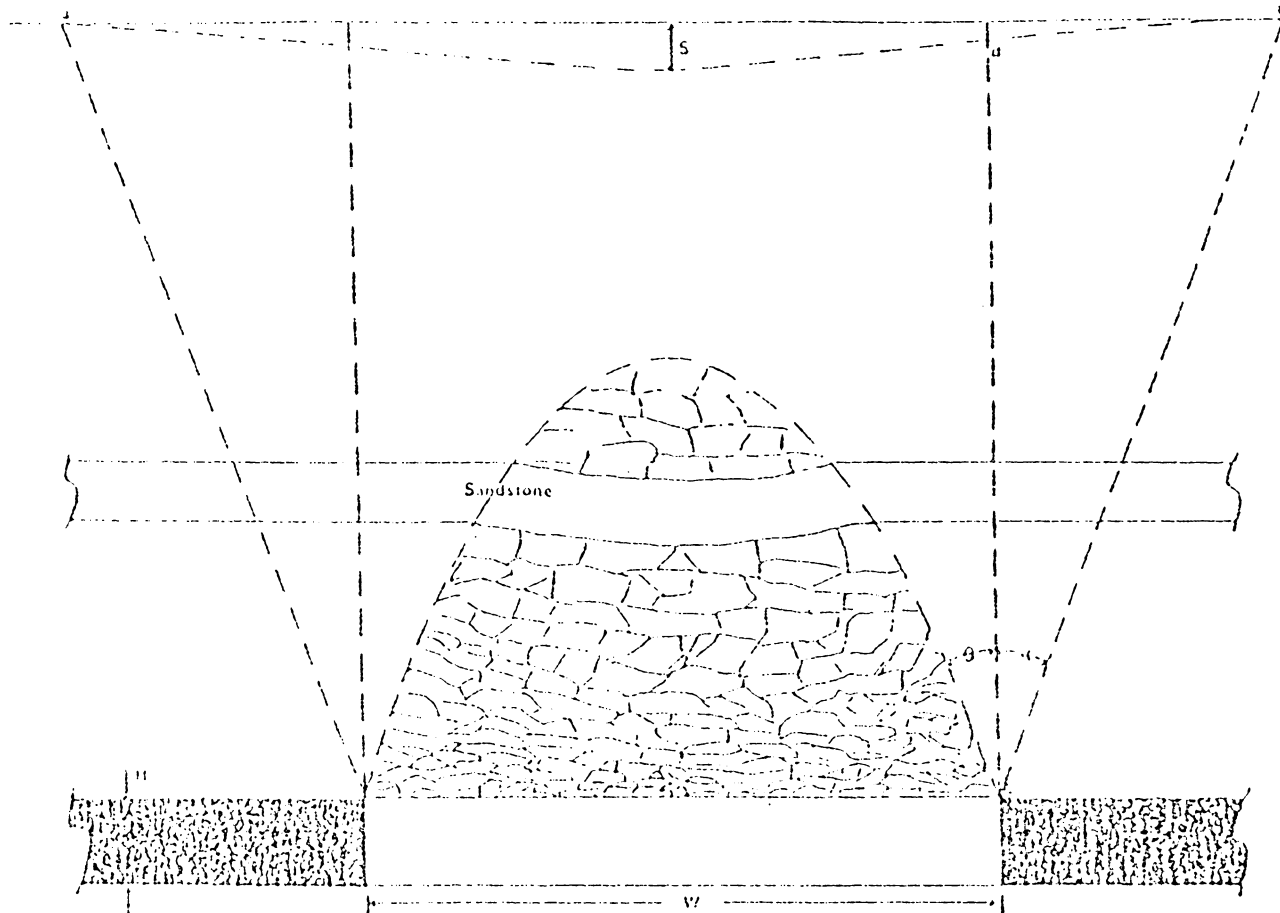


Figure 1.2.4 Mechanisms of Roof Caving Leading to Surface Subsidence (Peng and Cheng, 1980).

dence in the Western mining districts (Dahl and Choi, 1973, and Abel and Lee, 1980).

Peng and Kohli (1980) collected data from mines located in the moderate to steep hills of northern Appalachia. One case study involved a surface slope which varied from 0 to 35 percent along the mining panel and included subsidence measurements at various points from the center. The majority of the data collected indicated that changes in surface topography had little, if any, effect on the resulting surface displacement.

In another study of the effect of topography on subsidence, measurements were obtained from two coal mines, one in southwestern Pennsylvania and the other in northern West Virginia. Both mines were located in the Pittsburgh coal seam. The Pennsylvania mine employed a room-and-pillar extraction method, while the mine located in West Virginia utilized a longwall system beneath a valley floor, which stretched obliquely to the panel centerline. The subsidence contours of the West Virginia longwall mine are shown in Figure 1.2.5. These results were obtained from analysis of field data obtained from surveys performed for a period of months. Indications were that the subsidence was formed essentially symmetric to mining activity and was primarily affected by mining geometry, regardless of the irregular to-

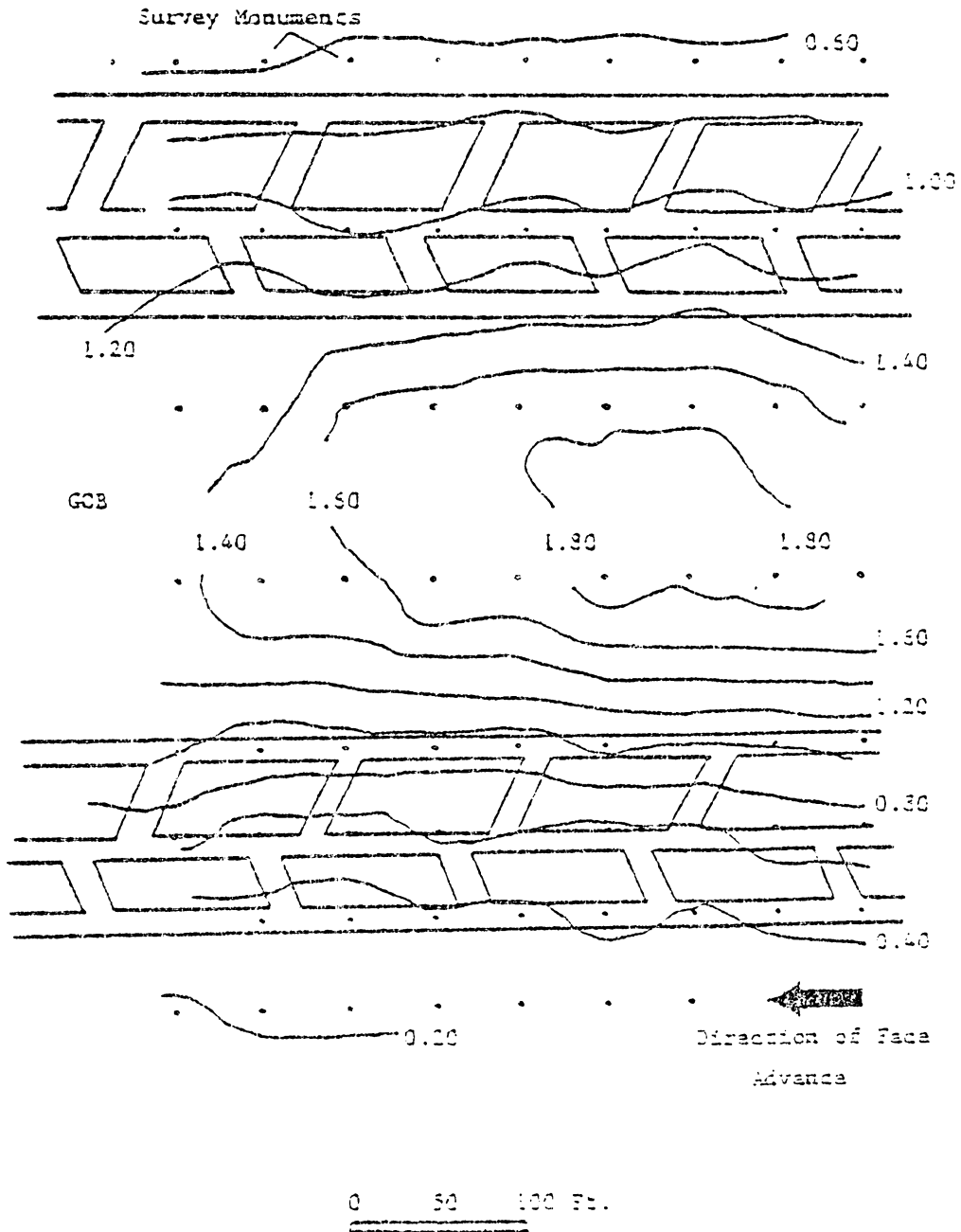


Figure 1.2.5 Subsidence Contours above West Virginia Longwall Panel (after Dhal and Choi, 1973).

pography. The surface slope was determined to not influence the formation of subsidence, except for a steep slope, which was found to affect the surface settlement. However, this influence was attributed to the depth of the seam, not to the variation in surface topography.

Gentry and Abel (1978) observed the surface displacements above a super-critical longwall panel in New Mexico, with known rapid topographic variation along the panel centerline. The coal seam being mined was approximately 9 feet thick with the overburden primarily consisting of sandstone, siltstone, and shale layers. The researchers suggested that topography significantly influenced the magnitude and distribution of the mining-induced surface displacements (Abel and Lee, 1980). The amount and type of vegetation at the surface is also thought to alter the subsidence, i.e., the desert ground may become disturbed from a slight underground movement, whereas an area with dense vegetation would be more stable--even in a steep terrain.

1.2.3 Time Factors

The concepts of time-dependent movement and the time of influence in mining subsidence need to be considered separately. The time-dependent portion of surface settle-

ment occurs during those periods when the face is no longer advancing. Partial extraction of room-and-pillar mining, has often caused the failure of pillars leading to subsidence. This phenomenon has been observed as long as 100 years after actual extraction, and may be more accurately attributed to creep rather than to subsidence (Peng and Cheng, 1980).

The rate of subsidence continues to be a broad area of interpretation. Young and Stoek (1916) suggested that the duration of surface movement increases with an increase in seam depth. Numerous studies have attempted to expound upon this theory (NCB, 1975). Wardell (1957) has suggested that the subsidence of a surface point initiates when the mining face enters an influence zone, or critical area and ceases once outside of this region.

The NCB used the assumption of a critical area to depict the development of subsidence for a surface point as the coal face passes beneath and beyond it. Figure 1.2.6 illustrates the average development curve obtained for British data. When the face has progressed a distance equal to approximately three-quarters of the depth ($0.75h$) from P, the subsidence first becomes measurable. Active subsidence of the surface point is more than 95 percent complete when the face has gone a distance of about $0.70h$ beyond it. Most

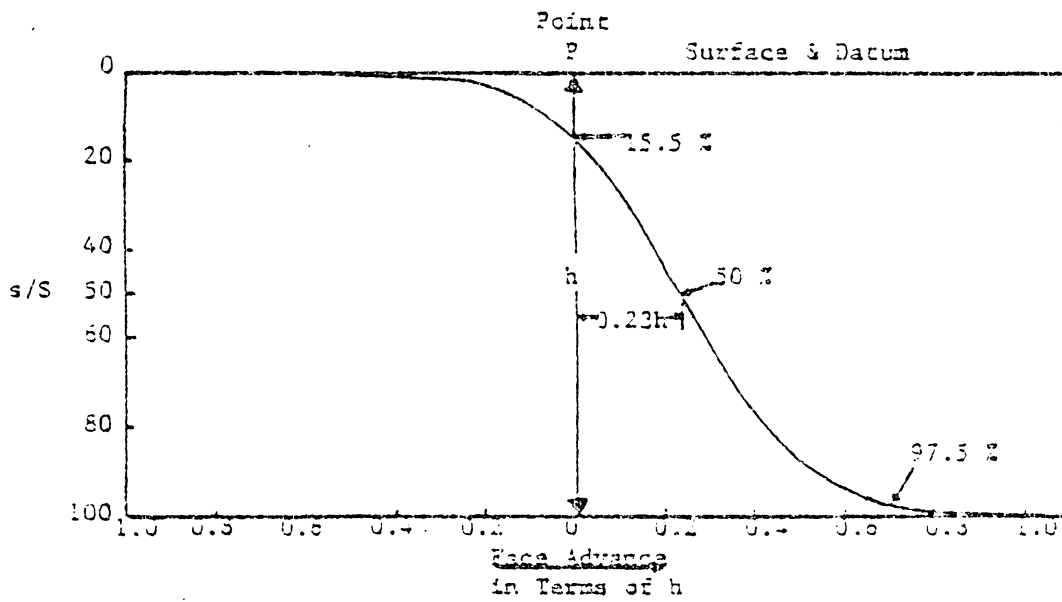


Figure 1.2.6 Typical Subsidence Development Curve (after NCE, 1975).

of the settlement occurs within this critical distance; therefore, very little residual subsidence results, with the maximum being about 9 percent of the total. The active subsidence is almost complete after the face has advanced a distance approximately equal to the limit angle beyond the surface point, while the maximum time-dependent subsidence typically appears at the point of half maximum displacement (NCB, 1975). Figure 1.2.7 illustrates the active and time-dependent subsidence, again for United Kingdom mining conditions.

As the mining face leaves the influence area of a surface point, further ground movements are believed to occur due to complex time-dependent stress redistribution processes in the overlying rocks (Orchard and Allen, 1974). Several studies have shown that the presence of thick competent beds in the overburden will cause delayed subsidence. Gradual lowering of the overlying rock mass is interrelated with the occurrence of weak beds while violent, and often delayed, failure is associated with the sudden collapse of strong roof rocks (Peng and Cheng, 1980). Piggot and Eynon (1977) suggested that the presence of one competent rock layer in the overburden, with a thickness of at least 1.75 times the opening width, delays or prevents subsidence failure.

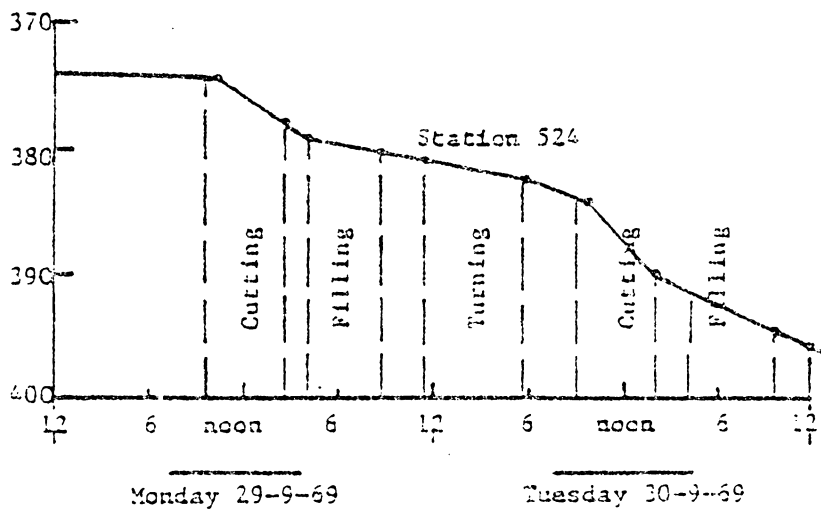


Figure 1.2.7 Active and Time-Dependent Subsidence (after NC3, 1975).

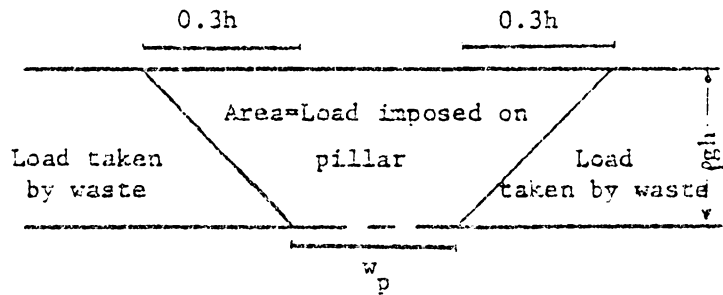
Analysis of the time factor of subsidence can aid in the area of mine design. Pre-determination of the maximum subsidence for an excavation would permit the design of support pillars based on the amount of load accepted by the caved waste and the amount being transferred over the solid rib. Figure 1.2.8 illustrates this concept for an advancing longwall face. The practice of unnecessarily employing low extraction ratios could be eliminated with a more efficient method of pillar design.

1.2.4 Structural Factors

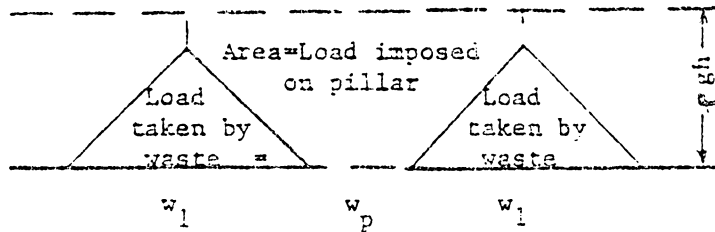
Mining-induced damage to a structure is dependent on the building's inherent strengths and weaknesses (VPI, 1981). Due to the interaction of a variety of factors, adjacent surface structures may respond differently to underlying extraction. Some considerations which will aid in assessing the reaction of a structure are: (a) its dimensions and shape, (b) the kind of materials composing the structure, (c) how well the materials used in construction were prepared, (d) the design of the foundation, and (e) the age or state of maintenance.

The severity of structural damage is directly related to its design and composition; therefore, general pre-

dictive solutions are possible (Voight and Pariseau, 1970). The NCB has developed a classification scheme for subsidence damage based on the length of the structure. Japanese and Polish workers have devised limiting values of strains which various structural designs may withstand (Goto, 1978, and Klemencsics, 1962). Table VI illustrates several limiting values of settlement for structural damage.



A. Pillar with extensive waste on both sides.



B. Pillar with waste less than $0.6h$ on either side.

Figure 1.2.8 Load imposed on pillar represented as area of the stress distribution enveloped not taken by gobs (Wilson and Ashwin, 1972).

TABLE VI
 (NCB, 1975)
 National Coal Board Classification of Subsidence Damage

Change of Length of Structure	Class of Damage	Description of Typical Damage
Up to 0.03 m	1. Very slight or negligible	Hair cracks in plaster. Perhaps isolated slight fracture in the building, not visible on outside.
0.03 m – 0.06 m	2. Slight	Several slight fractures showing inside the building. Doors and windows may stick slightly. Repairs to decoration probably necessary.
0.06 m – 0.12 m	3. Appreciable	Slight fracture showing on outside of building (or one main fracture). Doors and windows sticking; service pipes may fracture.
0.12 m – 0.18 m	4. Severe	Service pipes disrupted. Open fractures requiring rebonding and allowing weather into the structure. Window and door frames distorted; floors sloping noticeably; walls leaning or bulging noticeably. Some loss of bearing in beams. If compressive damage, overlapping of roof joints and lifting of brickwork with open horizontal fractures.
More than 0.18 m	5. Very severe	As above, but worse, and requiring partial or complete rebuilding. Roof and floor beams lose bearing and need shoring up. Windows broken with distortion. Severe slopes on floors. If compressive damage, severe buckling and bulging of the roof and walls.

1.3 Early Subsidence Theories

Establishing correlations between displacement phenomena which occur underground and at the surface, as well as interpreting the ambiguous elements which affect surface settlement, are two of the major difficulties encountered in a subsidence investigation. Before subsidence can be accurately predicted, a knowledge of the mechanism of ground movement, as it progresses from the excavation through the superincumbent strata to the surface, is necessary.

The first subsidence theories were developed primarily on experience, intuition, or on field observations of surface cracks, rather than on the mechanics of deformable bodies (Voight and Pariseau, 1970). Grond (1952) has broadly classified these earlier ideas into three categories:

1. Beam or Plate Theories
2. Arch or Dome Theories
3. Plastic and Pseudo-plastic Analyses

1.3.1 Beam or Plate Theories

The early theories of subsidence, as summarized by Adler and Sun (1976), assume the fractures to be vertical extensions to the surface from the ribsides of the opening as shown in Figure 1.3.1a. Although subsidence was recognized in Britain as early as the 15th century (Shadbolt, 1978), Belgian engineers first attempted to analyze the problem during the 1800s. Gonot (1858, 1871) defined the fractures to be normal extensions from the seam gradient. However, his hypothesis did not account for either steeply inclined seams or the angle of draw. Shultz (1867) and Sparre (1867) later suggested the breakage plane to be formed entirely by gravitational effects, with the limits of subsidence varying between the vertical and normal, depending on the overlying indicator of the mode of failure (Goodman, 1980). The latter two hypotheses are illustrated in Figures 1.3.1b and 1.3.1c.

The so-called beam theories of subsidence were suggested from studies performed by Halbaum (1905), Thiriart (1912), and Eckardt (1914) (quoted from Grond, 1953). The overburden was considered to behave as a beam (either simple or composite) which would eventually bend as a cantilever over the gob and ultimately fail, thereafter progressing through the overlying strata leaving crumbling beds in its

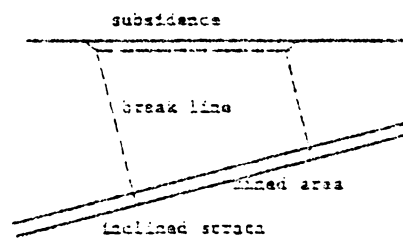
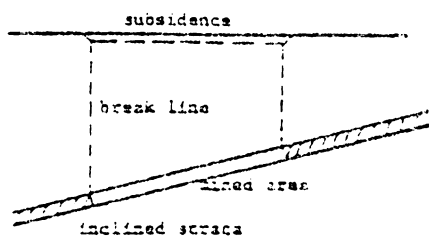
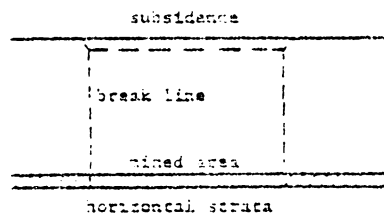
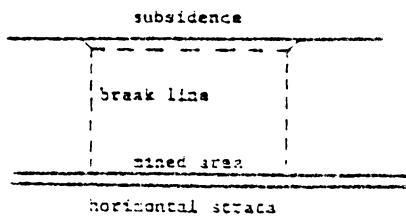


Figure 1.3.1a Vertical theory (Adler and Sun, 1976).

Figure 1.3.1b Normal theory (Adler and Sun, 1976).

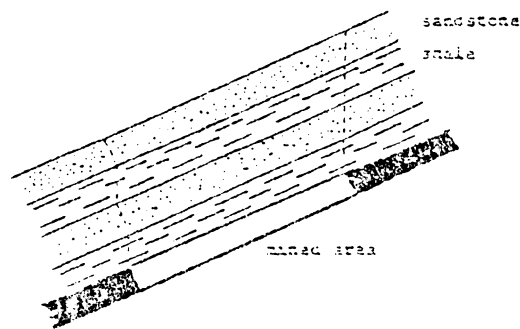


Figure 1.3.1c Schulz Theory (Adler and Sun, 1976).

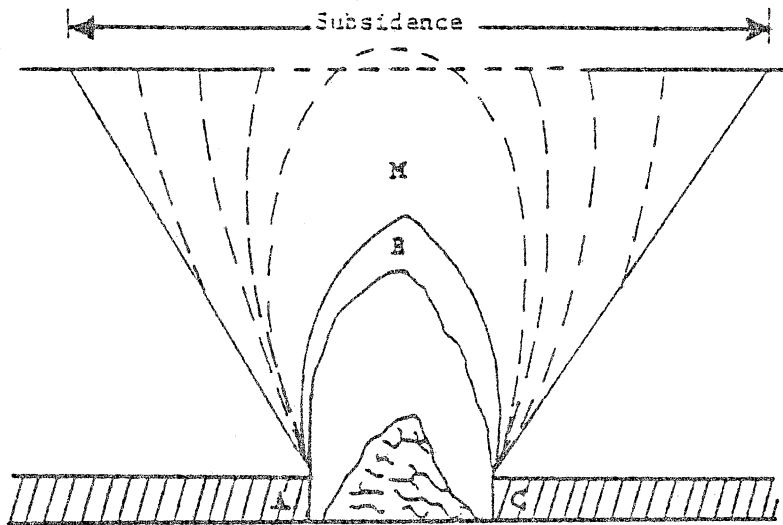
path (VPI, 1981). Afterwards, some degree of reconsolidation was believed to occur behind the face.

1.3.2 Arch or Dome Theories

The dome theory, illustrated in Figure 1.3.2a, was proposed by Rhiza (1882) to improve the earlier hypotheses. He assumed that displacements formed beyond the excavated area, with failure occurring in a parabolic shape after gravitational forces overcame cohesive forces in the immediate roof. A relaxed zone, surrounded by an area of increasing stress effects, was believed to occur next, causing the material under the arch to crumble and settle to a particular limit angle (VPI, 1981). Fayol (1885) later modified this theory by concluding that a semi-ellipsoidal dome was formed by the caving of horizontal beds (Adler and Sun, 1976). This concept is illustrated in Figure 1.3.2b.

1.3.3 Plastic and Pseudo-plastic Theories

A plastic or pseudo-plastic flow of strata into the gob, resulting from movements of the surrounding mass upwards, was another early hypothesis. Trompeter investigated this flow of strata and was probably the first engineer to describe the associative phenomenon of horizontal



ABC is an enlarging arch
 AMC is a dome of tearing

Figure 1.3.2a Rhiza's Theory (after Adler and Sun, 1976).

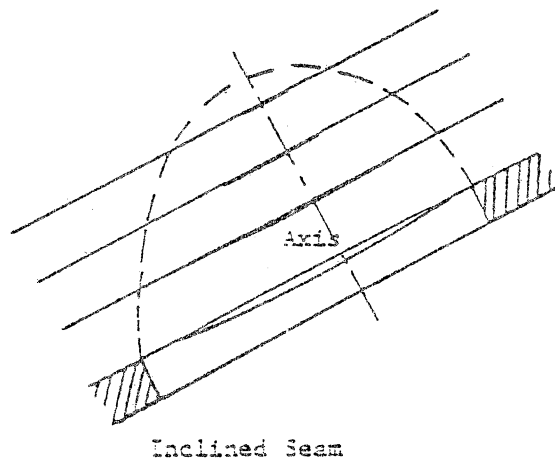
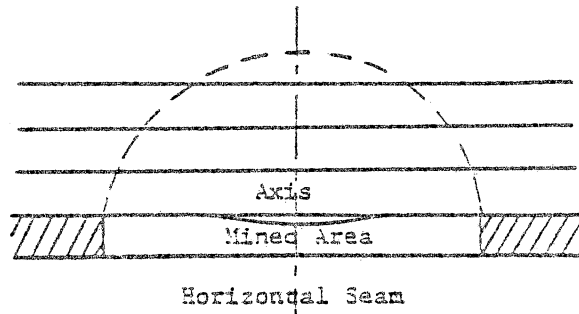


Figure 1.3.2b Fayol's Theory (after Adler and Sun, 1976).

displacements (quoted from Grond, 1953). Consequently, the term "Trompeter Zone" is commonly found in subsidence literature and is often used to define the limit of the zone of convergence.

1.4 Contemporary Subsidence Theories

Early subsidence studies were primarily concerned with defining basic principles and attempting to understand the mechanisms involved. Contemporary investigations, on the other hand, have been directed toward the development of a reliable subsidence prediction model. It is difficult to formulate such a model because of the large number of variables involved and the complex manner in which the strata overlying the excavation behave (Singh, 1978). Furthermore, subsidence may form in discontinuous steps, making the phenomenon even more difficult to control. Consequently, most prediction models refer to a relatively homogeneous mineral vein of nearly uniform thickness, a horizontal and flat surface topography, and a trough-shaped settlement.

Voight and Pariseau (1970) have divided the various approaches used to predict subsidence into two broad categories, the empirical and the phenomenological. Singh (1978) suggested that, for most engineering applications and for

flat seams, the empirical approach may provide sufficiently reliable predictions when applied to the same region. The phenomenological procedures, on the other hand, had varying degrees of success. A detailed classification of these subsidence models is given in Table VII.

1.4.1 Phenomenological Approach

The phenomenological approach was described by Voight and Pariseau (1970), as a process in which "the ground surrounding the excavation is replaced mathematically by an idealized material that deforms in accordance with the principles of continuum mechanics." Studies which utilize this approach are not as numerous as the empirical methods, and they often involve detailed mathematical derivations which lack exact descriptions of the idealized displacements (Singh, 1978).

Continuous theories assume the ground to behave as a continuous medium on the basis of traditional mathematical models of solids, i.e. the elastic, plastic, viscoelastic, and elastoplastic idealizations (VPI, 1981). Research is also currently being conducted on an elastic-plastic analysis of subsidence. The primary advantage of methods employing the principles of continuum mechanics is their wide applicability.

TABLE VII

Classification of Subsidence Prediction Methods

(Singh, 1978)

EMPIRICAL MODELS	PHENOMENOLOGICAL MODELS
<p>(1) Profile Functions (critical width)</p> <p>Knothe Exponential, 1953 Martos-Marr Exponential, 1958 VNIIMI--Trigonometric, 1958 Hoflaan--Trigonometric, 1964 Hyperbolic, 1957, 1965, 1966 British Field Data, 1966</p>	<p>(1) Elastic</p> <p>Sanford, 1954 Hackett, 1959 Berry and Sales, 1961-1963 Berry, 1963, 1964, 1969 Salamon, 1963-1964 Brown, 1968 Voight and Samuelson, 1969 Plevman, Deist and Ortlepp, 1969 Paniklor, 1970 Starfield and Crouch, 1972 Crouch, 1973</p>
<p>(2) Profile Functions (subcritical width)</p> <p>Hyperbolic, 1957 VNIIMI--Trigonometric, 1958 German Field Data, 1957, 1960 British Field Data, 1966</p>	<p>(2) Viscoelastic</p>
<p>(3) Influence Functions</p> <p>Hais, 1931-1932 Keinhorst, 1934 Beyer, 1945 Sann, 1949; Flaschentrager, 1957 Kochmanski, 1959</p>	<p>Berry, 1964 Inau, 1965 Marshall and Berry, 1967</p>
<p>(4) Stochastic Media</p> <p>Litwiniszyn et al, 1953 Richardt and Sauer, 1961 Sweet and Bogdanoff, 1965; Sweet, 1965 Schneidegger, 1966</p>	<p>(3) Plastic</p> <p>Dahl, 1967 Parisseau and Dahl, 1970</p>
	<p>(4) Elastic-Elastoplastic</p> <p>Dahl, 1972 Dahl and Choi, 1973, 1974</p>

(i) Elastic Solutions: Hackett (1959, 1964) first investigated the assumption of an elastic medium by considering the vertical direct stress around an excavation to be linearly increasing with depth, and the vertical and horizontal direct stresses being equal (Goodman, 1980). The surface displacements calculated by Hackett provided a good correlation with field-measured displacements.

Other analyses have included idealizations of two-dimensional homogeneous, isotropic, transversely isotropic, and and three-dimensional media (Berry and Sales, 1961, 1962, 1963). Each of these treatments was performed for three cases of the floor and roof closure, including nonclosure, where the two never meet; partial closure; and complete closure, where the roof and floor remain in contact over the entire width of excavation. Approximate solutions were found for assumptions of nonclosure and partial closure in a semi-infinite medium, and an exact solution was possible for complete closure (Voight and Pariseau, 1970). Subsidence determined by the isotropic medium idealization deviated considerably from the actual

field data; however, reasonable agreement was achieved for complete closure and field measurements (VPI, 1981).

Salamon (1964) and Jones and Bellamy (1973) also performed subsidence studies with elastic solutions, but their basic models were restricted for use in mines unusually deep for the United States. The idealization of an isotropic medium produced ground conditions similar to the deep hard rock mines of South Africa.

By utilizing the Fourier series, Voight and Samuelson (1969) developed a solution, based on plane strain, for homogeneous linear-elastic materials. Once again, an accurate correlation was not achieved between the model and field data.

(ii) Viscoelastic Solutions: Viscoelastic idealizations assume that final deformations which occur from subsidence, after any creep has ceased, may be estimated by using delayed elastic constants. Berry and Marshall (1969) and Imam (1965) attempted to include time as a variable in their description of mine subsidence by using the Cauchy integral theorem. Theoretical predictions based

on four parameter model representations were found to agree closely with subsidence observations in the British coalfields.

(iii) Plastic and Elastic-Plastic Solutions:

Two-dimensional plane strain laboratory models of isotropic subsiding ground were studied by assuming plastic deformations of the failure zone (Dahl, 1967; Pariseau and Dahl, 1968). From similar analyses, the overburden height-to-seam thickness ratio was determined to have a pronounced effect on the development of subsidence (VPI, 1981). Voight and Pariseau (1970) have suggested that the plastic zone about the working face, although small in volume, may have a significant influence on the final subsidence profile.

The phenomenological approach is versatile and at times it can provide information from which to categorize empirical studies. Efforts have been made--and will continue--to use computer routines related to existing theories, and to apply the finite element method as a predictive tool. Finite element solutions of elastic models presently indicate

the effects of inclined layers and topographic variations on subsidence (Voight and Pariseau, 1970). However, the complex mathematical procedures, the lack of empirical justification, and the oversimplified assumptions required have, in general, seriously limited the application of these methods.

1.4.2 Empirical Approach

Empirical methods are characterized by relatively simple mathematical formulae which are often accompanied by descriptions of the displacement mechanism involved (Voight and Pariseau, 1970). The main advantages of this approach are its simplicity and relative ease of application.

(i) Stochastic Media: Several investigators have attempted to define the fundamental relationships of subsidence by investigating the mechanism of failure as it progresses from the gob to the surface (Goodman, 1980). A variety of modeling materials have been employed for this purpose, including: solidified gelatin (King and Whetton, 1957), partially elastic material (Hoffman, 1964), sand (Pariseau and Dahl, 1968), stratified sand (Litwiniszyn, 1964; Bodziony, 1960), granulated

metal (Shalaghinov, 1963), and granulated glass (Martos, 1966). Other tests have included a photoelastic model constructed by Rankilor (1971) and a laser holographic interferometry model employed by Park et al (1977). Mechanical modeling possesses the advantage of accounting for both local geology and the geometry of the excavation, defining the most important parameters of rock which affect subsidence (Goodman, 1980). These methods have limited practical applications, however, because of the problem of realistic representation between model and prototype, thus making quantitative results difficult to obtain (Gray et al, 1976).

(ii) Profile and Influence Functions: A subsidence profile function has been described by Brauner (1978) to be:

...an equation of one-half the subsidence profile, ranging from full subsidence to zero subsidence. The subsidence is expressed in terms of full subsidence and the location of the profile points in terms of extraction depth or a proportional quantity. In case of supercritical extraction, the central region of the trough has the constant subsidence S_{max} . In case of subcritical extraction, the particular subcritical profile is determined from the critical

profile by using certain empirical and/or mathematical relations. The method is normally restricted to rectangular extraction areas in which the profile coincides with the centerline.

A variety of profile functions have been developed for the different coal fields of the world, including mines in Upper Silesia, Hungary, and the Soviet Union (Donets coal fields) (Brauner, 1973). Hyperbolic functions, based on both model and theoretical investigations, have also been suggested to describe subsidence (Brauner, 1973).

The profile functions most commonly used are the error integral form, employed with good success in Poland, and the trigonometric form well-utilized in the Russian coal fields (Munson and Eichfeld, 1980). Profile functions are commonly expressed as a function of the following parameters:

$$S(x) = f (B, s, S_{max}, d).$$

From Figure 1.4.1, B is shown to be one-half the critical radius, S_{max} is the full subsidence and d is the length between the point of half-maximum subsidence and the ribside. The subsidence is

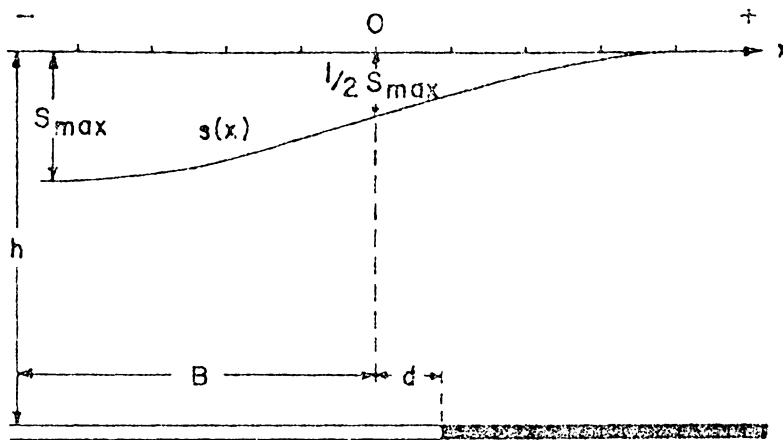


Figure 1.4.1 Subsidence Profile Function
(after Brauner, 1973).

generally expressed in terms of maximum settlement and the location of the profile points in terms of the extraction depth. The function $S(x)$ may be derived from analyses of field or model investigations.

In utilizing influence functions, it is assumed that an excavated opening can be divided into a finite number of small openings. Each one of the elemental openings is assumed to produce a subsidence basin, with the total sum equalling full subsidence of the trough (Peng, 1978). An element directly underneath a surface point has a greater influence on subsidence than does one on the edge. This analysis places no geometric limitations on the opening shape. The influence p , on a point P , is defined to be a function of the horizontal distance, r , between P and an element dA , or:

$$p = f(r).$$

The complete area under the curve, as illustrated in Figure 1.4.2, represents the value of S_{max} .

The influence function methods have been developed primarily for the Central European coal

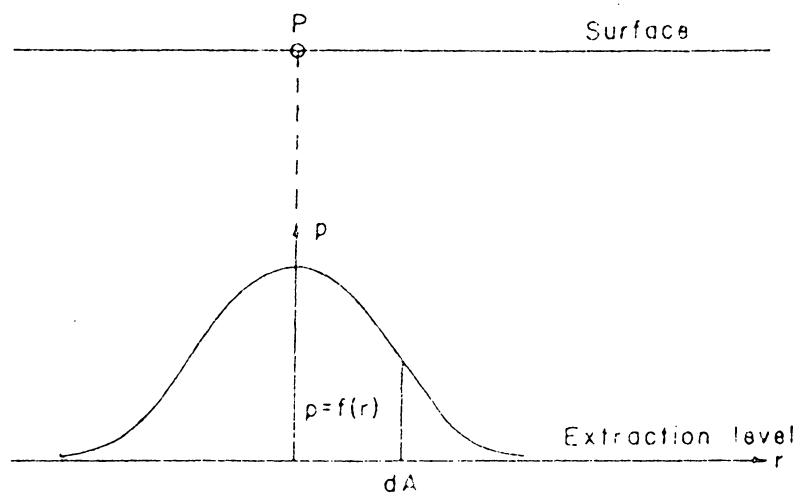


Figure 1.4.2 Influence Function (after Brauner, 1973).

fields, with the original work being accredited to German and Dutch engineers. These equations have been developed from experience in certain areas and/or from mathematical considerations. Brauner (1973) has described six of these functions and mentioned that others have been cited in literature.

The zone area method was originally designed to predict subsidence over non-regular longwall or room-and-pillar panels in the British coal fields, where the Subsidence Engineers Handbook was found to be inadequate. To apply the zone area system of analysis, the influence area is divided into a series of annular rings. Seven concentric circles were found to be the optimum number of zones to establish around the surface point of investigation, because five zones provided a lower accuracy and more than seven increased the necessary computations (Goodman, 1980). The area of influence for a surface point, P, is defined as a circular zone with radius 0.7 times the depth of the seam, as illustrated in Figure 1.4.3. This radius was established for British conditions with an average angle of draw of 35 degrees. To determine the

subsidence (as a percent of extraction) for the point P, the relative extracted area of each ring is found and multiplied by its respective ring factor. This procedure is continued for each ring and the resulting values are summed to provide the full subsidence.

By utilizing this system of analysis, Marr (1975) was able to predict subsidence for uniform and non-uniform extraction in the British coal fields. He also devised a reduction system by employing five zones to account for the effect of coal pillars on the final subsidence.

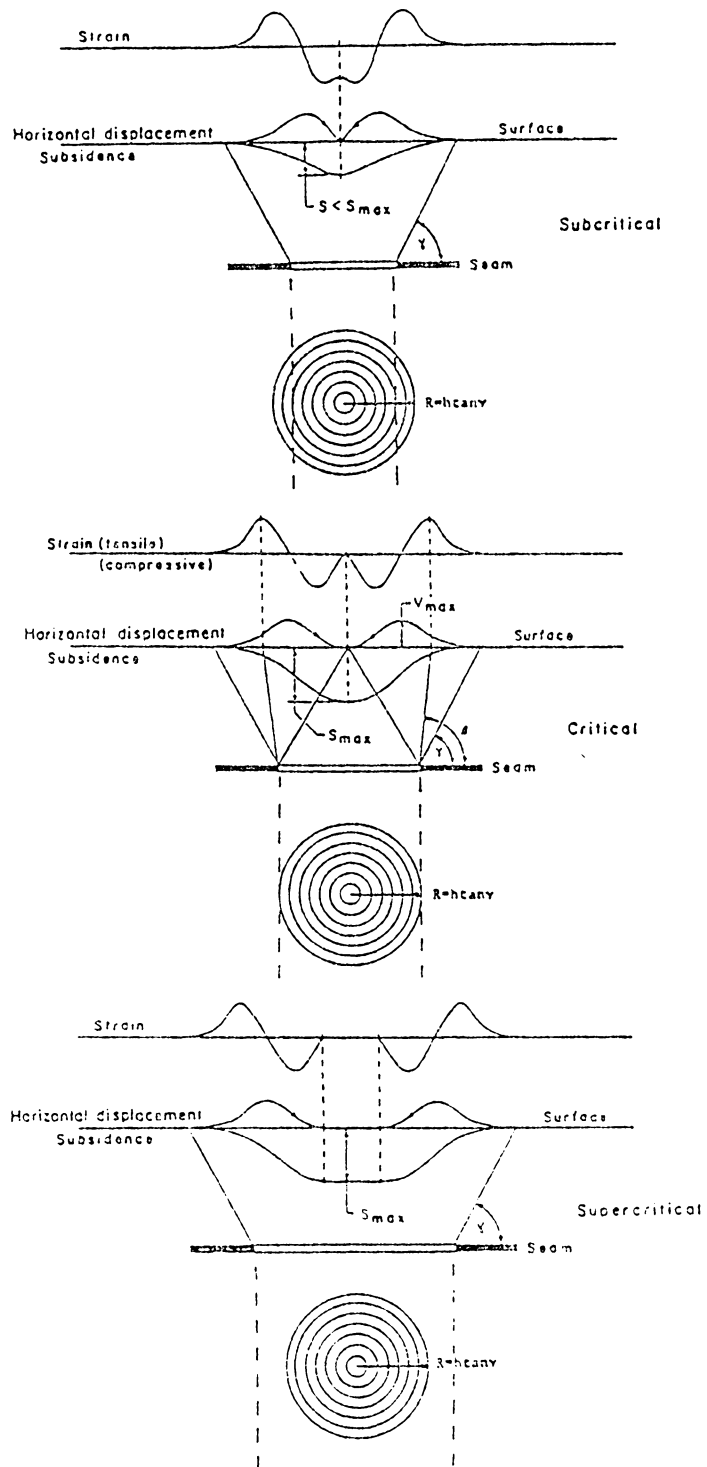


Figure 1.4.3 The Zone Area Method

Chapter II

DEVELOPING A SUBSIDENCE PREDICTION PLAN FOR U.S. MINING CONDITIONS

2.1 Selection of Prediction Method

All methods of subsidence prediction present certain advantages and disadvantages. Models employing the phenomenological approach have often proven to be difficult to apply in practice and require many assumptions and input parameters before they can be employed with any degree of accuracy. Empirical methods are generally more indicative of actual field data, but only for specific areas. The mechanical similitude required for stochastic models is the major drawback of this approach. Profile functions are expected to produce fairly accurate results for geometrically simple problems, but extension to more complex situations does not usually provide accurate results. Brauner (1973) has suggested that profile functions are capable of handling only three-dimensional problems to a limited extent, with further mathematical analysis often required. Influence functions have provided a basis for the zone area system, which is a subsidence prediction method adaptable to computer programming. However, this system was originally developed from information pertaining to the Midlands and Yorkshire Coal Fields of the United Kingdom (Marr, 1975).

Other disadvantages encountered with the use of profile functions are: (a) it is not necessary to extrapolate from previous subsidence data in any given area of application, i.e., the previous data must describe quantitatively the relationships between mine geometry and surface effects; (b) secondary subsidence is not predicted, which is otherwise known as the time dependent portion of the settlement; and (c) it is not possible to assess potential subsidence effects on aquifers (U.S. Dept of Energy, 1979).

The Subsidence Engineers' Handbook, compiled by the British National Coal Board, was developed on the principles of influence functions. Over 157 case studies of various dimensions were collected from the British coal fields to analyze subsidence. The handbook presents the results of these analyses in a series of graphs which are used to predict a subsidence profile by input of geometrical parameters of the panel. Because of the relative ease of its application, the handbook is widely used in the United States to predict the magnitude and extent of subsidence damage. However, such graphical procedures have resulted in overpredictions of both the maximum subsidence and its limits (Gentry and Abel, 1978; Goodman, 1980). This error is best attributed to the inherent differences of regional geology, mining methods, and stratigraphy between the United Kingdom and the domestic coalfields.

Compared to Britain, very little subsidence information has been collected in the U.S. Subsidence research was initiated in this country in the early 1900s (Young and Stoek, 1916; Herbert and Rutledge, 1927). Such studies, however, were not systematic, and until the sixties very little attention was given to this problem. Then, investigations of subsidence resumed in an attempt to collect data for validating methods (Imam, 1965; Dahl, et al, 1971, 1973, 1974). In addition, several coal companies were then in the process of monitoring surface displacements. The latter studies are mostly unpublished.

It was not until the late seventies that concentrated attempts were made to correlate existing studies with empirical data collected from mines in the same general area. The United States Bureau of Mines and Department of Energy were the main sponsors of a subsidence collection and monitoring process from private industry (USBM, 1976, 1977, 1979; Howell et al, 1976; Gentry, 1977; Agarwal and Mayer, 1979). Case studies were gathered from longwall panels in Illinois (Conroy, 1979), West Virginia (Kohli et al, 1980), Ohio (Peng et al, 1980), and New Mexico (Gentry et al, 1978). These studies attempted to correlate subsidence characteristics with data from other panels, but the results have not yet been fully evaluated (Goodman, 1980).

During this research, an effort was undertaken to accumulate published as well as unpublished information on subsidence in this country and to establish a subsidence data bank. Furthermore, it was decided that the development of an empirical prediction approach, similar to the British but based on the information from own domestic conditions, could prove invaluable to coal operators.

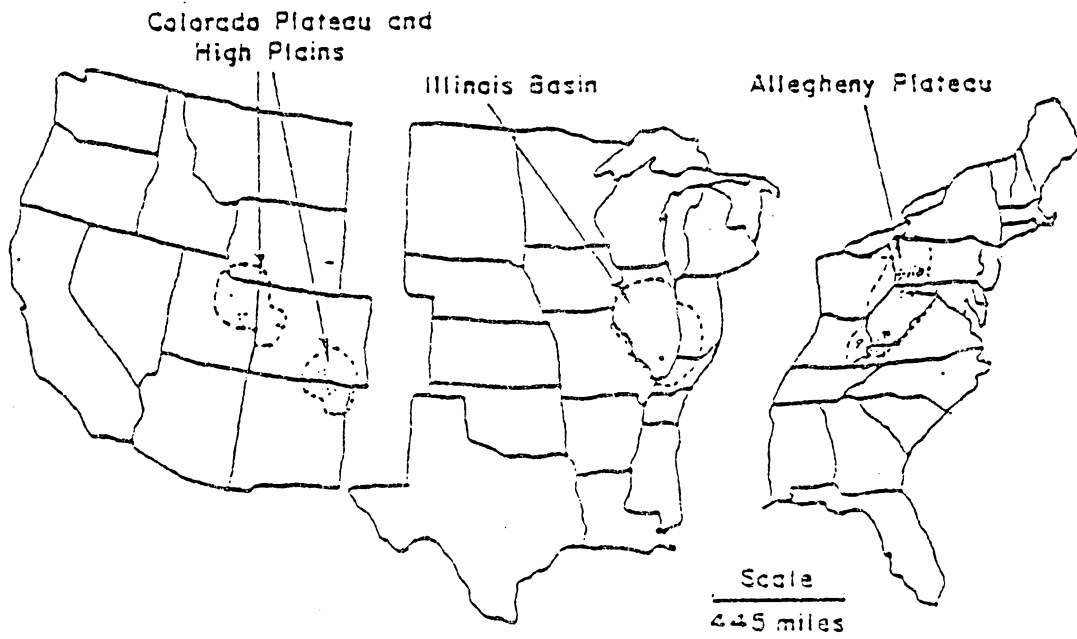
2.2 Regional Characteristics of Subsidence

Longwall mining currently accounts for approximately 7 per cent of United States coal production and continues to increase steadily. The main areas of longwall concentration are shown in Figure 2.2.1. This is a regionalization scheme which has been suggested by O'Rourke and Turner (1979) on the basis of the major physiographic and structural characteristics of the longwall mining areas. The three geographic regions are divided as follows:

- i) Allegheny Plateau: includes parts of Pennsylvania, Ohio, West Virginia, Virginia, Maryland, and Kentucky
- ii) Illinois Basin: includes most of Illinois and parts of Indiana and Kentucky
- iii) Colorado Plateau and High Plains: includes parts of Colorado, Utah, New Mexico, and Wyoming

A major part of native longwall activity is currently undertaken in the Allegheny Plateau, and consequently, a great deal of attention was focused in that region.

Figure 2.2.2 shows the location of coal mines in Great Britain, from which information was gathered to develop the Subsidence Engineers' Handbook. The narrow geographical boundary of these mines, similar in area to the coal mining region of the Allegheny Plateau, is referred to as the York-



Legend:

• site of coal mine

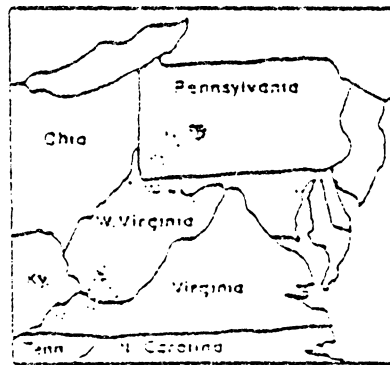


Figure 2.2.1 Location of Longwall Coal Mines in the United States (O'Rourke and Turner, 1979).

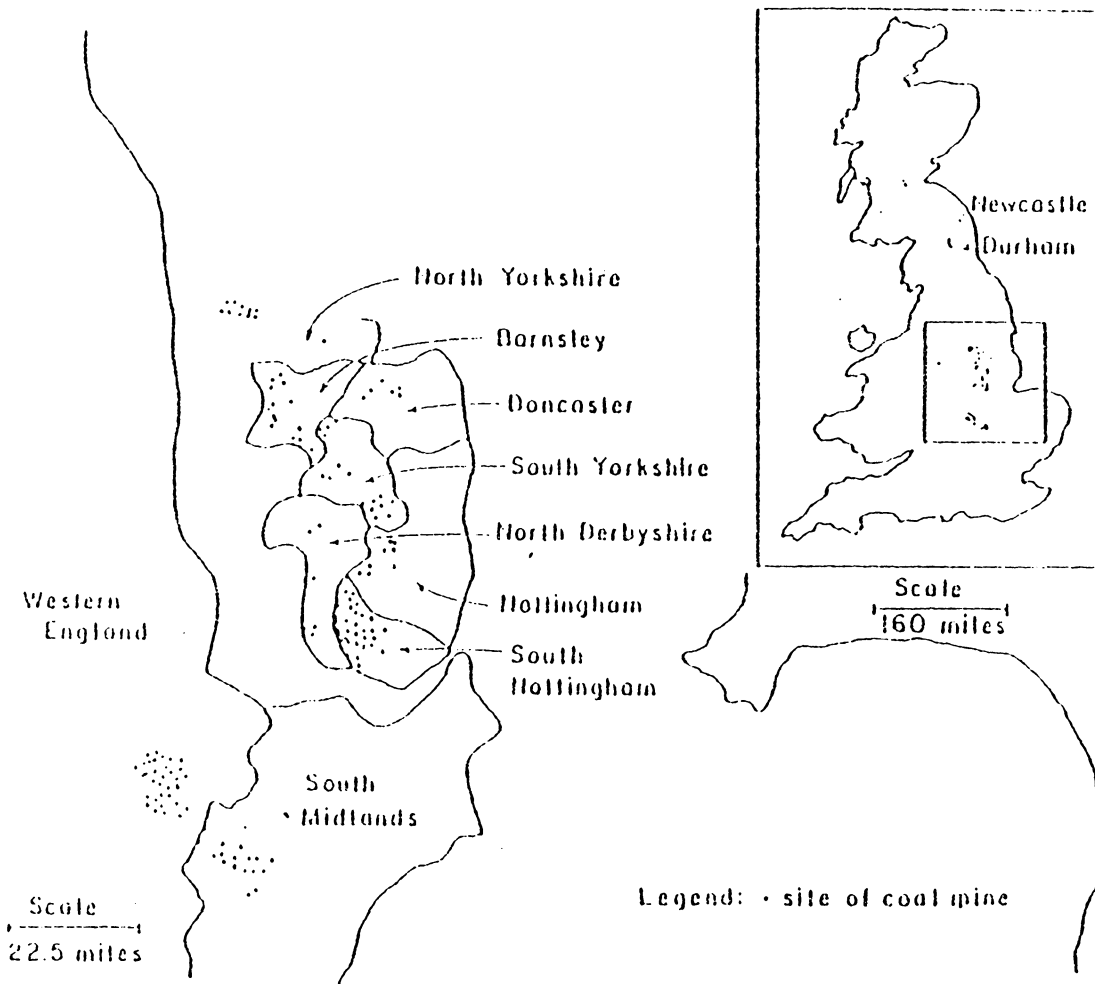


Figure 2.2.2 Location of Coal Mines Associated with HCB Case Histories of Subsidence (O'Rourke and Turner, 1979).

shire and Midlands Coalfields. The major coalbearing rocks are referred to as the Coal Measures. Approximately 98 per cent of the British field data was collected from the mines of this area, which possess similar geology, topography, and extent of previous workings.

O'Rourke and Turner (1979) have compared the regional geologic trends and lithologic characteristics of longwall mining panels in the United Kingdom and the United States with respect to four principal characteristics: a) the lithologic proportions in typical stratigraphic sequences of each region b) the regional structure, c) in-situ stresses, and d) topography. These properties have been found to differ significantly between the two countries.

2.2.1 Lithologic Proportions

The Coal Measures of the United Kingdom are generally composed of at least 75 per cent argillaceous or "soft rocks," i.e., shales, mudstones, siltstones, and underclays (Bell, 1975). The underclays, which vary in thickness from approximately 2 to 6 feet, are commonly found beneath the coal seams. The presence of typical "hard rocks", such as limestone or sandstone beds is not common: however, the immediate roofs in the area are occasionally composed of thick

sandstone layers. The sandstones beds are generally inconsistent in shape and thickness.

The Illinois Basin possesses stratigraphy comparable to that found in the United Kingdom. Shales commonly comprise as much as 70 percent of the overburden in this area, with thicknesses of around 30 feet being common. The underclays are generally 2 to 5 feet thick. Sandstone beds are scarce and usually occur as channel deposits, while limestone layers may make up as much as 10 percent of the coal-bearing strata.

The geology of the Allegheny Plateau is difficult to generalize, being relatively complex in nature (O'Rourke and Turner, 1979). The Pittsburgh seam, which is the most extensively mined coalbed of this region, is often used as a basis for comparison. Many lithologic variations exist in the coal-bearing strata of the Allegheny Plateau; however, the lower part of the overburden typically contains a calcareous type of rock, with the upper part containing a higher percentage of sandstone and limestone. It is common for as much as 50 or 60 percent of the strata above a mine to be composed of these hard beds. Referring to the geology of the Appalachian Region, O'Rourke and Turner (1979) suggested that:

...the typically high percentage of thick, competent sandstones and limestones and the

presence of high in-situ horizontal stresses are most likely to result in caving and ground movement propagation that will differ significantly from the well-established patterns developed on the basis of British experience.

Mining is performed in strata of Cretaceous age in the Colorado Plateau and High Plains Region, while the other two major mining regions possess strata of Pennsylvanian age. The York Canyon Mine provided data for a much-publicized case study of the Western region. The stratigraphy of this test panel is complex, consisting of many thin layers of sandstone, siltstone, and shale (Gentry and Abel, 1978). Sandstone channel deposits are occasionally found in the overburden, and rapid variations in the lithology are quite common. Sandstone is the strongest rock present in the sequence, often comprising about 30 per cent of the strata. A thin shale layer is usually found below the coal seam, with an average thickness of 1 foot.

2.2.2 Regional Structure

The Coal Measures demonstrate the influence of mountain building activity due to the presence of much folding and faulting. The strata of this region generally dip slightly to the east, with the presence of several small anticlines being common. The Measures were at one time in-

tensely eroded and subjected to at least two periods of glaciation (O'Rourke and Turner, 1981).

The Illinois Basin has several anticlinal belts inside a large area of trough-shaped sedimentary strata. The similarities between the Illinois and British Coal Measures are numerous. Both have developed primarily from mountain building activity during the same era, with the folds and faults present being roughly equal in intensity. Both regions have also endured spans of intense erosion and glaciation.

The Pittsburgh seam of the Allegheny Plateau is part of the Monongahela Group and occurs in a sedimentary basin. Most of the strata in this area have been subjected to folding, and as a result, there is a series of anticlines and synclines in the area. The seam generally grows larger near the synclinal troughs and thins at the anticlinal apices (O'Rourke and Turner, 1979).

Faulting and folding near the York Canyon Mine test panel exhibited normal amounts of displacement and have not adversely affected the immediate roof. Two primary fault orientations were discovered.

2.2.3 In-Situ Stresses

Recording of in-situ rock stresses has not been a standard procedure in the United Kingdom (Brown and Hoek, 1978). Pasamehmetoglu (1973) suggested 0.25 to be the ratio of horizontal to vertical stress of the eastern Coal Measures; however, this value is not fully compatible with the geologic history of the region (O'Rourke and Turner, 1979).

Few in-situ stress measurements are available from either the Illinois Basin or the Colorado Plateau and High Plains regions. Erosion of coal-producing rocks during the early Mesozoic era is believed to have resulted in relatively high horizontal stresses for the Illinois Basin (Damberger, 1977; Willman, 1975). Mining depths of 500 to 700 feet in this region have been estimated to possess in-situ horizontal to vertical stress ratios of approximately 1.5 (Ganow, 1975).

In-situ stresses have been well documented for the Allegheny Plateau. Horizontal stresses as high as 3,240 psi have reportedly caused rock failures of the immediate roof, as well as floor heave problems, for many of the mines in this region (Aggson, 1979; Dahl and Parsons, 1971).

2.2.4 Topography

With the possible exception of the Illinois Basin, the surface slope of coal mines in the United States is more rugged than that encountered in the British coal fields. The topography of the Midlands and Yorkshire Coalfields generally varies from gently rolling to rolling, while surface slopes of the Illinois Basin range from flat-lying to rolling (O'Rourke and Turner, 1979). Soil deposits anywhere between 10 to 50 feet in depth may be found above the Coal Measures, while the drift in the coal mining areas of Illinois is usually more than 50 feet. The surface slope of the Allegheny Plateau varies from extremely mountainous to undulating, with the relief above a longwall panel commonly varying by as much as 200 feet (O'Rourke and Turner, 1979). The York Canyon Mine has a rapid topographic variation along the panel's centerline. The slope in this area is very steep, and the terrain is rough and mountainous (Gentry and Abel, 1978).

2.3 Procedures

A combined approach, utilizing both empirical and analytical methods of subsidence investigation, was adopted for this research effort. The collected case studies, although not as numerous as those used by the NCB, were never-

theless sufficient to allow the development of significant trends.

The initial stage of the program involved the collection of subsidence data from literature as well as from unpublished sources. To implement this, many coal companies and federal agencies were contacted. Their response was very encouraging. Because of the importance of the Appalachian coalfield and its proximity to Virginia Tech, much effort was concentrated in that area. The data bank established for Appalachia is comprised of 34 subsidence case studies and is perhaps the most comprehensive in the country.

The subsidence information was processed and analyzed to evaluate the influence of the various parameters. The analyses include: (a) studying profiles of vertical displacement at various locations along the panel, (b) studying the time-dependent portion and development of subsidence along the length of a panel, and (c) determining the nature of geologic influence on the surface settlement. It was thus possible to establish regional subsidence trends which could be subsequently utilized to develop a subsidence prediction model for the Appalachian coalfield.

Chapter III

DEVELOPMENT OF A SUBSIDENCE DATA BANK

3.1 Collection of Data

Three primary sources were considered during the development of the subsidence data bank for the United States: (a) literature, (b) private industry, and (c) government agencies. An extensive literature survey was performed to gather all relevant publications, which resulted in the collection of eleven subsidence monitoring investigations (Ade-mak and Jeran, 1980; Choi and McCain, 1979; Schonfeldt et al, 1980; Greenwald et al, 1937; Maize and Greenwald, 1939; Maize et al, 1940; Maize et al, 1941; and, Montz and Norris, 1930).

The form letter, shown in Appendix A, was distributed to numerous mining companies and government agencies to request information pertaining to this research effort. The response was very successful and at the end of approximately 10 months, subsidence measurements taken above 34 longwall panels had been collected from the Allegheny Plateau coal-fields, including 23 unpublished and 11 published case studies. This is one of the most comprehensive subsidence data banks currently known for the United States mining conditions.

The study of subsidence above room-and-pillar mines will be conducted at a later date; therefore, any data pertaining to this mining method was omitted from the investigation. Two other surveys gathered from industry were also eliminated due to poor or incomplete field measurements.

Approximate geographic locations of the mines providing data for this research are shown in Figure 3.1.1. The regions are highlighted by a shaded area, instead of specific points, due to the proprietary nature of most of the information. Fourteen subsidence studies were gathered from southern Pennsylvania, nine from the northern West Virginia coalfields, four from eastern Ohio, two each from southern West Virginia and northern Alabama, while only one was from Virginia. A single case study was found in literature from each of the other two major regions, these being the Old Ben Mine in Illinois, and the York Canyon Mine in New Mexico (Conroy 1979; Gentry and Abel, 1978). As a result, the emphasis of this study was on data from the Allegheny Plateau Region.

All of the panels were referenced by a numerical system throughout this study, and in the occurrence of more than one panel in the same mine, an alpha-numeric system was used. For example, an excavation positioned in virgin territory was called Case 4, whereas two individual panels lo-

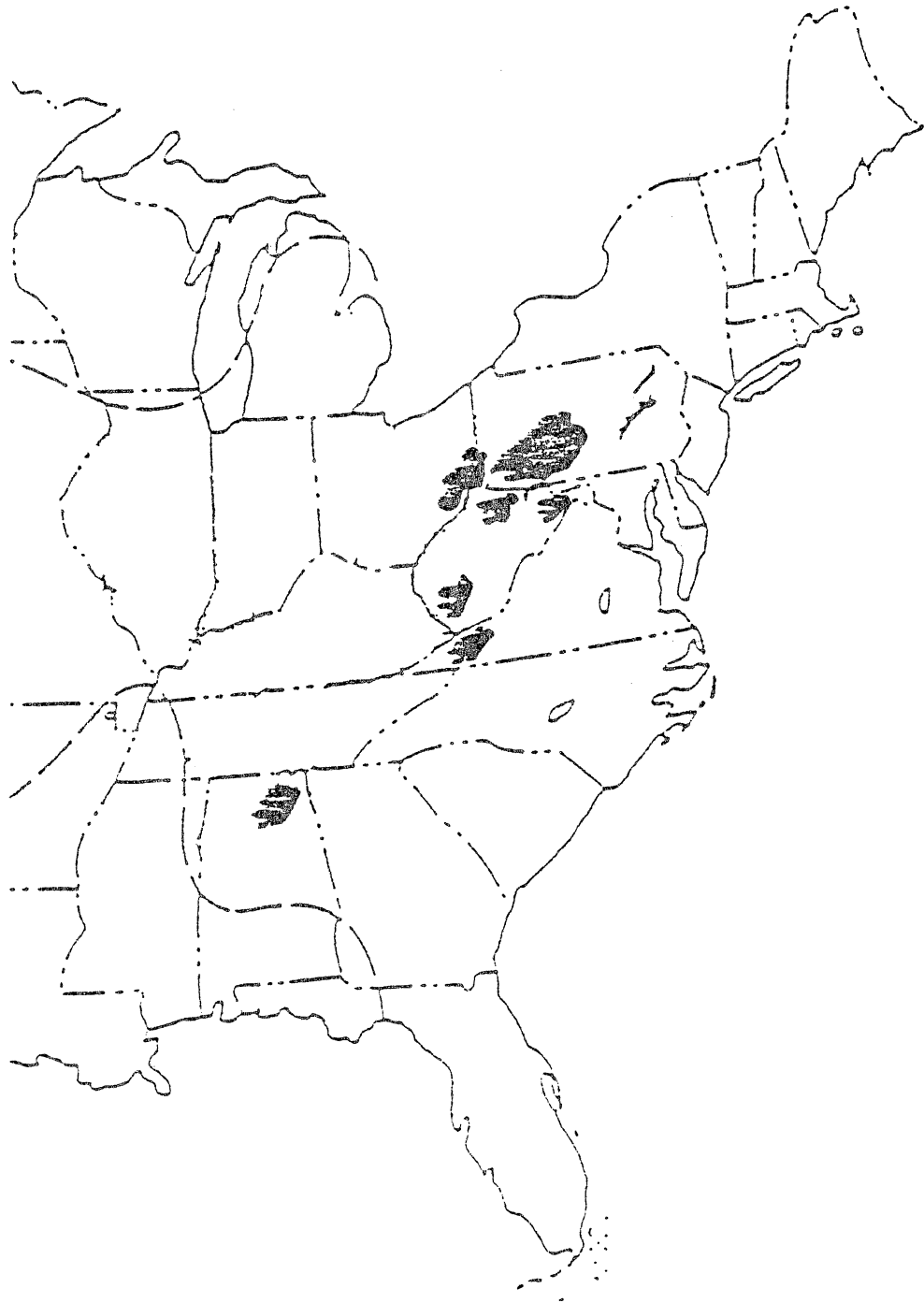


Figure 3.1.1 Location of the case studies.

cated adjacently or in the same mine were termed Case 4a and Case 4b. This system explains why the largest number assigned to a panel was 23 although there were a total of 34 panels.

The subsidence data do not include any cases with more than four panels from the same mine. Nineteen of the case studies involved the presence of adjacent panels; however, in most instances either the subsidence had been monitored before mining began on the second panel or one side of the excavation was located next to virgin territory. Consequently, the angle of draw and the maximum subsidence could be determined from an unbiased profile for the majority of the panels.

The case studies collected from literature did not include the raw subsidence data, but often did include some or all of the following information: (a) geographic locations, (b) diagrams of the panels (including dimensions and survey monument layouts), (c) geologic columns, (d) surface contours, and (e) subsidence, development, and/or travelling subsidence profiles. Data gathered from government and industry did include tables listing the displaced surface values. Every attempt was made to analyze the raw data consistently; however, there was obviously no control on the method used to process data from the published studies.

Therefore, appropriate references were included on all tables and figures to distinguish between data analyzed by outside sources and those analyzed in this study.

During collection of the subsidence information, each company was requested to supply diagrams of the panel being monitored, showing width, dimensions of the support pillars, and positions of the survey monuments. Many of the maps were poor in quality due to excessive copying and reducing, often making it difficult to determine the direction of face advance and other characteristics of the panel. One very difficult and time-consuming task was pinpointing the location of the mining face during the time of a particular survey. In most cases, however, it was possible to establish the approximate beginning and final dates of extraction.

The most common method of recording surface displacements is shown in Appendix B. This is a survey sheet which contains the titles of the measuring stations in the far left-hand column and the dates that the surveys were performed in the top row. The column entitled "Face Distance" indicates the position of the face with respect to the monument line, at the time of the study. A negative subsidence value means that there was downward movement of the surface point measured, while a positive sign indicates that the monument was subjected to some degree of uplift. Descrip-

tive information is included at the top of the subsidence sheet, including the name of the mine, the name or number of the longwall panel, and the total number of survey sheets used in the study.

3.2 Measuring Systems

Panek (1970) has stated that:

The ultimate goal of measuring subsidence is to develop a rational basis for predicting the magnitudes and locations of the significant subsidence components that occur as a consequence of subsurface mineral extraction... Accurate prediction or evaluation of subsidence components requires measurement of these components for a range of values of the parameters that specify the extraction geometry and the geological structure.

Rules governing the measurement of subsidence are relatively simple, with common surveying techniques generally being sufficient to determine the geometric displacements. Steel or wooden rods driven into the ground are generally adequate for survey monuments, provided no severe temperature changes are expected to affect the ground during the survey period (Peng, 1978). Under extreme conditions, there are methods available to position the monuments more securely (Panek, 1970). The frequency and quantity of surveys conducted is dependent upon the volume of material removed and the objectives of the individual study.

An initial survey would ideally be conducted in advance of mining to avoid problems with the interpretation of data. A final study should continue to monitor the time-dependent portion of subsidence after extraction has been completed. Panek (1970) has suggested guidelines for the frequency, quantity, and type of subsidence survey to be performed for a particular mining situation. Figure 3.2.1 illustrates one method of positioning the monuments above a longwall panel to obtain thorough measurements of the surface displacements. The survey stations have been established in both transverse and longitudinal directions above the panel and extend well beyond the ribsides. This was necessary to provide information for determination of the area of influence, stationary profiles, and non-stationary profiles. The observation points, denoted by the capital letters A, B, and C, need to be located in an area that will not be influenced by the subsurface extraction.

The subsidence surveys conducted for each case study were performed by company personnel. Whenever possible, interviews were held with these individuals to determine which survey procedures were used. Most of the monuments were either steel or wooden rods, anchored into the ground and surveyed with acceptable precision. Because all of the measurements were taken prior to this investigation, no

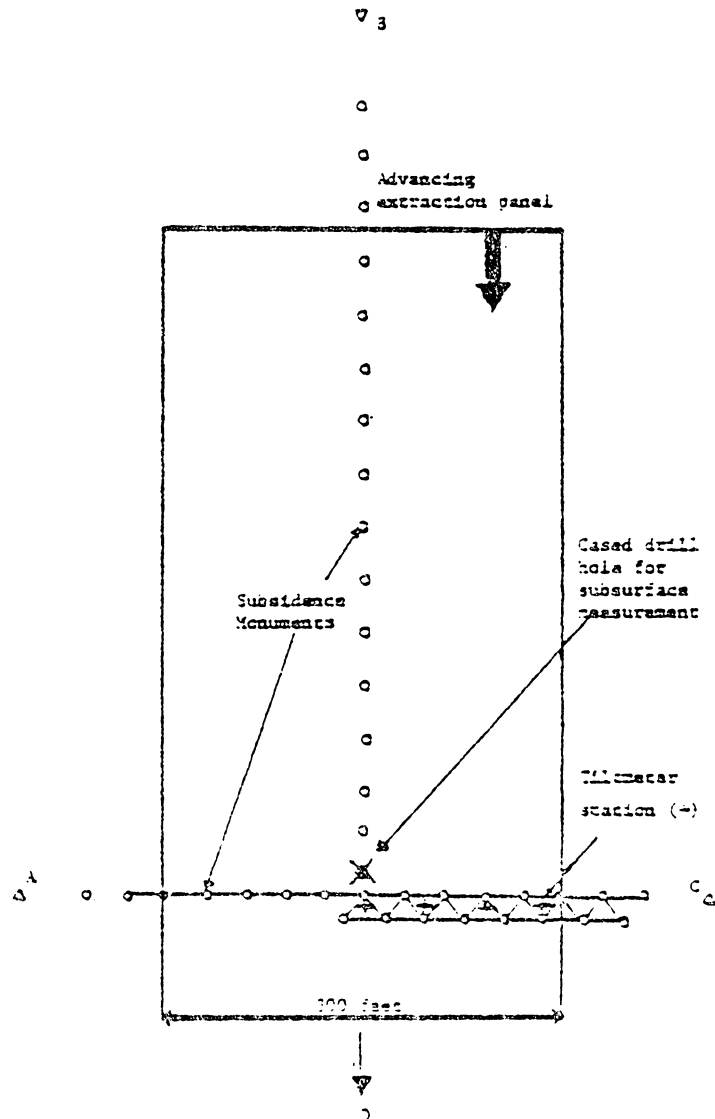


Figure 3.2.1 Example of surface subsidence measurement. Observation points A,B; reference points C, D (Panek, 1970).

guidelines could be placed on the procedure employed to obtain or record the displaced surface values. Therefore, the raw data was thoroughly scrutinized to eliminate questionable data points and possible surveying errors.

The survey monuments in most case studies were found to be positioned in one of four patterns: (1) transverse placement, i.e. parallel to the face line, (b) longitudinal placement on the panel, i.e. perpendicular to the face line, (c) a placement in proximity of surface structures, or (d) combinations of the aforementioned. The transverse monument layout was the most common type of subsidence survey conducted since this data provides sufficient information to plot a static subsidence profile. Assuming that the longwall extraction is of critical dimensions, the maximum subsidence and the limit angle of the panel may then be determined. In addition to a typical transverse pattern, eleven of the panels placed their survey monuments in a longitudinal direction above the panel. This type of configuration permits subsidence profiles along the face advance and graphs of the subsidence development to be plotted.

The remaining studies monitored subsidence near, or on, surface structures, railroads, or streams located above the longwall panels. Only three of the case studies obtained

measurements both transversely and longitudinally over the panel and also around a surface feature. Figure 3.2.2 demonstrates this most complex type of monument layout.

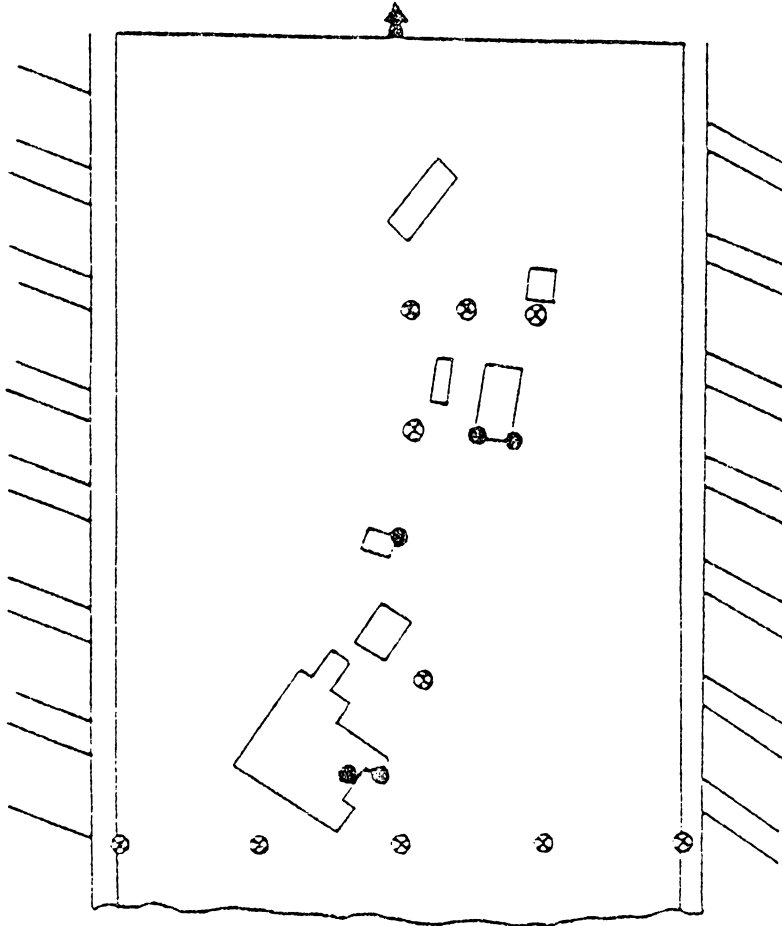


Figure 3.2.2 Map of longwall panel showing survey monuments positioned in both transverse and longitudinal directions, and also about the surface structures.

3.3 Geologic Information

The influence of geologic parameters on subsidence is an important concept in the analysis of subsidence data for the domestic coalfields. Therefore, emphasis was placed on the collection of topographic information and drill cores representative of each of the panels. Because mining companies require many drill cores and maps of the mine site during their exploration process, the geologic information made available was generally more than adequate. The drill logs were analyzed to determine the seam depth and thicknesses of the individual strata. Figure 3.3.1 illustrates a typical drill log from which the calculations were made.

Three factors greatly influence the subsidence characteristics of a given area:

- lithologic characteristics of the overburden, i.e. percentages of shale, sandstone, and limestone,
- relative position of strong or soft beds above the coal seam, and
- thickness of the above formations.

As mentioned previously, the principal lithologies common to the Allegheny Plateau coal-bearing strata are shale, sand-

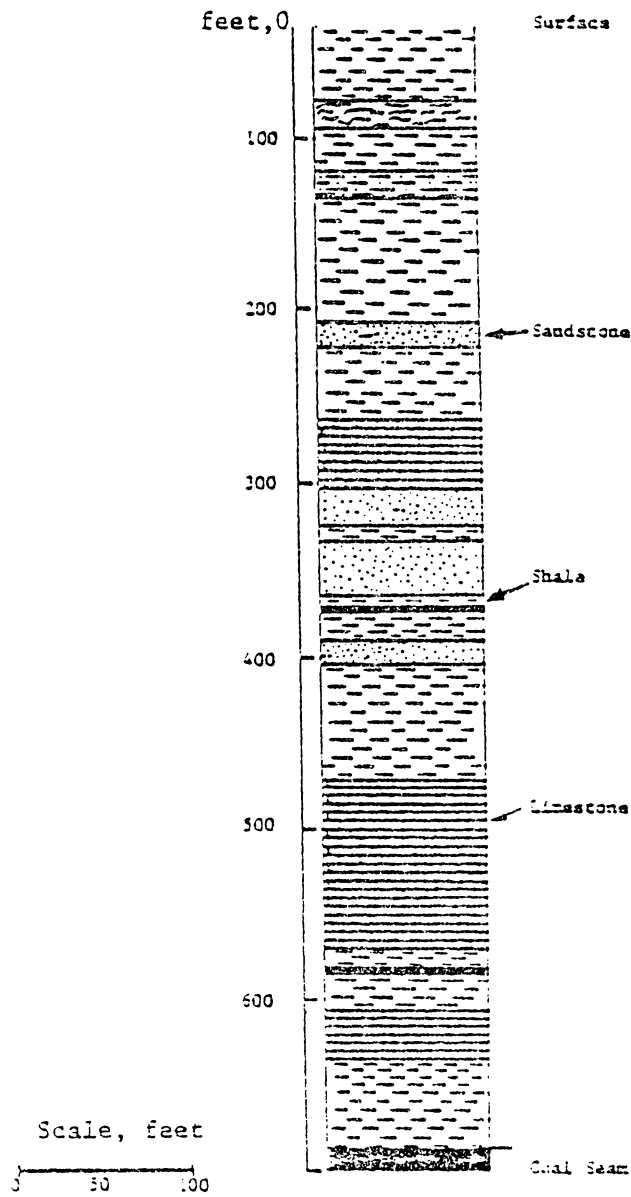


Figure 3.3.1 Typical drill log of northern West Virginia mine.

stone, and limestone. Therefore, these were the rock types chosen to study.

Calculations were made to determine the percent of each of the three rock types present in the overlying strata; these values were used to determine the influence of lithology on the maximum subsidence factor and the angle of draw. In order to implement this, the overlying strata was divided into two groups. The sandstone and limestone layers had a similar effect upon the subsidence and were, therefore, classified together and termed "hardrock". The thicknesses of the shale layers were summed with other soft strata, such as bone, fireclay, and coal, and appropriately termed "softrock". These distinctions were made throughout this analysis.

Plots of the lithology as a function of the maximum subsidence factor included data from every case study. The scatter and range of the points were large; this was attributed to the inclusion of subcritical data not representing the maximum possible subsidence of the panel. Thereafter, the subcritical data was omitted from the plots and more statistically conclusive graphs were obtained.

3.4 Developing the Subsidence Information

Stationary and dynamic profiles are associated with subsidence. Munson and Eichfeld (1980) have defined the stationary profiles to include: (a) transverse profiles over the rib side, which are at right angles to the direction of face advance, (b) longitudinal profiles at the beginning of the panel, parallel to the direction of face advance, and (c) longitudinal profiles at the end of the panel. Travelling profiles are said to encompass: (a) the draw occurring over the solid ahead of the advancing face (Sinclair, 1963), and (b) development profiles which describe the motion of a surface point over the panel as the face advances underneath and beyond it (Munson and Eichfeld, 1980).

The transverse profile is the most common subsidence plot because three important parameters--the maximum subsidence value, the offset of the inflection point from the ribside, and the angle of draw--may easily be determined from this diagram. The transverse profiles were plotted for each panel. The primary consideration in their construction was selecting data from a survey conducted during or after the monuments were in an area of critical extraction, or if this was not possible the point of maximum subsidence. Care was also taken to avoid the influence of previously mined areas.

- Maximum Subsidence: The maximum subsidence values of different panels are of significance in research; therefore, it is necessary to plot a transverse profile containing the largest subsidence above the panel. If the panel is subcritical, this subsidence value will not be representative of the maximum subsidence possible for the excavation. If the extraction is critical or supercritical, this value will be equal to the full subsidence of the panel. Before subsidence characteristics from two panels may be validly compared, they must be representative of critical dimensions. Otherwise, the value obtained from the subcritical panel will appear comparatively low. The same reasoning applies to comparisons made between subsidence values obtained from the same panel.

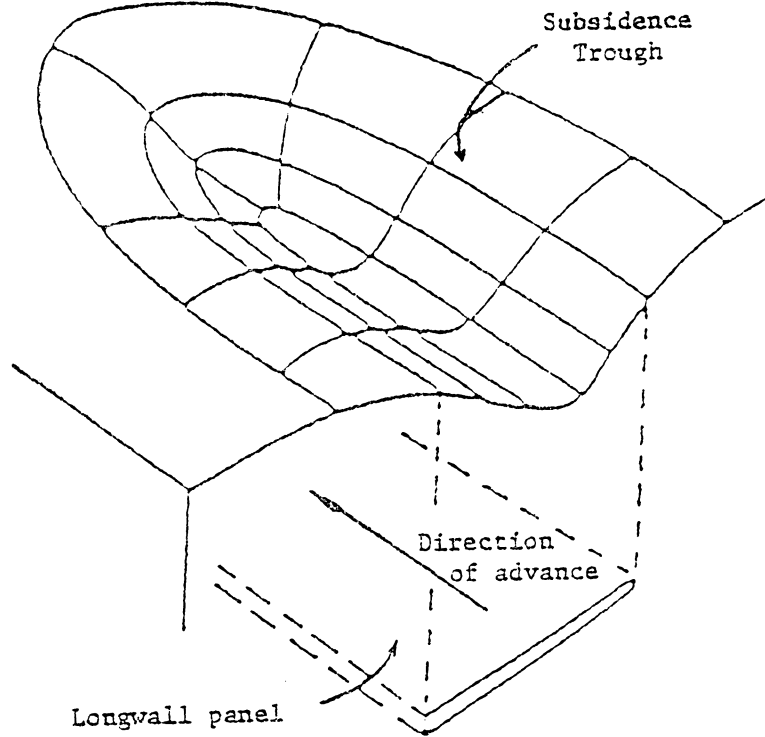
In several cases it was not possible to plot a transverse profile containing the largest vertical surface displacement. This was either due to either poor positioning of the monuments or insufficient data. In these cases the maximum settlement would occur at a surface point on the longitudinal survey line above a panel, instead of a transverse line. In order to determine whether the larger value was actually more critical or merely the result of a survey error, the longitudinal profile was also drawn. The largest difference found between the two maximum values was 0.6

feet, which corresponds to a subsidence factor variation of 9 percent.

Once a panel has undergone critical extraction, the maximum subsidence will be approximately equal for either a longitudinal or a transverse profile. This concept is clearly illustrated by Figure 3.4.1 where the centerline displacements reach their full value and then remain fairly constant. Therefore for critical extractions, the small difference found between the subsidence values in the longitudinal super-critical area were disregarded.

The values determined for maximum subsidence and the subsidence factors, in this study, were determined from the largest recorded displacements of the panel. However, the angle of draw, the value of subsidence at the rib, and the offset distance of the inflection point from the ribside were either observed or calculated from a transverse profile, which although critical in nature, did not always include the largest displaced values observed above the panel.

- Influence of Adjacent Panels: Two of the panels collected from industry, 3a and 3b, were influenced by old adjacent room-and-pillar workings. The transverse profiles of these two panels, which were separated by a double entry development, are shown in Figure 3.4.2. In this diagram, the



a) Three-dimensional view

Figure 3.4.1 Subsidence Trough Caused by Longwall Mining (O'Rourke and Turner, 1979).

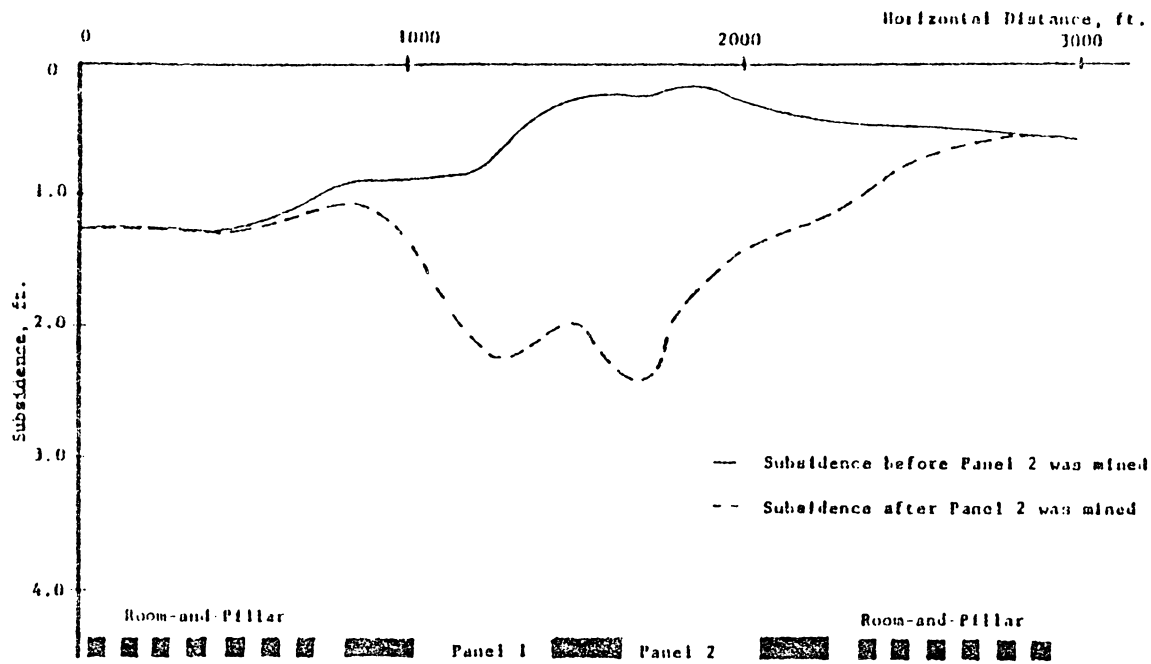


Figure 3.4.2 Transverse profiles of case studies 3a and 3b, showing the influence of the room-and-pillar sections.

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 approximately 0.6 feet and 0.3 feet of subsidence, respectively. The previously mined room-and-pillar sections appear to be causing the ground surface in these areas to become displaced by 0.6 feet for the first panel, and by 0.3 feet for the second panel. Therefore, the effect of room-and-pillar mining was subtracted from the total subsidence to establish the amount of surface displacement due to the longwall panels only. The profiles shown in Figure 3.4.3 were plotted with this assumption and were used to determine the maximum subsidence value and other surface displacement parameters of the panels.

- Surface Features : Mining companies are often interested in monitoring subsidence in the vicinity of gas lines, railroad tracks, streams, or other surface structures. In some cases, therefore, most of the monuments were placed in the vicinity of these structures and not at regular intervals, thus making complete profile calculations rather difficult.

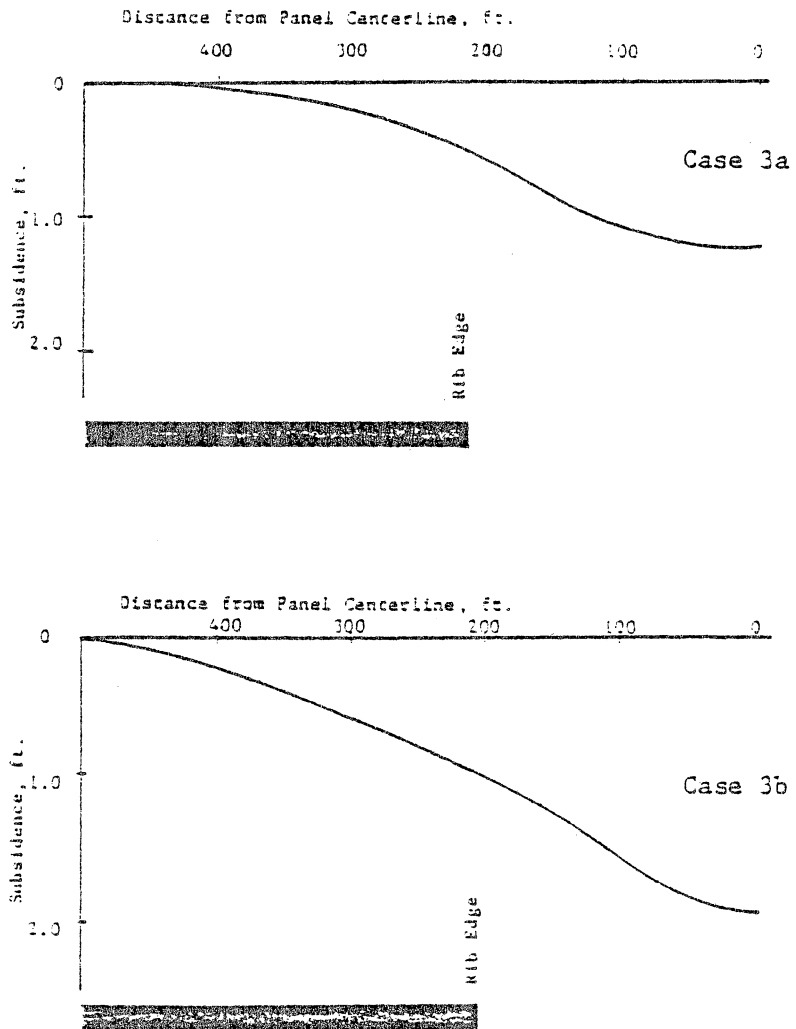


Figure 3.4.3 The transverse subsidence profiles of case studies 3a and 3b after the room-and-pillar influence has been subtracted.

Surface structures were located above the longwall panels 2c and 2d. Anticipating possible damage to the buildings, the mine personnel chose to monitor any displacements occurring to these structures. The position of the survey stations on the structures and at other locations on the panel enabled a complete transverse profile to be plotted for panel 2c. However, portions of the profile of panel 2d had to be approximated. Because there was a large horizontal distance between the last two monuments above panel 2d, it was necessary to interpolate the points of one-half of the subsidence profile.

- Angle of Draw: The angle of draw defines the limit of subsidence at the surface and it is perhaps the most difficult parameter to determine. Although the raw data often gave a zero survey reading, this value could only be assumed to provide a rough estimate of the location, because the survey readings are only as accurate as the monument spacing. To illustrate this point, consider two monuments, A and B, separated by 75 feet. Assuming that survey monument A was vertically displaced by 0.3 feet while monument B remained stationary, monument B can only provide an approximation of the zero point location because it was not determined whether the subsidence ended at a point somewhere between A and B.

For this research, three methods were utilized to determine the limit angle of a panel:

-when the zero point was known, the following equation was employed,

$$\theta = \tan^{-1} (x / h)$$

where,

θ = the angle of draw,
degrees

x = the horizontal distance
from the rib edge
to the zero point

h = the depth of the panel

-where two zero points were given, because ground uplift had occurred over the solid coal, Brauner's method was employed (see Figure 1.1.4), and

-when the zero point was unknown, the transverse subsidence curve was extended by curve-fitting procedures and the zero point was interpolated.

- Inflection Point: Investigations were performed initially to determine if the subsidence profiles of the case studies could be grouped on a regional geographic basis. As

a result of these analyses, the five groups shown in Figures 3.4.4 through 3.4.8 were obtained. Several of the half profiles, which were nearly identical in shape, were omitted from the graphs for clarity. Although the curves of Regions IV and V appeared to be highly correlated, further analysis of these curves and those of the other regions, revealed that the similarities in shape were due largely to the inflection point location, and not the geographical region of the panel.

The position of the inflection point is very important since it dictates the shape of the profile. Furthermore, as critical or supercritical conditions are approached, this point is displaced further inside the gob and thus can be used to differentiate between critical and subcritical extractions (NCB, 1975). This property was the primary consideration used in this study to facilitate the grouping of the profiles. Figure 3.4.9 shows the half-subsidence curves of critical and supercritical extractions, and Figure 3.4.10 those of the subcritical extractions. These plots have been non-dimensionalized by dividing the distance from the centerline by the depth and the subsidence at any point by the maximum subsidence. The inflection point is seen to be located between 0.1 and 0.3 over the gob for the critical panels, and the subsidence first appears at a point located between 0.6 to 0.8 from the centerline. The inflection point

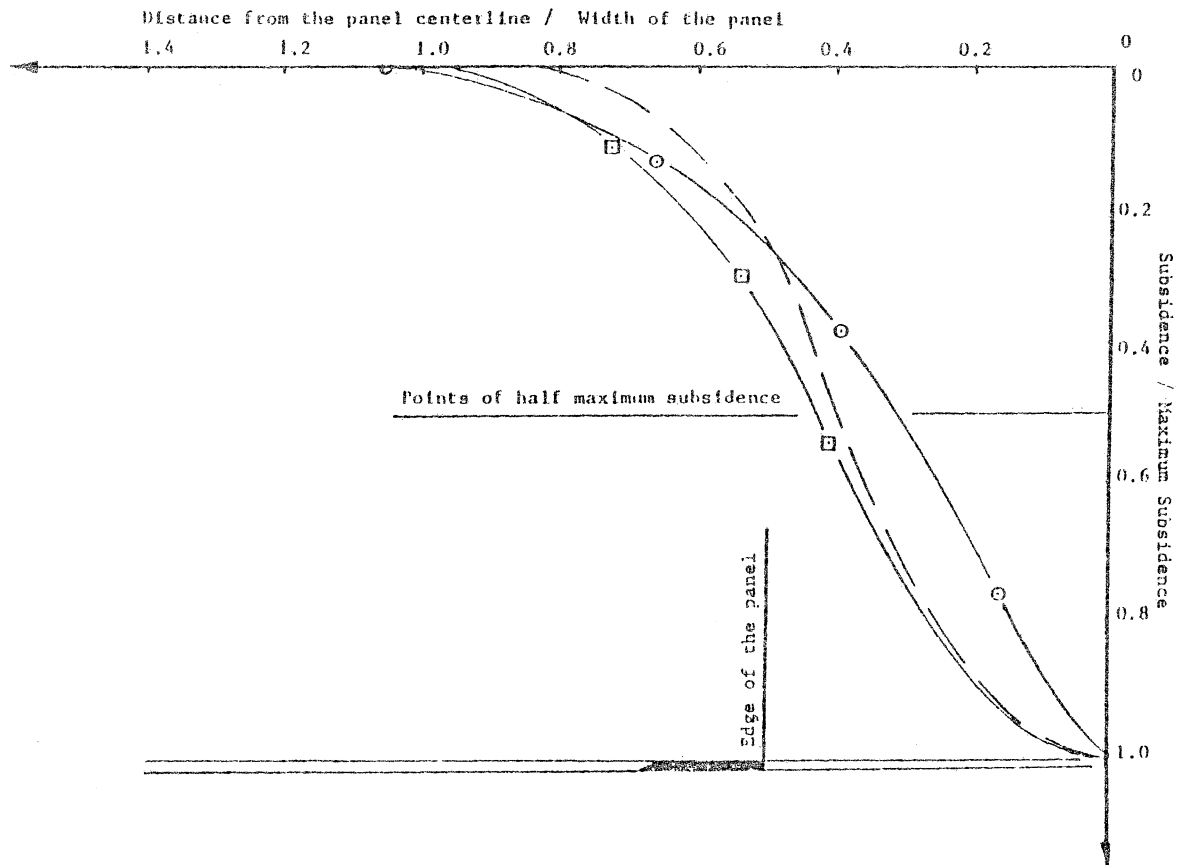


Figure 3.4.4 Half profiles of Region I--southwestern Pennsylvania.

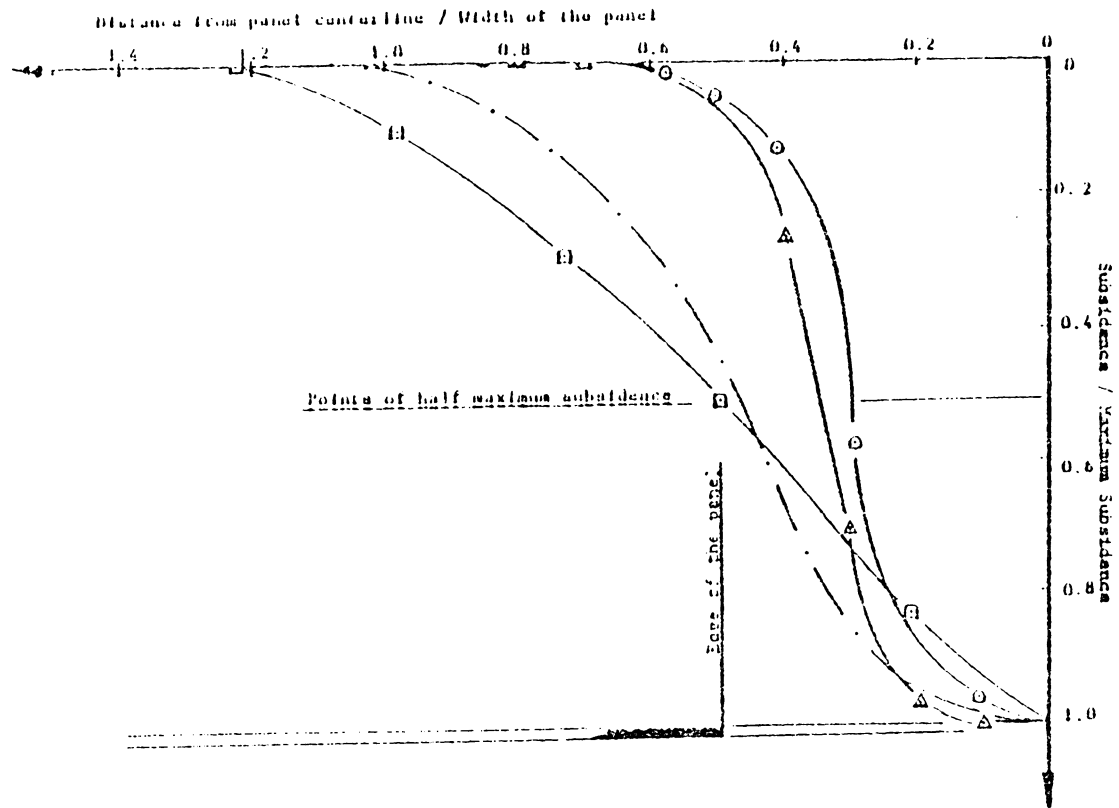
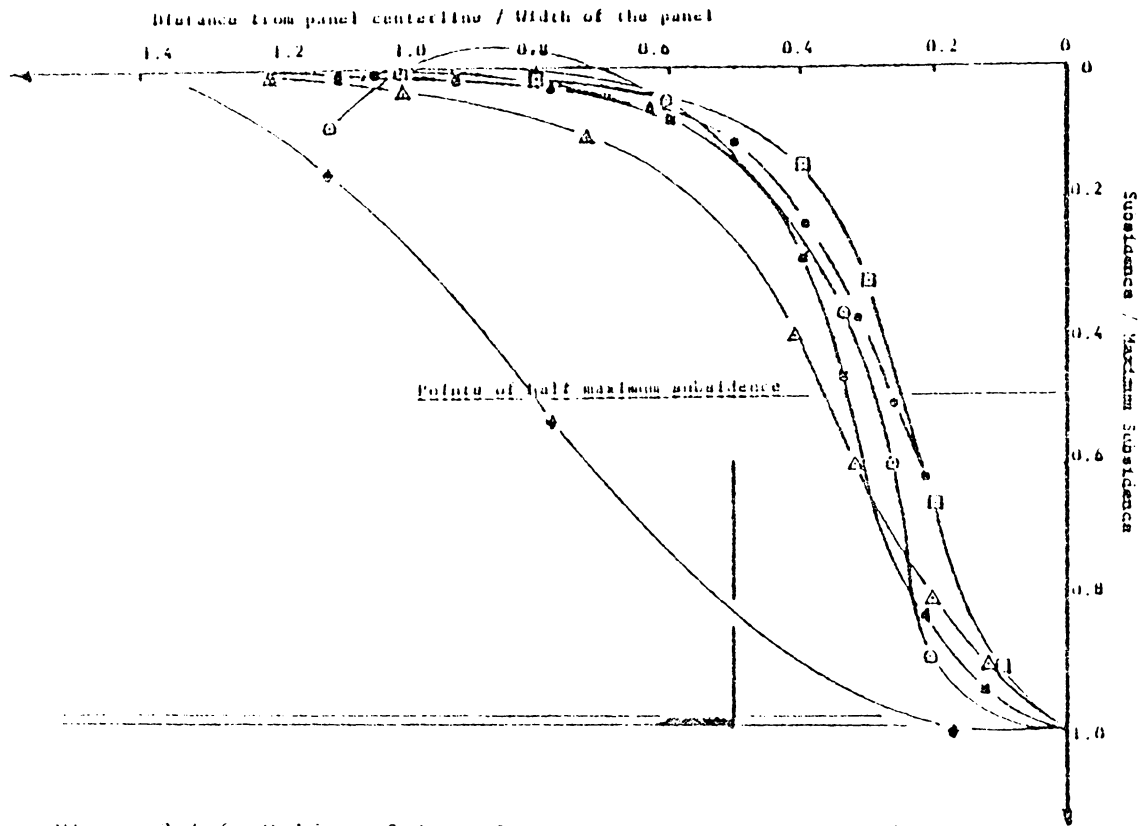


Figure 3.4.5 Half profiles of Region II--northern W.Va./southwestern Pa.



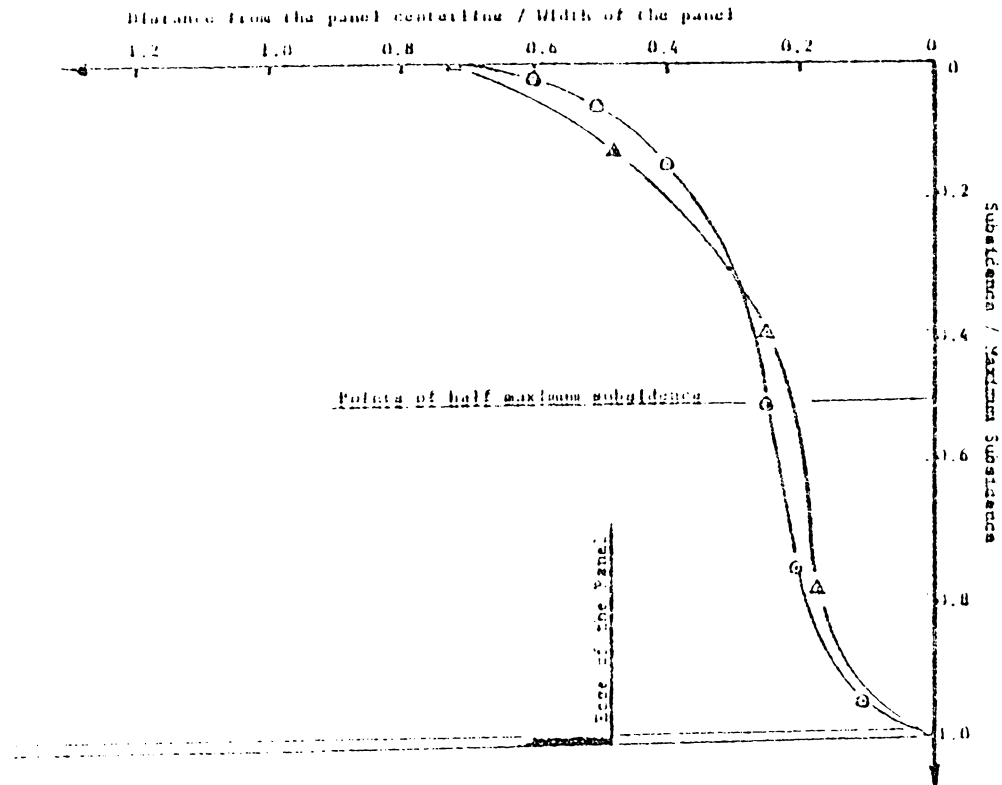


Figure 3.4.7 Half profiles of Region IV--southern W.Va./southwestern Va.

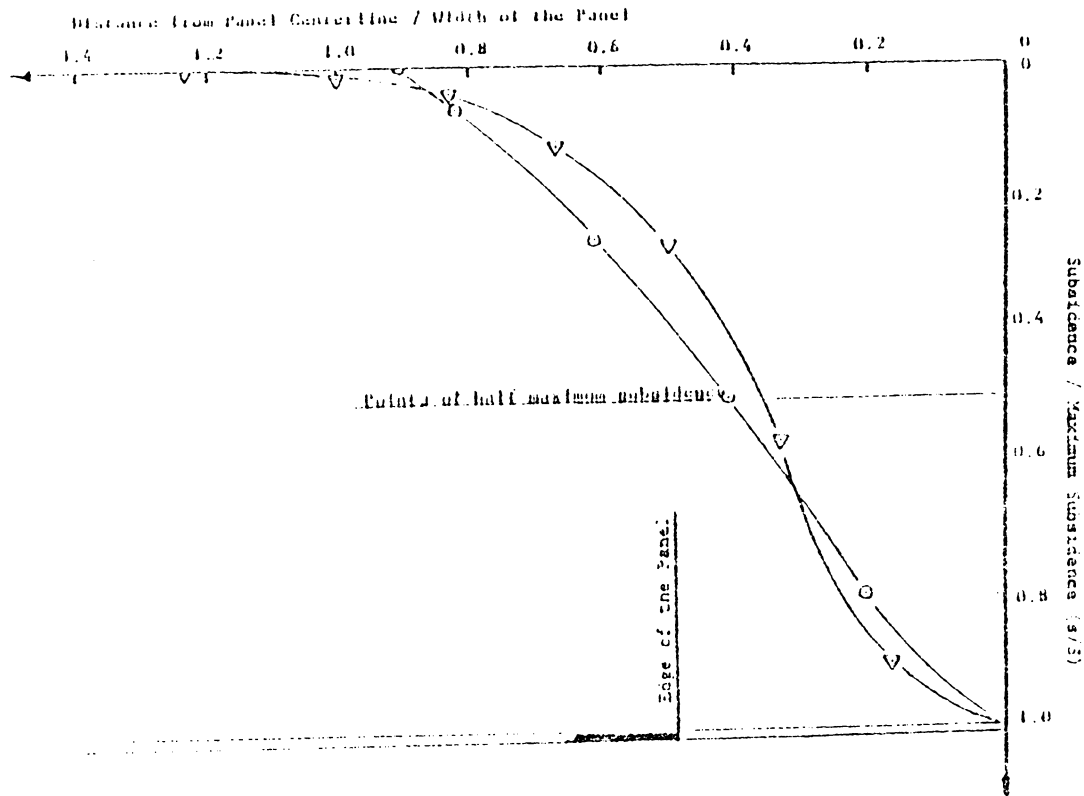


Figure 3.4.8 Half profiles of Region V--northern Alabama.

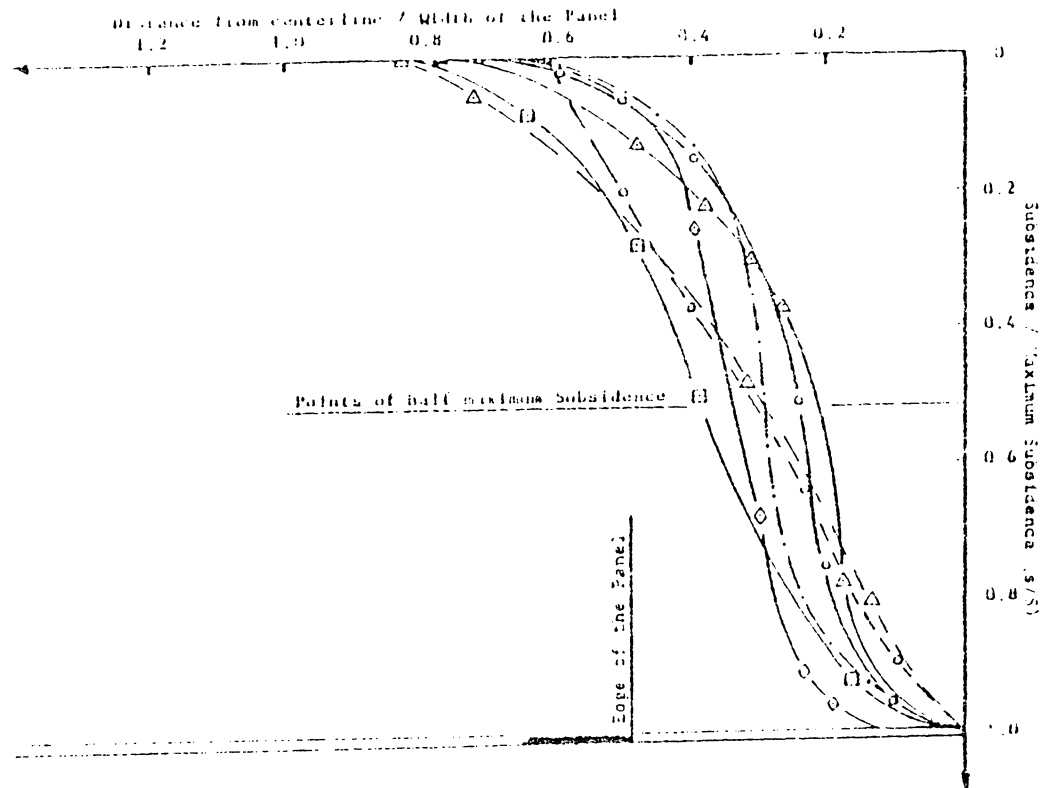


Figure 3.4.9 Typical half profiles and inflection points of the critical and supercritical Appalachian data.

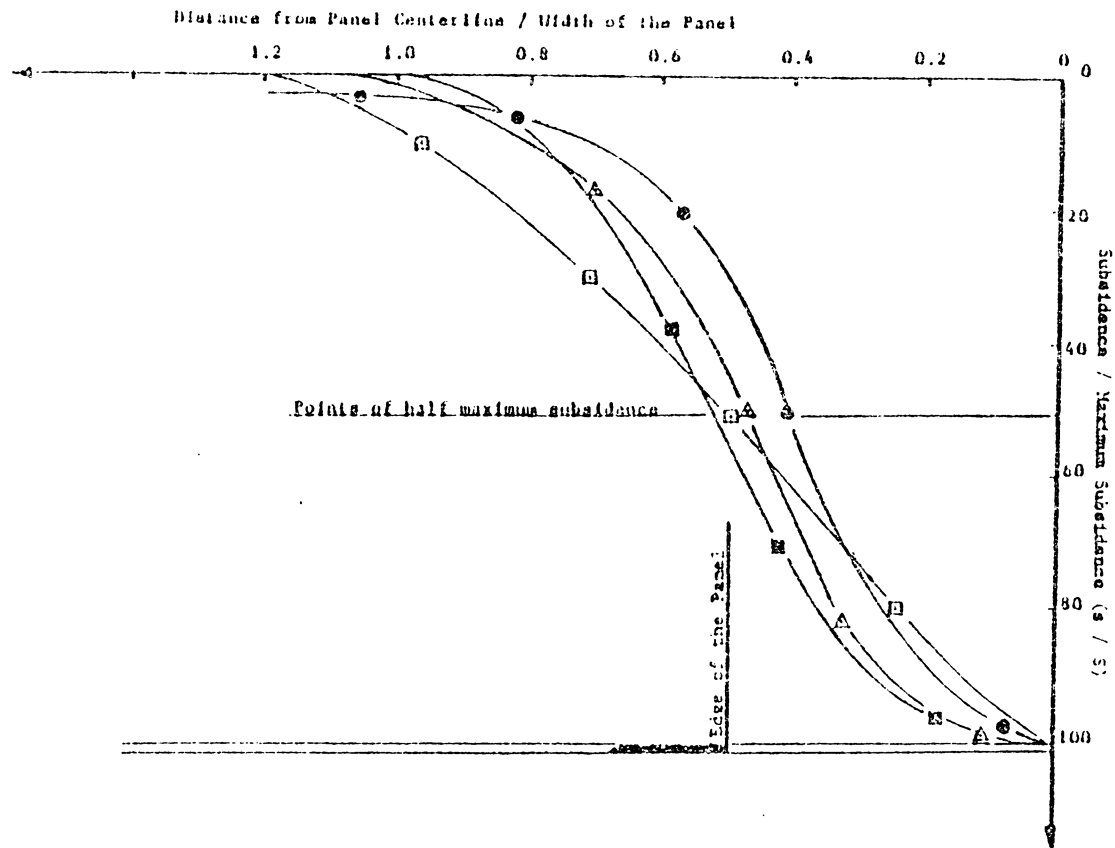


Figure 3.4.10 Typical half profiles and inflection points of the subcritical Appalachian data.

of the subcritical panels is located anywhere from 0.1 over the rib to 0.1 over the gob and the subsidence begins at a distance between 1.0 to 1.2 away from the centerline. It can be seen that, on the average, when the inflection point is located 0.2 inside the gob the excavation is generally critical, and if it is located nearer to or above the rib it is subcritical. These relationships are clearly illustrated in Figure 3.4.11. The data of this plot suggest the location of the inflection point for critical and subcritical extractions. Similar measurements in the United Kingdom have indicated that for critical extractions, the inflection point is located about $0.14h$ inside the gob. These trends support the observation of O'Rourke and Turner (1981), who suggested that although smaller amounts of subsidence are experienced in the United States, they may still induce as much as two to five times greater curvatures and strains.

All of the data used in this study were tabulated and analyzed in terms of the variables previously discussed. Table VIII presents the information used to establish the characteristic subsidence relationships above longwall panels in Appalachia.

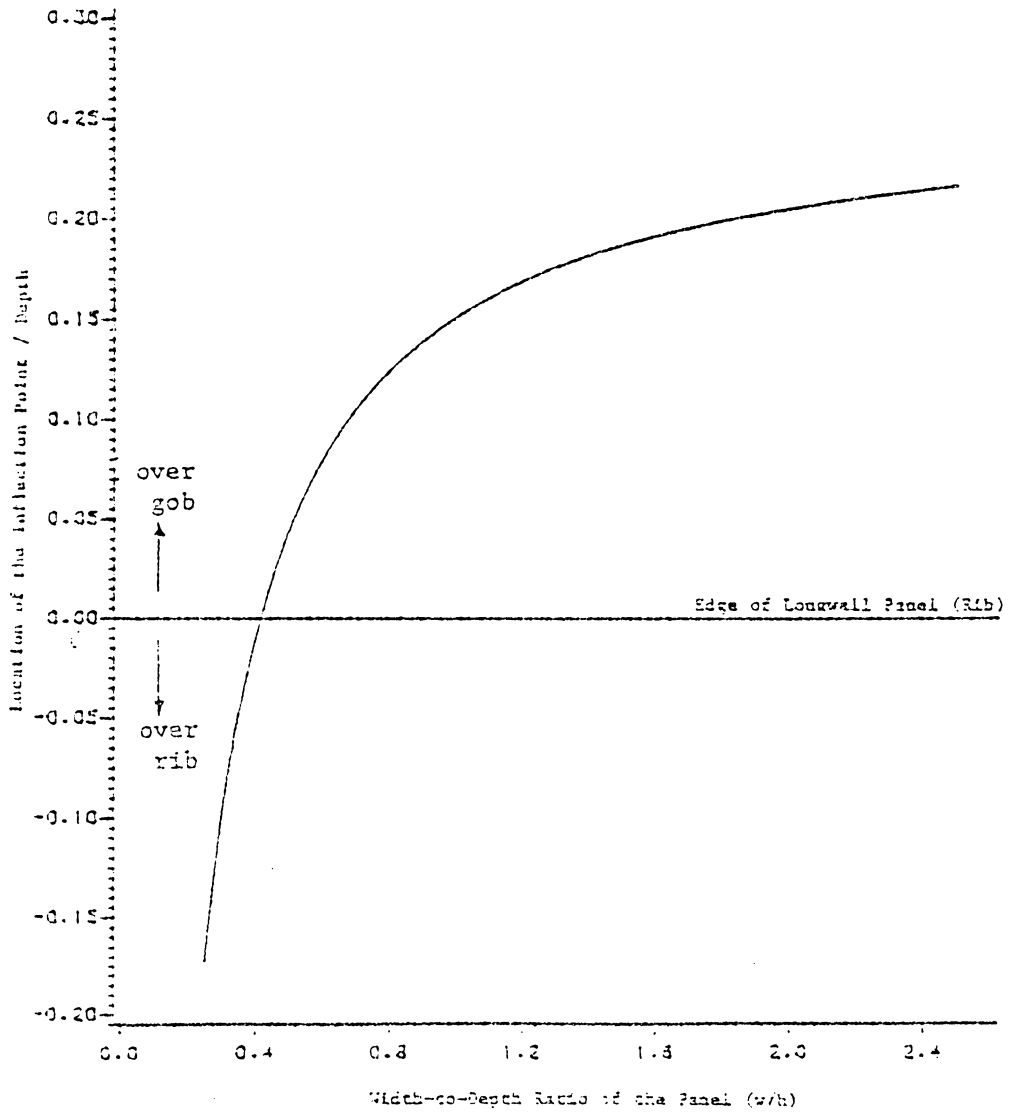


Figure 3.4.11 The effect of the width-to-depth ratio on the position of the inflection point.

TABLE VIII

SUBSIDENCE DATA OF THE COLLECTED STUDIES

Number	Old depth ft.	New depth ft.	w/h	w, ft.	draw degn.	s/l =	s, ft.	s/m	sc/m	d, ft.	d/h	Crit. Width	Class	Set.	Dist.	Shale	W.R.	Length ft.
1	610	550	1.11	4.5	22.6	0.11	2.7	0.47				130	Sub	18	2	60	40	2625
2a	450	500	0.90	4.0	27.3	0.11	1.46	0.37		25	0.05	452	Crit	17	-	69	31	2600
2b	455	455	1.00	4.0	17.4	0.08	1.22	0.31		50	0.11	285	Super	17	"	63	37	
2c	450	520	0.87	4.0	22.0	0.11	1.35	0.36		40	0.08	420	Super	28	"	72	28	
2d	450	280	1.61	3.8	14.9	0.10	2.60	0.63		155	0.55	391	Sink	38	"	66	34	
3a	410	740	0.58	6.4	18.7	0.05	1.71	0.27				500	Sub	12	10	78	22	2530
3b	410	800	0.51	6.1	20.2	0.08	1.26	0.21				589	Sub	12	10	78	22	2530
4a	500	230	2.17	5.0	31	0.02	1.03	0.37		120	0.52	276	Super	58	"	42	58	3735
4b	500	235	2.13	5.0	30	0.03	1.43	0.29		120	0.51	271	Super	58	"	42	58	3735
5a	500	240	2.08	5.0	32	0.02	2.43	0.49		102	0.43	300	Super	25	"	75	25	1500
5b	500	450	1.11	4.8	16	0.03	2.87	0.62		75	0.17	300	Super	24	"	76	24	1740
6a	450	600	0.75	5.3	27	0.06	2.63	0.48				600	Sub	4	33	63	37	4800
6b	450	650	0.69	5.3	15	0.05	1.9	0.62			0.14	351	Super	6	33	63	37	4400
7a	475	245	2.2	4.5	0	0	2.4	0.53		110	0.51	0	"	7	"	83	7	
7b	475	230	2.1	4.5	6	0.18	2.7	0.60		75	0.33	266	"	"	"	"	"	
8a	490	1400	0.35	5.4	14	0.03	0.30	0.06		-75		672	Sub	32	"	68	32	2650
8b	1210	1400	0.86	5.4	12	0.07	1.74	0.32		100		600	Super	"	"	"	"	3725
9a	485	615	0.79	6.5	27	0.07	3.9	0.60		85	0.17	520	"	8	17	75	25	1450
9b	485	615	0.79	6.5		0.19	4.2	0.65		80	0.13		"	"	"	"	"	
9c	474	515	0.86	6.5	25	0.15	4.0	0.62		60	0.13		"	"	"	"	"	
10	650	680	0.96	7.0			1.8	0.28								76	26	
11	380	530	0.72	6.2			2.2	0.37								36	64	
12	485	700	0.69	4.1	20	0.16	2.5	0.52		100	0.14	521	Sub	10	13	77	23	4200
13 (93)	470	400	1.18	3.7	21	0.11	2.8	0.76		110	0.28	302	Super			79	21	4550
14 (93)	400	750	0.80	5.3	15		3.35	0.61		145	0.19	402	Super				37	
15 (2)	600	350	1.09	5.3			3.28	0.60										
16 (17)	530	620	0.78	6.0	18		2.2	0.37		110						76	24	
17 (80)	1700	1700	1.3					0.20						6	18	53	47	
18 (35)	2200	322		5.5	18			0.40						22	28	50	50	
19 (53)	427			6.8	9			0.52				135	Super	11	30	59	41	
20 (54)	354			5.7	24			0.50				315	Super	11	9	78	22	
21 (55)	532			6.8				0.48						11	30	59	41	
22 (55)	299			6.8				0.46						11	30	59	41	
23 (60)	197			5.8	18			0.58				128	Super	52	0	52	48	

() Taken from Literature

Chapter IV

RESULTS

4.1 Mining Factors

The characteristics of the collected panels are summarized in Table VIII. The width of the excavations ranged from 380 to 610 feet. Adjacent panels whose support pillars had failed during extraction were considered as single excavations, which resulted in two panels having exceptionally large widths in excess of 1000 feet. The seam depth varied from 215 to 1700 feet and the average extraction thickness was 5.25 feet. Analysis of the data revealed some characteristic subsidence relationships and trends.

- Angle of Draw: The angles of draw ranged from 12 to 34 degrees with the exception of one sinkhole, which caused no draw. These limit values were plotted against their respective panel width-to-depth ratios and compared with British observations. The British data shown in Figure 4.1.1. reveal a scatter similar to the Appalachian values. While the NCB data approach a constant limit angle of 35 degrees, the Appalachian panels appear to reach a constant value at about 28 degrees. The graphs used in the Subsidence Engi-

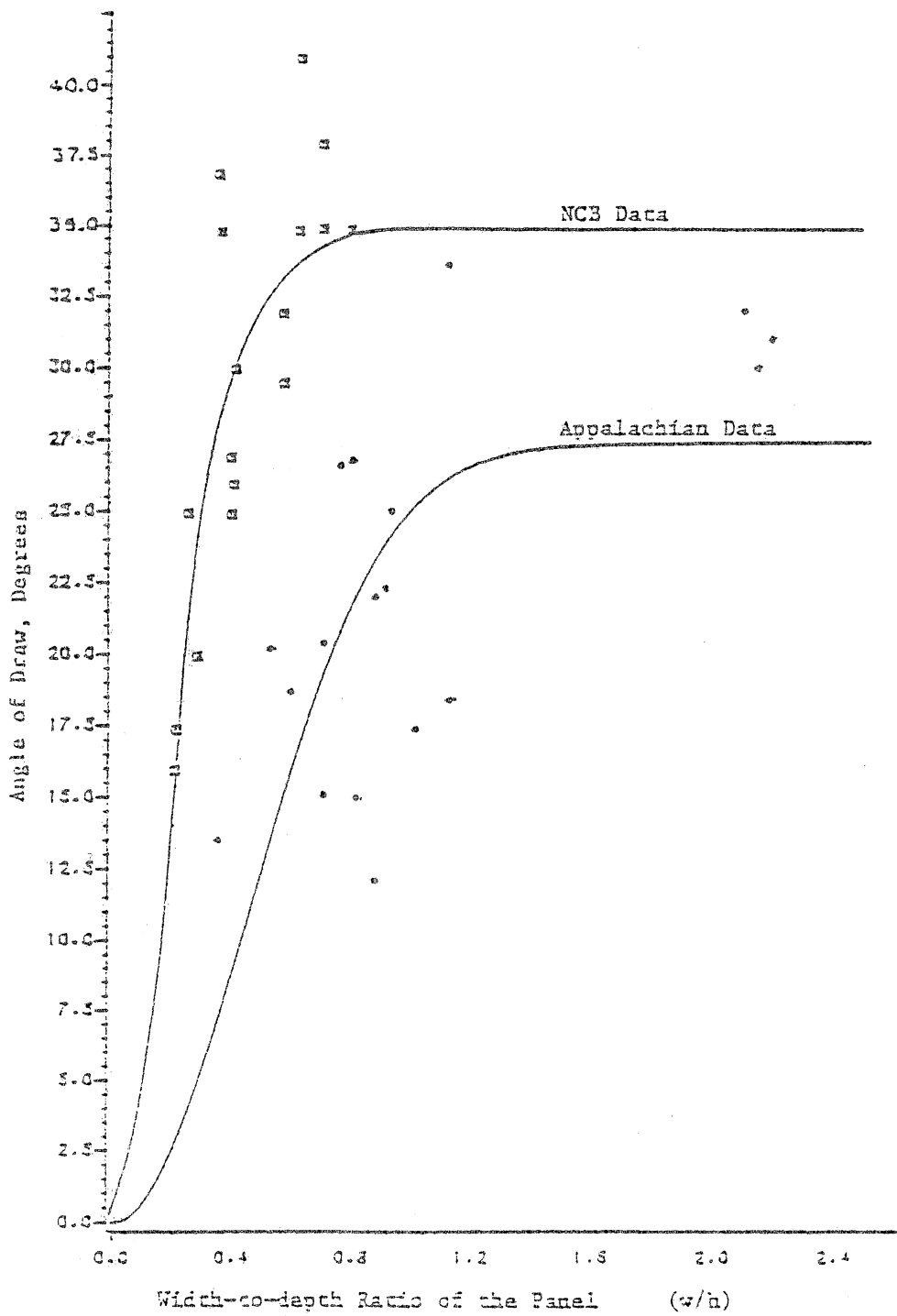


Figure 4.1.1 The influence of the width-to-depth ratio on the angle of draw.

neers' Handbook to predict subsidence profiles were developed for an average limit angle of 35 degrees. Because this average value is greater than the maximum limit angle found in Appalachia, the British prediction system significantly overestimates the extent of subsidence at the surface when applied in this region.

- Subsidence Factor: The surface subsidence was determined to be directly related to the volume and the depth of the extraction i.e., the subsidence factor increased as the width and the seam thickness of the panel increased. Figure 4.1.2 shows this trend and the range of subsidence factors determined for the Appalachian region. The large values observed in the central portion of the graph represent shallow mines which acted as sinkholes and had exceptionally large yields of subsidence at the surface. An improved relationship is observed when these values are eliminated. These findings agree with the results of previous investigators.

The subsidence factors of the collected panels were determined to decrease with increasing depth. This relationship is not obvious from the graph shown in Figure 4.1.3, because the majority of the data are located within a narrow range. These results disagree with the findings of Kohli et

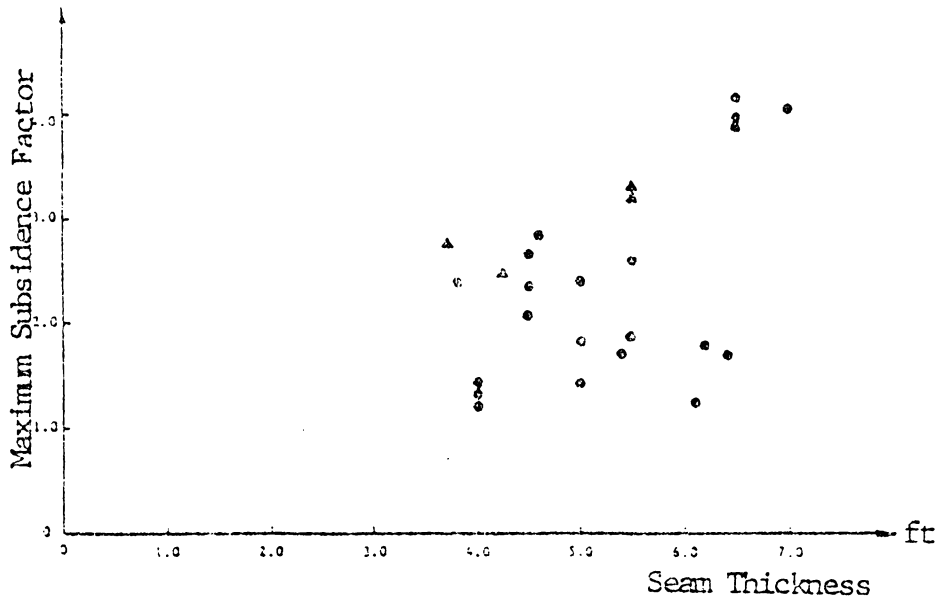


Figure 4.1.2a The effect of the seam thickness on the maximum subsidence factor, considering all case studies.

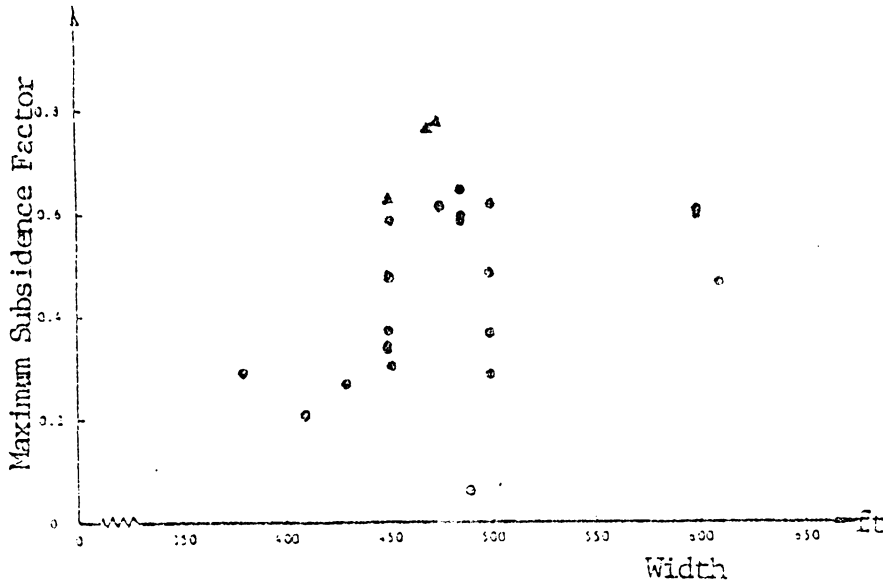


Figure 4.1.2 b The effect of the panel width on the maximum subsidence factor, considering all case studies.

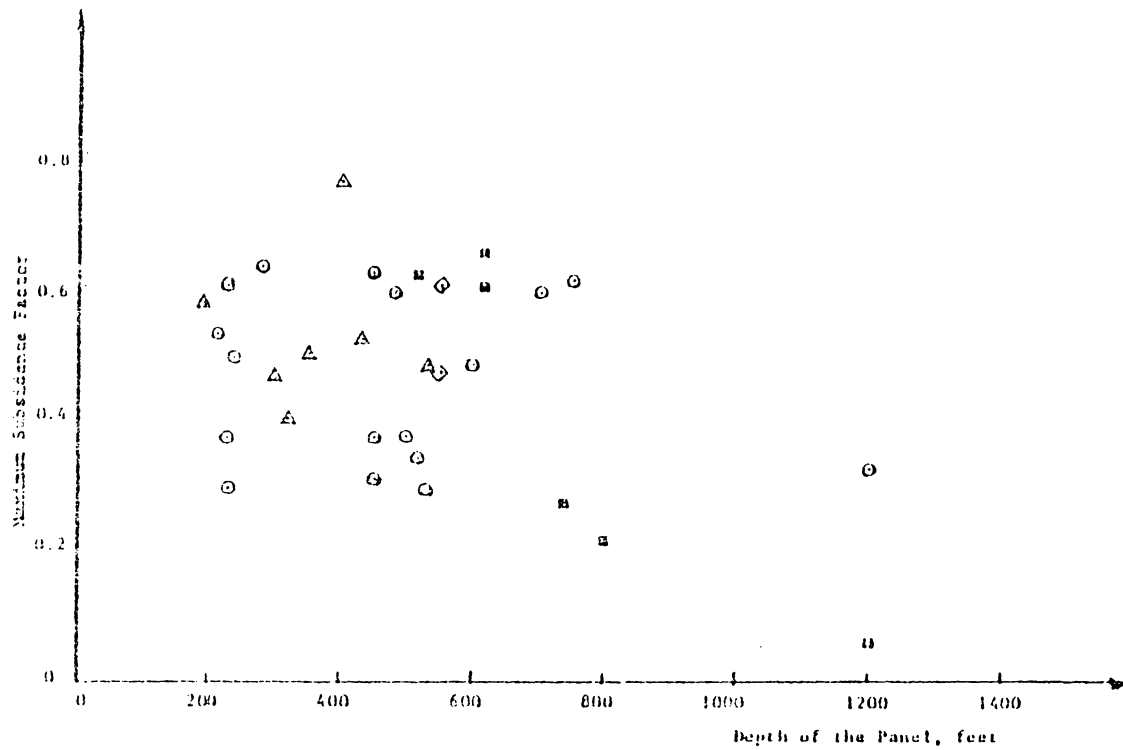


Figure 4.1.3 The effect of the panel depth on the maximum subsidence factor, considering all case studies.

al (1980), but they do agree with those of the NCB (1975) and Peng et al (1980). In the latter reference, this relationship was assumed to be the result of longwall mining which induced caving of the immediate and intermediate roof strata. This caving zone may propagate to a horizon located from 35 to 50 times the mining height above the seam. Although bed separation can occur, there will be no appreciable breakage. This allows the main roof strata to settle down in a continuous piece on the gob, without a significant increase in volume.

The subsidence factors are shown together with the NCB's limits for caving in Figure 4.1.4. Although the Appalachian range of subsidence factors is 0.20 to 0.76, the maximum value shown is 0.65, because the sinkhole data were not included in this graph. The general trends shown by the data from both regions appear to be similar; however, mining conditions in Appalachia demonstrate consistently smaller amounts of subsidence than in Britain. The curve shows that the upper limit for Appalachia is roughly 0.63, and asymptotic conditions are approached for panel width-to-depth ratios greater than 1.0 to 1.2. This corresponds to a ratio of 1.4 for British conditions, indicating that a smaller distance is required to reach critical subsidence conditions

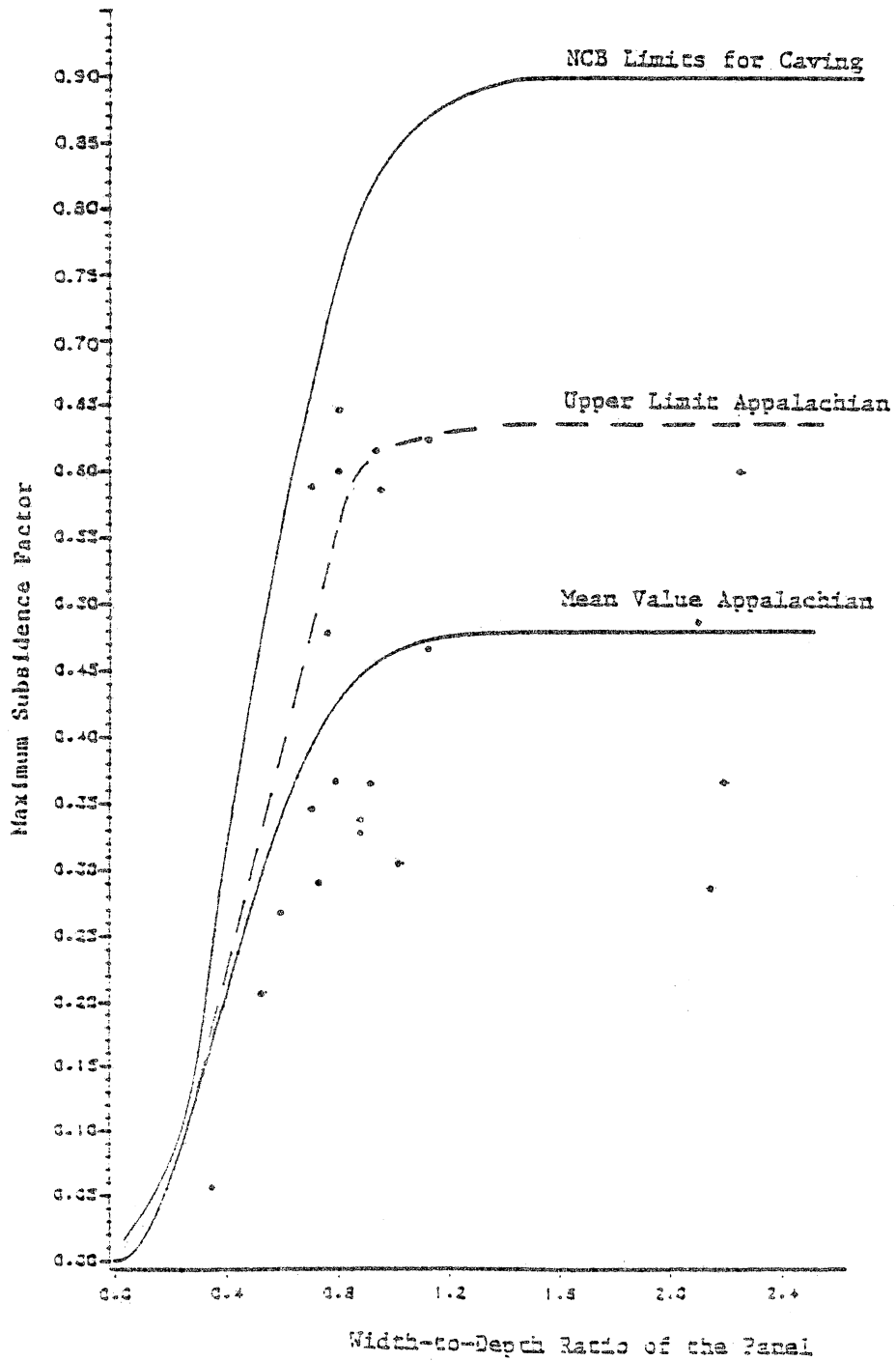


Figure 4.1.4 The influence of the width-to-depth ratio on the maximum subsidence factor.

in the Allegheny Plateau Region. Because the NCB's prediction graphs were developed from mines possessing significantly higher magnitudes of subsidence than generally found in Appalachian mines, the British charts have been found not only to overpredict the limit of subsidence at the surface, but also to overestimate the magnitude of this subsidence (Goodman, 1980).

It is interesting to note the variation of subsidence factors which were demonstrated by panels with equal width-to-depth ratios. For example, the ratio of 0.8 possesses subsidence values ranging from about 0.2 to 0.45 times the seam thickness. This scatter suggests that there is another variable which has an influence upon the subsidence, in addition to the panel geometry. For this reason, the effect of the overburden stratigraphy on subsidence was investigated.

4.2 Geologic Factors

The percent of shale, sandstone, and limestone present in the overburden of each panel was calculated from the collected drill core data. These values were then plotted as a function of the maximum subsidence factor and the angle of draw to develop characteristic trends. The analysis showed that increasing amounts of either sandstone or limestone in

the overburden cause a decrease in the subsidence factor. However, the range and scatter of the data points were large and an accurate linear relationship was not determined.

The limestone and sandstone beds appeared to have a similar influence on the subsidence; therefore, these two rock types were grouped together as hardrock formations, and their influence on the maximum subsidence factor was investigated. The result of this analysis is shown in Figure 4.2.1, which includes the subsidence factors of all case studies, including critical and subcritical panels. The subcritical extractions do not possess maximum subsidence factors representative of the full subsidence, or maximum possible subsidence. Consequently, these values were omitted from the plots of both rock types in order to eliminate the panel geometry variance from the analysis. A linear relationship was obtained from this procedure and is shown in Figure 4.2.2. In fact, the coefficient of determination is 0.54, and represents an acceptable fit for this type of analysis.

The percent of shale and other soft rocks in the overburden were also grouped and plotted against the maximum subsidence factor. The resulting graph is shown in Figure 4.2.3. Because the hardrock and the softrock comprising a

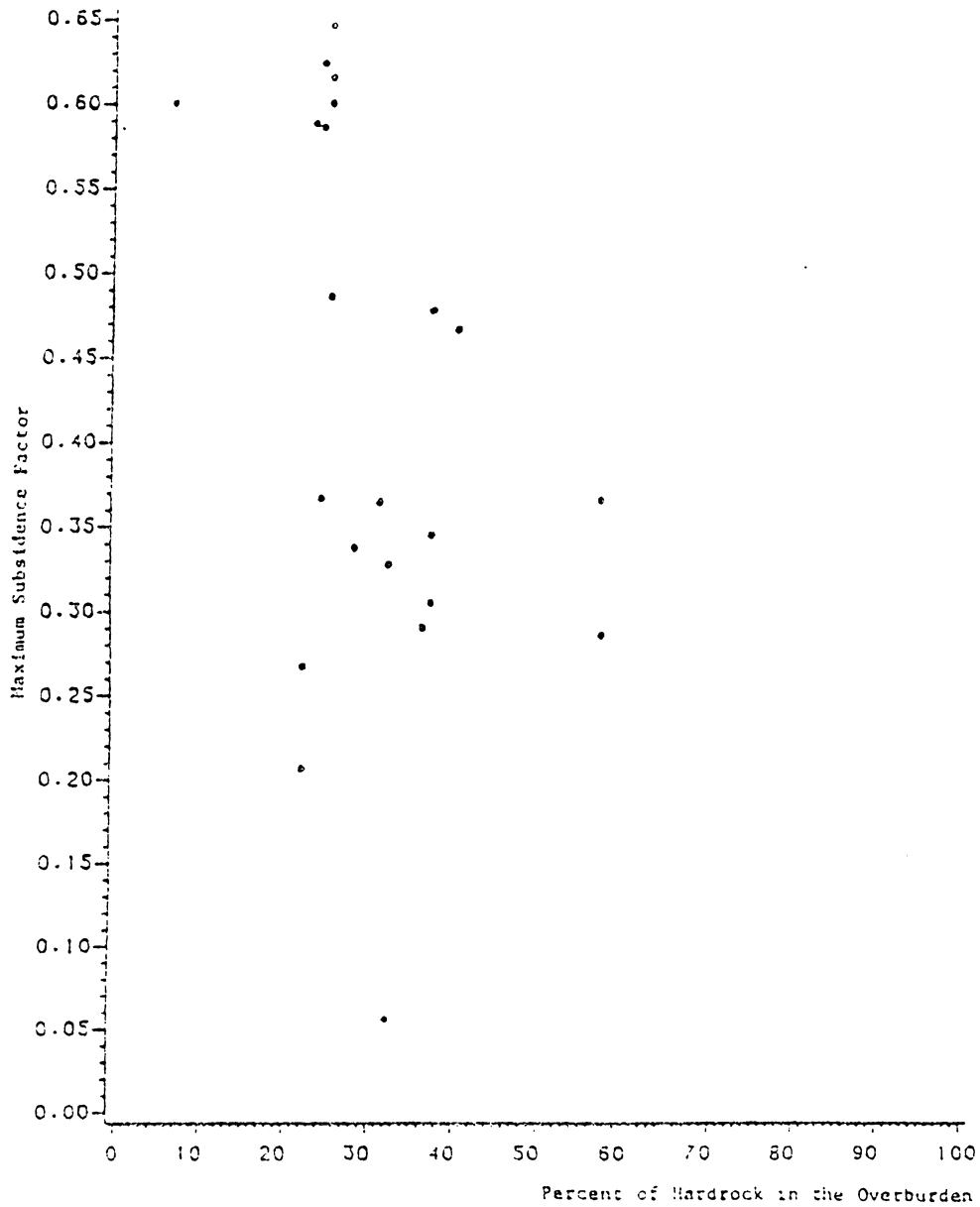


Figure 4.2.1 The Influence of Sandstone and Limestone in the Overburden on the Subsidence Factor for all Case Studies.

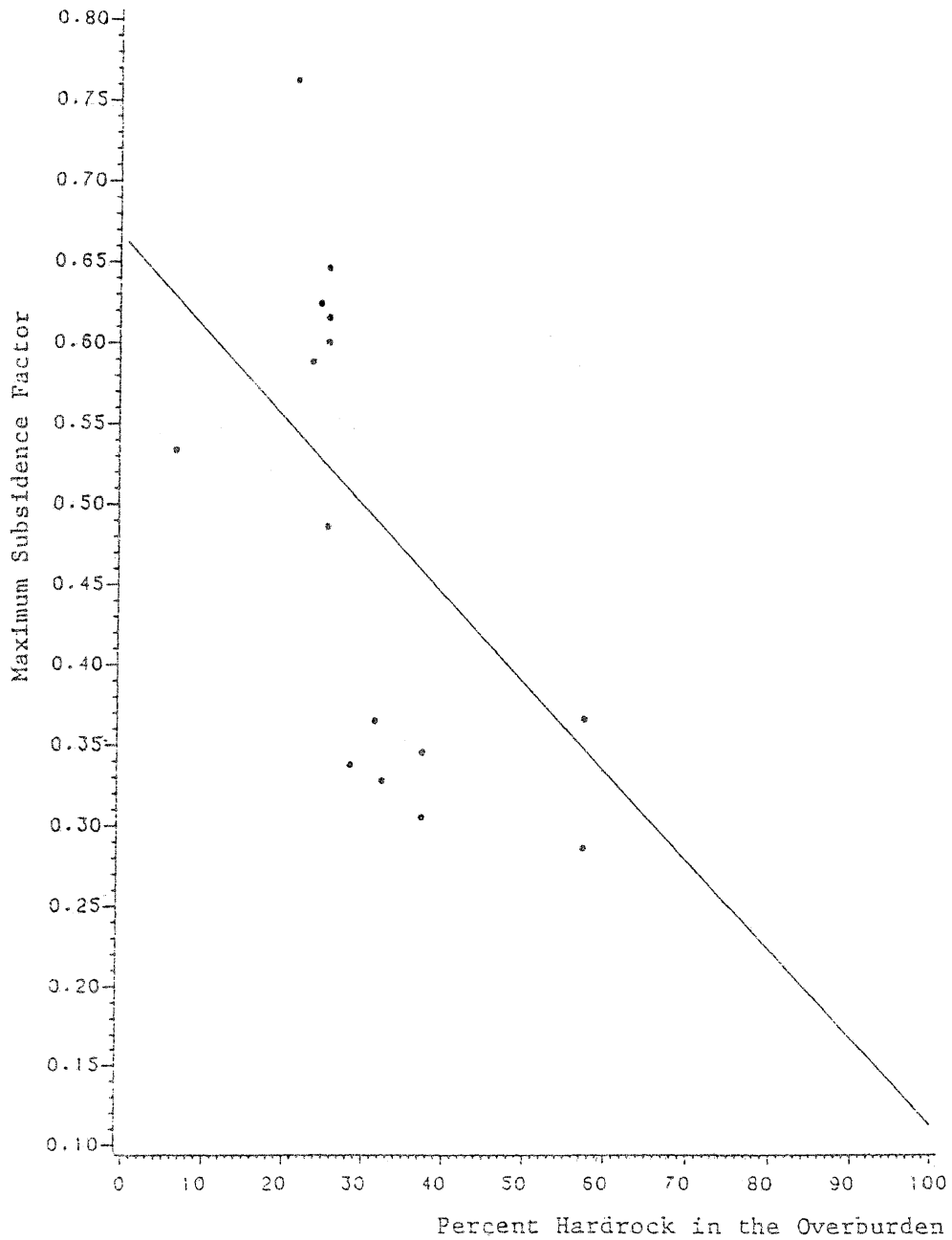


Figure 4.2.2 The Influence of Sandstone and Limestone in the Overburden on the Subsidence Factor for Critical and Supercritical Extractions.

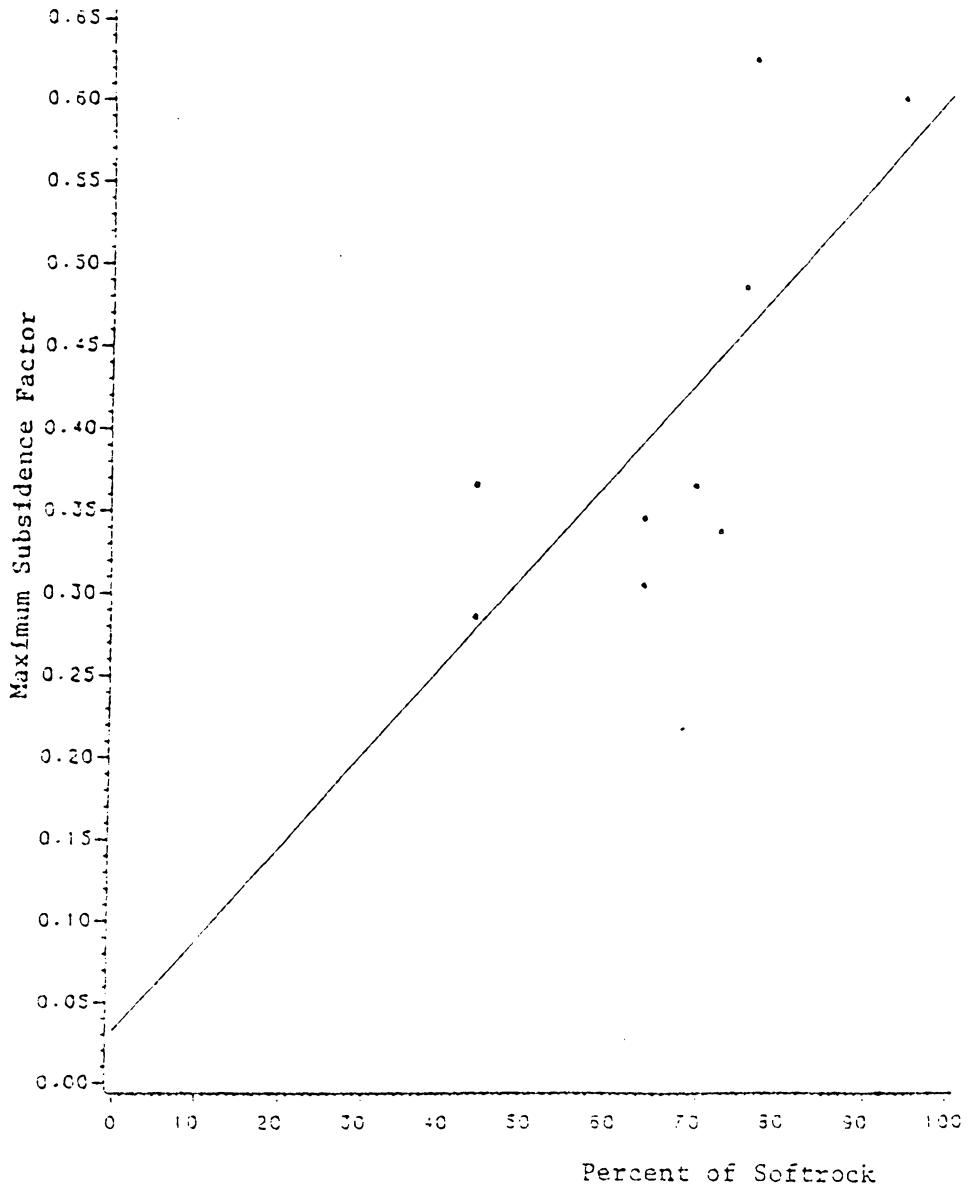


Figure 4.2.3 The Effect of the Softrock in the Overburden on the Maximum Subsidence Factor, Considering only the Critical and Supercritical Extractions.

single overburden are complementary, the plot of the softrock versus the subsidence is a mirror image of the previous relationship. It has been shown that an increase in the amount of softrock in the overburden will cause an increase in the subsidence factor, while an increase in the amount of hardrock will cause a decrease in the subsidence factor.

There were no obvious trends suggested from the plots of the angle of draw versus the different lithologic layers. This is most likely due to the complex nature, and the difficulty required to get an accurate measurement, of the limit angle.

The presence of a massive sandstone bed (or other hard rock layer) has been suggested to inhibit the surface subsidence (Peng and Cheng, 1980). This thick layer is believed to reduce or eliminate the propagation of caving or sagging strata and thus reduce the subsidence. The relative position of the strong stratum in the overburden is also an important consideration. However, the precise effect of these factors on subsidence is difficult to ascertain.

4.3 Prediction Model

The subsidence profiles determined for the collected panels were compared with NCB predictions of the same data.

Two of these plots are included in Appendix B. As expected, from the comparisons made in Figures 4.1.1 and 4.1.4, the overestimations are quite significant. It should be recalled at this point, that the British did not incorporate the effect of geology on subsidence into their empirical prediction system. Based on the linear relationship determined previously for the maximum subsidence factor and the percent of hardrock in the overburden, it is necessary to incorporate the influence of lithology into a subsidence prediction plan for Appalachia.

Before an empirical prediction model could be developed for the Appalachian Region, it was first necessary to determine the subsidence profile shape characteristic to this region. Because the subsidence profiles are greatly influenced by the position of the inflection point, it was necessary to develop a grouping system which is comprised of comparable subsidence data. In order to accomplish this, all of the case studies were divided into one of two categories--critical (which includes supercritical) and subcritical. The half profiles shown in Figures 3.4.7 and 3.4.8 illustrate the small range of data points which are located in each group, thus indicating that the mean profile of a group could be used to provide a fair representation of the

overall subsidence trend. Therefore, the average or mean profiles were calculated and drawn, as shown in Figures 4.3.1 and 4.3.2.

An extensive literature survey was performed to find a function which would describe most appropriately the mean profiles of each group. More than 20 empirical formulae have been developed to predict subsidence from underground coal mining (Chen and Peng, 1981). These functions have had varying degrees of success and are reported in many forms. Attempts were made to apply several of these equations to the field data of the collected panels, using the computer to perform the curve-fitting procedures. The function determined to most accurately describe the subsidence data was a hyperbolic tangent equation described by Brauner (1973). This profile function has been suggested from both model and theoretical investigations.

It was convenient to use the different referencing system illustrated in Figure 4.3.3 to compare the various profile functions (Brauner, 1973). The origin, or zero point, of this coordinate system is the inflection point and the variable x is the horizontal distance away from it. This distance x is expressed in terms of the distance from the centerline to the inflection point, B .

The subsidence, s , therefore is given by:

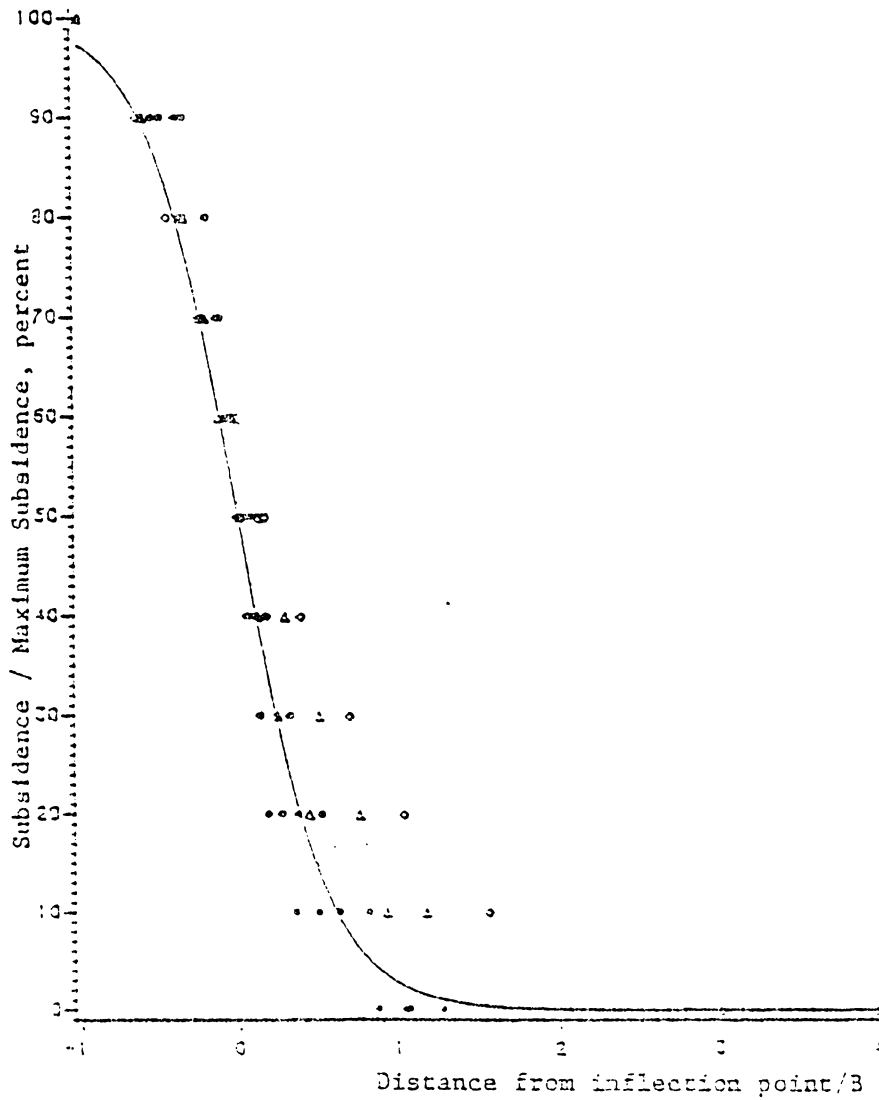


Figure 4.3.1 Typical half profiles and the mean profile of the critical and supercritical extractions.

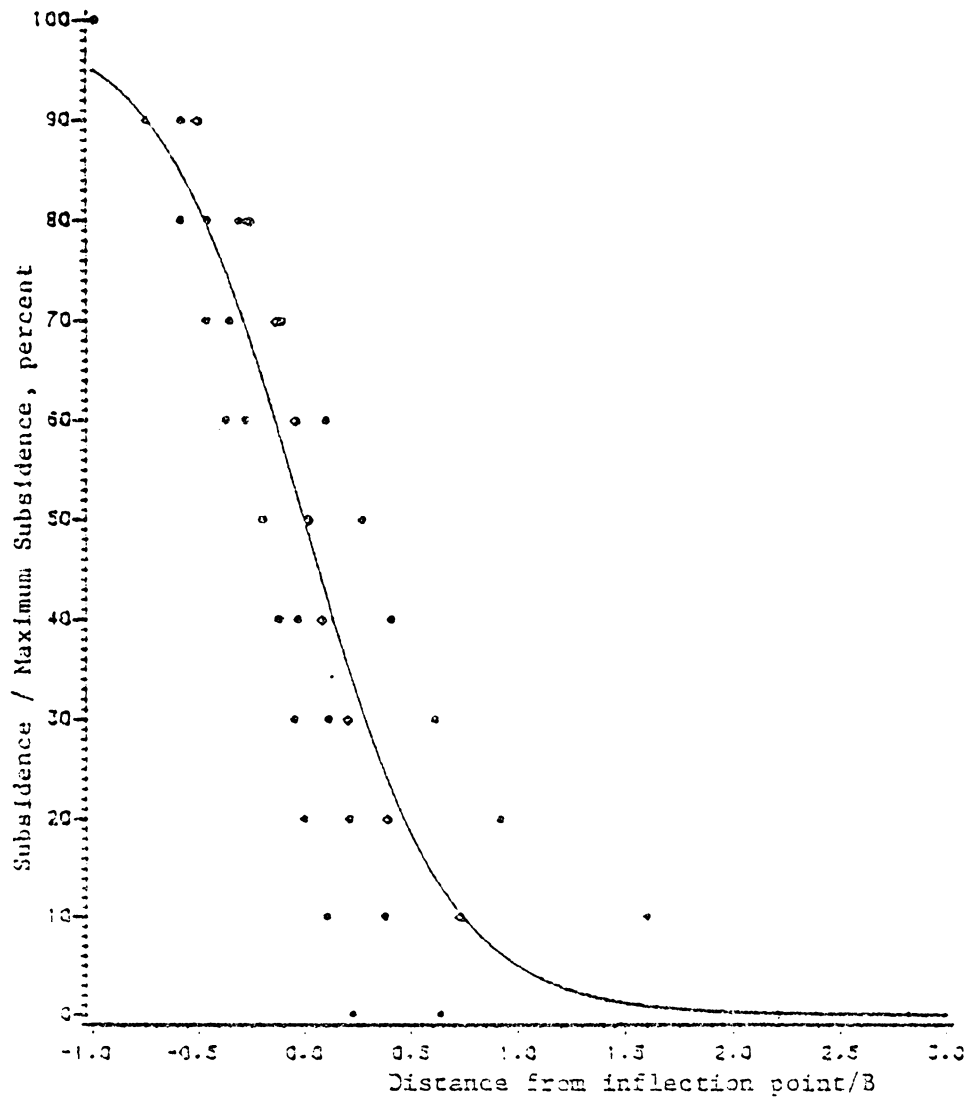


Figure 4.3.2 Typical half profiles and the mean profile of the subcritical extractions.

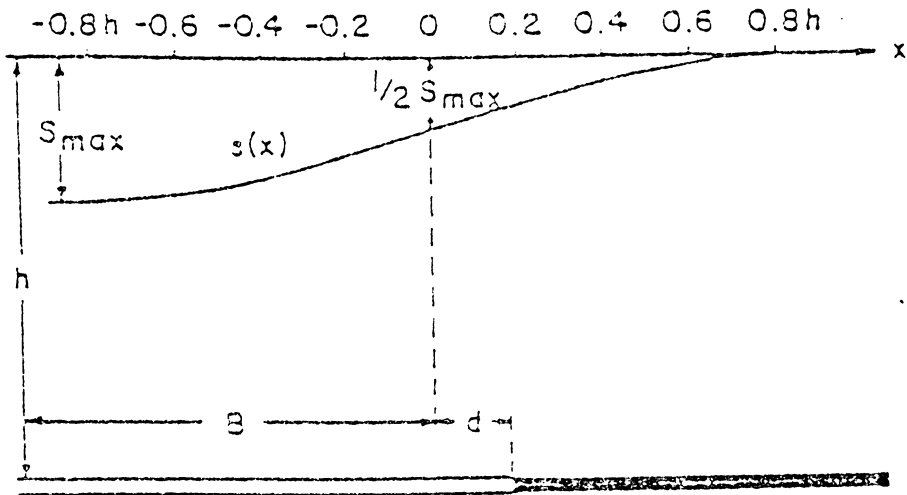


Figure 4.3.2 Referencing System (Brauner, 1973).

$$s = S_{\max}/2 \left(1 - \tanh (cx/B) \right)$$

where,

S_{\max} = Maximum subsidence

c = constant; 1.4 for subcritical panels, and 1.8 for critical or supercritical panels

The value of c was found by inputting the Appalachian field data into the computer. Figures 4.3.4 and 4.3.5 illustrate how accurately the hyperbolic tangent function predicts the mean subsidence curve of the two groups. The upper and lower bounds of the data are also shown.

The hyperbolic tangent equation, or the graphs of this equation, may be used to plot a subsidence profile if the maximum subsidence value is known. It was previously established that subsidence is a function of both the geometry of the panel and the lithology of the overburden. Based on these relationships, it is obvious that the subsidence will reach a certain magnitude and then remain fairly constant for a given width-to-depth ratio and percentage of hardrock, in a form suggesting an exponential curve. It is also known that asymptotic conditions will be met at a higher subsi-

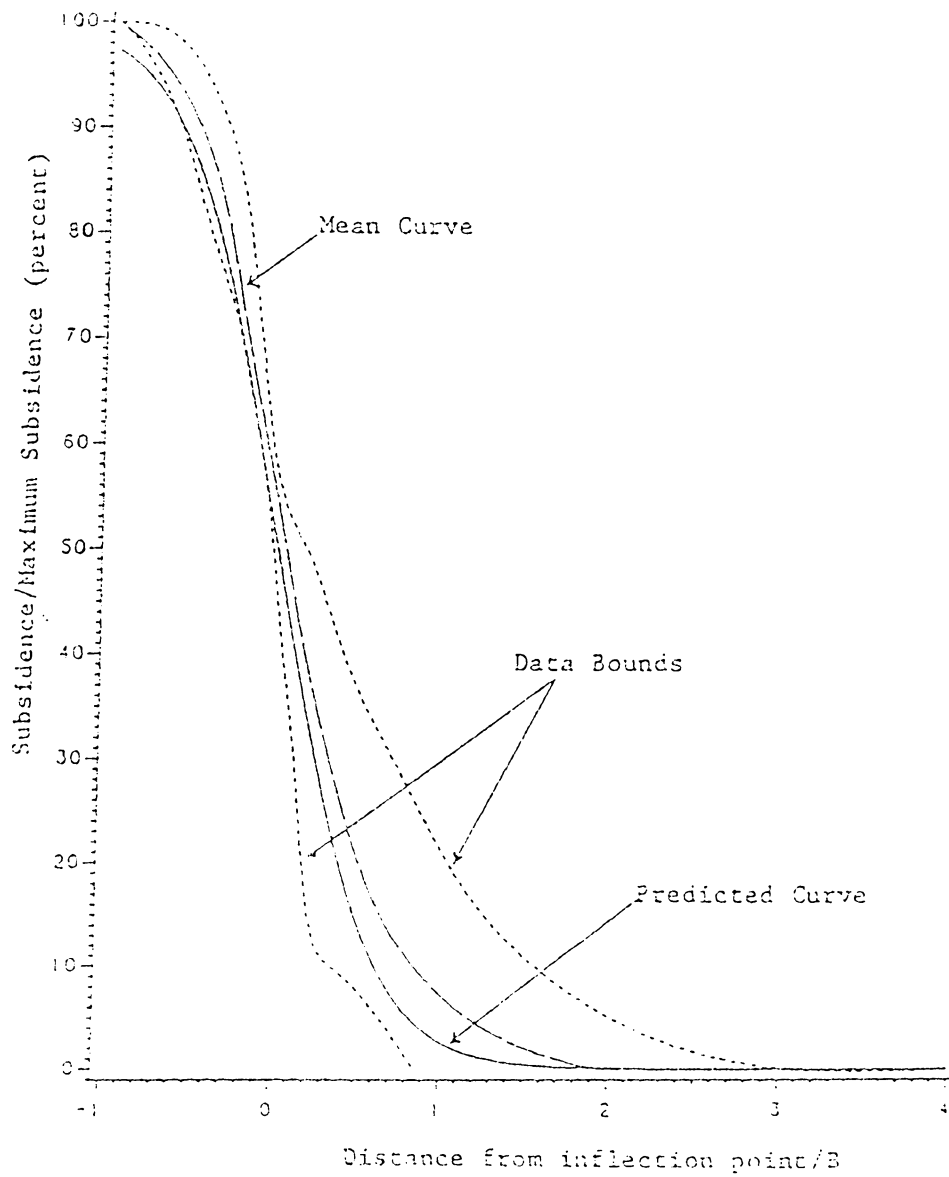


Figure 4.3.4 Determination of the Hyperbolic Tangent Profile Function for Critical and Supercritical Extractions.

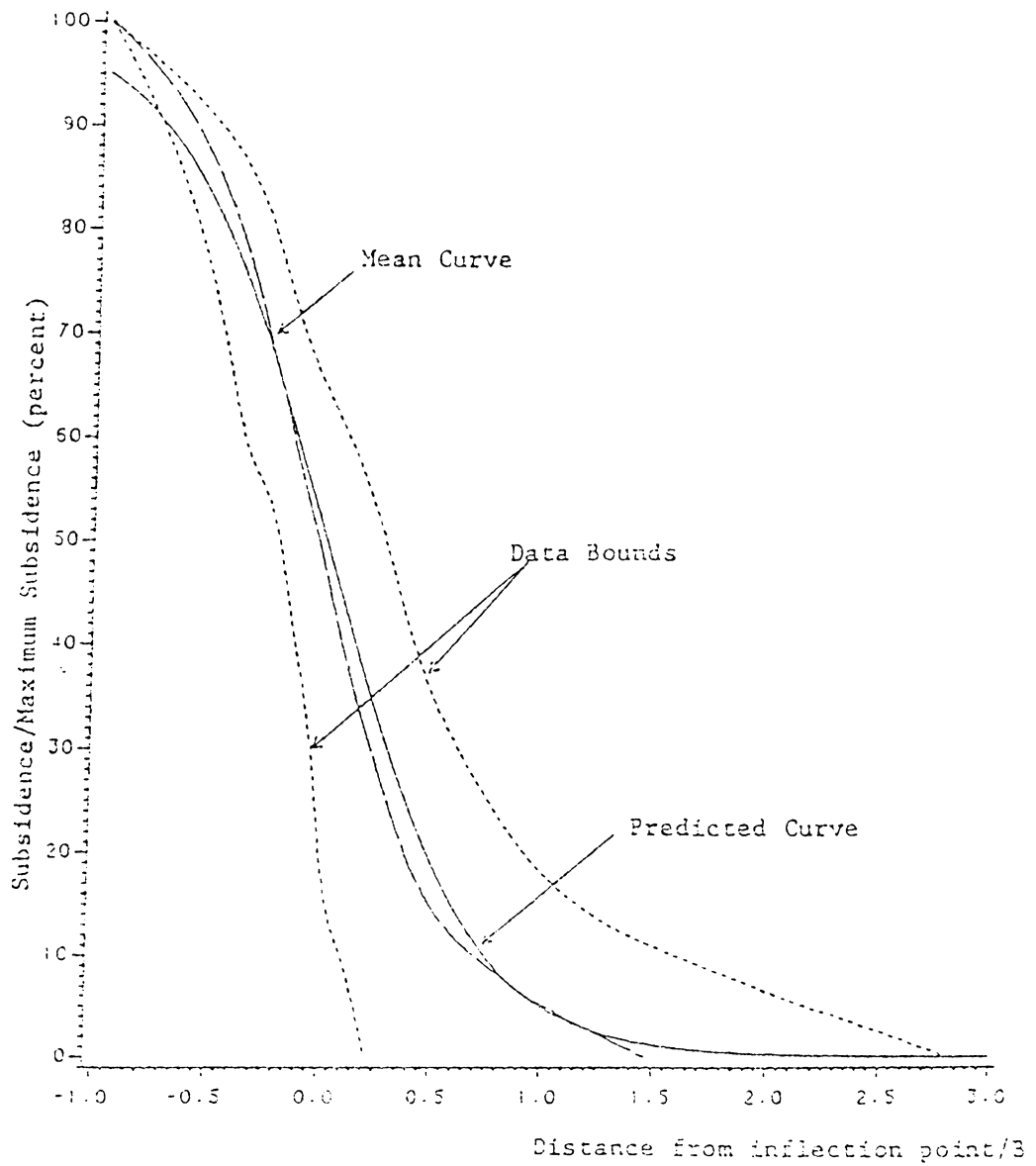


Figure 4.3.5 Determination of the Hyperbolic Tangent Profile Function for Subcritical Extractions.

dence value when a smaller percent of hardrock is present in the overburden. By mathematically combining the equations which describe these relationships, an expression containing all three variables was determined. The field data were fed into this equation and a nonlinear regression computer program was used to determine a series of curves. Thus, a three-dimensional relationship was established between the maximum subsidence factor, the percent of hardrock, and the panel geometry. Because the amount of hardrock found in the overburden of the collected panels ranged from 5 to 60 percent, the curves outside of this range were interpolated from the equation. This series of curves, which are shown in Figure 4.3.6, enable the maximum subsidence value for a given amount of hardrock and a certain width-to-depth ratio to be predicted in the Appalachian Region.

An entire subsidence profile can now be developed for Appalachian mining conditions. The maximum predicted subsidence factor is found from Figure 4.3.6. This value may then be used in conjunction with the hyperbolic tangent equation 4.3.1, to obtain subsidence values at different distances, x , from the panel centerline. The result is a subsidence profile which illustrates the magnitude, limit, and shape of the vertical surface displacements. These re-

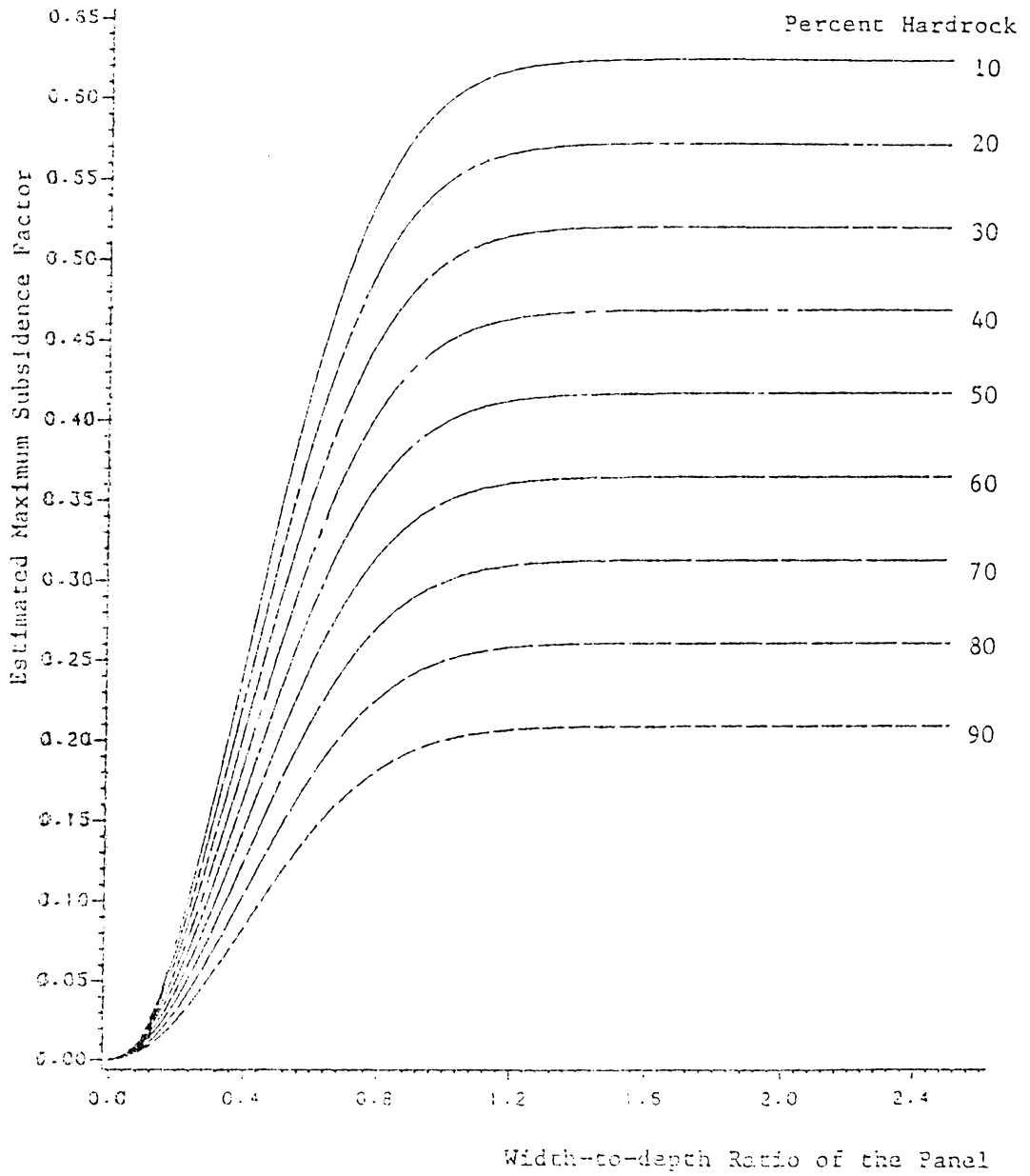


Figure 4.3.6 Determination of the Maximum Subsidence Factor From the Width-to-depth Ratio and the Percent of Hardrock.

relationships have been tabulated, using a computer program, and are shown in Tables IX and X.

The accuracy of this method was checked by inputting the raw data into the curves of Figure 4.3.6, and comparing the results with the actual subsidence values. The error determined between the field and predicted maximum factors was 17.5 percent. When compared with other prediction models, both empirical and theoretical, this empirical system can claim a superior accuracy.

A computer program was developed to plot the predicted subsidence profiles. The input required for this program includes the width-to-depth ratio of the panel, the seam thickness, the percent of hardrock in the overburden, and the maximum subsidence factor as determined from Table IX or Figure 4.3.6. The computer will plot the subsidence at any specified horizontal distance from the panel centerline. A description of the computer program and a sample output are included in Appendix D. Figures 4.3.7 and 4.3.8 illustrate the accuracy of the predicted profiles as plotted by the computer. A comparison between the actual and predicted subsidence profiles is presented in Appendix E.

Because the model is relatively simple to use, this approach is practical as well as reliable. This method is

TABLE IX
DETERMINATION OF MAXIMUM SUBSIDENCE

MAXIMUM SUBSIDENCE AS A PERCENT OF SEAM THICKNESS									
PERCENT HARD ROCK									
VII	10	20	30	40	50	60	70	80	90
0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
0.05	0.005	0.005	0.004	0.004	0.003	0.003	0.002	0.002	0.002
0.10	0.020	0.010	0.016	0.015	0.013	0.012	0.010	0.008	0.007
0.15	0.043	0.040	0.036	0.033	0.029	0.025	0.022	0.018	0.015
0.20	0.075	0.069	0.063	0.056	0.050	0.044	0.038	0.031	0.025
0.25	0.113	0.104	0.095	0.085	0.076	0.066	0.057	0.047	0.038
0.30	0.156	0.143	0.130	0.117	0.104	0.091	0.078	0.065	0.052
0.35	0.203	0.186	0.169	0.152	0.135	0.118	0.102	0.085	0.068
0.40	0.251	0.230	0.209	0.188	0.167	0.146	0.126	0.105	0.084
0.45	0.298	0.273	0.249	0.224	0.199	0.174	0.149	0.125	0.100
0.50	0.344	0.316	0.287	0.258	0.230	0.201	0.173	0.144	0.115
0.55	0.388	0.356	0.323	0.291	0.259	0.227	0.194	0.162	0.130
0.60	0.428	0.392	0.357	0.321	0.285	0.250	0.214	0.179	0.143
0.65	0.464	0.425	0.387	0.348	0.309	0.271	0.232	0.194	0.155
0.70	0.495	0.454	0.413	0.372	0.330	0.289	0.248	0.207	0.166
0.75	0.522	0.479	0.435	0.392	0.348	0.305	0.262	0.218	0.175
0.80	0.545	0.499	0.454	0.409	0.364	0.318	0.273	0.228	0.182
0.85	0.563	0.517	0.470	0.423	0.376	0.329	0.282	0.236	0.189
0.90	0.579	0.530	0.482	0.434	0.386	0.338	0.290	0.242	0.194
0.95	0.591	0.541	0.492	0.443	0.394	0.345	0.296	0.247	0.198
1.00	0.600	0.550	0.500	0.450	0.400	0.351	0.301	0.251	0.201
1.10	0.612	0.561	0.511	0.460	0.409	0.358	0.307	0.256	0.205
1.20	0.619	0.568	0.516	0.465	0.413	0.362	0.310	0.259	0.207
1.30	0.623	0.571	0.519	0.467	0.416	0.364	0.312	0.260	0.208
1.40	0.624	0.572	0.520	0.469	0.417	0.365	0.313	0.261	0.209
1.50	0.625	0.573	0.521	0.469	0.417	0.365	0.313	0.261	0.209
1.60	0.625	0.573	0.521	0.469	0.417	0.365	0.313	0.261	0.209
1.70	0.625	0.573	0.521	0.469	0.417	0.365	0.313	0.261	0.209
1.80	0.625	0.573	0.521	0.469	0.417	0.365	0.313	0.261	0.209
1.90	0.625	0.573	0.521	0.469	0.417	0.365	0.313	0.261	0.209
2.00	0.625	0.573	0.521	0.469	0.417	0.365	0.313	0.261	0.209
2.20	0.625	0.573	0.521	0.469	0.417	0.365	0.313	0.261	0.209
2.40	0.625	0.573	0.521	0.469	0.417	0.365	0.313	0.261	0.209
2.60	0.625	0.573	0.521	0.469	0.417	0.365	0.313	0.261	0.209
2.80	0.625	0.573	0.521	0.469	0.417	0.365	0.313	0.261	0.209
3.00	0.625	0.573	0.521	0.469	0.417	0.365	0.313	0.261	0.209

TABLE X

DETERMINATION OF THE SUBSIDENCE PROFILE

DISTANCE FROM THE CENTER OF THE PANEL IN TERMS OF DEPTH													
SUBSIDENCE AS A PERCENT OF MAXIMUM SUBSIDENCE													
W/H	0	.05	.1	.2	.3	.4	.5	.6	.7	.8	.9	.95	1.00
0.00	0.319	0.221	0.197	0.171	0.154	0.140	0.127	0.114	0.100	0.084	0.061	0.042	0.000
0.05	0.340	0.236	0.210	0.182	0.164	0.149	0.135	0.122	0.107	0.090	0.065	0.044	0.000
0.10	0.362	0.251	0.224	0.194	0.174	0.159	0.144	0.129	0.114	0.095	0.069	0.047	0.000
0.15	0.384	0.266	0.237	0.206	0.185	0.168	0.153	0.137	0.121	0.101	0.073	0.050	0.000
0.20	0.407	0.282	0.251	0.218	0.196	0.178	0.162	0.146	0.128	0.107	0.078	0.053	0.000
0.25	0.431	0.296	0.266	0.231	0.208	0.189	0.171	0.154	0.136	0.113	0.082	0.056	0.000
0.30	0.455	0.315	0.281	0.244	0.219	0.199	0.181	0.163	0.143	0.120	0.087	0.059	0.000
0.35	0.479	0.332	0.296	0.257	0.231	0.210	0.191	0.171	0.151	0.126	0.091	0.063	0.000
0.40	0.505	0.350	0.312	0.270	0.243	0.221	0.201	0.180	0.159	0.133	0.096	0.066	0.000
0.45	0.530	0.367	0.328	0.284	0.256	0.232	0.211	0.190	0.167	0.140	0.101	0.069	0.000
0.50	0.557	0.386	0.344	0.298	0.268	0.244	0.221	0.199	0.175	0.147	0.106	0.073	0.000
0.55	0.584	0.404	0.360	0.313	0.281	0.256	0.232	0.209	0.184	0.154	0.111	0.076	0.000
0.60	0.611	0.423	0.377	0.328	0.295	0.268	0.243	0.219	0.192	0.161	0.116	0.080	0.000
0.65	0.639	0.443	0.395	0.343	0.308	0.280	0.254	0.229	0.201	0.168	0.122	0.084	0.000
0.70	0.668	0.463	0.412	0.358	0.322	0.292	0.266	0.239	0.210	0.176	0.127	0.087	0.000
0.75	0.697	0.483	0.431	0.374	0.336	0.305	0.277	0.249	0.219	0.184	0.133	0.091	0.000
0.80	0.727	0.504	0.449	0.390	0.350	0.318	0.289	0.260	0.229	0.191	0.138	0.095	0.000
0.85	0.757	0.525	0.468	0.406	0.365	0.332	0.301	0.271	0.238	0.199	0.144	0.099	0.000
0.90	0.788	0.546	0.487	0.423	0.380	0.345	0.313	0.282	0.248	0.208	0.150	0.103	0.000
0.95	0.820	0.568	0.506	0.439	0.395	0.359	0.326	0.293	0.258	0.216	0.156	0.107	0.000
1.00	0.852	0.590	0.526	0.457	0.411	0.373	0.339	0.305	0.268	0.224	0.162	0.111	0.000
1.10	0.918	0.636	0.567	0.492	0.442	0.402	0.365	0.328	0.289	0.242	0.175	0.120	0.000
1.20	0.986	0.683	0.609	0.529	0.475	0.432	0.392	0.353	0.310	0.260	0.188	0.129	0.000
1.30	1.057	0.732	0.653	0.566	0.509	0.463	0.420	0.378	0.333	0.278	0.201	0.138	0.000
1.40	1.130	0.783	0.698	0.605	0.544	0.495	0.449	0.404	0.355	0.298	0.215	0.148	0.000
1.50	1.205	0.835	0.744	0.646	0.581	0.528	0.479	0.431	0.379	0.317	0.229	0.158	0.000
1.60	1.282	0.888	0.792	0.687	0.618	0.561	0.510	0.459	0.404	0.338	0.244	0.168	0.000
1.70	1.362	0.944	0.841	0.730	0.657	0.596	0.542	0.487	0.429	0.359	0.259	0.178	0.000
1.80	1.444	1.001	0.892	0.774	0.696	0.632	0.574	0.517	0.454	0.380	0.275	0.189	0.000
1.90	1.529	1.059	0.944	0.819	0.737	0.669	0.608	0.547	0.481	0.403	0.291	0.200	0.000
2.00	1.615	1.119	0.998	0.866	0.779	0.707	0.642	0.578	0.508	0.426	0.308	0.211	0.000
2.20	1.796	1.244	1.109	0.963	0.866	0.786	0.714	0.642	0.565	0.473	0.342	0.235	0.000
2.40	1.985	1.376	1.226	1.064	0.957	0.869	0.789	0.710	0.625	0.523	0.378	0.260	0.000
2.60	2.184	1.513	1.349	1.171	1.053	0.956	0.868	0.781	0.687	0.575	0.416	0.286	0.000
2.80	2.392	1.658	1.477	1.282	1.153	1.047	0.951	0.856	0.753	0.630	0.456	0.313	0.000
3.00	2.610	1.808	1.612	1.399	1.258	1.143	1.038	0.933	0.821	0.687	0.497	0.341	0.000

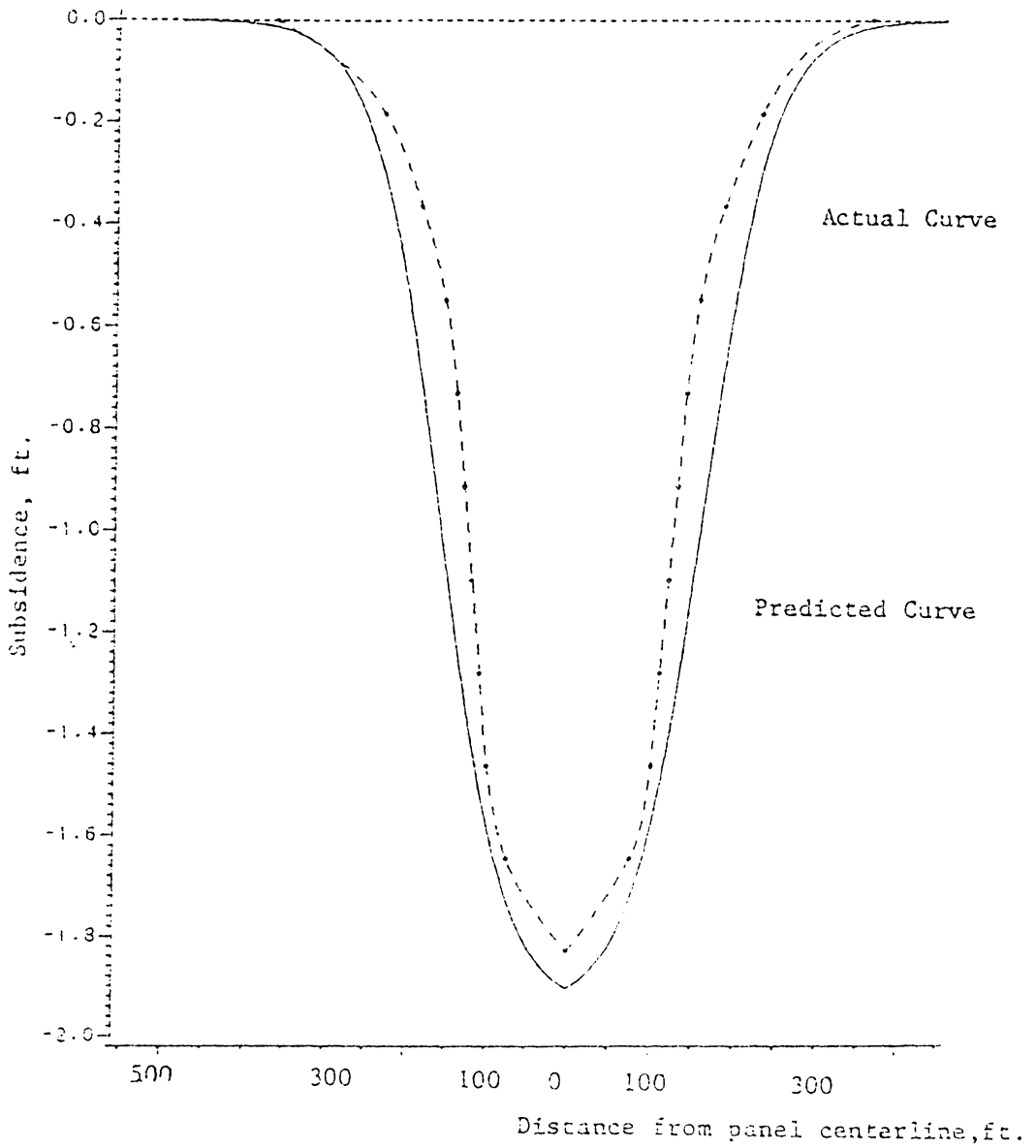


Figure 4.3.7 The Computer Plotted Subsidence Profile of Case Study 4a.

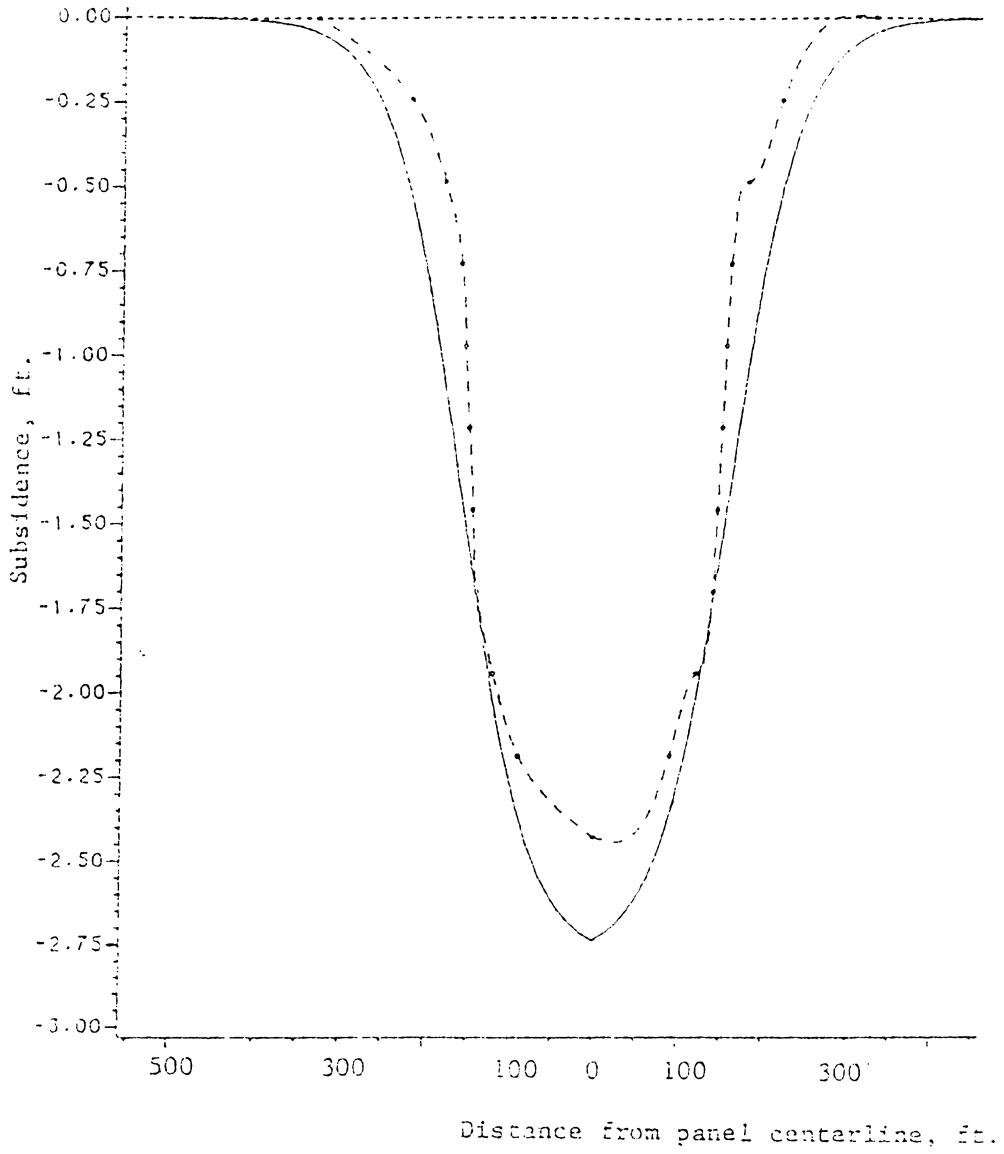


Figure 4.3.8 The Computer Plotted Subsidence Profile of Case Study 5a.

currently the only model which has incorporated the influence of geology into its predictive capabilities. Furthermore, it can be claimed that other prediction systems available do not provide these qualifications for Appalachian mining conditions, making this the most qualified system to be used by the Appalachian mine operator.

4.4 Time Factors

The development of subsidence is an important concept in the area of mine design. The time taken for a surface point to begin or complete subsidence is directly related to the stress redistribution above the waste area. This relationship can be used to obtain valuable guidelines for barrier pillar design.

The average development curves of the Appalachian longwall panels, which were not influenced by adjacent workings, are shown in Figure 4.4.1. These curves represent the development of subsidence for a surface point as the mining face approaches, passes underneath, and advances beyond the point. The surface point first responds to the approaching longwall face when the face is between $0.5h$ to $0.6h$ away from it. In the Appalachian Region, the surface has often been observed to heave beyond this range as a response to the cantilever action which begins at the support line (Ros-

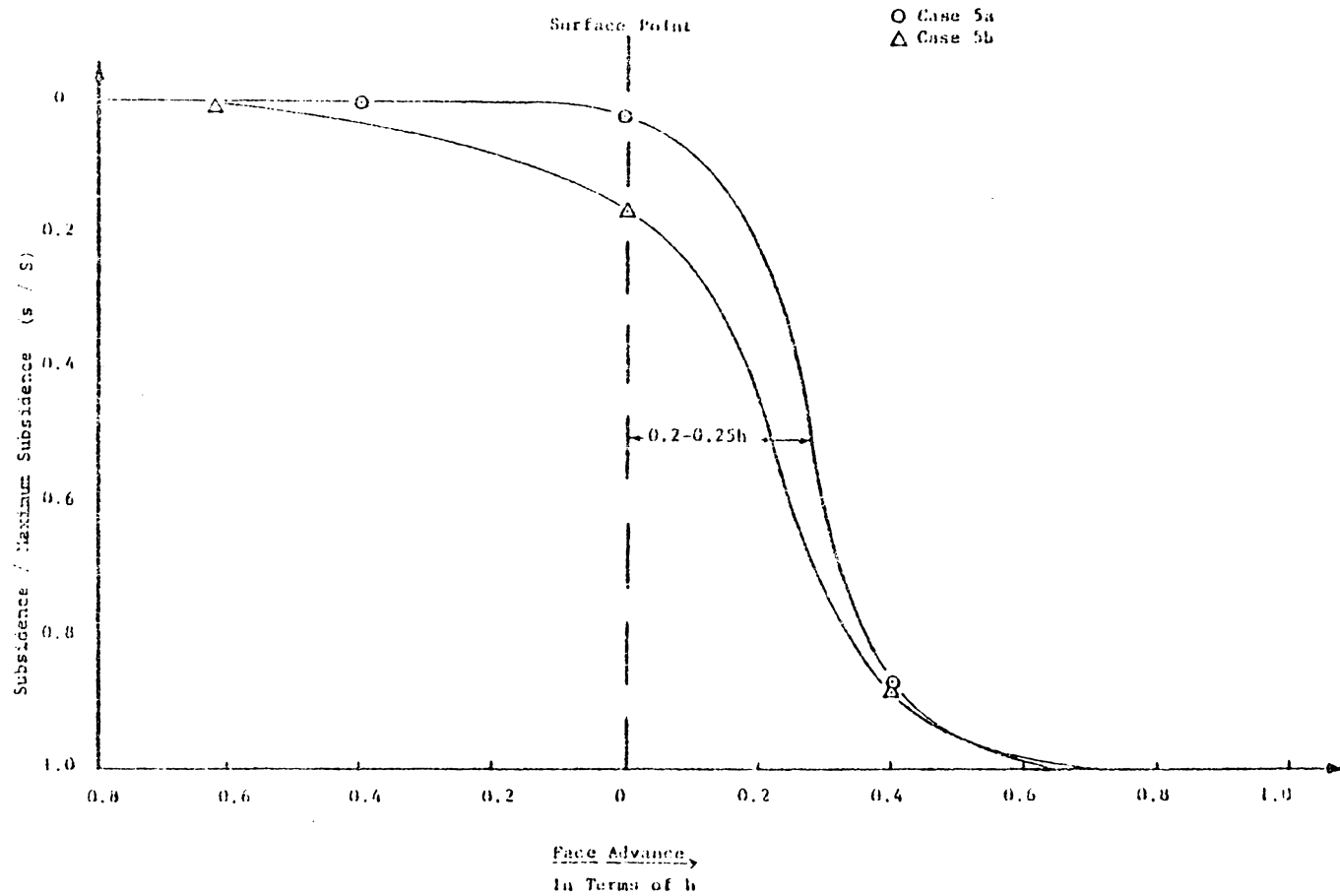


Figure 4.4.1 A typical development curve of the collected case studies.

coe, 1980). This positive subsidence, or uplift, has also been witnessed beyond the zero limit of subsidence along the sides of, in front of, and behind the panel. The range of $0.5h$ to $0.6h$ differs from the distance of $0.75h$ found for British conditions, once again indicating that smaller distances are required to reach critical conditions in Appalachia.

When the face has advanced about $0.55h$ beyond the surface point, the active subsidence of the point is complete, and is independent of further face advances along the panel. Although this distance is smaller than that found by the NCB ($0.7h$), the same fundamental relationship concerning the development of subsidence is observed. Active subsidence begins and is almost fully developed when the coal face has travelled a distance equal to approximately two times the draw before and beyond the point in question. This means that a surface point is subjected to vertical displacement only while the face is located within this critical distance, which has been determined to equal about $1.4h$ for British mines and $1.1h$ for Appalachian mines.

Although the critical width-to-depth ratios of the two mining regions differ, some similarities were found for the development of subsidence in the British and Appalachian coalfields. When the face is located below the point in

question, approximately 15 to 16 percent of the maximum subsidence is reached in both regions. Also, 50 percent of the active subsidence, in both coalfields, is complete when the face has advanced between $0.20h$ and $0.25h$ beyond it. The initial and final 0 to 5 percent of subsidence is difficult to determine and somewhat variable, so active subsidence is believed to be complete when approximately 98 percent of the maximum value is reached.

Chapter V

CONCLUSIONS AND RECOMMENDATIONS

During this research investigation, characteristic subsidence relationships and trends were established for the Appalachian coalfields. The collected information enabled the development of an empirical subsidence prediction model which can be applied to this region, with an accuracy of less than +20 percent. The primary and unique advantage of this prediction system is that the influence of the overburden lithology was incorporated into its design. Although the variation of lithology is one of the main reasons that an empirical subsidence prediction system is not generally applicable beyond the region it was developed, the effect of this variable on subsidence has not yet been included in any other predictive model. As a result, this method presents a more accurate and practical subsidence prediction capability. This is explicitly shown by the comparisons of Appendix D.

The empirical model presented here possesses the limitation of being primarily applicable in the Appalachian Region and may require modification before it can be applied

in other coalfields. This approach, however, is easy to use and provides accurate predictions. Therefore, it will prove to be invaluable to mine operators. Furthermore, other approaches, such as theoretical and mathematical approaches to mine subsidence, will be greatly facilitated and enhanced by the data bank and the relationships which have been established during this study.

Although the research performed during this investigation has covered a number of parameters which influence mine subsidence, there are several areas which require further investigation:

-Stratigraphy: The relative position and the thickness of the various layers in the overburden considerably affect surface subsidence; however, the precise nature of this influence is not yet known. An investigation involving the effect of the various bed thicknesses and their locations in the overlying strata on subsidence could greatly complement the lithologic influence already established in this study. These relationships could also be used to establish guidelines concerning the height of caving above a

particular seam. In addition, more research is needed to incorporate the competence of the various layers, the presence of water, and the significance of any discontinuities on the subsidence characteristics.

-Topography: The influence of topography on subsidence continues to be a somewhat controversial topic for subsidence engineers. It was not possible to perform a thorough investigation on this subject with the available data, because the majority of the case studies did not exhibit a significant variation in surface topography. In the few cases where the topography map indicated that a rolling or hilly terrain was present above a particular panel, several profiles were plotted at various positions along the panel. Although it appeared that the angle of draw was affected by this change in contour, the maximum subsidence was suggested to be independent of the variable. However, further analyses are required before significant conclusions can be made.

-Data Bank: The data which was gathered for this research originated from longwall mines located in five states within the Appalachian Region. However, some of the coalfields in this region have not been as highly researched as others. Consequently, it is recommended that efforts should continue to gather subsidence data from these coalfields, particularly from the mining districts of Kentucky, Virginia, and Alabama.

In addition, such a subsidence data bank should be attempted for the other longwall mining regions of the United States. Such a task can be greatly facilitated by the procedures and guidelines described in this research.

-Room-and-pillar Mining: Although longwall mining continues to increase in popularity in the United States, room-and-pillar mining is currently the method most widely used. It has been suggested that full pillar extraction will initiate a surface response similar to that caused by longwall panel extraction (Peng, 1978). However, the subsidence studies related to this mining

method remain virtually nonexistent. Therefore, it is recommended that subsidence monitoring programs for both full and partial room-and-pillar methods be performed, and the data subsequently analyzed in a fashion similar to what has been described in this work. Such a study is necessary to combat the often severe problems of abandoned mines.

-Survey Methods: All of the case studies which have been presented in this reasearch include data from surveys performed by mine personnel. For this reason, no established and consistent procedure was used to either gather or record the subsidence data. To ensure control over the quantity, quality, and method of obtaining future subsidence information, of any form, it is believed that a comprehensive study should be conducted, with great attention focused on factors such as the type of survey monument, the positioning and spacing of the stations, monitoring intervals, etc. Such a comprehensive investigation would enable the subsidence investiga-

tors to conduct the type of analyses desired and record the factors affecting ground movements.

-Strain Investigations: Vertical displacement of the ground surface is the most commonly monitored subsidence parameter. However, it has been established that the horizontal displacement, i.e. the strain induced by subsidence, is the factor which mostly causes damage to surface structures. Only two subsidence studies found in literature had monitored the horizontal displacements caused by mining. One of the case studies gathered for this research had also monitored the horizontal surface movements. Because this is the main subsidence characteristic associated with structural damage, greater efforts should be directed towards additional information. Analyses of this phenomenon would enable the development of better guidelines for the prediction and control of structural damage above coal mine operations.

Finally, surface subsidence is an inevitable consequence of underground coal mining. Although it cannot be prevented, at least under the existing technological and economical conditions, it can be controlled within acceptable environmental levels--if an accurate method of prediction is available. The research presented in this thesis could greatly facilitate the realization of this objective.

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Appendix A

EXAMPLE OF FORM LETTER



COLLEGE OF ENGINEERING

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Blacksburg, Virginia 24061

DEPARTMENT OF MINING AND MINERALS ENGINEERING (705) 961-6571

As you know many methods have been used to predict surface subsidence. The main problem with most of these techniques is that they are generalized and ignore regional geological variations. Our approach is basically an empirical one and our effort is concentrated in compiling, processing and regionalizing available subsidence data pertaining to longwall, as well as room-and-pillar mining. We firmly believe in a regionalized or even a sub-regionalized subsidence characterization and, as a result, we plan to process the data not only according to mining variables but also taking into account the geological environment. Our optimum goal is to present the mining industry with "easy to follow" guidelines regarding subsidence, in the form of simple tables and charts and furthermore, to establish this information according to regional and sub-regional trends.

As you can appreciate, our approach depends a great deal on the amount and quality of the collected data. In order to implement this, we have already collected most information which is available in the literature and in addition, we are in the process of contacting federal agencies and the mining industry for any unpublished information which is not available through publications and reports. Any such information forwarded to us will, of course, be treated confidentially. The basic parameters needed for our project are listed on the attached SUBSIDENCE INFORMATION page. From our part, we will be delighted to share with you our results and keep you informed on our progress.

Your help in this matter is appreciated and we look forward to receiving any information that you may have, or any suggestions that you would like to make.

Sincerely yours,

c.c. B. Webb
T. Triplett
attachment

Michael Karris
Associate Professor

SUBSIDENCE INFORMATION

- I. Topography of the area
- II. Approximate geologic column of the mining section
- III. Mine layout
 - A. Dip, depth, and thickness of the seam,
 - B. Mine maps,
 - C. Maps indicating locations of measurement stations,
- IV. Subsidence data
 - A. Subsidence readings,
 - B. Face advance relative to subsidence readings (if available),
 - C. Duration of subsidence measurements
 - D. Any irregularities observed during subsidence measurements.

Appendix B
EXAMPLE OF SURVEY SHEET

Appendix C

COMPARISONS OF NCB PREDICTIONS WITH ACTUAL FIELD
DATA

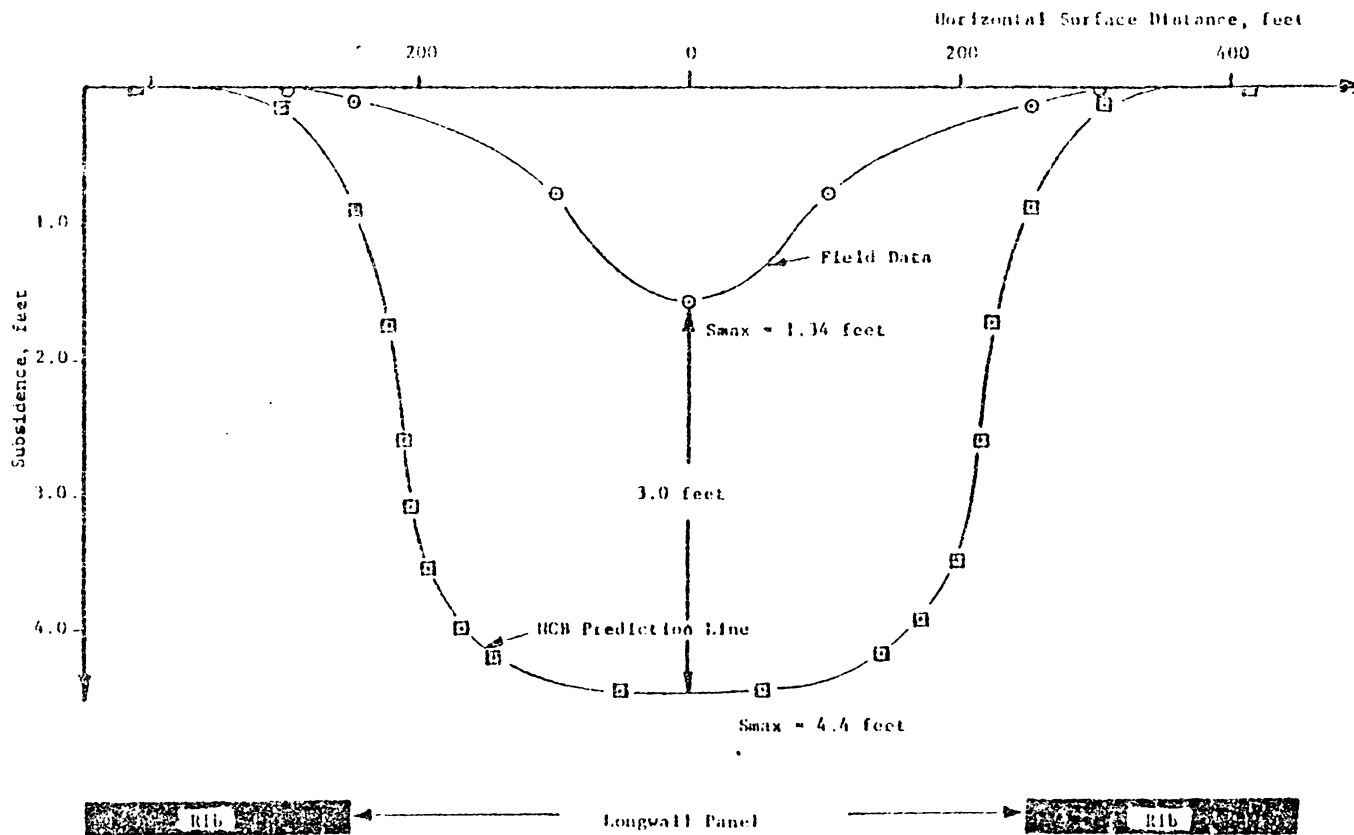


Figure C1: Comparison of Field Data with NCB Prediction.

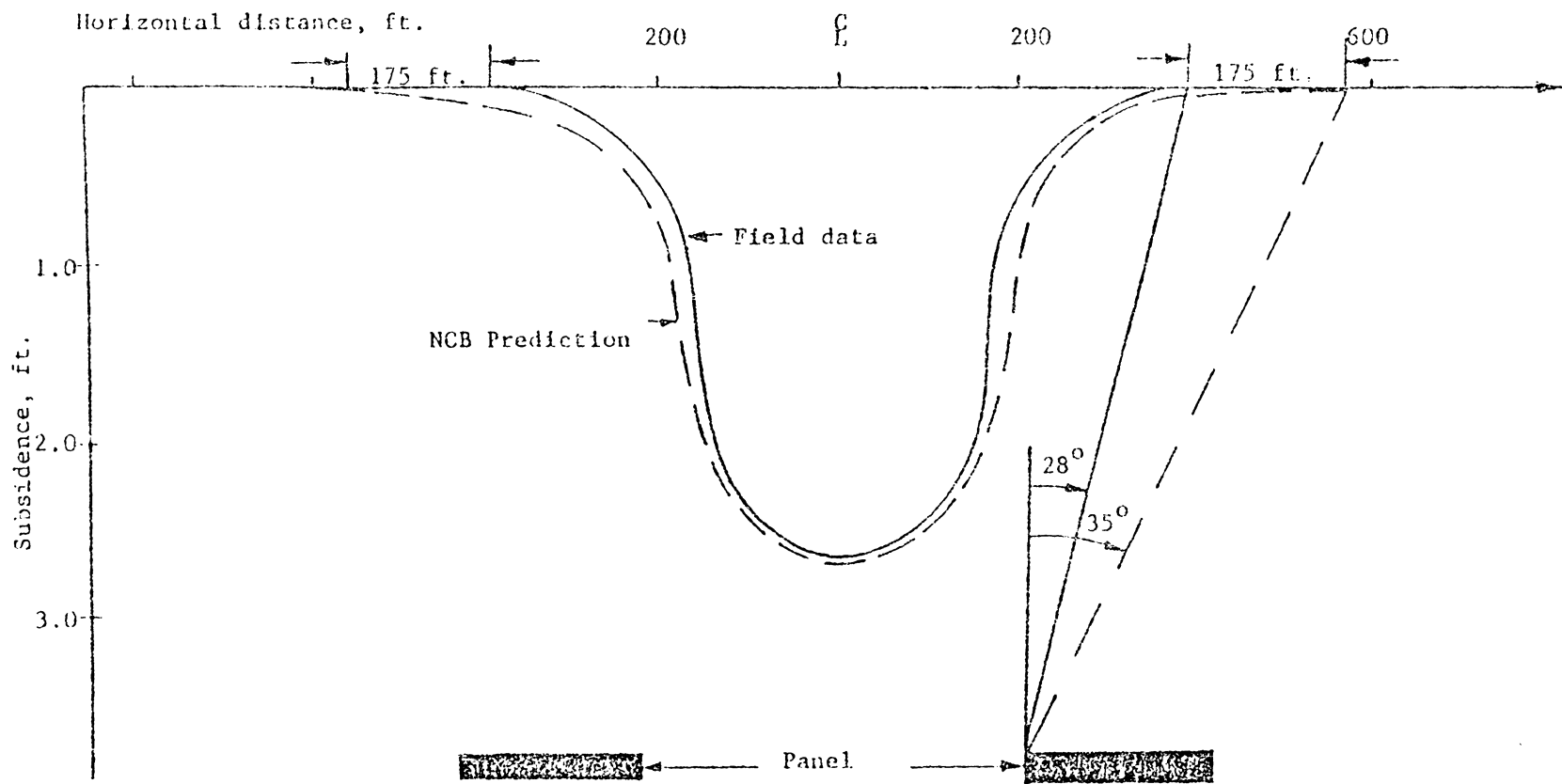


Figure C2 Comparison of Field Data with NCB Prediction.

Scale: 1"=200 ft.

Appendix D

DESCRIPTION OF COMPUTER PROGRAM

DESCRIPTION OF THE COMPUTER PROGRAM
WITH SAMPLE OUTPUT

A computer program was designed to provide plots of the predicted subsidence profiles. Although Figures 4.3.7 and 4.3.8 include the actual field subsidence profiles, the computer will only plot the predicted contour.

INPUT VARIABLES: A data set is composed of only one card. This card contains the observation number, the width of the excavation, the depth of the excavation, the seam thickness, the percentage of hardrock in the overburden, the width-to-depth ratio, the predicted distance from the center of the panel to the inflection point (obtained from Figure C1), and the predicted maximum subsidence value (obtained from Figure 4.3.6). These variables are abbreviated in the following manner:

OBS-Observation number

W-Width of the panel

H-Depth of the panel

M-Seam Thickness

HARD-Percent of Hardrock

WH-Width-to-depth ratio

BHAT-Predicted distance from centerline to inflection
point

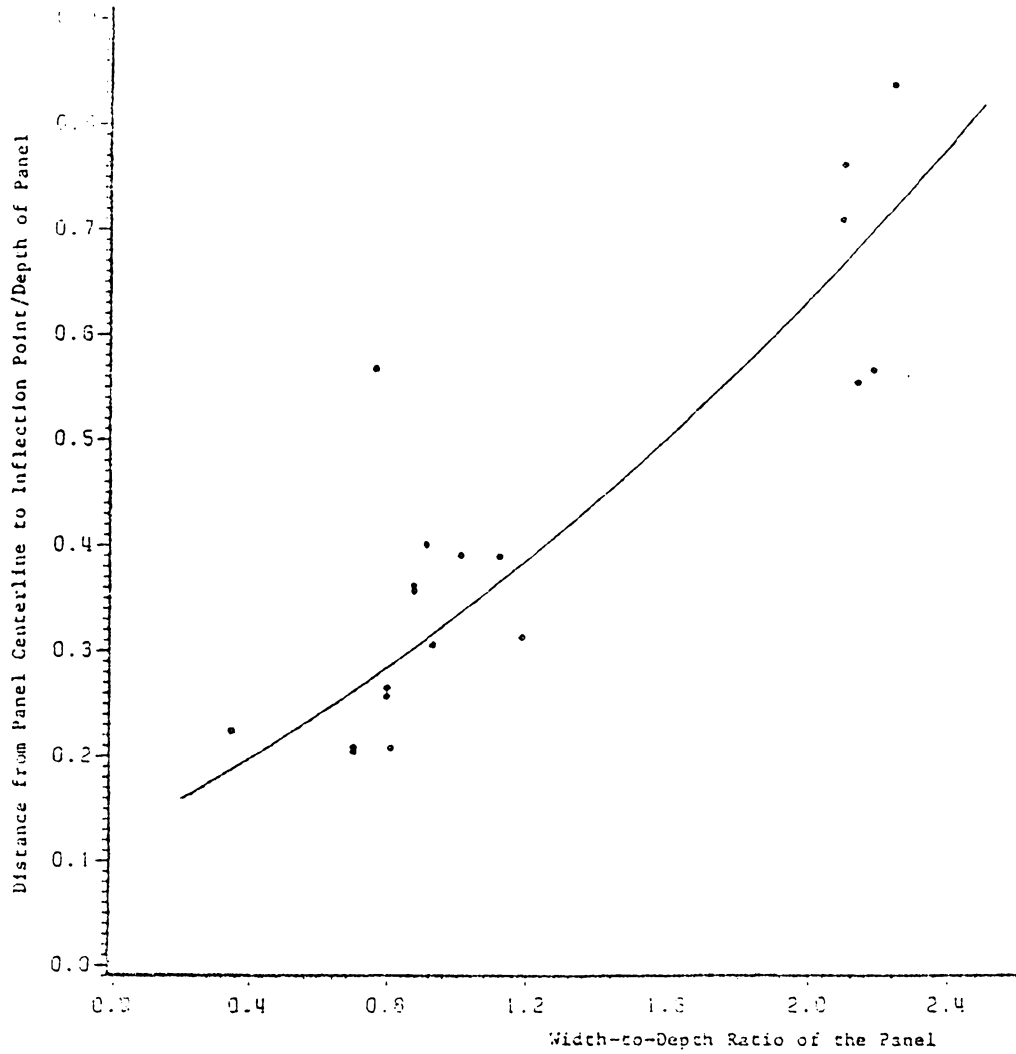


Figure D1: Prediction of B from the Actual Field Data.

SMAXHAT-Predicted maximum subsidence

OUTPUT VARIABLE: The output variables include the observation number, the horizontal distance from the centerline at which the subsidence was predicted, and the predicted subsidence value. These variables are designated as follows:

OBS-Observation number

X-Horizontal distance from the centerline SHAT-Predicted subsidence value

A brief summary of the computer program is presented on the next page. This is followed by two pages of sample output and a predicted contour, as plotted by the Virginia Tech CALCOMP plotter.

SAMPLE INPUT

PREDICTED DISTANCE TO INFLECTION POINT AND BALBOA SUBSIDENCE

OBS	n	H	B	HAAD	SH	BHAT	SHAADHAT
1	500	250	0	22	2	0.0358	0.502998

SAMPLE OUTPUT

OBS	X	SHAT
1	0.00000	0.502998
2	0.03179	0.500604
3	0.06358	0.557720
4	0.09537	0.554256
5	0.12716	0.550104
6	0.15895	0.545140
7	0.19074	0.539227
8	0.22253	0.532271
9	0.25432	0.523926
10	0.28611	0.514196
11	0.31790	0.502652
12	0.34969	0.489719
13	0.38148	0.474653
14	0.41327	0.457546
15	0.44506	0.438346
16	0.47685	0.417077
17	0.50864	0.393857
18	0.54043	0.368686
19	0.57222	0.342502
20	0.60401	0.315111
21	0.63580	0.287197
22	0.66759	0.259284
23	0.69938	0.231893
24	0.73117	0.205509
25	0.76296	0.180544
26	0.79475	0.157316
27	0.82654	0.136048
28	0.85833	0.116646
29	0.89012	0.099742
30	0.92191	0.084676
31	0.95370	0.071543
32	0.98549	0.060796
33	1.01728	0.050469
34	1.04907	0.042184
35	1.08086	0.035168
36	1.11265	0.029255
37	1.14444	0.024291
38	1.17623	0.020136
39	1.20802	0.016674

40	1.23961	0.013791
41	1.27160	0.011396
42	1.30359	0.009470
43	1.33518	0.007760
44	1.36697	0.006405
45	1.39876	0.005261
46	1.43055	0.004352
47	1.46234	0.003586
48	1.49413	0.002954
49	1.52592	0.002433
50	1.55771	0.002003
51	1.58950	0.001649
52	1.62129	0.001356
53	1.65308	0.001118
54	1.68487	0.000920
55	1.71666	0.000757
56	1.74845	0.000625
57	1.78024	0.000512950
58	1.81203	0.000422140
59	1.84382	0.000347397
60	1.87561	0.000285861
61	1.90740	0.000235255

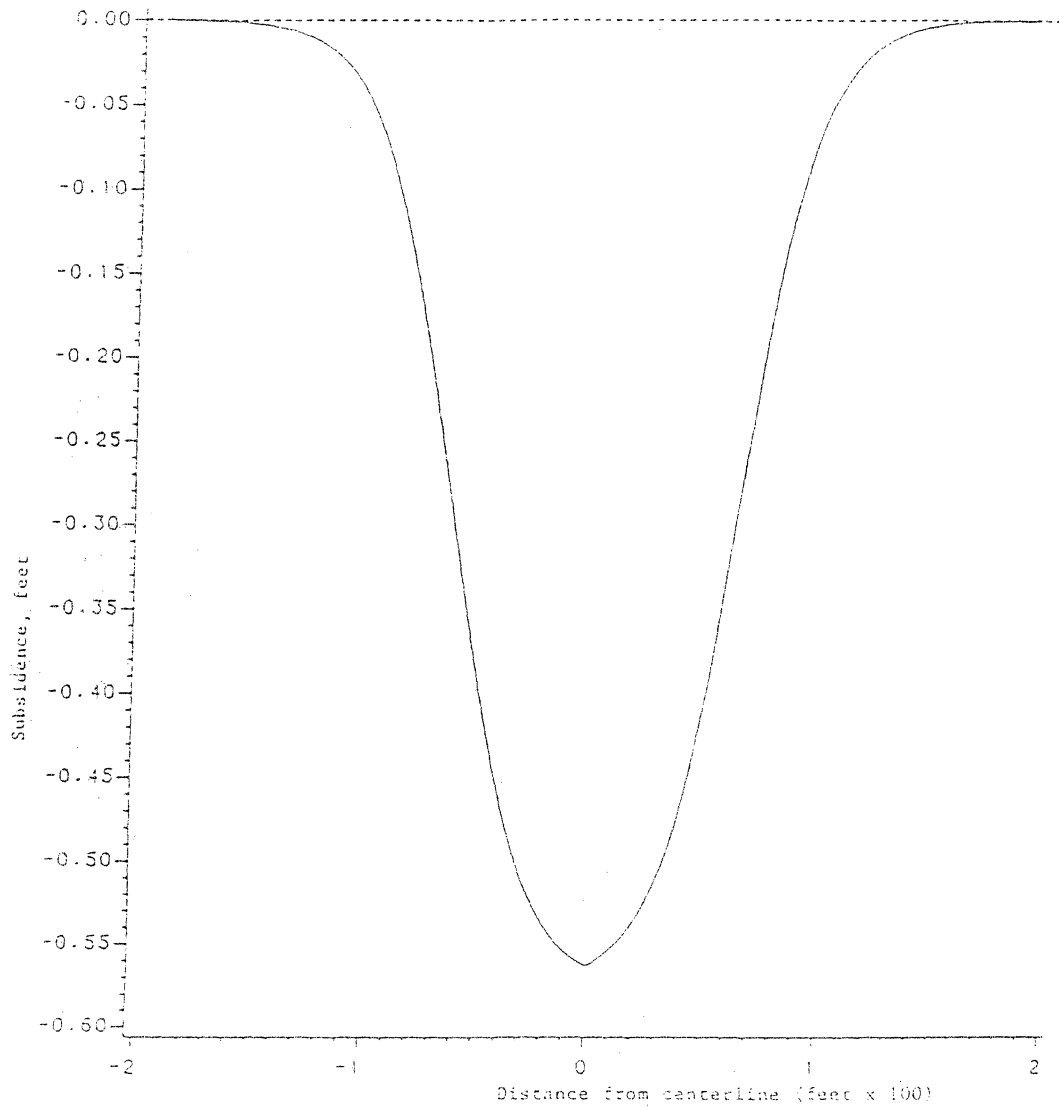
PREDICTED CONTOUR

Figure D2: Example of Predicted Contour for Hypothetical Longwall Extraction.

Appendix E

COMPARISONS OF THE EMPIRICAL PREDICTION METHOD
WITH THE RAW DATA

CASE STUDY 2A

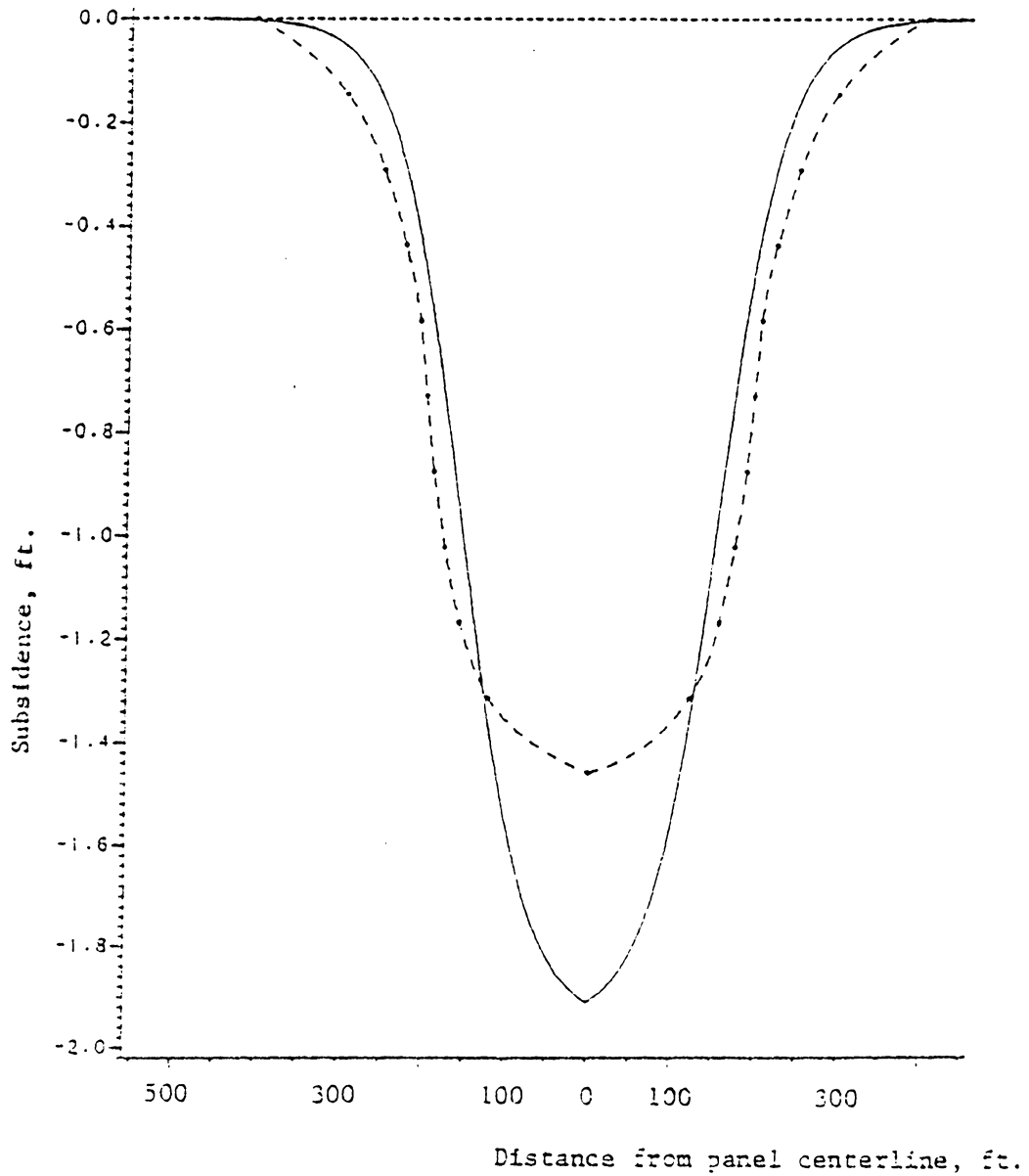
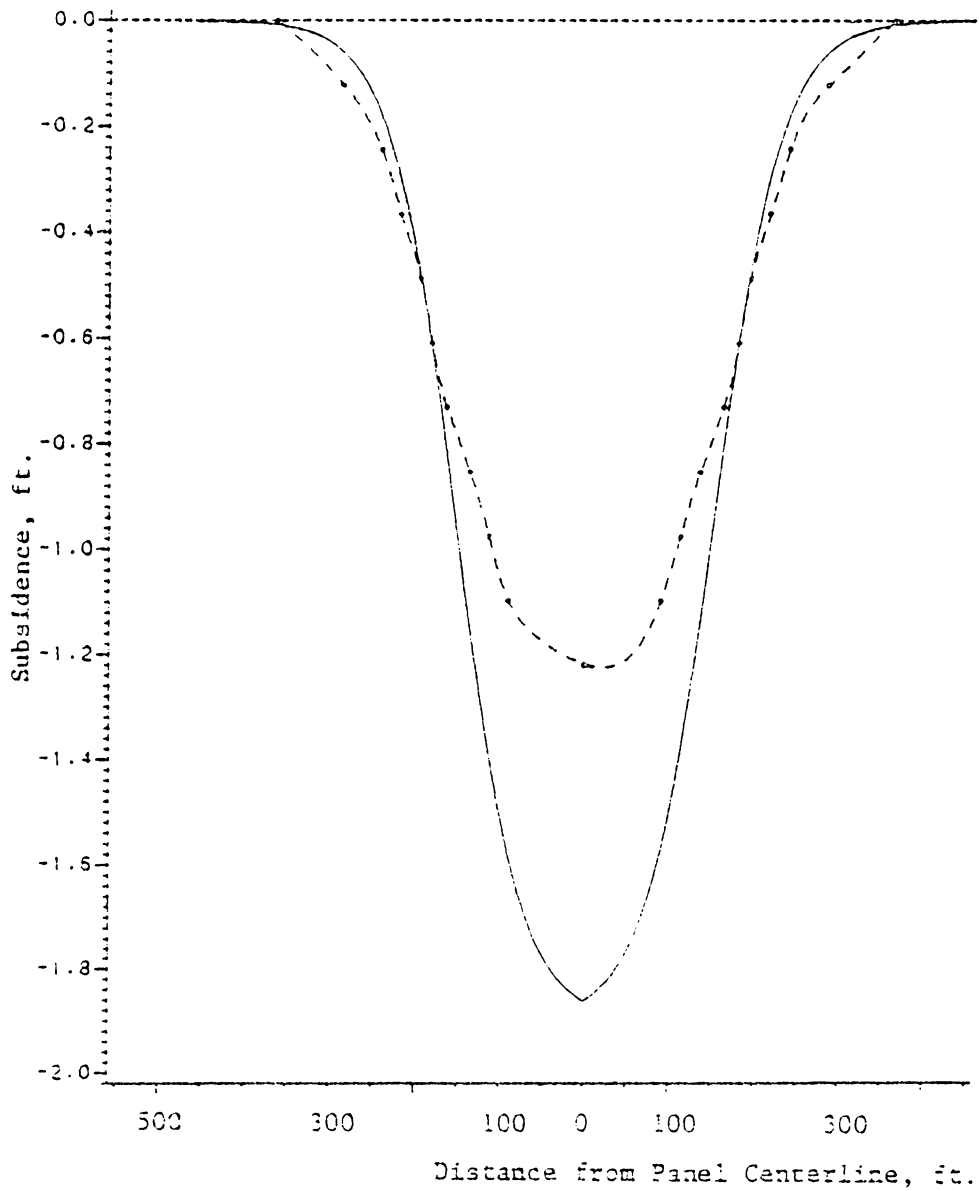


Figure E1: Estimated Subsidence Curve for Case 2a.

CASE STUDY 2B



SOLID LINE IS THE PREDICTED PROFILE
BROKEN LINE IS THE ACTUAL PROFILE
STARS INDICATE ACTUAL MEASUREMENTS

Figure E2: Estimated Subsidence Curve for Case 2b.

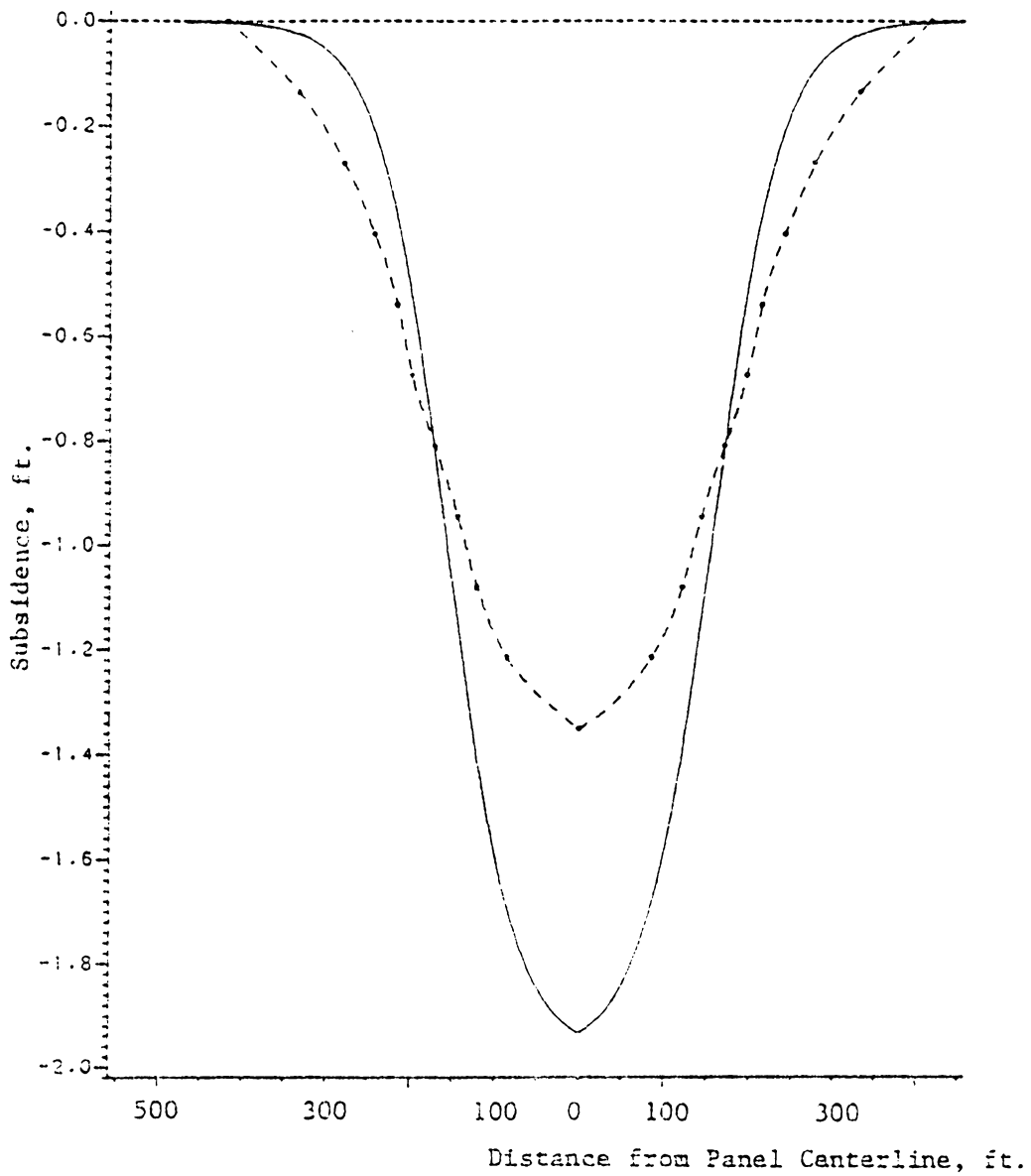
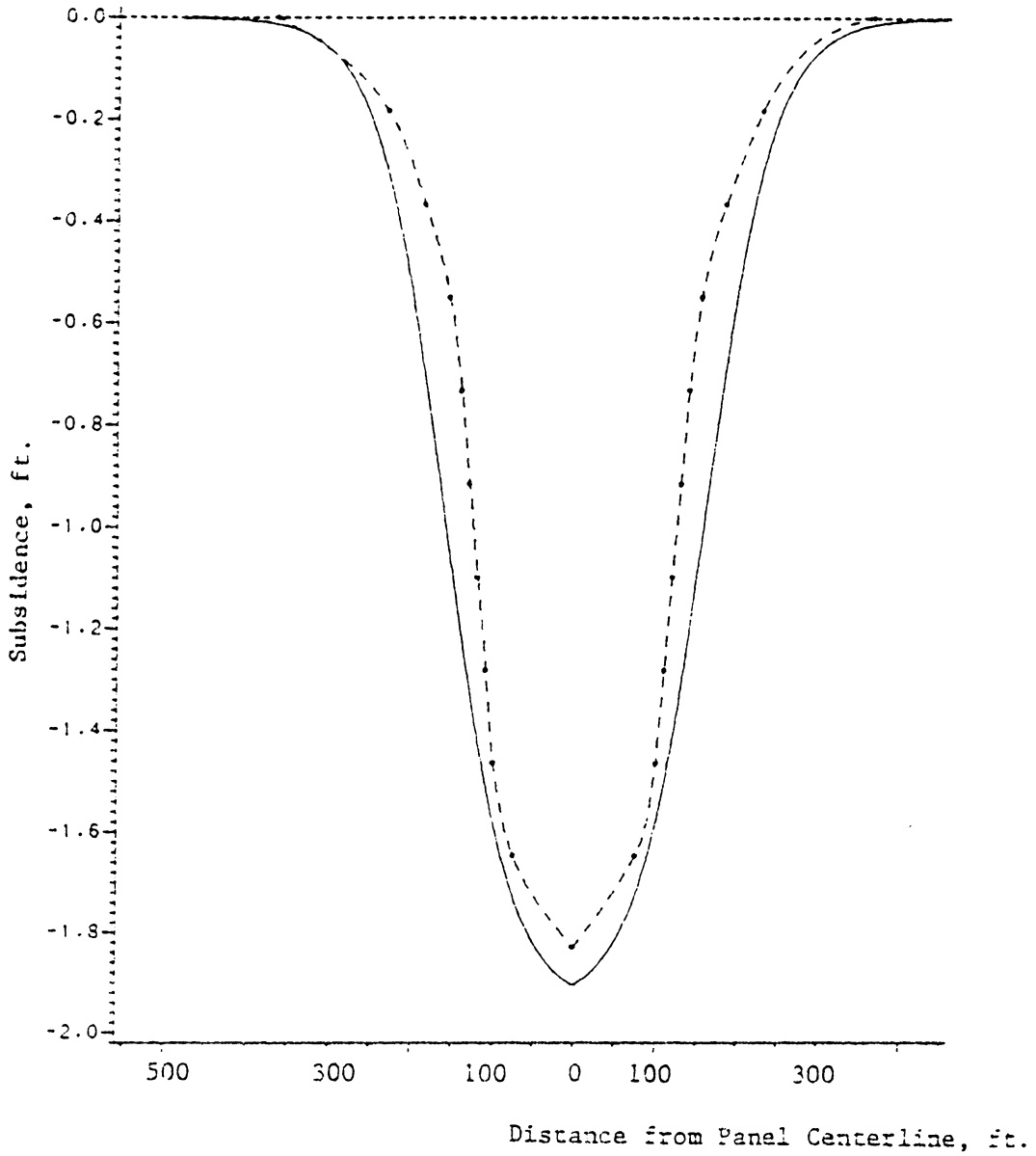
CASE STUDY 2C

Figure E3: Estimated Subsidence Curve for 2c.

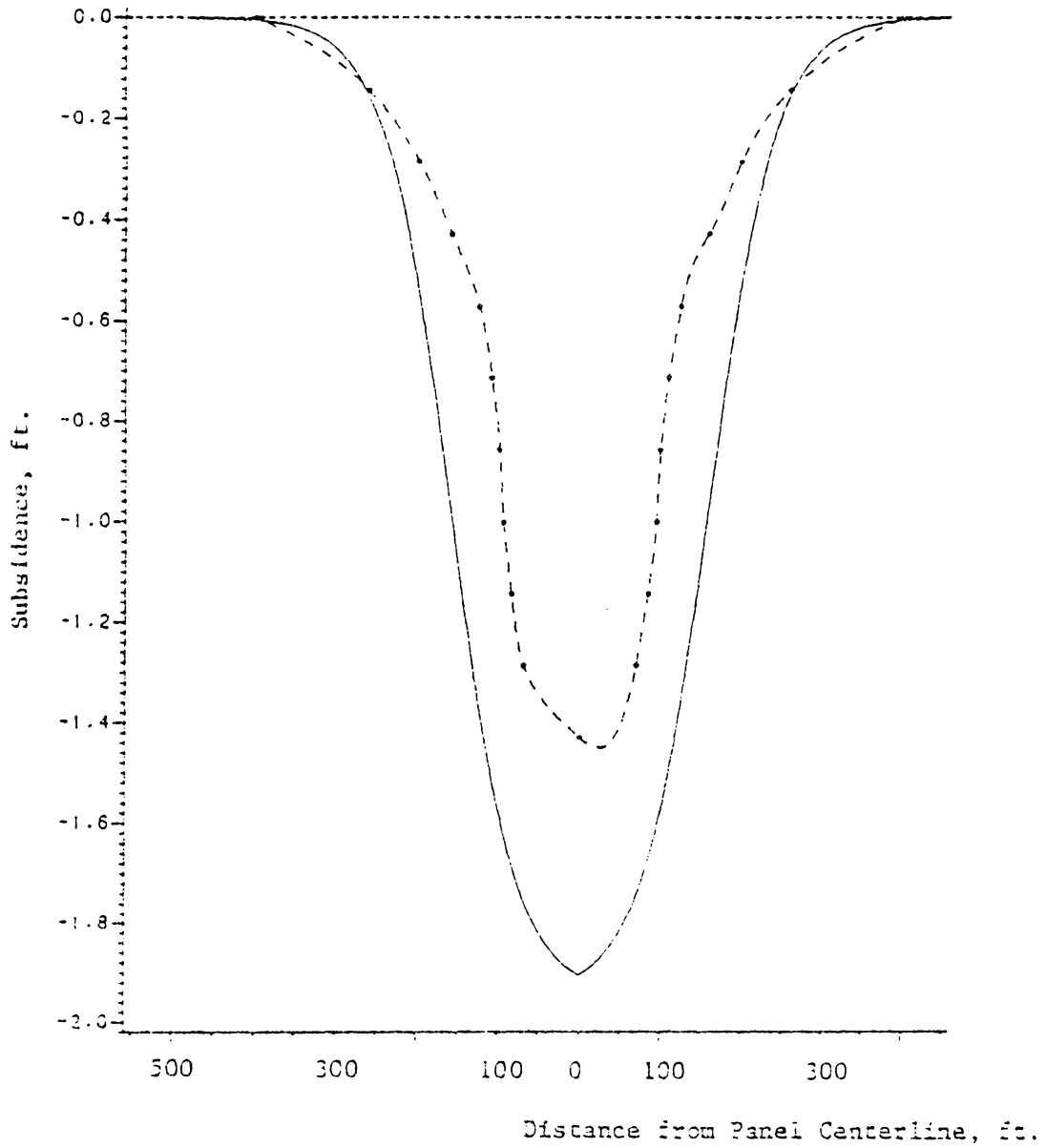
CASE STUDY 4A



SOLID LINE IS THE PREDICTED PROFILE
BROKEN LINE IS THE ACTUAL PROFILE
STARS INDICATE ACTUAL MEASUREMENTS

Figure E4: Estimated Subsidence Curve for Case 4a.

CASE STUDY 4B



SOLID LINE IS THE PREDICTED PROFILE
BROKEN LINE IS THE ACTUAL PROFILE
STARS INDICATE ACTUAL MEASUREMENTS

Figure ES: Estimated Subsidence Curve for Case 4b.

CASE STUDY 5A

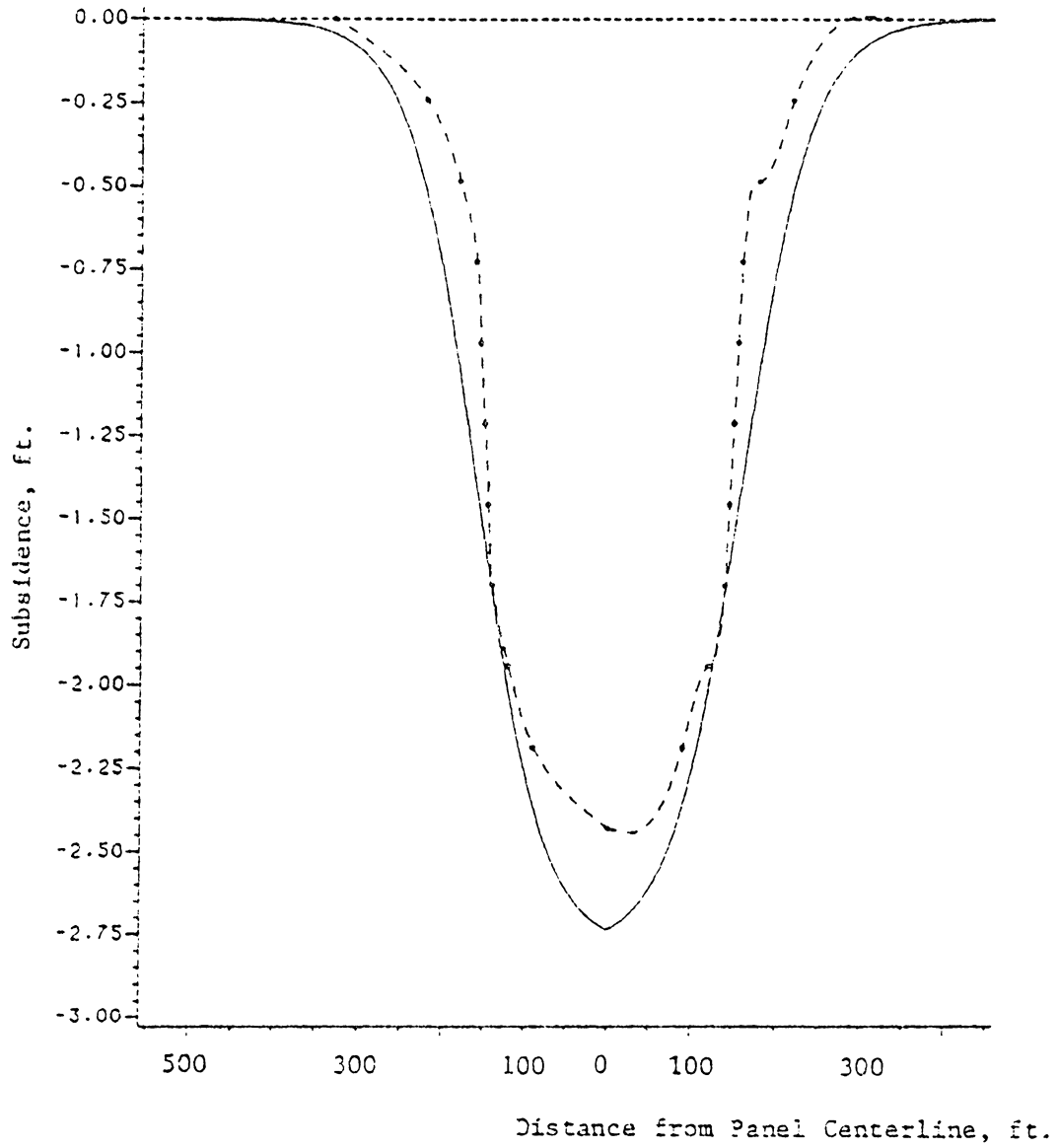
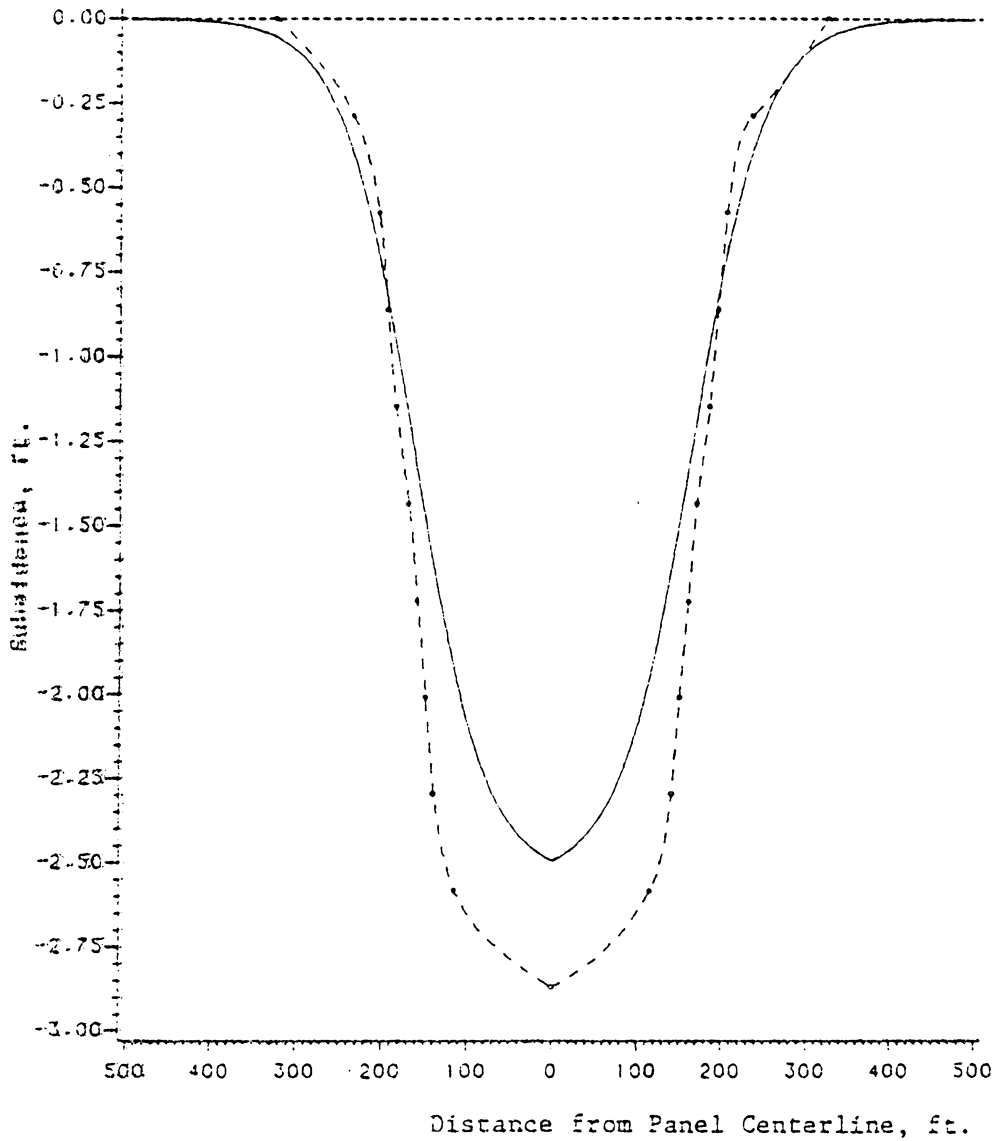


Figure E6: Estimated Subsidence Curve for Case 5a.

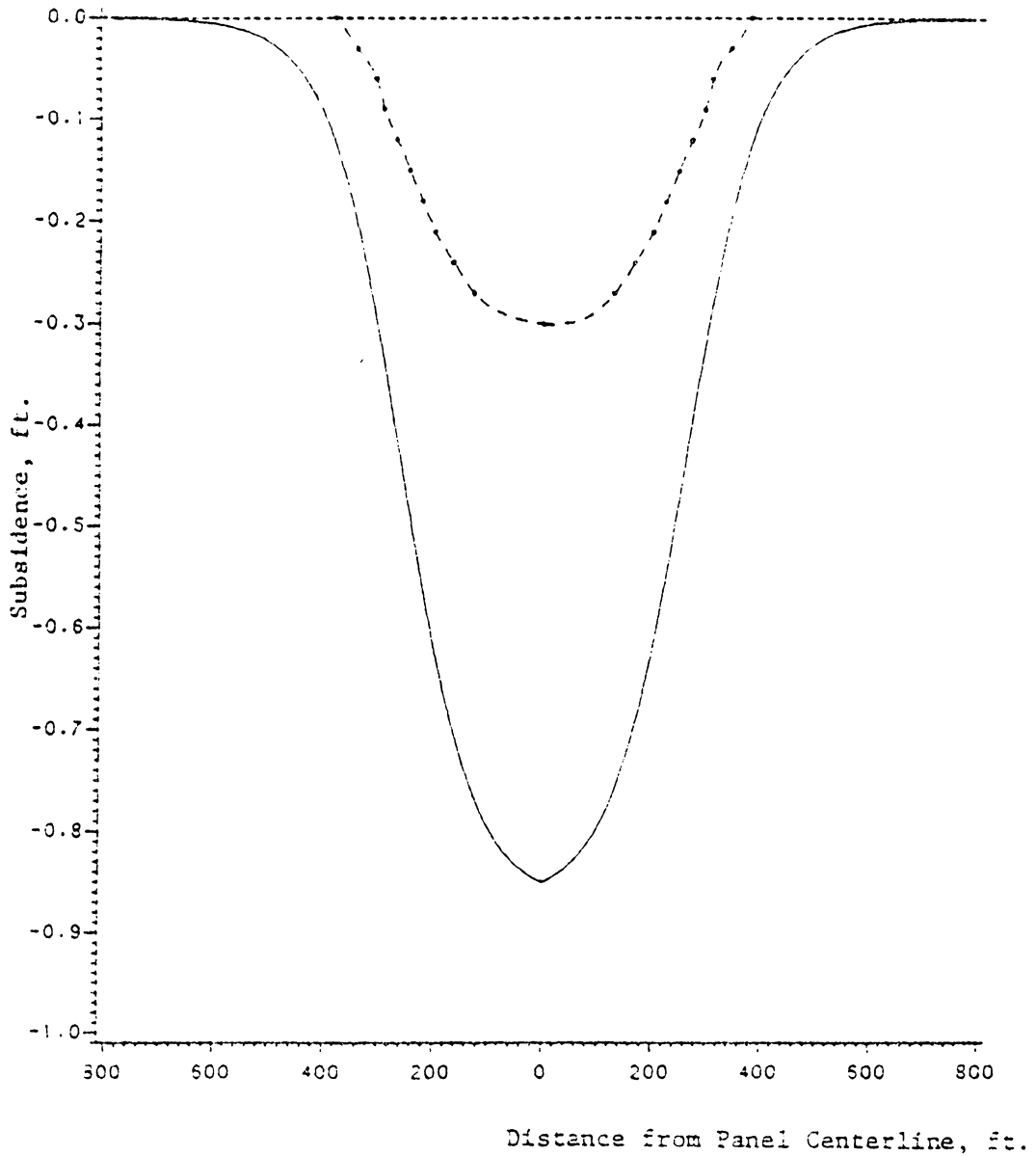
CASE STUDY 5B



SOLID LINE IS THE PREDICTED PROFILE
BROKEN LINE IS THE ACTUAL PROFILE
STARS INDICATE ACTUAL MEASUREMENTS

Figure E7: Estimated Subsidence Curve for Case 5b.

CASE STUDY 8A



SOLID LINE IS THE PREDICTED PROFILE
BROKEN LINE IS THE ACTUAL PROFILE
STARS INDICATE ACTUAL MEASUREMENTS

Figure ES: Estimated Subsidence Curve for Case 8a.

CASE STUDY 8B

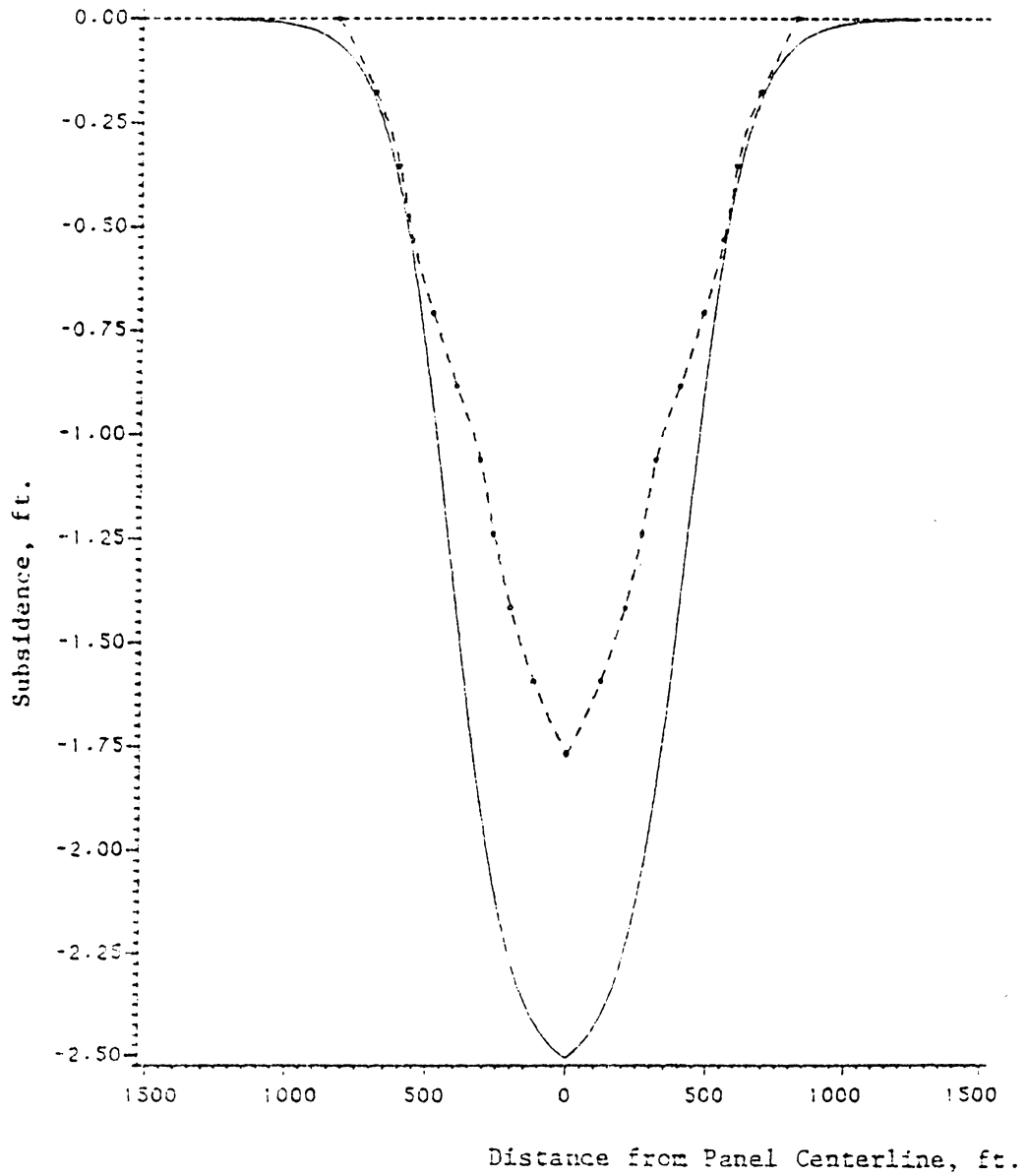


Figure E9: Estimated Subsidence Curve for Case 8b.

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A STUDY OF LONGWALL SUBSIDENCE IN THE APPALACHIAN
COALFIELD

by

Boneva Webb

(ABSTRACT)

Surface subsidence is an inevitable consequence of most underground coal mining. The United States Bureau of Mines has estimated that over 3,000 square miles of land in this country have been affected by subsidence, and it is currently estimated that an additional 2,400 to 3,800 square miles will be affected over the next twenty years.

Surface subsidence is a complex phenomenon which is influenced by many variables related to both mining and site conditions. Although it cannot be prevented, foreign experience has shown that it, nevertheless, can be controlled. In order to achieve this goal, however, methods of subsidence prediction and control must be developed for the United States mining conditions and justified with empirical data.

The objective of this research is to develop characteristic relationships of longwall subsidence and its related parameters from case studies gathered from the Appalachian coalfields. Furthermore, based on this information, an empirical, predictive capability will be developed which can be used to provide accurate and reliable predictions of subsidence in this region.