

INTERACTION EFFECTS DUE TO  
SUBSIDENCE IN MULTIPLE SEAM MINING

by

Stephen Leroy Webster

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APPROVED:

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C. Haycocks, Chairman

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M. Karmis

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G. Faulkner

---

J. R. Lucas

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Blacksburg, Virginia

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## I. INTRODUCTION

Coal seams occur in geologic measures or formations which often contain more than one mineable seam. Engineers International, 1981, estimated that of the 229 billion tons of bituminous coal reserves subject to underground extraction in the United States, 156 billion tons are in areas where more than one mineable seam exists. Although adverse mining conditions have long been associated with multiple seam mining, historically and currently, selection of the mining sequence has been based primarily on considerations of seam ownership, availability and economics, and not on possible adverse conditions created by previous mining.

In coalfields such as the Appalachian coalfield, where mining has been active for many years, experience in multiple seam mining has led to identification and classification of interaction problems as follows:

- Ground control problems.
- Ventilation problems.
- Drainage problems.

The most serious interaction problems are ground control in origin. Haycocks and Karmis, 1981, isolated ground control interaction into four areas:

- Pillar load transfer.
- Massive interseam failure.

- Arching.
- Subsidence.

The objective of this research is to determine what factors control the damage caused by subsidence in an upper seam and to develop a model which predicts when this damage will adversely effect upper seam mining.

Holland, 1951, stated that in the case of mining above old workings, subsidence is responsible for most of the negative effects of interaction. Further, factors contributing to subsidence and strata movements are in general too complicated for successful theoretical consideration; therefore, information is largely derived from observation and experience. Although much research has been done in the area of subsidence and ground movements since Holland made this statement over 30 years ago, the fact that the most widely used system of predicting surface subsidence, the National Coal Board's Subsidence Engineer's Handbook, is empirical in nature, is evidence that the statement is still true today.

In order to study subsidence in multiple seam mining and to predict damage to an overlying seam, case studies were collected and analyzed. From these studies a model was developed to estimate when the damages caused by subsidence will negatively affect the mining of an overlying seam.

## II. LITERATURE REVIEW

### 2.1 General Multiple Seam Mining

In coalfields containing more than one mineable seam of coal, the primary ground control consideration is the proximity to previously mined seams (Stemple, 1956).

Adjacent workings can be categorized as follows:

- An underlying or subjacent seam being previously mined.
- An overlying or superjacent seam being previously mined.
- Both seams being mined simultaneously, with either seam in advance.

Each category of multiple seam mining can produce interaction effects. These interaction effects can be classified, by origin, into three divisions (King, Whittaker and Batchlor, 1972):

- Stress field changes or anomalies due to old or current workings.
- Active strata displacement in other workings due to current workings.
- Triggered interaction due to the changes produced by current workings upon old workings.

Stress anomalies can be either natural in origin or induced by mining. In Table 1, King, Whittaker and Batchler, produce a broad classification system for stress anomalies. These stress anomalies can be caused by

Table 1. Classification of Stress Anomalies  
(after King, Whittaker and Batchlor, 1972)

<u>GENESIS OF ABNORMAL STRESS FIELD</u>	<u>EXAMPLE</u>
(1) Natural, due to geological dislocations, faults, ect.	Heavy lateral pressure in overthrust areas.
(2) Natural, due to inhomogeneity within a stratum or strata.	Difference between physical properties of certain seams.
(3) Combination of induced and natural stress anomalies.	Outbursts and rock bursts.
(4) Induced, outside the boundary of mining.	Abutment pressures in advances of faces, over the ribs and rib pillars.
(5) Induced, inside the boundary of mining.	Differential pressures due to the existence of roadways, packs or pillars inside the worked area.

geological discontinuities, depositional inhomogeneity within a geological unit or mining either inside or outside the boundary of mining.

Interaction problems caused by stress anomalies occur over and under remnant pillars left in a previously mined seam as well as over and under solid coal ribsides. Remnant and rib pillars left in a mined seam result in the strata immediately above and below the sides of the pillar being placed in a state of lateral tension. Conversely, the region immediately above and below the pillar is under a state of high compressive stress due to the surcharge effect of the overburden. This results in the strata immediately above and below the remnant pillar exhibiting characteristic multiple vertical fractures (Whittaker and Pye, 1976). This fracture pattern is shown in Figure 1. The characteristic features of the fractured ground are vertical fractures running parallel to the main axis of the pillar crossed by more widely spaced conjugate fractures orientated at 45 degrees to the vertical.

The effects of these stress anomalies were illustrated by Whittaker and Batchelor, 1972, in Figure 2. This figure plots convergence along a roadway, in an upper seam, over a remnant pillar left in a previously worked lower seam. The closure over the remnant pillar is much higher than the closure over either virgin coal or destressed gob areas.

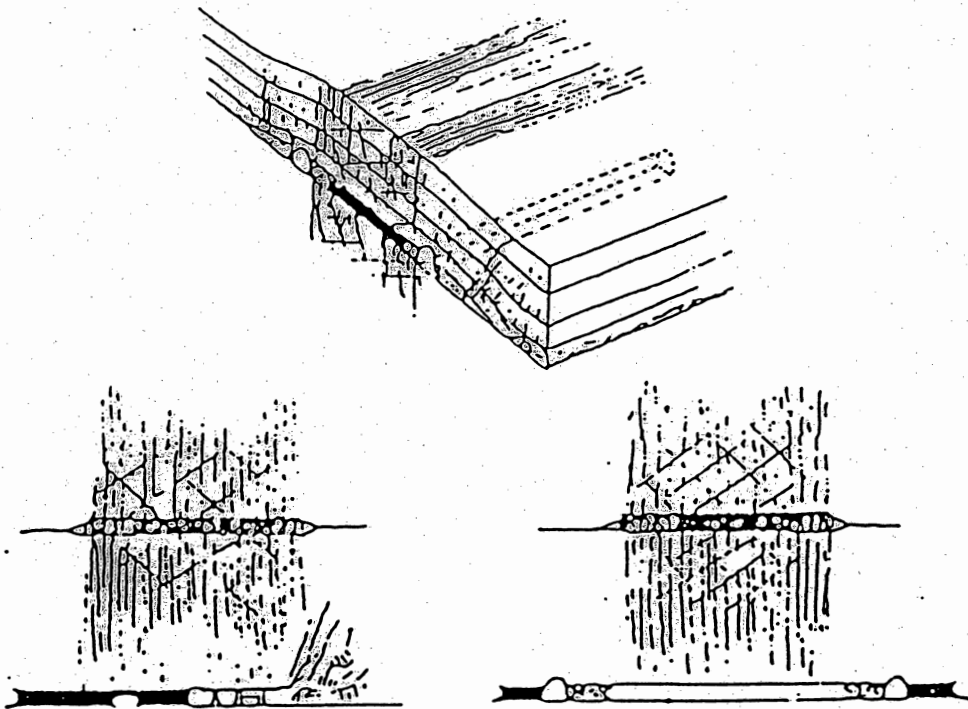


Figure 1. Fracture Pattern Observed in Practice  
(King, Whittaker and Batchlor, 1972)

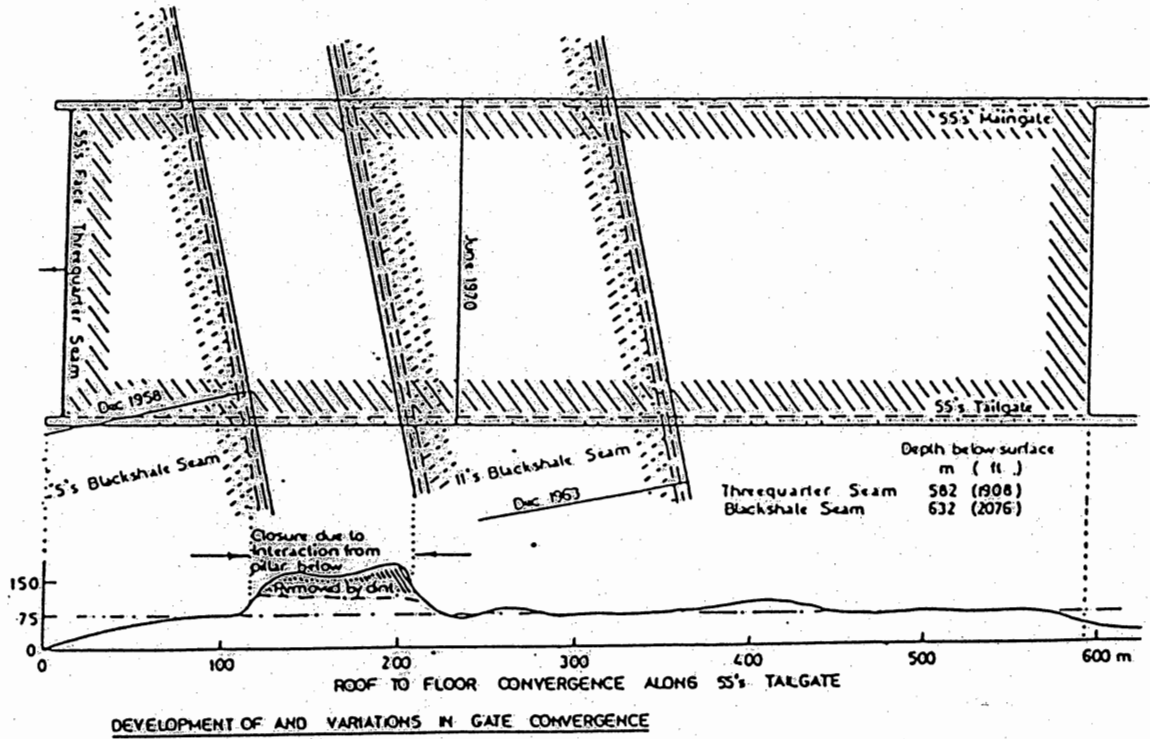


Figure 2. Convergence Along a Roadway  
(Whittaker and Batchlor, 1972)

Although these stress anomalies can cause severe problems, displacement effects rather than stress anomalies play the most important role in interaction problems (King, Whittaker and Batchelor, 1972). These displacement effects can be identified as bed separation, caving or slumping of strata.

Stemple, 1956, in his study of multiple seam mining operations, observed bed separation at an upper seam level of as much as several inches. This bed separation took the form of either the coal bed and underlying strata dropping away from the roof or of the floor and underlying strata dropping away from the coal. This sort of phenomenon is due to the sagging of strata created by subsidence over the lower extracted seam. It seems doubtful that the coal itself would have the necessary tensile strength to hang unsupported over the floor. In cases where the coal was found to hang above the floor a strong adhesion was found between the coal bed and the immediate roof.

Bed separation by itself usually does not adversely effect mine stability; however, it can cause both ventilation and drainage problems.

Rock failure or caving results when the rock forming the immediate roof of an opening fails. Failure is usually limited to a few feet of rock immediately above the mine opening, although in some cases beds have been observed to fall or cave to a height of 30 to 40 feet (Holland, 1951).

This failure usually has little effect on overlying coal seams. If, however, an overlying coal seam is in close proximity to a previously worked seam, as in the case of many rider seams, failure of this type can be extremely destructive.

Hedley, 1978, observed damage caused by this action at Elliot Lake, Ontario. Elliot Lake is an uranium mining district. The district contains from three to five seams of uranium bearing conglomerates, separated by quartzite beds ranging from a few feet in thickness to over 100 feet. Data collected from mines in the area are illustrated in Figure 3. This figure plots stable and collapsed workings on axes of span versus parting thickness.

An eyewitness account of a parting zone failure in an Elliot Lake mine, stated that the parting zone collapsed as one unit. This would suggest shear or tensile failure near the pillar edge.

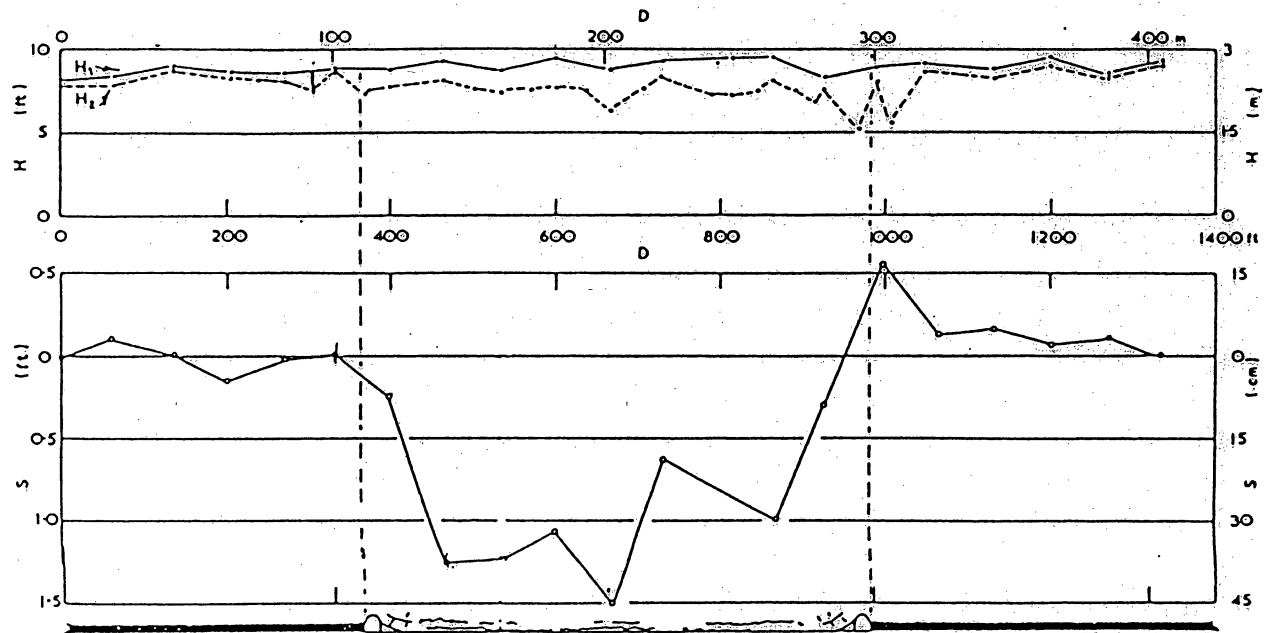
Along with bed separation and caving, the slumping or bending of strata is an important type of ground movement. As in surface subsidence, if the area of extraction is large enough, this slumping action is inevitable. As the strata above a mined coal seam is subsided, tension cracks are formed in the strata. These cracks can be the origin of many interaction problems. The problems can be ground control, ventilation or drainage in nature.

The process of slumping or active subsidence, can be



devastating to an upper seam, if development workings have been driven in it. Farmer, 1980, reported that roof strata above room and pillar workings which had remained stable with no support for more than 20 years, collapsed extensively during undermining. Farmer explained this by the tendency of joints and discontinuities to be opened by the tensile disturbance caused by undermining. Less severe results were obtained by King, Whittaker and Batchelor, 1972, in an experiment designed to observe the behavior of a roadway when affected by interaction from a lower working face. Figure 4 shows the final subsided profile on the roadway floor and also the change in height of the roadway. The figure shows a uniform closure between the rib sides with only superficial evidence of increased closure over the ribside. The authors attributed this to the fact that the extracted seam height of the lower seam was only three feet. In instances of extracted seam heights of six feet and greater, they state increased deformations over ribsides should be expected.

Besides displacement effects and stress anomalies, an equally important feature in interaction is the time dependent deformation of coal measures. This secondary deformation is caused by the relative stability of pillars in the lower seam. Stress anomalies caused by the mining of the upper seam over pillars left in the previously mined lower seam can cause the failure of these pillars. This in



*S* = Subsidence  
*H* = Roadway height  
*H*<sub>1</sub> = Initial height

*H*<sub>2</sub> = Final height  
*D* = Distance from datum

Figure 4. Subsidence Profile on Roadway Floor  
 (King, Whittaker and Batchlor, 1972)

turn can make for a new series of pressures and displacements in the upper seam. Because of this relationship, the results of interaction are not necessarily a consistent and final anomaly due to an earlier working. Subsidence engineers use a term, triggered subsidence, to denote an additional surface subsidence, consequent upon the disturbance of an old working by the current working in another seam. This is essentially interaction and any additional affects on the surface relate directly to innerburden activity (King, Whittaker and Batchlor, 1972).

The factors which govern interaction problems, include:

- The mining methods used in extracting the previously mined overlying or underlying bed, as well as the bed being currently mined.
- The percentage and uniformity of recovery in all beds concerned.
- The thickness of innerburden between the beds under consideration.
- The structural characteristics of the innerburden.
- The thickness of the coal seams mined.
- The time elapsed following the mining of the previously mined seam.

Dip of the coal seams is also a factor but in this discussion the seams are presumed to be horizontal or nearly so. There are cases where the seams mined are on rather sharp grades but they are exceptional and the results

observed in those cases are generally similar to those noted in nearly horizontal seams (Lazor, 1965).

The first factor in interaction is the mining method used in extracting the previously mined seam. The major types of mining today are longwall and room and pillar, with recovery being partial or complete. Each type of mining has characteristics making it applicable under different conditions. Each will also have a somewhat different effect upon overlying coal beds (Holland, 1951).

Longwall mining causes a gradual bending of the superincumbent strata, allowing it, above the caving height, to settle slowly upon the caved material. The subsidence starts in advance of the face and becomes complete at a distance of 100 to 600 feet behind the face (Stemple, 1956).

In room and pillar mining, where complete extraction is practiced, the subsidence is of a different nature. Where pillars are extracted in such a manner as to form a long extraction line, it is desired to relieve the pillars of as much weight as possible. This is accomplished by a methodical plan to break the superincumbent strata and allow it to fall in the extracted area. In instances where a strong roof is present, this method will cause subsidence which closely approaches the subsidence induced by longwall mining.

Room and pillar mining with partial extraction, that is the pillars left in place, will produce subsidence of a

distinctly different nature. If pillars are of sufficient size to support the overburden, any subsidence produced will be restricted to failure of the immediate roof. This failure is usually confined to strata ranging from a few inches to several tens of feet above the working. If pillars of a lesser size have been designed, these pillars will "crush out" and subsidence will extend to the surface.

The method of mining not only effects the ground movements in subsidence, but the amplitude of subsidence. Complete extraction, whether by longwall mining or room and pillar mining, will result in greater subsidence than extraction by room and pillar mining with pillars left in place. Further, differing sizes of the pillars left in partial extraction mining may cause a greater or lesser amplitude of subsidence. If pillars are of sufficient size to support the superjacent strata there will be negligible ground movement above the immediate roof. If, however, the pillars are not of sufficient size, they will crush out allowing a greater amount of subsidence, but not as much as complete extraction would induce. Because of this relationship between pillar size and the amplitude of subsidence and the fact that as pillar sizes are decreased, percent extraction increases. It can be seen that in room and pillar mining the percent extraction and the amplitude of subsidence are directly related.

As in surface subsidence, amplitude of subsidence is an

important factor in multiple seam interaction. This is evident when one portion of a seam subsides and its relative displacement from the rest of the seam is noted. Holland, 1951, noted vertical displacements in coal beds from a few inches to one or two feet, as shown in Figure 5. In cases of thin seams overlying thick seams, vertical displacements of this sort could actually cut a seam off, similiar to faulting action.

No matter what the percentage extraction, one very important factor is the uniformity of extraction. In the case of complete extraction, remnant pillars left in gob areas, and partial extraction, oversized pillars left in areas that are otherwise crushing out can be the seat of such high stresses that the roadways or workings above it will be completely destroyed and no support will be capable of retaining them (Stasen and von Dwyse, 1972).

It has long been known that if an extracted area in a coal seam becomes large enough, surface subsidence will be induced regardless of depth. This can be said of the effects of subsidence in an superjacent coal seam as well. The conditions and problems encountered in mining a seam which may be only 50 feet above one previously mined out are thus found to be similar to those in upper seams as high as 800 feet above the mined out seam (Lazor, 1965).

As in single seam mining, structural geology is an



Figure 5. Bending, Shearing and Readjustment of Level Caused by Subsidence in the Lower Seam (Holland, 1951)

important consideration, (Szwilski, 1979). Tectonic forces can be present in strata. In multiple seam mining, the stresses and displacements induced can have an additive effect on inherent planes of weaknesses.

The lithology of the strata in the innerburden is also an important factor. The shape of the dome of caved material formed above mine workings will depend mainly on the variations of the material in which it exists (Stemple, 1956). The lines of break are more steeply inclined; that is, the angle of draw is less in hard rock such as sandstone than in a soft rock such as shale.

Johnson, 1973, states that the presence of an intervening massive bed may have the effect of partially or even completely nullifying the transferred effects from workings in other seams.

The effects of geology can readily be seen by comparing British subsidence data with American data. The maximum subsidence in Britain can be up to 90 percent of the extracted thickness, whereas in the United States 70 percent is a more realistic figure (Styler and Dunham, 1980). This can be explained by the fact that the strata in the American coalfields are dominated by strong competent beds, while in the British coalfields there were no beds strong enough to have a noticeable dampening effect on the movements above the face.

There is a difference of opinion concerning the effect of

extracted seam height. Lazer, 1965, states that, within normal limits, the thickness of the lower mined out seam has little appreciable effect on the upper seam mining. However, it is commonly accepted that the vertical extent to which the overburden or superjacent strata are broken or disturbed depends on the thickness of the seam previously mined. In a study conducted by Engineers International, 1979, it was found that up to a distance equal to 10 to 12 times the thickness of the extracted seam, the strata is broken and fractured. This would indicate that there is a relationship between extracted seam height and damage.

As in single seam mining, the thickness of overburden is a factor in multiple seam mining. Stresses induced by multiple seam mining can be complicated and increased by a large cover load.

The last factor involved in interaction is time. When the mining of a superjacent coal seam is projected, it is important to know just when the subsidence caused by the mining of the lower seam may be expected to be complete. Most observations of the duration of subsidence have been made on the surface. Observations have ranged from six months to 25 years. The factors involved in controlling the duration of subsidence are (Stemple, 1956):

- Depth of overburden, or innerburden.
- Nature of the strata.

- Thickness of the bed mined.
- Method of mining.

## 2.2 Multiple Seam Design

Though an exact quantitative design for multiple seam mining is beyond the state of the art and is impractical due to ever changing geological conditions, a detailed examination of available literature has led to the following summary of successful techniques used to deal with problems encountered.

The first design consideration in multiple seam mining is the time lapse necessary to relieve stress buildup in rock strata and to allow for settlement. In the case of mining a seam of coal above a previously mined seam, the time period for stabilization is the time to full subsidence. This period can vary from months to many years. Optimum lag time is learned from experience in the local district; however, two years has proven adequate in most mining situations. In the case of mining a seam of coal below a previously mined seam, time allowed between the mining of seams for strata stabilization has little influence (Engineers International Inc., 1981).

In either order of mining, columnization has proven successful and is necessary when parting thickness is less than 50 feet. Columnization, shown in Figure 6, consist of

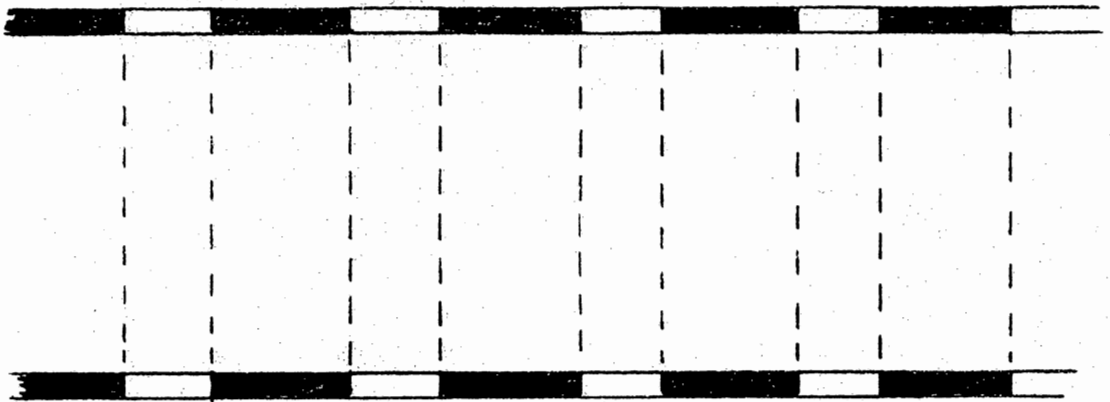


Figure 6. Columnization of Pillars (NCB, 1972)

locating each pillar in the seam being mined directly above or below a corresponding pillar in the previously mined seam. The method requires that pillars of similar size and shape be used in each seam. In the case of mining above previously mined coal seams, since designed pillar size is proportional to pillar loading or seam depth, ~~the~~ the size of the pillar adopted for columnization will be that designed for the lowest seam. The pillars, so designed, are oversized and reduce the recovery for the upper seam (Peng and Chandra, 1980).

If partial extraction room and pillar, was the method of mining in a previously mined lower seam, the upper seam should be columnized as previously detailed. If total extraction room and pillar was the method of mining, advantage can be taken of destressed areas over gob, if the gob is free of remnant pillars. Roadways can be located in the destressed areas thereby eliminating any chance of producing a piston of ground stresses through superimposed pillars.

Most of the information available concerning multiple seam longwall mining is British in origin. In Britain the most successful form of layout is to locate the present face over the old gob, as in Figure 7. Location of the face in such a destressed situation will promote excellent strata control conditions in both the face and in the roadways. This method, however, involves successively increasing the

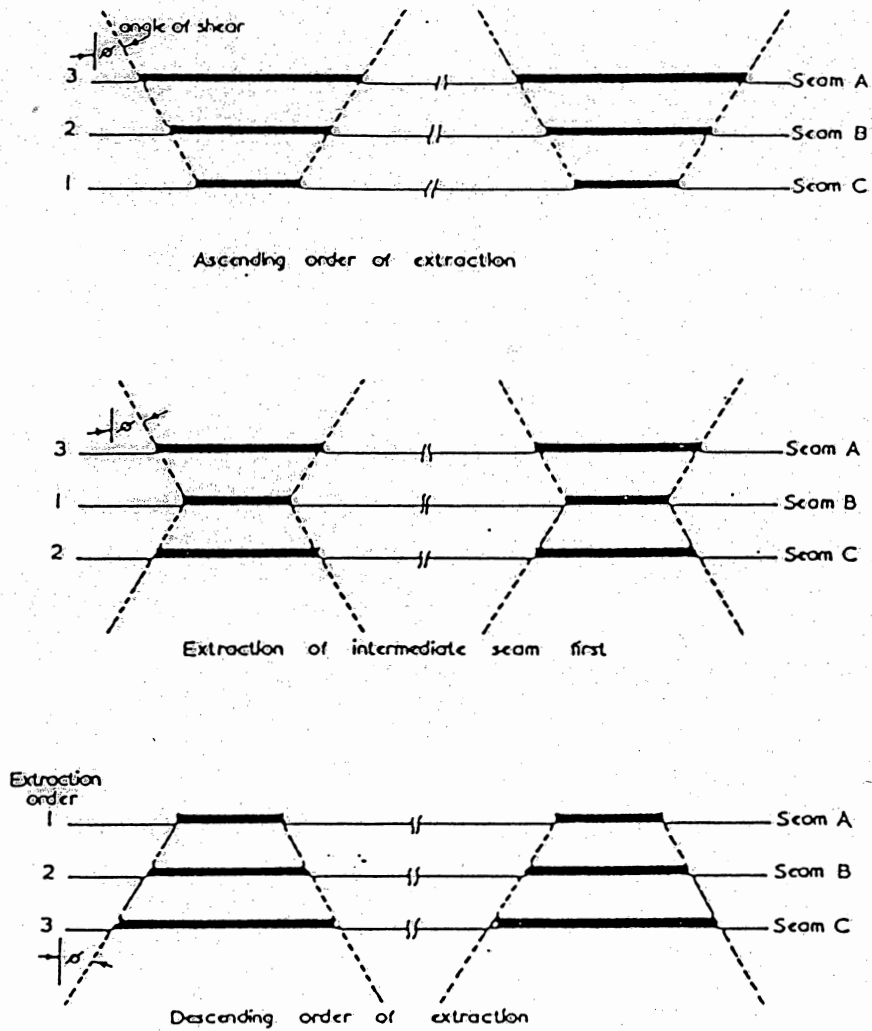


Figure 7. Layout of Rib Pillars for Extraction of Successive Seams (King and Whittaker, 1970)

size of rib pillars, which is wasteful of reserves.

An alternative layout, which incorporates roadway protection and conservation of reserves, is to locate the remnant rib pillar down the central axis of the present face as in Figure 8. Using this design the following can be achieved (Whittaker and Pye, 1976):

- The fractures created by the previous mining are kept intact much better, since the face is moving on end relative to the orientation of the main vertical interaction fractures.

- Only a small length of face is affected at one time.

- Convergence on the face is not affected, providing the interaction fractures are kept constrained.

- A more even subsidence profile and more balanced strain profile are produced at the surface.

- The successive build up of localized high pressure regions is avoided.

The effects of previous mining are very important when mine design is in areas containing more than one mineable seam of coal, but of equal importance are the effects produced on still other seams which may or may not be economical at present but may become so in the future. Hasler, 1951, divided damage to superjacent seams of coal into two categories:

- Unavoidable damage to a superjacent seam due to the prior removal of a lower seam without provision for adequate

## RIB PILLAR

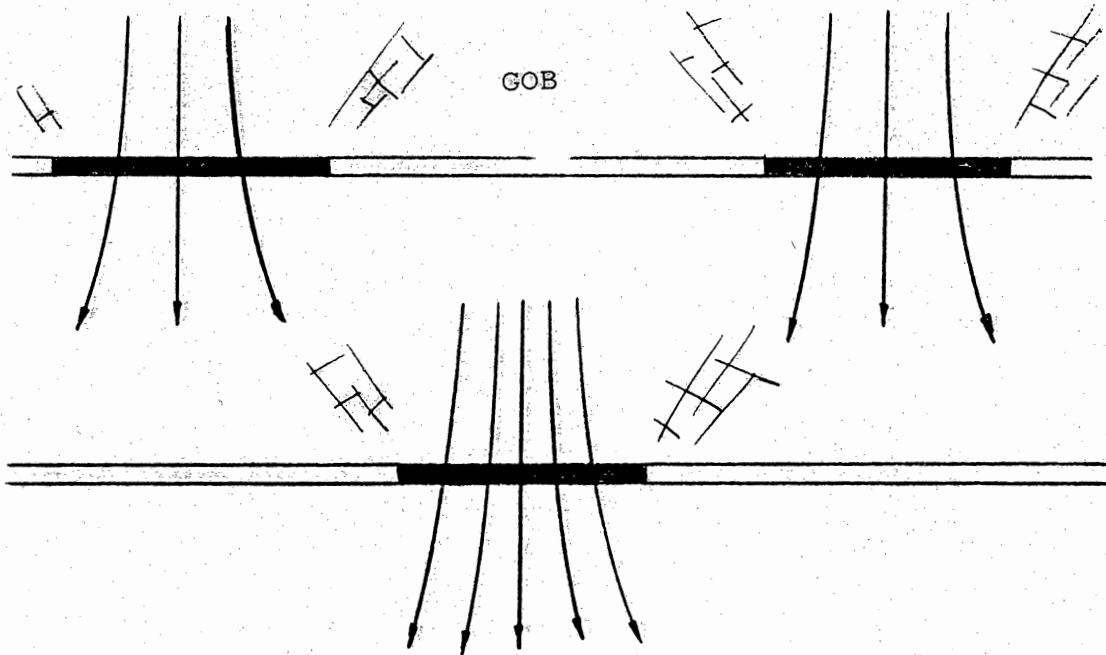


Figure 8. Remnant Pillars Located Down the Central Axis of the Present Face (Whittaker and Pye, 1975)

support.

- Avoidable damage to a superjacent seam due to remnant pillars being left in the previously mined seam along with the nonuniform extraction of that seam.

These avoidable damages can be eliminated with proper design and good operating procedures. In full extraction room and pillar mining, Holland, 1951, states that besides eliminating remnant pillars, pillar lines should be kept long and straight to reduce shearing of overlying strata as well as to promote subsidence by bending rather than by shearing.

### 2.3 Roof Strata Actions

The added complexities produced by advances in mining technology in the last half century have led to the development of several approaches to strata movement, including: beam theory; pressure arch theory; and dome theory. These theories employ the more fundamental concepts of strength of materials, structural analysis and soil mechanics. Although it appears unrealistic to apply such conventional techniques since strata are seldom of ideal materials, are usually influenced by unspecified geologic conditions, and are generally of complex geometry, they still remain the only satisfactory approaches available for initially attacking the problem (Adler, 1976).

The effects of an opening created in a seam of coal on

the overburden are as follows:

- At remote distances above the working, subsidence may occur on the surface.
- At intermediate distances above the working, a pressure dome or arch structure is formed.
- Near the workings, the immediate roof will deflect downward in beam or plate action. If the immediate roof has transverse fractures, a voussoir arch may form.

Field observations have been made of cavities which have become vaulted or peaked, remaining stable without artificial support. These observations have led to the adoption of several arch or dome theories.

The pressure arch theory was developed in Britain. The distribution of forces in the vicinity of narrow workings, as in roadways, was determined as early as 1936 and is shown in Figure 9. The immediate roof bends downward and is freed from the weight of the beds above. The weight is transferred to the solid rib sides and a pressure arch is developed above the excavation. The strata within this arch is destressed.

For wide workings, as in longwall panels or pillaring sections, one abutment can be visualized as resting on solid coal and the other on the gob at some distance back from the solid coal as shown in Figure 10.

From British field observation, it has been determined that the maximum possible width between the pressure arch

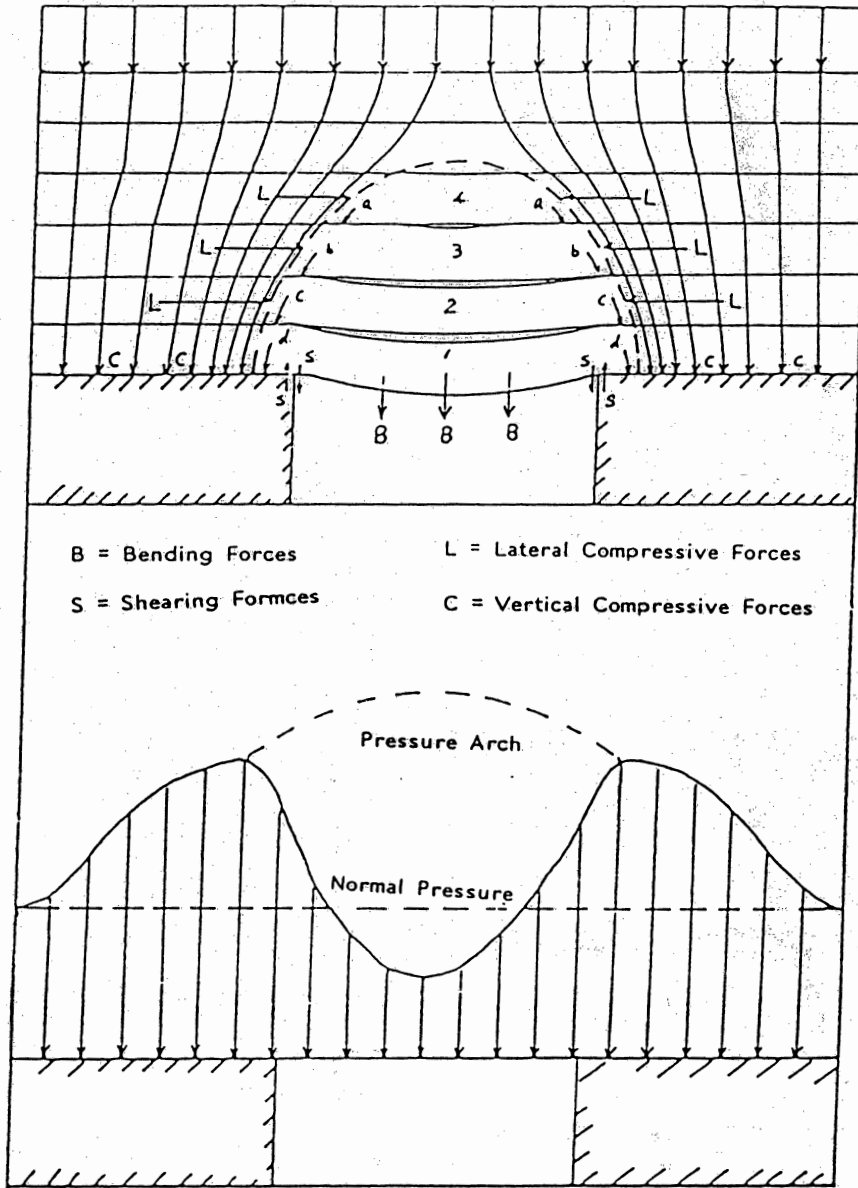


Figure 9. Pressure Arch for Narrow Opening (AIME, 1935-36)

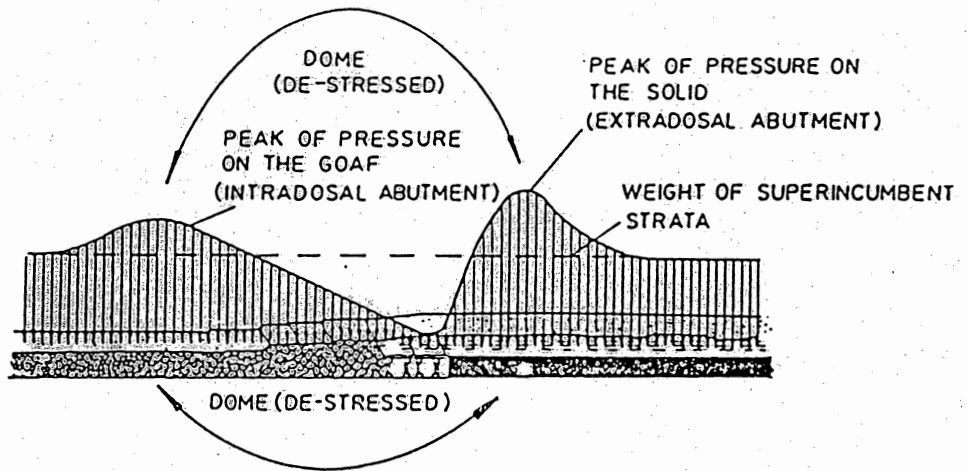


Figure 10. Pressure Arch for a Wide Opening (Denkhaus, 1964)

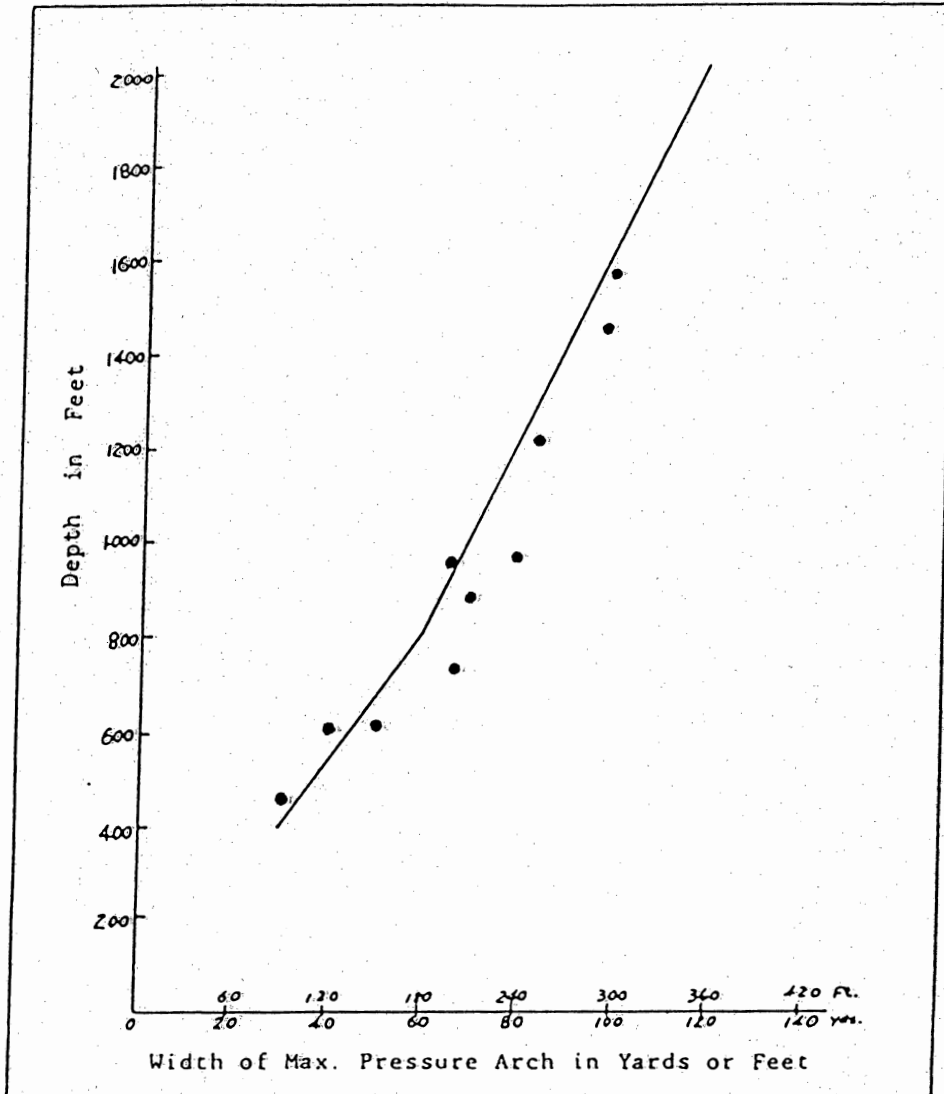


Figure 11. Width of Maximum Pressure Arch for Various Depths (NCB, 1954)

abutments generally increases with depth. Figure 11 plots these observed widths versus depth of mining. The maximum width of the pressure arch can be calculated from the following empirical formula (Peele, 1941):

$$W = 0.15 \times D + 60 \dots \dots \dots \text{Eq. 1}$$

where:      W = width of maximum pressure arch in feet  
               D = depth of arch below surface in feet

If the excavation width exceeds the maximum width of the pressure arch, roof fracturing will occur and the load will be transmitted directly to the pillars rather than to the abutments. These pillars may fail under these excessive loads.

The estimated peak pressure in the abutment zone due to the pressure arch is shown in Figure 12. This graph shows the variation of abutment stress with depth using the maximum feasible arch that could exist at any distance below the surface (N.C.B., 1954).

If mine workings are not driven with vaulted or peaked roofs, the rock at the top of the opening often will collapse. Caving will continue until the roof has assumed a dome shape, after which equilibrium will be reestablished. This "dome theory" has been extensively examined and is illustrated in Figure 13. This figure represents the

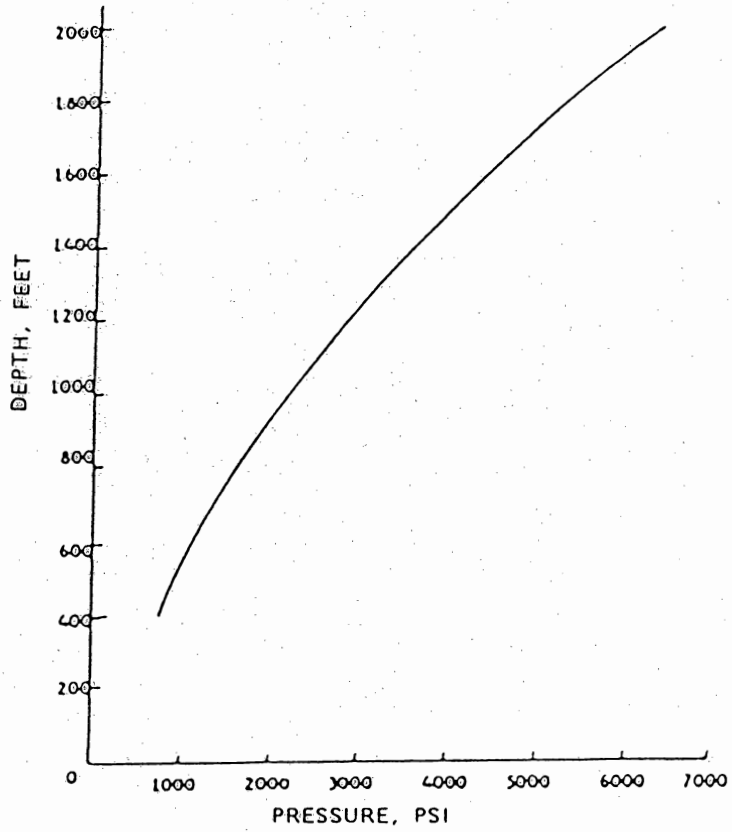


Figure 12. Estimated Pressure in Abutment Zones of the Maximum Pressure Arch (NCB, 1954)

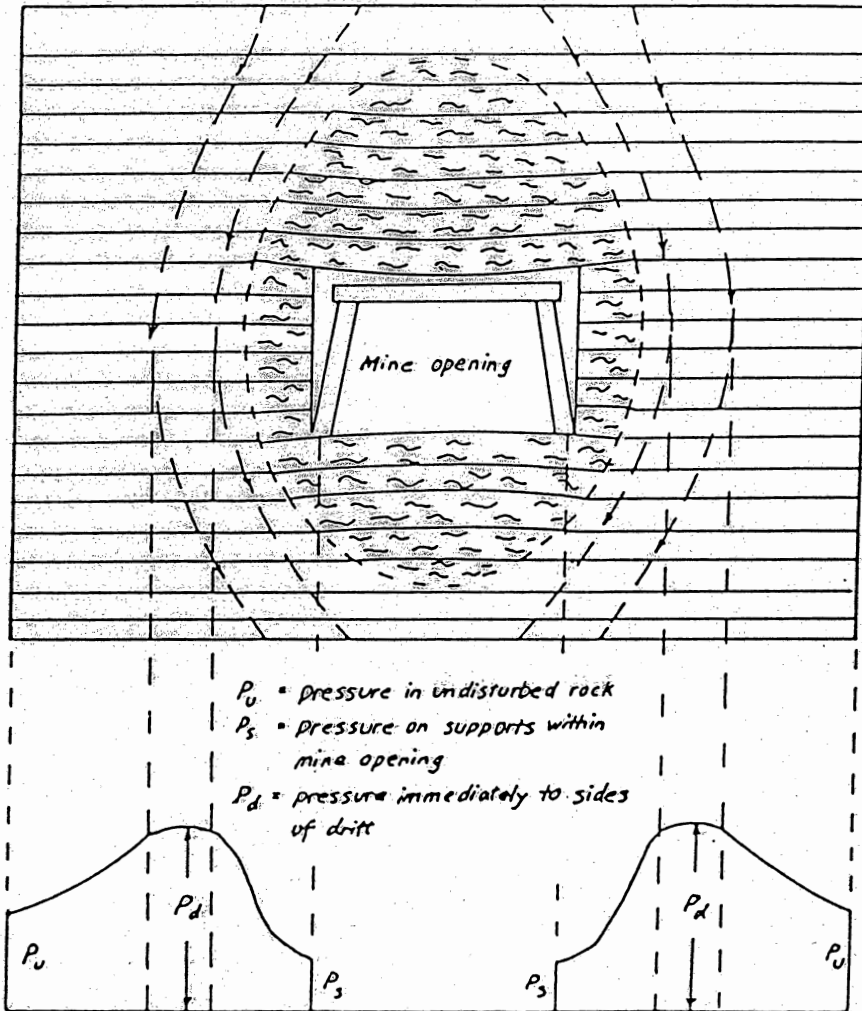


Figure 13. Pressure Dome and Stress Trajectories Around a Drift (Dinsdale, 1935)

cross-section of a working, with the elliptical curve being termed the pressure ring. The hanging wall within the ring is separated from the rock outside the ring as a result of horizontal shearing and vertical tension and rests upon the supports within the working. The pressure on the immediate ribs and supports within the pressure ring is small compared to the stresses a short distance inside the pillars on each side of the working. The pressure on the supports is proportional to the depth.

In the general case, the dome above an excavation is three-dimensional; deriving a formula to describe its shape is difficult. The problem is therefore simplified to the two-dimensional case. The cross-sectional shape of the excavation is determined normal to the longitudinal axis as shown in Figure 14.

From simple statics, the height of the dome can be calculated as follows (Dinsdale, 1935):

$$h = (P / (8 \times H)) \times (2 \times L \times S + S \times S) \dots \text{Eq. 2}$$

where:

- h = height of dome
- P = pressure on dome
- H = horizontal force
- L = width of abutments
- S = span of opening

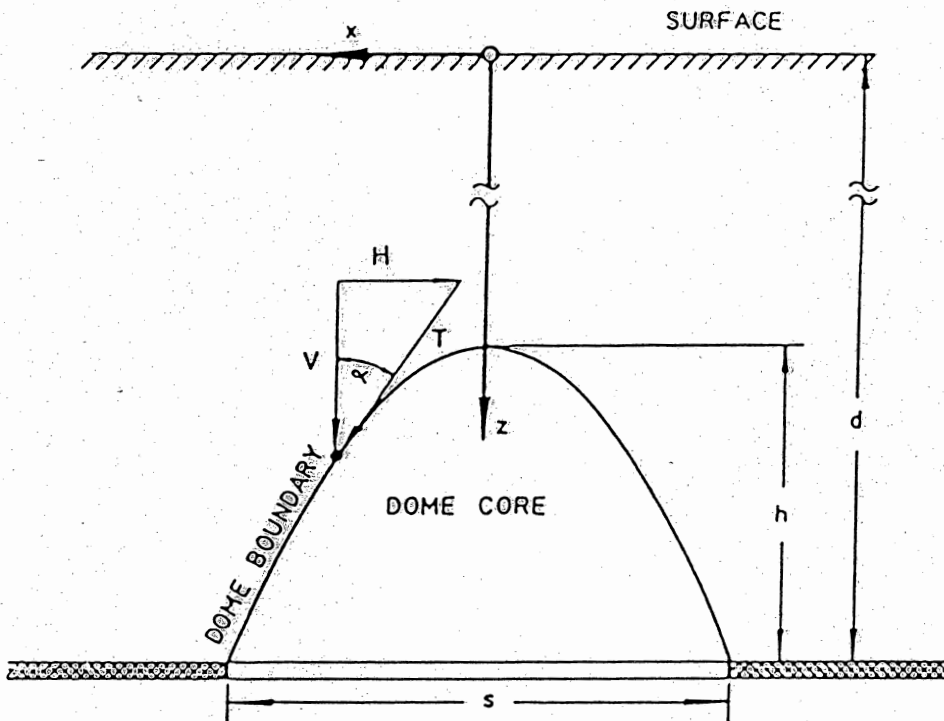


Figure 14. Forces at Dome Boundary (Denkhaus, 1964)

For further evaluation of dome characteristics, a distinction must be made between two possible cases: insufficiently cohesive rock in the dome and sufficiently cohesive rock in the dome.

If the rock is insufficiently cohesive, a portion of the core of the dome will separate gradually from the dome boundary while the span of the dome is being increased. The relationships between the span and the height of the dome is as follows (Denkaus, 1964):

$$s = 8 \times \sigma_s \times d / w \times (1-h/d) \times \log (1-h/d) \dots \text{Eq. 3}$$

$$h = 0.63 \times d \dots \dots \dots \text{Eq. 4}$$

$$s = 2.96 \times \sigma_s \times d / w \dots \dots \dots \text{Eq. 5}$$

where:  $s$  = span of dome (feet)  
 $h$  = height of dome (feet)  
 $d$  = overburden (feet)  
 $w$  = specific weight  
 $\sigma_s$  = uniaxial compressive strength (psi)

If the rock is sufficiently cohesive, the core of the dome will not separate from the dome boundary. The boundary will therefore carry the weight of the core. If the span becomes too large, the weight of the core material can exceed the cohesive resistance and a sudden collapse of the

core may occur. The relationships between the span and the height of the arch for this case are as follows (Denkaus, 1964):

$$s = (8 \times \sigma_s \times d/w) \times (1 - h/d) \dots \text{Eq. 6}$$

$$h = 0.5 \times d \dots \dots \dots \text{Eq. 7}$$

$$s = (4 \times \sigma_s \times d)/w \dots \dots \dots \text{Eq. 8}$$

In both cases, sufficiently cohesive material or insufficiently cohesive material, if the span exceeds the limits given by these equations, the dome will fail. This failure could extend to the surface or in the case of multiple seam mining, certainly to a superjacent seam. Wardell and Eynon, 1968, stated that at shallow depth and fairly homogeneous and strong overburden, strata could shear at the abutments and rather than gradual subsidence, complete and sudden collapse into the extraction area would occur. Figure 15, is an example, illustrated by Holland, 1951, of massive innerburden failure caused by removal of underlying pillars.

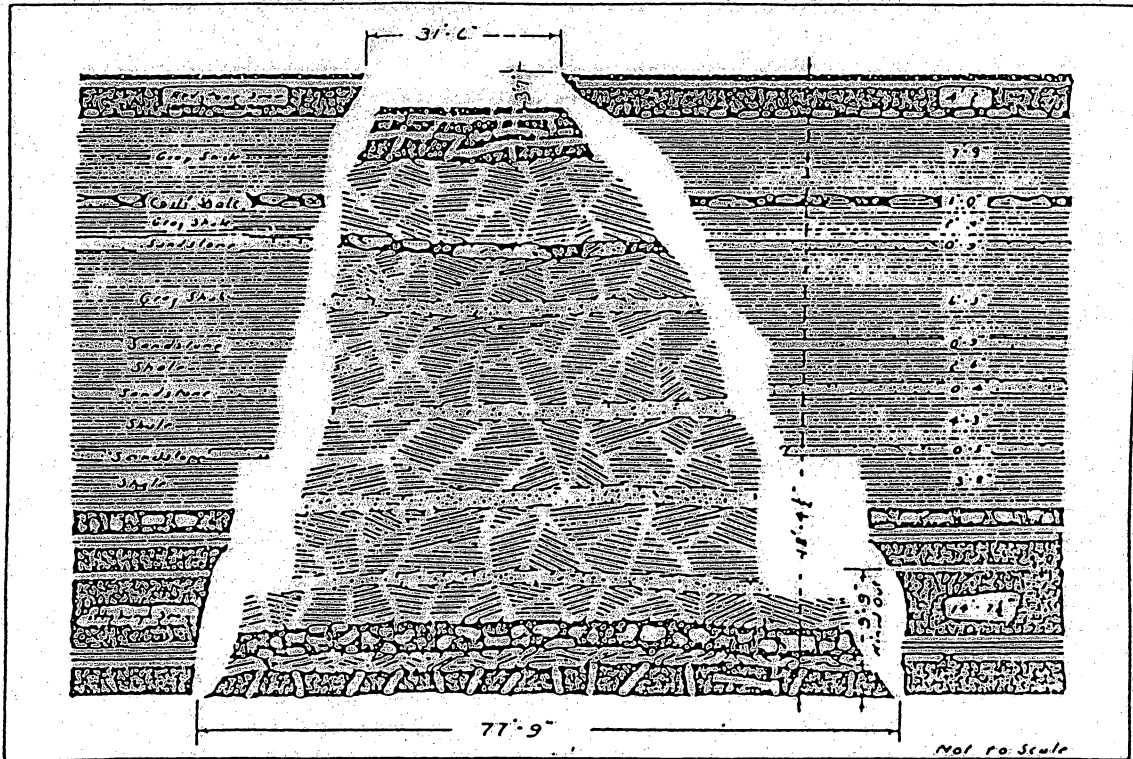


Figure 15. Massive Interseam Failure (Holland, 1951)

Beam theory was developed in the early part of the Twentieth Century. This theory was developed primarily to explain surface subsidence. However, presently beam theory is being used to explain some of the phenomena occurring closer to the excavation, such as the deformation and failure of the immediate roof.

Beam theory is appropriate for roof analysis in bedded formations in which the bedding planes are relatively smooth and flat. Because of the weak bond between beds, the roof rock will, either immediately or a short time after mining, become detached from the overlying rock and form a layer or beam which is loaded only by its own weight. For analysis it is assumed that the mine roof behaves like a body loaded beam, which can be approximated by a uniformly loaded beam where the load is equal to the rock density multiplied by the thickness of the strata. For shallow mines, the mine roof is assumed to be equivalent to a simple beam. For deep mines, the mine roof is assumed to be equivalent to a beam fixed at both ends. The following assumptions are made in beam theory (Adler, 1976).

- The beam is of a homogeneous, isotropic and elastic material.

- The beam is straight and has a uniform cross-sectional area along an axis of symmetry.

- All loads and reactions are perpendicular to the axis of the beam and lie in the same plane, which is a

longitudinal plane of symmetry.

- The beam span is at least twice the beam thickness.

If the length of a working is less than twice its width, it must be analyzed as a three dimensional problem based on the more complex flat plate theory.

If the mine roof is made of two or more layers, two cases must be considered: thicker or stiffer layers overlying thinner layers; or, thinner layers overlying thicker or stiffer layers. Both cases are illustrated in Figure 16.

In the first case, each layer or bed acts independently, hence, the beds do not load each other. The stress and deflection in each layer can then be calculated as for a simple beam.

In the second case, the lower layer is loaded by the upper ones and the additional loading must be considered.

The concept of the voussoir arch was introduced into mining to account for the relative stability of roof strata which are too broken to act simply as beams. Roof material has been observed to stand unsupported over large areas while it is in such a state as to rule out the existence of the tensile strength required by beam theory. The principles which support this broken material are similar to the principles involved in constructing masonry arches. It has been found that the behavior of a brick beam closely resembles that of certain types of roof met in practice.

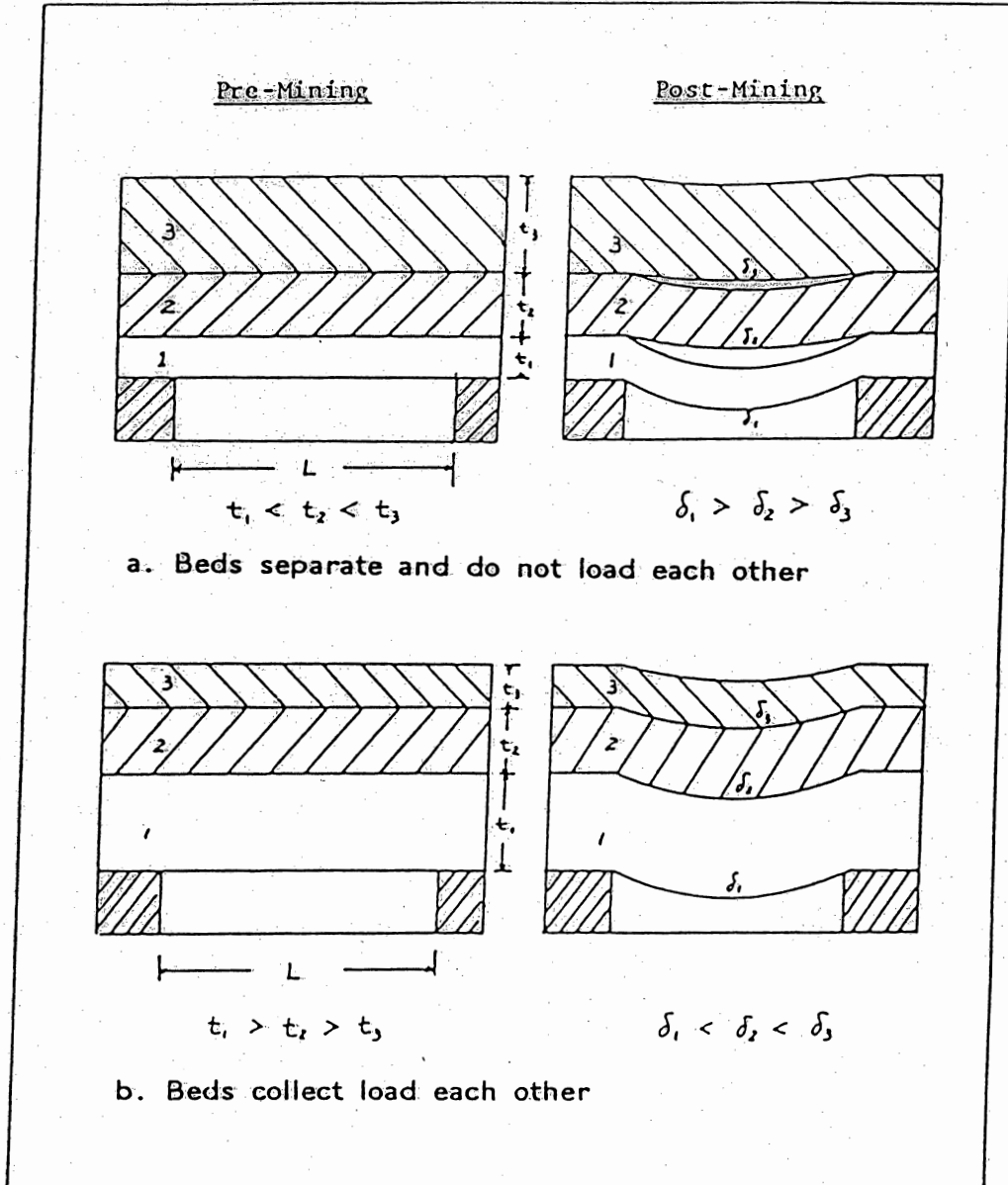


Figure 16. Cases of Layered Roof  
(Adler and Sun, 1976)

Sandstone roofs are particularly subject to this action (Adler, 1976).

The strata movements discussed thus far have been confined to strata in the immediate roof and strata of intermediate distances above the mine workings, where a pressure dome or arch structure is formed. At more remote distances, a different mechanism occurs, subsidence. Most of the early research that was done in the area of ground control was undertaken specifically to understand subsidence more fully.

Although the fact that mining could cause surface subsidence had been known for centuries, no attempt was made to systematically investigate the mechanisms which cause surface subsidence until the 1820's. At that time because of widespread movements and subsequent structural damage suffered by the city of Liege, Belgium, a research effort was initiated. The most notable achievement of the Belgian school of that era was the publication of Gonot's treatise "Lor de La Normal" in 1871 (Karmis, Haycocks, Webb and Triplett, 1981).

The first theory of mining subsidence which was generally accepted was the vertical theory. This early nineteenth century theory stated that the breaks or fractures in the strata overlying an underground excavation occurred vertically above the boundary of the mine workings. This implied that the area effected by subsidence on the surface

was, in the case of horizontal seams, equal to the area mined underground and, in the case of inclined seams, less than the area mined underground. Using this theory, pillars were left unworked vertically below buildings which were to be protected. Occasionally pillars of sizes larger than the buildings to be protected were left in place. This was intended to provide a safety margin against the crushing and deterioration of pillar edges and did not reflect any anticipation of the "draw effect".

Pillars designed using this theory were too small and failed to protect surface structures effectively. Because of these failures, British courts enacted laws whereby vertical pillars were required plus yards on either side of the area requiring support. This was later increased to yards on either side of the area requiring support, due to still more failures (Shadbolt, 1978).

At approximately the same time that the vertical theory was being developed in Britain, Gonot was making field observations and conducting a study of subsidence in the Leige region of Belgium. It was generally accepted in Belgium at that time there was a "harmless depth" of mining. This harmless depth was taken to be 100 meters. If mining was to take place at a depth of more than 100 meters, the strata overlying the workings would support the surface and no damage would take place. Gonot opposed this theory. He suggested that the working of a coal seam resulted in lines

of fracture at right angles to the inclination of the seam. He argued subsidence would be produced between the projections of these lines at the surface. With level seams Gonot's theory, the normal theory, projected the same results as the vertical theory. However when inclined seams were mined, the two theories differed. The vertical theory predicts damage directly above the workings whereas the normal theory predicts damage on the down dip side of the workings.

The normal theory initiated debate throughout Europe. German engineers, Schulz and Sparre, 1867 criticized it, saying that the nature of the strata played a role in the orientations of the cracks. They suggested that inclined beds of shale would fracture vertically, whereas inclined beds of sandstone would fracture on the dip side normally and on the rise side vertically. Sparre suggested that each stratum should be considered individually and the over all fracture would lie between normal and vertical. A French engineer, Callon, suggested that when caving was practiced bulk increased, depending on the manner and to what height the roof collapsed. He also suggested that caving in a seam with a weak roof would cause subsidence to widen out in a funnel fashion, whereas caving in a seam with a hard roof would cause subsidence to form a bell-shaped cavity as in Figure 17.

An Austrian professor Rziha, 1882, was the first to

suggest the formations of a dome above mine workings. He stated that when rock is undermined it will stay undisturbed until gravity exceeds cohesion. At that time the rock will fail either by falling, tearing or both. With time, a dome-shaped space is formed moving away from the center of the excavation both vertically and laterally. If the excavation becomes large enough, this dome will extend to the surface. The effected surface area would be larger than the area of excavation if the excavation is sufficiently large. This was the first use of the idea of "draw".

Rziha considered the vertical settlement in subsidence to be caused by a combination of collapse into an excavation and a dewatering effect on the overlying strata. The latter effect causes a decrease in volume. He believed that the amplitude of subsidence decreased with depth and that at great depths there would be no effect on the surface.

The next major work in the area of subsidence was undertaken in France. Fayol in 1885 published a paper which some believe to be the most important contribution in the area of subsidence of the nineteenth century. He conducted investigations in three areas:

- Laboratory tests.
- Test on physical models.
- Observations of surface movements above mine workings.

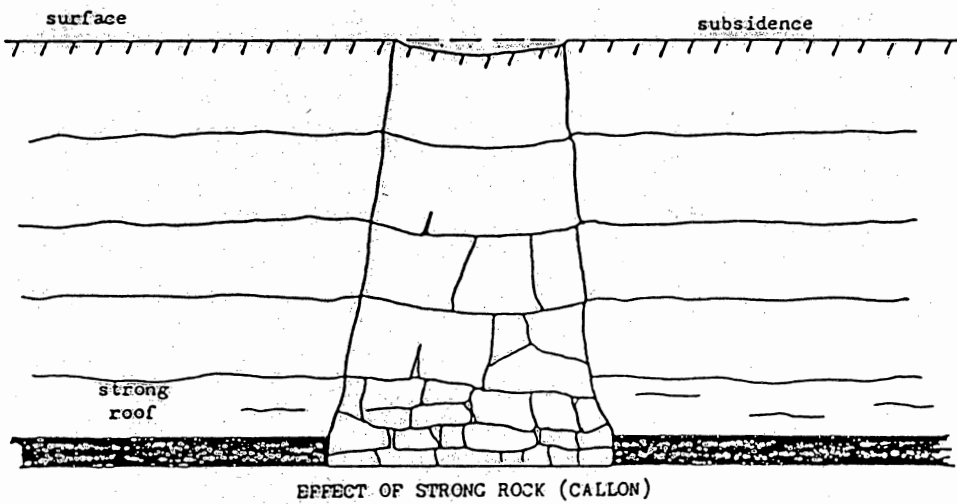
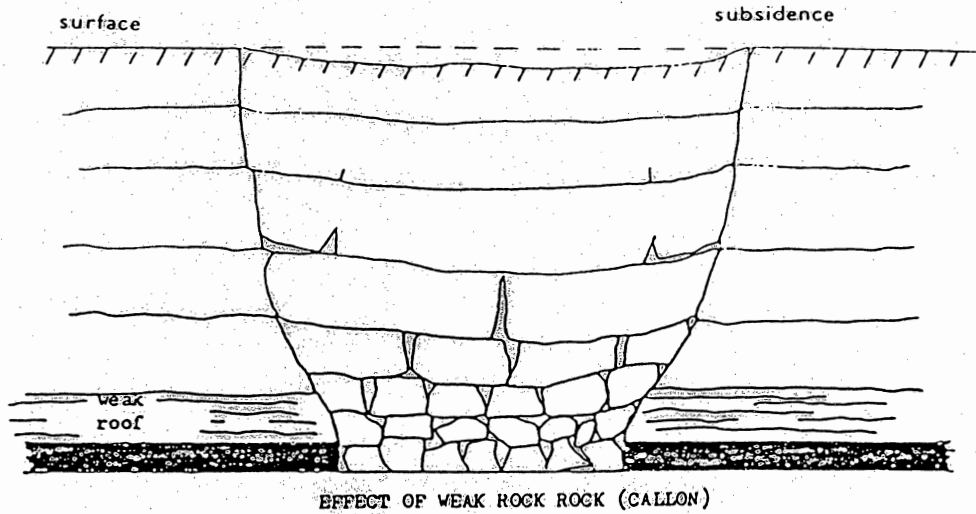


Figure 17. Callon's Suggested Effects of Rock Strength (after Shadbolt, 1978)

In his laboratory test he experimented with beams of iron, canvas, rubber and wood supported at both ends. He allowed these beams to deflect under their own weight. He observed that:

- The degree of curvature increased with the distance between supports.

- When beams are stacked, the lower beam bends more and the upper beam bends less than if there were only one beam.

- The lowest beam always bends the most; curvature becomes less as the distance above the opening is increased and at a certain distance beams no longer deflect.

Fayol concluded from his beam experiments, that the lower part of each beam lengthens more than the upper part. Therefore a beam placed on top of another beam is unable to conform to the exact shape of the lower beam. This causes the points of support to approach each other as more beams are added. Eventually the points of support contract and there is continuous contact between beams. These points of support form a dome.

Fayol also conducted model tests in which he attempted to reproduce on a small scale the movements of both the surface and the intervening strata caused by mine workings. In his model, Fayol used wooden laths which could be removed to represent the coal seam to be mined. The overlying strata were artificially reproduced using layers of earth, sand, clay and plaster. The effects he observed are shown in

Figure 18.

Fayol's field observations were conducted in areas where the overburden ranged from 18 to 300 meters and the extracted seam height ranged from 1.3 to 20 meters. From his observation he concluded:

- When thin seams are extracted at great depths, subsidence developed regularly over an area greater than the area worked.

- When thick seams are extracted at shallow depths, subsidence occurred suddenly and dramatically, as in block collapse.

- Over the edge of subsiding areas an area of extension developed, surface cracks could appear.

Dickinson used the term "draw" for the first time in 1896. He defined draw as being the horizontal distance between the extreme point of the subsidence and the vertical projection of the mine workings. He attempted to relate the way in which ground movements developed to the action of geological faults.

From the beginning of the Twentieth Century, more attention was given to strata movement and the theories discussed previously were developed. This emphasis on ground movement led to the divergence of thought on subsidence prediction. While some mathematically complex analytical techniques were being developed, others were

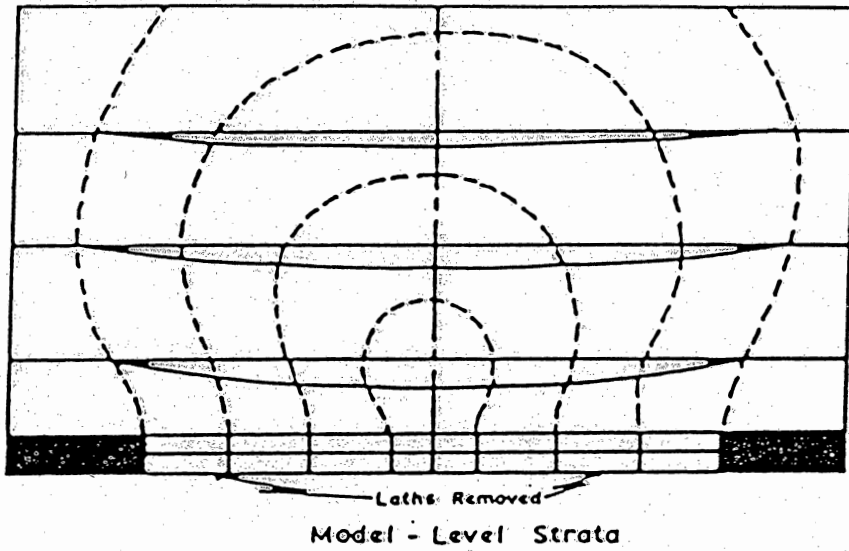


Figure 18. Fayol's Model Test (Shadbolt, 1978)

developing sophisticated empirical techniques. Analytical techniques were developed based on concepts ranging from continuum theory to stochastic media. The most comprehensive and widely used empirical method was developed in Britain by the National Coal Board. This method is based on data from surface surveys above longwall workings in Britain. These longwall workings are at depths ranging from 80 feet to 2,730 feet with width to depth ratios between 0.16 and more than 4. From this data, a number of tables and graphs have been compiled for use in predicting ground movement at the surface. The complete surface subsidence profile along with the associated strain profile can be obtained by following these graphs and charts.

Other empirical methods are based on formulas, either being profile functions or influence functions. Profile functions pertain to long extracted workings which are sufficiently wide such that the maximum possible subsidence has occurred over the central axis of the working. The least width, such that this maximum is just attained, is called the critical width; the smaller and larger widths are called sub-critical and super-critical respectively and are illustrated in Figure 19.

An influence function is an expression for the effect of an element of extraction. It is supposed that the principle of superposition can be applied so that the total effect of all such elements is additive. The complete subsidence

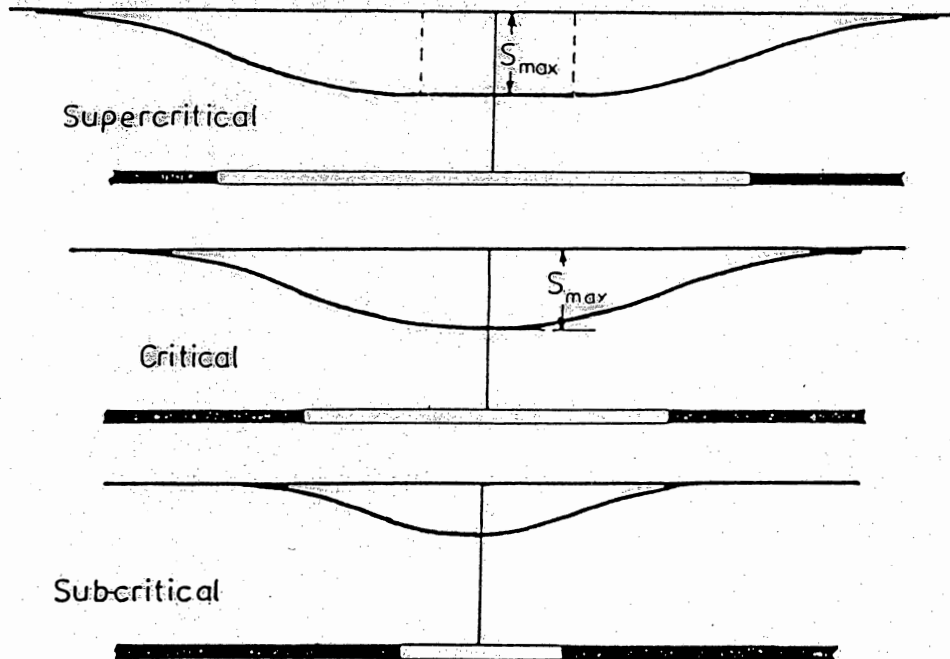


Figure 19. Relationship Between Super, Sub and Critical Workings (Berry, 1978)

profile for the entire working can be obtained by integrating the function over the width of the working. An advantage of the influence function approach is that the function can be integrated over the whole area of extraction, yielding subsidence predictions for extraction regions of various shapes. Influence functions, and in particular, the zone area method, are adaptable to computerization as shown by Marr, 1975 and Goodman, 1980.

Figure 20 summarizes ground movements from the mine working to the surface. When an underground opening is established, the original equilibrium is disturbed with resultant stress concentrations. While many factors are involved in the opening's stability, the span, undoubtedly is one of the most important factors in failure. Assuming the opening is relatively small, the overlying rock strata can bridge across the opening and little if any movement of the top and bottom will occur. However, as the span increases, a point is reached where the stress in the overlying rock strata exceeds some strength value of the rock and the top breaks. If the opening span is limited to some sub-critical value or is at great depth, a pseudo-arch will form achieving stability before rupture occurs to the surface. The boundary of this arch is thought to approximate an ellipse in form with the major axis vertical and equal to four times the span; there has been little field research to substantiate this theory. If the

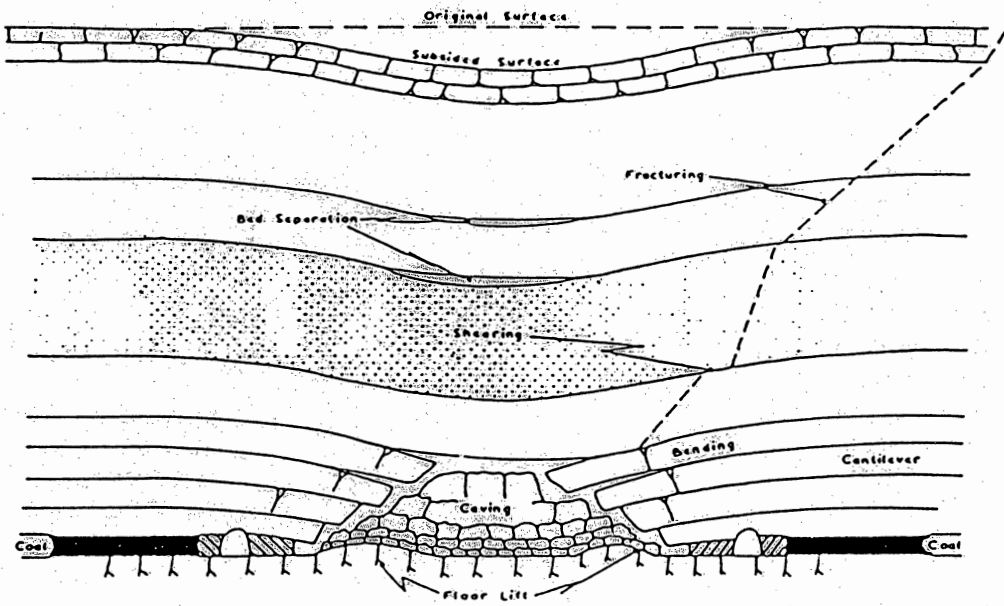


Figure 20. Strata Movements Resulting From Underground Mining (Shadbolt, 1978)

width of this opening is increased at this horizon to some critical value or the same span is created in a shallower seam, the overlying strata will progressively rupture to the surface and the characteristic subsidence trough is formed as in Figure 21 (Stefanko, 1973).

#### 2.4 Statistical Models in Multiple Seam Mining

It is universally recognized that because of the highly nonhomogeneous and anisotropic nature of geology, it is impossible to achieve absolute certainty in the design and operation of an underground mine. That the concepts of probability must form an integral part of any rational attempt to describe the nature of these things follows from the realization that one must necessarily predict expected performance of the geologic universe on the basis of past experience or of a limited number of material tests (Wane, Hassialis and Boshkov, 1964).

With the importance of statistical models understood, two attempts to statistically analyze multiple seam interaction factors and predict their effects on second seam mining will be discussed.

The first study was conducted by Dunham and Stace in Britain for the National Coal Board. The purpose of the investigation was essentially to define the influence of a variety of interactive situations on the stability of underground excavations. Concentration of the study was

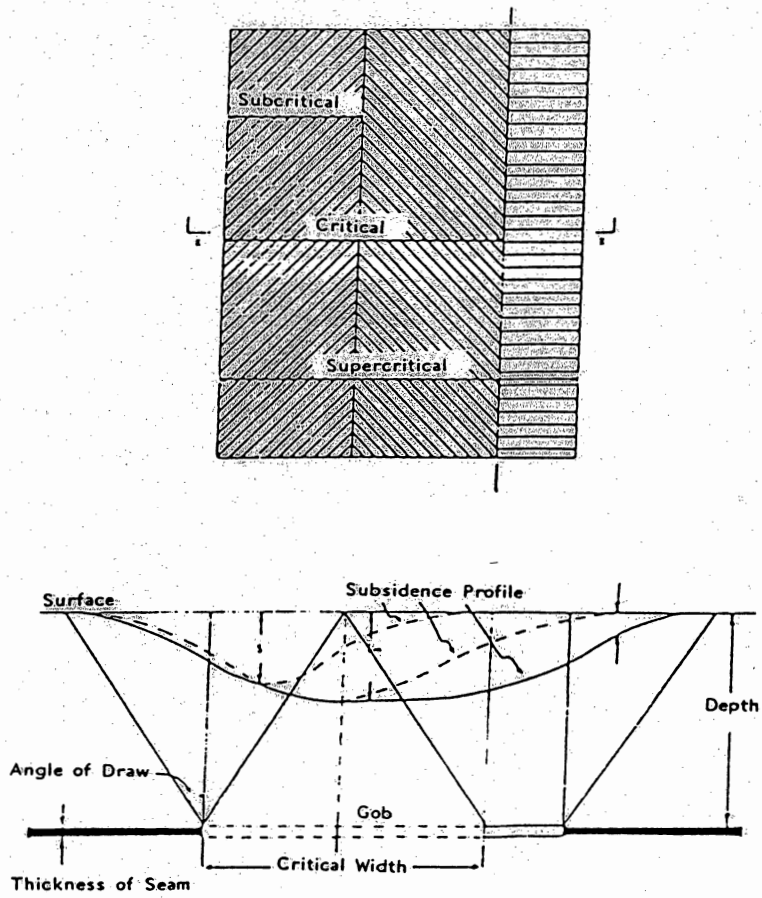


Figure 21. Subsidence Trough (Stefanko, 1973)

placed in roadways and in faces worked by the longwall method which is predominant in Britain.

A number of case studies of interaction situations were analyzed, mainly in Britain's northeast coalfields. A typical interaction situation will be illustrated.

The effects from rib edges, left in coal seams previously mined on a subjacent gate roadway to an advancing longwall panel, were measured. Figure 22 shows the location of the present workings relative to the previous workings. Panel R41 is a 212 yard long advancing longwall face worked in seam R. Instrumentation was set in the gate roadways of this panel. Rib edges in seams P and M which overlie seam R are also shown. The vertical distances to seams P and M are 130 and 310 feet, respectively.

Instrumentation consisted of 13 roof-floor convergence stations located in the main gate. Stations 1 through 4 were located under both seam P and seam M gobs. Stations 5, 6 and 7 were located under the rib edge in seam M but under the gob of seam P. Stations 8 through 12 were located under rib edges in both superjacent seams.

The results of the monitoring program are given in Figure 23, which plots mean working height against distance from the face. A general closure is noted at all stations; however, at stations 8 and 9 an increase in closure over the previous stations is noted. These stations lie 15 and 40 feet, respectively, beyond the solid rib in seam P. The

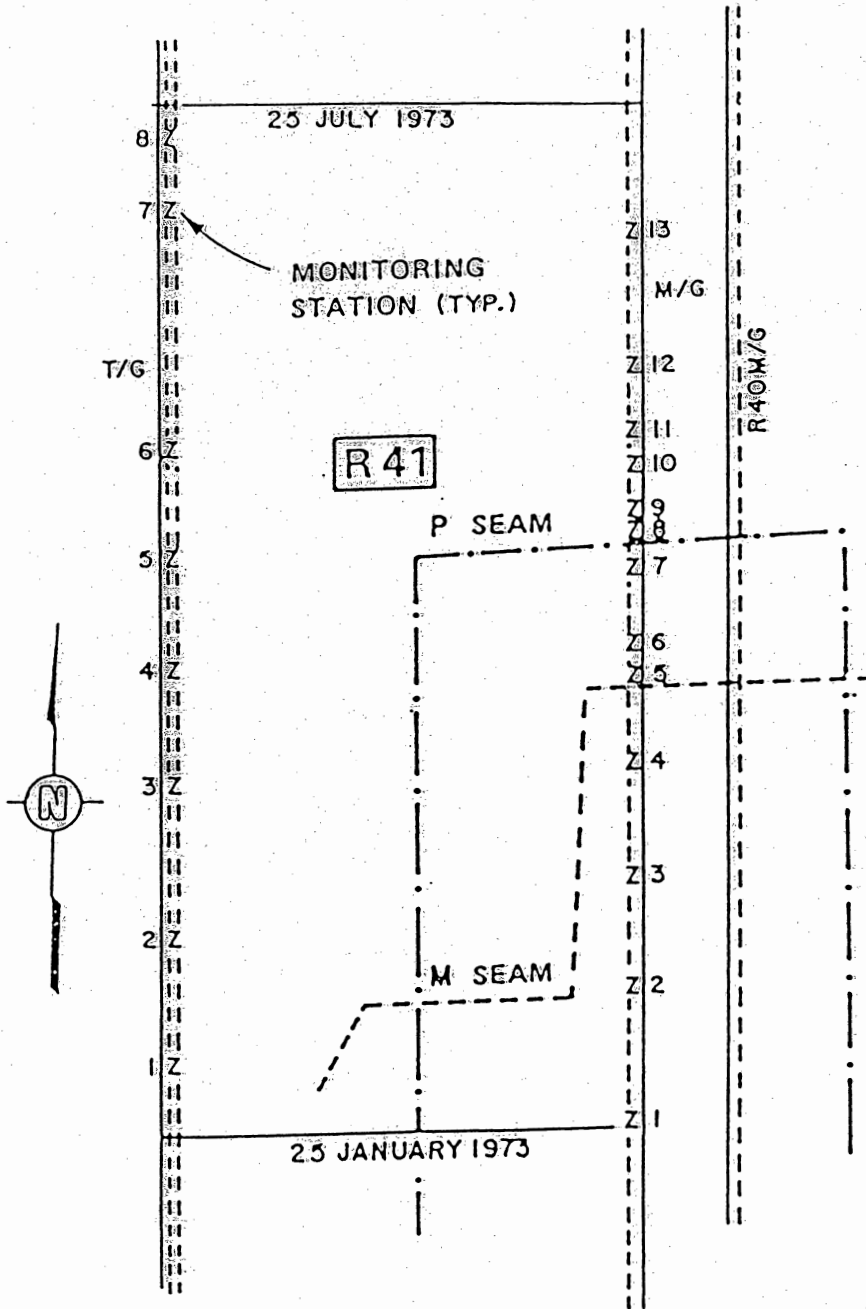


Figure 22. Plan of the Workings at Colliery A (Dunham and Stace, 1978)

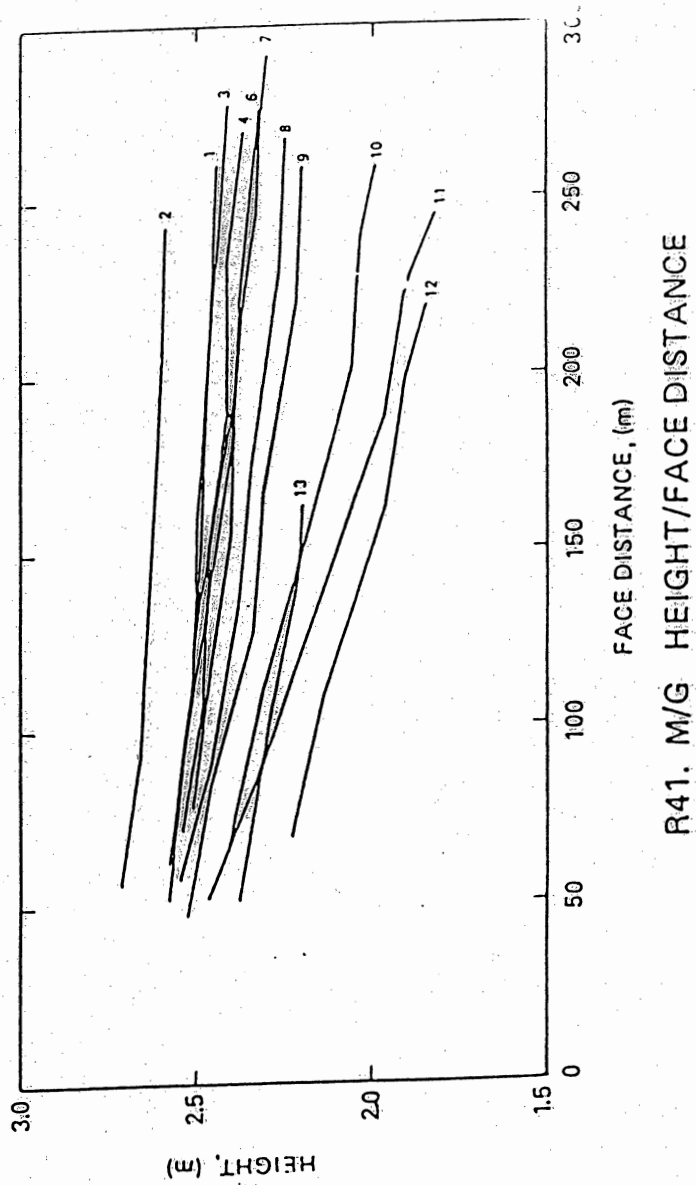


Figure 23. Mean Roadway Height Versus Distance from the Face (Dunham and Stace, 1978)

worst effects were felt between stations 10 and 12, lying 100 and 230 feet, respectively, beyond the rib edge. Improvement in condition as the face advanced farther under the solid coal in the overlying seams is illustrated by the measurements at station 13.

The results from all of the interaction sites suggested that the major variables effecting the extent of damage are as follows:

- The initial stability of the roadway.
- The vertical or perpendicular distance between the affecting rib edge and the roadway.
- The geometry of the affecting rib edge.
- The sequence of working all seams in an area.
- The age factor.
- The superimposition of two or more rib edges.

To develop a simple mathematical model, four of the variables were specified:

- X1 = Initial stability.
- X2 = Vertical seam interval.
- X3 = Age of the rib edge.
- X4 = Geometry of the rib.

To quantify the initial stability of the roadway, Dunham and Stace used the NCB/MRDE Roadway Nomogram. This nomogram was originally produced to provide a broad prediction of the type of conditions that could be experienced in a roadway. A numerical value between 1 and 18 is assigned the roadway

assessment of the initial stability and is based on a roadway factor, the equivalent depth and the rate of advance. The roadway assessment is divided into three categories:

1 - 5 Good conditions.

6 -10 Moderate conditions, maintenance required.

10-18 Poor conditions, heavy maintenance required.

The vertical interval and the age of the rib edge were measured in feet and years, respectively. The geometry of the rib edge was given one of the following values:

1 = Single rib edge.

2 = Narrow pillar, superimposed abutments.

3 = Isolated or semi-isolated remnant pillars.

Multiple linear regression was used to analyze the data and the following predictive model was developed:

$$Y = 0.546 + 0.084 \times X1 - 0.003 \times X2 \\ - 0.015 \times X3 + 1.427 \times X4 \quad \dots \text{Eq. 9}$$

Y represents a scale roadway damage index ranging from 1 to 5, with:

1 = No effect.

2 = Slight measurable effect, but roadway stability is uneffected.

3 = Moderate effect, requiring a small amount of roadway maintenance.

4-5 = Roadway damage is serious, heavy repair work will be required.

From the coefficients, it can be seen that the rib edge geometry is the dominant influence. The negative coefficients of both seam interval and age of rib edge could not be totally explained by the authors. One possible explanation would be simply the sample size of the study, only 21 cases were examined. Also the mathematical model adequately predicted the interaction damage in only 13 of the 21 case studies.

In the conclusion of their report, the authors stress the importance of obtaining more data. They suggest that simple measuring systems could be used to cover a large number of sites.

HRB-Singer, Inc., under a contract from the United States Bureau of Mines, conducted another research project. This project attempted to estimate the impact of coal seam interaction on the Eastern Coal Province of the United States. The primary objective of the study was to provide estimates of expected coal recovery, expressed as a percentage of the original in-situ reserves, when another seam had been previously mined, either subjacent or superjacent. A further objective was to determine the factors that effect the recovery of seams so as to minimize further damage.

The study collected data from four mines located in West

Virginia and Pennsylvania. In each of the mines, active mining was taking place in a second seam. The study examined both mining above and below previous workings. Concentration was, however, placed on the case of mining above previous workings.

A statistical model was developed to predict the maximum percent extraction in one of the test mines which had been undermined previously. The mine was divided into square blocks, each of 16 acres. Fifty blocks were chosen as test blocks for the analysis. For each block, 43 observations were made and an additional 20 variables were calculated, resulting in a total of 63 variables.

First a statistical model was developed for 31 of the 50 test blocks. These 31 blocks represented test blocks in which the extraction had not been total. The rationale was that if pillars in the previously mined seam had an effect on coal recovery in the current seam, then one could not legitimately use variables describing these pillars if the pillars had all been removed.

Of the 63 candidate variables, four variables were chosen statistically to predict percent extraction in the upper seam. They were identified as follow:

- X15 = Upper mine percent extraction (percent).
- X37 = Previous mine percent extraction (percent).
- X52 = Vertical distance between seams (feet).
- X60 = Overburden above previous mine (feet).

X61 = Time elapsed between mining (years).

The following prediction equation was produced using multiple linear regression:

$$\begin{aligned} X15 = & 146.824 + 0.2718 \times X37 + 0.2563 \times X52 \\ & + 0.0307 \times X60 - 105.5506 \times \log X61 \quad . . . \text{Eq. 10} \end{aligned}$$

The logarithm of X61, time elapsed, was used instead of X61 and the authors did not explain why this was done.

A second statistical model was built using all 50 of the test blocks. The same procedure was followed with the same variables being found significant. The following prediction equation was produced:

$$\begin{aligned} X15 = & 191.823 + 0.2266 \times X37 - 0.1583 \times X52 \\ & + 0.0158 \times X60 - 105.8583 \times \log X61 \quad . . . \text{Eq. 11} \end{aligned}$$

In a review of the HRB-Singer report, Engineers International question the coefficients determined. The coefficient of the previous mine percent extraction was 0.2718 for the first equation and 0.2266 for the second equation. These positive coefficients indicate that the higher the percent extraction in the lower previously mined seam, the higher the percent extraction can be expected in the upper seam. This may be reasonable for near total extraction, indicating more uniform extraction, hence more

uniform subsidence; for partial extraction, this relationship seems doubtful.

Next, consider the coefficient of the vertical distance between seams. The coefficient determined for the first equation was 0.2562, while for the second equation it was -0.1583. HRB-Singer claim both results are significant at varying levels. There is some question how a coefficient can be significant while positive yet still be significant while negative. A positive coefficient would seem reasonable.

The last coefficient in both regression equations is the coefficient for the logarithm of time. In both equations the coefficient is approximately -105. The negative sign is again troublesome. This would indicate that mining should take place in an upper seam as soon as possible after the extraction of the lower seam. This is contrary to established mining practice.

HRB-Singer state that these regression equations are mine specific and new equations would have to be developed for each new multiple seam mine. This severely limits their applicability to new mine design.

### III. Case Studies

In order to analyze the effects of subsidence in multiple seam mining, case studies were collected from published literature. In all, 60 case studies were collected and analyzed. Most of the situations described were from the Appalachian Coal Fields, in particular, from the states of West Virginia and Pennsylvania. Foreign case studies were also examined. Several British studies, which involved instrumentation in longwall gate roadways or in room pillar workings above active longwall panels, were examined and found to be very useful. Canadian studies of both coal and uranium multiple seam mines were examined as well as American studies conducted in western states, including Wyoming and Utah.

Several examples of the case studies collected will be presented.

#### 3.1 Case Study No. 1

This case study is typical in that the mines discussed are located in West Virginia (Peng and Chandra, 1980). It is, however, one of the few case studies in the Appalachian region in which the mining method used in the lower previously mined seam was longwall. This lower seam, the Eagle Seam, is approximately seven feet in height and had been worked extensively by longwall methods. The upper

seam, the Campbell Creek Seam, is approximately six and one-half feet in height. Mining in this seam is relatively new and most of the mining that had been completed had been by room and pillar methods. Longwall methods were however being used in the area of the study.

The innerburden is approximately 190 feet thick. The geologic section, which consists primarily of sandstones and shales, is illustrated in Figure 24. The overburden varies considerably because of mountainous terrain.

In 1977 a longwall panel was driven in the upper seam over a longwall panel in the lower seam that had been extracted in 1971. The immediate roof was a shale 15 feet in thickness. The overburden above the upper seam was on the order of 1,100 feet.

Over the gob of the lower panel, the quarterly advance rate had averaged 400 feet. As the rib edge was reached the advance rate had dropped to 115 feet. At approximately 180 feet beyond the rib edge, roof control problems became so acute that the face could no longer be advanced and the equipment had to be removed by rescue entries, as illustrated in Figure 25. The angle from the lower seam rib edge to where the face became stuck is above 40 degrees, this is higher than would be expected or would be predicted from surface subsidence studies in the Appalachian coal fields.

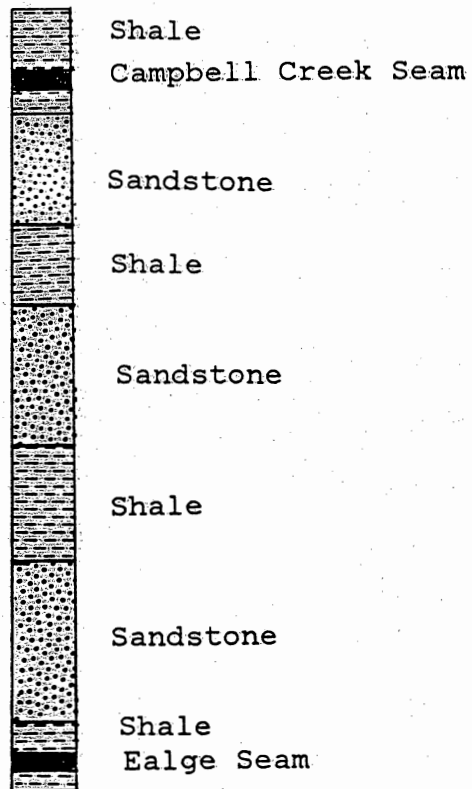


Figure 24. Geological Column of Case Study No. 1 (Peng and Chandra, 1980)

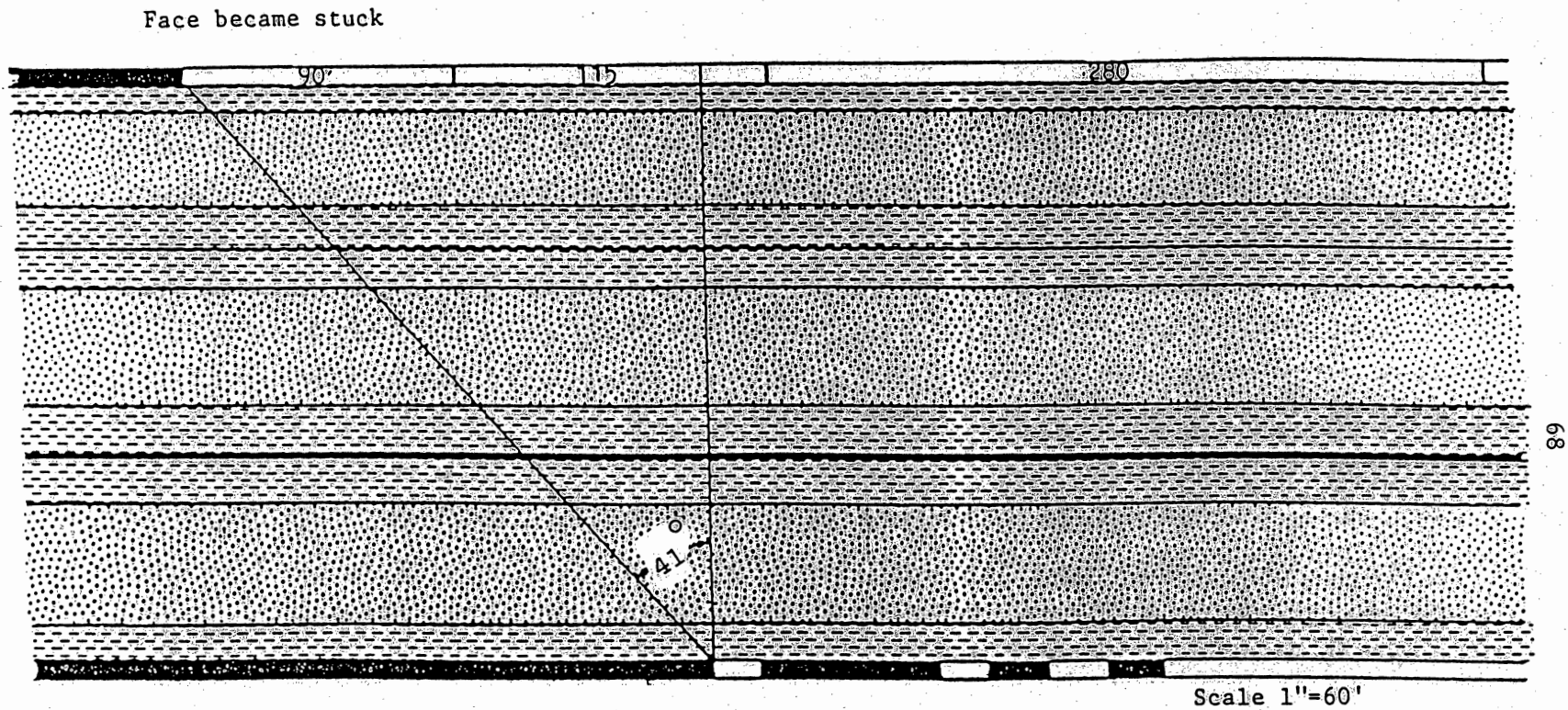


Figure 25. Cross-section of Case Study 1

### 3.2 Case Study No. 2 (Farmer)

Case Study 2 is British in origin. Farmer, 1980, conducted the study at Lynemouth Colliery to determine ground movements above a longwall face. Active mining was taking place in the Brass Thill Seam which lies 160 meters below the sea bed and 200 meters below mean sea level. The workings in the Brass Thill Seam are overlain by old room and pillar workings in the Main Seam 75 meters above. Figure 26 illustrates the geological column of the innerburden. The workings presented an ideal opportunity for observation of strata deformation above a longwall face.

The first face to be extracted in the Brass Thill seam was designated as K4. The extraction height was 1.6 meters. The Main Seam above had been worked approximately 13 years prior.

Instrumentation above panel K4 consisted of two vertical drill holes, drilled to a depth of nearly 70 meters, to within 5 meters of the Brass Thill Seam. Wire extensometers were installed in the holes and anchored at approximately 10 meter intervals. Both holes were located on the panels center line with the first hole, D1, 25 meters, and the second hole, D2, 100 meters from the face start line. Horizontal boreholes were also drilled into pillars to determine pillar deformation. Convergence stations were

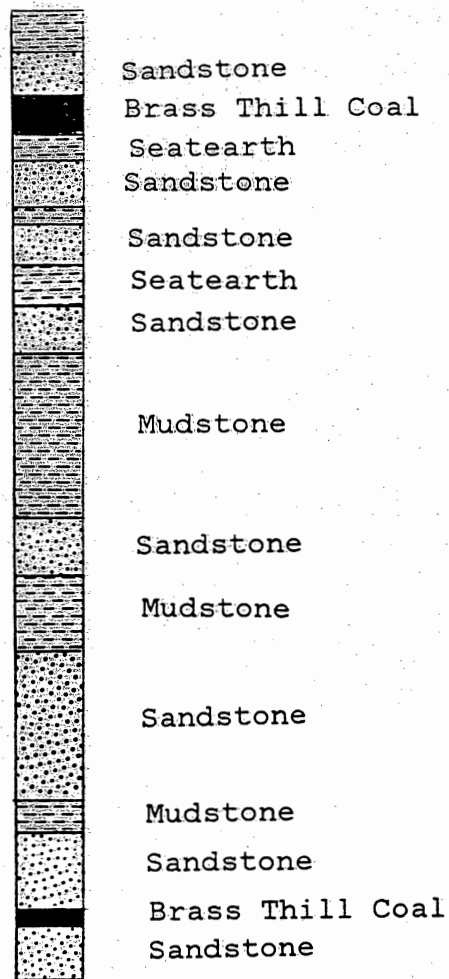


Figure 26. Geological Column of Case Study No. 2 (Hodkin, Dunham and Farmer, 1980)

also installed at junctions and in roadways. Instrumentation is shown in Figure 27. Relative vertical settlements from D1 and D2 are illustrated in Figure 28. The apparent uplift of the lower strata can be seen as a geometrical rather than a geotechnical feature resulting from lower settlement rates in the higher layers. Figure 29 illustrates the subsidence profile measured as compared to NCB predicted subsidence. The measured subsidence is substantially less than the predicted values. A possible explanation presented by the authors is that the large tensile strains measured suggest bed separation is occurring and thus smaller subsidence is occurring.

### 3.3 Case Study No. 3 (Agapito et al)

In 1976, Agapito, Bennett and Hunter, conducted a rock mechanics study at the Big Island Trona Mine in Wyoming to determine the feasibility of mining two superimposed, 10 foot thick, trona seams. Trona is a mineral used to produce soda ash. Mining in the trona seam is conducted by partial extraction room and pillar methods with conventional equipment.

In the lower seam, which lies 850 feet below the surface, extraction began in 1962. Mining is designed for full overburden support with extraction at 60 percent. In 1975 extraction began in the upper seam, 33 feet above the

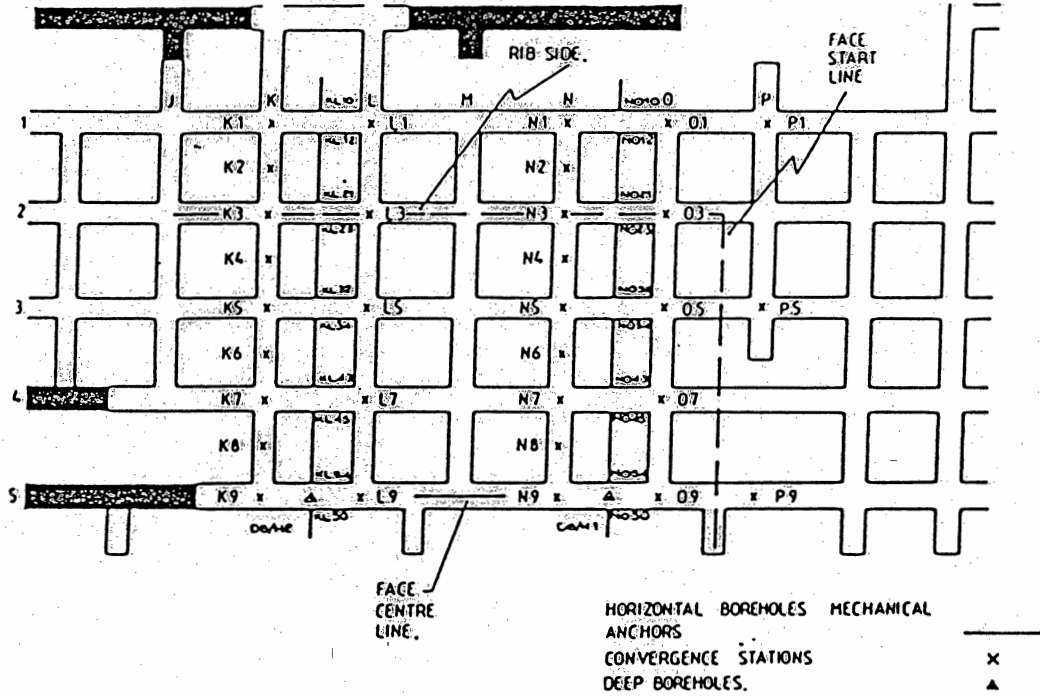


Figure 27. Position of Instrumentation for Case No. 2 (Farmer, 1980)

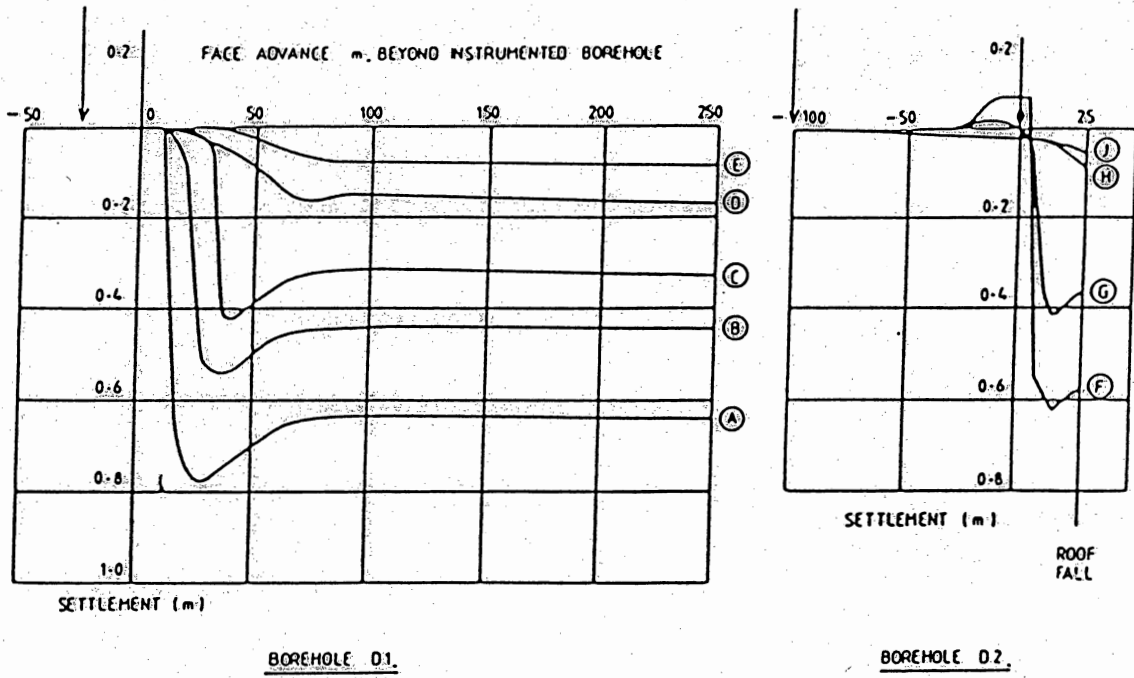


Figure 28. Relative Vertical Movement Measured from the Main Seam (Farmer, 1980)

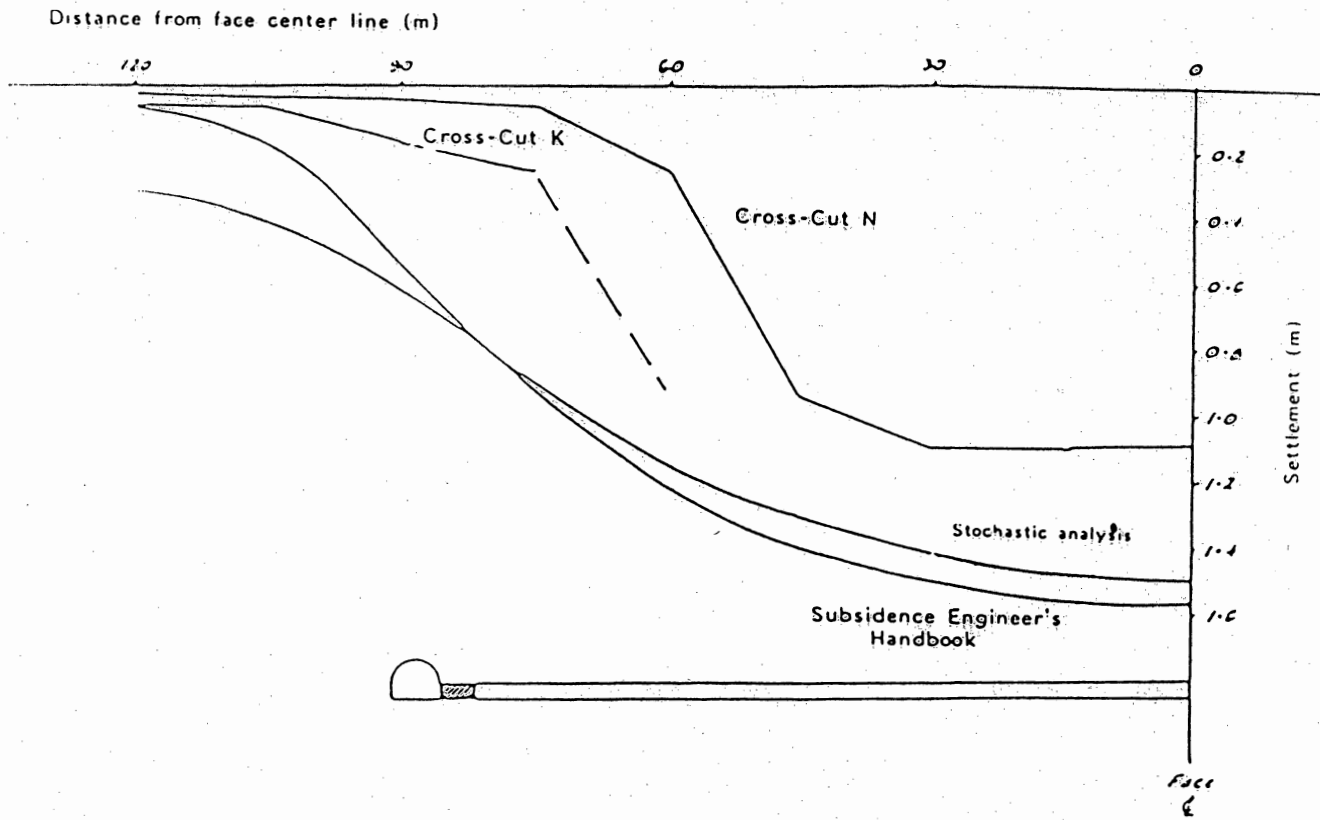


Figure 29. Settlement at Cross-cut Normal to Face Line (Hodkin, Dunham and Farmer, 1980)

lower seam. The innerburden consists of marlstones and shales, as shown in Figure 30.

A test panel was mined in the upper seam, with superimposed pillars, three years after the lower seam had been extracted. The objectives of the program were:

- First, to monitor stability and ensure safety of personnel and equipment.
- Second, to obtain basic design information for future mine designs involving higher extractions.

Single-point borehole extensometer measurements were made at different levels both from the roof of the lower bed and from the floor of the upper bed. Upper bed mining induced an immediate movement. Total displacements were small, with a maximum of 0.25 inches. This maximum measurement is as of two months after the upper seam had been mined. Regular inspections of the upper and lower panels indicated sound structural conditions. Upper bed blasting did however, induce spalling of loose roof slabs and pillar corners in the lower bed panel. Damage was minor but safety considerations precluded personnel entering the lower panel while mining was taking place in the upper bed. From these observations it was concluded that concurrent upper and lower seam mining should not be conducted with the mining faces less than 300 feet apart horizontally.

Future plans at the Big Island Trona Mine include continuing to monitor displacements and strains in pillars

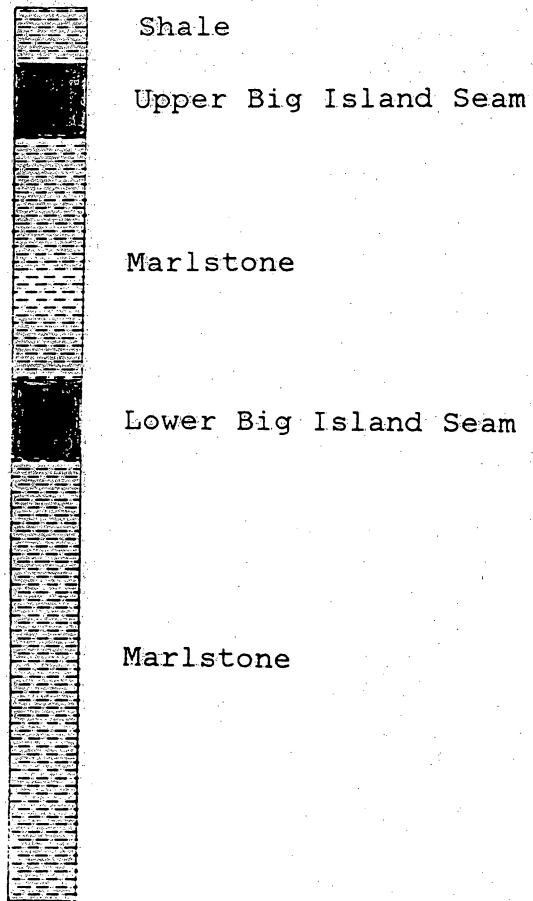


Figure 30. Geological Column of Case Study No. 3 (Agapito, Bennett and Hunter, 1979)

with progressively higher extractions to determine optimum safe extraction ratios.

#### 3.4 Case Study No. 4 (Hasler)

Case study 4 is more typical of the case studies analyzed. The mine under consideration is located in Cambria County, Pennsylvania, (Hasler, 1951). Figure 31 illustrates the geological column of the region. There are many seams of coal in the region. In this particular case study the lower seam, the Lower Kittanning Seam, had been mined before the upper seam, the Upper Freeport Seam. Both seams were approximately 42 inches in height. The innerburden was 180 feet thick and consisted mostly of shales with some sandstone and coals.

The lower seam had been mined approximately two years before extraction of the same area in the upper seam began. Extraction in both seams was by room and pillar methods. Some areas of the lower seam had been pillared while in other areas pillars had been left in place. The upper seam pillars were columnized over pillars in the lower seam.

In areas where pillars had been left in the lower seam for support, no problems occurred in the upper seam other than a marked reduction in the amount of water encountered. Major disturbances occurred, however, in the upper bed over areas where the underlying bed had been pillared.

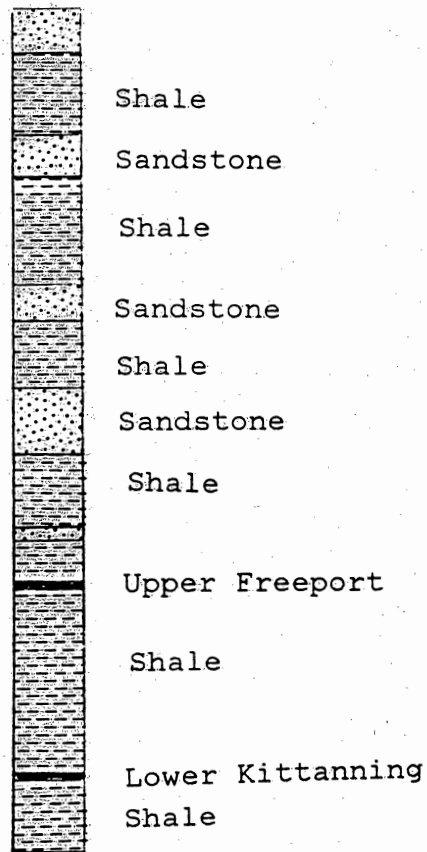


Figure 31. Geological Column of Case Study No. 4 (Hasler, 1951)

### 3.5 Case Study No. 5 (Stemple)

Case study 5 is also typical. The mine is located in Monongalia County, West Virginia (Stemple, 1956). The lower seam, the Pittsburgh Seam, had been extracted five years prior to the extraction of the upper seam, the Sewickley Seam. The Pittsburgh Seam averages 96 inches in height. The Sewickley Seam lies 85 feet above the Pittsburgh Seam. The innerburden is primarily shale and is illustrated in Figure 32. The overburden above the Sewickley Seam is approximately 400 feet thick. Extraction in the Pittsburgh Seam had been by room and pillar methods with overall extraction about 60 percent. Some areas, however, had been robbed and therefore localized areas of total extraction existed.

Upper seam workings, which were not aligned with the lower seam workings, met with varying degrees of success. No disturbance was felt in the upper seam over areas where the pillars were left in the lower seam. In areas above the robbed sections of the Pittsburgh Seam, the floor, coal and roof were found to be fractured. Figure 33 overlays workings from both seams. It can be seen that as the upper seam workings approached the robbed area of the lower seam, bad top conditions developed and the mining had to be stopped.

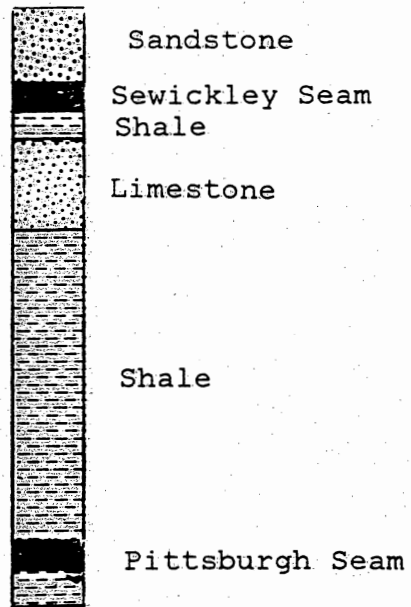


Figure 32. Geological Column of Case Study No. 5 (Zacher, 1952)

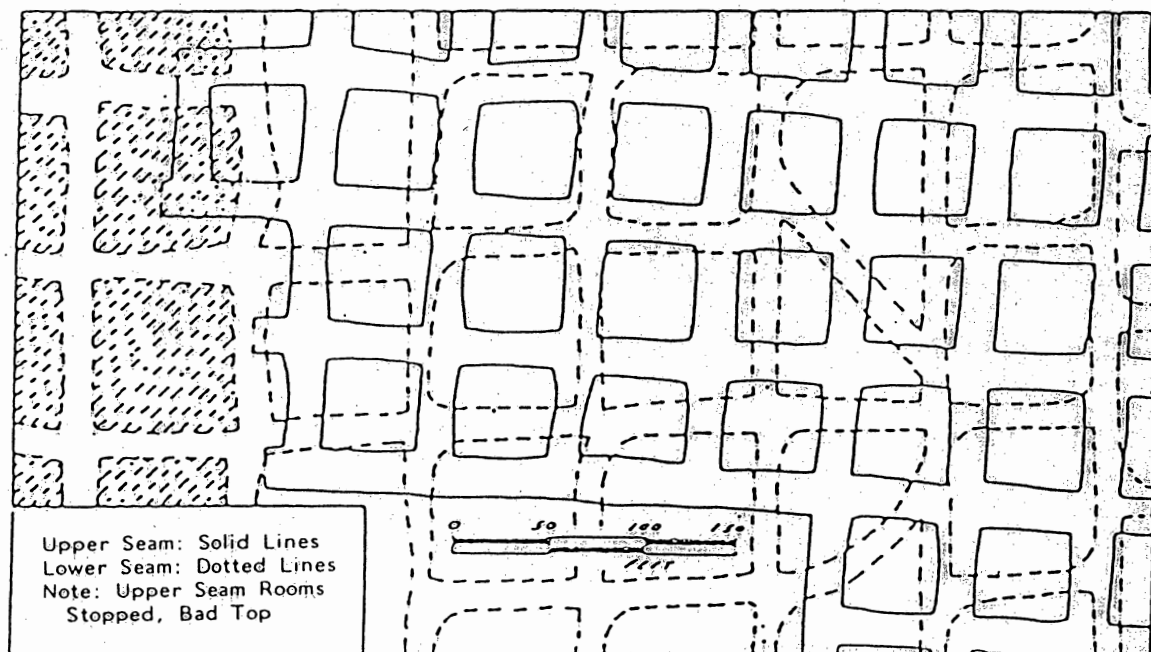


Figure 33. Overlays of Mine Maps for  
Case Study No. 5 (Stemple, 1956)

#### IV. Model Development

In an attempt to predict multiple seam mining problems in the Appalachian Coal Field, the case studies that were collected were analyzed. Of the 60 case studies collected, 44 were from this region. Only these 44 studies were used in the analysis.

For each of the 44 case studies, a damage level was assigned using a six point scale as follows:

- 0 = No damage.
- 1 = Fractures present in the upper seam  
(no roof problems associated).
- 2 = Fractures with movement visible.
- 3 = Roof problems encountered.
- 4 = Major roof problems encountered  
(entire entries caved).
- 5 = Coal abandoned due to roof control problems.

For the analysis, this damage level was correlated with the following factors:

- Innerburden thickness.
- Percent sandstone or "hardrock" in the innerburden.
- Percent extraction of the lower previously mined seam.
- Lower seam height.
- Time.
- Overburden above the upper seam.

Tables 2 through 6 contain the data collected from the

Table 2A. Case Studies

CASE STUDY SOURCE	INTER- BURDEN (FEET)	% SAND- STONE	% EXTRAC- TION	SEAM HEIGHT (INCHES)	TIME (YEARS)	OVER- BURDEN (FEET)	DAMAGE
STEMPLE	50	30	70	52	1	800	2
STEMPLE	230	65	65	42	6	650	1
STEMPLE	125	70	70	45	1	375	0
STEMPLE	75	45	65	68	0.5	150	4
STEMPLE	70	55	65	53	0.5	500	1
STEMPLE	65	7	70	46	3	220	2
STEMPLE	65	30	60	62	1	80	0
STEMPLE	350	50	60	54	0.5	175	0
STEMPLE	350	50	90	54	0.5	175	4

Table 2B. Case Studies

CASE STUDY SOURCE	INTER- BURDEN (FEET)	% SAND- STONE	% EXTRAC- TION	SEAM HEIGHT (INCHES)	TIME (YEARS)	OVER- BURDEN (FEET)	DAMAGE
HASLER	160	40	80	38	0	400	4
HASLER	145	40	65	38	10	350	1
HASLER	145	40	85	38	0	350	4
HASLER	180	20	70	42	2	725	1
HASLER	43	10	80	40	0	250	5
HASLER	42	10	85	51	12	175	2
HASLER	42	10	85	51	0	175	5
HASLER	45	10	85	42	0	300	5
PENG & CHARDRA	23	5	85	48	10	300	5

Table 2C. Case Studies

CASE STUDY SOURCE	INTER- BURDEN (FEET)	% SAND- STONE	% EXTRAC- TION	SEAM HEIGHT (INCHES)	TIME (YEARS)	OVER- BURDEN (FEET)	DAMAGE
PENG & CHANDRA	300	50	65	68	10	600	0
PENG & CHANDRA	190	60	90	84	6	110	5
STEMPLE	145	50	90	54	12	250	1
STEMPLE	510	50	80	57	10	200	1
STEMPLE	65	50	75	68	5	375	3
STEMPLE	470	15	90	90	9	150	3
STEMPLE	300	50	80	165	9	400	2
STEMPLE	275	50	90	40	4	50	2
STEMPLE	420	35	50	44	17	150	0

Table 2D. Case Studies

CASE STUDY SOURCE	INTER- BURDEN (FEET)	% SAND- STONE	% EXTRAC- TION	SEAM HEIGHT (INCHES)	TIME (YEARS)	OVER- BURDEN (FEET)	DAMAGE
STEMPLE	65	60	80	48	15	400	1
STEMPLE	40	100	75	51	15	230	5
STEMPLE	900	40	90	48	35	200	2
STEMPLE	95	5	88	36	20	300	3
STEMPLE	40	0	85	57	10	300	3
STEMPLE	140	15	90	38	7	620	3
STEMPLE	150	10	50	44	5	125	0
STEMPLE	80	15	60	96	5	400	0
STEMPLE	80	15	85	96	5	400	2

Table 2E. Case Studies

CASE STUDY SOURCE	INTER- BURDEN (FEET)	% SAND- STONE	% EXTRAC- TION	SEAM HEIGHT (INCHES)	TIME (YEARS)	OVER- BURDEN (FEET)	DAMAGE
STEMPLE	145	7	65	72	9	300	0
STEMPLE	100	0	65	72	9	350	0
STEMPLE	150	30	80	48	3	150	3
STEMPLE	150	30	80	48	0	150	2
STEMPLE	210	15	75	42	2	750	3
STEMPLE	11	0	75	42	0	750	5
STEMPLE	100	50	65	60	25	200	0
STEMPLE	50	90	88	60	20	600	3

case studies. Plots of the data were made to see if trends or relationships were present. From early plots it became obvious that percent extraction was the dominant factor and that to develop relationships, other factors should be plotted against percent extraction. These plots are shown in Appendix A. From these plots it became obvious that a quantitative level of damage could not be predicted from the data. A pattern could, however, be seen in all plots except overburden versus percent extraction; therefore, overburden was eliminated from the model.

Each plot could be divided into two areas; no appreciable damage consisting of levels of damage 0 no damage and 1 fractures present but no roof problems associated; and damage consisting of all higher levels of damage. This pattern or natural grouping was later verified statistically by cluster analysis.

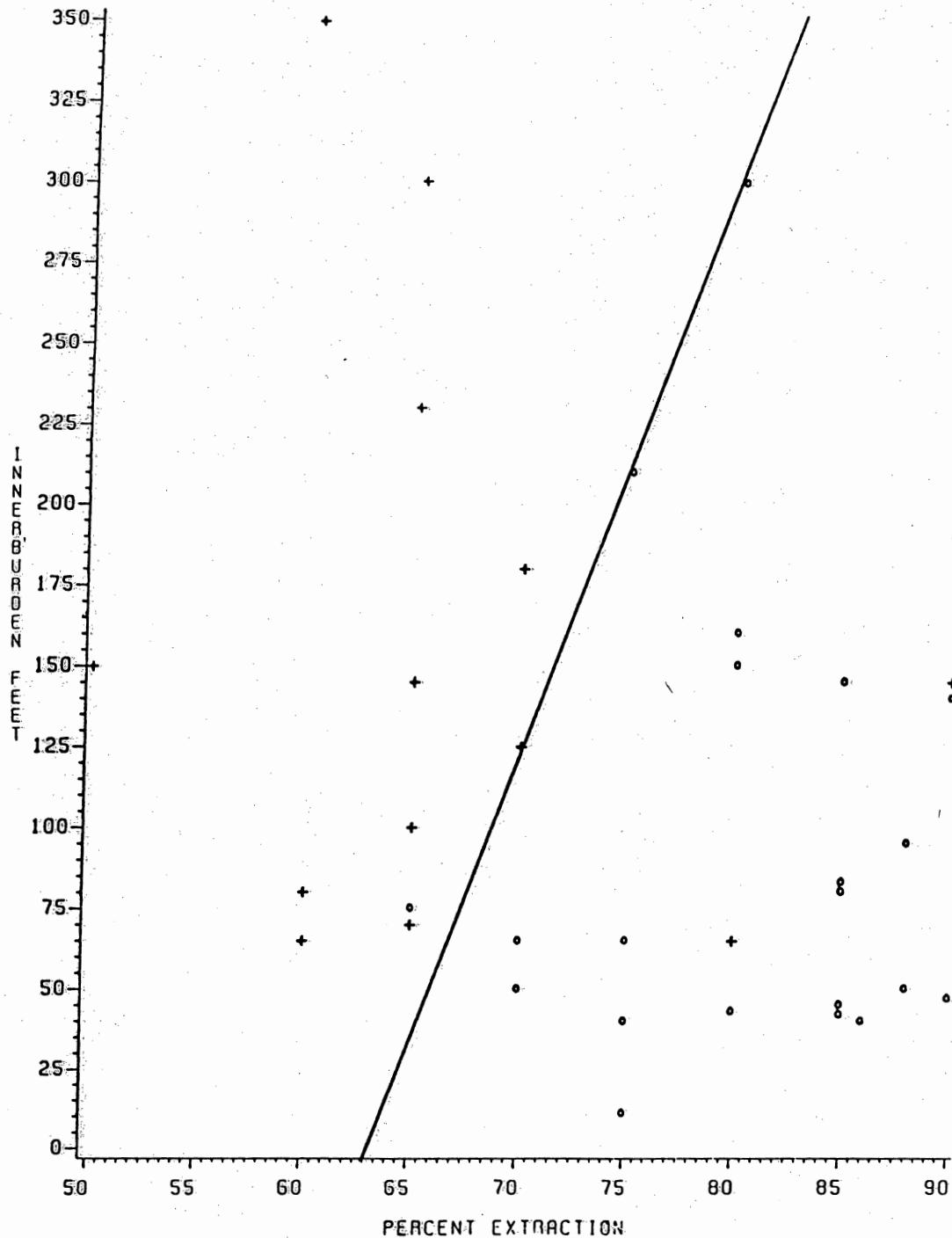
Cluster analysis is a technique used in many empirical fields to identify groups or clusters of data which are similar. Each individual data point or case study may be represented by a point in a multidimensional Euclidean space. The technique attempts to group these points into disjoint sets which it is hoped will correspond to marked features of the sample (Gower, 1967). Cluster analysis is often used where large arrays of data have been collected but strong theoretical structures, which might otherwise guide the analysis are lacking; the problem is then one of

discovering whether there is any structure inherent in the data (Johnson, 1967). The procedure is detailed in Appendix B.

This clustering or natural grouping indicates that, although the exact degree of damage cannot be predicted from the included variables, a useful separation in the data does exist. This separation divides damage into two subgroups, no appreciable damage and damage. No appreciable damage is defined as no harmful effects on second seam mining. Figures 34 through 37 illustrate the pattern for each of the variables plotted against percent extraction.

In order to develop a model involving more than two variables, these patterns had to be inter-related. Many methods were attempted but the following proved most successful. The first variables to be inter-related were innerburden thickness and seam height. This was accomplished by creating a ratio of innerburden thickness to seam height. This ratio was plotted against percent extraction. Figure 38 illustrates that with three variables inter-related, a separation is still apparent.

Time was the next factor to be included in the model. A multiplicative relationship was assumed. The innerburden to seam height ratio was multiplied by time and plotted versus percent extraction. In Figure 39 it can be seen that with this combination of the four included variables most of the variability in the model can be explained. From this point



LEGEND: DAMAGE    + + + 0    + + + 1    o o o 2  
                      o o o 3    o o o 4    o o o 5

FIGURE 34. INNERBURDEN VERSUS PERCENT EXTRACTION

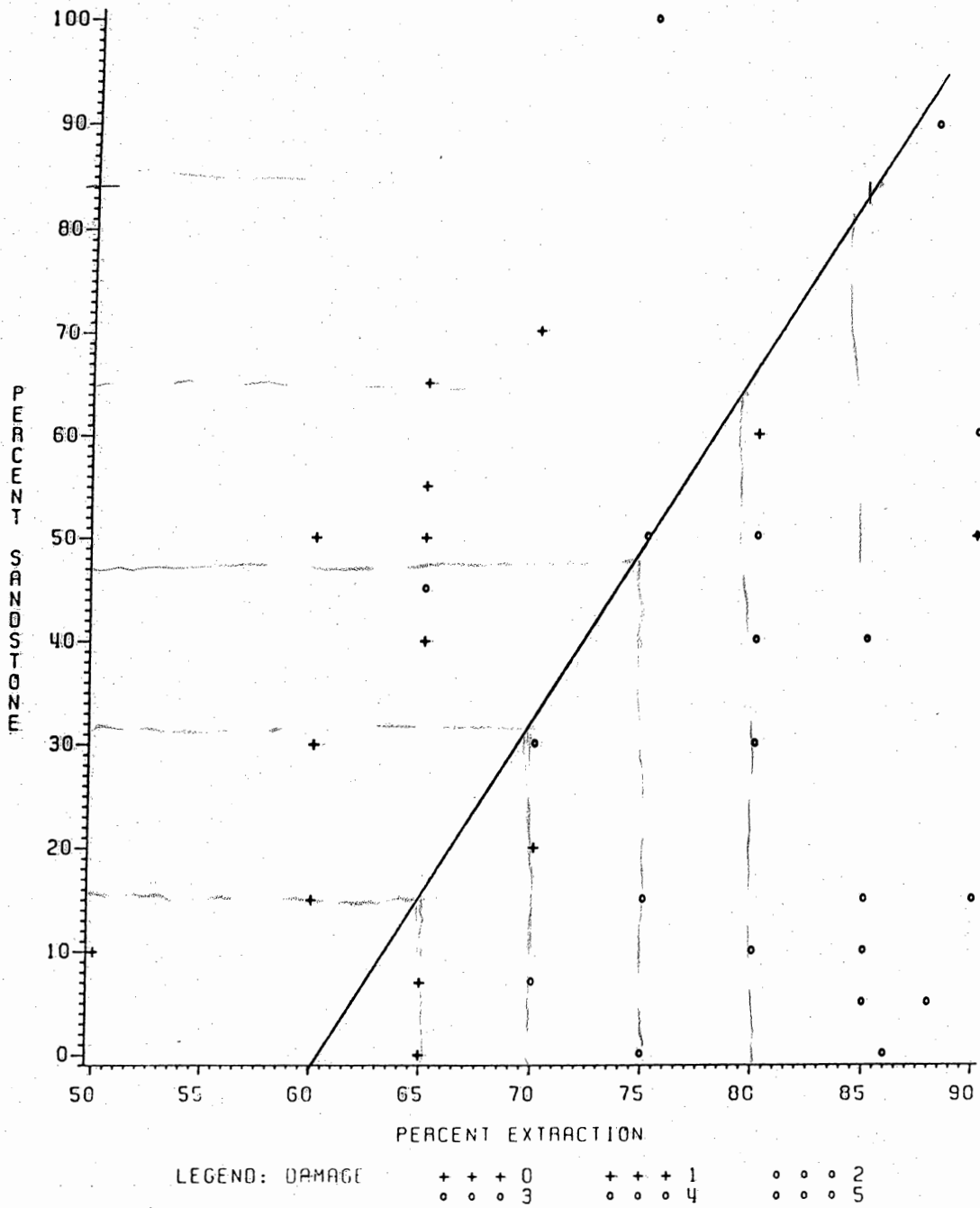


FIGURE 35. PERCENT SANDSTONE VERSUS PERCENT EXTRACTION

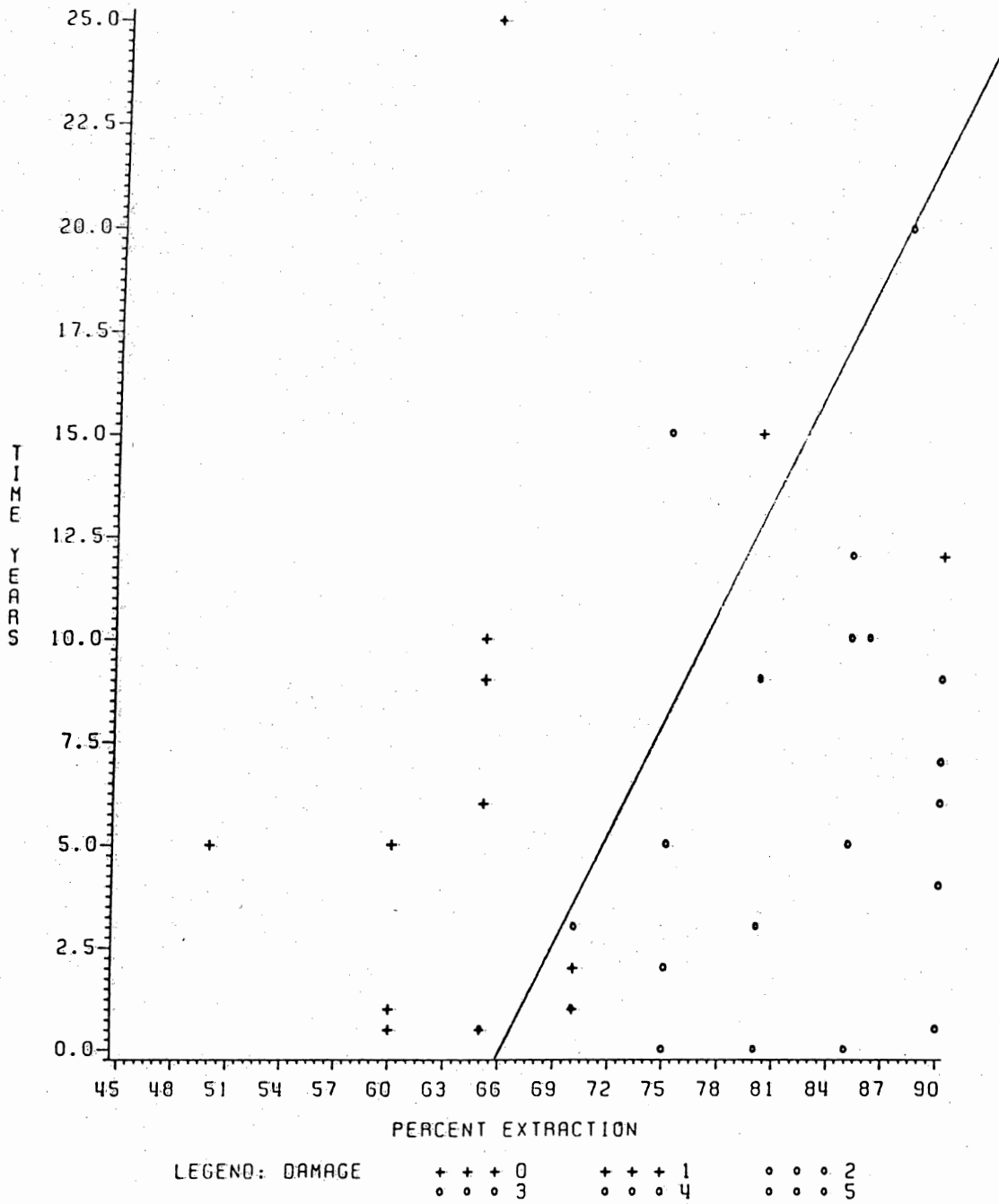
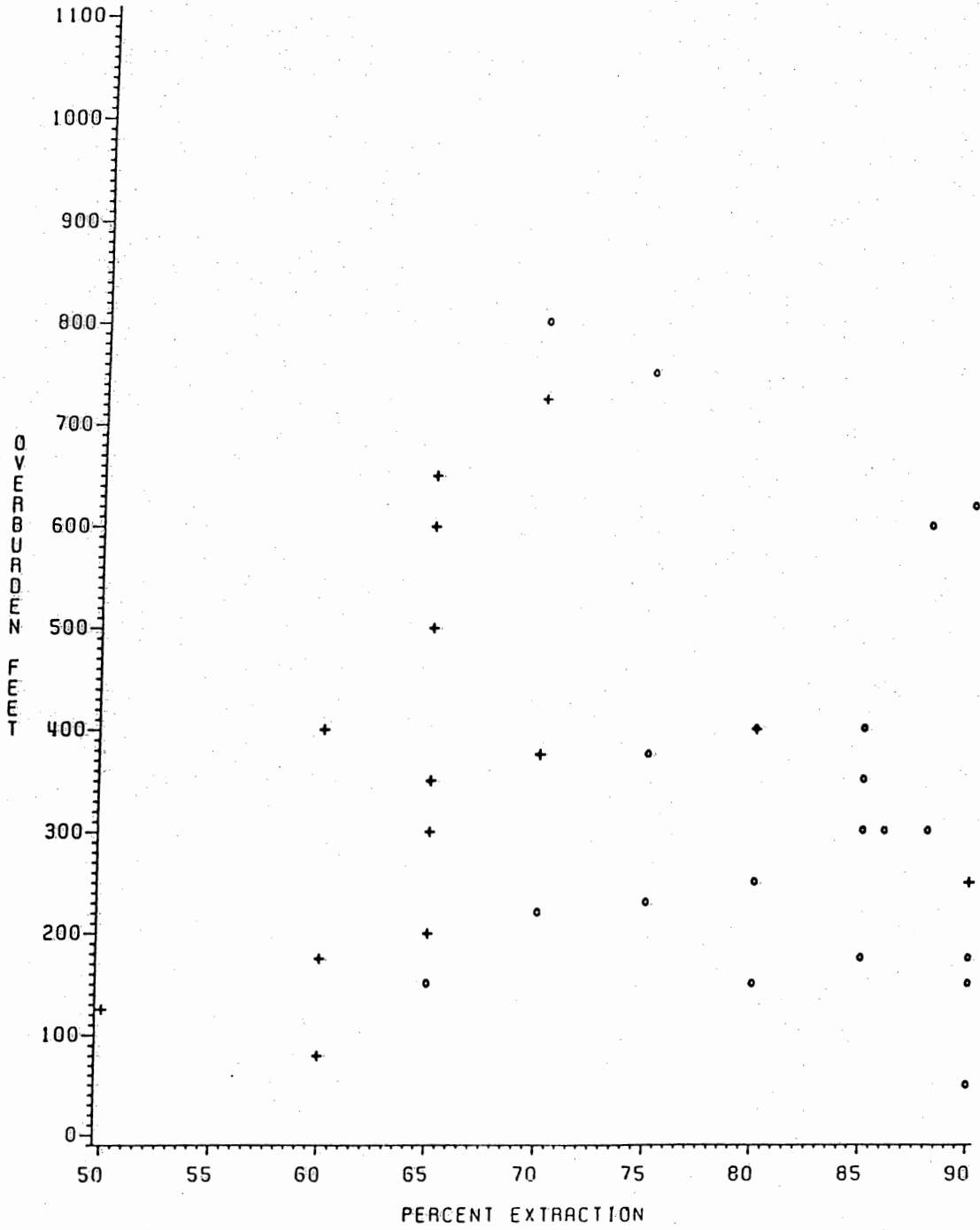


FIGURE 36. TIME VERSUS PERCENT EXTRACTION



LEGEND: DAMAGE    + + + 0    + + + 1    o o o 2  
                           o o o 3    o o o 4    o o o 5

FIGURE 37. OVERBURDEN VERSUS PERCENT EXTRACTION

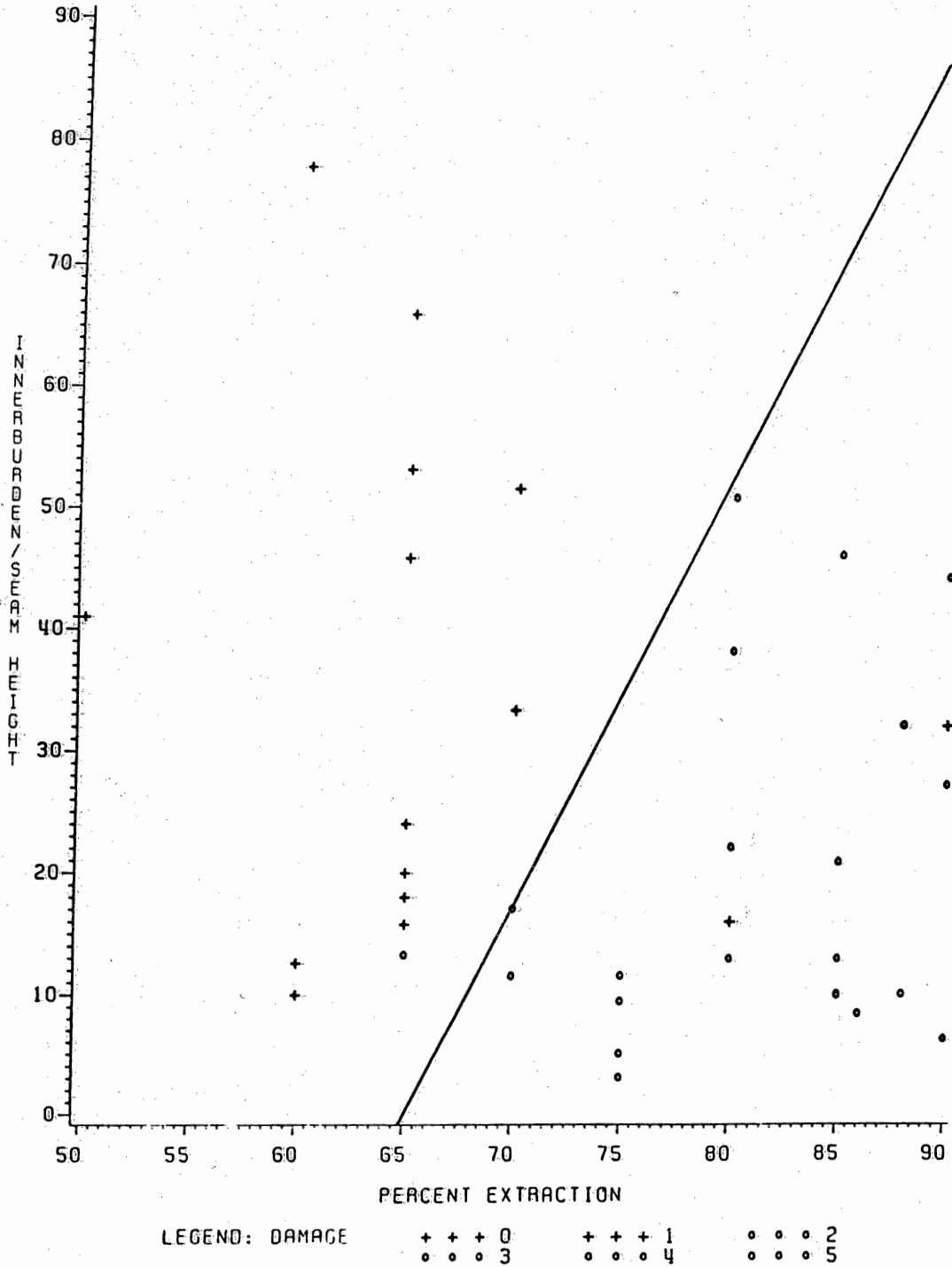
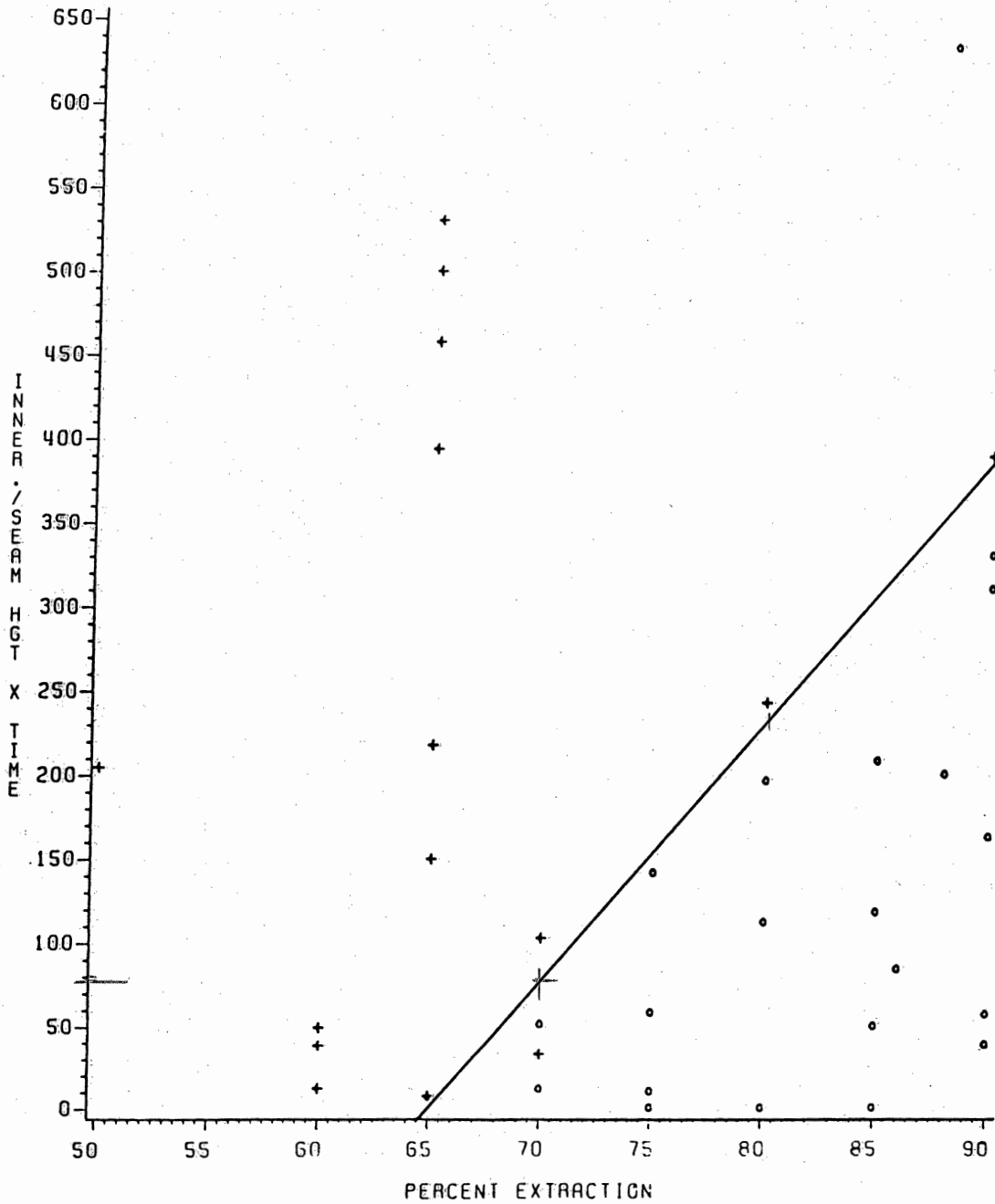


FIGURE 38. INNERBURDEN/SEAM HEIGHT VERSUS PERCENT EXTRACTION



LEGEND: DAMAGE    + + + 0    + + + 1    o o o 2  
                           o o o 3    o o o 4    o o o 5

FIGURE 39. INNER./SEAM HGT X TIME VERSUS PERCENT EXTRACTION

a nomogram was developed with another factor, percent sandstone or hardrock, to be included in the model later.

From Figure 39 an equation was developed involving the following variables:

- Innerburden thickness.
- Seam height.
- Time.
- Percent extraction.

This equation represents the boundary between no appreciable damage and damage. It was produced by multiple linear regression. Calculations are shown in Appendix C. The resulting equation is as follows:

$$1239 = 18.83 \times X - Y \quad . . . . \text{Eq. 12}$$

where: X = percent extraction  
Y = (innerburden/seam height) x time

This equation could be expressed in a form so as to produce a damage factor as follows:

$$DF = 1239 + Y - 18.83 \times X \quad . . . \text{Eq. 13}$$

where: DF = damage factor

This damage factor could be interpreted as a safety factor. When the factor is positive, no interaction problems should be anticipated in second seam mining. When the factor is negative, damage should be anticipated in second seam mining. The magnitude of a negative damage factor can not be interpreted as a degree of damage but rather as a degree of certainty that damage will effect upper seam mining.

For ease of calculation, a nomogram was produced as shown in Figure 40. For ease of construction and use, equation 13 was modified to:

$$DF = 620 + 0.5 \times Y - 9.42 \times X \dots \text{Eq. 14}$$

The model did, however, show some variance that could not be explained by the factors involved. No attempt had been made, thus far, to correlate geology with damage. To do this, the calculated damage factor was plotted versus percent sandstone or hardrock. From Figure 41, it became apparent that percent sandstone was a factor. A rotation was present in the plot. For stable conditions, higher positive damage factors were needed for low percent sandstone than were needed for higher percent sandstone. A

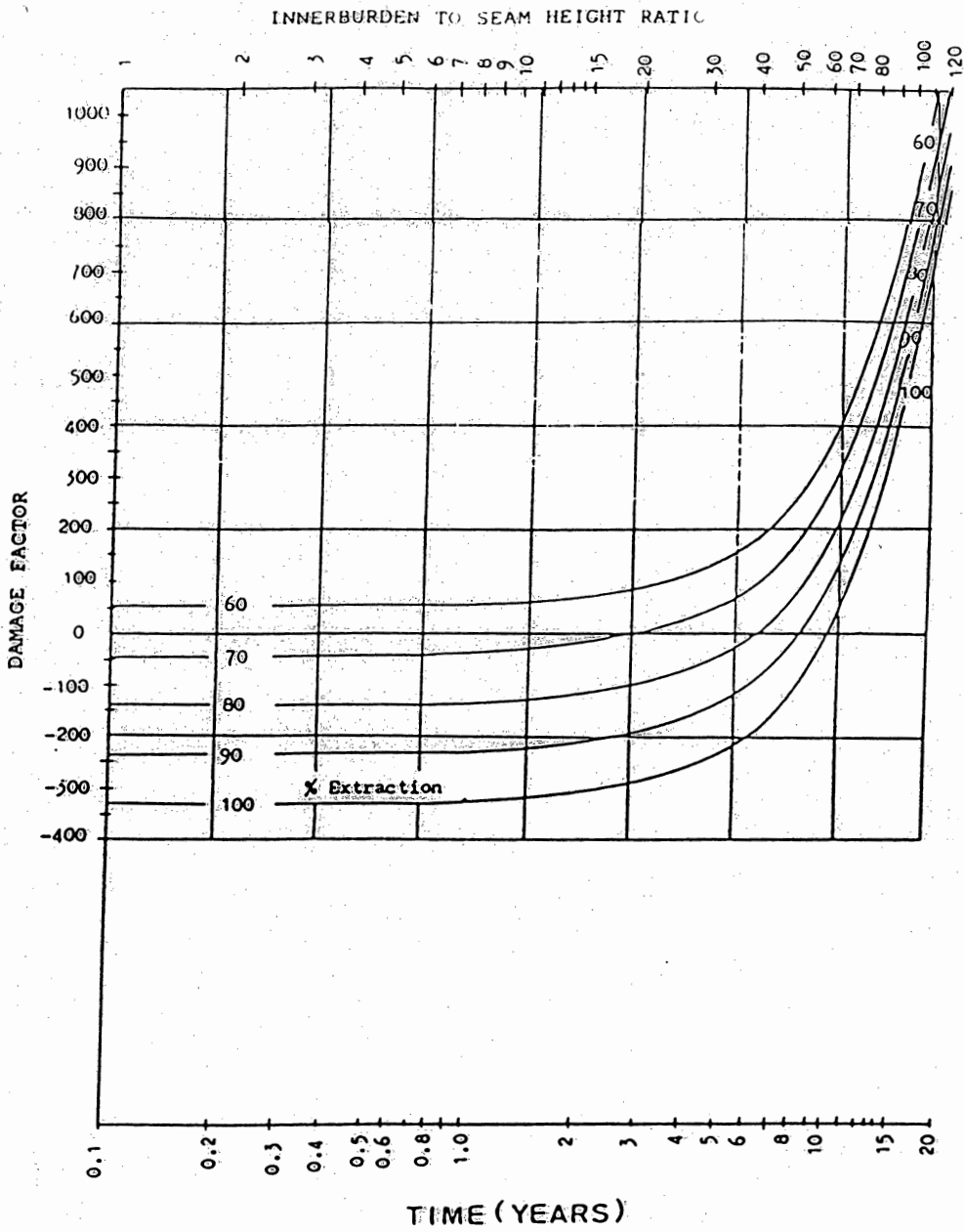


Figure 40. Nomogram

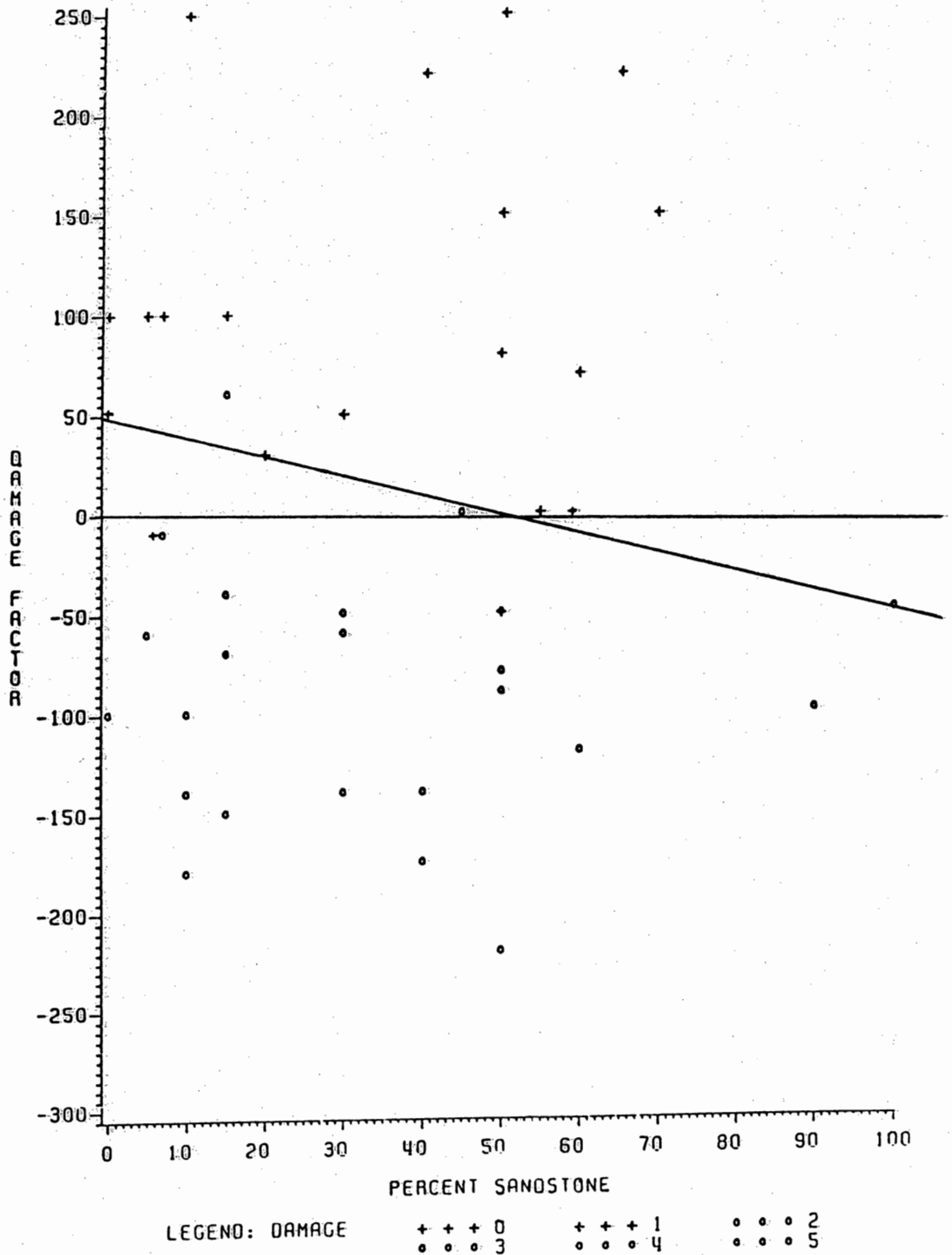


FIGURE 41. DAMAGE FACTOR VERSUS PERCENT SANDSTONE

simple linear relationship for the adjustment was developed as follows:

$$\text{ADF} = \text{DF} + (\text{Z} - 50) \quad . . . . . \text{Eq. 15}$$

where: ADF = adjusted damage factor  
Z = percent sandstone or hardrock

With the model now complete, the Adjusted Damage Factor predicts damage to an upper seam in all but 3 of the 44 case studies analyzed. Although the exact extent of the damage is not predicted by the model, the presence of damage is predicted in 93 percent of the case studies. Appendix D contains an example of the model's use.

## V. Summary

To determine the factors which govern damage, caused by subsidence, in multiple seam mining an understanding of strata movements above mine workings was necessary.

The creation of a void or working in a seam of coal by underground mining produces a disturbance in the natural stress field. The effect of the stress changes cause strata deformation and displacement which, depending on the dimensions of the opening, can extend to the surface. When a void of sufficient size is made, the immediate roof breaks and falls into the cavity. The collapsing, or caving, material is in the form of broken blocks and therefore increases in bulk and occupies a greater volume. At a height of 10 to 15 times the extracted seam height, caving stops. This caved material offers some support to the overlying beds of rocks and bed separation occurs. Upper beds tend to sag uniformly like a continuous beam and assume a fairly regular trough-shaped curve which continues to develop to the surface. Figure 20 summarizes ground movements from the excavation to the surface.

Once strata movements above underground workings were understood, case studies were analyzed to determine the factors which control damage to an upper seam. From this study, the following factors were determined to be relevant:

- Innerburden thickness.
- Percent sandstone or hardrock of the innerburden.

- Extracted height of the lower seam.
- Percent extraction of the lower seam.
- Time.

Having determined the controlling factors, a model was built which predicts when damage to an upper seam will effect mining in that seam. The model accurately predicted damage in 41 of the 44 case studies collected from Appalachian coalfields.

The model was designed not to be used to predict an exact quantitative level of damage, but to be used as a design tool based on past experience to determine when interaction problems will have to be dealt with. As in all predictive models based on experience in one geologic region, successful application should be confined to that region. The principles and factors involved in other regions would be the same; however, the relationships could vary, thus rendering the model less accurate.

If the model predicts that damage is likely in an upper seam, it is not the author's intent to suggest that the seam is unminable, but rather that interaction should be considered in the mine layout. Case studies indicate that shear fractures are induced above remnant pillars and above solid coal rib edges. These areas, allowing for the effects of draw, should be identified in the upper seam and mine layout should reflect their existence. Other problems caused by tension cracks and by bed separation should be

considered also.

The accuracy of the model suggests that the approach used is viable and that model results can be applied with confidence in the Appalachian coalfields.

## VI. Conclusions and Recommendations

### 6.1 Conclusions

Based on the findings of this research the following conclusions can be made:

1) The effects of lower seam mining on an upper seam can be grouped statistically into two groups:

- 1) No appreciable damage.
- 2) Damage.

2) Using this grouping, prediction of when to anticipate interaction problems in an upper seam is possible, given the following variables:

- 1) Innerburden thickness.
- 2) Percent sandstone of innerburden.
- 3) Extracted seam height.
- 4) Percent extraction of the lower seam.
- 5) Time lapse.

3) As in surface subsidence, there is no harmless depth. Case studies have reported damage in upper seams where innerburden has been as much 900 feet while other case studies have indicated no damage with innerburden as small as 65 feet.

4) Percent extraction of the lower seam is a dominating factor. If percent extraction is held below a limiting value, case studies suggests that for room and pillar mining methods, the roof will arch and only minimal subsidence will

occur in beds above the height of caving. If extraction is below this limiting value (approximately 65 percent) and extraction is uniform, damage should not be anticipated in seams above the height of caving.

## 6.2 Recommendations

In areas like the Appalachian region where mining operations have been active for many years, predictive models based on past experience are very useful. In areas where mining is relatively new, however, a large enough data base would not be available to adequately predict conditions. With the need to predict interaction problems not only in established mining fields but in new coal fields as well, a method not based on past experience but on a theoretical understanding of the mechanisms involved is necessary.

Any theoretical approach to interaction problems must lead directly to an estimation of deformation since this is the significant factor that influences mining. A knowledge of stress fields is of little practical use if it cannot be correlated with deformations.

The Appalachian coalfields present an excellent opportunity to study both interaction problems and surface subsidence above room and pillar workings. If surface subsidence troughs and the displacements and strains associated could be predicted, they could be correlated with

previously collected interaction case studies. With this data base and a minimal amount of field measurements in active multiple seam operations, damage could be predicted based on displacement and strain. The knowledge acquired in the Appalachian region could then be more easily applied to other regions.

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APPENDIX A

VARIOUS DEVELOPMENT PLOTS

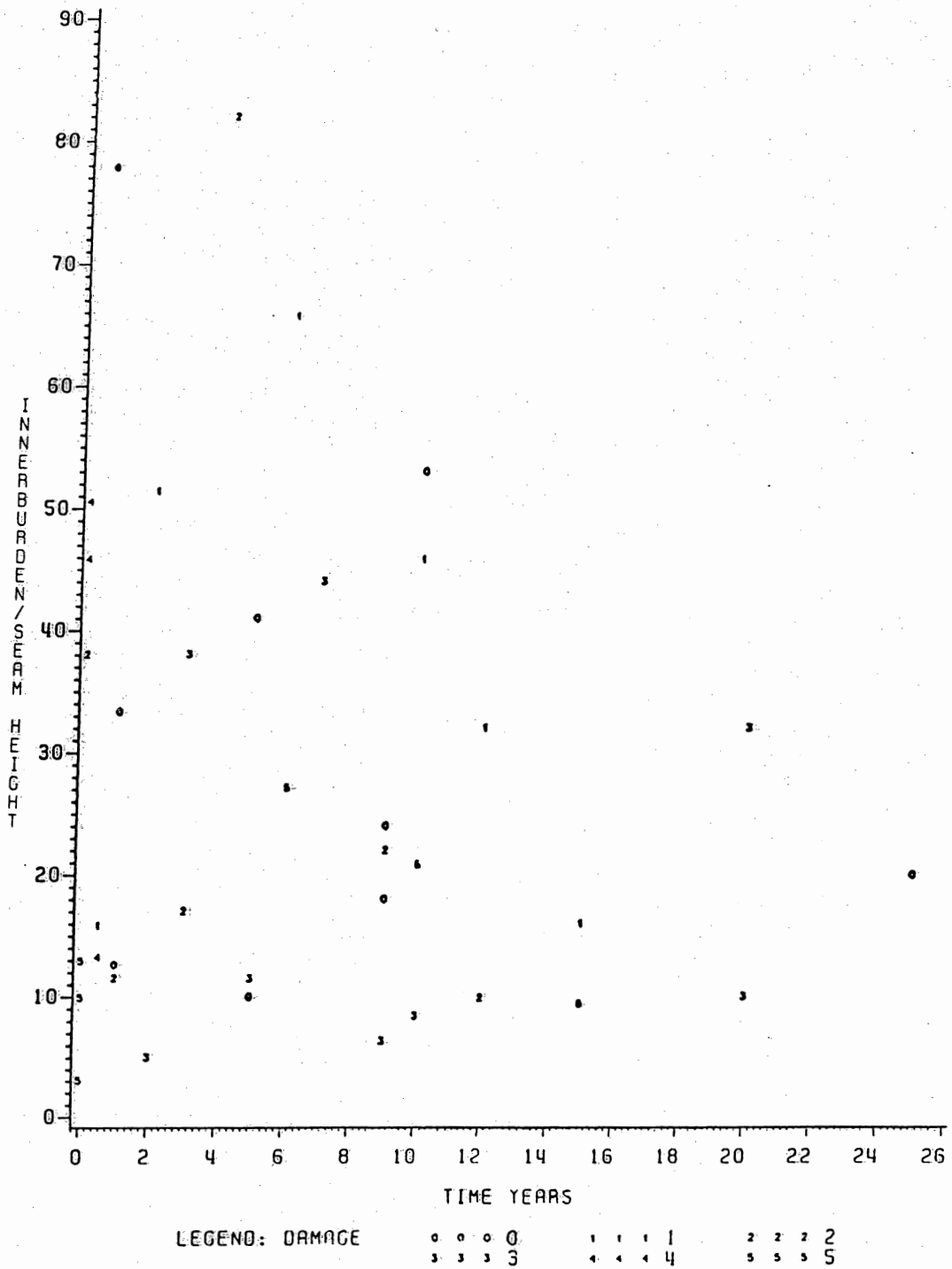
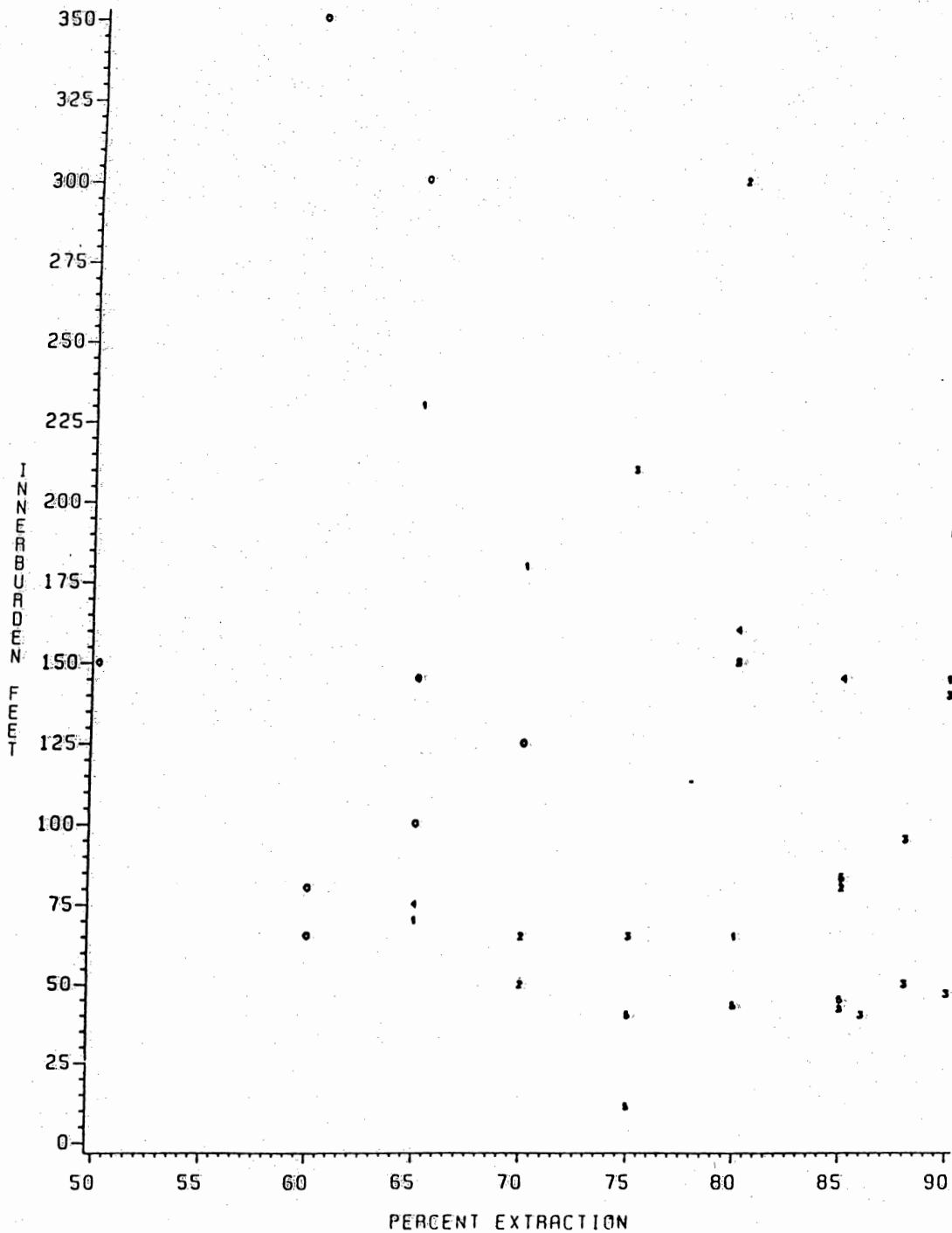


FIGURE 42. INNER./SEAM HEIGHT VERSUS TIME



LEGEND: DAMAGE      0 0 0 0      1 1 1 1      2 2 2 2  
                          3 3 3 3      4 4 4 4      5 5 5 5

FIGURE 43. INNERBURDEN VERSUS PERCENT EXTRACTION

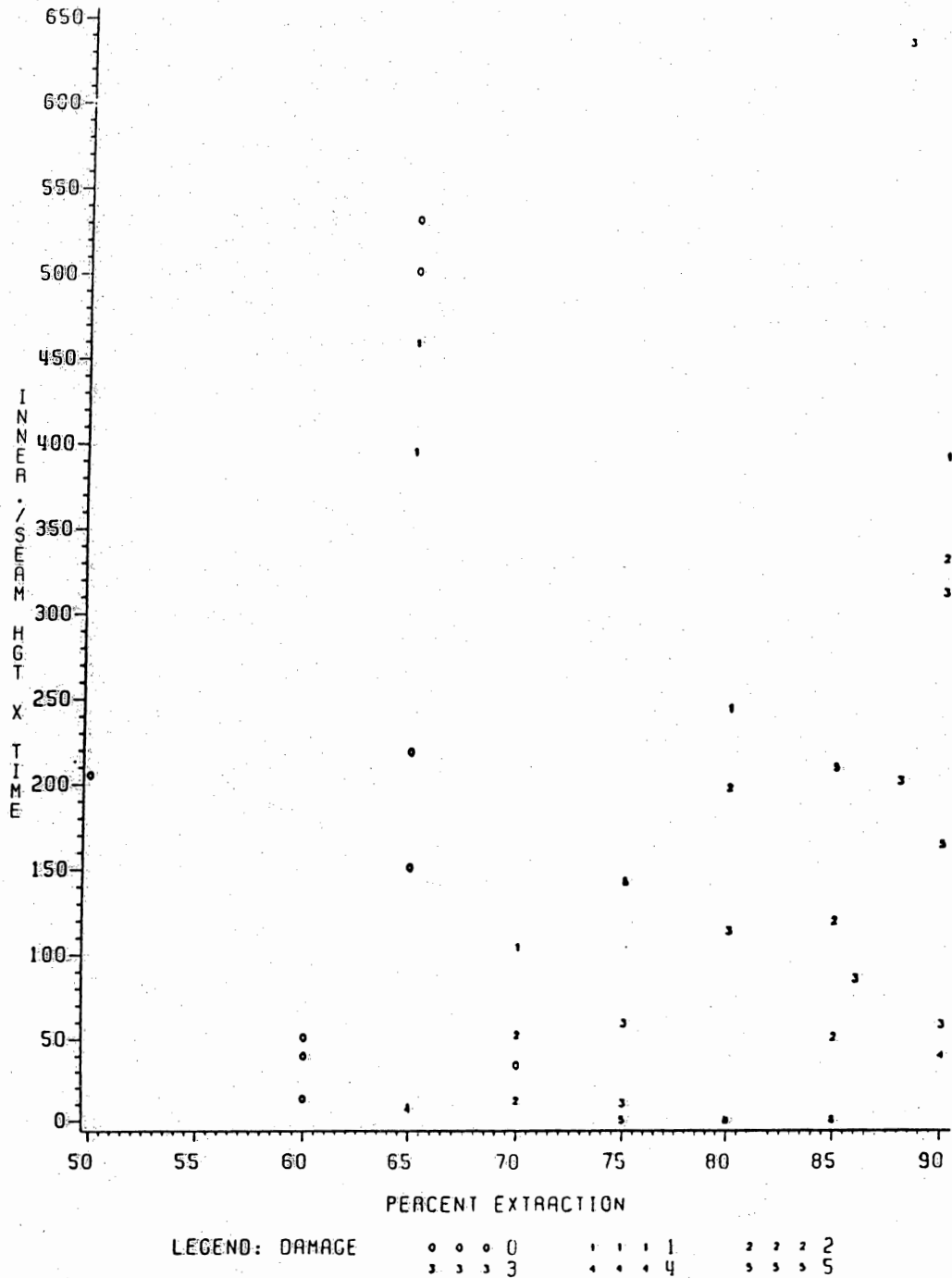
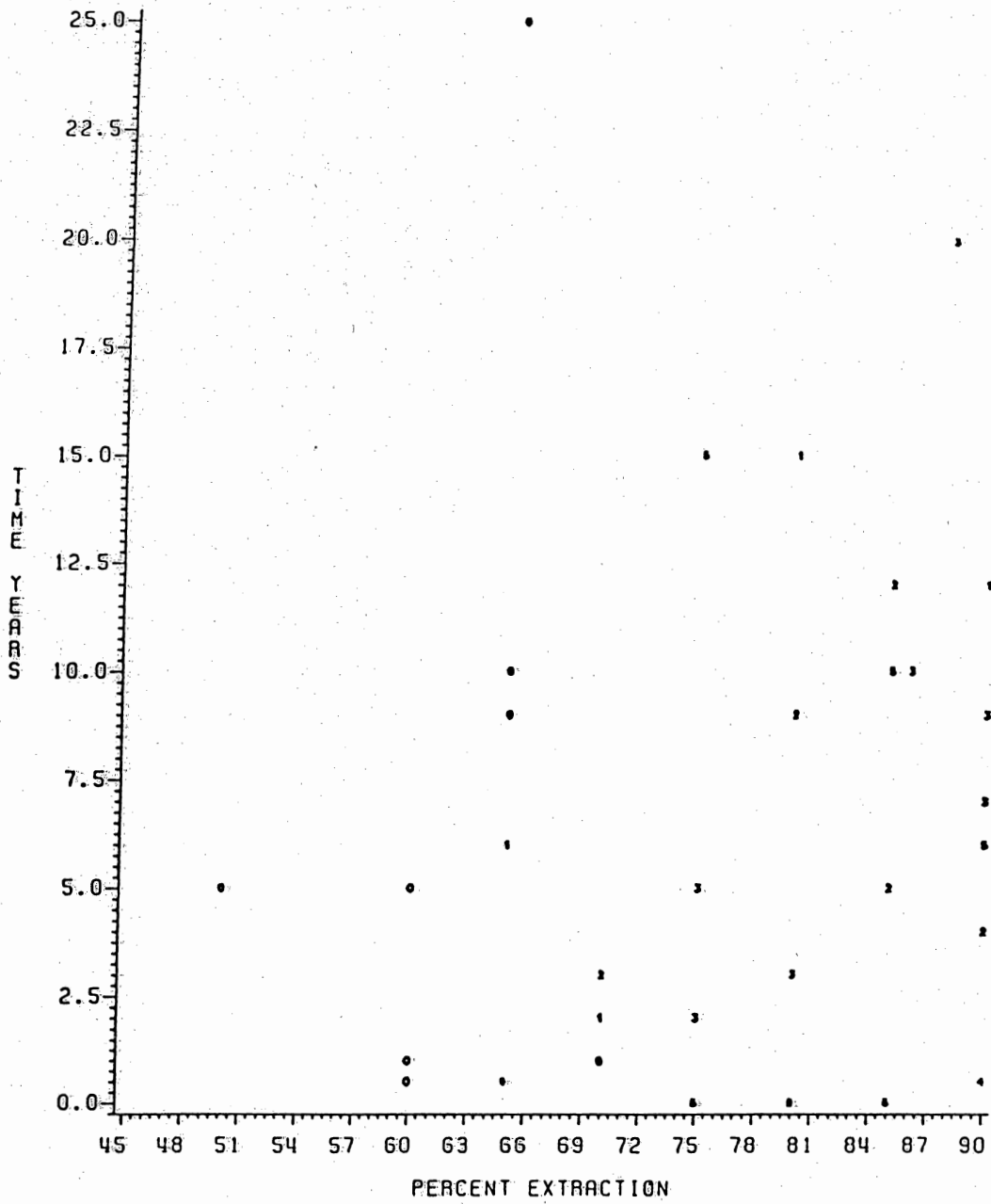
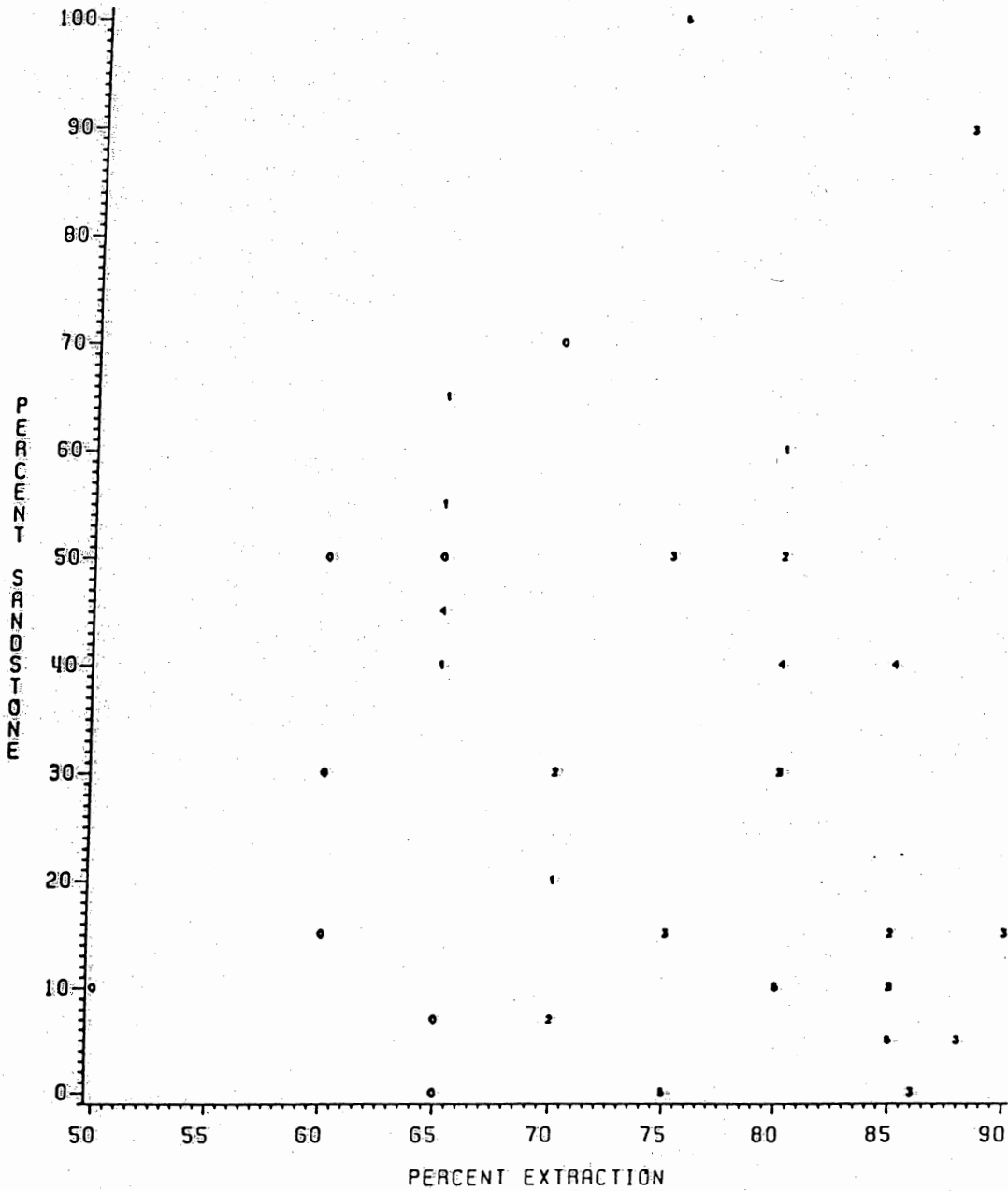


FIGURE 44. INNER./SEAM HGT X TIME VERSUS PERCENT EXTRACTION



LEGEND: DAMAGE    0 0 0 0    1 1 1 1    2 2 2 2  
                      3 3 3 3    4 4 4 4    5 5 5 5

FIGURE 45. TIME VERSUS PERCENT EXTRACTION



LEGEND: DAMAGE    0 0 0 0    1 1 1 1    2 2 2 2  
                      3 3 3 3    4 4 4 4    5 5 5 5

FIGURE 46. PERCENT SANDSTONE VERSUS PERCENT EXTRACTION

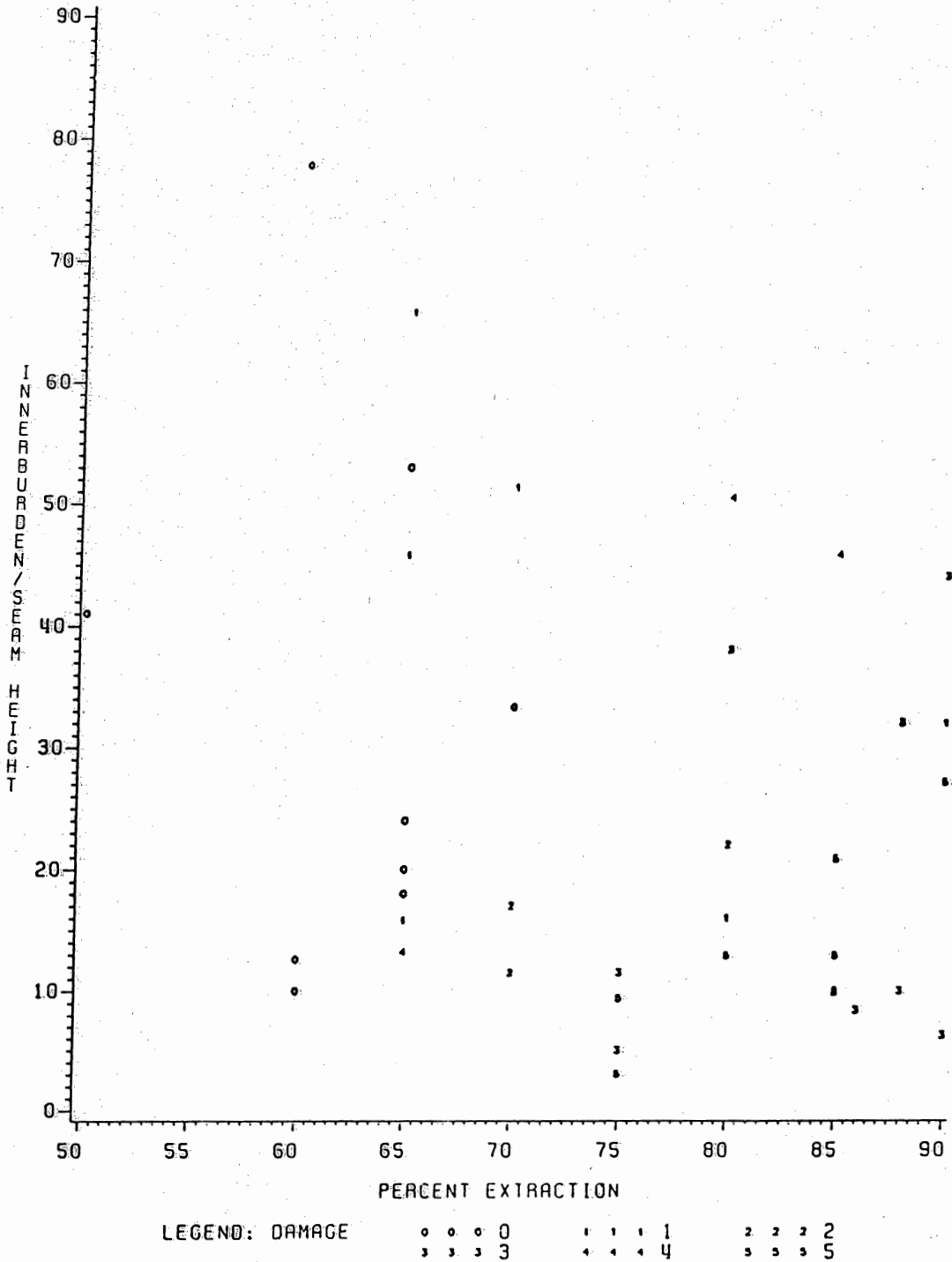


FIGURE 47. INNERBURDEN/SEAM HEIGHT VERSUS PERCENT EXTRACTION

## APPENDIX B

### CLUSTER ANALYSIS

### Cluster Analysis

Initially case studies were analyzed using cluster analysis, to see if natural groupings or clusters existed around individual levels of damage. After experimentation it became apparent that these groupings could not be developed. There was however a useful structure present. Tables 7 and 8 summarize a computer output in which two natural groupings or clusters can be seen.

Cluster 1 includes 23 case studies, all but one of which are of damage level 2 or higher. Cluster 2 includes 18 case studies of which 14 are of damage level 0 or 1. This grouping suggests that the case studies fall into two groups as was previously assumed in the empirical model building procedure. One group includes damage levels 0 and 1, indicating that if damage were to occur in an upper seam it would not effect mining. The second group includes all higher damage levels, indicating that damage is to be expected and that this damage will adversely effect mining in an upper seam.

Table 3. Cluster Analysis Group 1

CLUSTER	DAMAGE	ADF	EXTR	INNER	TIME
1	2	-70.0	70.0	50.0	1.0
1	3	-80.0	75.0	65.0	5.0
1	2	-53.0	70.0	65.0	3.0
1	3	-60.0	88.0	50.0	20.0
1	5	-105.0	85.0	83.0	10.0
1	4	-150.0	80.0	160.0	0.0
1	2	-160.0	80.0	150.0	0.0
1	4	-185.0	85.0	145.0	0.0
1	5	-110.0	90.0	190.0	6.0
1	3	-75.0	75.0	210.0	2.0
1	1	-50.0	90.0	145.0	12.0
1	3	-105.0	90.0	140.0	7.0
1	3	-80.0	80.0	150.0	3.0
1	5	-180.0	80.0	43.0	0.0
1	5	-220.0	85.0	42.0	0.0
1	5	-220.0	85.0	45.0	0.0
1	2	-195.0	85.0	80.0	5.0
1	2	-140.0	85.0	42.0	12.0
1	3	-150.0	86.0	40.0	10.0
1	5	-150.0	75.0	11.0	0.0
1	4	-220.0	90.0	350.0	0.5
1	2	-50.0	80.0	300.0	9.0
1	2	-90.0	90.0	274.0	4.0
1	MEAN	-126.0	82.6	123.0	4.8

Table 4. Cluster Analysis Group 2

CLUSTER	DAMAGE	ADF	EXGR	INTR	TIME
2	1	235.0	65.0	230.0	6.0
2	0	250.0	65.0	300.0	10.0
2	0	80.0	60.0	350.0	0.5
2	0	170.0	70.0	125.0	1.0
2	0	150.0	65.0	100.0	25.0
2	1	210.0	65.0	145.0	10.0
2	0	210.0	50.0	150.0	5.0
2	4	-5.0	65.0	75.0	0.5
2	1	5.0	65.0	70.0	0.5
2	0	30.0	60.0	65.0	1.0
2	3	25.0	90.0	47.0	9.0
2	5	0.0	75.0	40.0	15.0
2	1	60.0	80.0	65.0	15.0
2	3	55.0	88.0	95.0	20.0
2	0	65.0	60.0	80.0	5.0
2	0	50.0	65.0	100.0	9.0
2	1	0.0	70.0	180.0	2.0
2	0	57.0	65.0	145.0	9.0
2	MEAN	91.5	67.9	131.2	8.0

APPENDIX C

LINEAR REGRESSION FOR MODEL EQUATION

## DATA POINTS

X = Percent Extraction

Y = (Innerburden/Seam Height) x Time

X	Y	XY	X <sup>2</sup>
65	20	1,300	4,225
70	52	3,640	4,900
70	105	7,350	4,900
65	0	0	4,225
75	125	9,375	5,625
80	230	18,400	6,400
90	390	35,100	8,100
90	560	50,400	8,100
605	1,482	125,565	46,475

$$\bar{X} = 75.65 \quad \bar{Y} = 185.25$$

$$n = 8 \quad \Sigma XY = 125,565 \quad \Sigma X^2 = 46,475$$

$$B = \frac{\Sigma X Y}{\Sigma X^2} - \frac{n \bar{X} \bar{Y}}{\Sigma X^2}$$

$$B = 18.83$$

$$C = \bar{Y} - B\bar{X}$$

$$C = -1,238.86$$

$$Y = B + CX$$

$$Y = 18.83X - 1,239$$

APPENDIX D

EXAMPLE OF MODEL USE

### Example of Model Use

A coal company is considering developing a mine in the upper coal seam. This seam overlies the lower seam. The lower coal seam had been extracted to a seam height of five feet, one year prior. Extraction had been by room and pillar methods to a 70 percent extraction ratio. Drill logs indicate the innerburden between seams is 90 feet and it consists of approximately 40 percent sandstone.

#### Pertinent Data

innerburden = 90 feet  
 seam height = 5 feet  
 percent sandstone = 40 %  
 time = 1 year  
 percent extraction = 70 %  
 innerburden/seam height = 18

using Figure 48  
 DF = -30  
 using equation 15  
 ADF = DF + (Z - 50)

where: ADF = Adjusted Damage Factor  
 AD = Damage Factor  
 Z = Percent Extraction

$$\underline{\underline{ADF = -40}}$$

This indicates that interaction problems should be expected in the upper seam, if the seam is to be mined.

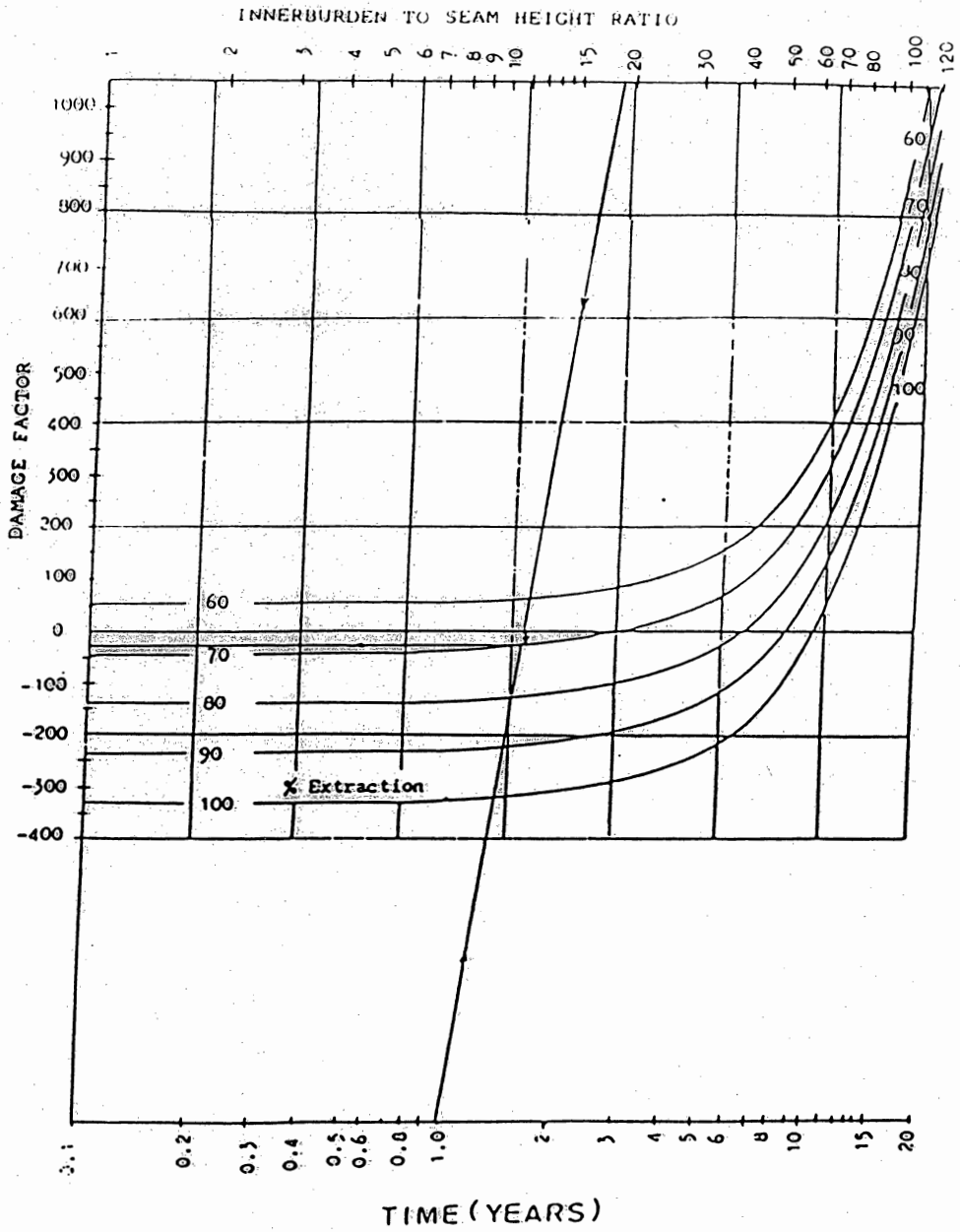


Figure 48. Example of Nomogram's use

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the scanned document**

INTERACTION EFFECTS DUE TO  
SUBSIDENCE IN MULTIPLE SEAM MINING

by

Stephen L. Webster

(ABSTRACT)

The Appalachian coal fields contain many contiguously placed seams of coal. Mining in these seams has been active over such an extended period of time that considerable knowledge has been gained in the area of multiple seam mining.

It is commonly accepted that the preferred sequence of extracting contiguous seams is in descending order. However, in the past, selection of the mining sequence has been based primarily on seam ownership, availability and economics, not on ground control considerations.

One of the major ground control mechanisms that must be considered in mine design, when contiguous seams have not been extracted in descending order, is subsidence. This investigation examines the affects of subsidence not on the surface but on mineable seams of coal lying above the seam that has been extracted. Case studies were collected from the Appalachian region. These studies were analyzed to determine which factors could be correlated with damage. An empirical model was then developed to predict when interaction problems caused by subsidence will noticeably effect mining in an upper seam.