Monitoring and Prediction of Surface Movements above Underground Mines in the Eastern U.S. Coalfields

by

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(ABSTRACT)

The increased impact on mine subsidence during the recent years led to the development of two semi-empirical prediction methods for the eastern United States coalfields. The methods are based on an extensive data bank, which includes a total of twenty three panels, from nine case studies, which were instrumented during this research effort. An extensive field monitoring program, utilizing a digital computer tacheometer, was developed and implemented for this purpose.

The first prediction method using a profile function, provides a fast and convenient method for prediction of vertical movements above mine panels of uniform geometry. More specifically the hyperbolic tangent function is utilized, as adapted to regional data. The developed model is capable of accurate general predictions for the Eastern U.S. coalfields.

The second method is based on the Budryk-Knothe influence function. The parameters used in this method were mainly determined from the monitored case studies. The use of such a method requires primarily a computer, however, it can negotiate mine sections of complex conditions and can calculate subsidence as well as any other mode of deformation on the surface.

For the prediction of the parameters required for the application of both methods a number of relationships between mining and subsidence factors were established through the analysis of the collected data.

Computer software were developed for the analysis of the data as well as for the application of the prediction methods.

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CHAPTER 1

INTRODUCTION

Surface subsidence caused by underground mining has become an important environmental consideration for mining operations in the United States. In order to address this problem, a significant research effort was initiated by Virginia Polytechnic Institute and State University during the past few years The objectives of this research included the following:

- Establishment of a comprehensive data bank of subsidence case studies for the eastern coalfields, which can be used by other researchers and mining companies.

- Implementation of a detailed surface movement monitoring program for longwall and room and pillar operations.

- Development of methods for predicting vertical (subsidence) and horizontal ground movements above mining operations for the eastern U.S. coalfields.

During the first stages of this program a large amount of data were collected from the literature, the mining industry and government agencies. Based on that data, a number of prediction methods were proposed by Virginia Polytechnic Institute and State University (Goodman, 1980; Webb, 1982; Hasenfus, 1984). However, several problems were encountered regarding the reliability and adequacy of the collected information, i.e. infrequent monitoring, inappropriate length and spacing of monument lines, lack of horizontal displacement recordings, etc. It must also be mentioned that a considerable percentage of the cases were collected from a specific area, i.e. mines operating in the Pittsburgh seam in southern Pennsylvania or northern West Virginia. Furthermore, no guidelines existed regarding the accuracy of the measuring equipment, the layout of the monitoring stations, and the frequency of the surveys.

The approach pursued in this research is a semi-empirical one, utilizing field data and mathematical models to investigate the problem.

After consideration of the limitations of the available data a monitoring program was initiated in the Appalachian coalfield. A monitoring method using a high accuracy digital computer tacheometer and following well established guidelines for monument type and spacing was implemented and tested. Initially four mines were selected for field work. Subsequently, five more mines were instrumented, in order to complement the data bank with information for a much needed range of mining and subsidence parameters.

The data from the monitoring program, as well as that collected from various other sources, were then analyzed. A number of statistical relationships were developed, relating mining parameters, such as mining method, extraction ratio, panel geometry, overburden geology, to ground movement parameters such as maximum subsidence, angle of draw, location of the inflection point of the subsidence profile and maximum strain.

A number of prediction methods were tested for their potential application. Two methods were selected, a profile function method and an influence function method. The former can be used as a fast, accurate and convenient tool for the calculation of subsidence profiles above rectangular and uniform panels, whereas the latter may be used for the prediction of any mode of surface deformation at any point, irrespective of excavation geometry.

Finally, computer methods were developed for both the analysis of the collected data as well as for the application of the prediction methods.

CHAPTER 2

GROUND MOVEMENT PREDICTION USING EMPIRICAL METHODS

The prediction methods pursued under this project included two well accepted approaches: profile functions and influence functions. The first prediction technique is developed by fitting mathematical curves onto the measured subsidence profiles, without requiring any behavior model definition. The other method is based on theoretical assumptions, as described in detail in section 2.2 and is adjusted regionally using field measurements.

2.1 Profile Functions

Profile function methods describe the distribution of subsidence values along a half profile (Figure 2.1), orthogonal to the longitudinal axis of the underground excavation, by means of a mathematical function or tables. These methods have been utilized in many coal mining regions around the world (NCB, 1975; Brauner, 1973; Munson and Eichfeld, 1980; Webb, 1982).

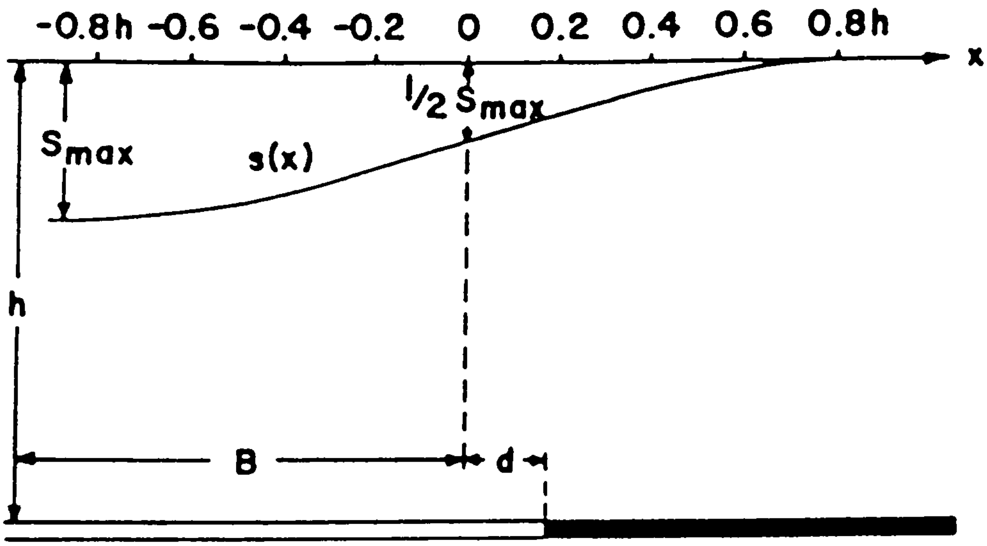

Figure 2.1. Profile Function Definitions (after Brauner, 1973).

Two steps are followed for the application on such a method; first the amount of maximum subsidence (S_{max}) has to be calculated for the given mining conditions and then the distribution of subsidence values along a profile above the mine opening has to be determined (Brauner, 1973).

Maximum subsidence is usually given, for a particular coal mining region and mining method, in terms of certain parameters including the panel width, depth, extraction ratio, method of backfilling and certain quantitative parameters describing the geological conditions.

For the calculation of the distribution of subsidence values, a specific function which is tangent, or asymptotic, to two values (S_{max} and zero) can be used. Asymptotic functions, however, never reach the values of zero and S_{max}, as will be discussed in section 6.1. The main consideration for the selection of a function is its ability to fit regional subsidence data. Depending of the shape of the measured profiles a function symmetric around the inflection point of the profile may be selected; the location of the inflection point with respect to the point of $0.5S_{max}$ must also be considered.

Based on regional field data, the best fit function is determined. A statistical analysis of the regional field data is also necessary for the calculation of parameters used in these equations for each specific application. Table 2.1 presents a range of functions which have been used successfully in various coalfields worldwide. In some cases the subsidence profile is described by tables instead of by a mathematical function for easy implementation.

The profile function methods are simple to use, requiring minimal calculations and providing a satisfactory degree of accuracy for the geographical region for which they have

Table 2.1. Typical Profile Functions

$$s = 0.5\, S_{max} \left\{ 1 - \tanh\left[\frac{cx}{B} \right] \right\}$$

$$s = S_{max}\, \exp\left\{ -\frac{1}{2} \left[\frac{x + B}{B} \right]^2 \right\}$$

$$s = 0.5 S_{max} \left\{ 1 - \frac{x}{B} - \frac{1}{\pi} \sin\left[\frac{\pi x}{B} \right] \right\}$$

$$s = S_{max} \sin^2 \left\{ \frac{\pi}{4} \left[\frac{x}{b} - 1 \right] \right\}$$

been developed. These methods are also easily adaptable to regional mining and geologic conditions, since only a few parameters have to be determined from field data. Major limitations include the fact that these methods are mainly used for simple rectangular and, theoretically, infinitely long excavations and thus they have difficulties in negotiating panel corners.

2.2. Influence Functions

The influence function methods were developed primarily in the central European coalfields. They have been discussed in detail by Litwiniszyn (1957), Knothe (1957), Brauner (1973) and Kratzsch (1983).

In this approach, a so-called **function of influence** is assigned for every point of the rock strata, such that the integral of this function over a given area represents the subsidence (vertical displacement) caused at that point by the excavation of the seam below.

The magnitude of the horizontal movement can be obtained by additional assumptions, for instance by regarding the relationship between horizontal movement and the first derivative of the vertical movement function (slope).

Consider two Cartesian coordinate systems, an "x, y, z," whose origin is at the seam level, and an "s, t, z," whose origin is at the level where the subsidence trough is considered, where z is a common vertical axis for the two systems.

If the location of a point P (s, t, z) is given by coordinates s, t, z, where z is the elevation of the horizontal plane at point P, and the function of influence is given by G (x, y, s, t, z), the vertical movement (subsidence) of this point caused by the excavation over an area A will be:

$$S(s,t,z) = \iint_A G(x,y,s,t,z)dxdy$$

When mining is conducted using a straight linear advance, and one panel dimension is infinitely longer than the other, the problem can be considered as a cross-sectional problem, in the direction orthogonal to the face advance. In this case subsidence S (s,z) at point P (s,z) can be calculated from the equation:

$$S(s,z) = \int_{x1}^{x2} g(x,s,z)dx$$

where, g (x, s, z) = function of influence.

Considering movement at a point located on the surface, i.e. z is constant and equal to depth (h), the general equations for subsidence will have the form:

- for a three-dimensional case

$$S(s,t) = \int\int_A G(x,y,s,t)dxdy$$

- for a cross-sectional case

$$S(s) = \int_{x1}^{x2} g(x,s)dx$$

The above relation is shown in Figure 2.2. According to the above, if the function of influence is known, it is possible to calculate vertical movement at any point above the excavation.

When the integral of the influence function has an exact solution, the distribution of subsidence can be described easily by mathematical expressions, which allow subsidence calculations at any point. Otherwise tables of integral values have to be used. Furthermore, differentiation of the subsidence distribution function may describe other deformation parameters as slopes (first derivative) and curvatures (second derivative). By applying additional assumptions (i.e. relation between horizontal movement and slope and incompressibility of the medium), determination of horizontal movements and strains is possible.

During the past fifty years many different formulas for influence functions have been used by researchers and have been described in the literature, particularly by Brauner (1973) and Kratzsch (1983).

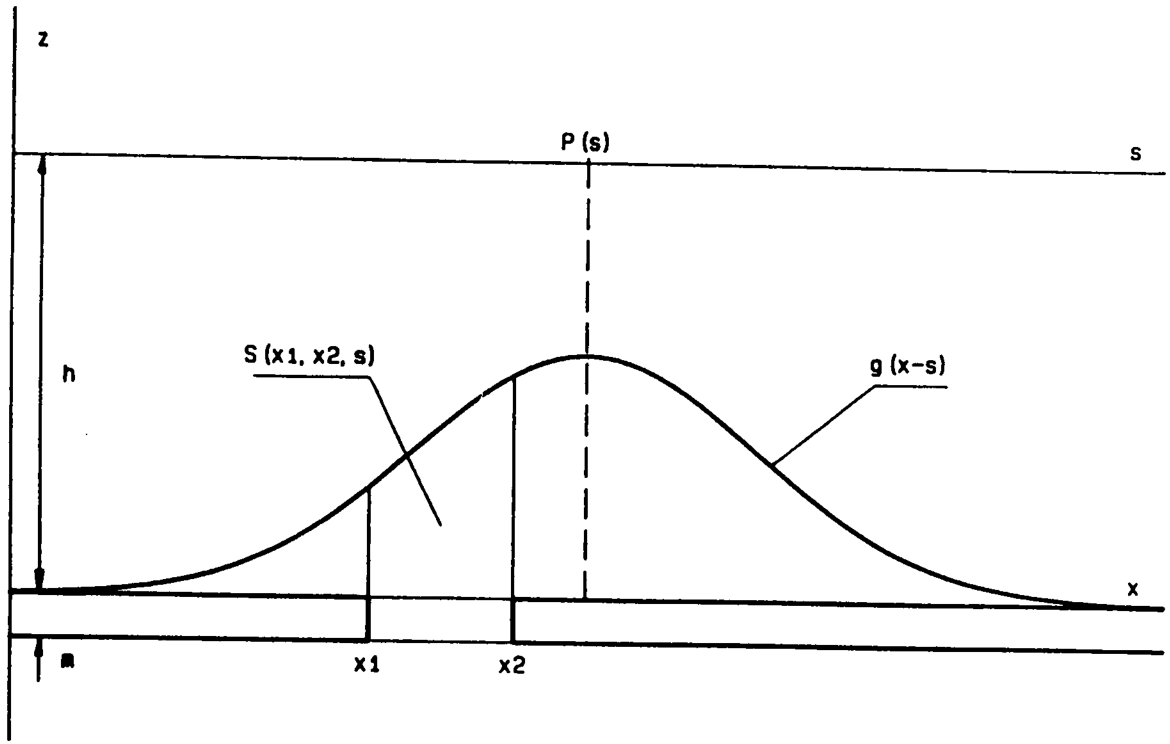

Figure 2.2. Influence Function Definitions.

2.3. Required Field Parameters

A number of mining and subsidence factors have to be obtained from the mine maps or plans, borehole logs, surface contour maps and from field measurements, for the development and application of these prediction methods.

More specifically, for the development of the profile function method, the seam thickness, percent hardrock in the overburden, width-to-depth ratio, mining system and the extraction ratio are needed in order to develop relationships which can predict maximum subsidence. The width-to-depth ratio is also related to the position of the inflection point as well as to parameters determining the shape of the subsidence profile.

For the influence function method, seam thickness, percent hardrock, mining system and the extraction ratio are also required for the calculation of the value of S_{max} corresponding to a supercritical excavation. The location of the inflection point is related to the width-to-depth ratio. The distribution and magnitude of the subsidence and strain profiles are controlled by the parameters r and B, which have to be statistically determined from the subsidence and strain profiles respectively. A digital model of the surface topography of the area around the monument lines, a digitized mine plan, and the geological characteristics of the region are all required for this purpose.

The subsidence parameters measured at a specific site can also be used for the development of an accurate site specific prediction model. This can be accomplished by modifying the parameters of an existing prediction equation so that it can accurately describe the measured ground movements at the specific location. This site-specific prediction technique can subsequently be utilized to predict subsidence or strain along any surface point above that mine. It should be mentioned that the profile function and the influence function methods are more convenient than other approaches, such as the zone area method, for site specific application because of the smaller number of parameters describing the distribution of subsidence related variables.

2.4. Comparison of Prediction Methodology and Its Applicability to the Eastern U.S. Coalfields

As mentioned previously, the hyperbolic tangent function can be used for the calculation of subsidence along a profile orthogonal to the direction of face advance for an excavation of a rectangular shape. It also assumes that the excavation has one dimension infinitely longer than the other. By using simple nomograms or tables developed from regional field data, this function provides an accurate and convenient tool for subsidence prediction. Furthermore, it is easily adaptable for site specific application, when such data are available.

For the calculation of subsidence at any point above an excavation of any shape, the influence function may be used. For mine sections of irregular shapes, or where areas are of varying mining heights, or where a difference in extraction ratio or seam elevation exists, the section is separated into homogeneous subsections.

An influence function method, as previously described, can be used for the determination of subsidence and horizontal movements on the surface. The amount of movement caused by each of the subsections is calculated and the total value of subsidence is then calculated by superposition.

The influence function method primarily requires the use of a computer. Furthermore, the appropriate location of the inflection point, for the influence function method, requires adjustment of the theoretical boundary using a nomogram.

In conclusion, the following recommendations can be made regarding the application of these empirical methods in the United States

Profile Function: Recommended for longwall and room and pillar subsidence predictions of regular mining plans.

Influence Function: Recommended for subsidence or horizontal movement calculations for any mining system and extraction geometry.

CHAPTER 3

SUBSIDENCE MONITORING PROGRAM

3.1. Selection of Case Studies

A number of criteria were set for the selection of mines to be monitored during the initial stages of this program. These criteria considered both mining and site parameters.

Regarding the former, critical or supercritical panels were preferred (width-to-depth ratio equal or greater than 1.2) where available, in order to measure the maximum possible subsidence for the given conditions. Interaction of other panels was also considered, including neighboring panels or multiple seam mining. Initially, panels without any influence from other panels were selected. Later, the monitoring program included two cases of multiple seam mining and several cases of mine sections consisting of several panels. Other mining parameters included the geology of the overburden, seam thickness and the depth of the excavation. These parameters determined the selection of panels in order to complement the data bank with case studies of different characteristics. Finally, given the time limitations of this research program, the production schedule of the mine section under consideration was examined. Monuments were usually installed after development of the section under investigation had been initiated and before any secondary extraction had occurred.

Site criteria included the accessibility to the area above the mine section, as well as the topography and the vegetation.

Initially four sites were selected for monitoring; one longwall and three room and pillar mines. During the progress of this program some of the lines were extended to cover more panels and additional mines were also instrumented. The final program included a total of sixteen room and pillar and seven longwall panels in nine mines located in Wise, Dickenson and Buchanan counties in Virginia (Figure 3.1).

3.2. Monitoring Equipment

3.2.1. Description

From the initial stage of this research effort, it was decided that the monitoring equipment should allow for a fast and accurate measuring procedure. Because of the large number of subsidence monuments above each mine, the number of panels under investigation and the mountainous terrain, a high accuracy total station system was selected, utilizing a Zeiss Elta-2 recording computer tacheometer for measuring both vertical and horizontal surface movements.

The basic system included the surveying instrument, a number of reflectors, three tripods, a number of reflector rods, an HP86 computer with two disc drives, a data converter, a printer, a plotter and a digitizing tablet.

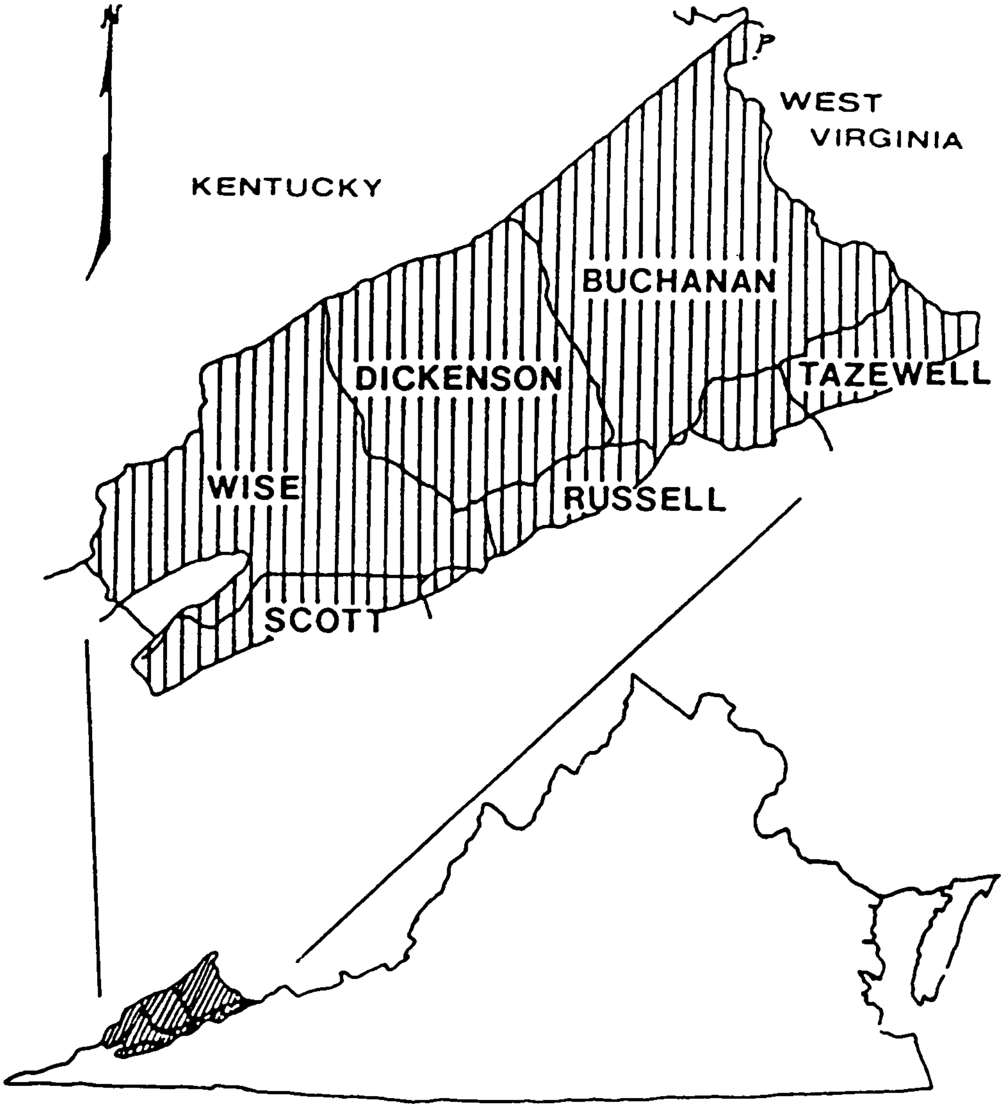

Figure 3.1. Location of Case Studies Monitored by Virginia Tech.

The surveying instrument (Figure 3.2) included a digital theodolite with a built-in EDM. The accuracy of this instrument, according to the manufacturer, was in the range of 0.6″ for vertical and horizontal angle measurements and ± 5mm ± 2ppm for distance measurements. The built-in computational capabilities included automatic calculation of the position of the instrument with respect to the geodetic network through free or forced stationing and direct reading of horizontal angles, distances and coordinates of the targets. The instrument was also capable of adjusting the measurements automatically for scale factor, offset of the reflectors, horizontal collimation error, vertical index error and atmospheric conditions. Further capabilities included calculation of coordinates of sideshot and traverse points. All necessary data were entered through the key pad. As a result the operator was able to measure up to 150 points over a six hour period, utilizing five to eight traverse stations.

The memory of the unit had a capacity of up to 880 lines of field data and/or calculated coordinates, thus eliminating the need for most field notes and further calculations. A major disadvantage of the unit was its weight (about 48 lb) and large size.

A set of retro-reflectors (Figure 3.3) was used for distance measurements with the instrument. Each reflector had one prism mounted on a tiltable holder for use on steep sites. For long sighting distances, reflector sets of three or more prisms had to be used. The reflectors could be set on a tripod or on a rod. When set on a tripod, the vertical distance of the prism from the tribrach was equal to that of the telescope of the instrument to the tribrach, thus facilitating traverse calculations and increasing the accuracy of the procedure by eliminating the error due to instrument height readings.

Specially designed adaptors, similar to those used by other researchers (Allgaier, 1981), were made for the secure attachment of the reflector rods on the monuments, as shown

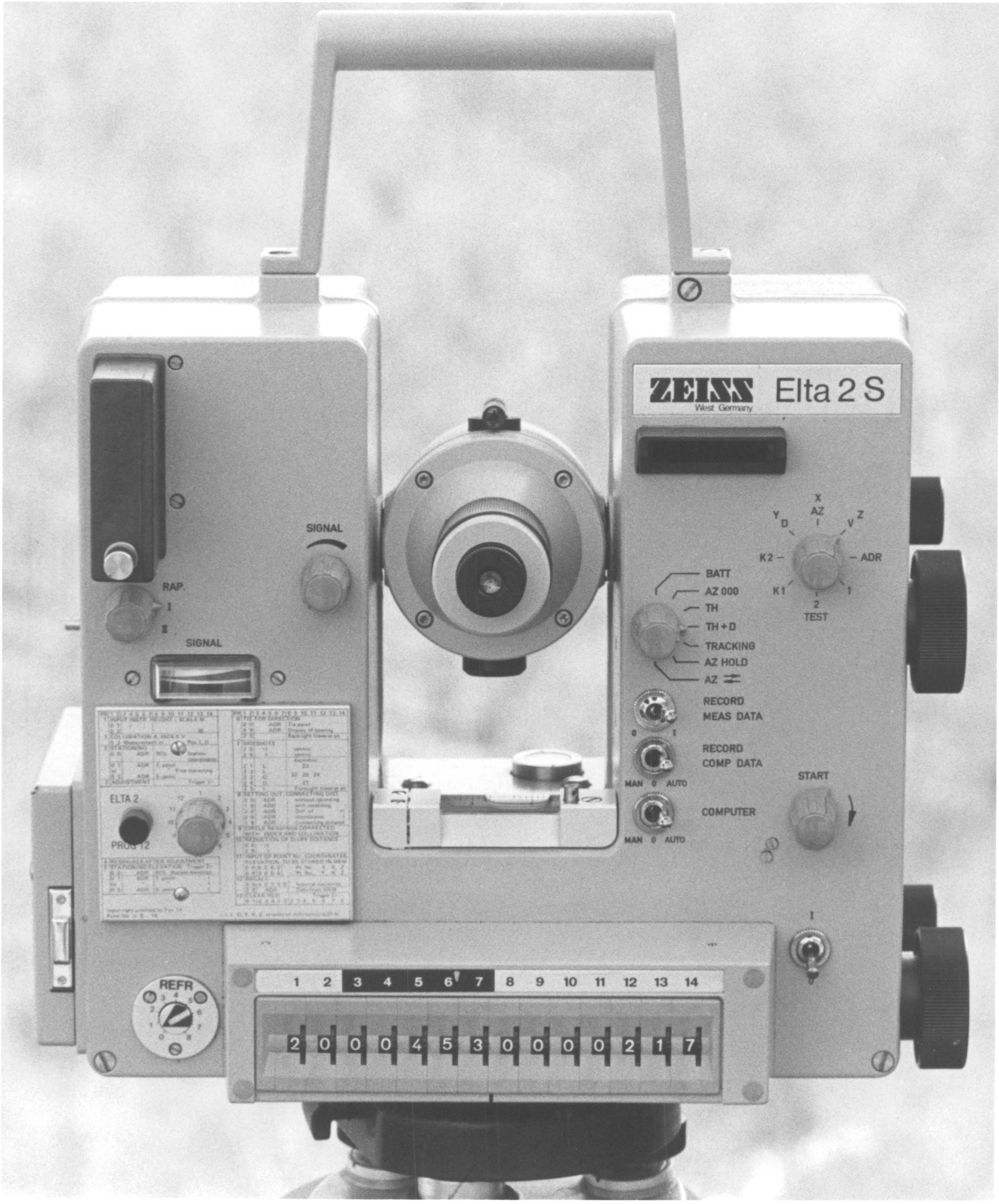

Figure 3.2. The Electronic Tacheometer ZEISS-Elta 2.

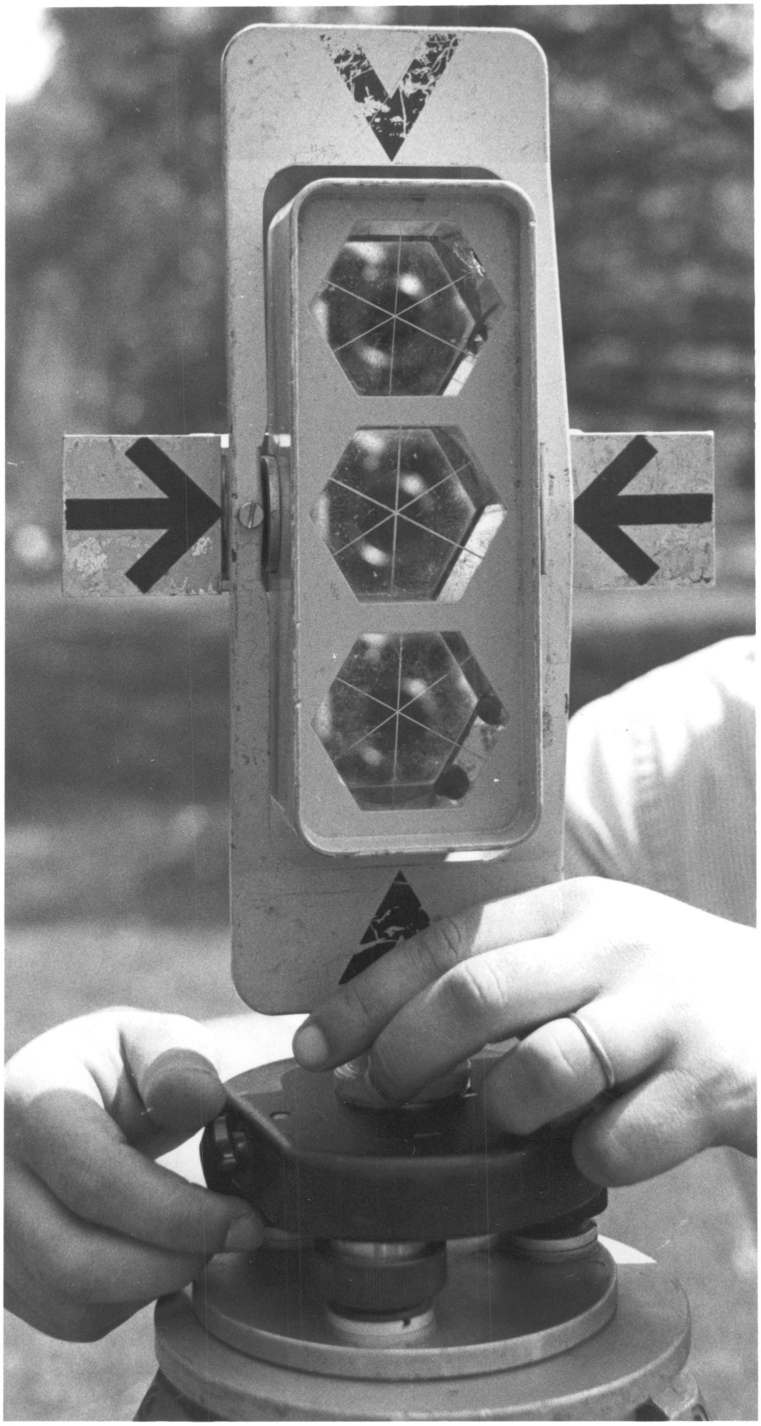

Figure 3.3. Retro-Reflector Used with the Elta-2 Equipment.

in Figure 3.4. These adaptors consisted of two hollow cylindrical parts, used for securing the reflector rod and the monument respectively, which were connected with a friction adjusted spherical articulation. These special adaptors proved to be necessary in order to avoid errors due to movement during the time required for distance measurement (about 5 seconds).

Finally, the data stored in the instrument memory were transferred, through use of the data converter (DAC 100), to the HP86 computer for processing and permanent storage on magnetic disks.

Although precision leveling is considered to be the preferred method of measuring vertical movements, the Elta-2 was especially selected for this task because of the accuracy it was able to provide. In addition, it could simultaneously calculate horizontal coordinates and it was far more time-efficient, especially on steep terrains such as those negotiated in this study, than leveling, since the latter would have required a considerable number of turning points.

3.2.2. Calibration

Calibration of EDM equipment is necessary when the instrument is originally acquired as well as at periodic intervals.

For this purpose the baseline located at the Virginia Tech airport was used. The surveying instrument was initially calibrated when purchased in May, 1983. It was then calibrated two more times, in both cases after being shipped to the manufacturer for service.

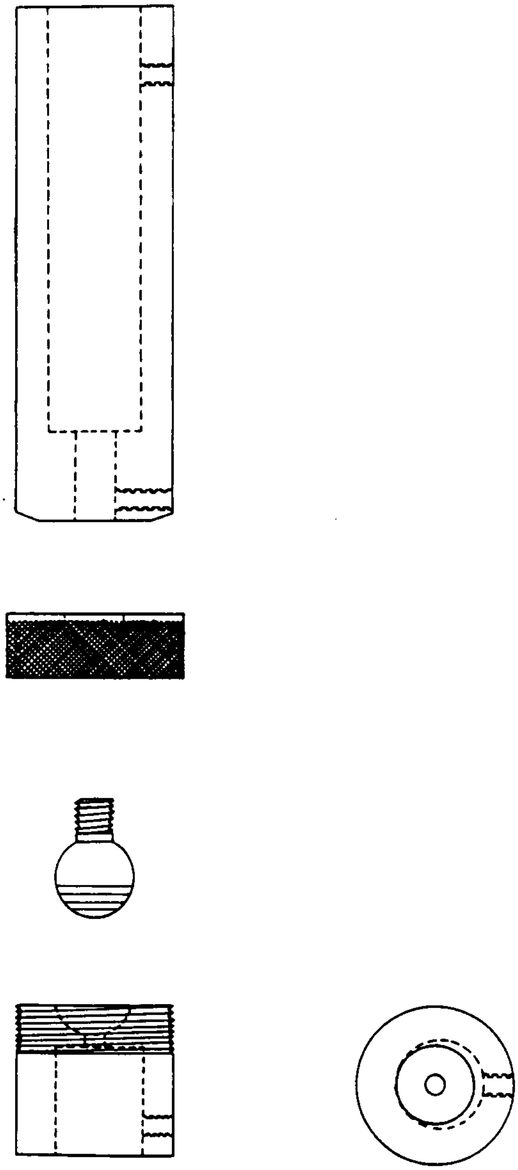

Figure 3.4. Adaptor for Centering the Reflector Rod on the Monument.

The calibration procedure recommended by the National Oceanic and Atmospheric Administration was followed (Fronczek, 1977). In summary, it involved the repeated measurement of a number of known and calibrated distances. Adjustment was consistently made for temperature and barometric pressure. Using the least squares method, two parameters were determined, the offset error of the reflectors and the scale factor of the EDM. These parameters were necessary for the adjustment of the measured data. However, the equipment used for this research program had the ability to adjust the measured values automatically if these parameters were inputted through the keyboard. Appendix A presents, in summary, the least squares method. A computer program was developed in order to facilitate the calculations.

EDM instruments also exhibit a built-in cyclic error, the period of which is dependent upon the highest frequency used for measurement. A test was performed in order to determine the period and the magnitude of this error. The results of this test are presented in Appendix A. Due to the significance of this error special precautions were taken during monitoring (section 3.5).

3.3. Selection of Monuments

Selection of subsidence monuments depends on the desired accuracy, available equipment, weather conditions and topography. Elaborate monuments consisting of long metal rods anchored with concrete to a depth of 2 feet under the frost line are often suggested for accurate results when measuring vertical movements. However, this type of installation can be quite expensive and may require a truck-mounted drill, thereby effectively preventing its use in mountainous terrain when a large number of stations is to be installed.

The most practical alternative proved to be the use of steel rods, in lengths ranging from 2 to 5 feet, penetrating the ground to a depth of at least 1 foot beyond the frost line. The monuments used in this study were of one inch diameter hot-roll steel rods and had a sharp machined edge which was driven into the ground using either a sledge hammer or a gasoline-powered jackhammer, depending upon ground conditions. A special adaptor was placed at the top of each monument to prevent deformation during installation.

During this research effort no significant differences that could have been due to the possible effects of frost heave were observed between monuments of different lengths. The only disadvantage of the shorter monuments was that a small number of them were loosened and had to be abandoned.

3.4. Subsidence lines

Above each panel or section a number of longitudinal and transverse monument lines were installed. The lines were extended well beyond the maximum expected area of influence on either side (0.8 times the depth beyond the edges of the extraction) to ensure the determination of the angle of draw. A set of reference points was also established outside of the area of influence for each case study. Following the guidelines suggested by the British National Coal Board (N.C.B., 1975), which are also accepted in this country, the spacing of the monuments was approximately 0.05 times the depth to allow the accurate calculation of the distribution of horizontal strains along the monitoring lines. It should be noted, however, that distances of less than 25 feet between stations are not recommended because of the resulting equipment errors in the calculation of horizontal movements or strains due to the error of the EDM instrument. The final effort included approximately 1,200 stations over 35,000 feet of monitoring lines. Typical examples of monument layout are shown in Figures 3.5 to 3.10.

3.5. Monitoring Procedures

After a mine panel or section was selected for instrumentation, a set of reference points were installed with the help of the mine surveyors. All traverses had to be closed with an acceptable error, depending on equipment and mine benchmark accuracy. Based on these reference points, a transverse and a longitudinal monument line were established above the panel. These lines were then cleared of vegetation for a width sufficient to permit maximum direct sight with the surveying instrument, as long as was permitted by the topography, in order to minimize the number of stations during traversing.

Monuments were installed at the proper spacing using the total station, usually on a localized coordinate system. Monuments were then surveyed at least twice before mining was initiated in order to ensure correct initial coordinates and elevations. Acceptable errors during the initial surveys were 0.01 ft for elevations and 0.02 ft for horizontal coordinates.

Special precautions were taken in the surveys in order to minimize errors. For traversing, the three tripod method was always used in order to avoid errors from the positioning of the instrument and the targets. Furthermore, in order to eliminate the cyclic error due to the use of EDM equipment, the same exact stations were always used during subsequent surveys at the same mine site. Also during monitoring, a specially designed adaptor was used for centering and securing the reflector rods on the monuments.

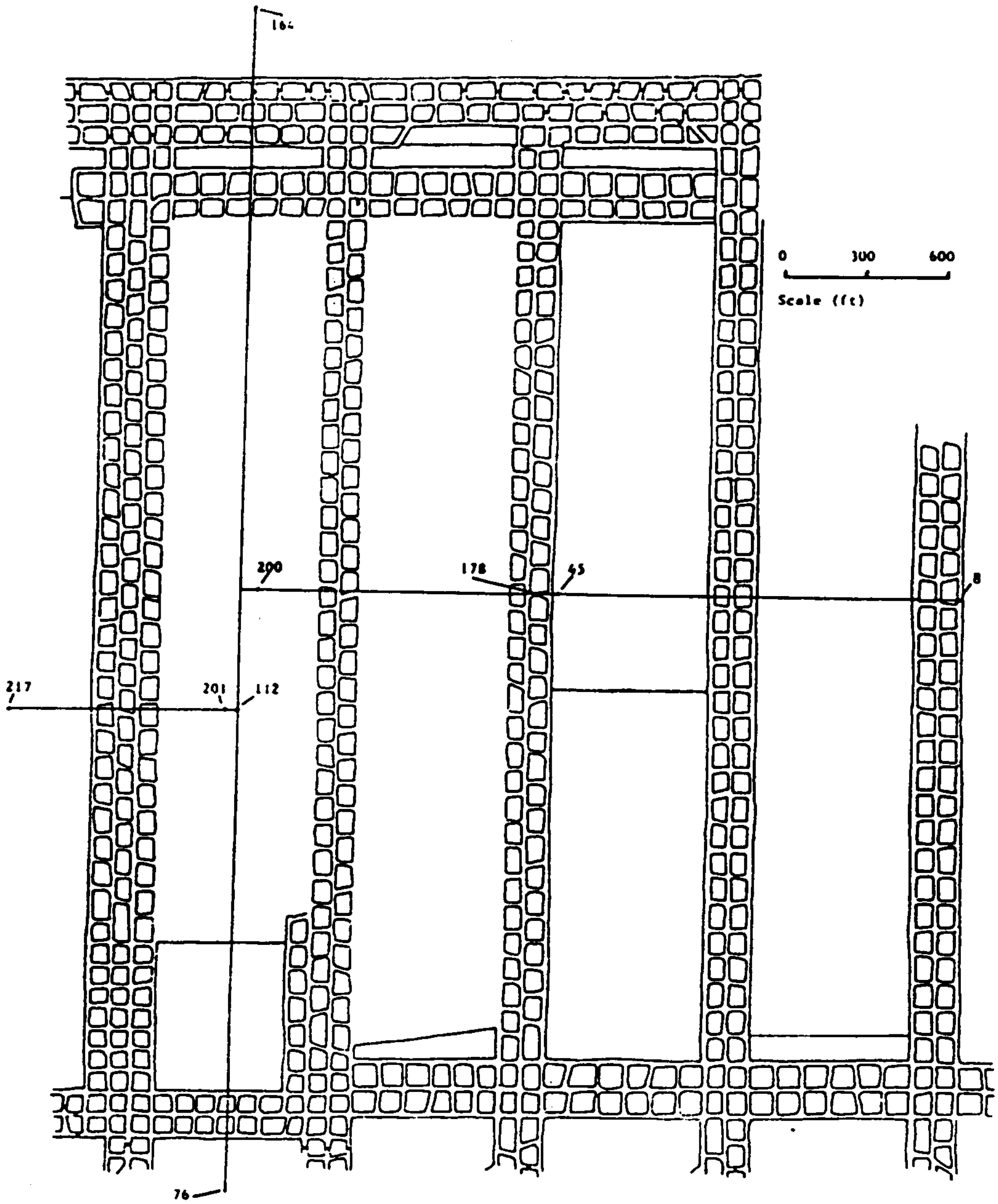

Figure 3.5. Monument Layout for Case Study LUVA-VT1.

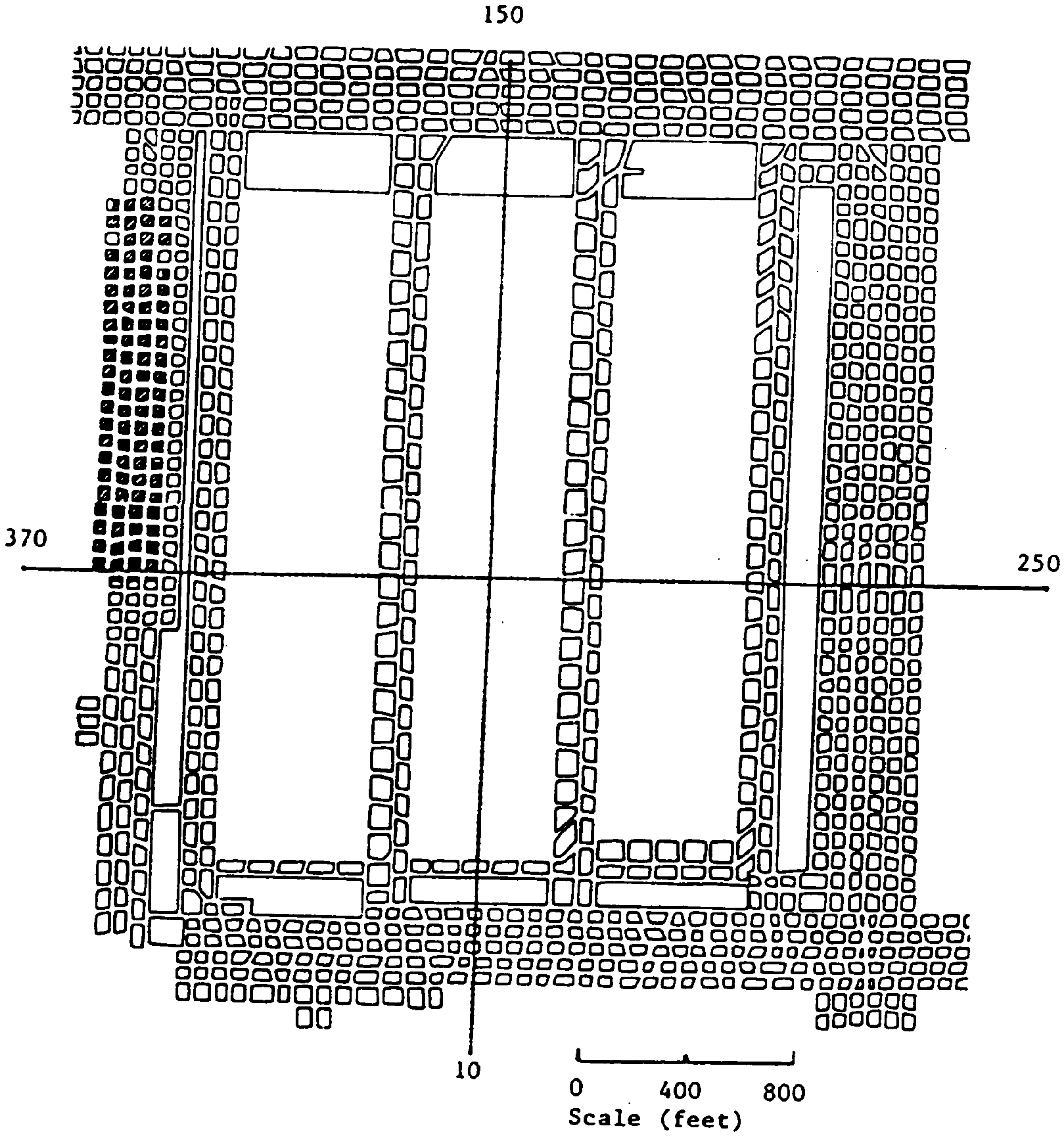

Figure 3.6. Monument Layout for Case Study LUVA-VT2.

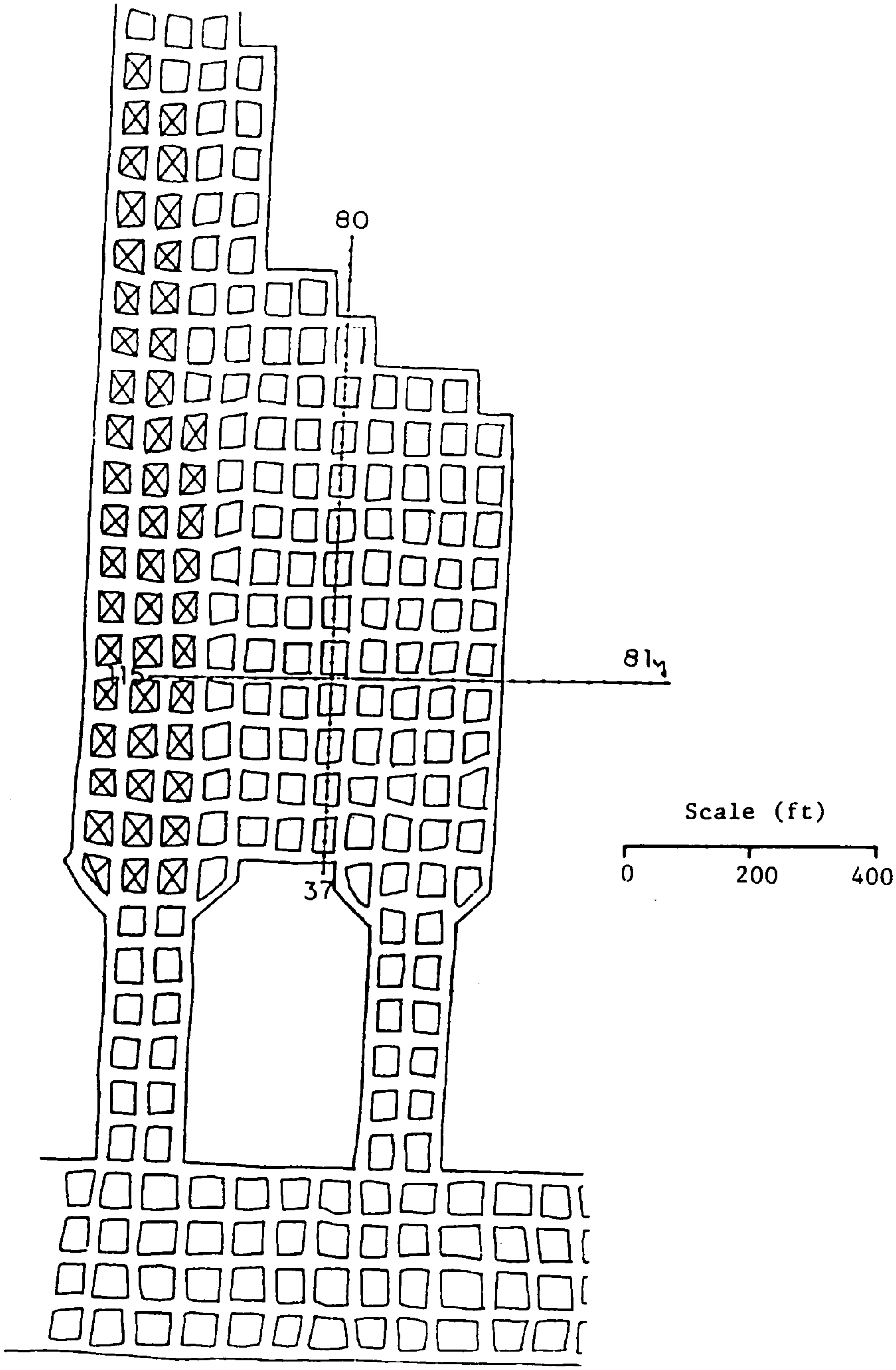

Figure 3.7. Monument Layout for Case Study RUVA-VT1.

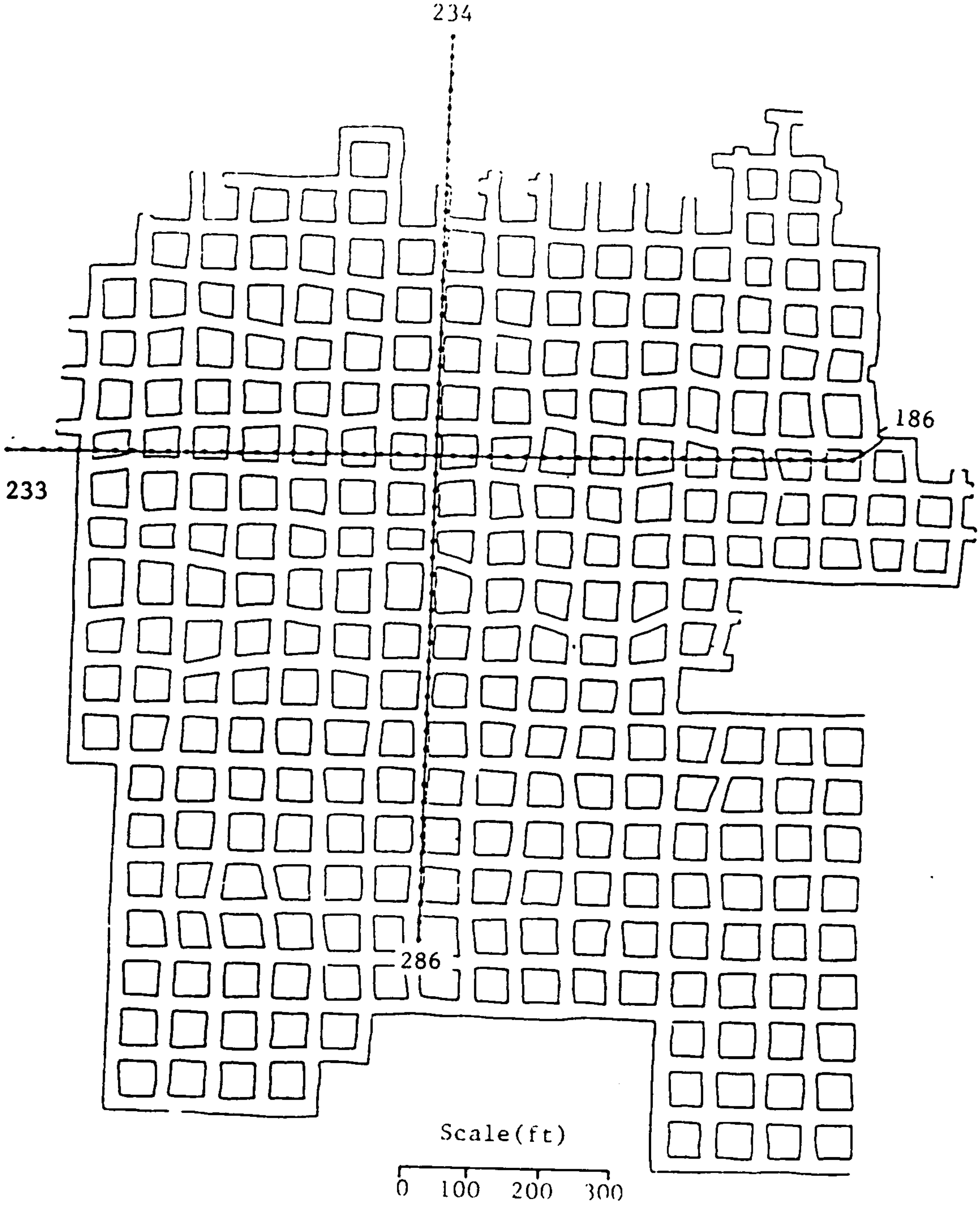

Figure 3.8. Monument Layout for Case Study RUVA-VT2.

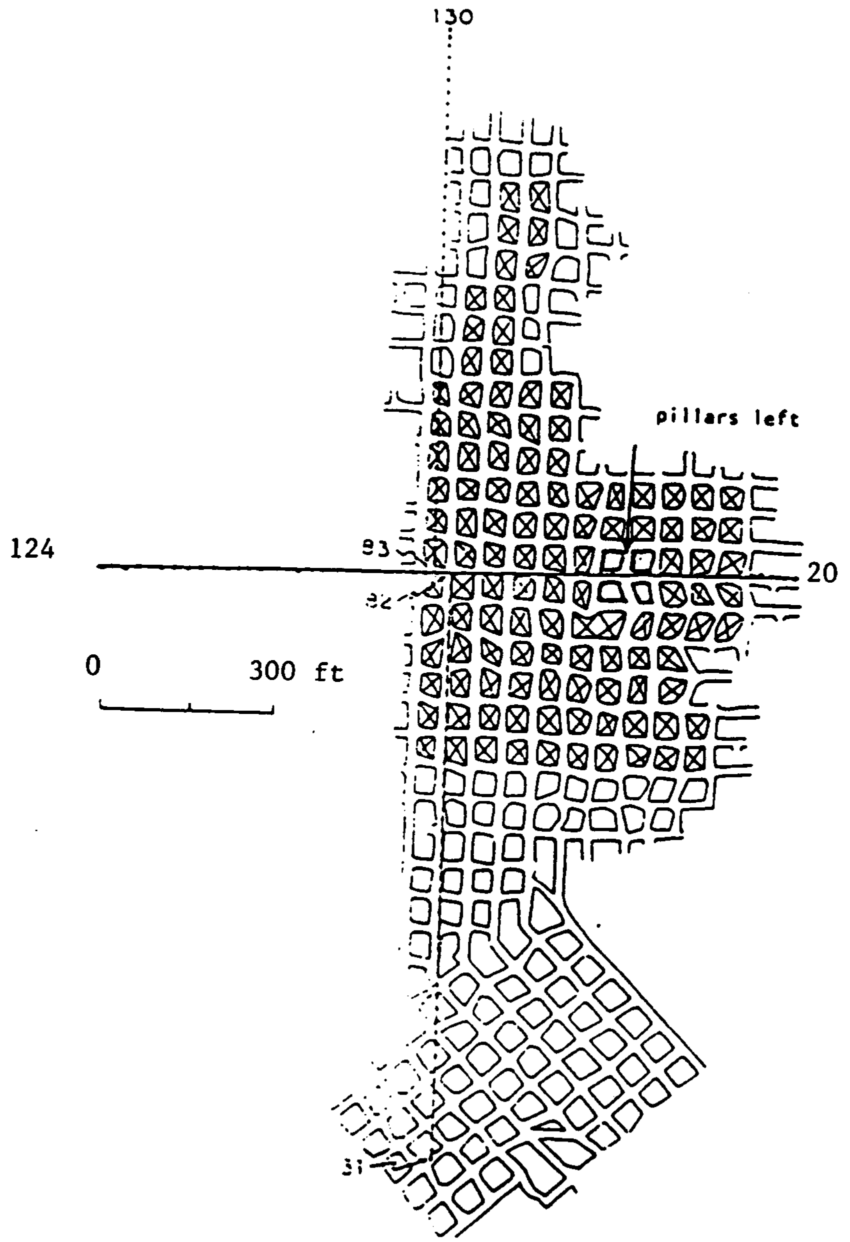

Figure 3.9. Monument Layout for Case Study RUVA-VT3

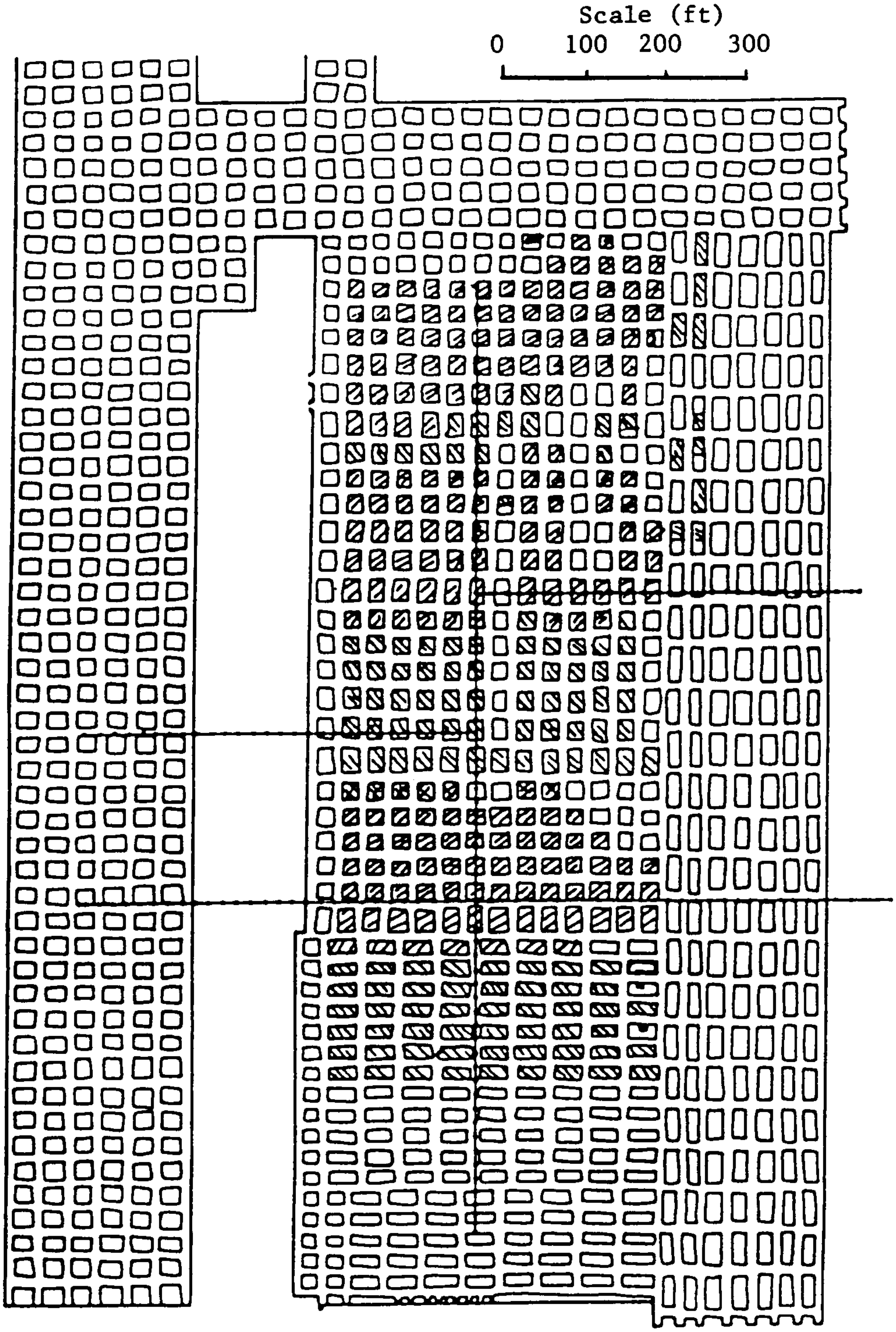

Figure 3.10. Monument Layout for Case Study RUVA-VT5.

After mining started, the monument lines were scheduled for surveying every seven to fifteen days. Surveys were conducted at the same frequency, even after mining was completed, until ground-movement slowed down considerably. At that time, the interval between surveys over segments of the lines not showing significant movement was increased.

3.6. Data Transfer and Analysis

3.6.1. Computer Hardware

The computational work on the data was minimized by using two similar HP86 computer systems.

The first system was located in the field, near the monitoring sites. A data converter (DAC100, manufactured by Carl Zeiss) allowed for the transfer of the field data, through an RS232 serial interface, from the removable memory of the tacheometer to the HP86 computer. The system included a printer for tabulating the field and calculated data and a small pen-plotter (HP7470) for drawing profiles and contours.

The second system was located at Virginia Tech. Field data were obtained from the surveying crew on magnetic diskettes. The system included a printer, a medium sized plotter (6 pen), a large plotter (8 pen, E size paper) and a digitizing tablet.

3.6.2. Computer Software

The software required for the data transfer from the surveying equipment to the computer diskettes was provided with the initial system. It also allowed for limited editing of the field data.

Field data were in the form of raw data, i.e. slope distances and angles, or calculated data, i.e. horizontal coordinates and elevations of the measured points. Furthermore, the entire survey procedure could be followed from a tabulation of the data and thus surveying errors could be traced if the calculated results appeared to be out of range.

A computer program was developed for the calculation of ground-movement related parameters from the field data. From one or more of the surveys conducted before mining was initiated, an "initial survey" file was established which described the exact location of each monitoring point. Subsequent surveys were compared to this file, and subsidence, strains and other parameters were calculated for each point. The program had the ability to handle missing points, double points, double measurements, the averaging of strains, etc.

A software package was also developed for the presentation of results using a plotter. It was able to automatically calculate the appropriate scale according to the size of the monitoring lines and the magnitude of the subsidence parameters to be plotted. As with most programs developed during this research program, compatibility of the data files with commercially available surveying and plotting software was a major concideration.

These programs in general did not permit for editing of the calculated values. However, whenever results appeared to be out of range, specific observations are deleted.

A detailed description of the software is presented in Appendix B.

CHAPTER 4

SUBSIDENCE CASE STUDIES

4.1. Referencing System

During the progress of this research effort it became evident that, due to the proprietary nature of many case studies, the establishment of an imaginative identification and referencing system was required. Considerable effort was therefore devoted to developing such a system and, subsequently, reclassifying all case studies measured under this research effort, or collected from other sources, according to this system. The final referencing method is on an index code of the following form:

A B ST-VT N

where,

A = the type of mining, i.e. L for longwall and R for room and pillar panels;

B = the source and proprietary nature of the case study, i.e. P for published in the literature and U for unpublished proprietary case study;

ST = the two letter state identification based on guidelines established by the U.S. Postal Service for use with zip codes;

VT (if present) = A case study which was monitored by Virginia Tech; and

N = the number of the case study on a state basis.

The following are two examples of the coding system:

1. LPAL2 means a longwall mine (L), with data which have been published in the literature (P), in the state of Alabama (AL), being the second (2) longwall case study available for the analysis in this state.

2. RUVA-VT4 means a room and pillar mine (R), containing unpublished information (U), in the state of Virginia (VA), monitored by Virginia Tech (VT), being the fourth (4) room and pillar case study available for analysis in this state.

Although this indexing system may appear to be complex, it is actually quite simple to use and contains all the information that is relevant in identifying case studies.

4.2. Initial Collection of Subsidence Case Studies

In the original stages of this research a number of subsidence case studies, for both longwall and room and pillar mines, were collected from the literature, from state and federal agencies and from mining companies. The information required for this analysis, however, often exceeded the published results and additional data for these case studies had to be obtained directly from the coal companies involved. In addition, most unpublished case studies were of a proprietary nature and were directly retrieved from company files. Finally, although the basic mining parameters were easily determined for all the above case studies, certain subsidence parameters, i.e. angle of draw, inflection point position and, most importantly, values of horizontal movement, were not available for all cases.

During the collection and analysis of these case studies, a number of problems were encountered regarding the reliability and adequacy of the information. Typically, mining companies that monitored subsidence were only interested in a specific area or structure above the mine and the monitoring lines were not always extended beyond the expected limits of influence. On several occasions monuments had been installed along a road for convenience. The spacing of the monuments was not always within acceptable limits. The frequency of monitoring sometimes depended upon the availability of the surveyors and not on the development of the subsidence profile, and often residual subsidence was ignored. In a few cases, monuments were installed after mining had already been initiated. Finally, very few case studies included measurements of horizontal movement, which are very important for the calculation of the potential effect on structures. It should also be mentioned that there is a considerable need for guidelines regarding the accuracy of the measuring equipment, the layout of the monitoring stations, and the frequency of the surveys.

In order to alleviate these problems, a systematic monitoring program of vertical and horizontal movement was initiated above a number of selected panels in the southern Appalachian coalfields.

4.3. Case Studies Monitored Under This Research Program

4.3.1. Monitoring Program

Initially, four case studies were selected. These involved one longwall and three room and pillar mines, and necessitated instrumentation of six panels. Based on the preliminary results derived from these case studies, it was decided that additional sites should be selected with emphasis on complementing the data already obtained. With this in mind, three more mines were identified for monitoring during the second phase of the research. In this case, mines were selected for comparison between room and pillar and longwall subsidence in similar geologic conditions and for the enhancement of the data base so that special cases of interest could be included, such as areas of very steep topography and sites with very high percent of hardrock in the overburden.

A total of nine mines including 23 longwall and room and pillar panels were monitored under this research program. Table 4.1 presents the location, mining system and coal seam for each of these case studies. A detailed description of each case study is presented in Appendix C.

Table 4.1. Monitored Case Studies

Case Study	Location	Mining System	Seam
LUVA-VT1	Dickenson County	Longwall	Jawbone
LUVA-VT2	Wise County	Longwall	Dorchester
RUVA-VT1	Wise County	Room and Pillar	Parsons
RUVA-VT2	Wise County	Room and Pillar	Clintwood
RUVA-VT3	Wise County	Room and Pillar	Clintwood
RUVA-VT4	Wise County	Room and Pillar	Jawbone
RUVA-VT5	Buchanan County	Room and Pillar	Red Ash

4.3.2. Brief Description of Sites

Case Study LUVA-VT1 was a longwall mine located in Dickenson County, Virginia. The terrain was covered with dense forest and the area above the panels under consideration was rolling with steep grades. An old strip mine lay above part of the first panel. The mine was operating in the Jawbone seam. The panel initially selected was the first in a row of four longwall panels. The face was 600 feet long (from rib to rib) and the total advance was 2730 feet. The second panel was 560 feet long at the face and the total advance was 3070 feet. The third panel was 625 feet long at the face. Between panels, two rows of 60 foot wide pillars were left with 20 foot wide entries. Initially, one longitudinal and one transverse monitoring line were installed above the first panel. Due to the existence of the old highwalls and other obstacles, several monuments were at 100 foot intervals (around the middle of the panel). Later the transverse line was extended to cover the second, third and fourth panels.

Case Study LUVA-VT2 was a longwall mine located in Wise County, Virginia. The terrain was covered by thick forest which had to be partially cleared before the initiation of monitoring. The area above the panels under consideration was rolling with steep grades, and a number of strip mines were operating in the area. The longwall mine was operating in the Dorchester seam. Figure 4.1 shows a typical geological column for the strata above the mine (percent hardrock 45-60). The section selected for monitoring consisted of three longwall panels. The face at the first panel was 570 feet wide (from rib to rib) and the total advance was 2710 feet. The second panel was 550 feet wide and the total advance was 2620 feet. The third panel was 540 feet wide and achieved a total advance of 2710 feet. Two rows of pillars were left between panels, 45 and 75 feet wide respectively, with 20 foot entries. Monitoring lines were installed above the first three longwall panels. The longitudinal line was placed along the center of the middle panel.

Case Study RUVA-VT1 was a room and pillar panel located in Wise County, Virginia. The terrain was covered by dense forest and the area above the panel was rolling with steep grades (Figure 4.2). An old reclaimed strip mine lay above a small part of the panel. The panel selected for monitoring was the second last of an extraction sequence. The mine was operating in the Parsons seam. Figure 4.3 shows a typical geological column for the strata above the mine. Each panel had five entries 20 feet wide on 60

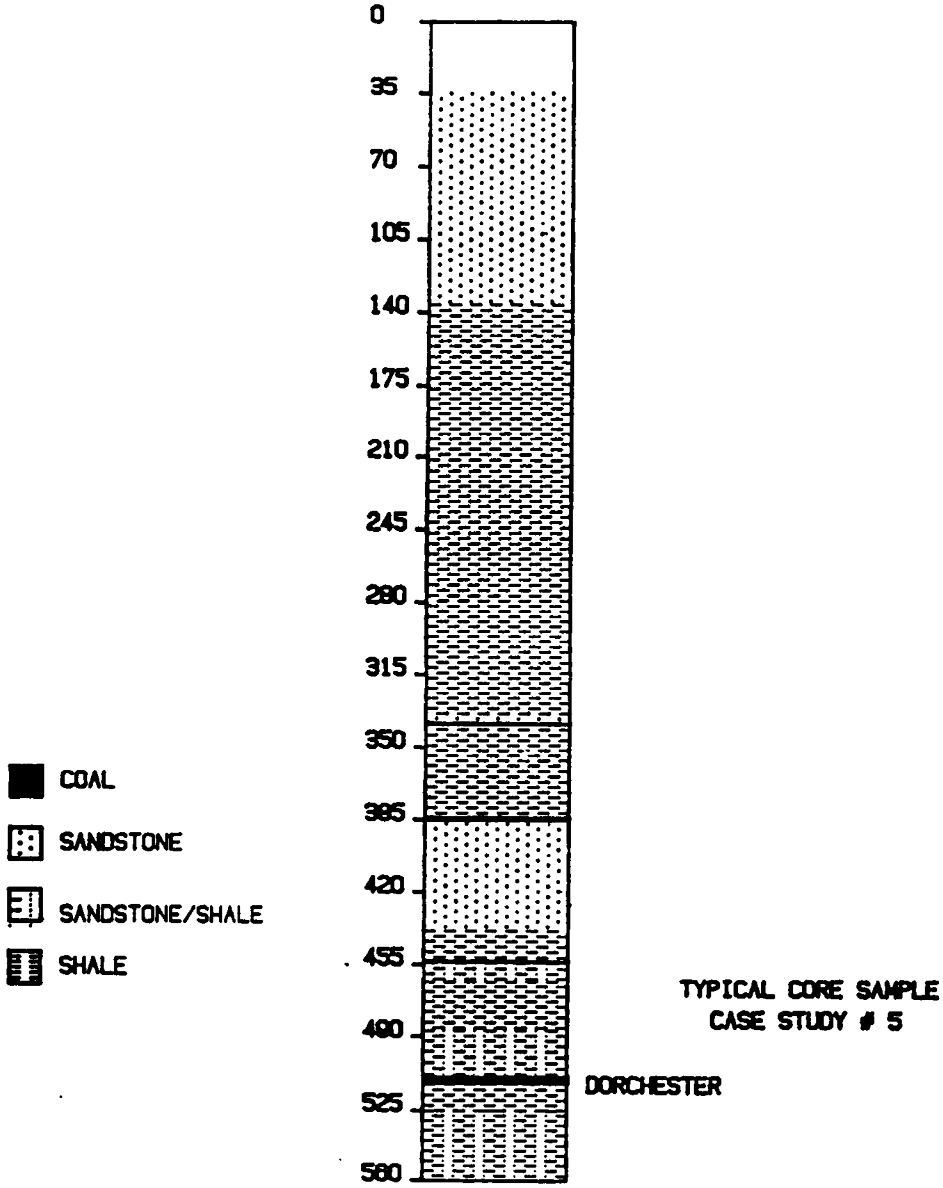

Figure 4.1. Geological Column for Case Study LUVA-VT2.

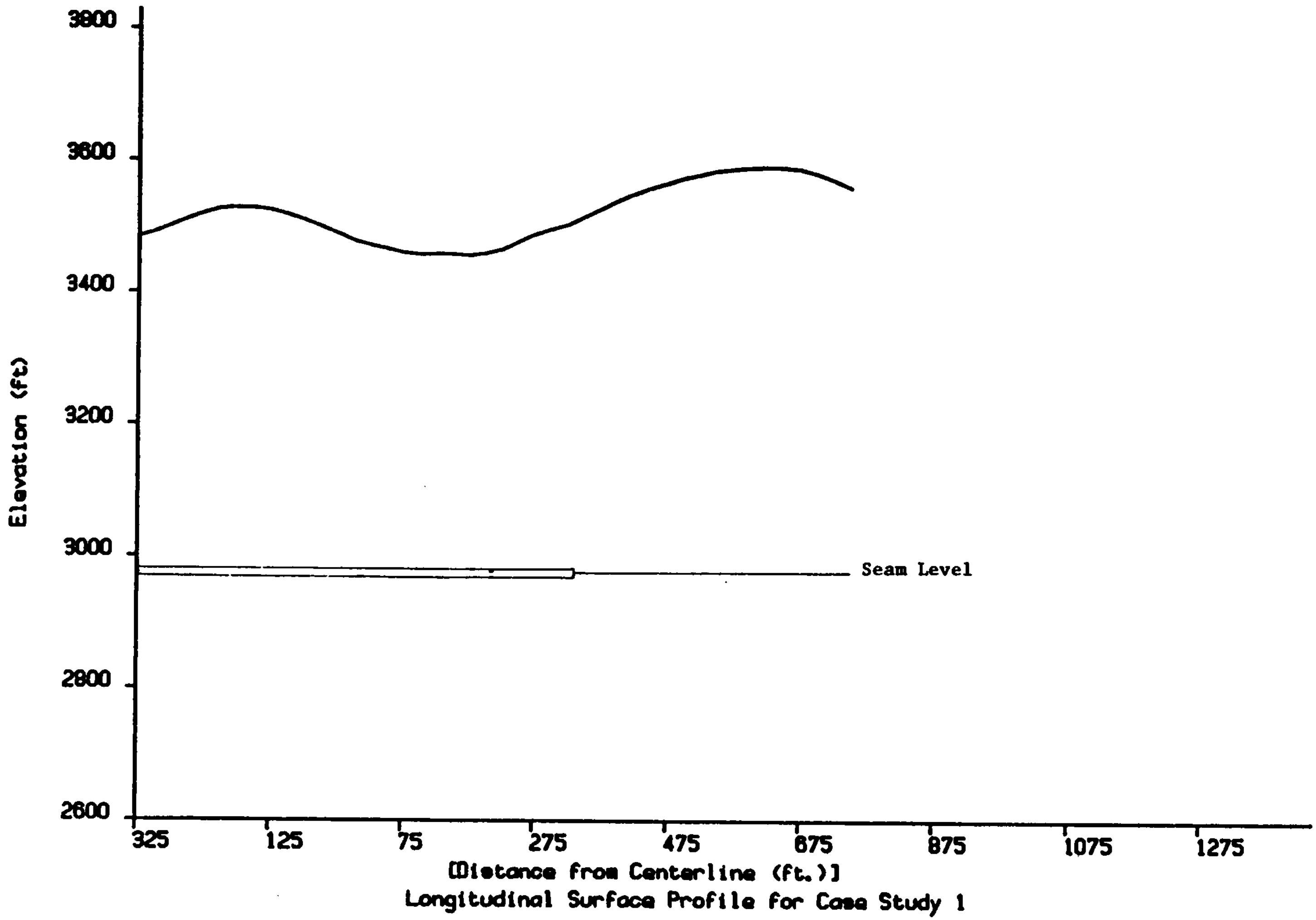

Figure 4.2. Typical Surface Profile for Case Study RUVA-VT1.

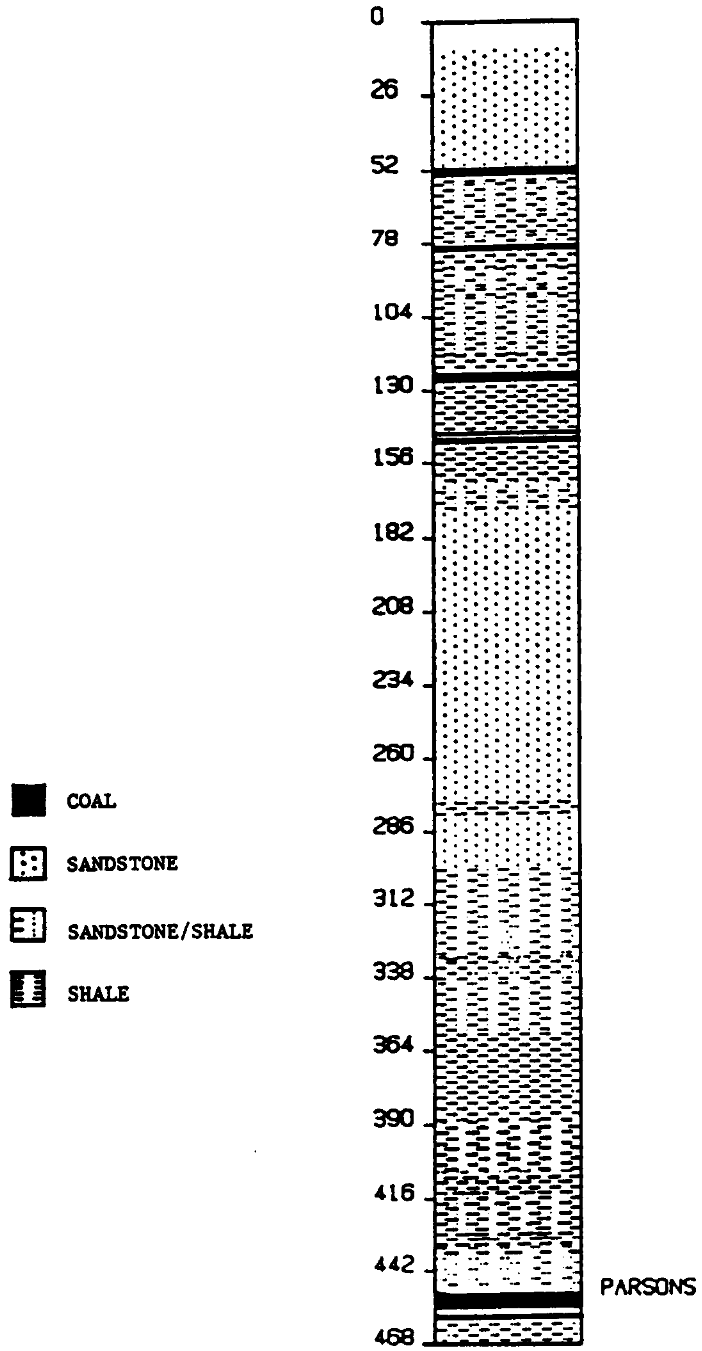

Figure 4.3. Geological Column for Case Study RUVA-VT1.

foot centers. Pillar extraction was achieved through use of a "wing" plan: the pillar was split along its center line, which allowed cuts to be taken to the right and the left. This method permits an extraction ratio of approximately 85 percent. During pillaring one or two rows of pillars to the side of the solid coal were left for ventilation purposes. Two monitoring lines were installed above the panel. They were positioned according to its planned shape.

Case Study RUVA-VT2 was a room and pillar mine also located in Wise County, Virginia. The terrain was covered by dense forest and the area above the panel was rolling with average grades. The mine was operating in the Clintwood seam. Figure 4.4 shows a typical geological column for the strata above the mine. The extraction ratio varied between 85 percent and 50 percent. The monitoring lines were positioned above a section consisting of three panels and covered all three panels. This section was lying under two ridges and mining was initially planned to extend as close to the outcrop as possible. It was also planned that all pillars, with the exception of those left around the final excavation for ventilation purposes, would be extracted. However, due to ground control problems the initial plan was modified, which resulted in much more complex subsidence characteristics.

Case Study RUVA-VT3 was a room and pillar mine, adjacent to the mine in Case Study RUVA-VT2. The panel under consideration was separated from the first panel in Case Study RUVA-VT2 by a distance of approximately 100 feet. The extraction ratio was about 85 percent. The mine selected was a relatively small operation in a shallow seam. The panel which was instrumented was planned to mine the coal lying from the outcrop to the property boundary of the neighboring mine and, therefore, it was not of a rectangular shape.

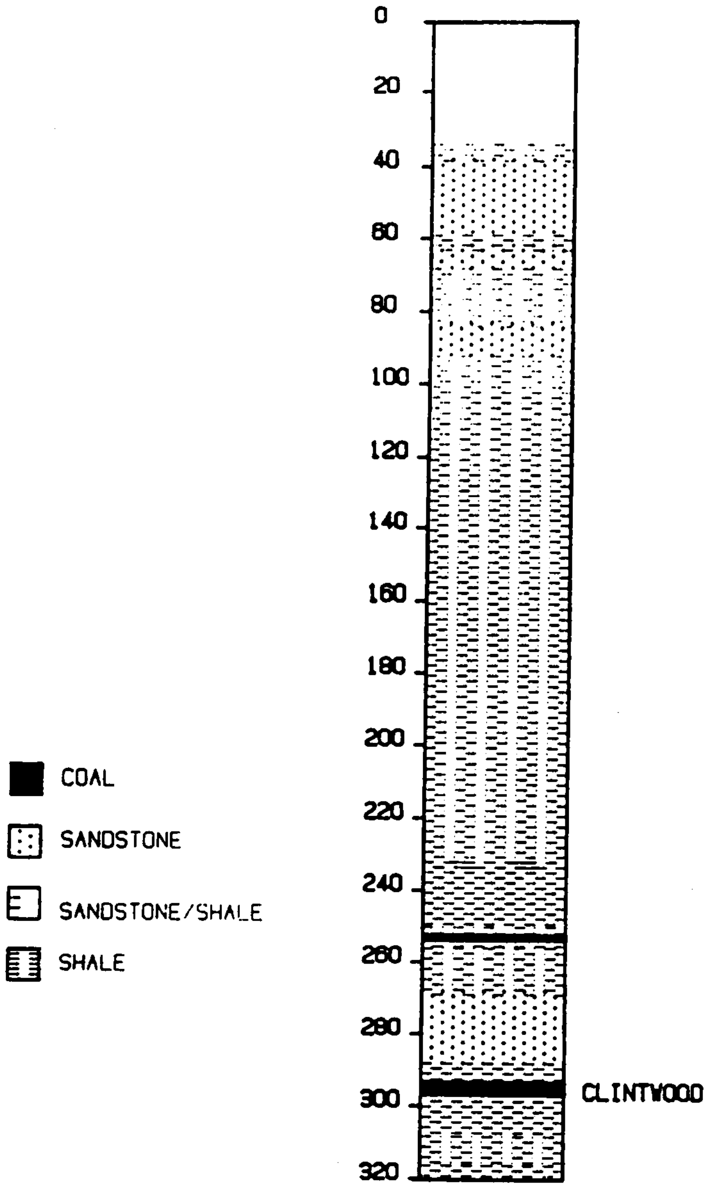

Figure 4.4. Geological Column for Case Study RUVA-VT2.

Case Study RUVA-VT4 was a room and pillar section selected for its geologic similarity to the longwall mine of Case Study LUVA-VT1. However due to roof problems only a small number of pillars were extracted, without noticeable movement on the surface.

Case Study RUVA-VT5 was a room and pillar section in a mine located in Buchanan County, Virginia. The terrain was covered by dense forest and the area above the panel was rolling with steep grades. The mine was operating in the Red Ash seam. The average recovery at the mine was 85 percent. The mine plan consisted of a series of eight panels, each having six to seven 20 foot wide entries, with a varying configuration of pillar sizes. It was originally planned that all pillars would be fully extracted, with the exception of those left around the final excavation for ventilation purposes. However, during mining, a number of pillars were left in place, which, resulted in a varying extraction ratio over the section under consideration. In addition, pillars were also extracted from the surrounding development works. Measurements were made for the last five panels and the surrounding development works. A transverse line and three longitudinal lines were installed. Due to the extent of the monitoring system and the difficult topography, a complete monitoring required two surveys, each starting from a different station.

Case Study RUVA-VT6 was a room and pillar section in a mine located in Buchanan County, Virginia. The terrain was covered by dense forest and the area above the panel was rolling with steep grades. The mine was operating in the Red Ash seam. The average recovery at the mine was 85 percent.

Case Study RUVA-VT7 was a room and pillar section located in Buchanan County, Virginia. One transverse and two longitudinal monument lines were installed in order to monitor surface movements over three panels. The lines were installed during the development of the first panel. However, due to unexpected change of the production plans, pillar recovery was not implemented and, therefore, results were not available for this mine

4.3.3. Typical Results

Site instrumentation of all case studies followed the guidelines described in Chapter 3. Above each panel or section under consideration, monuments were installed during the development stage of the panel. A minimum of three initial surveys were usually conducted. The first survey tied the system of monuments to the mine. The purpose of the second survey was to determine the coordinates and elevation of each monument. The third survey was run in order to double check the data.

After the extraction of pillars or the advance of the longwall face was initiated, the monument lines were surveyed every seven to ten days. However, if rapid development of subsidence was observed (e.g. Case Study RUVA-VT2), surveys were taken every four to five days. After the mining had ceased, surveys were conducted at the same frequency until ground movement slowed down, and the time span between subsequent surveys was gradually expanded to a month. The last survey was generally taken several months after the completion of mining, unless movement was still observed.

In Case Study LUVA-VT1, maximum observed subsidence was 4.1 feet, or about 65 percent of the seam thickness, observed above the centerline of the first panel eighteen months after mining of the panel had been completed. The reason for this delayed subsidence was partly due to the influence of the adjacent panel which was mined subsequently, and partly due to the natural or residual subsidence settlement which occurred with time. The effect of these factors was to increase maximum subsidence from 3.6 feet, or about 50 percent of seam thickness, observed three months after mining had been completed, to 4.1 feet or 65 percent of the seam thickness. Maximum horizontal compression during mining was 0.6 percent which dropped to a residual value of 0.35 percent. Maximum observed horizontal tension was in the range of 0.6 percent. Figure 4.5 shows data obtained during and after mining of the first panel. Figures 4.6 and 4.7 show the data obtained during mining of the four instrumented panels. The angle of draw was in the range of 16 to 21 degrees in the longitudinal direction and 16 to 18 degrees in the transverse direction.

In Case Study LUVA-VT2, maximum observed subsidence was 2.6 feet, or about 47 percent of the seam thickness, above the centerline of the second panel. Maximum horizontal compression during mining was 1.0 percent. Maximum observed horizontal tension was in the range of 0.9 percent. The angle of draw was in the range of 31 degrees in the longitudinal direction and 17 to 26 degrees in the transverse direction. Figure 4.8 shows data obtained during and after mining of the section.

During mining at site of Case Study RUVA-VT1, the development of the subsidence profile was very rapid. The final profile was observed 3 to 4 weeks after mining had been completed. Later surveys did not indicate any significant change due to residual subsidence. Maximum measured subsidence was 2.1 feet. The angle of draw was approximated to be 30 degrees with respect to the transverse line and 14 degrees with reference to the longitudinal (parallel to the face advance) axis. Maximum horizontal compression was in the range of 0.15-0.20 percent and maximum tension was in the range of 0.30-0.35 percent. Figures 4.9 and 4.10 show data obtained during this monitoring program.

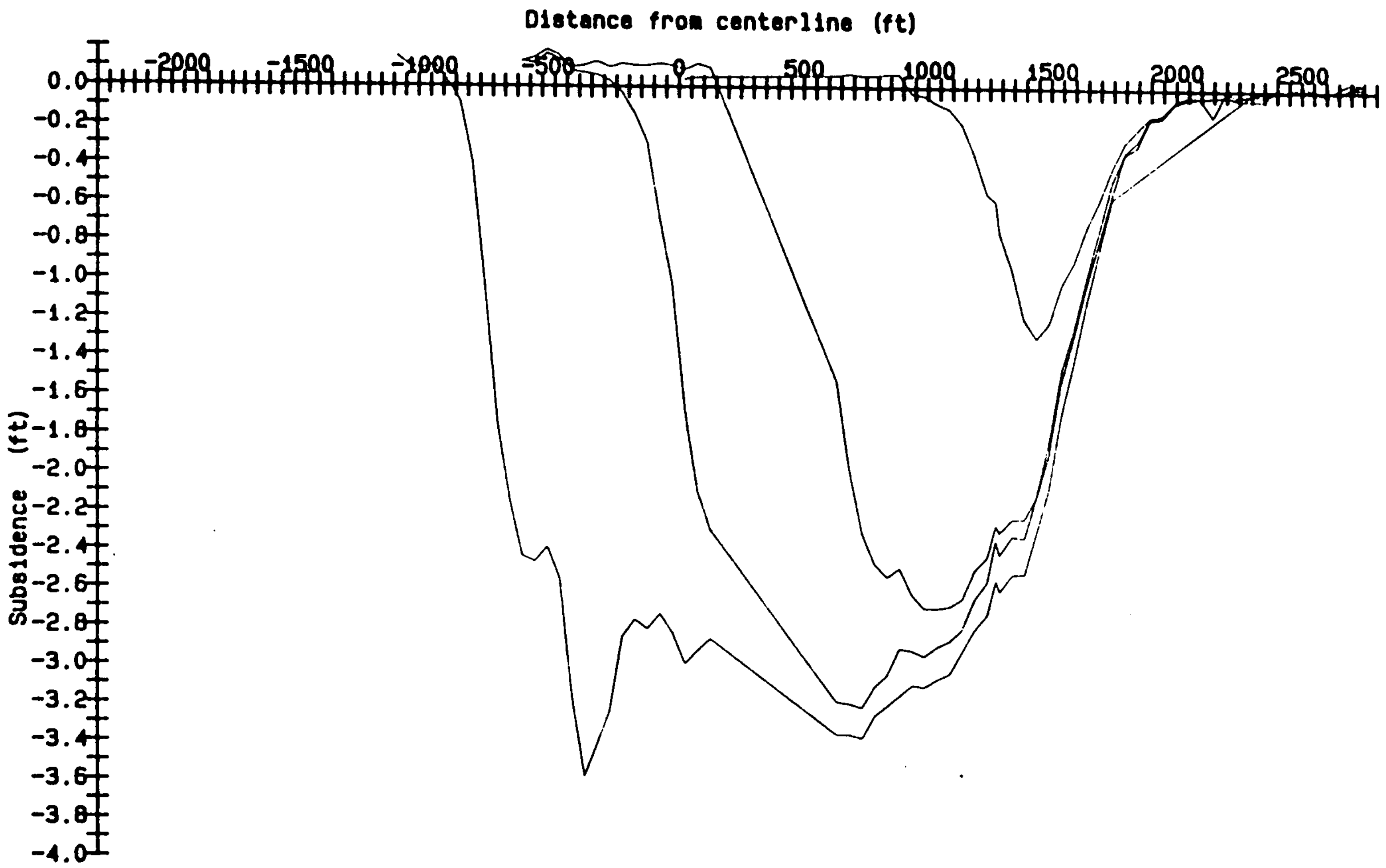

Figure 4.5. Longitudinal Subsidence Development During Mining of Panel #1, Case Study LUVA-VT1.

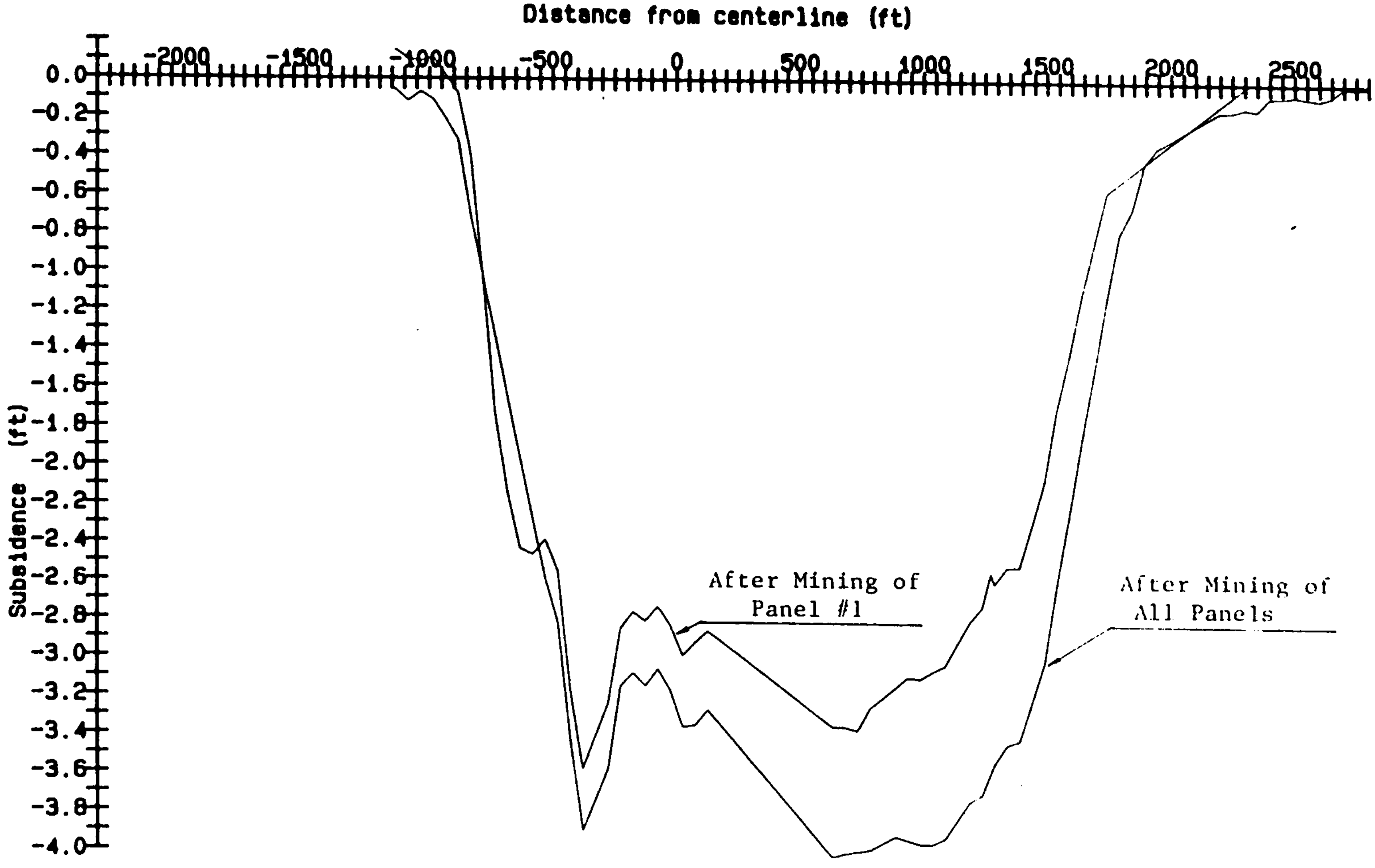

Figure 4.6. Longitudinal Subsidence Profiles for Panel #1, Case Study LUVA-VT1.

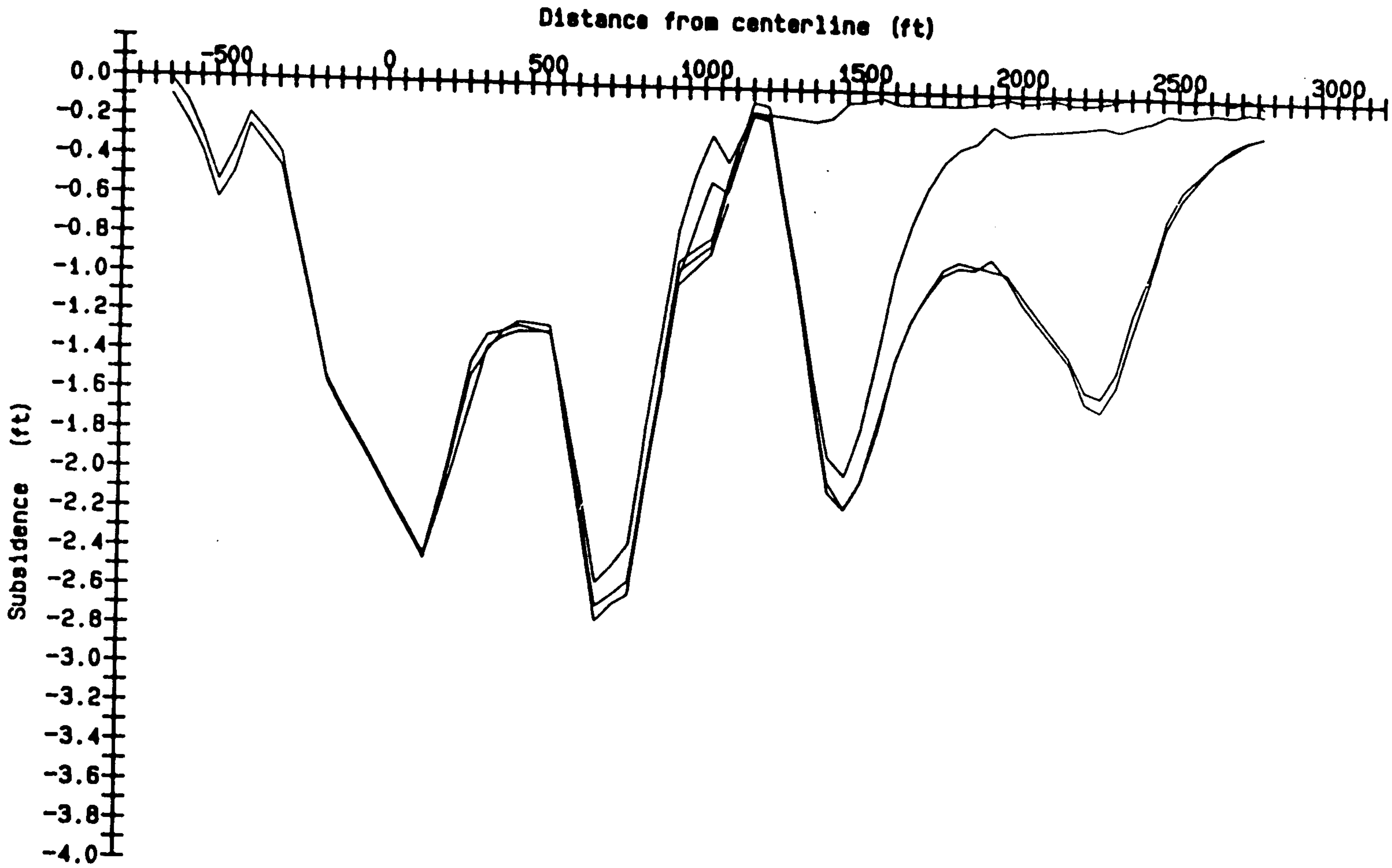

Figure 4.7. Transverse Subsidence Profiles for Case Study LUVA-VT1.

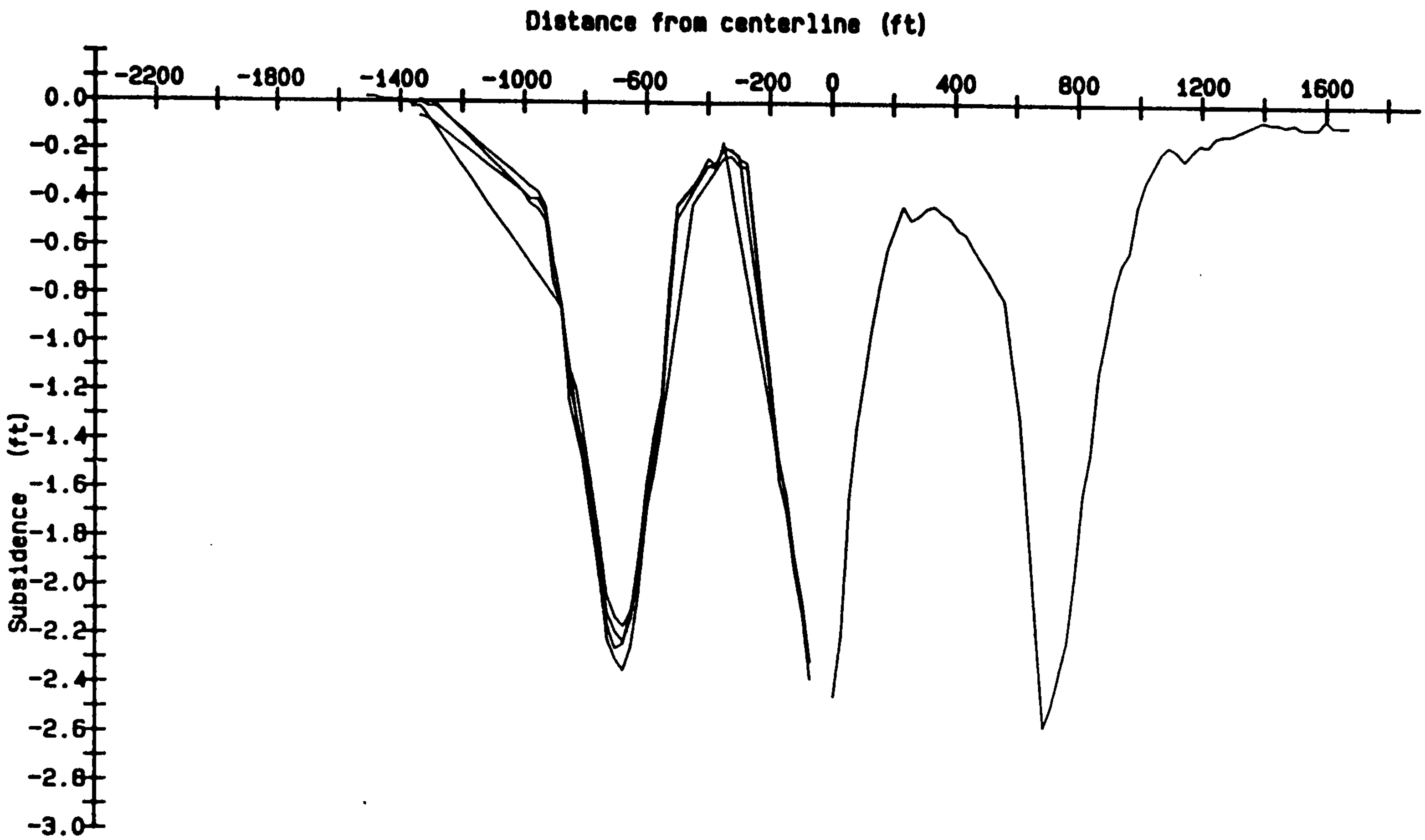

Figure 4.8. Transverse Subsidence Profiles for Case Study LUVA-VT2.

In Case Study RUVA-VT2, maximum measured subsidence was 2.5 feet, or 0.5 times the seam thickness. Maximum horizontal compression was in the range of 0.50-0.75 percent and maximum tension was in the range of 0.35-0.75 percent. Figures 4.11 and 4.12 show data obtained during this monitoring program. The angle of draw was in the range of 14.0-15.5 degrees.

In Case Study RUVA-VT3, maximum measured subsidence was 2.6 feet or 0.52 times the seam thickness. Maximum horizontal compression was 1.50 percent and maximum tension was 1.05 percent. Figure 4.13 shows the data obtained during this monitoring program. The effect of pillars left in place is illustrated by the hump of the transverse subsidence and strain profiles. It should be noted that the subsidence and strain values were higher on one side of the panel than on the other due to shallower depth at the former location. The angle of draw was in the range of 14.0-20.6 degrees.

In Case Study RUVA-VT5 maximum, measured subsidence was 1.8 feet. Maximum horizontal compressive strain was in the range of 0.34-0.7 percent and maximum tensile strain was in the range of 0.35-0.6 percent. The angle of draw was in the range of 15-16 degrees.

In Case Study RUVA-VT5 the measured maximum subsidence was 1.65 feet. Maximum horizontal compressive strain was about 0.4 percent and maximum tensile strain was approximately 0.42 percent. The angle of draw was in the range of 16 degrees.

4.4. Final Subsidence Data Bank

For the purpose of the analysis, information from different panels in the same mine was averaged if their mining parameters, i.e. mining height, depth, panel width and percent

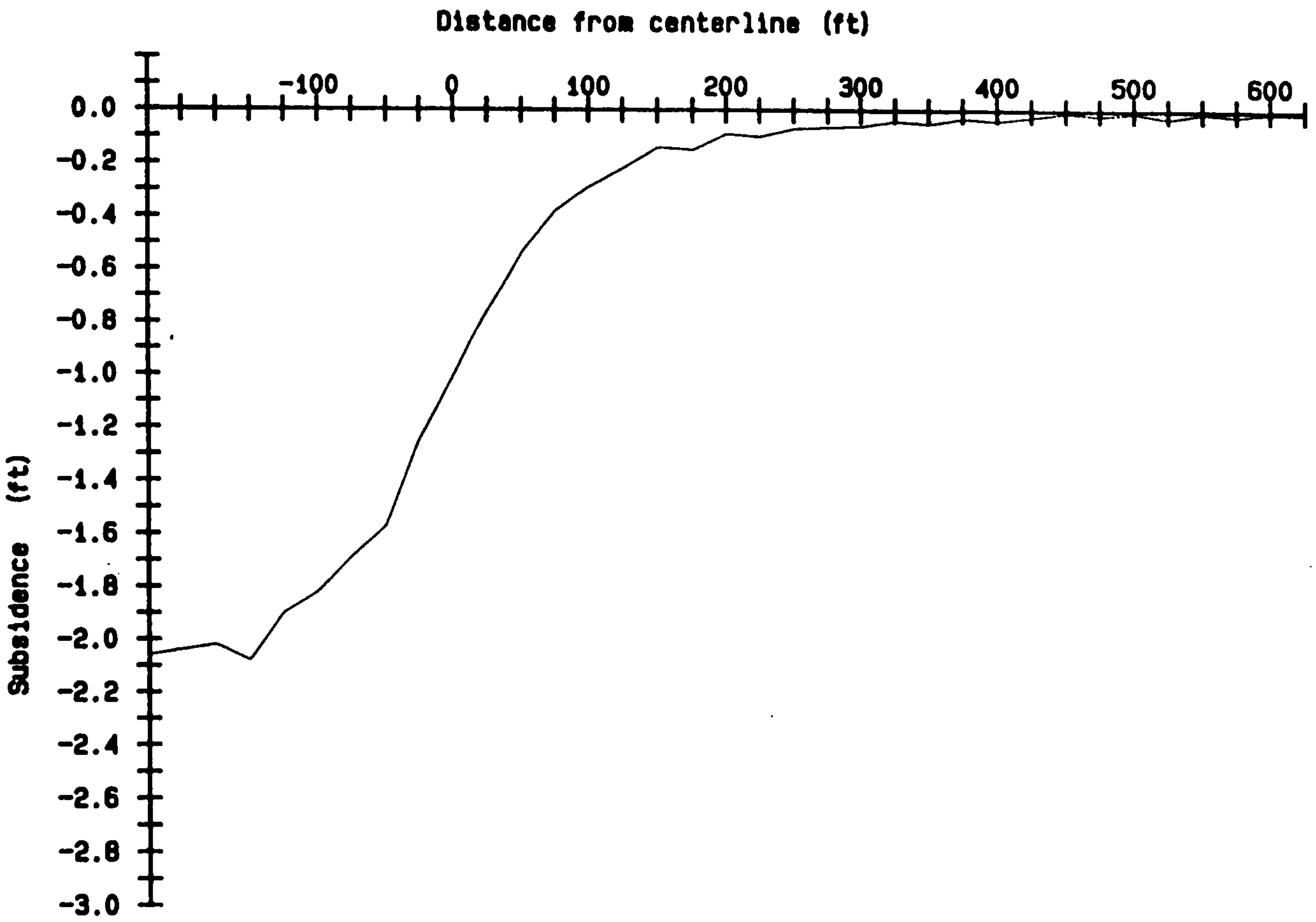

Figure 4.9. Final Transverse Subsidence Profile for Case Study RUVA-VT1.

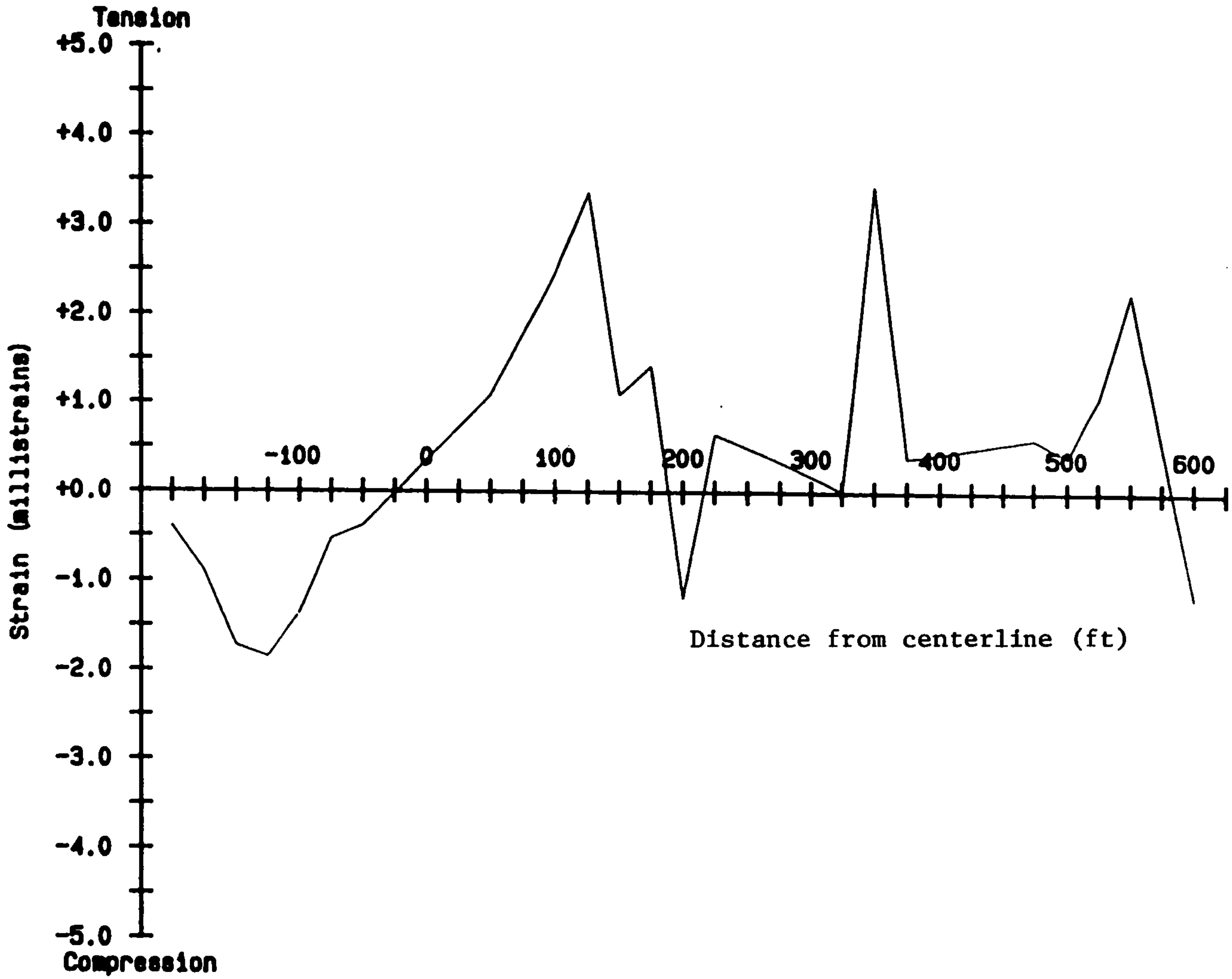

Figure 4.10. Final Transverse Strain Profile for Case Study RUVA-VT1.

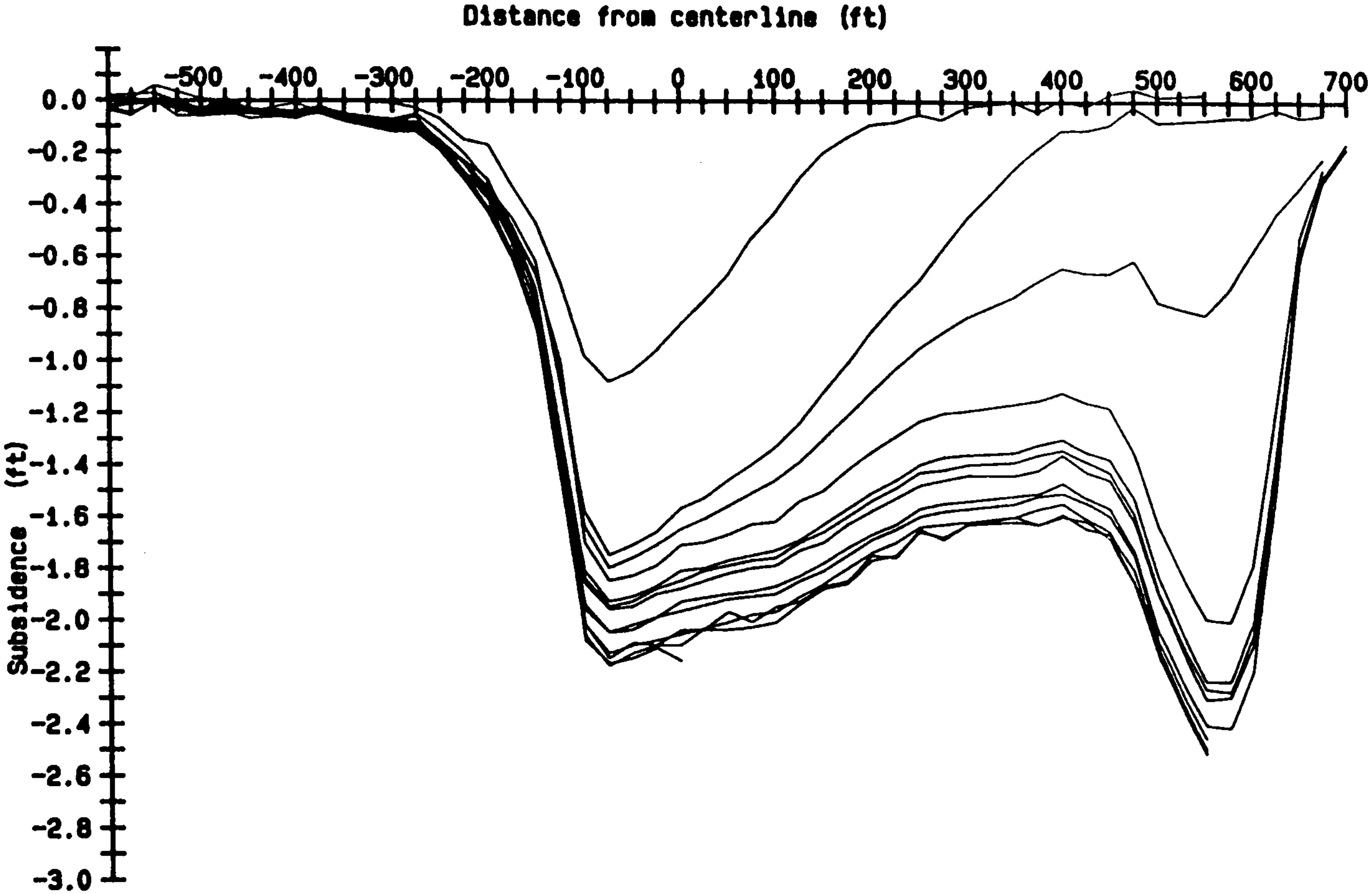

Figure 4.11. Longitudinal Subsidence Profiles for Case Study RUVA-VT2.

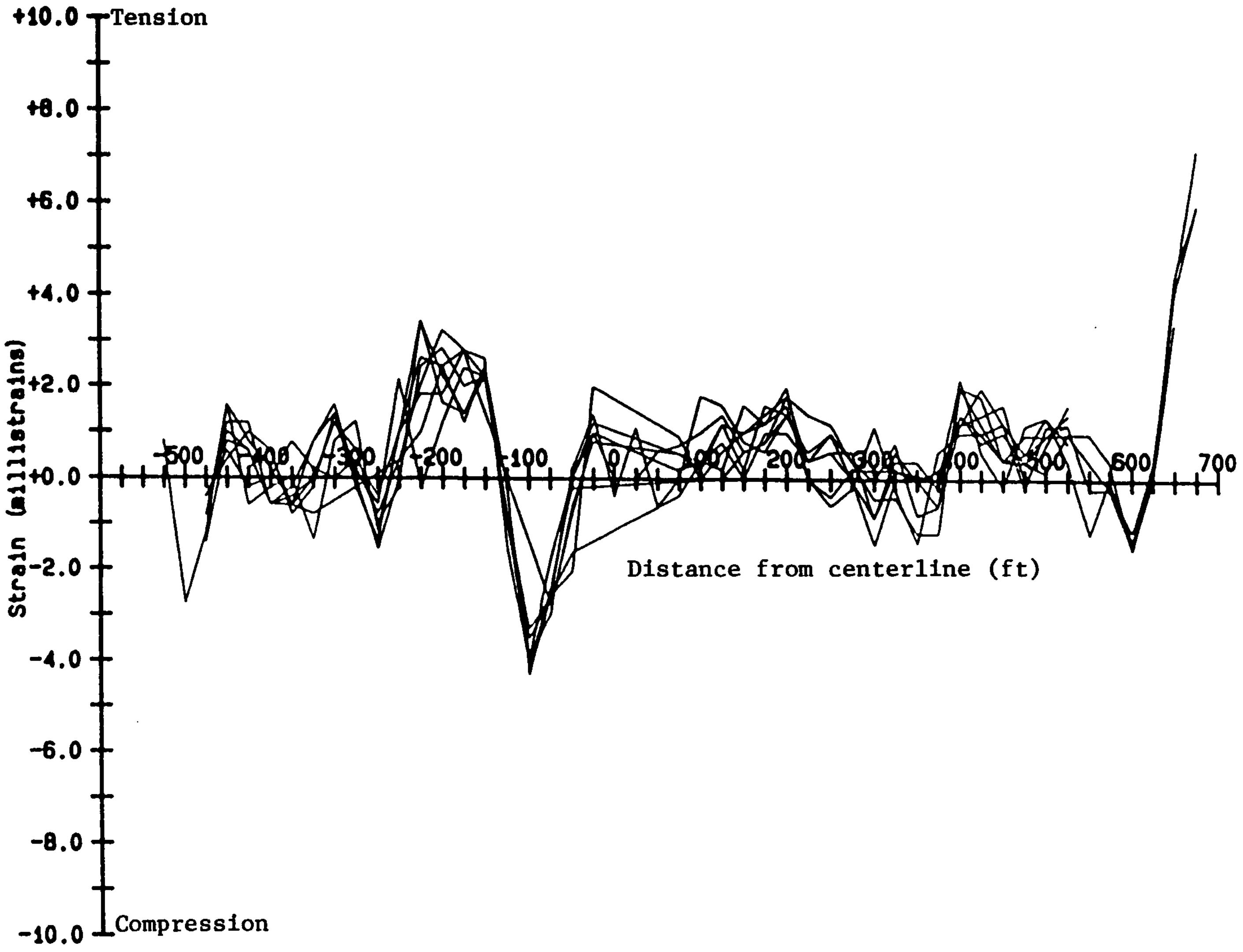

Figure 4.12. Longitudinal Strain Profiles for Case Study RUVA-VT2.

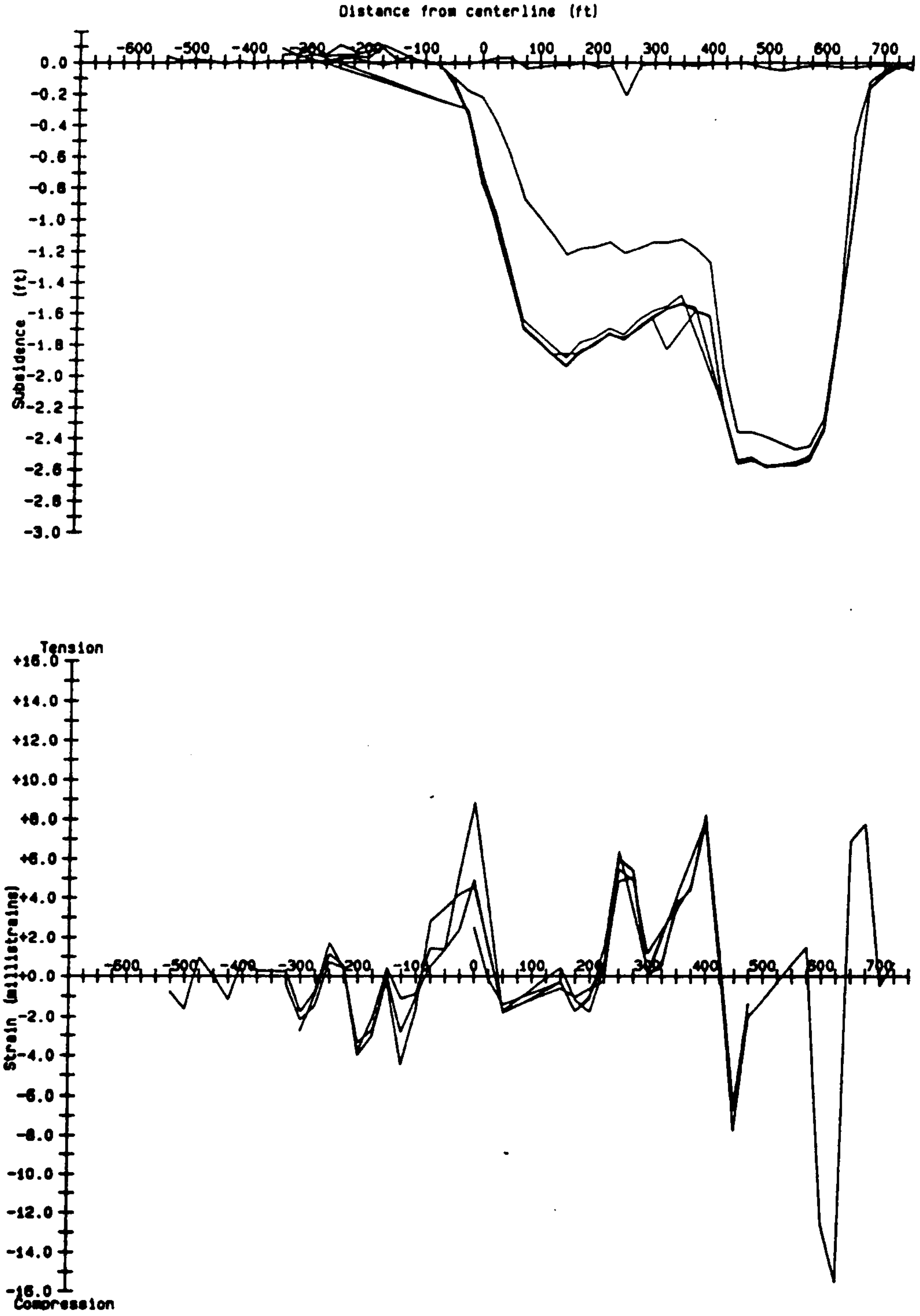

Figure 4.13. Transverse Subsidence and Strain Profiles for Case Study RUVA-VT3.

hardrock in overburden, and their subsidence parameters, i.e. angle of draw, S_{max}, location of inflection point, etc., were comparable. Otherwise these panels were treated as separate case studies.

4.4.1. Longwall Case Studies

The longwall analysis included information from 22 mines or 45 longwall panels located in these mines. The total number of individual cases used to develop the basic longwall relationships was 36, after elimination due to averaging information from panels in the same mine or inadequate data. The geographic distribution of these cases is given in the table below:

Location	Case Studies
Alabama	3
Ohio	5
Pennsylvania	7
West Virginia	18
Virginia	3
Total	36

It should be noted that two of the three Virginia case studies, involving seven panels, were those monitored under this research effort. Appendix D presents a listing of all of these case studies, with references, where relevant. Table 4.2 summarizes the mining parameters for the longwall case studies.

4.4.2. Room and Pillar Case Studies

The room and pillar analysis included information from 49 mines or over 70 panels located in these mines. The total number of individual cases, after elimination due to averaging information from panels in the same mine or inadequate data, which were used to develop the basic room and pillar relationships, was 60. In many cases, however, very limited information was available for data analysis from these case studies. The geographic distribution of these cases is given in the table below:

Location	Case Studies
Alabama	1
Maryland	4
Pennsylvania	47
West Virginia	3
Virginia	5
Total	60

It should be noted that all of the Virginia case studies, involving sixteen panels in seven mines, were monitored under this research effort. Appendix E presents a listing of the room and pillar case studies, as in the case of the longwall data. Tables 4.3 and 4.4 summarize the mining parameters of the room and pillar data by considering two groups of case studies according to the extraction ratio.

Table 4.2. Mining Parameters - Longwall Panels Used in the Analysis

Name	W	h	m	L	HR(%)
LPAL1	600	500	4.5	--	26
LPAL2a	460	1500	5.4	2650	30
LPAL2b	1100	1500	5.4	3725	30
LPOH1a	485	750	6.5	4750	23
LPOH1bc	485	450	6.5	4725	30
LPOH1d	474	350	6.5	1950	30
LPOH1ef	480	700	7.25	5000	24
LPOH2	485	700	4.3	4200	23
LPPA2	610	550	4.5	2625	41
LPPA4ab	450	510	4.15	--	31
LPPA4c	460	455	4	--	39
LPPA4d	445	290	4	--	26
LPPA5	380	530	6.2	--	25
LPPA6	430	400	5.5	--	25
LPPA7	470	400	3.7	4650	21
LPWV1a	450	600	5.5	4800	37
LPWV1b	450	600	5.5	4400	37
LPWV1c	600	660	5.5	--	23
LPWV1d	600	550	5.5	--	23
LPWV1e	605	600	5.5	--	37
LUWV3	450	480	7	3140	23
LUWV4a	500	300	4.9	5600	32
LUWV4b	500	250	4.9	5500	32
LPWV5	450	620	6	--	41
LPWV6	450	750	6	--	50
LPWV7a	600	750	5.5	--	25
LPWV7b	600	680	5.5	--	29
LPWV9ab	500	275	5	3490	58
LPWV9c	500	520	6.2	--	65
LPWV10a	450	650	--	--	55
LPWV10b	335	600	--	--	51
LPWV11	620	610	6.5	--	18
LPWV12abc	617	726	6.8	4670	35
LPVA1	2210	1700	--	--	47
LUVAVT1	600	700	7.25	2700	46
LUVAVT2	560	600	5.5	2660	50

Table 4.3. Mining Parameters - High Extraction Room and Pillar Panels Used in the Analysis

Name	W	h	m	L	%HR	%R
RUAL1	--	495	4.25	--	26	87
RPMD2	--	180	8.5	--	--	85
RPMD3	--	112	8.5	--	--	90
RPPA1	360	325	6.5	380	22	75
RPPA2a	430	375	6.5	2600	15	80
RPPA3	840	375	4.7	1940	39	90
RPPA4	910	650	6.2	3000	31	88
RPPA5	720	725	6.0	2000	33	85
RPPA5	1460	750	6.1	2500	29	88
RPPA6	1955	745	5.7	2500	30	88
RPPA7	500	535	6.5	2100	31	88
RPPA8	--	329	5.5	--	50	83
RPPA9a	470	350	7.2	--	41	85
RPPA9b	570	425	7.2	--	41	85
RPPA9c	1100	532	6.8	--	41	85
RPPA10	300	354	5.4	--	20	90
RPPA11a	--	297	7.0	--	41	85
RPPA11d	--	430	6.9	--	41	85
RPPA12	--	370	6.5	--	27	94
RPPA12	--	595	6.5	--	27	94
RPPA13	--	178	7.0	--	--	90
RPPA14	550	392	8.0	--	--	90
RPPA15	--	725	8.0	--	--	90
RPPA16	--	31	8.0	--	--	90
RPPA17	--	84	4.0	--	--	90
RPPA18	--	25	8.0	--	--	--
RPPA19	--	---	8.0	--	--	--
RPPA20	--	438	6.5	--	--	--
RPPA21	--	80	7.0	--	--	90
RPPA22	--	245	7.5	--	--	90
RPPA23	--	325	7.0	--	60	85
RUPA24a	--	540	6.25	--	31	85
RUPA24b	--	578	6.5	--	31	85
RPPA25	--	338	7.1	--	22	88
RUPA26	--	615	8.2	--	25	85
RUPA27	--	345	6.0	--	44	85
RUPA28	--	320	6.0	--	44	85
RUPA29a	--	255	6.75	--	30	85
RUPA29c	--	325	6.75	--	30	85
RUPA30	--	620	7.0	--	22	85
PUPA31	--	370	5.4	--	50	85
RPPA32	--	320	7.1	--	43	87
RUPA34	600	600	5.5	900	50	90
RPWV1	325	555	6.0	800	47	90
RPWV2	830	800	5.0	--	64	78
RUWV4	400	690	6.5	2000	70	100
RUVAVT1	525	540	5	--	32	85
RUVAVT2	980	365	5	--	80	85
RUVAVT3	680	258	5.5	--	80	85
RUVAVT5	2000	590	3.7	800	50	85
RUVAVT6	1200	490	3.9	1050	50	85

Table 4.4. Mining Parameters - Low Extraction Room and Pillar Panels Used in the Analysis

Name	W	H	m	L	%HR	%R
RPMD1a	--	300	8.75	--	--	--
RPMD1b	--	300	8.33	--	--	--
RPPA2b	430	350	6.5	2000	15	58
RPPA11b	--	429	7.25	--	41	54
RPPA11c	--	429	7.25	--	41	64
RPPA11e	--	430	6.9	--	41	57
RPPA11f	--	430	6.9	--	41	63
RUPA29b	--	255	6.75	--	30	47
RUPA29d	--	325	6.75	--	30	47

CHAPTER 5

ANALYSIS OF RESULTS

A number of relationships were established based on the data collected from all case studies, and these relationships were used for the regional application of the prediction methods. They included:

- Correlation of maximum subsidence (S_{max}), and angle of draw with mining and geological factors pertaining to the excavated area. These subsidence field parameters were required input for all the prediction techniques used throughout this study.
- Evaluation of ribside subsidence value and location of inflection point, also from mining factors. The former was required for the application of the zone area prediction method, whereas the latter was needed to implement the influence and the profile function methods.

Separate analysis was performed initially for each of these categories of data using the case studies pertaining to:

- Longwall or high extraction room and pillar panels; and
- Low extraction room and pillar sections.

Regarding the data used in this analysis, information from different panels in the same mine was averaged, if their mining, lithologic, topographic and subsidence parameters were comparable, as mentioned in Chapter 4. Otherwise these panels were treated as separate case studies. However, although the basic mining parameters were easily determined for all of the collected studies, certain subsidence parameters, i.e. angle of draw, inflection point position and, most importantly, values of horizontal movement, were not available for all cases.

5.1. Basic Relationships for Longwall and High Extraction Room and Pillar Panels

Data from longwall and high extraction room and pillar case studies were combined, taking into account a correction factor for the extraction ratio. Thus the sample size was increased and the resulting relationships may be used for both longwall and room and pillar case predictions.

5.1.1. Analysis of Maximum Subsidence

The magnitude of the maximum subsidence, obtained at the center of the panel, was shown to be influenced by both panel geometry as well as geology.

Figure 5.1 shows the maximum subsidence factor ($\frac{S_{max}}{m}$), where m is the mining height, as a function of the panel width-to-depth ratio (W/h), for the longwall case studies.

The figure shows two lines constructed from these results. Line 1 represents the average values of $\frac{S_{max}}{m}$, whereas Line 2 is an envelope line, covering all data points. For the

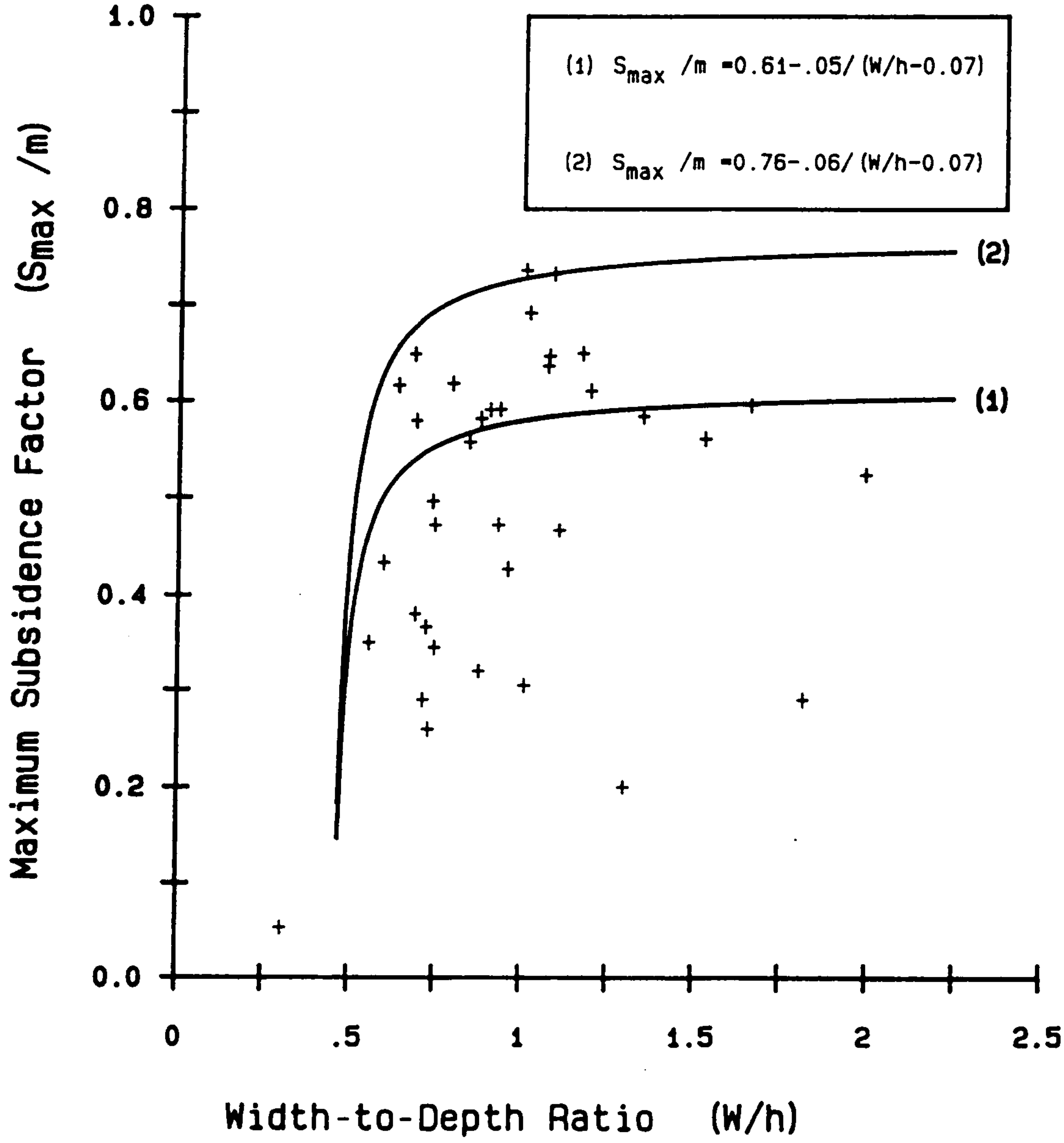

Figure 5.1. Effect of Width-to-Depth Ratio on the Maximum Subsidence Factor (Longwall Case Studies).

purpose of this analysis the envelope relationship was utilized for prediction purposes, which implies a safety margin.

In addition, asymptotic conditions were approached when $\frac{S_{max}}{m}$ was about 0.76, as W/h approached 1.0 to 1.2, i.e. the critical panel dimensions. This trend is different from the experience documented in other coalfields, i.e. Britain, where $\frac{S_{max}}{m}$ values were shown to approach 0.90 for critical sizes of $W/h \geq 1.4$.

The distribution of points, however, indicated that, in addition to the geometrical factors, another set of controls can have a significant impact on maximum subsidence values. This is the impact of the geological conditions encountered on the site, including such factors as lithology, bed thickness and position of different strata from the mined coal seam. Due to the complexity of the problem, however, the only relationship that could be established was that of $\frac{S_{max}}{m}$ versus lithology, the latter being expressed as the percentage of hard rock in the overburden. This is shown in Figure 5.2, where only critical or supercritical panels were considered, thus removing the influence of panel geometry on $\frac{S_{max}}{m}$. A high correlation was obtained for this relationship, which allowed at least one geological control to be included in subsidence prediction.

Figures 5.1 and 5.2 have been compounded in Figure 5.3, which has been used extensively and with remarkable accuracy for prediction of S_{max} in conjunction with all prediction methods utilized in this study. The same results are also presented in a tabulated form in Table 5.1.

Figure 5.4 shows the maximum subsidence factor ($\frac{S_{max}}{m}$) divided by the extraction ratio, as a function of the panel width-to-depth ratio, W/h, for the high extraction room and pillar case studies. Since under, typical mining practices, the maximum extraction ratio

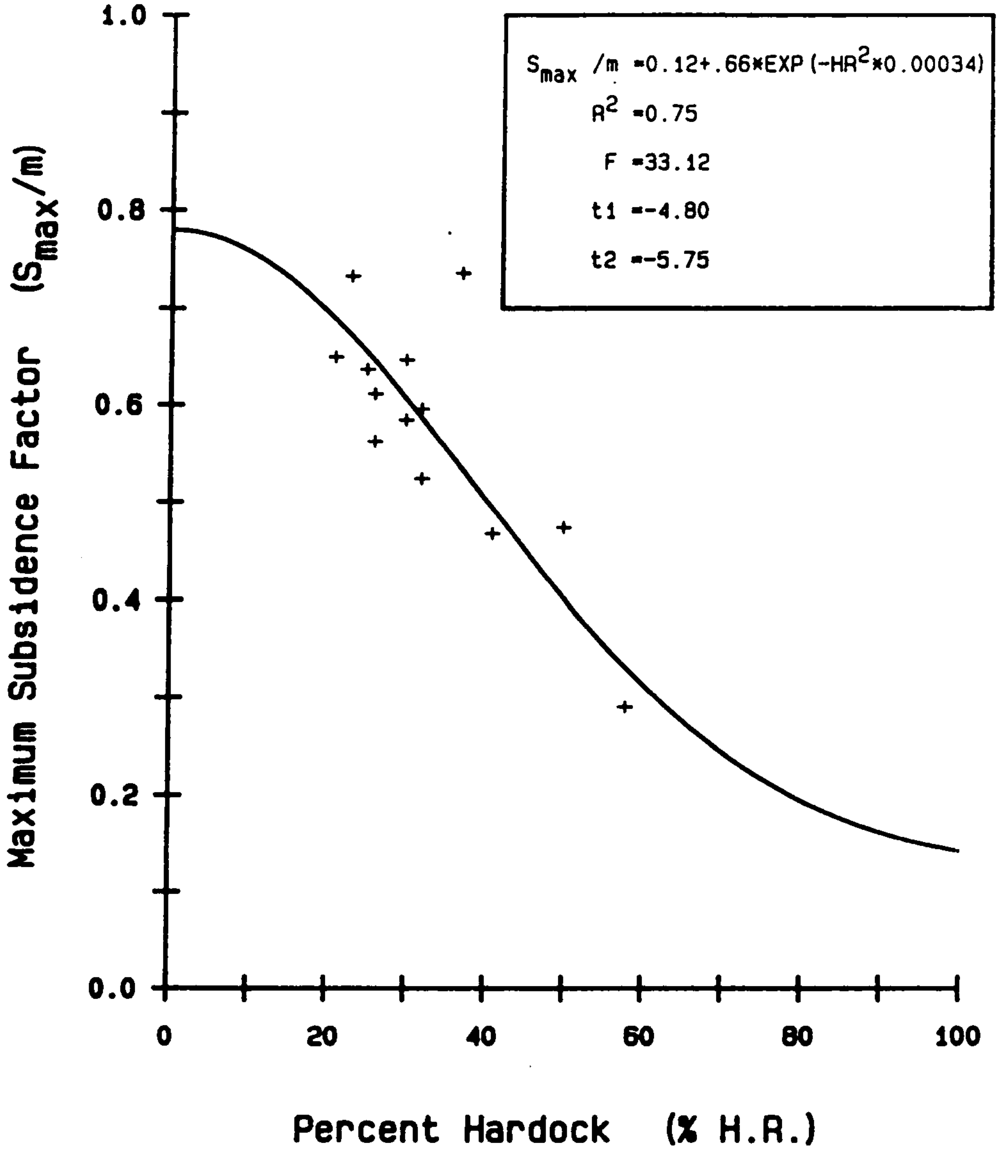

Figure 5.2. Influence of Hardrock in Overburden on the Maximum Subsidence Factor (Critical or Super-critical Panels, Longwall Case Studies).

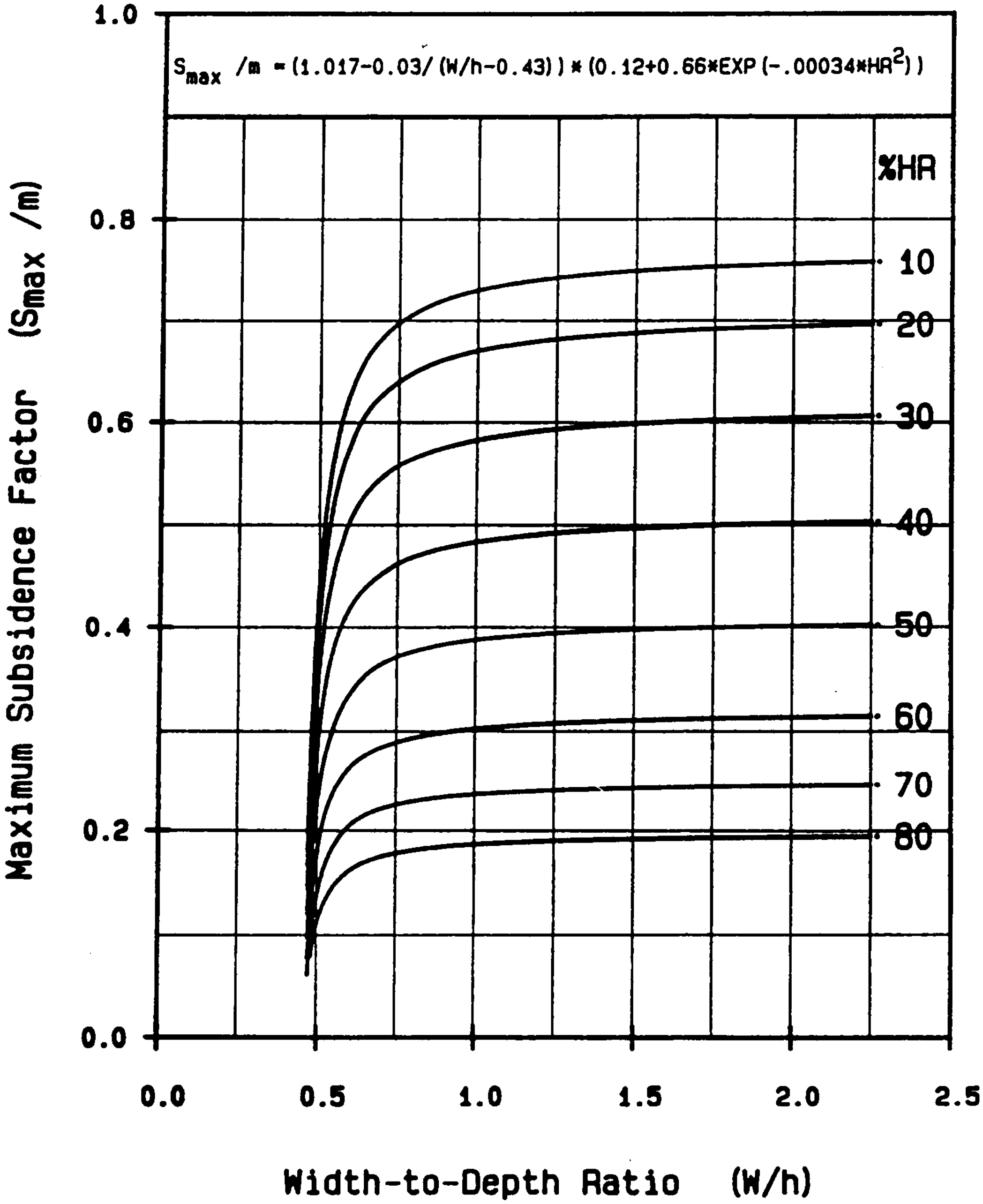

Figure 5.3. Prediction of the Maximum Subsidence Factor (Longwall Case Studies).

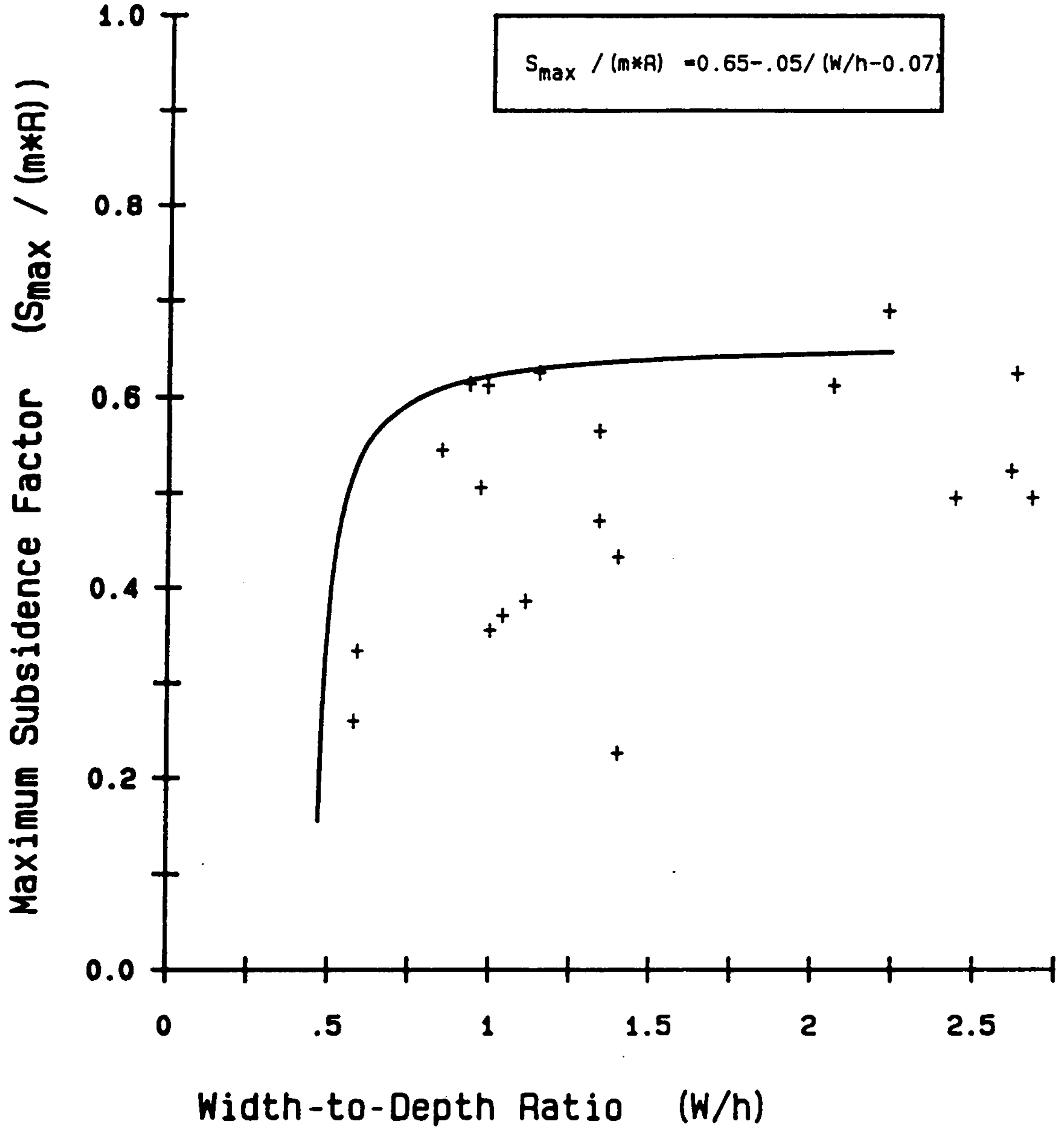

Figure 5.4. Effect of Width-to-Depth Ratio on the Adjusted Maximum Subsidence Factor (High Extraction, Room and Pillar Case Studies).

may be taken as 85 percent, this upper limit was assumed even for case studies claiming a higher extraction ratio. The plotted line is an envelope line covering all data points, similar to the longwall analysis, which can be used for prediction purposes, again with some safety margin. The line also suggests asymptotic conditions towards an $\frac{S_{max}}{m}$ value of about 0.65, as W/h approaches 1.0 to 1.2, i.e. the critical panel dimensions.

A statistical relationship between the subsidence factor and the geologic conditions was not as evident here as in the longwall cases, due to the more complex configuration. However, for prediction purposes, the relationship of Figure 5.2 may be assumed to be applicable. Figure 5.5 has been derived from Figures 5.2 and 5.4 for the purpose of determining the maximum subsidence factor from the width-to-depth ratio and the percent of hardrock in the overburden for high extraction room and pillar cases (see also Table 5.2). It has been tested successfully for several case studies.

5.1.2. Analysis of Angle of Draw

Figure 5.6 represents the relationship of the angle of draw with W/h for the longwall case studies. As expected, steady-state conditions of about 30 degrees were reached in the critical-supercritical range.

The same relationship for the room and pillar case studies is presented in Figure 5.7. Steady-state conditions of 28 to 30 degrees were reached in the critical-supercritical range.

Although the data were extensively tested, a correlation between angle of draw and geological factors could not be established for the longwall nor the room and pillar case studies.

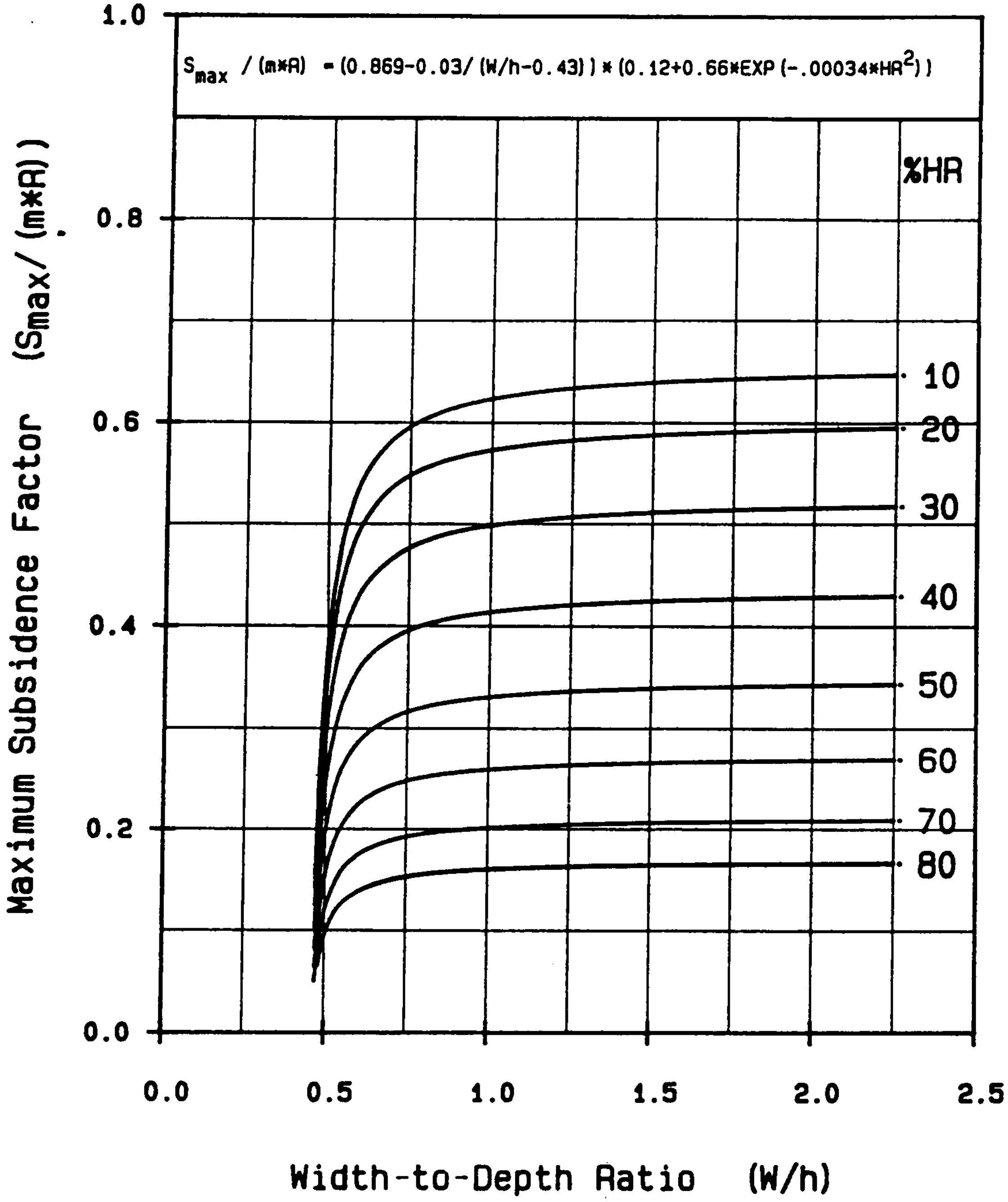

Figure 5.5. Prediction of the Adjusted Maximum Subsidence Factor (High Extraction, Room and Pillar Case Studies).

Table 5.1. Calculation of Maximum Subsidence Factor, ($\frac{S_{max}}{m}$), for Longwall panels

Percent Hardrock in the Overburden								
W/h	10%	20%	30%	40%	50%	60%	70%	80%
0.4	0.66	0.61	0.53	0.44	0.35	0.28	0.21	0.17
0.5	0.70	0.64	0.56	0.46	0.37	0.29	0.23	0.18
0.6	0.72	0.66	0.57	0.47	0.38	0.30	0.23	0.18
0.7	0.73	0.67	0.58	0.48	0.39	0.30	0.23	0.19
0.8	0.73	0.67	0.59	0.49	0.39	0.30	0.24	0.19
0.9	0.74	0.68	0.59	0.49	0.39	0.31	0.24	0.19
1.0	0.74	0.68	0.59	0.49	0.39	0.31	0.24	0.19
1.1	0.75	0.68	0.60	0.49	0.40	0.31	0.24	0.19
1.2	0.75	0.69	0.60	0.50	0.40	0.31	0.24	0.19
1.3	0.75	0.69	0.60	0.50	0.40	0.31	0.24	0.19
1.4	0.75	0.69	0.60	0.50	0.40	0.31	0.24	0.19
1.5	0.75	0.69	0.60	0.50	0.40	0.31	0.24	0.19
1.6	0.75	0.69	0.60	0.50	0.40	0.31	0.24	0.19
1.7	0.76	0.69	0.60	0.50	0.40	0.31	0.24	0.19
1.8	0.76	0.69	0.60	0.50	0.40	0.31	0.24	0.19
1.9	0.76	0.70	0.61	0.50	0.40	0.31	0.24	0.19
2.0	0.76	0.70	0.61	0.50	0.40	0.31	0.24	0.19

Table 5.2. Calculation of Adjusted Maximum Subsidence Factor, ($\frac{S_{max}}{m R}$), for High Extraction Room and Pillar Panels

Percent Hardrock in the Overburden								
W/h	10%	20%	30%	40%	50%	60%	70%	80%
0.4	0.57	0.52	0.45	0.38	0.30	0.24	0.18	0.15
0.5	0.60	0.55	0.48	0.40	0.32	0.25	0.19	0.15
0.6	0.61	0.56	0.49	0.41	0.32	0.25	0.20	0.16
0.7	0.62	0.57	0.50	0.41	0.33	0.26	0.20	0.16
0.8	0.63	0.58	0.50	0.42	0.33	0.26	0.20	0.16
0.9	0.63	0.58	0.50	0.42	0.34	0.26	0.20	0.16
1.0	0.63	0.58	0.51	0.42	0.34	0.26	0.21	0.16
1.1	0.64	0.59	0.51	0.42	0.34	0.26	0.21	0.16
1.2	0.64	0.59	0.51	0.42	0.34	0.27	0.21	0.16
1.3	0.64	0.59	0.51	0.43	0.34	0.27	0.21	0.16
1.4	0.64	0.59	0.51	0.43	0.34	0.27	0.21	0.17
1.5	0.64	0.59	0.52	0.43	0.34	0.27	0.21	0.17
1.6	0.65	0.59	0.52	0.43	0.34	0.27	0.21	0.17
1.7	0.65	0.59	0.52	0.43	0.34	0.27	0.21	0.17
1.8	0.65	0.59	0.52	0.43	0.34	0.27	0.21	0.17
1.9	0.65	0.59	0.52	0.43	0.34	0.27	0.21	0.17
2.0	0.65	0.60	0.52	0.43	0.34	0.27	0.21	0.17

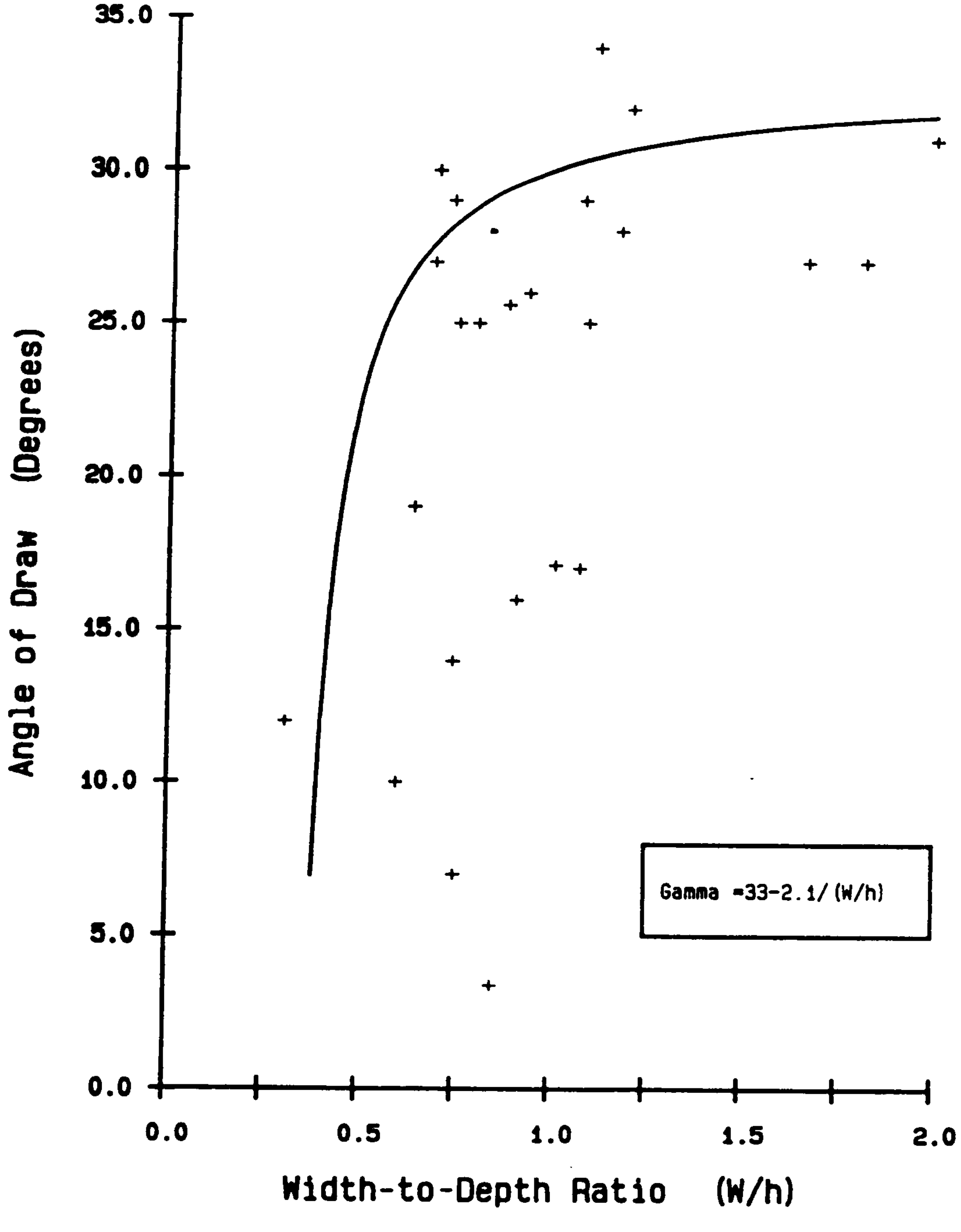

Figure 5.6. Effect of Width-to-Depth Ratio on the Angle of Draw (Longwall Case Studies).

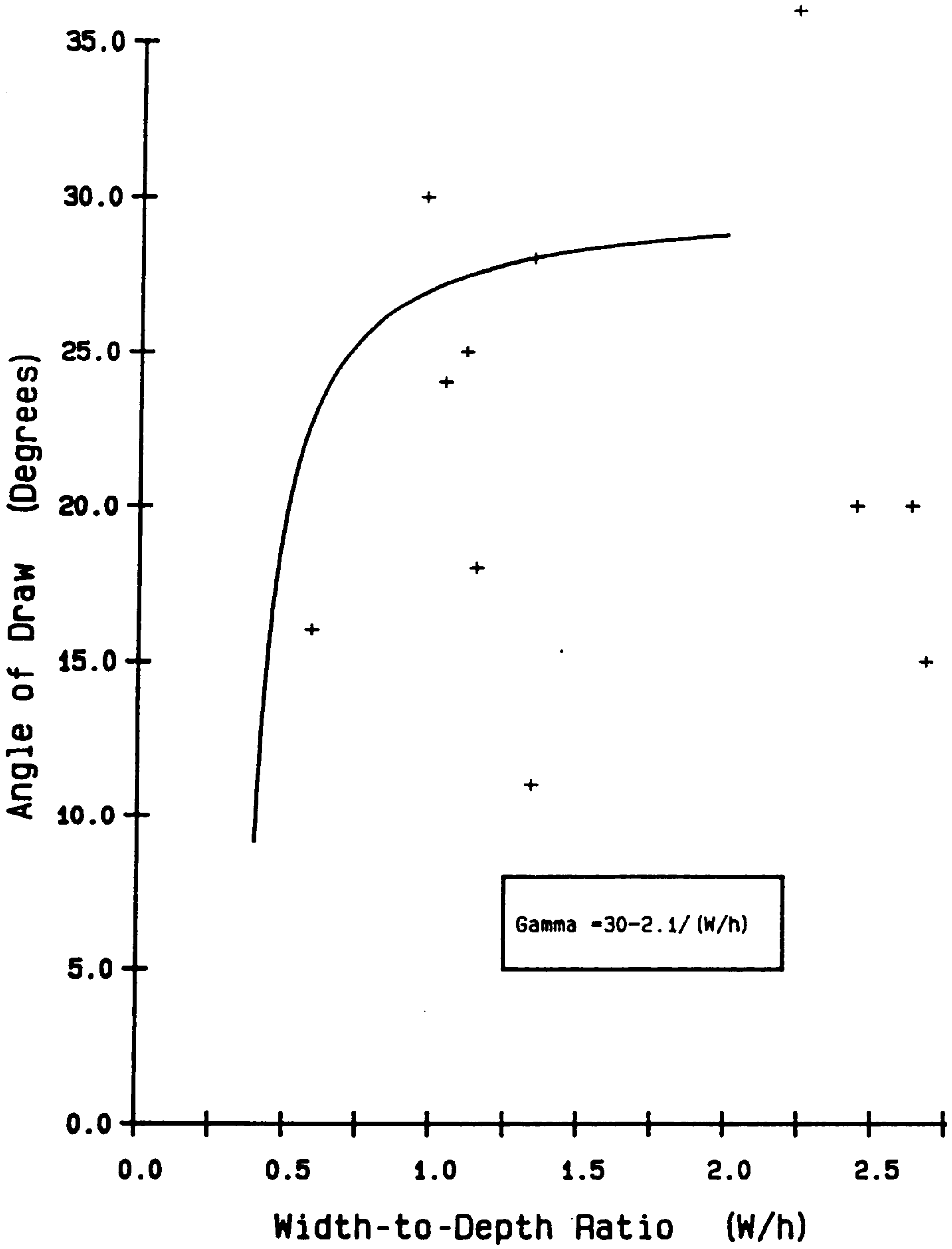

Figure 5.7. Effect of Width-to-Depth Ratio on the Angle of Draw (High Extraction, Room and Pillar Case Studies).

5.1.3. Location of Inflection Point

The inflection point defines the transition between horizontal tensile and compressive strain zones. Its location is of paramount importance for the application of the influence and the profile function methods.

Figure 5.8 shows the statistical relationship of the inflection point location with respect to W/h for the longwall case studies. As expected, this point moved from the rib (negative vertical axis) towards the center of the panel for increasing W/h. A similar relationship for the room and pillar data is shown in Figure 5.9, displaying trends comparable to the longwall data.

The similarity in the relationships between the location of the inflection point and the width-to-depth ratio for longwall and room and pillar case studies suggests that all data points could be considered collectively as shown in Figure 5.10. A high statistical correlation was indicated by the field data. An envelope line, as shown in Figure 5.11, was however preferred for prediction purposes, despite its potential for underpredicting the distance of the inflection point to the rib, thus resulting in a higher value of ribside subsidence and a wider area of influence. This nomogram is recommended when using the influence and profile function methods. The distance from the inflection point to the rib, however, can be accepted as being directly proportional to the depth, for supercritical conditions, only within the limits of the database used in this analysis, i.e. for depths ranging from about 300 to 1000 feet. A maximum value of d = 230 feet is, therefore, recommended.

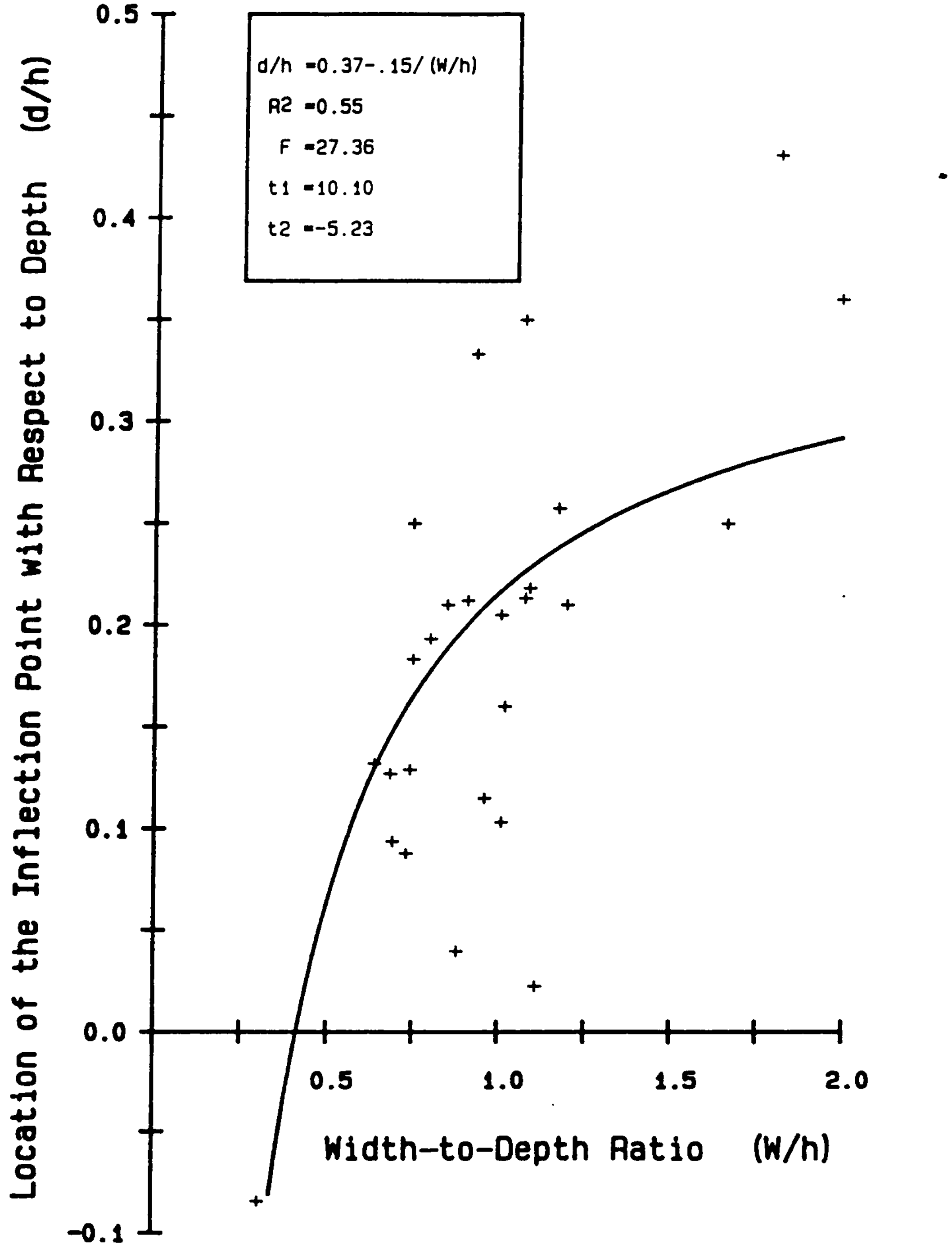

Figure 5.8. Effect of Width-to-Depth Ratio on the Location of the Inflection Point (Longwall Case Studies).

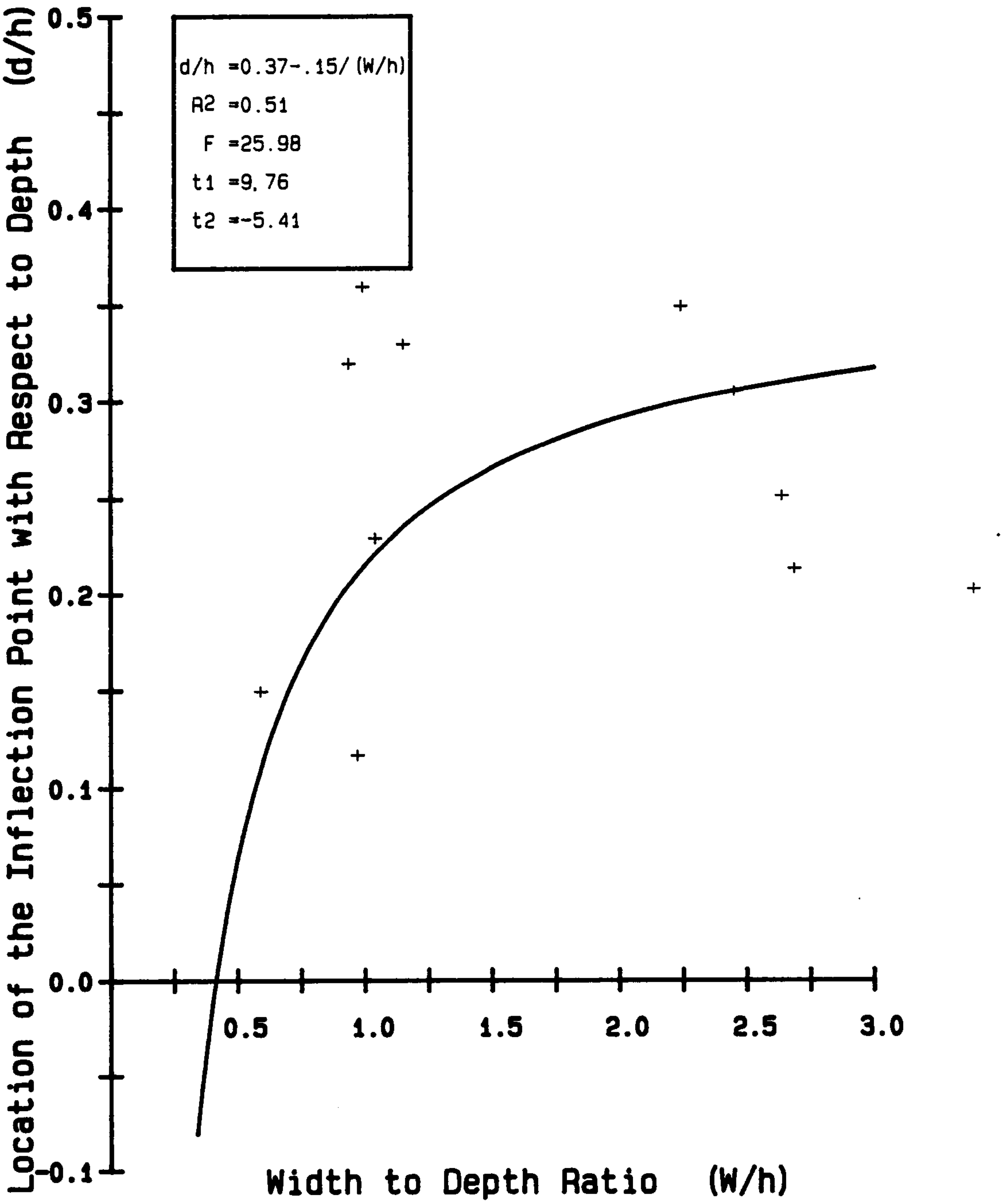

Figure 5.9. Effect of the Width-to-Depth Ratio on the Location of the Inflection Point (High Extraction, Room and Pillar Case Studies).

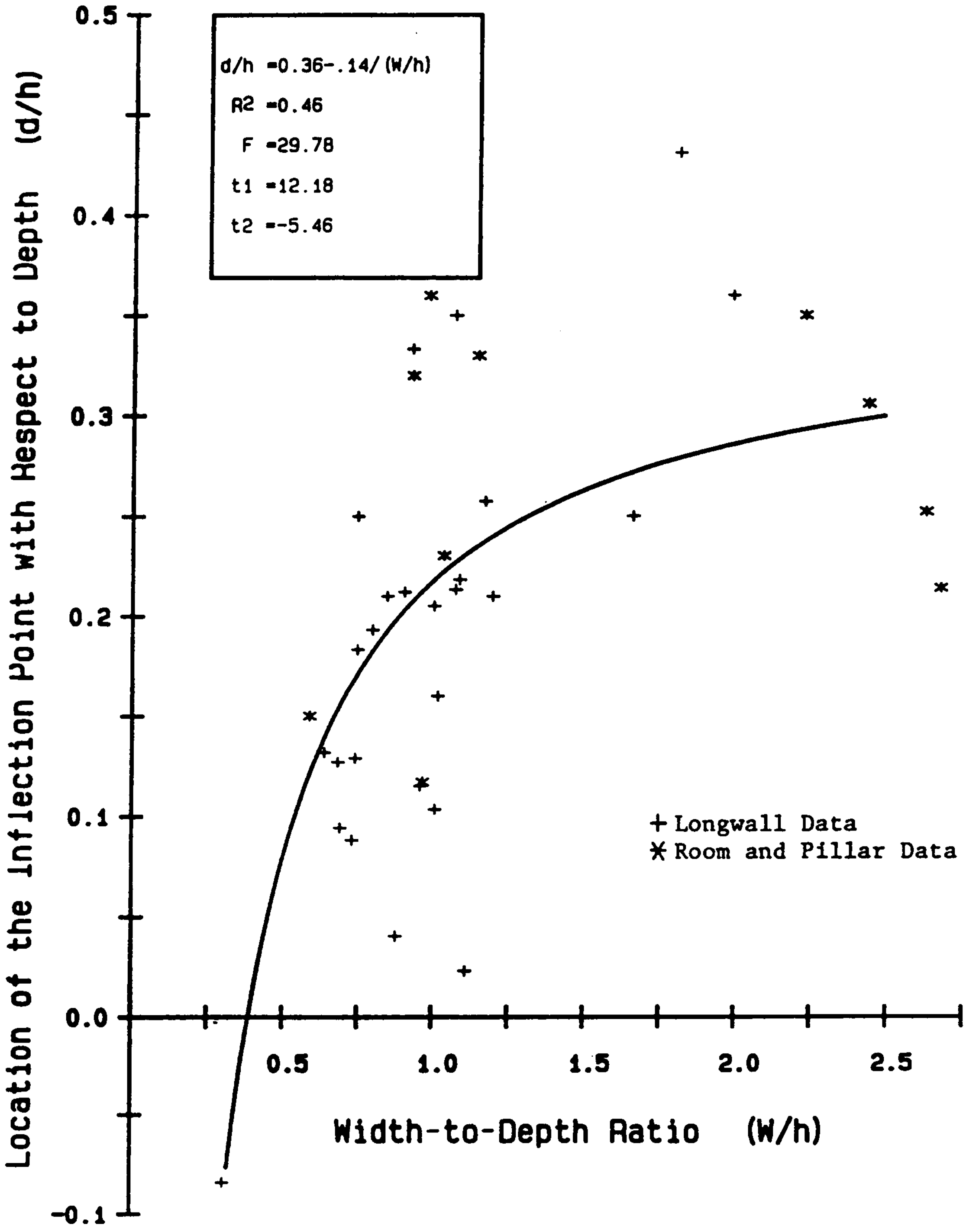

Figure 5.10. Effect of the Width-to-Depth Ratio on the Location of the Inflection Point for all Case Studies.

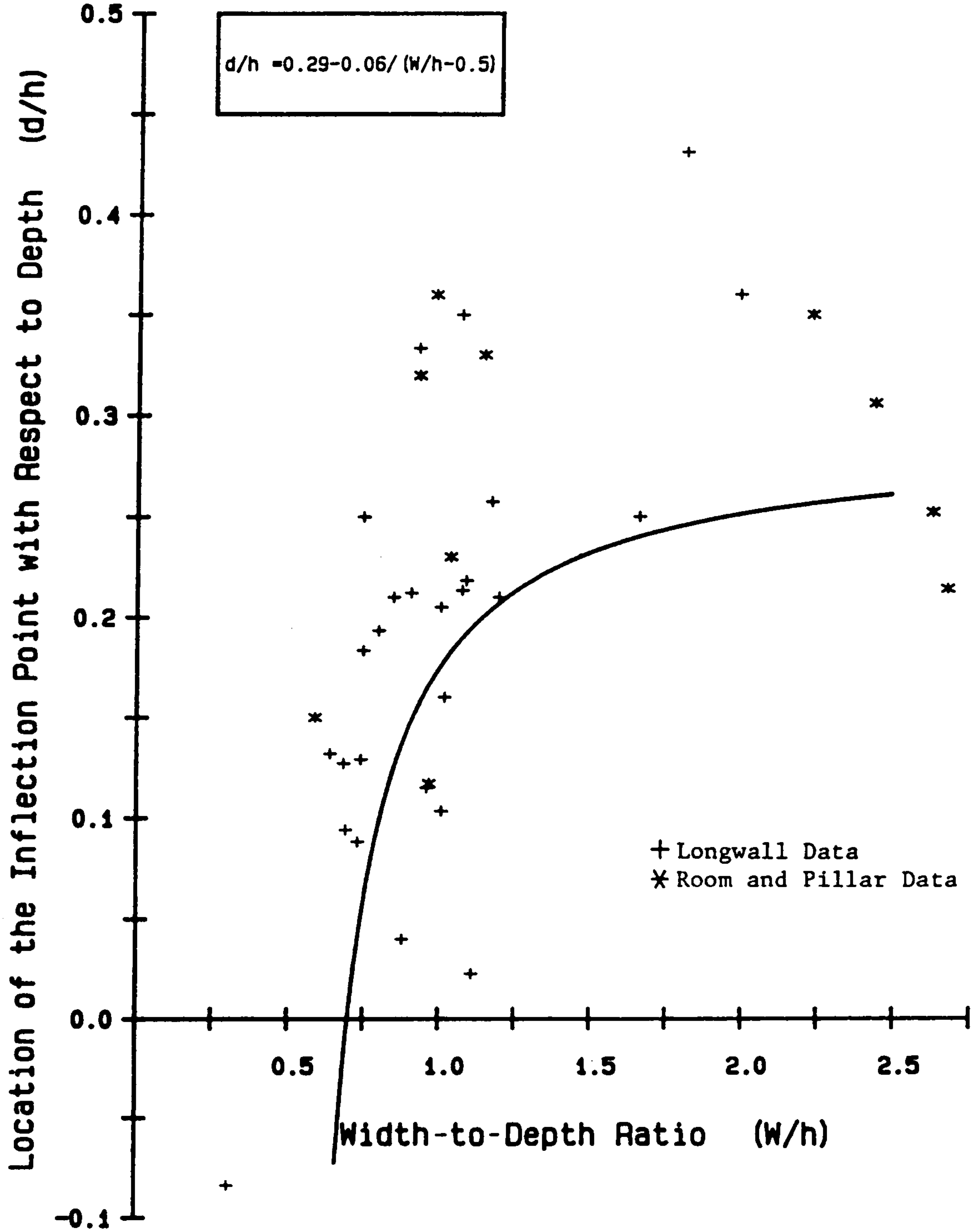

Figure 5.11. Location of the Inflection Point Using an Envelope Line for all Case Studies.

5.1.4. Analysis of Ribside Subsidence

Ribside subsidence, in terms of maximum subsidence, is important for the application of the zone area method.

Figure 5.12 presents its relationship to W/h ratio for the longwall data. By combining data from longwall and high extraction room and pillar case studies, a statistical relationship was established. This relationship, presented in Figure 5.13, has been used for the zone area analysis. A minimum value of $\frac{S_r}{S_{max}} = 0.12$ is recommended when calculating the zone factors and the exponent n for supercritical cases (Figure 5.14).

5.1.5. Analysis of the Principal Influence Angle.

The angle of principal influence (β or, usually, $\tan\beta$) is one of the basic parameters used in the influence function method. The value of this parameter has a great significance on the distribution of the deformations on the surface, as well as on the predicted values of the deformation indices, such as subsidence, slope and strain.

This parameter may be related to the geological characteristics of the overburden; however, a statistical relationship could not be established in this analysis for prediction purposes. An average value was, therefore, calculated from the case studies collected by Virginia Tech as well as from other data pertaining to the Appalachian coalfield as follows:

$$\tan\beta = 2.31 \pm 0.40$$

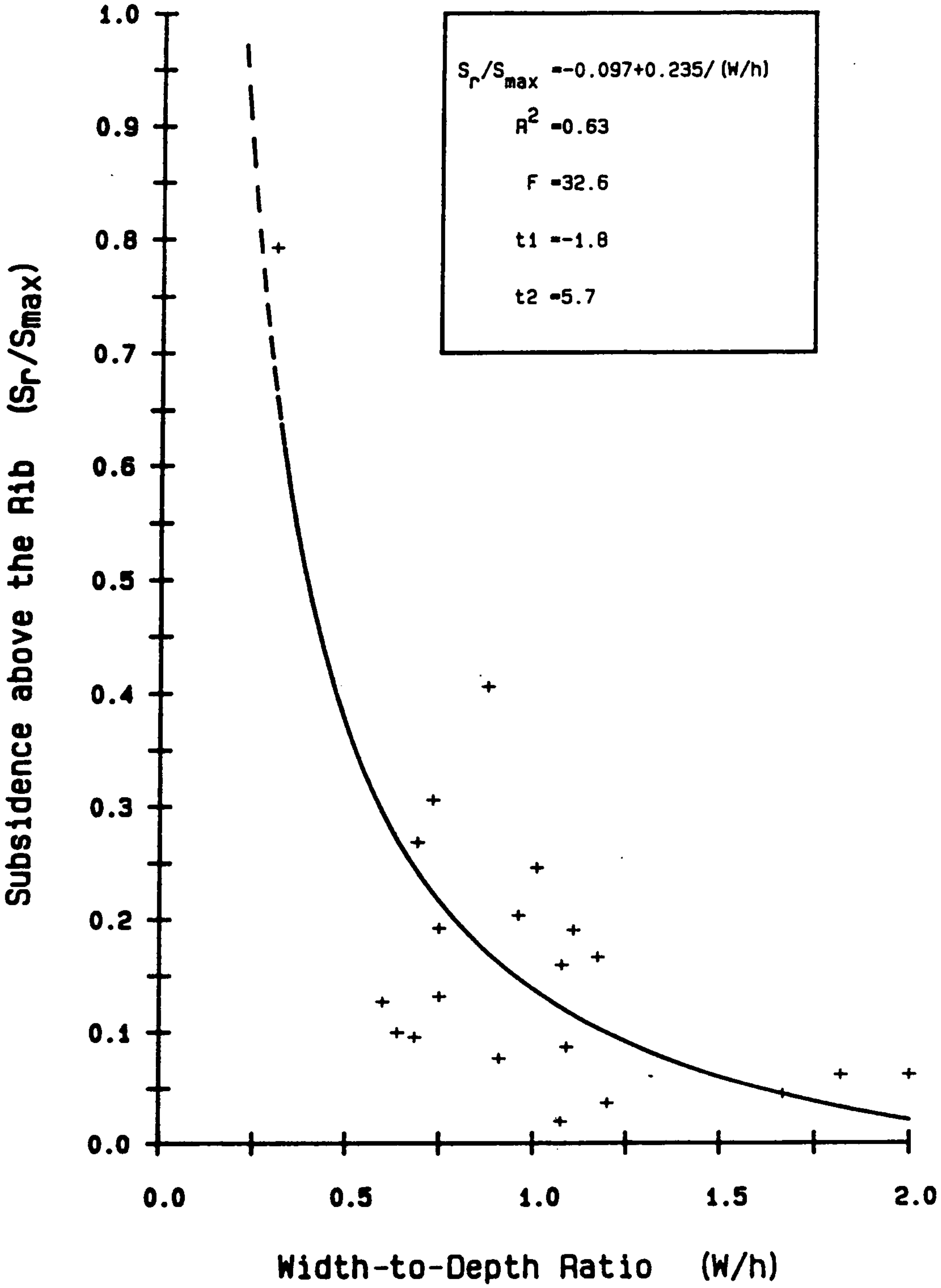

Figure 5.12. Effect of Width-to-Depth Ratio on Ribside Subsidence (Longwall Case Studies).

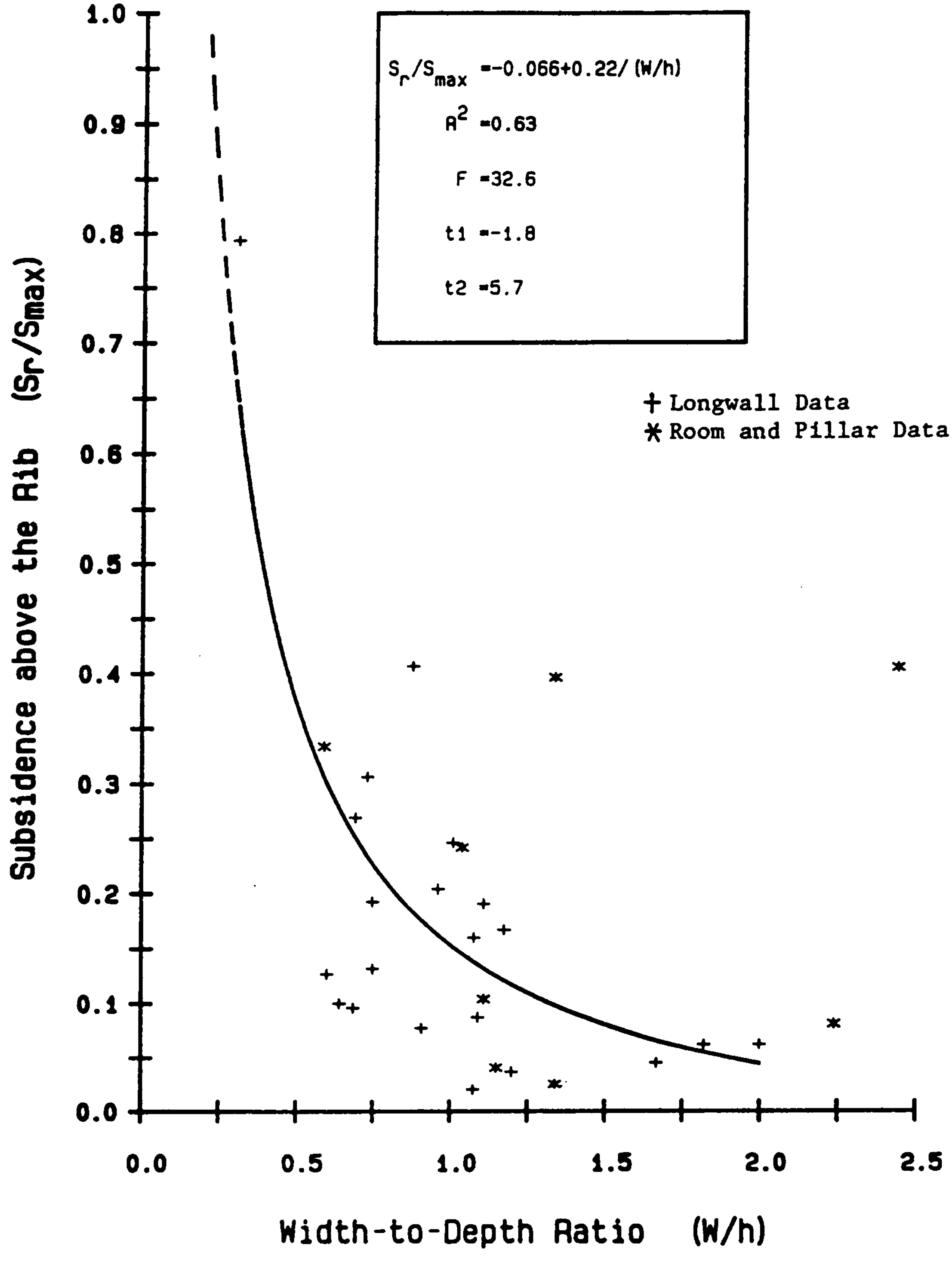

Figure 5.13. Effect of Width-to-Depth Ratio on Ribside Subsidence for all Case Studies.

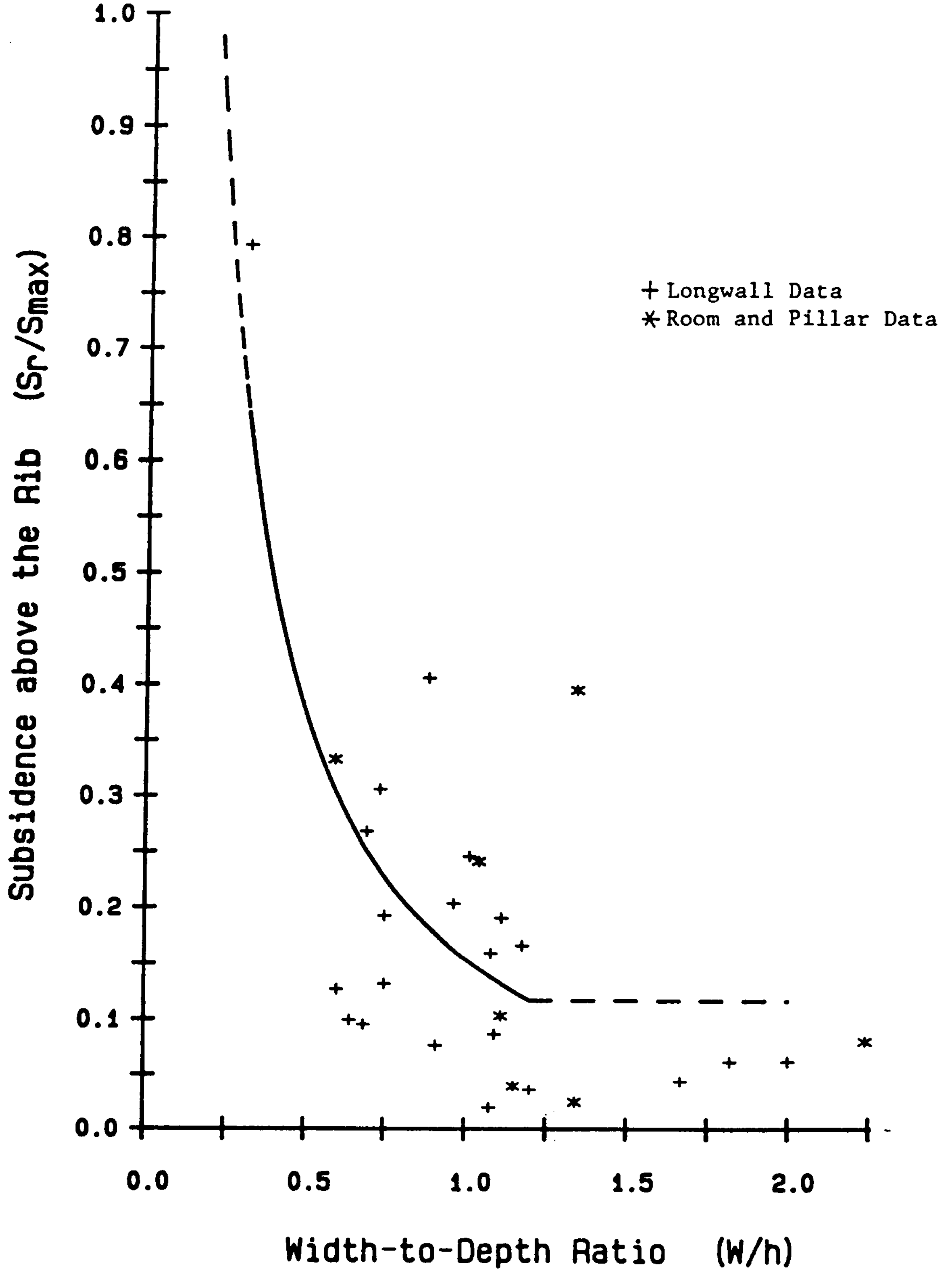

Figure 5.14. Prediction of Ribside Subsidence Using the Minimum Value Constraint.

5.1.6. Analysis of the Horizontal Strain Factor (B)

Factor B was used to calculate horizontal strain as a function of curvature. In the original stages of this research a direct relationship between strain and curvature was sought which could describe B independently of any other mining parameters (Karmis et al., 1983). As more case studies became available through this research effort, it became apparent that such a relationship would be difficult to establish (Figure 5.15). As a result, a different approach was adopted, based on the work of Awershin (1947), Budryk (1953) and Akimov and Zemicev (1970), which has suggested that the magnitude of the horizontal strain factor (B) is a function of the excavation depth or the radius of principal influence (r).

For each of the monitored case studies, as well as for two literature case studies where horizontal measurements were available, factor B was determined by comparing the measured strain and the fitted curvature profiles.

Using the established values of parameter B and the corresponding values of tan β, r and h, a statistical relationship was found (Figure 5.16) expressed by the equation:

$$B = (0.35 \pm 0.05)\, r$$

or

$$B = (0.35 \pm 0.05) \frac{h}{\tan \beta}$$

where,

r = radius of the principal influence;

h = depth of the excavation; and

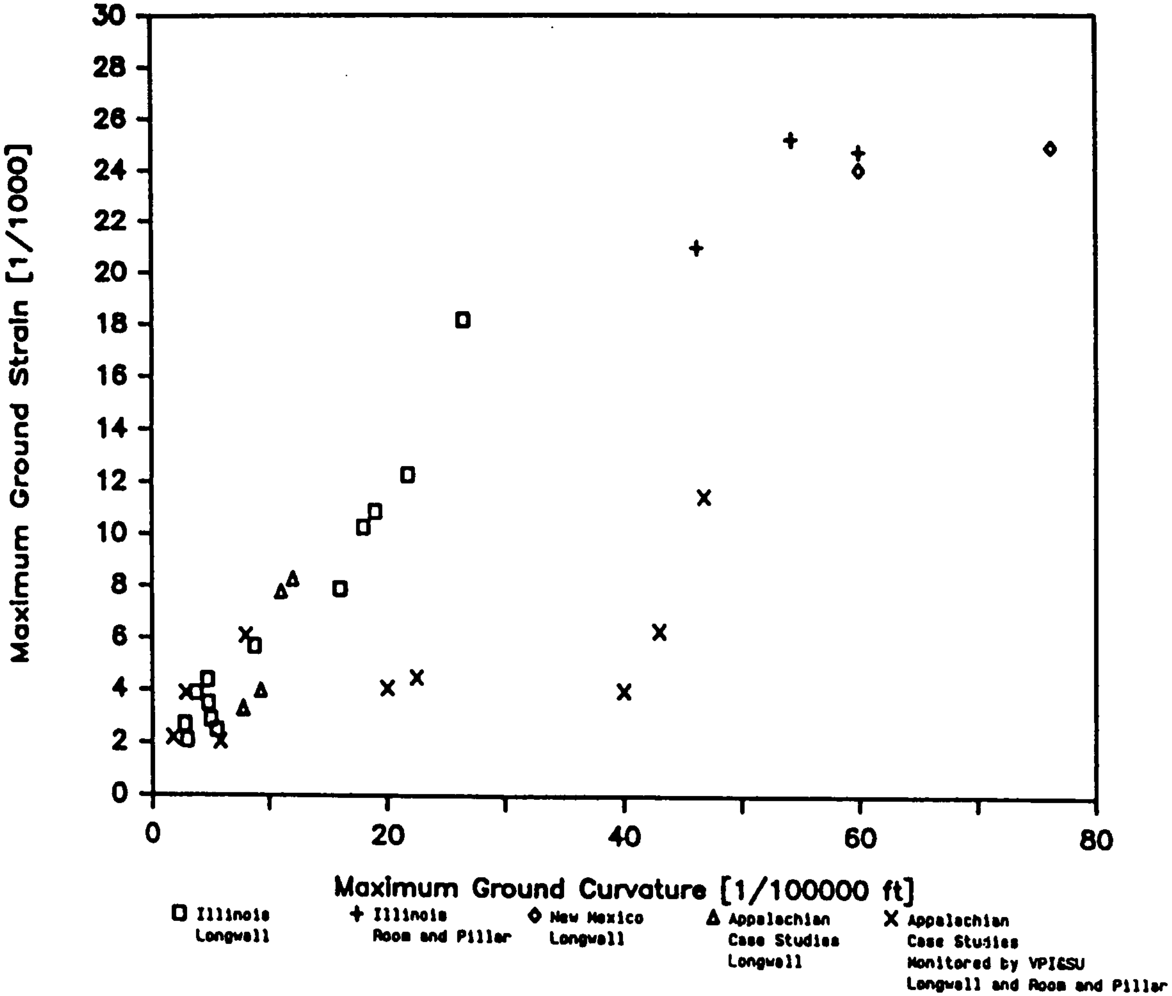

Figure 5.15. Maximum Ground Strain and Curvature Data (modified after Karmis et al., 1983).

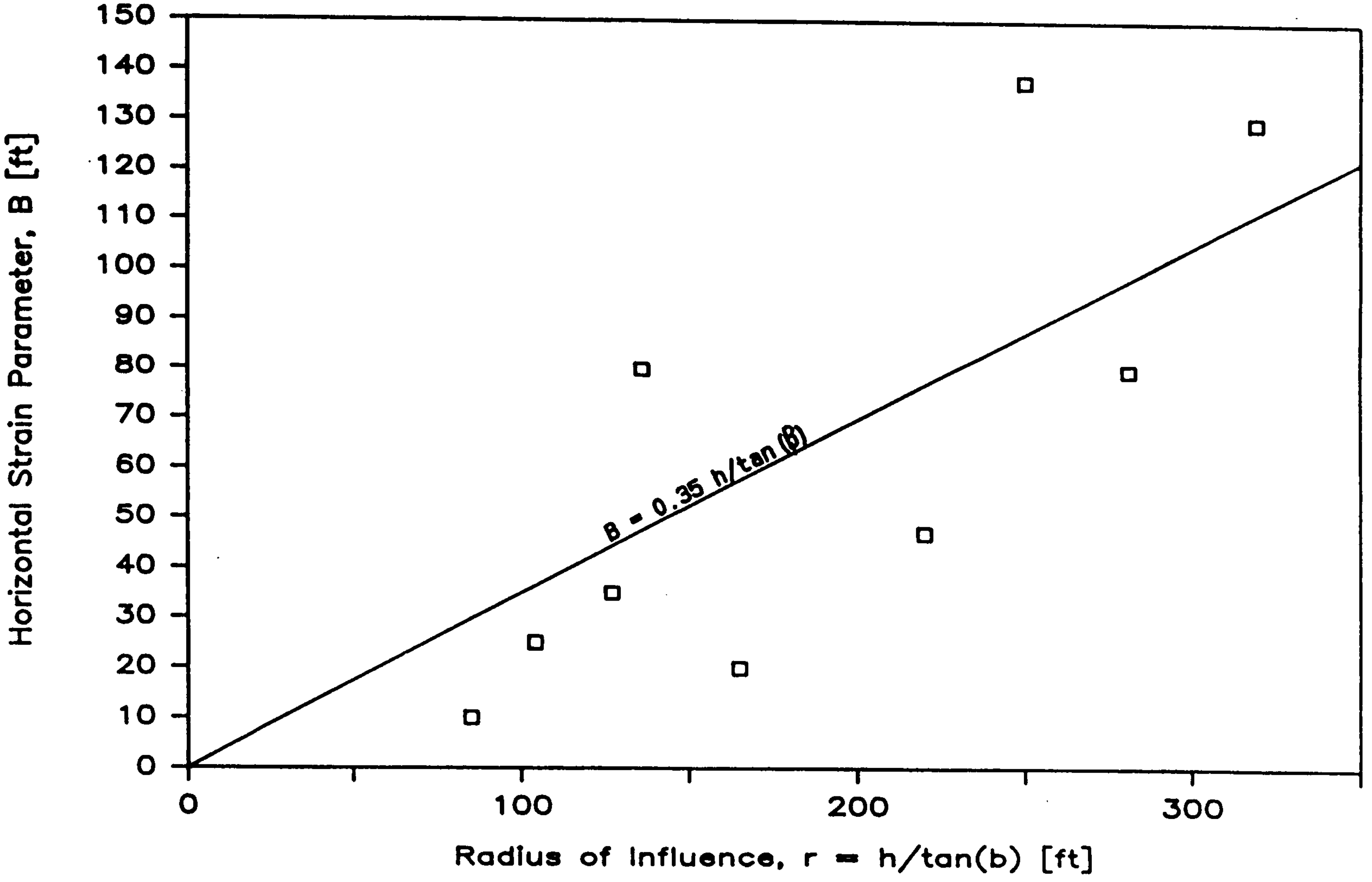

Figure 5.16. Effect of Radius of Influence on the Horizontal Strain Parameter.

β = angle of the principal influence.

The second equation is more convenient for prediction purposes.

5.2. Basic Relationships for Low Extraction Room and Pillar Mines

The term "low extraction room and pillar mining" encompasses extraction of panels where the remnant coal provides sufficient support for the overlying strata, i.e. where stable pillars are left in place. The analysis for the calculation of S_{max} was different in this case from the high extraction data since pillar size and stability must also be considered.

After extensive data analysis and careful consideration of various prediction models, it was determined that a model similar to that originally proposed by Wardell (1969) and adopted by Abel and Lee (1980) was most representative. Analysis of this model by Hasenfus (1984) suggested a relationship between maximum subsidence for critical and supercritical extractions and a parameter $\frac{h}{1-R}\frac{m}{W_p}$, where h, R, m, and W_p represented panel depth, extraction ratio, mine height, and pillar width, respectively (Figure 5.17). This parameter has been subsequently termed the stress-strength factor, due to its relationship to the tributary average stress formulation ($\frac{\gamma h}{1-R}$), and the empirical strength expression related to the pillar shape factor ($\frac{W_p}{m}$), i.e. inverse function of pillar strength.

The above function may be used for the prediction of S_{max}. The remaining subsidence parameters must be determined from the same relationships that were developed for high extraction conditions.

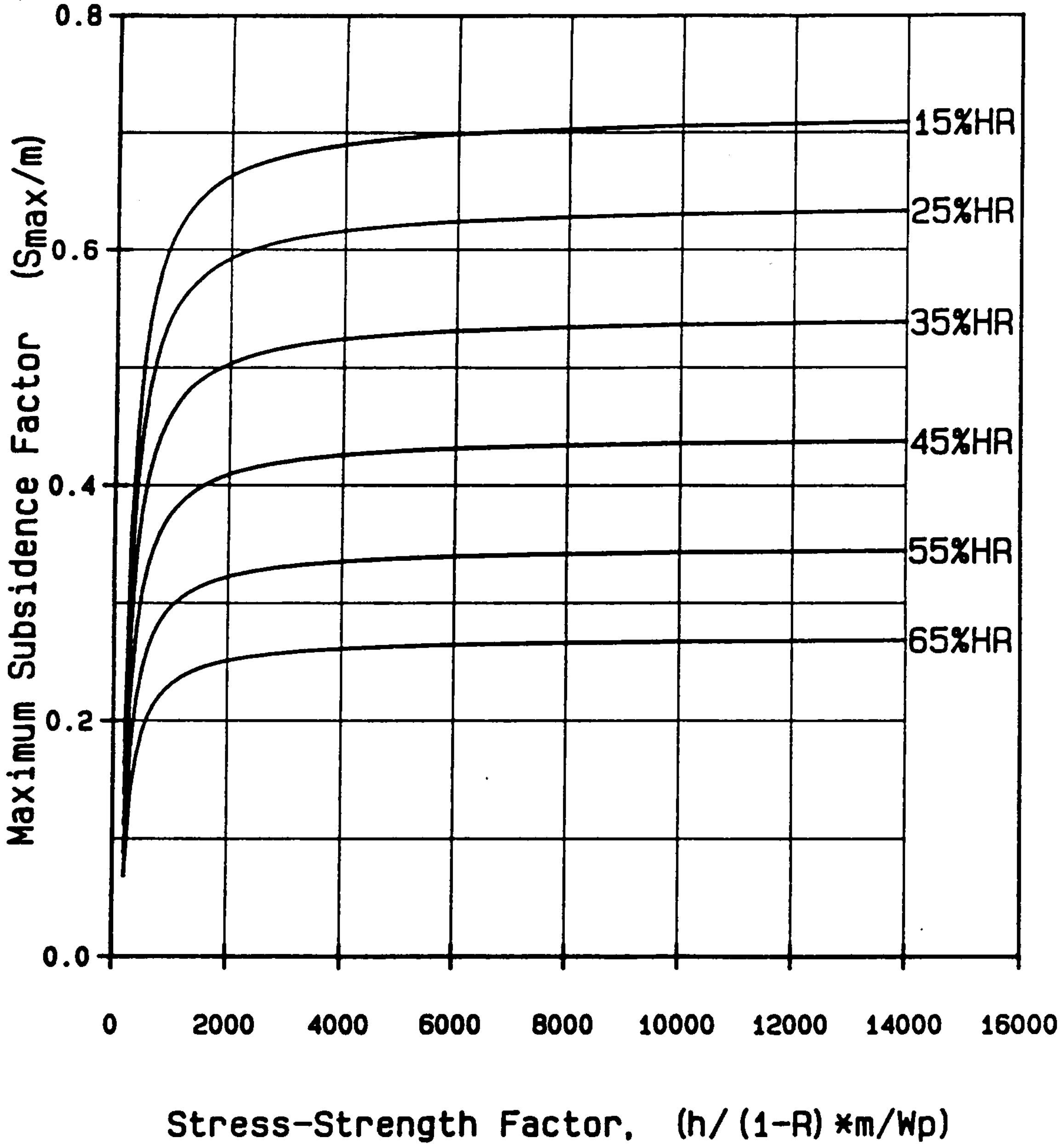

Figure 5.17. Prediction of Maximum Subsidence Factor for Low Extraction Room and Pillar Case Studies Using the Stress-Strength Factor Principle (modified from Hasenfus, 1984).

CHAPTER 6

APPLICATION OF PREDICTION TECHNIQUES

A number of parameters discussed in the previous chapter were incorporated in the empirical prediction methods, so that the latter could be applicable to the mining and geological conditions of the eastern United States coalfields. Based on these regional prediction techniques, a number of computer software packages were developed.

6.1. Application of the Profile Function Method

Profile function methods are simple to use and are easily adaptable to regional subsidence characteristics, as discussed in Chapter 2. During this research program, a model recommended by Kohli et al. (1980), Webb (1982) and Virginia Polytechnic Institute and State University (1983) was compared to the collected data bank and was adjusted for eastern coal regions.

The function recommended for use in the U.S. coalfields is given as follows:

$$S(x) = 0.5S_{max}\left\{1 - \tanh\left[\frac{cx}{B}\right]\right\}$$

where,

$S(x)$ = subsidence at x;

x = distance from the inflection point;

S_{max} = maximum subsidence of the profile;

B = distance from the inflection point to point of S_{max}; and

c = constant.

Based on the initial data bank, which did not include the case studies monitored by Virginia Tech, a regional model was developed (Karmis et al., 1981, 1984a, 1984b). This model was tested during the monitoring program and has been successfully used by the industry.

A number of problems, however, were encountered. Due to the limitations of the available data, a linear relationship was used for correlating S_{max} to the overburden geology, thus considerably underpredicting the value of S_{max} for a high percentage of hardrock in the overburden. Furthermore, the predicted profile did not always fit the actual measured profile, usually due to overprediction of the area of influence. It should be mentioned that the latter cannot be avoided, since the dispersion of field data leads to the implementation of the safety factor, as discussed in sections 5.1.3 and 5.1.4.

This prediction model was applied to the monitored case studies for comparison. It was furthermore adjusted, by manipulating the parameters, in order to obtain the curve which best fit the measured profile.

A comprehensive statistical analysis of all available data, including the monitored case studies and new case studies collected from various sources, led to the modification of the predictive relationships, as presented in section 5.1.

Given the mining parameters, the values of S_{max} can be determined from Figure 5.3 or Figures 5.5 and 5.17 and, similarly, d from Figure 5.11. The value of S_{max} can also be obtained from Table 5.1 or Table 5.2.

Parameters c and B define the shape of the profile. Constant c was determined to be equal to 1.4 for subcritical or 1.8 for critical and supercritical cases. Parameter B is defined as the distance from the inflection point to point of S_{max}. For critical and subcritical cases, S_{max} is observed at the center of the profile, therefore:

$$B = 0.5W - d$$

For supercritical panels, since the transition from critical to subcritical panel geometry was observed at W/h = 1.2, the distance from the rib to the point of maximum subsidence was assumed to be equal to 0.6 times the depth of the overburden (h), and:

$$B = 0.6h - d$$

After the subsidence parameters have been determined, it is then possible to calculate the subsidence profile above a mine panel. However, the profile function which is used (i.e. hyperbolic tangent) does not reach its maximum value at the panel center, especially in the case of subcritical or critical panels. An adjustment can be made by using a corrected value (S'_{max}) for the calculations:

$$S'_{max} = \frac{S_{max}}{S_{center}} S_{max}$$

It should be emphasized that this method is capable of calculating profiles for two dimensional situations, i.e. the panel dimension orthogonal to the profile should theoretically be infinite. In practice, the boundaries of the panel parallel to the profile should be at a horizontal distance of more than 0.7 times the depth from the profile under consideration, thus eliminating any impact on the maximum calculated values.

Table 6.1 presents the distribution of subsidence for different W/h ratios in terms of S_{max}. The latter can be easily calculated from Table 5.1.

6.2. Application of the Budryk-Knothe Influence Function Method

Influence function methods for subsidence prediction have been the most common approach in the coalfields of central and eastern Europe. The influence function method was chosen as one of the techniques to be tested under this project because of its ability to consider any mining geometry, to negotiate superposition of the influence from a number excavated areas having different mining characteristics, and also to calculate strains as well as other related deformation indices. After reviewing the functions available in the literature, it was decided to utilize the bell-shaped Gaussian function, often also referred to as "Knothe's method of prediction" (Knothe, 1957). This method assumes that the influence function g(x,s), for the cross-sectional case, is given by:

$$g(x,s) = \frac{S_o(x)}{r} \exp\left[- \pi \frac{(x - s)^2}{r^2} \right]$$

where,

- r = radius of principal influence = $\frac{h}{\tan \beta}$;
- h = mining depth;
- β = angle of principal influence as defined in Figure 6.1;
- s = location of the point, P(s), where subsidence is considered;

Table 6.1. Subsidence Distribution Using the Profile Function Method

Subsidence in Terms of S_{max}

s/S_{max}	0.00	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90	1.00
W/h	Distance from the Panel Center (in terms of depth)										
0.7	0.55	0.54	0.44	0.38	0.34	0.29	0.25	0.21	0.16	0.10	0.00
0.8	0.61	0.55	0.46	0.40	0.36	0.32	0.27	0.23	0.18	0.12	0.00
0.9	0.61	0.55	0.46	0.41	0.36	0.32	0.28	0.23	0.18	0.12	0.00
1.0	0.65	0.59	0.50	0.43	0.38	0.34	0.30	0.25	0.20	0.13	0.00
1.1	0.71	0.62	0.53	0.47	0.41	0.37	0.32	0.27	0.22	0.14	0.00
1.2	0.79	0.65	0.56	0.50	0.45	0.40	0.36	0.31	0.25	0.17	0.00
1.3	0.88	0.68	0.59	0.53	0.49	0.44	0.40	0.35	0.30	0.22	0.00
1.4	0.98	0.73	0.64	0.58	0.54	0.49	0.45	0.40	0.35	0.26	0.00
1.5	1.08	0.78	0.69	0.63	0.59	0.54	0.50	0.45	0.39	0.31	0.00
1.6	1.18	0.83	0.74	0.68	0.63	0.59	0.55	0.50	0.44	0.36	0.00
1.7	1.28	0.88	0.79	0.73	0.68	0.64	0.60	0.55	0.49	0.40	0.00
1.8	1.38	0.93	0.84	0.78	0.73	0.69	0.65	0.60	0.54	0.45	0.00
1.9	1.48	0.98	0.89	0.83	0.78	0.74	0.70	0.65	0.59	0.50	0.00
2.0	1.58	1.03	0.94	0.88	0.83	0.79	0.75	0.70	0.64	0.55	0.00

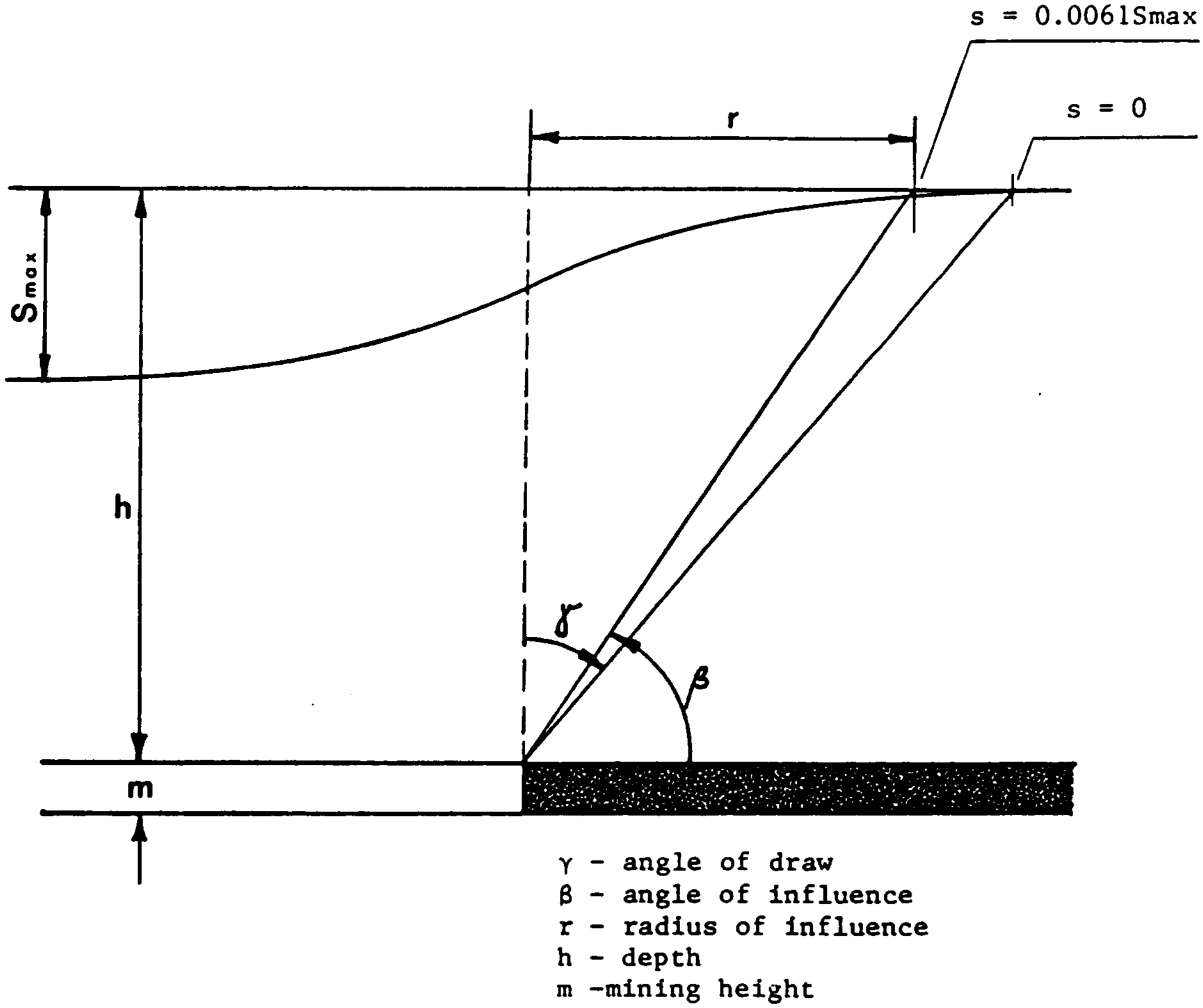

Figure 6.1. Definition of the Angle of Influence.

x = location of the infinitesimal element of excavation; and

$S_o(x)$ = convergence of the roof of the infinitesimal element of excavation.

Subsidence at any point P(s), therefore, can be expressed by the following integral (Figure 6.2):

$$S(x,s) = \frac{1}{r}\int_{-\infty}^{+\infty} S_o(x)\exp\left[-\pi\frac{(x-s)^2}{r^2}\right]dx$$

where,

$S_o(x)$ = m(x) a(x);

m(x) = height of excavation (void); and

a(x) = roof convergence (subsidence) factor.

If m(x) and a(x) are constants (they do not change along the x coordinate), and therefore:

$$S_o(x) = S_{max} = m\,a = \text{constant} \qquad \text{for } x_1 \le x \le x_2$$

where, x_1 and x_2 are the limits of the excavation and

$$S(x,s) = \frac{S_{max}}{r}\int_{x_1}^{x_2}\exp\left[-\pi\frac{(x-s)^2}{r^2}\right]dx$$

6.2.1. Calculation of Deformation Indices

Through the rotation of the Gauss function, g(x), around its axis of symmetry, a surface, g(x,y), is obtained, which represents the function of influence for the three dimensional case:

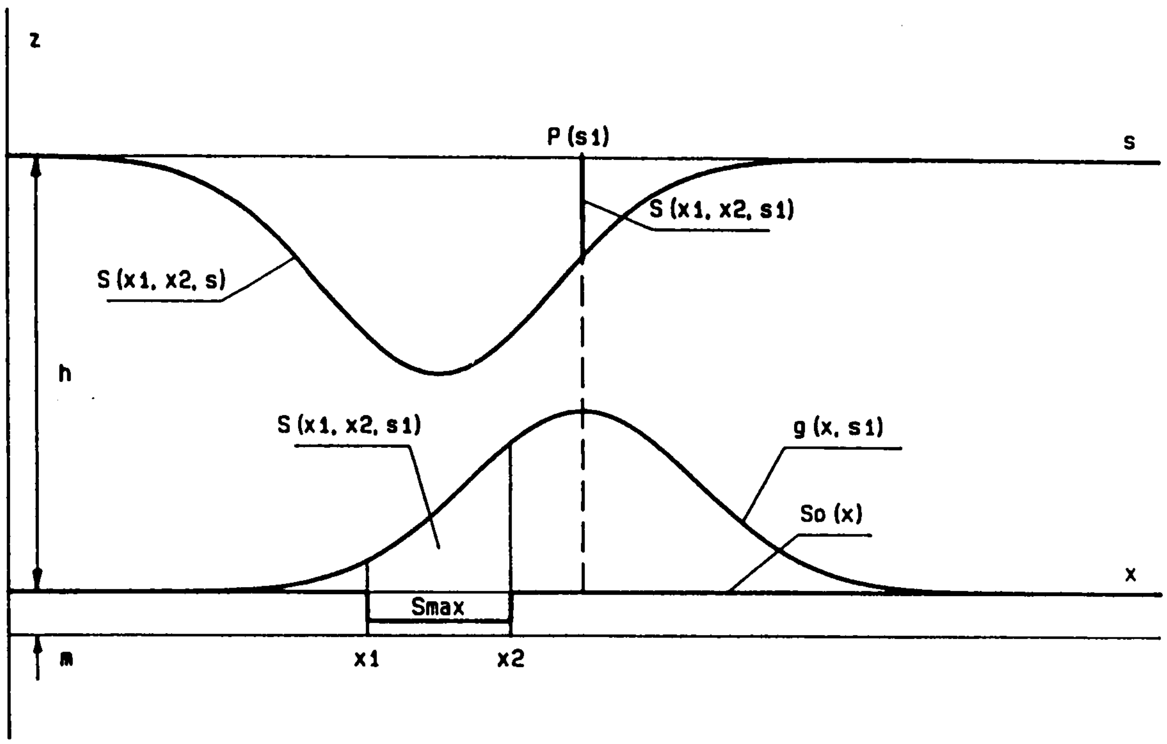

Figure 6.2. Relationship Between the Influence Function Distribution and the Surface Subsidence Profile.

$$g(x,y,s,t) = \frac{1}{r^2}\exp\left[-\pi\frac{(x-s)^2+(y-t)^2}{r^2}\right]$$

Consequently, subsidence at a point P(s,t) can be expressed as a definite integral:

$$S(x,y,s,t) = \frac{1}{r^2}\int\int_A S_o(x,y)\exp\left\{-\frac{\pi}{r^2}\left[(x-s)^2+(y-t)^2\right]\right\}dxdy$$

where,

A = area of excavation; and

$S_o(x,y)$ = function of roof convergence for the excavation area.

If the excavation area is of a rectangular shape (Figure 6.3), the origins of the surface and excavation coordinate systems are common, i.e. at prediction point P(0, 0), and the convergence of the roof is constant $S_o(x,y) = S_{max}$. The above equation can be written in the form:

$$S(x,y) = \frac{S_{max}}{r^2}\int_{x_1}^{x_2}\exp\left[-\pi\frac{x^2}{r^2}\right]dx\int_{y_1}^{y_2}\exp\left[-\pi\frac{y^2}{r^2}\right]dy$$

The other deformation indices can be calculated as follows.

Slope:

in the x-direction

$$T_x = \frac{\partial S(x,y)}{\partial x} = \frac{S_{max}}{r^2}\left[\exp\left(-\pi\frac{x_2^2}{r^2}\right)-\exp\left(-\pi\frac{x_1^2}{r^2}\right)\right]\int_{y_1}^{y_2}\exp\left[-\pi\frac{y^2}{r^2}\right]dy$$

in the y-direction

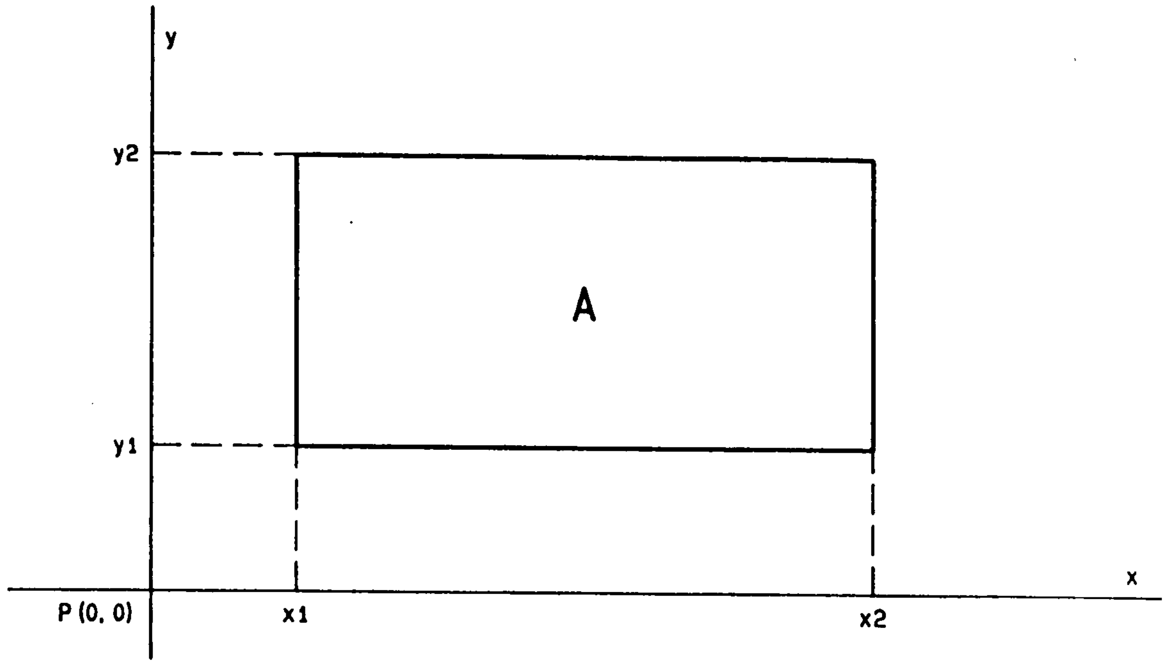

Figure 6.3. Coordinates of Boundaries for Rectangular Parcels.

$$T_y = \frac{\partial S(x,y)}{\partial y} = \frac{S_{max}}{r^2}\left[\exp\left(-\pi\frac{y_2^2}{r^2}\right) - \exp\left(-\pi\frac{y_1^2}{r^2}\right)\right]\int_{x_1}^{x_2}\exp\left[-\pi\frac{x^2}{r^2}\right]dx$$

directional slope

$$T_\psi = T_x \cos\psi + T_y \sin\psi$$

where, ψ = directional angle

principal (maximum) slope

$$T_m = \sqrt{T_x^2 + T_y^2} \quad \text{and} \quad \tan\psi_{T_m} = \frac{T_y}{T_x}$$

Curvature:

in the x-direction

$$K_x = \frac{\partial T_x}{\partial x} = -\frac{2\pi S_{max}}{r^4}\left[x_2\exp\left(-\pi\frac{x_2^2}{r^2}\right) - x_1\exp\left(-\pi\frac{x_1^2}{r^2}\right)\right]\int_{y_1}^{y_2}\exp\left[-\pi\frac{y^2}{r^2}\right]dy$$

in the y-direction

$$K_y = \frac{\partial T_y}{\partial y} = -\frac{2\pi S_{max}}{r^4}\left[y_2\exp\left(-\pi\frac{y_2^2}{r^2}\right) - y_1\exp\left(-\pi\frac{y_1^2}{r^2}\right)\right]\int_{x_1}^{x_2}\exp\left[-\pi\frac{x^2}{r^2}\right]dx$$

directional curvature

$$K_\psi = K_x\cos^2\psi + 2\Lambda_{xy}\sin\psi\cos\psi + K_y\sin^2\psi$$

where, ψ = directional angle; and

Λ_{xy}= second partial derivative of S(x,y) with respect to x and y.

$$\Lambda_{xy} = \frac{\partial^2 S(x,y)}{\partial x \partial y} = \frac{S_{max}}{r^2}\left[\exp\left(-\pi\frac{x_2^2}{r^2}\right) - \exp\left(-\pi\frac{x_1^2}{r^2}\right)\right]\left[\exp\left(-\pi\frac{y_2^2}{r^2}\right) - \exp\left(-\pi\frac{y_1^2}{r^2}\right)\right]$$

principal curvatures

$$K_{1,2} = \frac{1}{2}(K_x + K_y) \pm \sqrt{\frac{1}{4}(K_x - K_y)^2 + \Lambda_{xy}}$$

$$\tan \psi_{K1,2} = \frac{2\Lambda_{xy}}{K_x - K_y}$$

where, $\psi_{K1,2}$ = directional angles of the principal curvatures.

Horizontal Displacement:

in the x-direction

$$U_x = -BT_x$$

in the y-direction

$$U_y = -BT_y$$

directional displacement

$$U_\psi = -BT_\psi$$

and principal maximum displacement

$$U_m = \sqrt{U_x^2 + U_y^2} \quad \text{and} \quad \tan \psi_{Um} = \tan \psi_{Tm} = \frac{U_y}{U_x}$$

Horizontal Strain:

in the x-direction

$$E_x = - BK_x$$

in the y-direction

$$E_y = - BK_y$$

shear strain

$$E_{xy} = - B\Lambda_{xy}$$

directional strain

$$E_\psi = - BK_\psi = E_x \cos^2\psi + 2E_{xy} \sin\psi \cos\psi + E_y \sin^2\psi$$

principal strains

$$E_{1,2} = - BK_{1,2} = \frac{1}{2}(E_x + E_y) \pm \sqrt{\frac{1}{4}(E_x - E_y)^2 + E_{xy}}$$

$$\tan\psi_{E1,2} = \tan\psi_{K1,2} = \frac{2E_{xy}}{E_x - E_y}$$

where, $\psi_{E1,2}$ = directional angles of the principal curvatures.

In the case of irregular (polygonal) parcels of excavation, it is more convenient to use formulas which allow calculations of subsidence above excavations of circular shape through the use of polar coordinates.

6.2.2. Required Field Parameters and Their Determination

There are three basic parameters listed in the original version of the method:

- maximum subsidence on the surface for the critical or supercritical mining conditions (S_{max});
- mining depth (h); and
- angle of principal influence (β).

The use of Knothe's method for prediction of the horizontal strains at the surface, and an adjustment of the surface profile because of the "edge effect" (inflection points of the subsidence profiles are usually shifted into the center of extraction areas) require definition of two additional parameters:

- the "horizontal strain" parameter (B), which relates the horizontal strains to the curvatures of the subsidence profile; and
- the "edge effect" parameter (d), which describes the distance between the real rib of the excavation and the position of the inflection point of the profile for supercritical or critical conditions.

A graphical interpretation of the above described parameters is shown in Figure 6.4.

There are a several practical methods for establishing the values of the above listed parameters. The simplest approach is monitoring of surface movements on a line which is located near the edge of the excavation and is positioned perpendicular to the rib. In this case, the equations for the half-plane excavations can be used for determining these parameters.

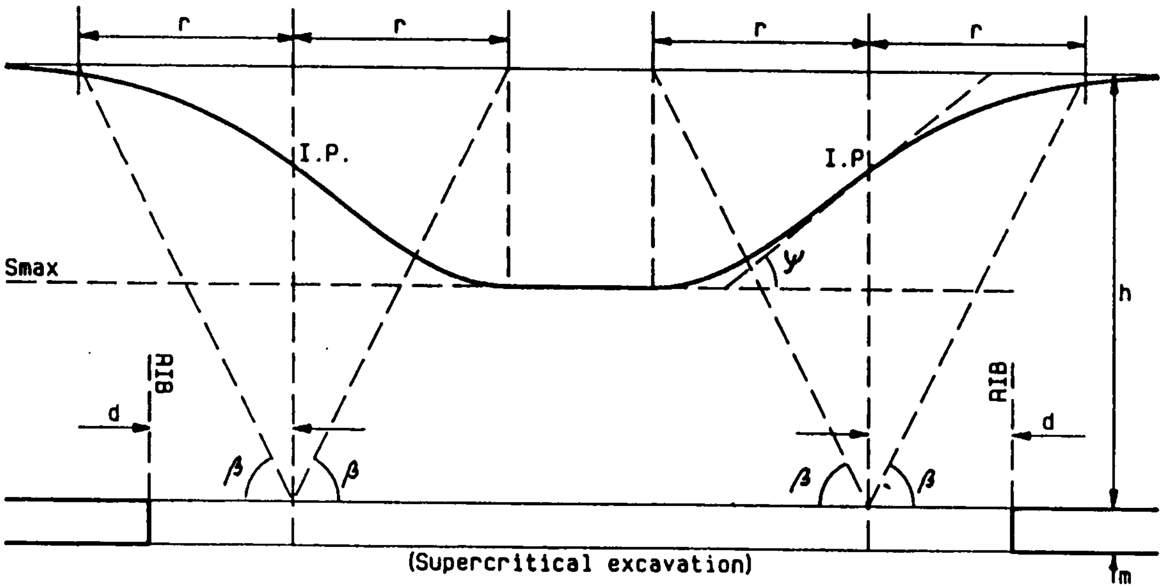

Figure 6.4. Graphical Interpretation of Subsidence Parameters (Knothe's Method).

The value of the maximum subsidence (S_{max}) can be derived directly from the flat part of the subsidence profile, which usually starts at a distance of 0.6 times the depth from the edge of the excavation towards the center of the panel.

The maximum subsidence can also be expressed as a product of the subsidence factor (a) and the height of excavation (thickness of seam) (m):

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

The angle of the principal influence (β), the radius of principal influence (r) and the depth of excavation (h) are related by the equation:

$$\tan\beta = \frac{h}{r}$$

The value of the influence dispersion parameter (r), also referred to as the radius of principal influence, for the surface and the angle of principal influence (β) can also be derived from the profile of a final subsidence trough.

Two methods can be used:

1. The first method is based on the relation between maximum subsidence (S_{max}) for the supercritical or critical trough and the maximum slope (T_{max}) of this trough (at the inflection point)

$$r = \frac{S_{max}}{T_{max}}$$

2. The second method, which is more accurate, uses the whole trough profile to establish the value of parameter r.

In this case, the theoretical profiles are calculated and plotted for different values of r and then compared to the field data. The magnitude of the radius of influence (r) will be equal to the value used for plotting of the theoretical trough profile which best fits the field data. This method has an additional advantage in that it can also be used to establish the magnitude of the "edge effect" parameter (d).

From the practical point of view, the best and fastest results can be obtained by using the first method to establish the approximate value of the parameter r and subsequently using the second method to ascertain the accurate value.

The **horizontal strain parameter** (B) can be established from the relationship:

$$B = -\frac{E_{max}}{K_{max}}$$

where,

E_{max}= maximum value of the horizontal strain (from the field data) measured on the surface; and

K_{max}= maximum value of the calculated curvature on the surface using the previously established parameters, a, r and d.

The value of parameter B found in this way is true only for the surface level (or for any other level where the subsidence-strain data are collected).

According to Awershin (1947) and to other authors (Budryk, 1953; Akimov and Zemicev, 1970), the magnitude of the "horizontal strain parameter" (B) is a function of the excavation depth or "radius of principal influence" (r).

Using the established values of parameter "B" and the corresponding values of parameter r, a relationship was found between these two parameters (section 5.1.6).

The above methods of establishing values for these parameters, were used for all the case studies monitored in this project. The results are presented in Table 6.2.

6.2.3. Prediction of the Deformation Indices on the Surface

The precalculation process of the deformation indices is divided into three stages:

1. input data preparation;
2. calculation of values of deformation indices for the chosen surface points; and
3. graphical presentation of the results.

Under typical mining conditions, at least on mining plans, excavation sections can be divided into homogeneous rectangular parcels. However, very often due to ground control problems, pillars are not fully extracted and the mine section can only be described by parcels of polygonal shape. Therefore, two different approaches had to be developed; the first for regular (rectangular) mining panels and the second, for panels of irregular (polygonal) shape.

6.3. Computer Software

6.3.1. The Profile Function Prediction Program

A computer program was developed for the application of the profile function prediction method. The functions describing the statistical correlation between mining and

Table 6.2. Values of Parameters for the Influence Function Method

	PARAMETERS			
Case Study	Subsidence Factor (a)	Angle of Influence (tan β)	"Edge Effect" (d) *	Horizontal Strain Factor (B) **
RUVA-VT1	0.43	2.46	160	0.047
RUVA-VT2	0.42	4.30 ***	73	0.010
RUVA-VT3	0.37-0.53	2.20	5-55	0.025
RUVA-VT5	0.57	1.85	120	0.130
RUVA-VT6	0.42	1.95	150	0.138
LUVA-VT1	0.55	3.02	90-160	0.020
LUVA-VT2	0.50	2.54	100-200	0.080
LPWA9	0.29	2.13	125	0.080

Average Angle of Influence (tanβ) = 2.31

Average Horizontal Strain Factor (B) = $0.35 \dfrac{h}{\tan \beta}$

* To be used for **solid coal rib**

** To be used for prediction on the surface only

*** Value ignored

subsidence factors were included in the program, and only the input of the first is required. The required parameters are:

- Seam thickness (m);
- Depth of the excavation (h);
- Panel width (W);
- Percent hardrock in the overburden (%HR); and
- Mining method including extraction ratio and pillar size for room and pillar cases.

S_{max} and d are calculated from the above factors using the appropriate relationships, depending on the mining method.

Next, from the value of W/h it is determined whether the panel under consideration is subcritical, critical or supercritical, the value of c is selected and the value of B is calculated from the panel geometry and the value of d (section 6.1).

For the purpose of convenience, the center of the x-axis is located at the panel center and the following transformation of coordinates is performed:

$$x' = x - 0.5W + d$$

where, x' = distance from the inflection point; and

x = distance from the panel center.

The distribution of subsidence values above the panel is then calculated from the profile function.

In summary, the computational procedure includes the following steps:

Step 1: Input m, W, h, %HR, mining method, R and W_p (for room and pillar cases)

Step 2: $S_{max} = S_{max}(m,W,h, HR,R)$ and $d = d(W,h)$

Step 3: If $W/h \geq 1.2$, then $c = 1.8$, else $c = 1.4$

Step 4: If $W/h \geq 1.2$, then $B = 0.5W - d$, else $B = 0.6h - d$

Step 5: $x' = x - 0.5W + d$

Step 6: $S'_{max} = \frac{S_{max}}{S_{center}} S_{max}$

Step 7: $s(x) = 0.5S'_{max}\left\{1 - \tanh\left[\frac{cx'}{B}\right]\right\} =$

$$= 0.5S'_{max}\left\{1 - \tanh\left[\frac{c(x - 0.5W + d)}{B}\right]\right\}$$

The program has been written in BASIC for the HP and IBM personal computers, and modifications for use on other computer systems are simple. Adaptations for site specific application will also require minimal changes. The results can be presented in a tabulated form or by delineating the profiles on a plotter.

6.3.2. Computer Software Based on the Influence Function Method

The distribution of subsidence related indices on the surface is described by a number of complicated mathematical equations requiring considerable computational effort, and thus necessitating the use of computers. Therefore, the development of the computer software for the subsidence calculations became a major factor in the utilization of this prediction approach.

Three sets of programs were developed; the first for the preparation of the mining parameter data, the second for the calculation of the deformation indices and the third for the graphical presentation of the results. A number of commercially available software packages may also be used for data preparation and graphical presentation, since special attention was given to software compatibility.

For the preparation of the input mining data, the following programs can be used:

A. COORDS (PacSoft Inc., 1983) This program creates the coordinate file of the prediction points on the surface, which can be used as an input file for the prediction programs. The data is entered manually using the keyboard.

B. 7580 DIGITIZING (PacSoft Inc., 1983) This program creates the coordinate file of the prediction points on the surface directly from a topographic map of the surface, using a digitizer or a plotter.

C. MINDIG This program creates a new data file or edits an existing file describing the mine plan, including information about the parcel boundaries as well as their mining parameters (mining height elevation, subsidence factor). It is used for polygonal parcels with the use of a digitizer or plotter.

D. MINDIGr Similar to MINDIG, to be used for rectangular parcels.

For the calculation of the deformation indices six programs were developed, according to the shape of the parcels and to the required output:

A. DEFPRED This program calculates the values of the deformation indices at any point on the surface (Prediction Points File) and creates files (xxPREDyyy) containing the calculated data. The shape of the parcels may be polygonal or rectangular.

B. DEFPREDg This program calculates the values of the deformation indices at the grid points defined on the surface and creates files containing the calculated data. The shape of the parcels may be polygonal or rectangular. The output files (xxTOPOyyy) are compatible with PacSoft Inc. software, which can be used for plotting profiles or contours from the results.

C. DEFRECT This program calculates the values of the deformation indices at any point on the surface (Prediction Points File) and creates files (xxPREDyyy) containing the calculated data. The shape of the parcels must be rectangular and the sides parallel to the axes of the coordinate system.

D. DEFRECTg This program calculates the values of the deformation indices at the grid points defined on the surface and creates files containing the calculated data. The shape of the parcels must be rectangular and the sides parallel to the axes of the coordinate system. The output files (xxTOPOyyy) are compatible to PacSoft Inc. software, which can be used for plotting profiles or contours from the results.

E. DEFRECTl This program calculates the values of the deformation indices at points along a curvilinear line defined on the surface. It may be used for prediction along roads, pipelines, railroads or power lines. It creates files (xxPREDyyy) containing the calculated data. The shape of the parcels must be rectangular and the sides parallel to the axes of the coordinate system.

F. DEFOPT This program calculates the values of the deformation indices at grid points defined on the surface and creates files containing the calculated data. It is recommended for analysis leading to the optimal shape of the excavation front, in the case of staggered or concave fronts. The shape of the parcels must be rectangular and the sides parallel to the axes of the coordinate system. The output files (xxTOPOyyy) are compatible to PacSoft Inc. software, which can be used for plotting profiles or contours from the results.

For the presentation of the results two programs were written for the plotting of profiles (DEFGRAPH) and three dimensional projections (DEF3-D). Contour plotting software developed by third parties may also be used.

These programs were initially developed in BASIC for HP computers. Use of a digitizer or of a plotter with digitizing capabilities of appropriate dimensions is recommended. Versions of the programs for use with the IBM-PC are also available, but input parameters and coordinates must be entered manually.

All the programs are combined into a package called the Surface Deformation Prediction System (SDPS-1). This system is compatible with the Subsidence Monitoring System, consisting of two programs SUB-STR and ZSF-COF which allow the calculation of deformation indices, the editing and format conversion of the data obtained during monitoring. The system is also compatible to the Topography package (PacSoft Inc.). Interconnection of the programs and data flow are described on the chart of Figure 6.5.

6.4. Typical Application

Two examples, one longwall mine and one room and pillar mine, have been chosen to illustrate the analysis of the field data collected during this research and the application of the prediction methods. It should be mentioned that in all these cases the profile

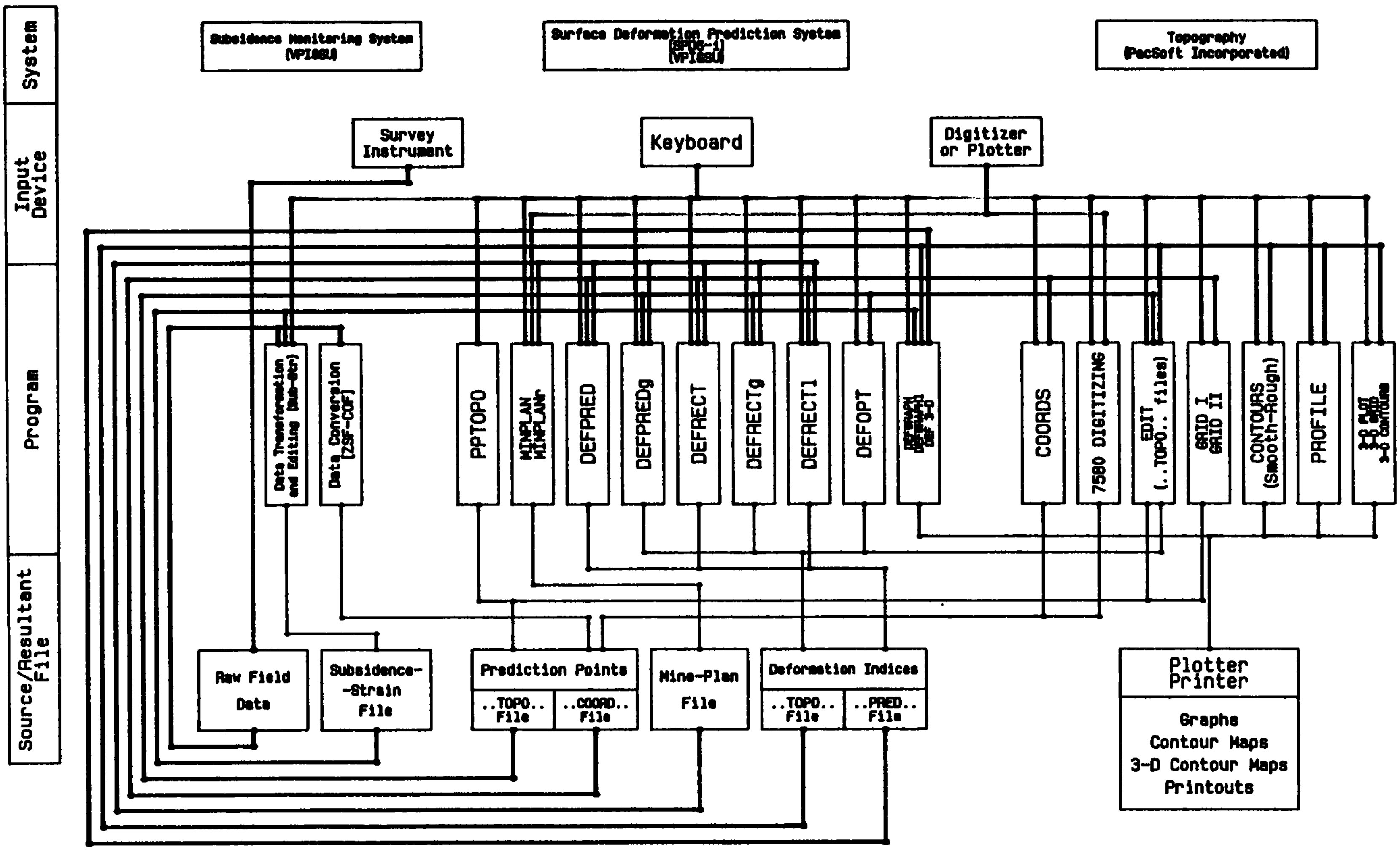

Figure 6.5. Typical System Flow Chart.

function method is used as a purely **predictive** tool, whereas the influence function demonstrates its curve **fitting** potential.

6.4.1. Analysis of Case Study LUVA-VT2

This case study was monitored under this research and a description of the mining conditions is presented in Appendix C and sections 3.4 and 4.3. Maximum observed subsidence was about 47 percent of the seam thickness, and occurred above the centerline of the second panel. Maximum horizontal compression during mining was 1.0%. Maximum observed horizontal tension was in the range of 0.9%.

Considering only the first panel, the predicted subsidence profile using the profile function method yields the following results:

S_{max} = 2.37 feet (measured: 2.6 - 2.7 feet);

d = 94 feet (measured: 100 feet); and

c = 1.4 (for subcritical panels).

It should be mentioned that the Case Study LUVA-VT2 was included in the statistical analysis for the development of the prediction method.

The Budryk-Knothe influence function method is shown in Figures 6.6 and 6.7 for the transverse and longitudinal subsidence profiles. Although the panels were of a rectangular shape, they were sub-divided when they were digitized because of variations in depth and seam thickness.

Using the influence function method, the best fit line was obtained when the following subsidence parameters were used in the equation:

$\frac{S_{max}}{m}$ = 0.70 (theoretical, supercritical conditions);

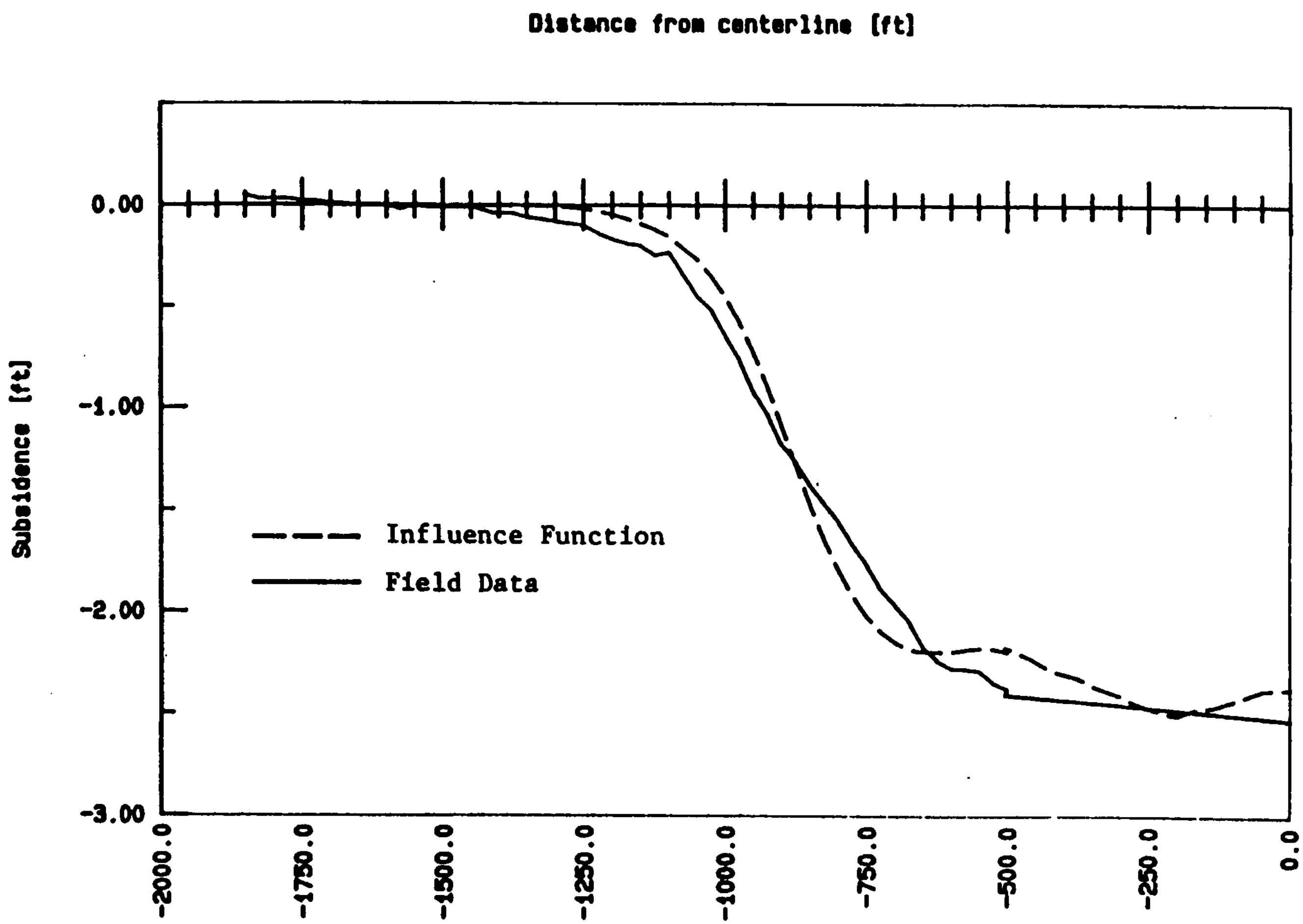

Figure 6.6. Longitudinal Subsidence Profile for Case Study LUVA-VT2

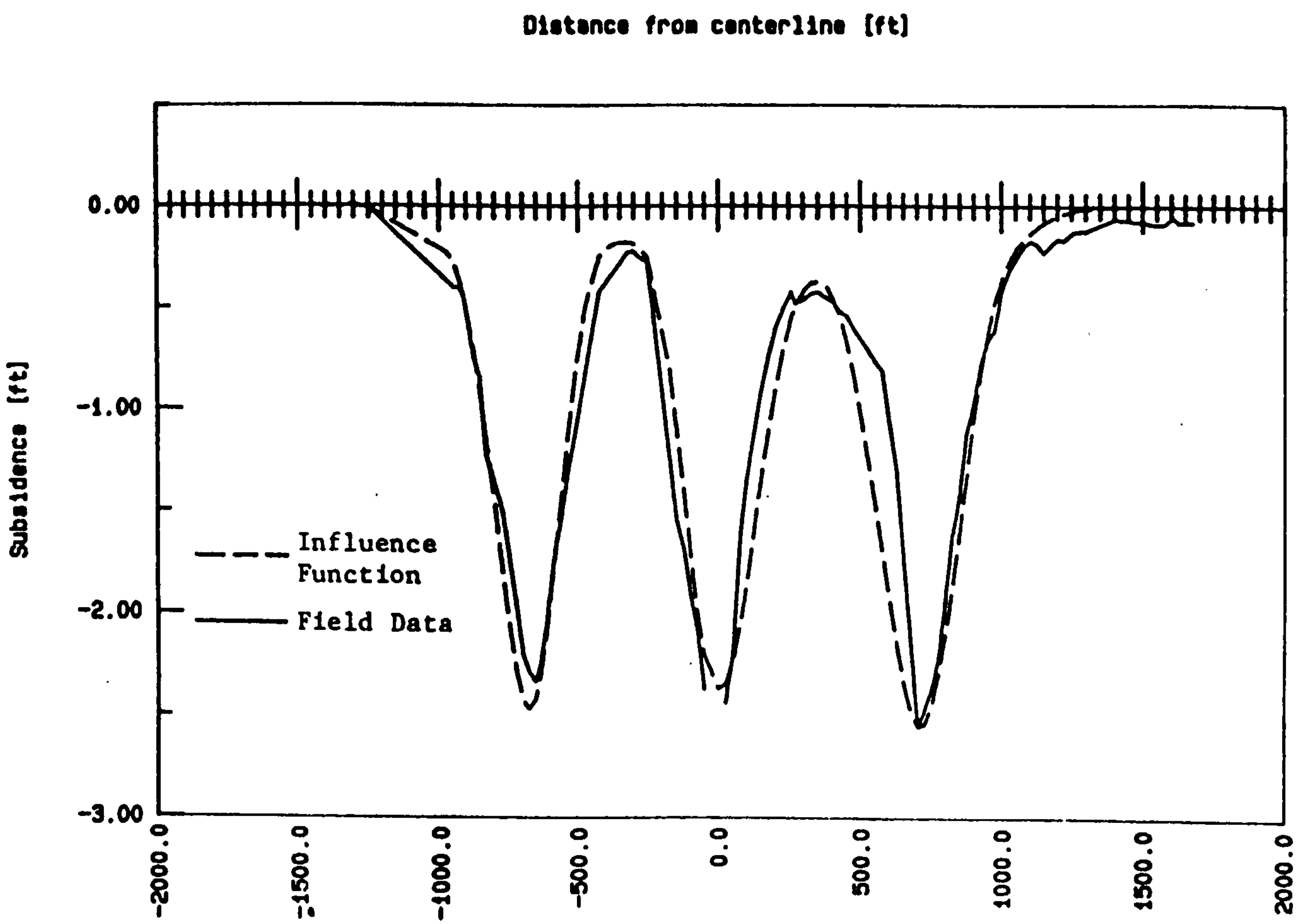

Figure 6.7. Transverse Subsidence Profile for Case Study LUVA-VT2.

$\frac{S_{max}}{m}$ = 0.04 (above pillars);

$\tan \beta$ = 2.54; and

d = 200 feet

6.4.2. *Analysis of Case Study RUVA-VT2*

This was a small room and pillar mine also in Virginia. The terrain above the monitored panels is covered by dense forest and it is rolling with average grades. The average mining height was 5 feet at an approximate depth of 365 feet. The extraction ratio in this mine varied from 50 to 85 percent. A detailed description of the site, and the mine plan for this case study are given in section C.4 in Appendix C. It was planned that all pillars, with the exception of those left around the final excavation for ventilation purposes, would be extracted. However, due to ground control problems, the initial plan was modified. Figure 6.8 shows the final excavation plan and the position of the monitoring lines.

Maximum measured subsidence was 2.5 feet. Maximum horizontal compression was in the range of 0.5-0.75% and maximum tension was in the range of 0.35-0.75%.

When applying the Budryk-Knothe influence function method, the complexity of the final plan of the mined section dictated the analysis of the problem in three-dimensions. Because of the considerable variation in extraction ratio, within the section under consideration, the latter was divided into sub-sections of similar characteristics (Figure 6.8, Table 6.3). The line surrounding all subsections, drawn at a distance, d, from the edge of the excavation, describes the theoretical boundary of the excavation, above which lay the inflection points. Distance, d, was determined from the field data. The data describing these areas is given by the following subsidence parameters:

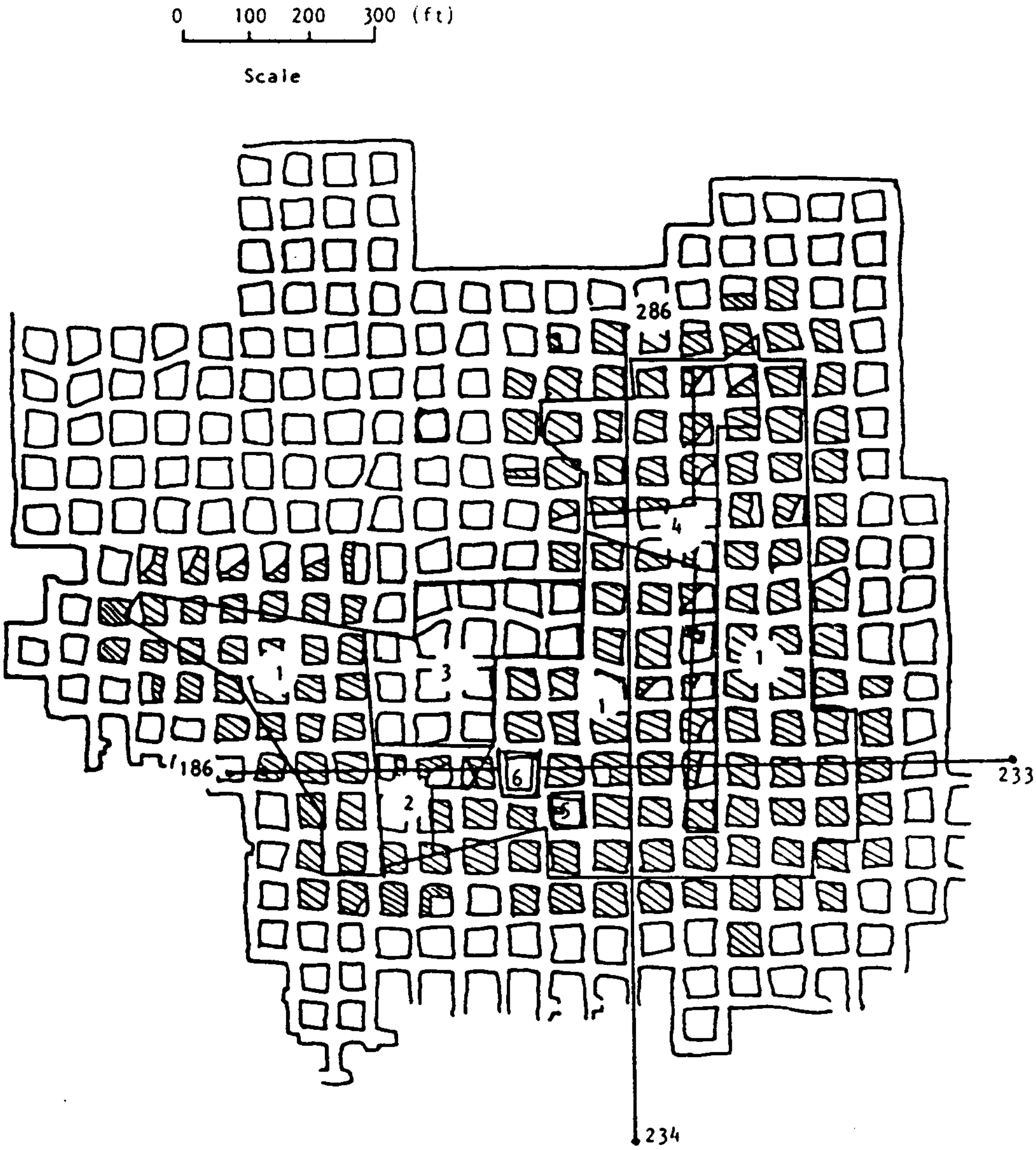

Figure 6.8. Final Mine Plan for Case Study RUVA-VT2

Table 6.3. Case Study RUVA-VT2 - Section Parameters.

Subsection	S_{max} (feet)	Elevation (feet)	Mining Height (feet)	Extraction (%)
1	2.1	2,400	5	85
2	1.85	2,400	5	70
3	1.05	2,400	5	50
4	1.85	2,400	5	70
5	0	2,400	5	0
6	0	2,400	5	0

where;

r = 85 feet
d = 73 feet
H = 2,765 feet (elevation at the surface)

$\frac{S_{max}}{m}$ = 0.405;

tan β = 4.29;

d = 73 feet; and

B = 10 (where B is the strain-curvature correlation factor, in units of length.

The rest of the results from the application of the method are presented on Figures 6.9 through 6.12.

6.5. Accuracy of Predictions

A number of case studies were used to demonstrate the accuracy of the prediction methods. It should be mentioned that these case studies were included in the statistical analysis, as presented in Chapter 5.

The mining parameters, listed in Tables 4.2 and 4.3, were used as input for the prediction methods. The resulting predicted subsidence and strain profiles were then compared to the field data.

For two case studies monitored under this research, both the profile function and the influence function methods were used for subsidence and strain predictions, and the results are presented in Figures 6.13 through 6.16.

It may be observed that the prediction of S_{max} was accurate in both cases. In Case Study LUVA-VT2, however the distance from the inflection point to the rib was over-predicted. This can be expected since an envelope line was used for predicting d. A

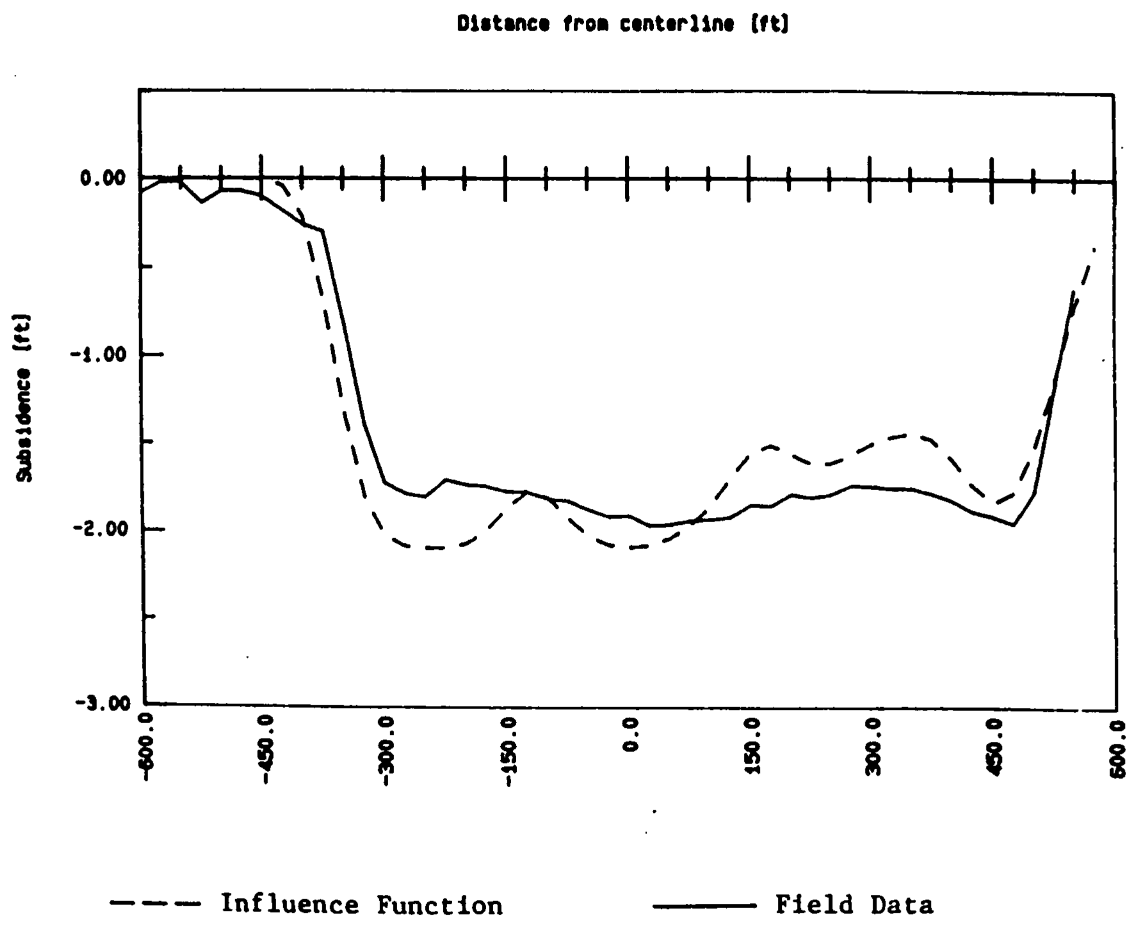

Figure 6.9. Longitudinal Subsidence Profile for Case Study RUVA-VT2.

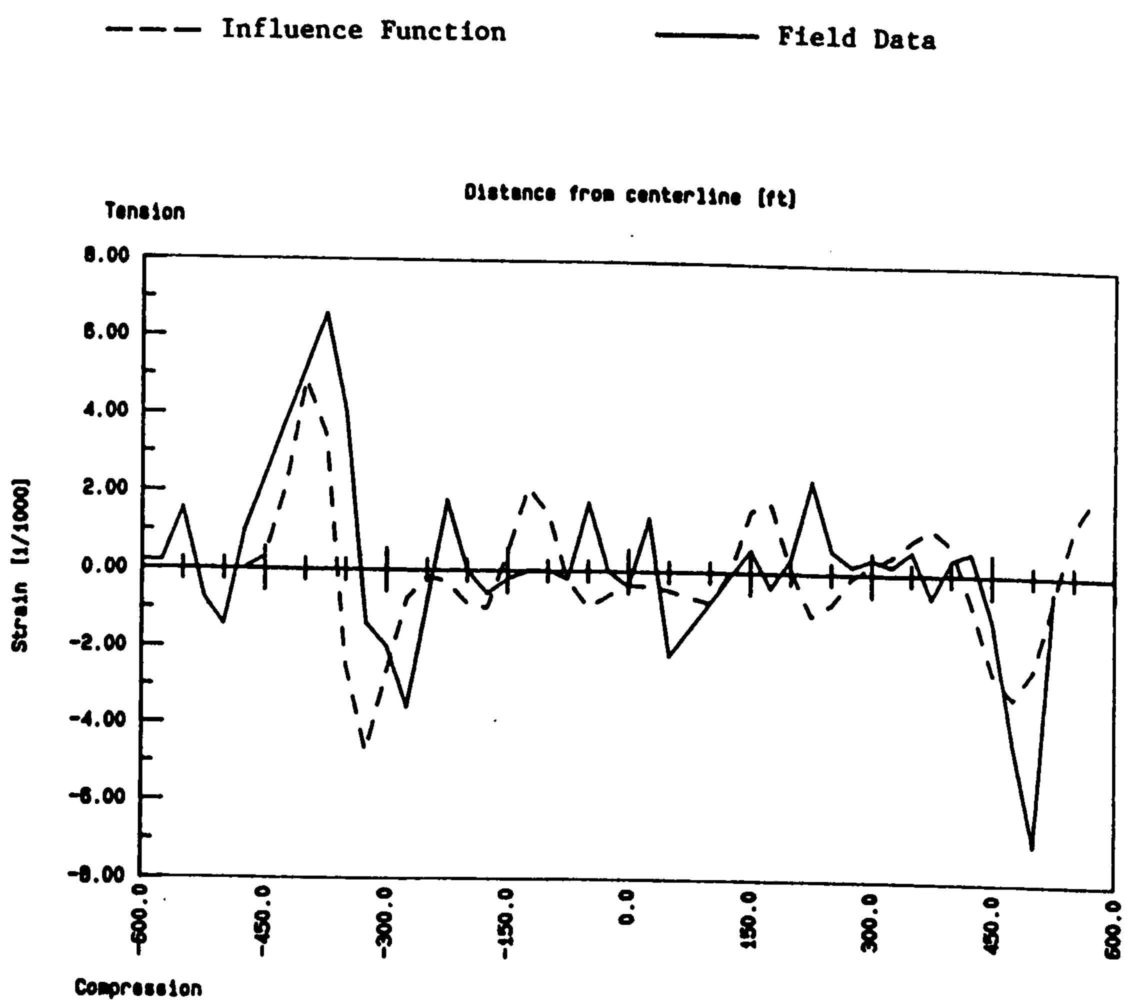

Figure 6.10. Longitudinal Strain Profile for Case Study RUVA-VT2

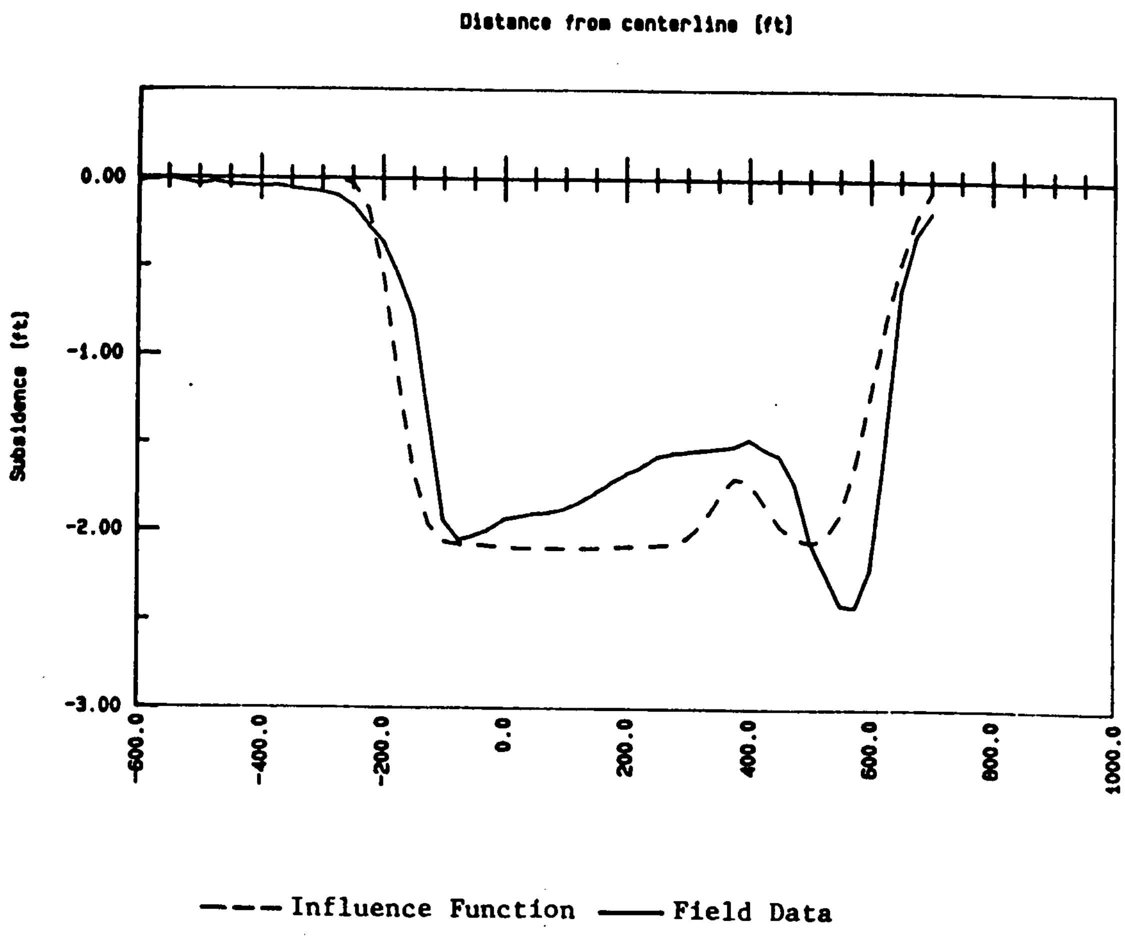

Figure 6.11. Transverse Subsidence Profile for Case Study RUVA-VT2.

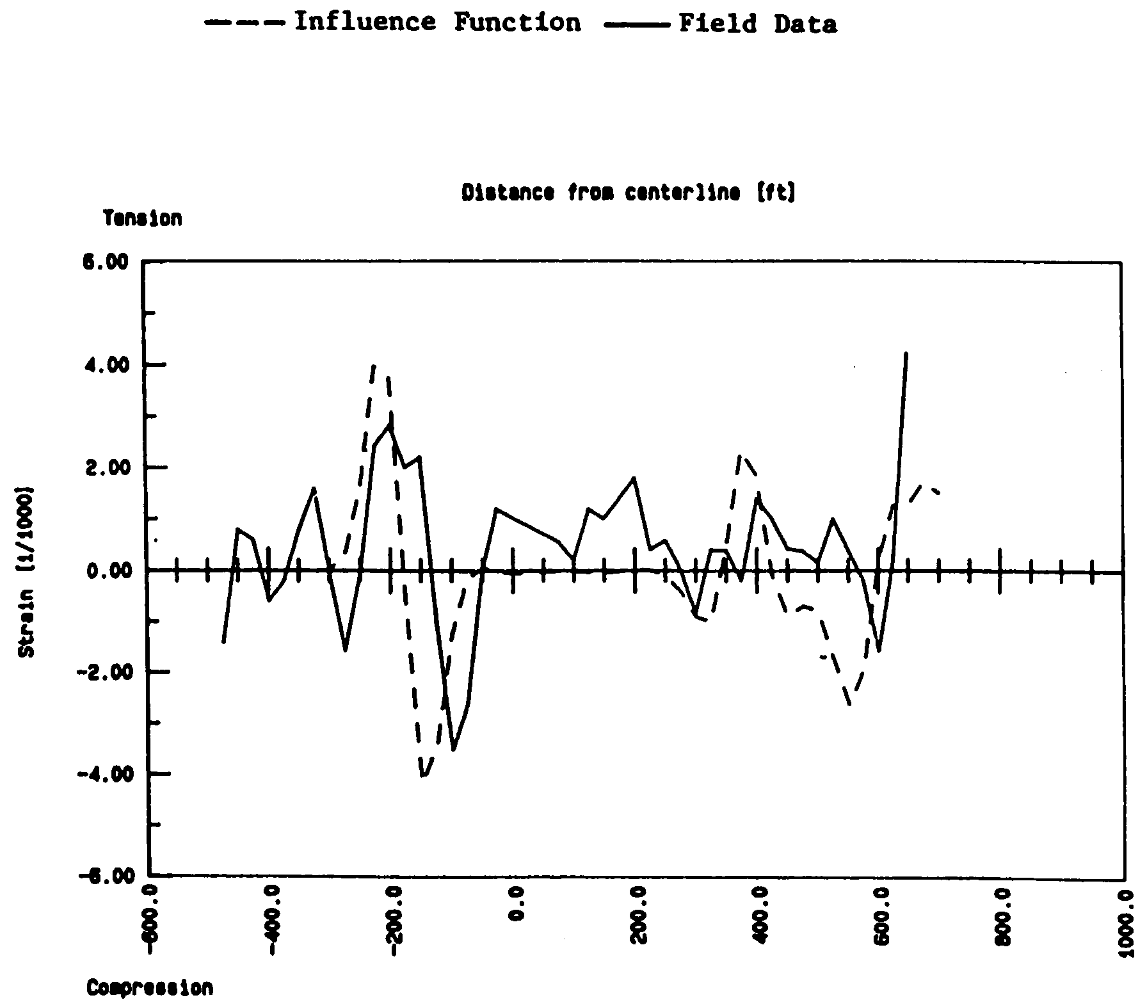

Figure 6.12. Transverse Strain Profile for Case Study RUVA-VT2.

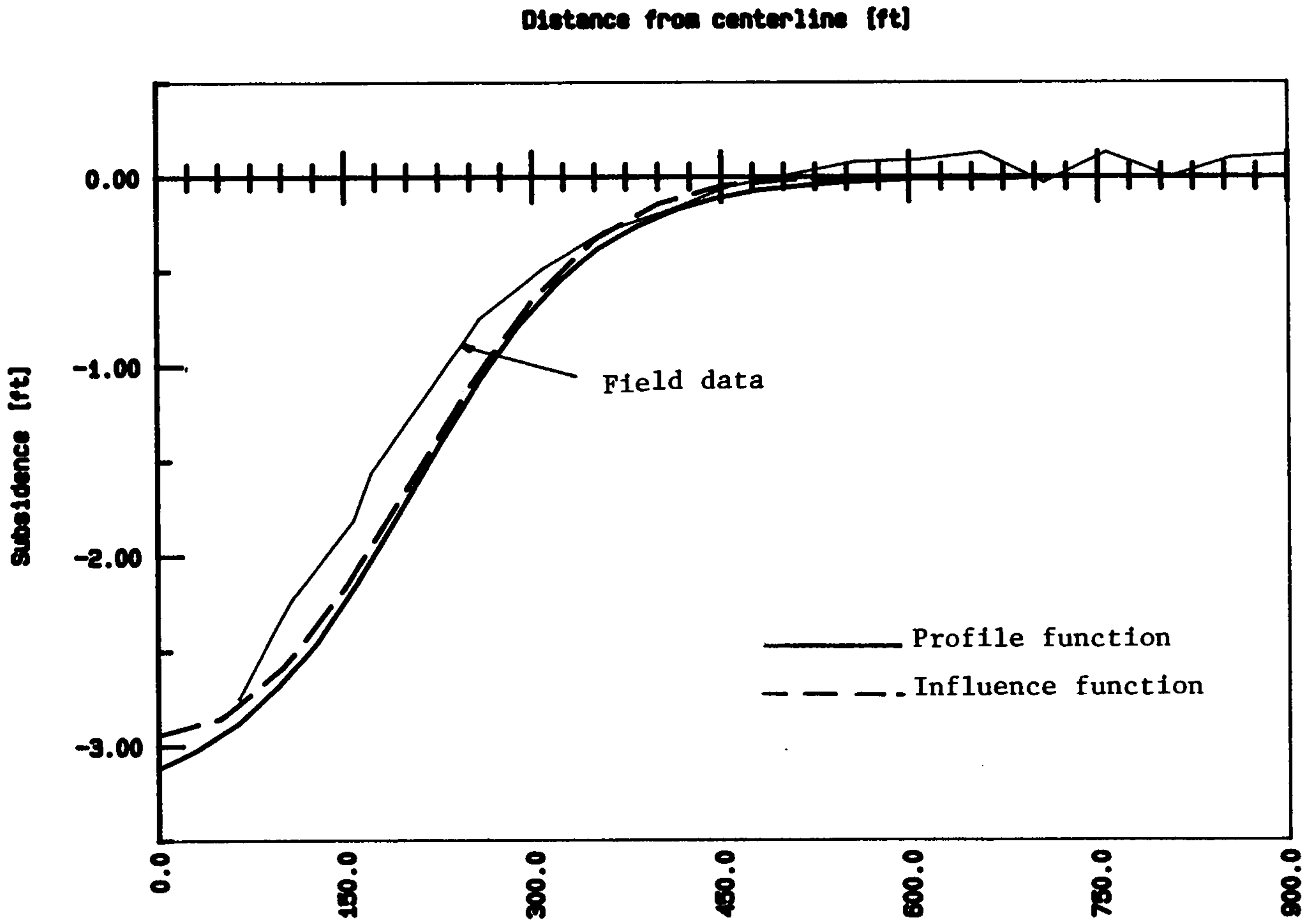

Figure 6.13. Predicted and Measured Subsidence Profiles for Case Study LUVA-VT1.

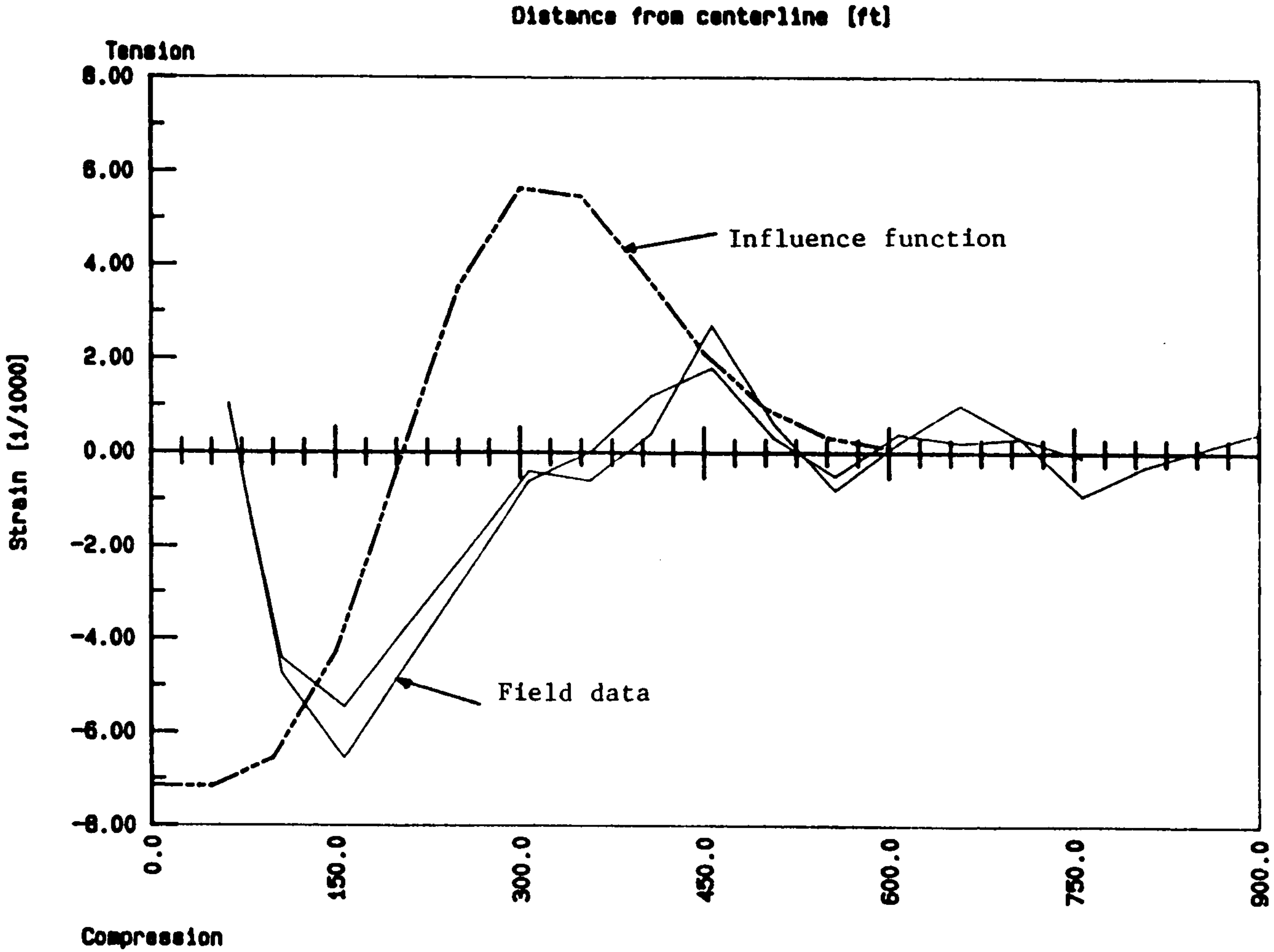

Figure 6.14. Predicted and Measured Strain Profiles for Case Study LUVA-VT!.

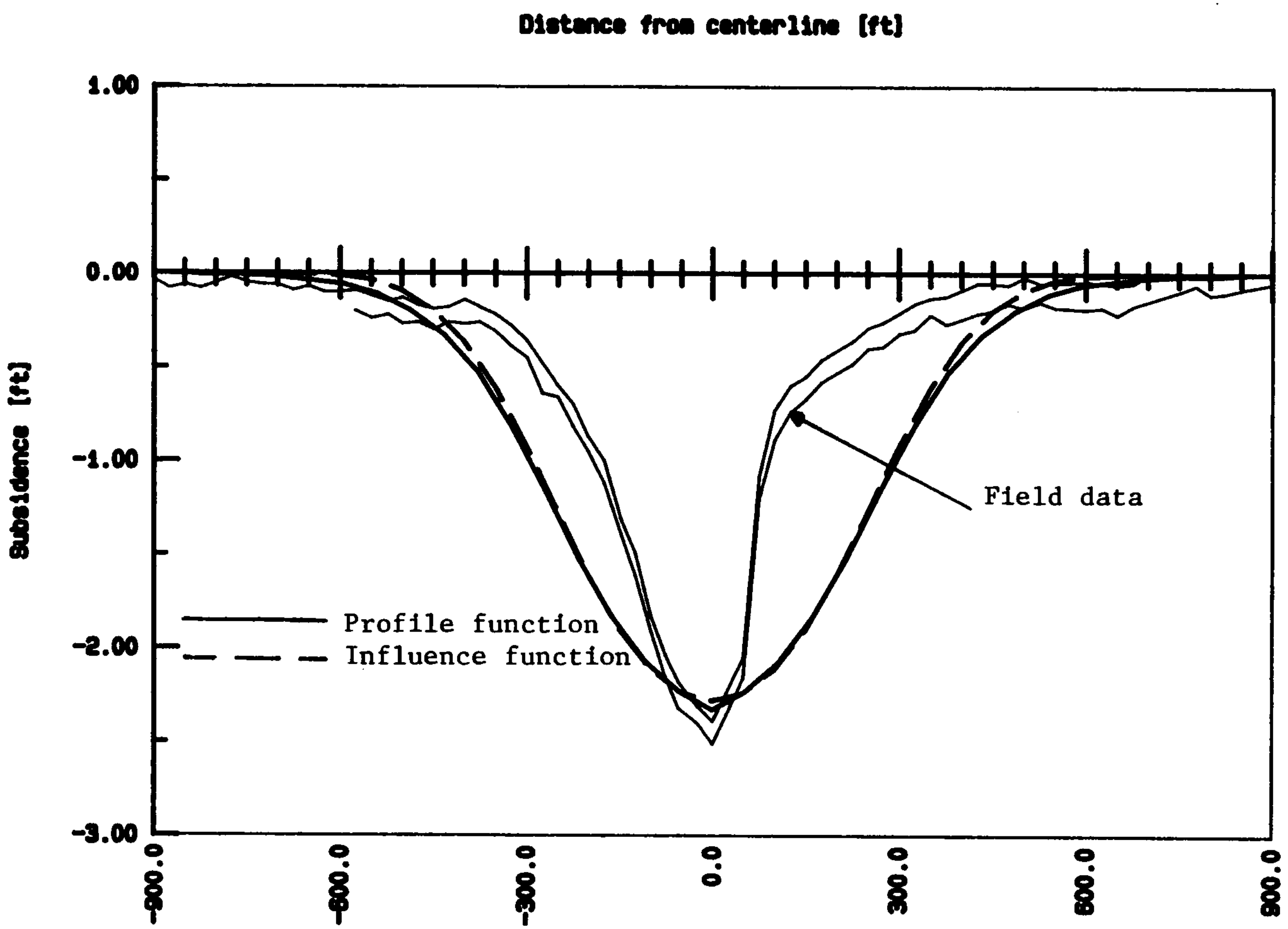

Figure 6.15. Predicted and Measured Subsidence Profiles for Case Study LUVA-VT2.

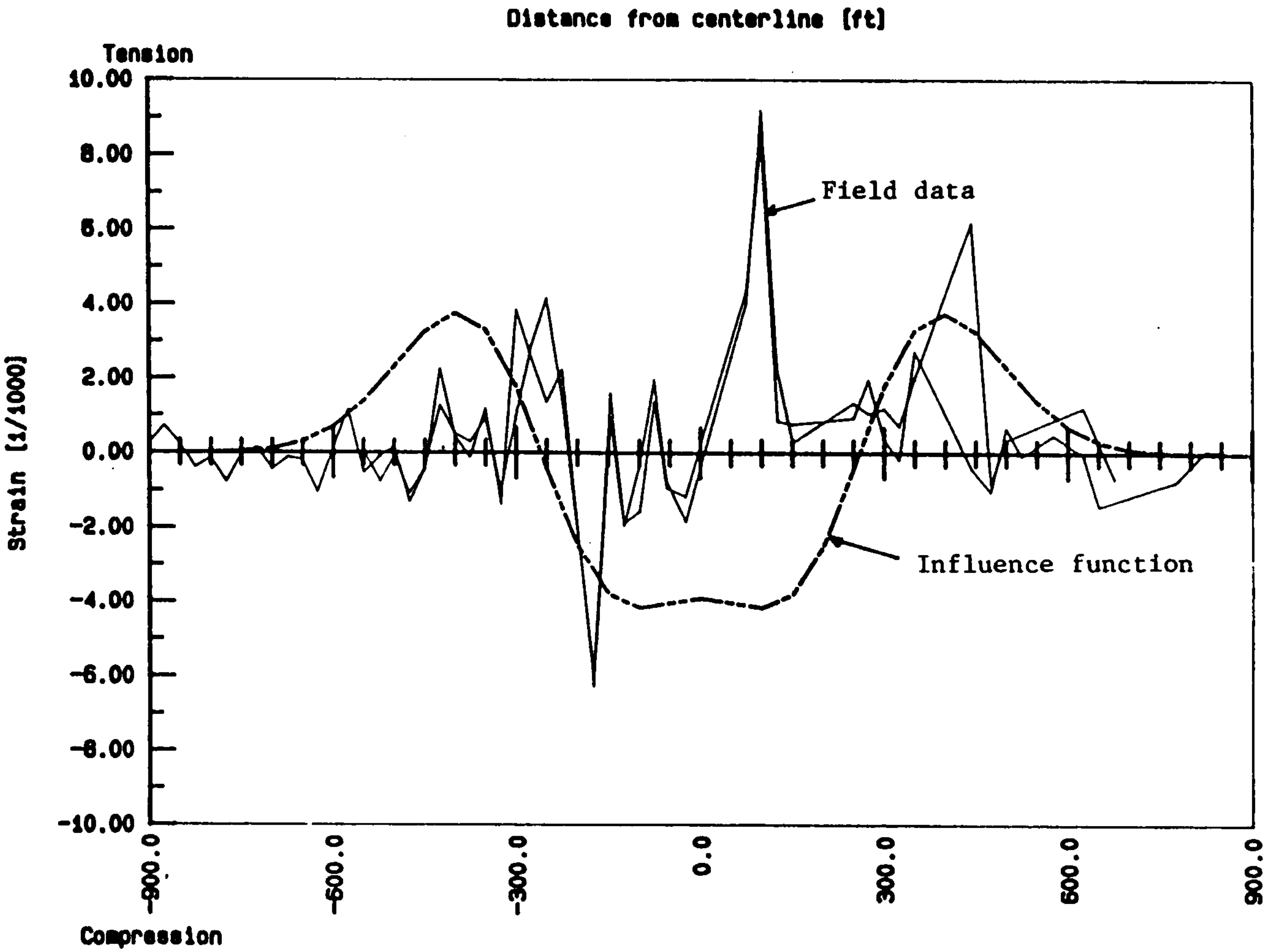

Figure 6.16. Predicted and Measured Strain Profiles for Case Study LUVA-VT2.

second factor in this case study was the local tectonic conditions, which possibly resulted in vertical separation and translation of blocks within the overburden. The latter was observed on the surface in the form of tension cracks. This behavior produced the anomalies in the strain profile, i.e. high tensile strains along the compressive zone (Figure 6.16).

On the strain profile of Case Study LUVA-VT1, the measured profile appeared to have been shifted outwards from the center of the panel. This phenomenon may be attributed to the high surface slope which can cause downslope translation of the strain profile. Although the influence of topography is an important factor, the limited field data available in this study did not permit a quantitative analysis.

From Figures 6.13 and 6.15 it may be observed that both prediction methods resulted in very similar prediction profiles. This is due to the fact that S_{max} and d are obtained from the same nomograms and tables, as well as to the fact that the same database was used for the analysis of both methods. Figures 6.17 through 6.20 present field and predicted subsidence profiles for a number of case studies collected from various sources. In all cases, the prediction of S_{max} was well within acceptable limits. In some cases, however, d may be over-predicted, due to the use of an envelope line, as explained before.

A comparison of predicted and field values for S_{max} and d is presented in Tables 6.4 through 6.7. From Table 6.4 it may be observed that the prediction of S_{max} for longwall panels is very accurate (average error 16 percent), with the exception of a number of panels within the same mine (LPPA4 a, b, c). For room and pillar cases the average error was 31 percent. This is due to the fact that the extraction ratio reported by the

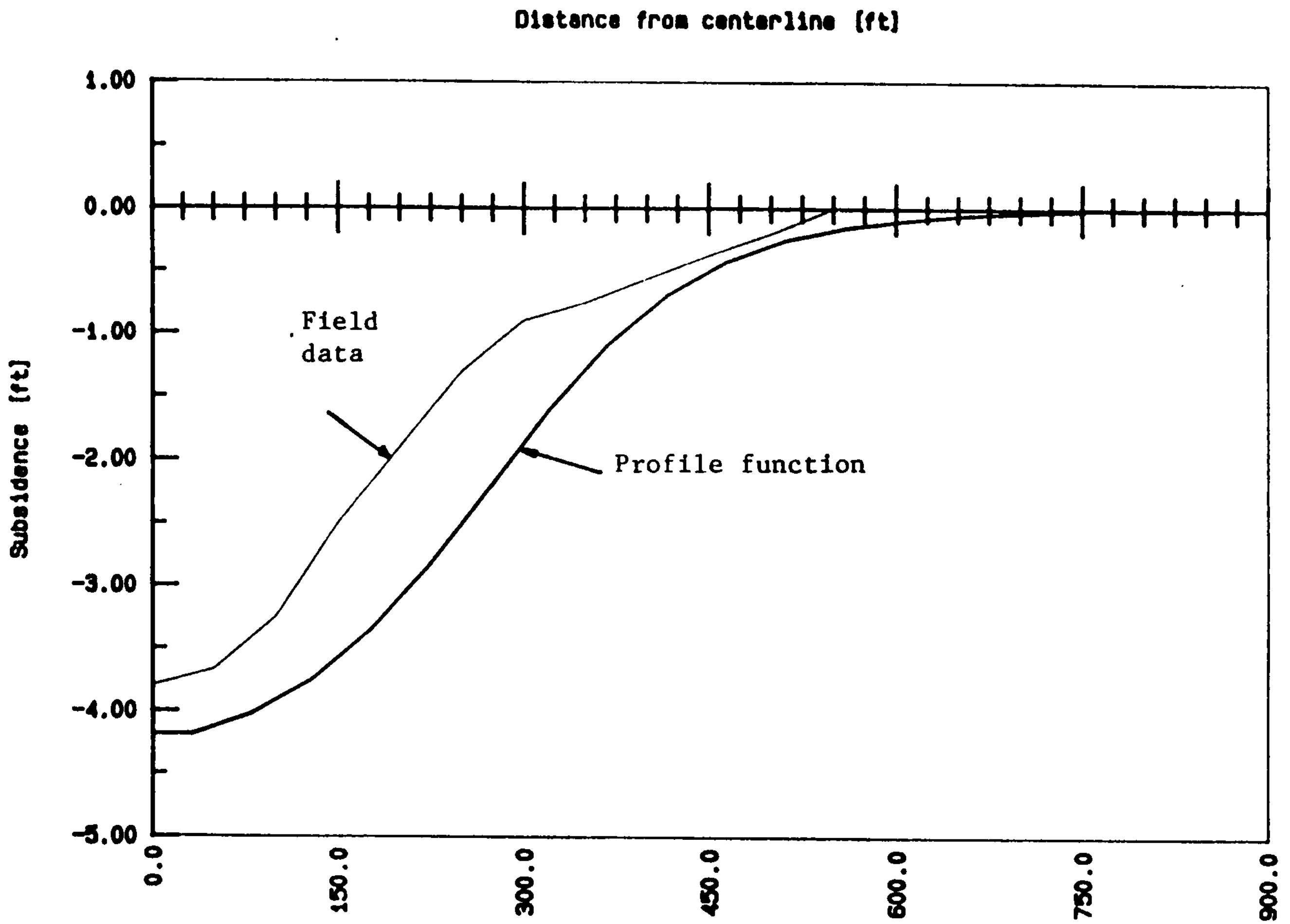

Figure 6.17. Predicted and Measured Subsidence Profiles for Case Study LPOH1a.

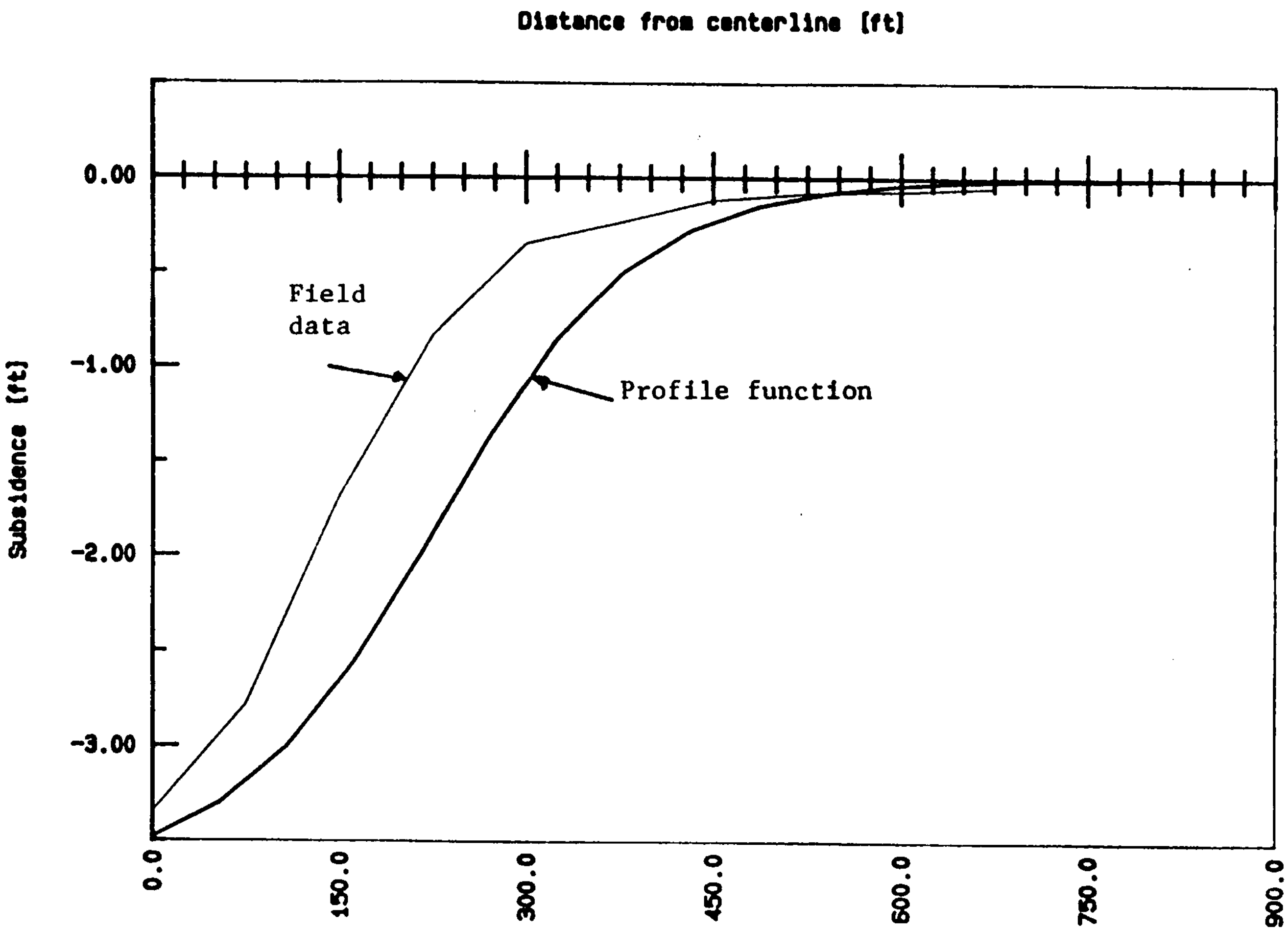

Figure 6.18. Predicted and Measured Subsidence Profiles for Case Study LPWV7a.

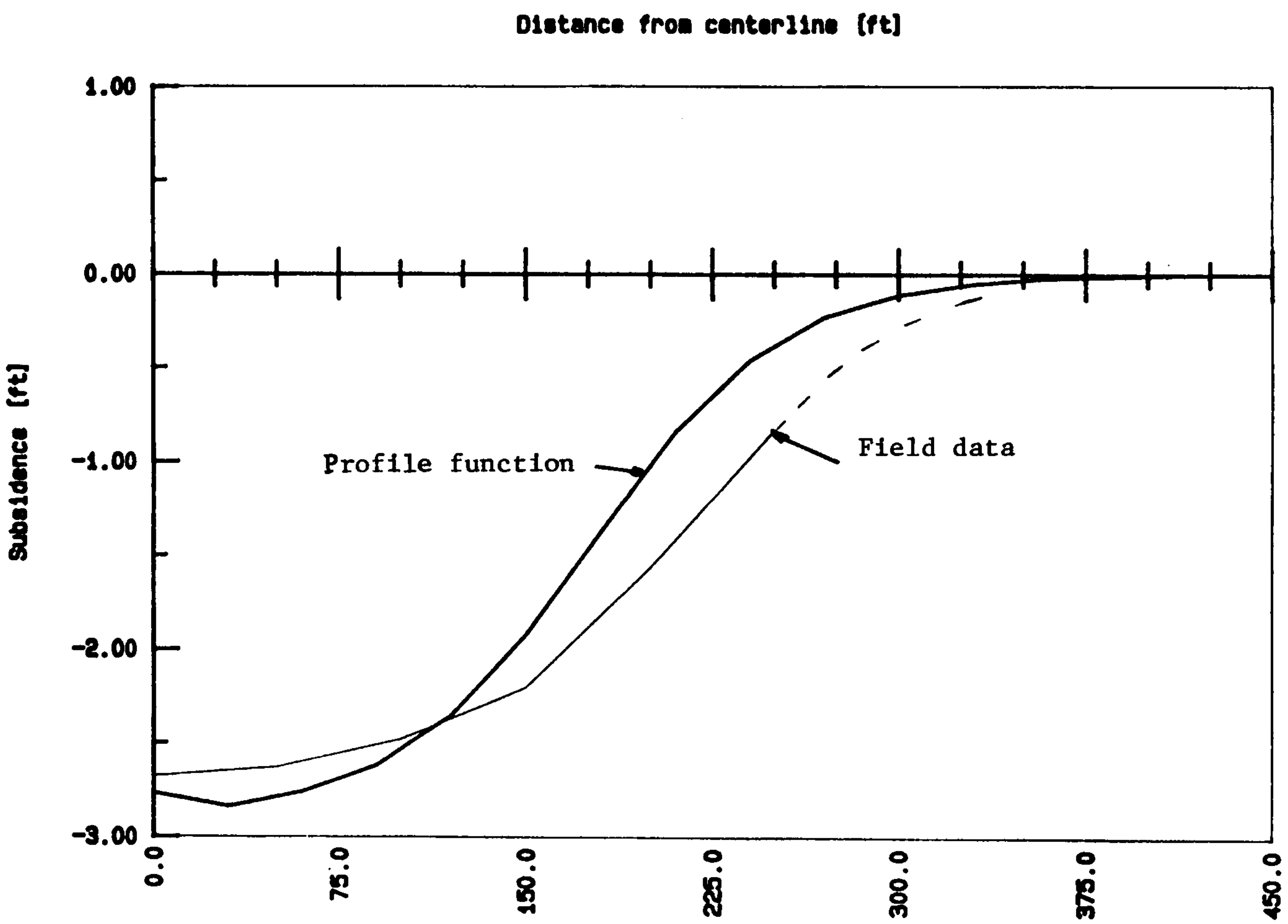

Figure 6.19. Predicted and Measured Subsidence Profiles for Case Study RPPA10.

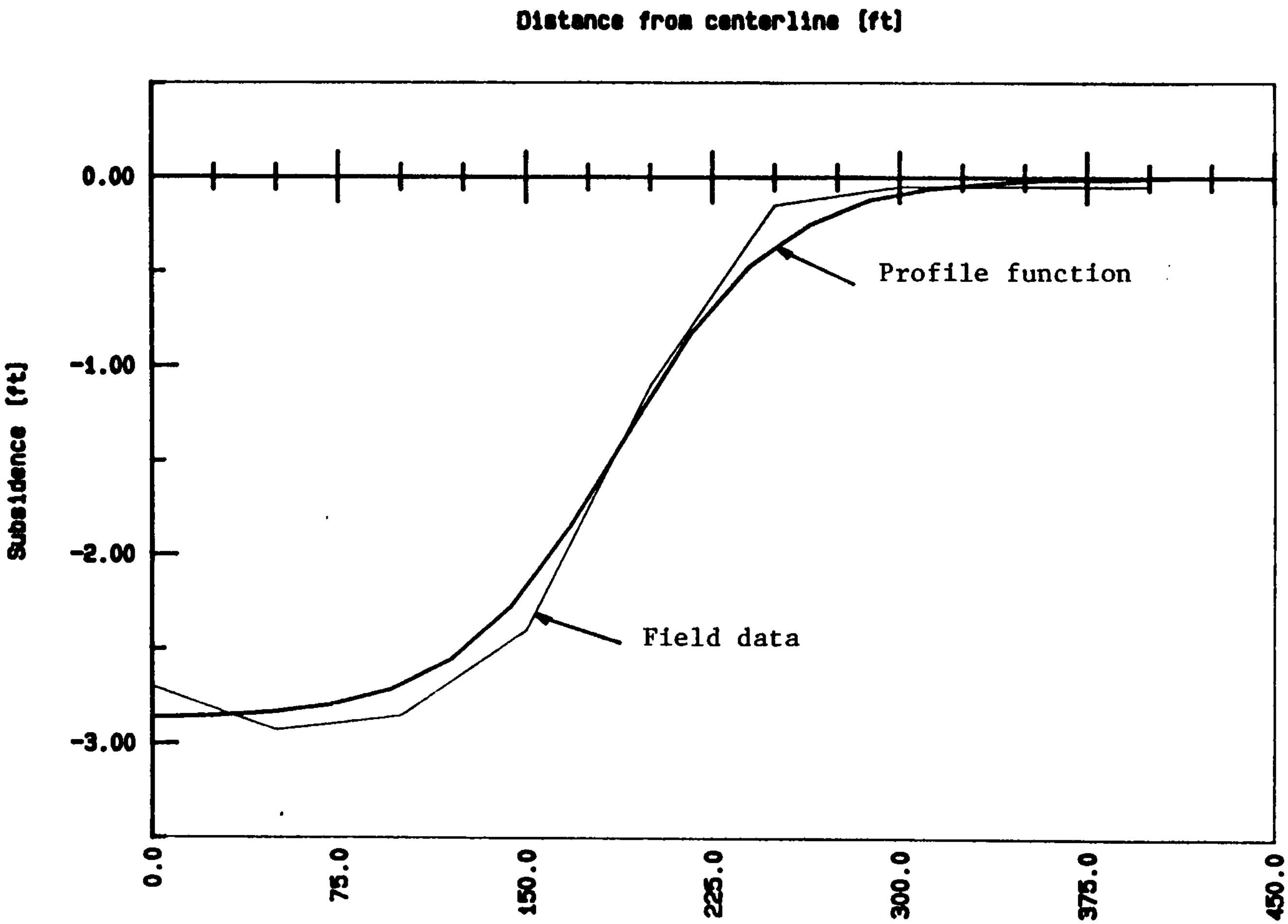

Figure 6.20. Predicted and Measured Subsidence Profiles for Case Study RUWV4a.

Table 6.4 Comparison of Measured and Predicted Smax/m values for Longwall Case Studies and Relative Error (for h < 1500ft).

Case Study	h (ft)	W (ft)	m (ft)	HR (%)	Smax/m measured	Smax/m predicted	Error (%)
LPAL1	500	600	4.5	26	0.611	0.630	3
LPOH1a	750	485	6.5	23	0.615	0.591	4
LPOH1ef	700	480	7.25	24	0.648	0.594	8
LPOH2	700	485	4.3	23	0.581	0.605	4
LPPA2	550	610	4.5	41	0.467	0.479	3
LPPA4ab	510	450	4.15	31	0.32	0.566	77
LPPA4c	455	460	4	39	0.305	0.496	63
LPPA4d	290	445	4	26	0.563	0.638	13
LPPA7	400	470	3.7	21	0.649	0.672	4
LPWV1a	600	450	5.5	37	0.473	0.493	4
LPWV1b	600	450	5.5	37	0.345	0.493	43
LPWV1c	660	600	5.5	23	0.591	0.641	8
LPWV1d	550	600	5.5	23	0.733	0.652	11
LPWV1e	600	605	5.5	37	0.736	0.516	30
LUWV3	480	450	7	23	0.591	0.643	9
LUWV4a	300	500	4.9	32	0.596	0.582	2
LUWV4b	250	500	4.9	32	0.524	0.585	12
LPWV5	620	450	6	41	0.367	0.452	23
LPWV7a	750	600	5.5	25	0.618	0.612	1
LPWV7b	680	600	5.5	29	0.581	0.585	1
LPWV9ab	275	500	5	58	0.29	0.329	13
LPWV10a	650	450	--	55	0.38	0.321	16
LPWV10b	600	335	--	51	0.35	0.309	12
LUVAVT1	700	520	7.25	46	0.497	0.406	18
LUVAVT2	600	560	5.5	50	0.473	0.385	19
					average		16

Table 6.5 Comparison of Measured and Predicted Smax/m values for Room and Pillar Case Studies and Relative Error

Case Study	h (ft)	W (ft)	m (ft)	HR (%)	R (%)	Smax/m measured	Smax/m predicted	Error (%)
RPPA1	325.00	360.00	6.50	22.00	75.00	0.29	0.42	45
RPPA2a	375.00	430.00	6.50	15.00	80.00	0.50	0.48	3
RPPA3	375.00	840.00	4.70	39.00	90.00	0.62	0.39	36
RPPA4	650.00	910.00	6.20	31.00	88.00	0.20	0.44	120
RPPA5a	725.00	720.00	6.00	33.00	85.00	0.52	0.40	23
RPPA5b	750.00	1460.00	6.10	29.00	88.00	0.46	0.46	0
RPPA6	745.00	1955.00	5.70	30.00	88.00	0.46	0.46	1
RPPA7	535.00	500.00	6.50	31.00	88.00	0.54	0.42	21
RPPA9a	350.00	470.00	7.20	41.00	85.00	0.48	0.35	27
RPPA9b	425.00	570.00	7.20	41.00	85.00	0.40	0.35	12
RPPA9c	532.00	1100.00	6.80	41.00	85.00	0.52	0.36	31
RPPA10	354.00	300.00	5.40	20.00	90.00	0.49	0.50	2
RUPA34	600.00	600.00	5.50	50.00	90.00	0.32	0.30	8
RPWV1	555.00	325.00	6.00	47.00	90.00	0.30	0.26	12
RPWV2	800.00	830.00	5.00	64.00	78.00	0.29	0.18	37
RUWV4	690.00	400.00	6.50	70.00	100.00	0.26	0.16	37
RUVAVT1	540.00	525.00	5.00	32.00	85.00	0.43	0.41	6
RUVAVT2	365.00	980.00	5.00	80.00	85.00	0.42	0.14	66
RUVAVT3	258.00	680.00	5.50	80.00	85.00	0.53	0.14	73
RUVAVT5	590.00	2000.00	3.70	50.00	85.00	0.57	0.29	49
RUVAVT6	490.00	1200.00	3.90	50.00	85.00	0.42	0.29	30
						average		31

Table 6.6 Comparison of Measured and Predicted d/h values for Longwall Case Studies and Relative Error (for h < 1500ft and d positive).

Case Study	h (ft)	W (ft)	m (ft)	HR (%)	d/h measured	d/h predicted	Error (%)
LPAL1	500	600	4.5	26	0.21	0.21	1
LPOH1bc	450	485	6.5	--	0.21	0.19	10
LPPA2	550	610	4.5	41	0.23	0.19	15
LPPA4c	455	460	4	39	0.1	0.18	76
LPPA6	400	430	5.5	25	0.35	0.19	46
LPPA7	400	470	3.7	21	0.26	0.20	21
LPWV1a	600	450	5.5	37	0.25	0.06	77
LPWV1b	600	450	5.5	37	0.18	0.06	68
LPWV1c	660	600	5.5	23	0.21	0.15	29
LPWV1d	550	600	5.5	23	0.22	0.19	13
LPWV1e	600	605	5.5	37	0.21	0.18	16
LUWV4a	300	500	4.9	32	0.25	0.24	4
LUWV4b	250	500	4.9	32	0.36	0.25	30
LPWV7a	750	600	5.5	25	0.19	0.10	49
LPWV9ab	275	500	5	58	0.43	0.25	43
LPWV9c	520	500	6.2	--	0.12	0.16	37
LUVAVT1	700	520	7.25	46	0.13	0.05	63
LUVAVT2	600	560	5.5	50	0.33	0.16	53
					average		37

Table 6.7 Comparison of Measured and Predicted d/h values for Room and Pillar Case Studies and Relative Error

Case Studies	h (ft)	W (ft)	m (ft)	HR (%)	R (%)	d/h measured	d/h predicted	Error (%)
RPPA2a	375.00	430.00	6.50	15.00	80.00	0.33	0.20	39
RPPA3	375.00	840.00	4.70	39.00	90.00	0.35	0.26	27
RPPA5a	725.00	720.00	6.00	33.00	85.00	0.36	0.17	52
RPPA7	535.00	500.00	6.50	31.00	88.00	0.32	0.16	51
RPWV2	800.00	830.00	5.00	64.00	78.00	0.23	0.18	21
RUVAVT1	540.00	525.00	5.00	32.00	85.00	0.12	0.17	43
RUVAVT2	365.00	980.00	5.00	80.00	85.00	0.21	0.26	23
RUVAVT3	258.00	680.00	5.50	80.00	85.00	0.25	0.26	4
RUVAVT5	590.00	2000.00	3.70	50.00	85.00	0.20	0.27	33
RUVAVT6	490.00	1200.00	3.90	50.00	85.00	0.31	0.26	15
						average		31

mining companies, which was of great significance to the analysis of the results, was not always reliable.

The predicted values of d were generally higher than the measured values (Tables 6.6 and 6.7). This result was expected, since the envelope line was used for prediction. It should be emphasized that an error of 35 percent, reflects a horizontal distance on the surface of less than 45 feet, for a typical mining depth of 600 feet, which is well within acceptable limits. In some cases, for design purposes, it may be preferable to predict d using the average (Figure 5.10) rather than the envelope relationship.

CHAPTER 7

CONCLUSIONS - RECOMMENDATIONS

Surface movements due to underground mining exhibit regional characteristics and, as a result, the development of prediction methods must rely on the collection of local field data. The prediction methodology and the computer software developed under this research effort, pertaining to the eastern United States mining and geological conditions, may provide the technology needed for predicting surface movements.

The research showed that the profile function method can be used for rapid calculation of vertical settlements on a line above a mine panel. The use of the case studies monitored under this research effort improved the range, accuracy and applicability of the method, which is still the most realistic and simple approach to the subsidence prediction problem. This method is recommended for subsidence prediction in cases where a general distribution of the expected subsidence values above a mine is required.

The influence function approach is designed to yield a more detailed and complete calculation of ground movements, in any mode and at any depth, on a grid or at any specific point, than any other method. The study showed that the Budryk-Knothe function is the most applicable formulation for the eastern United States mining conditions. It can calculate all types of surface deformations and, furthermore, can be easily adapted to mine sections of complex geometrical configuration. The computer software developed under this research will be necessary for this purpose due the complexity of the calculations.

The methods developed in this study are recommended for general prediction purposes. The empirical relationships derived from the field data were based on simple statistical analyses, which resorted in many instances to envelope lines, due to insufficient data. As a result, a margin of safety is associated with these predictions (e.g. calculation of S_{max} or position of inflection point). These relationships, however, may be used with confidence when undertaking general predictions within the same coal region, especially for cases with mining and geological parameters which are within the range of those used in this analysis. For cases where the accuracy of the ground movement predictions is of critical importance, e.g. where the impact of ground movement on certain structures is likely to be severe, it is strongly recommended that the required field parameters used in the calculations be re-established from a monitoring program on the site in question. The general prediction methods developed under this research can, subsequently, be adjusted easily to become site specific.

Future work on the subject should be centered around the following topics:

- Analysis of the time effect and rate of face advance on the development of surface movements. Such a study may be initially based on the available data.

- Monitoring of case studies with extreme values for depth and percent hardrock in the overburden. The new data will increase the accuracy of the prediction techniques when applied for very deep or very shallow mines, as well as for case studies where a high percent of hardrock is present in the overburden.

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APPENDIX A

Instrument Calibration

A.1 Scale Error and Constant Offset Error.

The baseline located at the Virginia Tech Airport was used for calibrating the surveying instrument. The line has been adjusted by the National Oceanic and Atmospheric Administration (NOAA). It consists of five stations at nominal distances of 150, 400, 1000 and 1400 meters from the zero meter point.

The calibration procedure recommended by the National Oceanic and Atmospheric Administration was followed (Fronczek, 1977). In summary, it involved the repeated measurement of a number of known and calibrated distances. Adjustment was consistently made to compensate for changes in temperature and barometric pressure. Using the least squares method, two parameters were determined, the offset error for each reflector and the scale factor of the EDM.

The method is based on the assumption that the differences between the measured distances and the published (adjusted) distances of the baseline can be attributed to a scale factor, to a constant correction (offset), or both. The basic equation is given as follows:

$$V = D_A - D_H - SD_A - C$$

where,

S = the scale factor (unknown);

C = constant (offset, unknown);

D_A = the published (calibrated) horizontal distance;

D_H = the measured horizontal distance; and

V = the residual.

When a number of measurements are conducted, the resultant system of equations yields the following solution:

$$S = \frac{n\Sigma(D_A \Delta) - \Sigma D_A \, \Sigma\Delta}{n\Sigma D_A^2 - [\Sigma D_A]^2}$$

$$C = \frac{\Sigma D_A^2 \Delta \, \Sigma\Delta - \Sigma D_A \, \Sigma D_A \Delta}{n\Sigma D_A^2 - [\Sigma D_A]^2}$$

where,

n = the number of observations; and

$\Delta = D_A - D_H$

These parameters were necessary for the adjustment of the measured data. However, the equipment used for this research program had the ability to adjust the measured values automatically, if these parameters were inputted through the keyboard. A computer program was developed in order to facilitate the calculations.

The surveying instrument was initially calibrated twice when purchased, in May, 1983. During the first test the instrument was positioned at all five stations and all combinations of distances were measured ten times in both directions. The following values were calculated:

S = 0.0000175; and

C = 0.088 ft.

After the instrument had been adjusted for the offset error in the laboratory, the second test was performed using a scale factor of 1.000018. The following values were calculated:

S = 0.000001195; and

C = -0.011 ft.

Therefore the scale factor should be $1.000018+0.000001=1.000019$.

The values of S and C were tested against the hypothesis that they were equal to zero. The following t-test at a 99% confidence level was performed:

H_0 : $S=0.000019=0$

H_1 : $S \neq 0$

Except if:

$$t_{0.005,8} < t_s = \frac{S}{SD_S} < t_{0.995,8}$$

or if:

$$-3.355 < \frac{19x10^{-6}}{2x10^{-6}} < 3.355$$

Therefore the scale error of the instrument is statistically different from zero and the scale factor of 1.000019 has to be applied. Similar results were also obtained for the constant offset error.

The instrument was calibrated two more times, in both cases after being shipped to the manufacturer for service and returned. During these tests, however, measurements were only taken from the zero meter station.

A.2. Resolution.

The resolution of an EDM instrument describes its capability to distinguish individual divisions of a unit of length. This quality index is very significant for subsidence measurements since the monuments were always monitored from the same stations and the expected relative movements were small, especially in the horizontal direction.

A resolution bar from the Department of Civil Engineering at Virginia Tech was used. Tests were performed at distances of 400 and 1400 meters. The standard deviation of the differences between the measured intervals and the intervals on the bar was equal to ±0.79mm, or 0.00026ft, which also represents the resolution of the instrument.

A.3. Cyclic Error.

The cyclic error is a systematic and non-linear error. In order to determine its amplitude a series of short distances were measured over two wave lengths (20 m). The measured distances were then compared to the known distances. The cyclic error was determined to be ± 2.22mm, or ±0.0007ft.

APPENDIX B

Monitoring Software

The following software packages were used for the collection, analysis and presentation of the field data (included are programs developed at Virginia Tech, as well as those purchased from software manufacturers):

1. ZEISSTRANS: This package has been developed by Land Innovation Inc. for the transfer of data between the memory of the tacheometer (ELTA2) and the HP86 computer.

   The memory of the tacheometer is placed into the data converter (DAC 100) and the data are transferred to magnetic diskettes. Limited editing of the data is possible and allows for correction of point numbers and target heights.

2. SUB-STR: This program, developed at Virginia Tech, calculates subsidence, strains, and other related variables from field data.

   Two data files are required for this purpose: the initial, as well as the current, survey file of the site. The initial survey file is sorted by point number, and this version is also stored on the disk for future use. A maximum of 500 points can be used. Each line on the file contains information on the procedure which was followed, as well as the number of each point and its coordinates and elevation.

   After the sorted initial survey file has been read, the current survey file is read and sorted. If errors have been made during the surveying, parts of the survey must be repeated. In that case, the operator is asked to select the correct lines from the file during execution of the program.

Calculations of subsidence, strains and other related variables are then performed for each point. Subsidence is calculated as the difference between elevations. Horizontal strains are calculated from the horizontal distances between points. Horizontal coordinates are only used to calculate these distances, and an error at the beginning of a survey does not effect the accuracy of strain calculations.

Files containing calculated data are then stored on diskettes.

3. SUB-PLOT: This program, developed at Virginia Tech, is used for plotting calculated data, i.e. subsidence and strains, with minimum operator interaction. It automatically adjusts the scale for different mine panel dimensions and/or calculated variables, and plots axes and assigns labels.

   Special attention was given to the compatibility of the data between programs developed during this research, and to commercially available surveying and plotting software.

APPENDIX C

Monitored Case Studies

C.1. Case Study LUVA-VT1

C.1.1. Site Description

Case Study LUVA-VT1 was a longwall mine located in Dickenson County, Virginia. Depth ranged between 480-1050 feet. The terrain was covered with dense forest and the area above the panels under consideration was rolling with steep grades. An old strip mine lay above part of the first panel.

The mine was operating in the Jawbone seam and the mining height was in the range of 6-7.5 feet. Figure C.1 shows a typical geological column for the strata above the mine (percent hardrock 45-47).

C.1.2. Mine Description and Instrumentation

The panel initially selected was the first in a row of four longwall panels. The face was 600 feet long (from rib to rib) and the total advance was 2730 feet. The second panel was 560 feet long at the face and the total advance was 3070 feet. The third panel was 625 feet long at the face. Between panels, two rows of 60 feet wide pillars with a 20 foot entry (total 140 feet) were left.

Initially one longitudinal and one transverse monitoring line were installed above the first panel. Monuments were placed at 50 foot intervals. The longitudinal line (points 66-164) was positioned along the center of the panel. At both ends the lines were extended well beyond the maximum expected area of influence. Due to the existence of the old highwalls and other obstacles, several monuments were at 100 foot intervals (around the middle of the panel). Furthermore some of the monuments had to abandoned be-

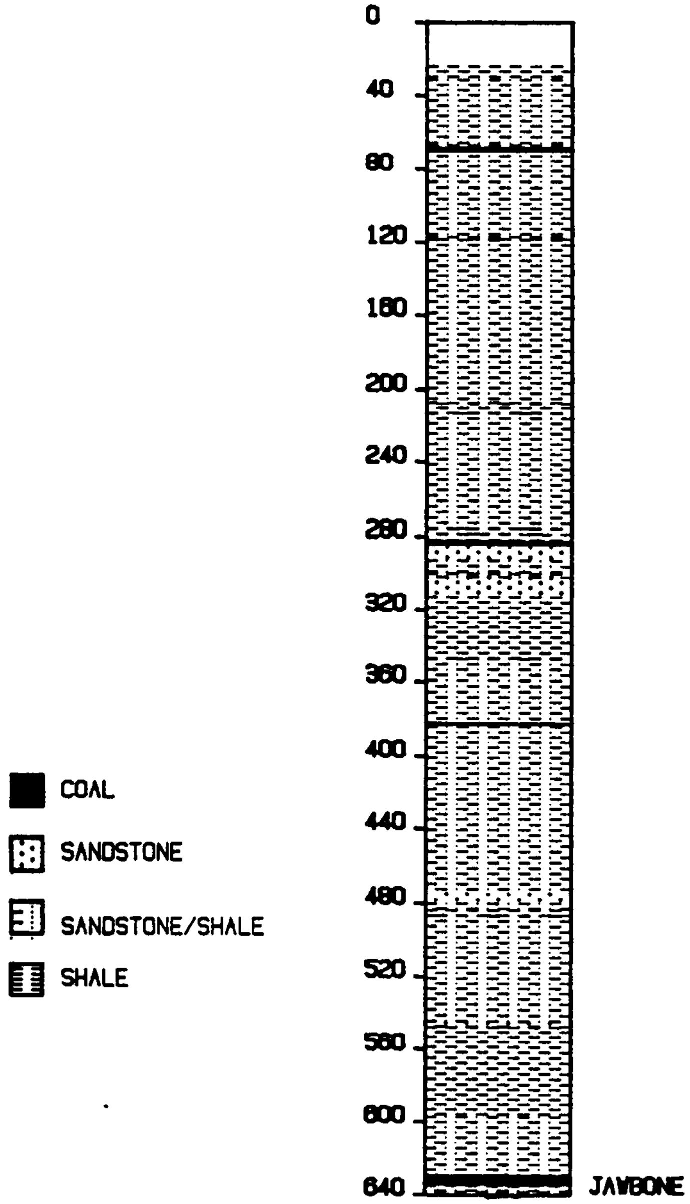

Figure C.1. Geological Column for Case Study RUVA-VT1.

cause of slope failure at some of the highwalls. Two benchmarks were installed beyond point 164. The transverse line (points 178-200 and 201-217) was staggered because of the existence of a highwall and other topographic features.

The monuments consisted of one inch diameter hot roll steel rods. They were properly machined at one end to facilitate their penetration into the ground. Two lengths were used, five feet and two feet, in equal numbers.

In total 137 monuments were installed over 7100 feet of lines, plus several benchmarks and control points. Figure 3.5 presents the mine plan and the monument line layout for this case study.

The transverse line was later extended to cover the second, third and fourth panels. An additional 33 monuments, over 1650 feet of line, plus three more benchmarks were therefore installed (points 6-45).

C.1.3. Monitoring

The monuments were installed before mining of the first panel was initiated. Two surveys were conducted in order to tie the system of monuments to the mine. After the monuments were installed, three surveys were conducted, to determine the coordinates and elevation of each monument.

The efficiency of the surveying technique, which utilized a computerized digital tacheometer with built in EDM, permitted the completion of each survey, i.e. taking over 150 measurements, from 12 stations, over a distance of 8000 feet, in 10-12 hours (two days).

After mining was initiated, the monument lines were scheduled to be surveyed every seven to fifteen days. However, since subsidence developed rapidly, surveys were more frequent whenever the schedule of the monitoring team permitted. Surveys were conducted at the same frequency, even after mining had been completed, until ground movement slowed down. At that time the interval between surveys over segments of the lines not showing significant movement was increased.

In total forty two surveys were conducted between September 1983 and August 1985. Tables C.1 and C.2 and Figures C.2, C.3, C.4 and C.5 are samples of the results calculated after each survey.

C.2. Case Study LUVA-VT2

C.2.1. Site Description

Case Study LUVA-VT2 was a longwall mine located in Wise County, Virginia. Depth ranged from 530 to 870 feet. The terrain was covered by thick forest which had to be partially cleared before the initiation of monitoring. The area above the panels under consideration was rolling with steep grades and a number of strip mines operate in the area.

The mine was operating in the Dorchester seam and the mining height was in the range of 5.5 feet. Figure 4.1 shows a typical geological column for the strata above the mine (percent hardrock 45-60).

Table C.1. Subsidence and Strain Measurements for Case Study LUVA-VT1.

INITIAL SURVEY FILE: <MCINTn >
CURRENT SURVEY FILE: <MC042084 >

Total number of measured points 73

Pt#	Subsidence	Strain
90	.15	-999
91	.1	-1.96138325548E-4
92	.09	1.02656459798E-4
93	.11	-4.62770386397E-6
94	.02	2.03563306113E-4
95	-.08	8.01774681922E-4
96	-.4	1.49528335756E-3
97	-1.03	8.90498874074E-4
98	-1.73	-8.00646637765E-4
99	-2.15	-1.91333830187E-3
100	-2.44	-2.48236091019E-3
101	-2.47	-2.89829044363E-3
102	-2.39	-3.32037257564E-3
103	-2.56	-3.17860112271E-3
104	-3.18	-3.37346869176E-3
105	-3.59	-999
107	-3.25	-999
108	-2.86	1.76481842498E-3
109	-2.77	-2.25695935104E-3
110	-2.82	-2.69983901479E-3
111	-2.74	-1.36647217596E-3
112	-2.84	3.4086731152E-3
113	-3	3.50935058153E-3
114	-2.93	3.03523891335E-4
115	-2.87	-999
120	-3.37	-999
121	-3.37	5.92880814991E-4
122	-3.39	3.09809630078E-4
123	-3.27	-2.90544754305E-4
124	-3.22	-999
126	-3.11	-999
127	-3.12	1.21215416286E-4
128	-3.08	5.07325114429E-4
129	-3.05	-999
131	-2.82	-999
132	-2.74	-1.54969461307E-3
133	-2.56	8.03869065842E-4
134	-2.62	6.45474428572E-4
135	-2.53	-8.87756457639E-4
136	-2.53	-999
138	-2.08	-999

Table C.1. (continued)

Pt#	Subsidence	Strain
142	-.84	2.51844926041E-3
143	-.57	-999
154	-.02	-999
178	.08	-999
179	.1	1.9020666143E-3
180	.11	-9.94277331411E-5
181	.12	-3.20511946047E-7
182	.12	4.90090014105E-4
183	.1	9.9863554776E-5
184	0	-3.04982118895E-4
185	.13	-9.02787424207E-4
186	-.03	3.0307985723E-4
187	.13	1.00570309324E-3
188	.09	1.99965581859E-4
189	.08	-7.98671297049E-4
190	999	6.15413643367E-4
191	-.05	2.70856935582E-3
192	-.18	4.02874144591E-4
193	-.29	-6.01229583286E-4
194	-.49	-4.03874731815E-4
195	-.75	-999
197	-1.56	-999
198	-1.81	-5.4590522697E-3
199	-2.23	-4.41770079348E-3
200	-2.75	9.59298326292E-4
201	-2.59	6.80194342674E-4
202	-1.82	1.47621540419E-3
203	-1.29	-999

Table C.2. Subsidence and Strain Measurements for Case Study LUVA-VT1.

INITIAL SURVEY FILE: <MCINT1n >
CURRENT SURVEY FILE: <MC081985 >

Total number of measured points 83

Pt#	Subsidence	Strain
90	-.06	-999
91	-.12	-1.95456032819E-4
92	-.07	6.0358899135E-4
93	-.11	2.89598066854E-4
94	-.21	-4.93651284568E-4
95	-.32	4.03923473363E-3
96	-.71	-999
102	-2.6	-999
103	-2.83	-3.08285360663E-3
104	-3.44	-2.69502922568E-3
105	-3.91	-2.52338967572E-3
106	999	-1.68059017228E-3
107	-3.59	1.39111151975E-3
108	-3.16	1.35765812113E-3
109	-3.09	-2.7074038656E-3
110	-3.16	-3.28798853554E-3
111	-3.07	-1.18646874386E-3
112	-3.18	4.47449599239E-3
113	-3.37	3.20463761543E-3
114	-3.36	3.03523891335E-4
115	-3.28	-999
120	-4.05	-999
121	-4.03	-999
123	-4.01	-999
125	-3.94	-999
126	-12.39	1.06710385622E-3
127	-3.98	1.00306069319
128	-3.98	1.04218042975E-4
129	-3.95	-999
131	-3.76	-999
132	-3.72	-999
134	-3.56	-999
135	-3.46	-1.69394089065E-3
136	-3.44	-999
138	-3.03	-999
139	-2.62	-3.15757539092E-3
140	-2.25	-3.18073989574E-3
141	-1.87	-2.39151468122E-3
142	-1.51	9.00774356328E-4
143	-1.13	5.03561920733E-3
144	-.79	5.64373101665E-3

Table C.2. (Continued)

Pt#	Subsidence	Strain
152	-.15	-999
153	-.15	-4.14209271498E-4
154	-.13	4.915285059E-4
155	-.14	4.98652919627E-4
156	-.07	-3.96597889182E-4
157	-.07	5.20737374709E-4
158	-.06	-999
160	-.08	-999
161	-.06	-9.40924367449E-5
162	-.01	5.62108794123E-6
163	-.02	8.06741690572E-4
164	-.01	-999
6	-364.73	-999
178	-.59	-999
179	-.85	-999
181	-1.01	-999
182	-1.57	1.27580033668E-3
183	-2.04	-9.04582014548E-4
184	-2.6	-5.0570687833E-4
185	-2.65	-1.50248075449E-3
186	-2.74	-1.92361672996E-3
187	-2.22	-1.02472642741E-3
188	-1.75	9.96520201259E-4
189	-1.24	-999
191	-1.22	-999
192	-1.27	8.1194133382E-4
193	-1.37	1.07320895807E-3
194	-1.5	-999
197	-2.44	-999
203	-1.55	-999
206	-.45	-999
207	-.34	3.69494563964E-3
208	-.24	2.79423234912E-3
209	-.49	5.57974456881E-3
210	-.62	5.10156484011E-3
211	-.39	-1.09837979185E-3
212	-.23	-3.98553270642E-3
213	-.1	-999
203	-1.55	-999

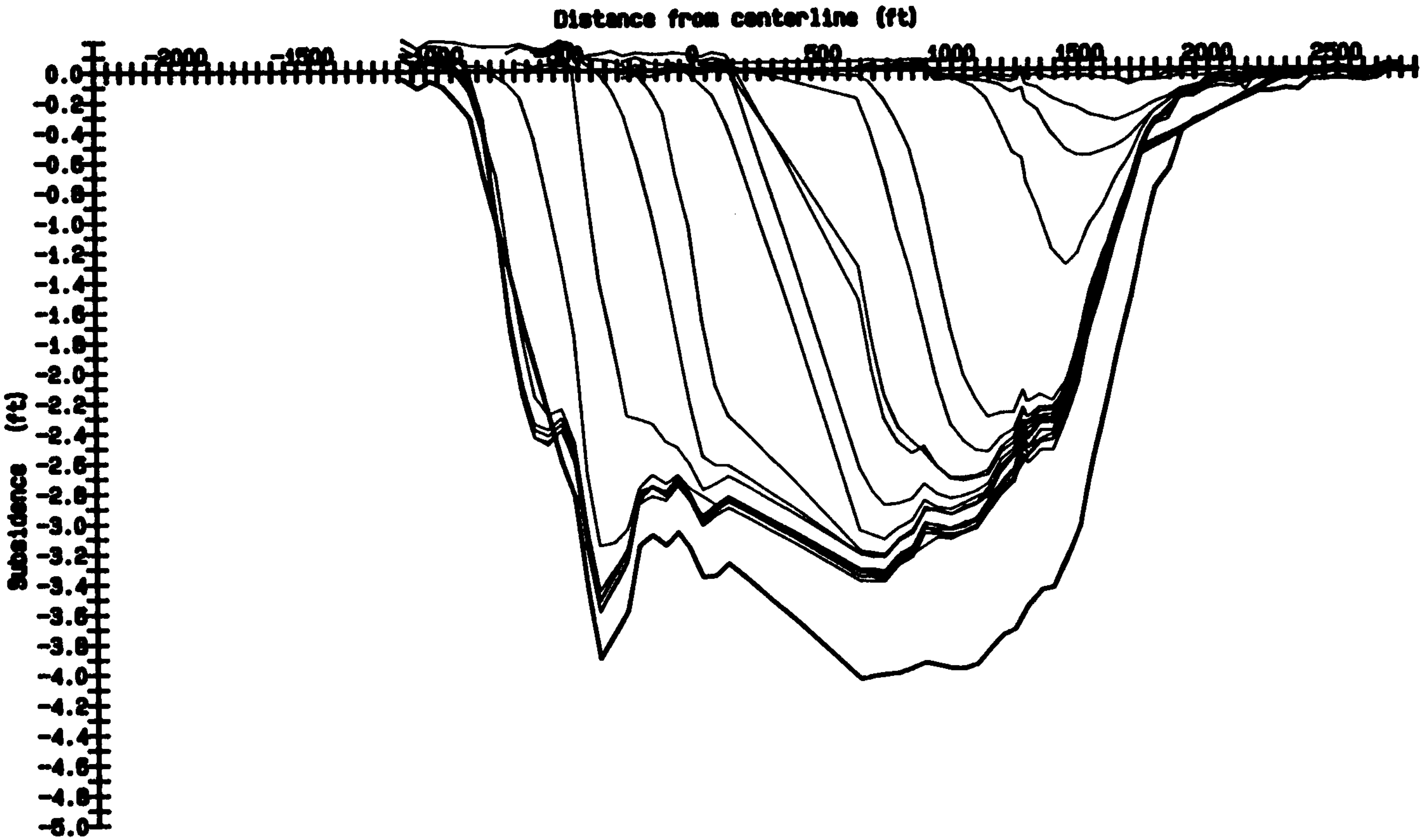

Figure C.2. Longitudinal Subsidence Profiles for Case Study LUVA-VT1.

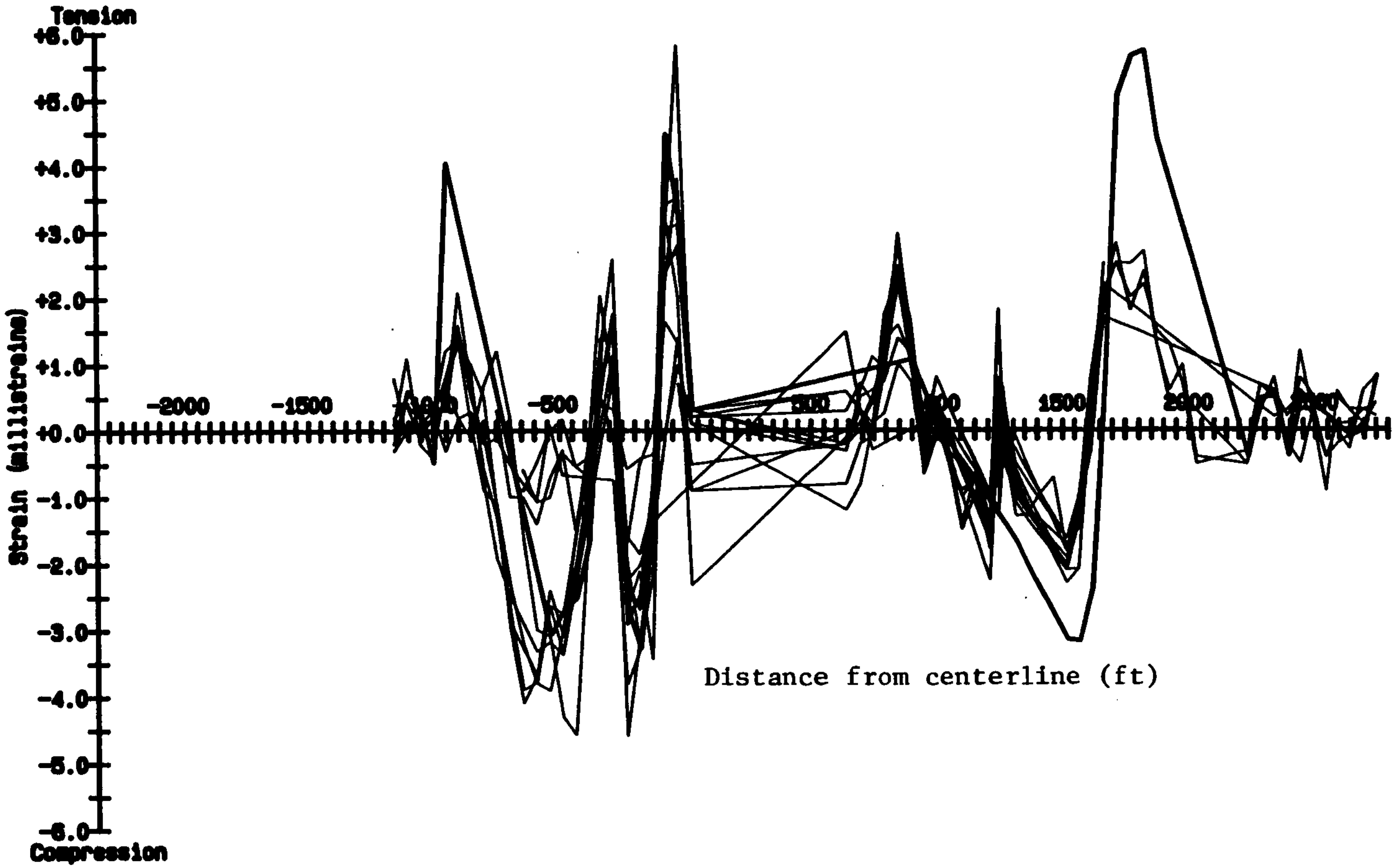

Figure C.3. Longitudinal Strain Profiles for Case Study LUVA-VT1.

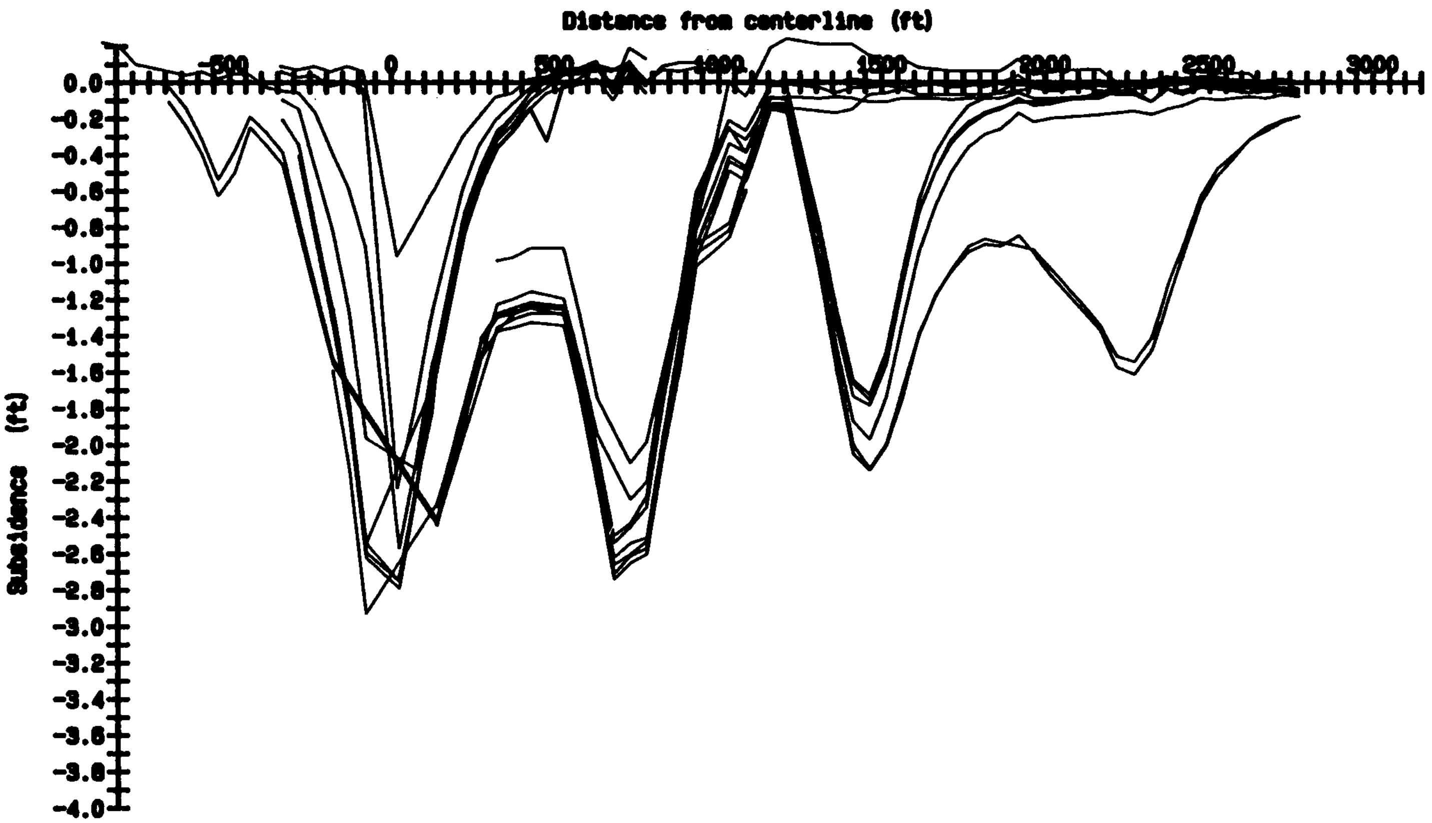

Figure C.4. Transverse Subsidence Profiles for Case Study LUVA-VT1.

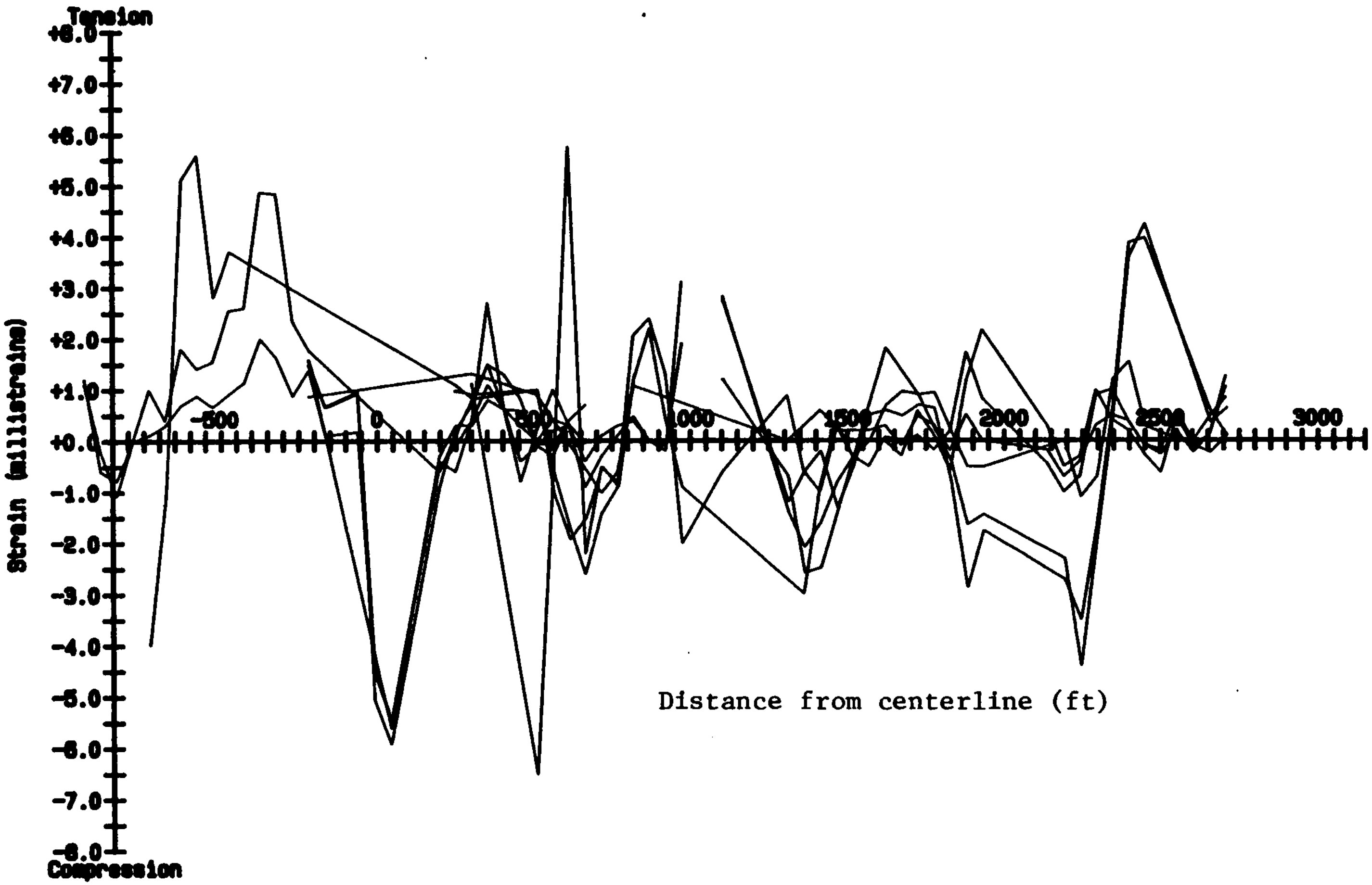

Figure C.5. Transverse Strain Profiles for Case Study LUVA-VT1.

C.2.2. Mine description and Instrumentation

The section selected for monitoring consisted of three longwall panels. The face at the first panel was 570 feet wide (from rib to rib) and the total advance was 2710 feet. The second panel was 550 feet wide and the total advance was 2620 feet. The third panel was 540 feet wide and achieved a total advance of 2710 feet. Two rows of pillars were left between panels, 45 and 75 feet wide respectively, with 20 foot entries.

Monitoring lines, one longitudinal and one transverse, were installed above this section (Figure 3.6). Monuments were placed at 25 foot intervals. The longitudinal line (points 10-150) was positioned along the center of the second panel. At both ends the lines were extended well beyond the maximum expected area of influence. Due to topographic features several monuments were at larger intervals (mostly along the transverse line, above the third panel). Furthermore some of the monuments had to be abandoned because of loosening of the ground during the development of tensile strain after mining, because of slope failures and because of the development of a nearby strip mine. Two reference benchmarks were installed beyond point 10.

Two lengths of monuments were used, five feet and three feet, in a ratio of one to three. In total, 260 monuments were installed over 7700 feet of survey lines, plus several benchmarks and control points.

C.2.3. Monitoring

The monuments were installed before mining of the first panel was initiated. Two surveys were conducted in order to tie the system of monuments to the mine. After the monuments were installed, three surveys were conducted, to determine the coordinates and elevation of each monument.

After mining was initiated, the monument lines were scheduled to be surveyed every seven to fifteen days. It should be mentioned that access was impossible a few times due to bad weather conditions. Surveys were conducted at the same frequency, even after mining had been completed, until all ground movements slowed down. At that time the interval between surveys over segments of the lines not showing significant movement increased.

In total 36 surveys were conducted between April 1984 and January 1986. Tables C.3 through C.6 and Figures C.6 through C.9 present typical results calculated after each survey.

C.3. Case Study RUVA-VT1

C.3.1. Site Description

Case Study RUVA-VT1 was a room and pillar panel located at Wise County, Virginia. The average depth was in the range of 540 feet. The terrain was covered by dense forest and the area above the panel was rolling with steep grades. An old reclaimed strip mine lay above a small part of the panel.

The panel was the second last of an extraction sequence and was operating in the Parsons seam, having an average thickness of 5 feet. Figure 4.3 shows a typical geological column for the strata above the mine.

Table C.3. Subsidence and Strain Measurements for Case Study LUVA-VT2.

INITIAL SURVEY FILE: <BTIN1n >
CURRENT SURVEY FILE: <BT012985 >

Total number of measured points 115

Pt#	Subsidence	Strain
38	-.24	-999
40	-.37	-999
41	-.42	2.60545927975E-3
42	-.52	7.51982773801E-4
43	-.64	1.97302627887E-4
44	-.76	-4.40348069945E-4
45	-.86	-1.86617352707E-3
46	-.97	-9.2791721412E-4
47	-1.04	-1.53423847422E-3
48	-1.14	-9.66043545413E-4
49	-1.22	2.0397763505E-3
50	-1.29	-3.25437742672E-4
51	-1.38	-1.34396380223E-3
52	-1.46	-1.56380585797E-4
53	-1.58	-7.10710937696E-4
54	-1.64	2.32029405807E-3
55	-1.72	3.6868074157E-3
56	-1.83	-5.11902305546E-4
57	-1.92	-6.50716412228E-3
58	-1.94	-2.39980645775E-3
59	-1.96	3.42591859624E-3
60	-1.97	2.84319037259E-3
61	-2	-4.08133632021E-4
62	-2.03	.154965444033
63	-2.07	1.42138367958E-4
64	-2.05	-.372419182525
65	-2.1	-1.43058364101E-3
66	-2.09	-3.47154794111E-3
67	-2.08	-8.04198653285E-3
68	-2.08	6.77189852903E-3
69	-2.19	-999
71	-2.19	-999
72	-2.18	7.89651312509E-3
73	-2.27	-1.87534406902E-4
74	-2.32	-1.32512630722E-3
75	-2.3	1.59289077756E-3
76	-2.34	1.69231239103E-3
77	-2.28	2.9363238002E-3
78	-2.38	3.59912447699E-3
79	-2.34	3.19120105437E-4
80	-2.36	6.21941986116E-4

Table C.3. (continued)

Pt#	Subsidence	Strain
84	-2.02	1.50850189791E-3
85	-1.97	2.67460749972E-4
86	-1.99	-999
90	-2	-999
91	-1.97	1.31135665466E-3
92	-1.88	-7.02525585337E-3
93	-1.78	-3.74406851663E-3
94	-1.85	-6.48030726016E-3
95	-1.61	-7.14392327622E-3
96	-1.58	-.002194725345
97	-1.5	-2.57558353289E-3
98	-1.43	-1.71232629958E-3
99	-1.37	1.45049773791E-3
100	-1.25	-1.00382273165E-2
101	-999	-2.42755293849E-3
102	-1.16	1.12786685205E-2
103	-1.17	7.09701131249E-4
104	-1.39	-1.84938491705E-3
105	-1.43	1.60717027859E-4
106	-1.21	7.92600672025E-4
107	-1.09	-5.70253825547E-4
108	-.9	-7.21639111446E-3
109	1.15	1.4934017068E-3
110	-.69	9.84735221078E-3
111	-.62	-1.9718751083E-3
112	-.53	-1.01858494852E-3
113	-.47	1.88347663099E-4
114	-.35	1.97773705062E-3
115	-.24	-999
117	-.22	-999
118	-.17	5.16588093893E-4
119	-.2	2.25996340304E-3
120	-.1	8.41457442449E-4
121	-.1	-1.56877538317E-3
122	-.07	1.06485906901E-3
123	.01	1.92543956691E-3
124	-.07	-9.07657238887E-5
125	-.01	-5.7132237563E-4
126	-.03	5.12571010049E-4
127	.01	-6.88337513111E-4
128	.12	3.94668376709E-4
129	.1	1.49773011968E-3
130	.08	2.0662560455E-4
131	.02	-999
294	-1.24	-999
295	-1.43	-5.58460911808E-3
296	-1.67	-1.43891648748E-2

Table C.4. Subsidence and Strain Measurements for Case Sudy LUVA-VT2.

INITIAL SURVEY FILE: <BTIN1n >
CURRENT SURVEY FILE: <BT061185 >

Total number of measured points 64

Pt#	Subsidence	Strain
38	-.24	-999
60	-2.25	-999
61	-2.28	-2.25697412463E-3
62	-2.29	.157809286945
63	-2.36	-1.42101671097E-4
64	-2.34	-.372395114238
65	-2.36	-1.79666388916E-3
66	-2.37	-5.19760074217E-3
67	-2.35	2.92097423826E-3
68	-2.36	1.9365273678E-3
69	-2.44	-2.21094941704E-3
70	-2.42	-6.06467688712E-4
71	-2.41	-9.66180444665E-4
72	-2.42	-4.37648965886E-3
73	-2.47	-999
75	-2.5	-999
78	-2.54	-999
79	-2.55	1.18907171575E-3
80	-2.47	5.21783820402E-5
81	-2.38	3.42044595987E-3
82	-2.3	2.27618649649E-3
83	-2.2	2.21784316967E-3
84	-2.15	1.87292377292E-3
85	-2.1	1.18683465878E-4
86	-2.1	-999
90	-2.06	-999
91	-2	-3.0604925681E-4
92	-2	-7.19917952224E-3
93	-1.88	-3.61783143792E-3
94	-1.92	-6.91398177448E-3
95	-1.66	-7.22413315216E-3
96	-1.63	-3.66958451261E-3
97	-1.6	-2.46163738615E-3
98	-1.52	-6.20822158853E-4
99	-1.49	2.37818594029E-3
100	-1.41	-1.19521893632E-2
101	-1.35	-2.99446452507E-3
102	-1.33	.013138040208
103	-1.37	-5.04665519866E-5
104	-1.64	-999
106	-1.56	-999

Table C.4. (continued).

Pt#	Subsidence	Strain
110	-1.59	-1.98068289733E-4
111	-1.6	-1.11885549242E-3
112	-1.62	-3.00830749125E-4
113	-1.66	1.18332461811E-3
114	-1.67	-3.63387401077E-4
115	-1.72	-999
117	-1.93	-999
118	-2.02	-1.19233716441E-3
119	-2.14	1.30349398162E-3
120	-2.16	-1.84170400802E-3
121	-1.99	-4.3999198291E-3
122	-1.7	-1.80638852083E-4
123	-1.36	-2.88073099982E-4
124	-1.2	-1.26386691067E-3
125	-.95	-8.66253828103E-4
126	-.75	-2.09653208431E-4
127	-.55	2.76860038748E-4
128	-.46	1.53765184651E-3
129	-.26	-999
75	-2.5	-999

Table C.5. Subsidence and Strain Measurements for Case Study LUVA-VT2.

INITIAL SURVEY FILE: <BTIN1n >
CURRENT SURVEY FILE: <BT122085 >

Total number of measured points 118

Pt#	Subsidence	Strain
10	.05	-999
11	.05	8.24747271786E-5
12	.05	-3.98859182322E-5
13	.05	-2.80433465307E-4
14	.05	0
15	.05	5.56788953207E-4
16	.03	-4.21134354076E-4
17	-.01	-7.28547187989E-4
18	.03	3.94778478386E-4
19	.02	2.11298898441E-3
20	.01	1.00598635097E-3
21	0	2.78951404503E-4
22	-.01	3.9946401401E-4
23	-.01	-3.14878931024E-4
24	-.01	-3.20492993345E-4
25	-.02	1.87505688849E-4
26	-.03	3.19530864134E-4
27	-.04	-1.70823946021E-4
28	-.05	1.92499932034E-3
29	-.06	1.12126481662E-3
30	-.07	-1.33244336048E-3
31	-.09	-1.09272166281E-4
32	-.1	2.36864159278E-3
33	-.12	3.22183414213E-4
34	-.16	1.62911199618E-4
35	-.19	2.6954367506E-3
36	-.18	1.33214255196E-3
37	-.23	2.38827862198E-4
38	-.24	-999
40	-.43	-999
41	-.5	.002251661563
42	-.61	1.50491479868E-3
43	-.75	1.58507161877E-4
44	-.9	-4.40348069945E-4
45	-1.02	-1.95074845759E-3
46	-1.15	-1.56545216455E-3
47	-1.25	-3.72314945292E-3
48	-1.34	-4.05765405263E-4
49	-1.45	3.99737443142E-3
50	-1.53	-999

Table C.5. (continued)

Pt#	Subsidence	Strain
56	-2.14	-8.29016583133E-4
57	-2.24	-6.46398068697E-3
58	-2.25	-1.67964757752E-3
59	-2.27	3.42591859624E-3
60	-2.27	3.72309897879E-3
61	-2.33	1.953707968E-4
62	-2.35	.156063254394
63	-2.39	-9.51484803786E-4
64	-2.4	-.373660028646
65	-2.38	-1.94860570577E-3
66	-2.43	-2.42179409832E-3
67	-2.42	-3.60235116934E-3
68	-2.4	-1.84654401149E-3
69	-2.5	2.02805314811E-3
70	-2.48	7.75313336353E-4
71	-2.47	-3.96991896409E-4
72	-2.48	4.42100305212E-4
73	-2.53	-1.63416283353E-3
74	-2.59	-3.67350074321E-4
75	-2.54	2.59030440159E-3
76	-2.61	1.53170384538E-3
77	-2.6	2.25871803904E-3
78	-2.59	3.64896277813E-3
79	-2.56	-7.49988083403E-4
80	-2.49	-5.19851762861E-4
81	-2.44	3.2515808808E-3
82	-2.35	2.03686730461E-3
83	-2.25	2.21784316967E-3
84	-2.19	1.59555651523E-3
85	-2.14	1.92973082561E-4
86	-2.14	-999
90	-2.1	-999
91	-2.03	4.12661149503E-3
92	-2.08	-999
94	-1.95	-999
95	-1.69	-7.51840565199E-3
96	-1.67	-3.26969861233E-3
97	-1.62	-3.0917772039E-3
98	-1.54	-2.22734391372E-4
99	-1.49	2.13485567853E-3
100	-1.44	-999
258	.01	-999
259	0	5.51565863551E-4
260	-.01	-999
262	-.4	-999
263	-.4	1.29274013873E-4
264	-.46	3.83836464013E-3
265	-.74	6.17753541071E-3

Table C.5. (continued)

Pt#	Subsidence	Strain
270	-1.7	-7.21927400375E-4
271	-1.95	-1.01450912513E-3
272	-2.21	-2.39404610147E-3
273	-2.29	-3.89105762421E-3
274	-2.34	-3.04189192699E-3
275	-2.24	-2.20921702368E-3
276	-2.02	-8.65979727927E-4
277	-1.69	1.74354873735E-4
278	-1.54	-1.33238951736E-3
279	-1.34	-999
283	-.42	-999
287	-.23	-999
288	-.22	-3.46845862584E-3
289	-.26	4.99589294033E-4
290	-.27	-999
293	-29.04	-999
294	-1.55	1.05595373854
295	-1.69	-6.07107043082E-3
296	-1.93	-1.27597267392E-2
297	-2.1	-1.29762496302E-3
298	-2.37	-999

Table C.6. Subsidence and Strain Measurements for Case Study LUVA-VT2.

INITIAL SURVEY FILE: <BTIN1n >
CURRENT SURVEY FILE: <BT011686 >

Total number of measured points 114

Pt#	Subsidence	Strain
10	.05	-999
11	.03	1.16474742644E-3
12	.03	1.11727384425E-3
13	.03	3.20548114031E-4
14	.02	5.83288159018E-4
15	.02	3.97554438499E-4
16	.01	-999
18	0	-999
19	0	8.37251173927E-4
20	0	5.62789153529E-4
21	-.02	1.5871096889E-4
22	0	2.40977591541E-4
23	-.01	-6.29701567807E-4
24	-.01	-3.71547074034E-4
25	-.01	7.62684239465E-4
26	-.04	-1.16341961094E-4
27	-.04	-5.93595346623E-4
28	-.06	2.24813184996E-3
29	-.07	8.02551457183E-4
30	-.08	-1.49257426296E-3
31	-.09	2.05791147031E-4
32	-.1	-2.20804047724E-3
33	-.14	6.02932247437E-4
34	-.17	4.5351552742E-3
35	-.19	1.6091934766E-3
36	-.2	1.00999908992E-3
37	-.25	7.55139357842E-4
38	-.23	-999
40	-.45	-999
41	-.52	2.21667005854E-3
42	-.64	1.1283302653E-3
43	-.76	-1.18529555776E-4
44	-.92	-4.40348069945E-4
45	-1.03	-1.57636105565E-3
46	-1.17	-1.36741972886E-3
47	-1.26	-1.72497765588E-3
48	-1.37	-7.63386696372E-4
49	-1.46	1.92022323445E-3
50	-1.55	-4.48629318446E-4
51	-1.66	-1.53776405884E-3
52	-1.76	-1.96782404534E-4
53	-1.88	-9.00716661853E-4

Table C.6. (continued)

Pt#	Subsidence	Strain
56	-2.17	-1.08117202637E-4
57	-2.24	-6.10929897089E-3
58	-2.28	-2.0794667457E-3
59	-2.28	3.4639736061E-3
60	-2.29	3.00267365121E-3
61	-2.35	-9.29751177655E-4
62	-2.38	.156612172365
63	-2.41	-999
80	-2.53	-999
301	-2.44	-999
302	-2.19	-3.12623717656E-3
303	-1.62	3.76523467548E-4
304	-1.33	-1.02768755178E-2
305	-999	4.16984121056E-3
306	-.92	1.79069343958E-2
307	-.75	4.95462511059E-3
308	-.6	1.08916457699E-2
309	-.51	7.78313450493E-3
310	-.42	3.65668354755E-3
311	-.48	-999
312	-.46	-999
313	-.43	-999
314	-.42	2.35885936389E-3
315	-.45	9.47127536558E-4
316	-.47	1.44581718488E-3
317	-.52	2.0423299356E-3
318	-.54	1.62372954984E-3
319	-.6	-999
321	-.7	-999
322	-.76	1.89326997486E-3
323	-.81	1.39636011789E-3
324	-1.07	7.7384160438E-3
325	-1.3	-999
328	-2.56	-999
329	-2.47	-1.03773816697E-3
330	-2.34	-1.16274742139E-3
331	-2.21	1.8599580754E-3
332	-1.94	-7.81632840316E-4
333	-1.61	-4.3994413578E-4
334	-1.44	1.56413594124E-3
335	-1.11	-7.05822348011E-3
336	-.95	-8.40384824371E-3
337	-.77	2.19139711781E-3
338	-.66	3.40668783106E-3
339	-.61	3.71672304511E-3
340	-.42	1.08407047783E-3
341	-.32	-1.42517631841E-3

Table C.6. (continued)

Pt#	Subsidence	Strain
347	-.19	-2.37237607143E-4
348	-.16	4.76085970639E-4
349	-.17	-2.40601777022E-4
350	-.13	-7.24256917352E-4
351	-.12	-3.17327581459E-3
352	-.12	-999
356	-.06	-999
357	-.07	.001318962194
358	-.07	4.566576263E-4
359	-.08	-1.02274991422E-3
360	-.07	-8.07349243768E-4
361	-.09	-1.91513608542E-4
362	-.09	1.12322541028E-3
363	-.09	9.83536047156E-4
364	-.05	-1.61006507609E-4
365	-.08	-999
367	-.08	-999

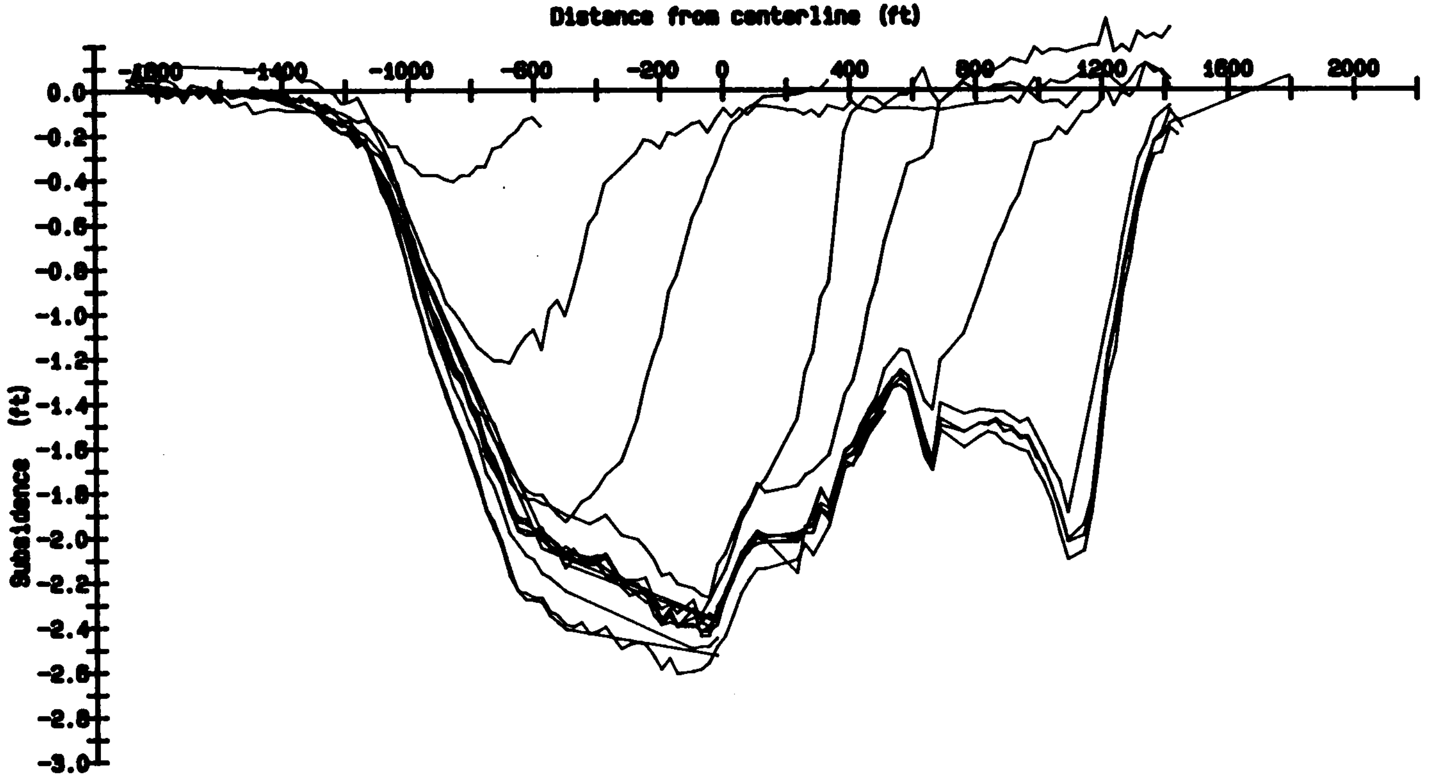

Figure C.6. Longitudinal Strain Profiles for Case Study LUVA-VT2.

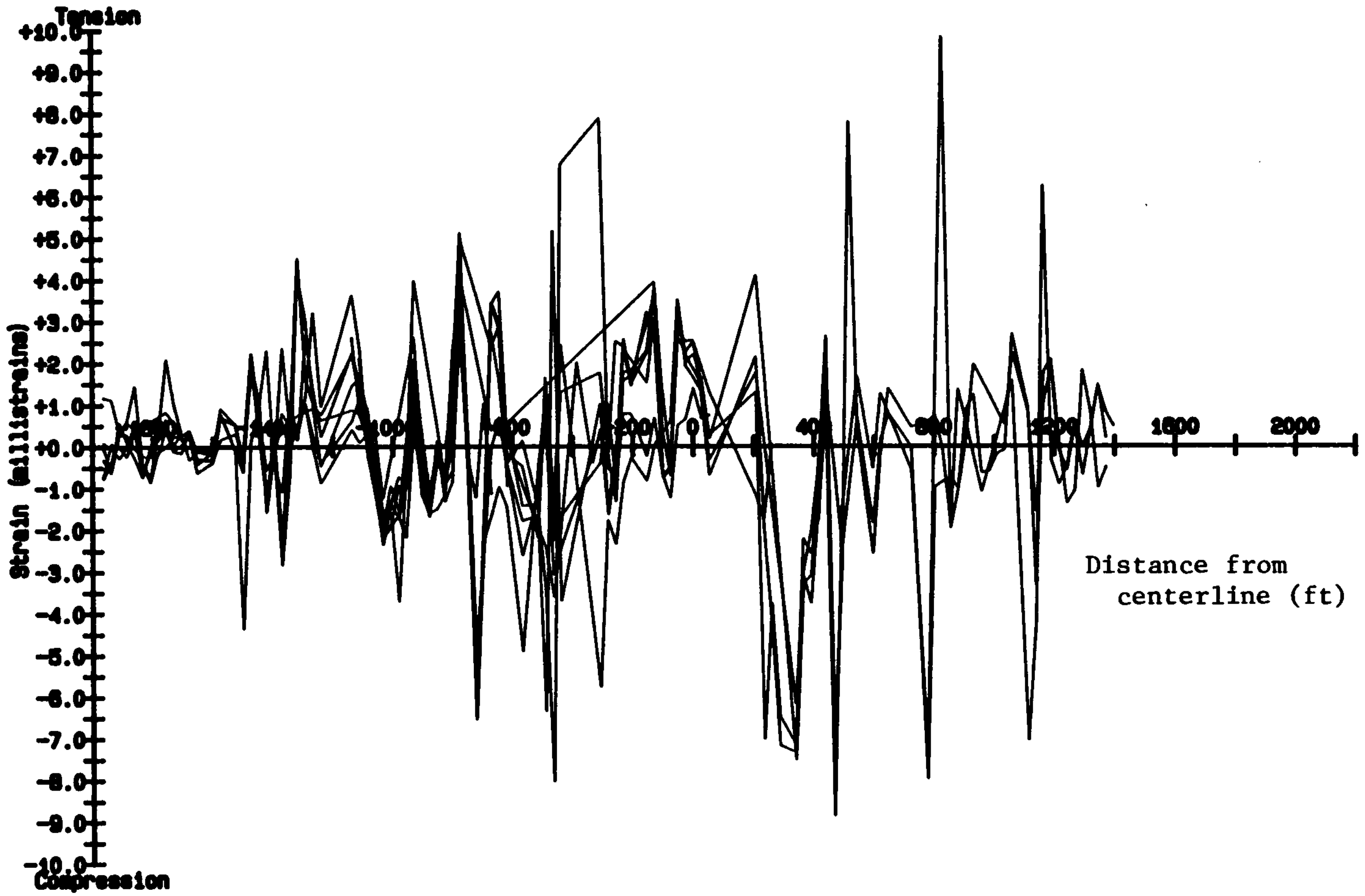

Figure C.7. Longitudinal Strain Profiles for Case Study LUVA-VT2.

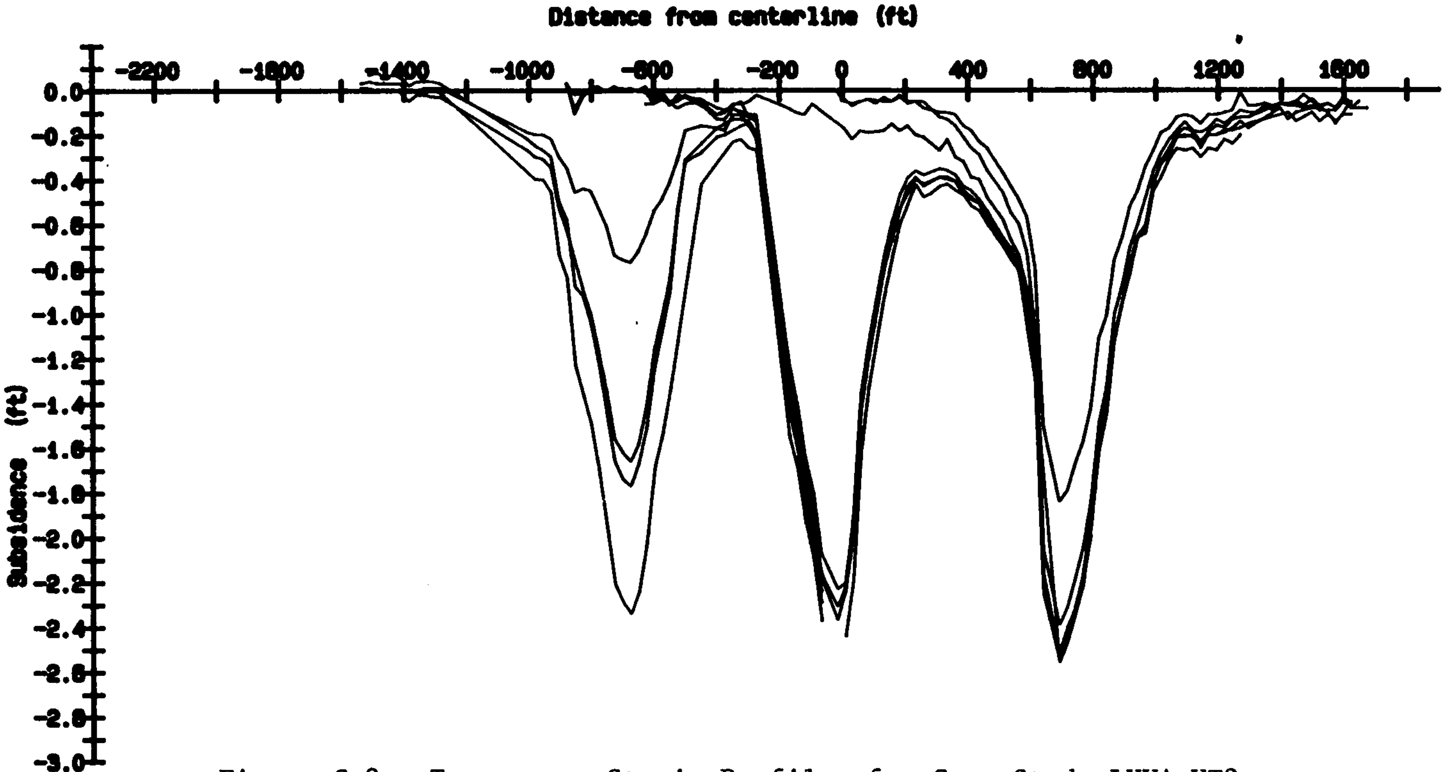

Figure C.8. Transverse Strain Profiles for Case Study LUVA-VT2.

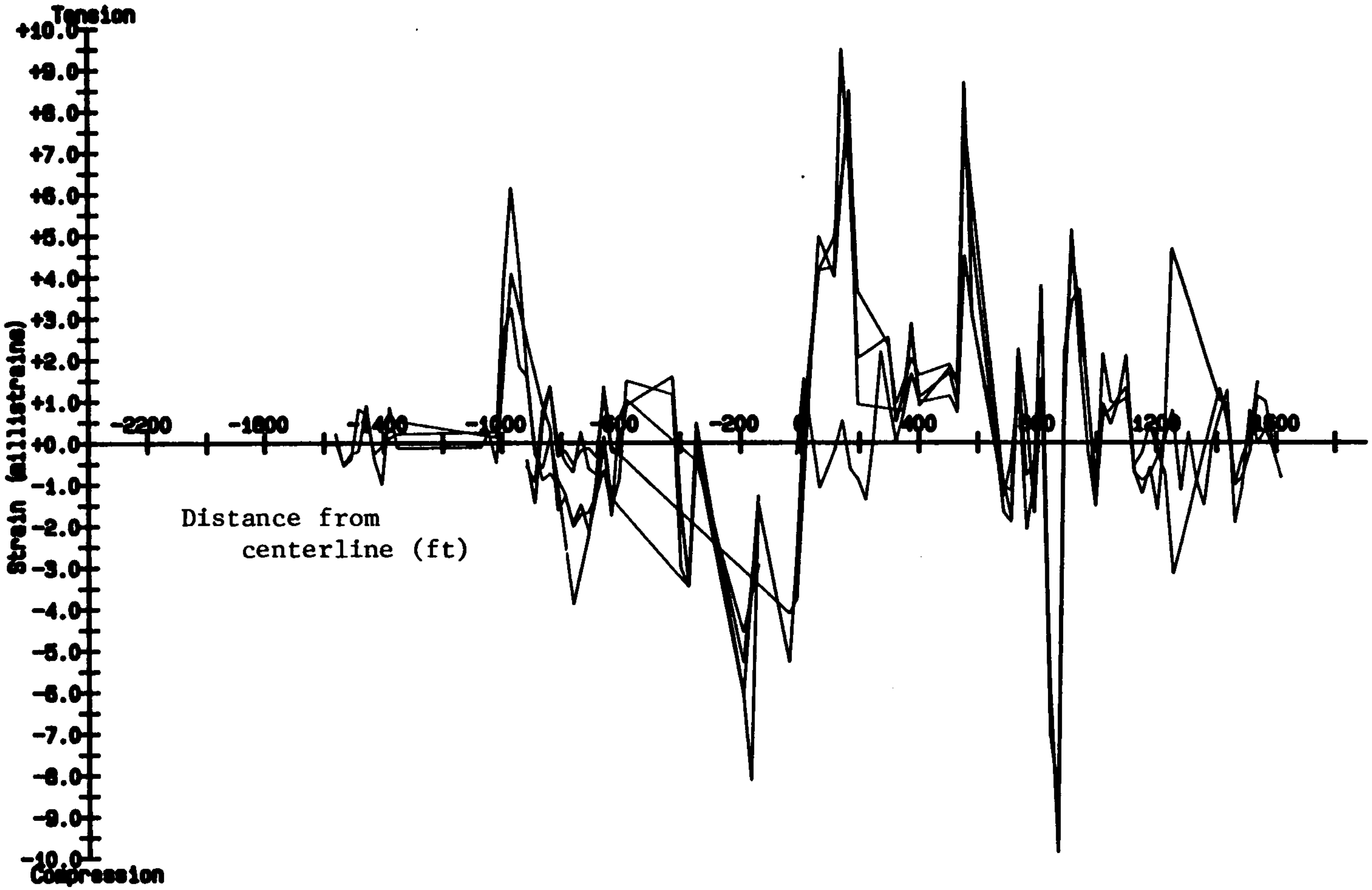

Figure C.9. Transverse Strain Profiles for Case Study LUVA-VT2.

Pillar extraction was achieved using a "wing" plan: the pillar was split along its center line which allows cuts to be taken to the right and the left. This method permits an extraction ratio of approximately 85%.

C.3.2. Mine Description and Instrumentation

The panel selected for monitoring was the second last in an extraction sequence. Each panel had five entries 20 feet wide at 60 feet centers. During pillaring, one or two rows of pillars, to the side of the solid coal, were left for ventilation purposes. In addition, when driving the panel, a solid pillar of 160 feet was left towards the previously extracted area. Crosscuts were at 75 feet centers.

After the panel was completed, crosscuts were driven towards the previous panel. The crosscuts were connected by entries at 60 feet centers, with simultaneous extraction of the pillars. During this stage, the final layout for the panel in question consisted of eight rows of pillars: one left in the previously extracted area, three in the solid pillar that was initially left between the panels and four in the panel (Figure 6). Initial plans were to excavate seven of these rows leaving one for ventilation. However, two rows of pillars were finally left, to be taken when the next panel would be mined.

Two monitoring lines were installed above the panels. They were positioned according to its planned shape. The longitudinal line was placed along the projected center line of the panel (points 37-80). However, because not all pillars were recovered as planned, this line was eventually displaced from the panel center axis. The first point (#37) was located above the edge of the excavation; beyond this point lay the old strip mine where monuments were not placed. On the other side of the strip mine, three benchmarks were established, well beyond the expected area of influence. At the other end of the panel the line was extended beyond the area of influence (point #80). The transverse line started well beyond the area of influence (point #81) and was extended above the gob area of the previous panel (point #115).

The spacing of monuments was 25 feet. Two lengths of monuments were used, five feet and two feet, at a ratio of one to three.

C.3.3. Monitoring

The monuments were installed during the development of the panel. Three initial surveys were conducted. The first survey tied the system of monuments to the mine. The purpose of the second survey was to determine the coordinates and elevation of each monument. The third survey was run in order to double check the data.

Each survey was completed within four to five hours. The procedure included taking three initial back-sights, moving the instrument to nine stations over a rough terrain and taking 79 measurements. The accuracy of these surveys was checked with the use of a precision level, a procedure which took more than two working days to complete.

After the extraction of pillars was initiated the monument lines were surveyed every seven to ten days. Six surveys were conducted within a period of two months. After the mining had ceased, surveys were conducted at the same frequency until ground movement slowed down and the time span between subsequent surveys was gradually expanded to a month. The last survey was taken four months after the completion of mining. The monitoring lines were then removed during the development of a nearby strip mine. In total, fourteen surveys were conducted. Table C.7 and Figures C.10 trough C.13 present typical results calculated after each survey.

Table C.7. Subsidence and Strain Measurements for Cas Study RUVA-VT1.

INITIAL SURVEY FILE: <ELINT >
CURRENT SURVEY FILE: <EL020884 >

Total number of measured points 68

Pt#	Subsidence	Strain
37	-.21	-999
38	-.27	8.68782968722E-4
39	-.37	1.78939923029E-3
40	-.49	1.88207613859E-3
41	-.62	5.2997245514E-4
42	-.72	-1.14747353509E-4
43	-.78	4.2814181575E-4
44	2.41	-999
46	-.99	-999
47	-.99	-9.957484126445E-4
48	-1.01	3.68121553117E-4
49	-1.02	-3.7527635263E-4
50	-1.01	2.15752806398E-4
51	-.99	-1.60396440295E-4
52	-.92	3.24770157475E-4
53	-.91	-4.13389497194E-5
54	-.77	5.32838613994E-4
55	-.74	2.0349803622E-3
56	-.7	4.09315303173E-4
57	-.54	-3.45767077361E-3
58	-.55	-3.63583657441E-3
59	-.5	-2.22048761484E-3
60	-.39	-1.95672542474E-3
61	-.31	2.96938351931E-3
62	-.23	3.19367656105E-3
63	-.17	-1.67717795308E-5
64	-.13	1.05716815824E-3
65	-.1	1.47688272169E-3
66	-.06	9.30818932302E-4
67	-.05	1.61228196334E-3
68	-.02	1.71877960918E-3
69	0	-3.66869275882E-4
70	0	-999
72	.02	-999
81	-.01	-999
82	-.01	-1.19430024771E-3
83	-.02	5.35552657106E-4
84	-.01	2.28186068929E-3
85	-.03	1.07236883582E-3
86	-.01	4.07788618667E-4

Table C.7. (continued)

Pt#	Subsidence	Strain
92	-.05	3.46854044751E-3
93	-.04	1.81191204427E-5
94	-.06	-999
96	-.07	-999
97	-.1	6.55461469849E-4
98	-.09	-1.19775140528E-3
99	-.15	1.43006545176E-3
100	-.14	1.0921663872E-3
101	-.22	3.38149227437E-3
102	-.29	2.4690580836E-3
103	-.38	1.79807262808E-3
104	-.54	1.09263512574E-3
105	-.76	-999
107	-1.25	-999
108	-1.57	-3.88364504151E-4
109	-1.69	-5.31829437139E-4
110	-1.82	-1.36912242023E-3
111	-1.9	-1.85342516004E-3
112	-2.08	-1.72831628474E-3
113	-2.02	-8.93097514006E-4
114	-2.04	-4.00198908153E-4
115	-2.06	-999
300	41.79	-999
110	-1.82	-1.36912242023E-3

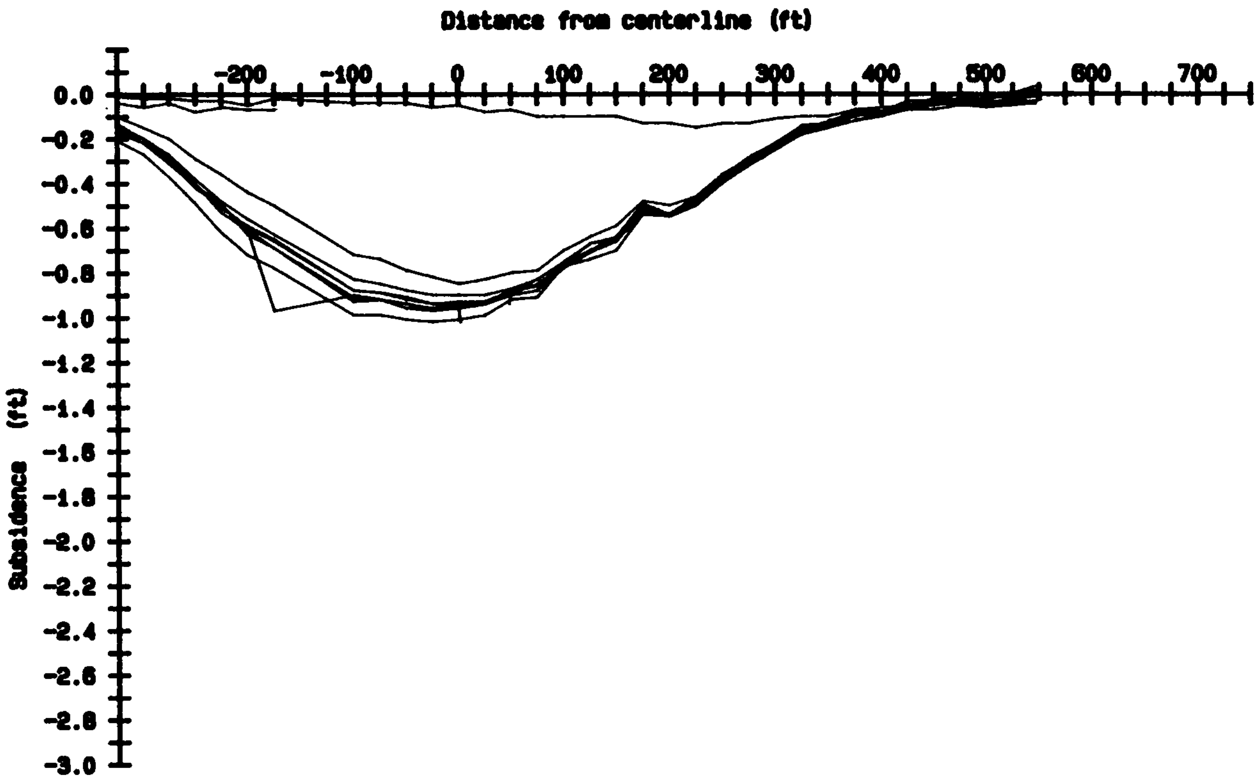

Figure C.10. Longitudinal Subsidence Profile for Case Study RUVA-VT1.

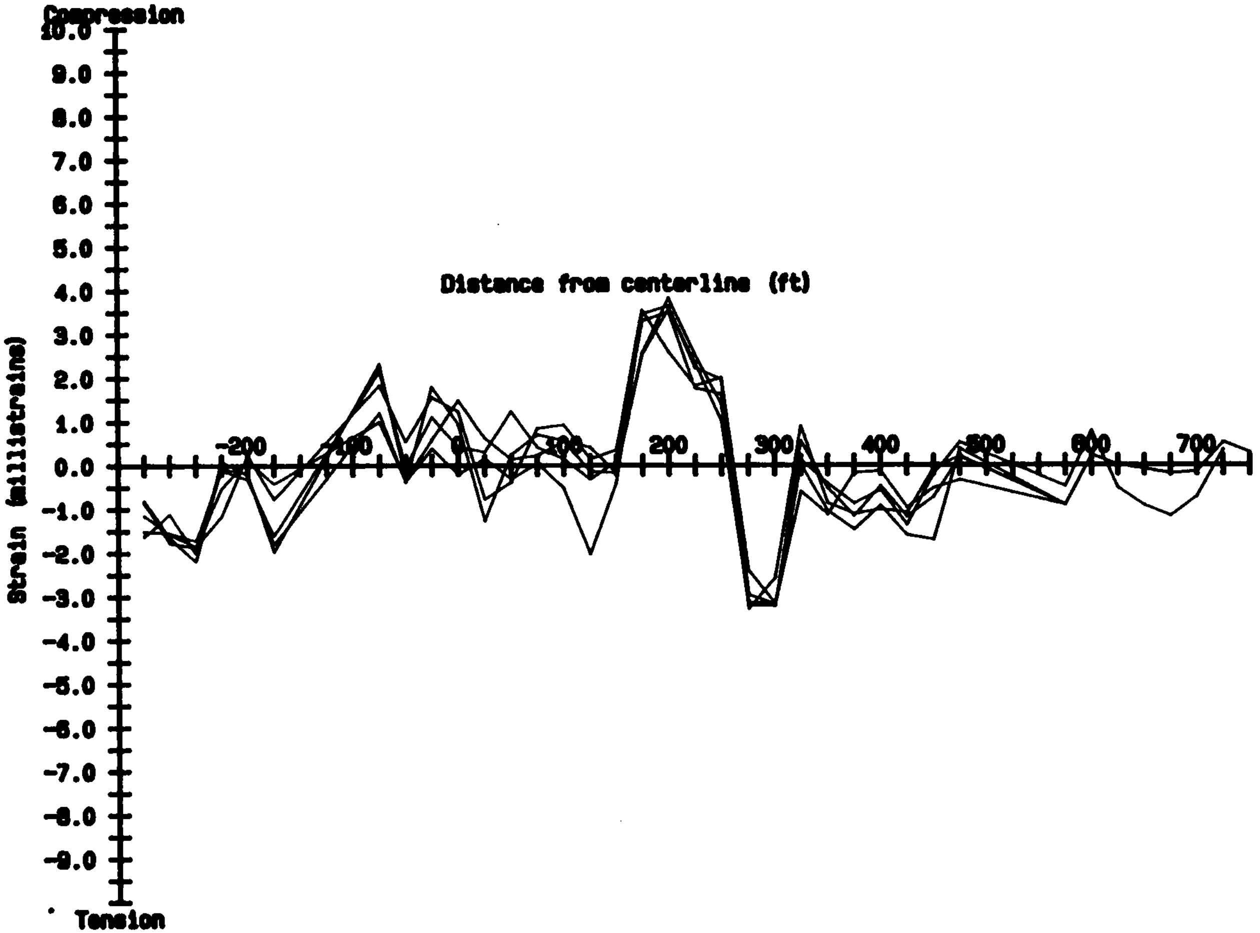

Figure C.11. Longitudinal Strain Profiles for Case Study RUVA-VT1.

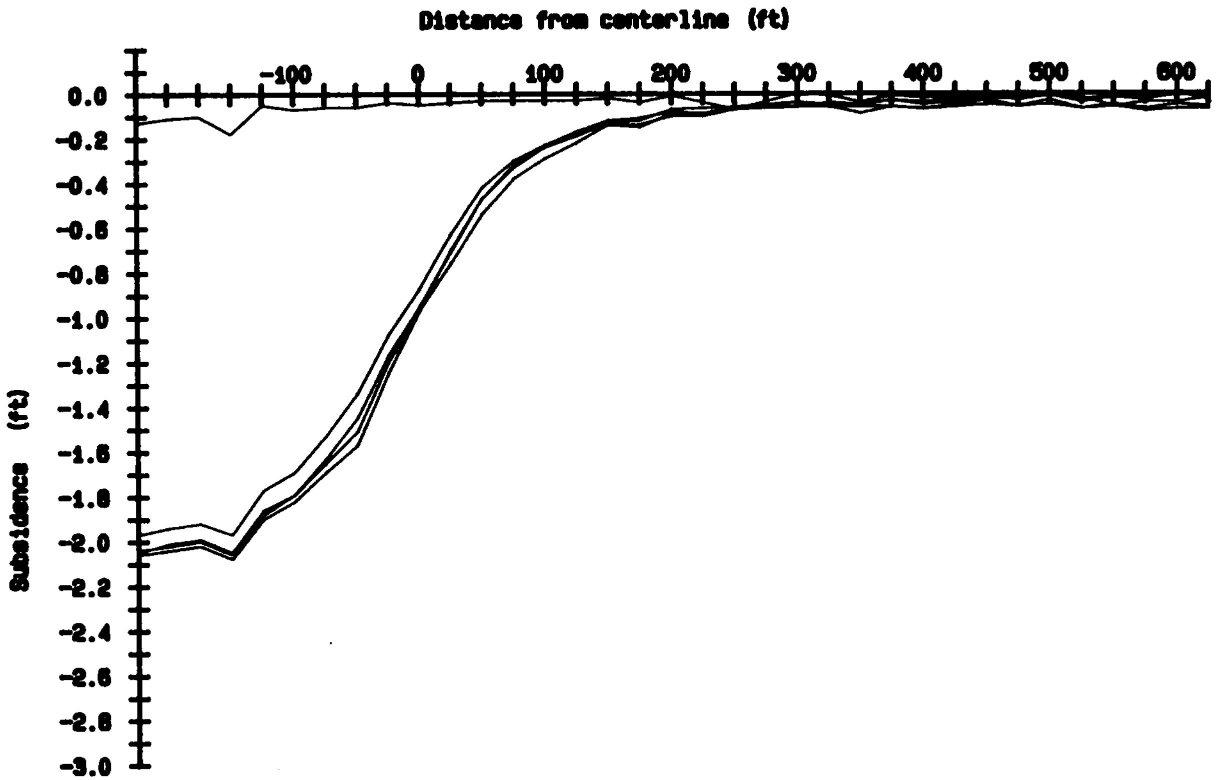

Figure C.12. Transverse Strain Profiles for Case Study RUVA-VT1.

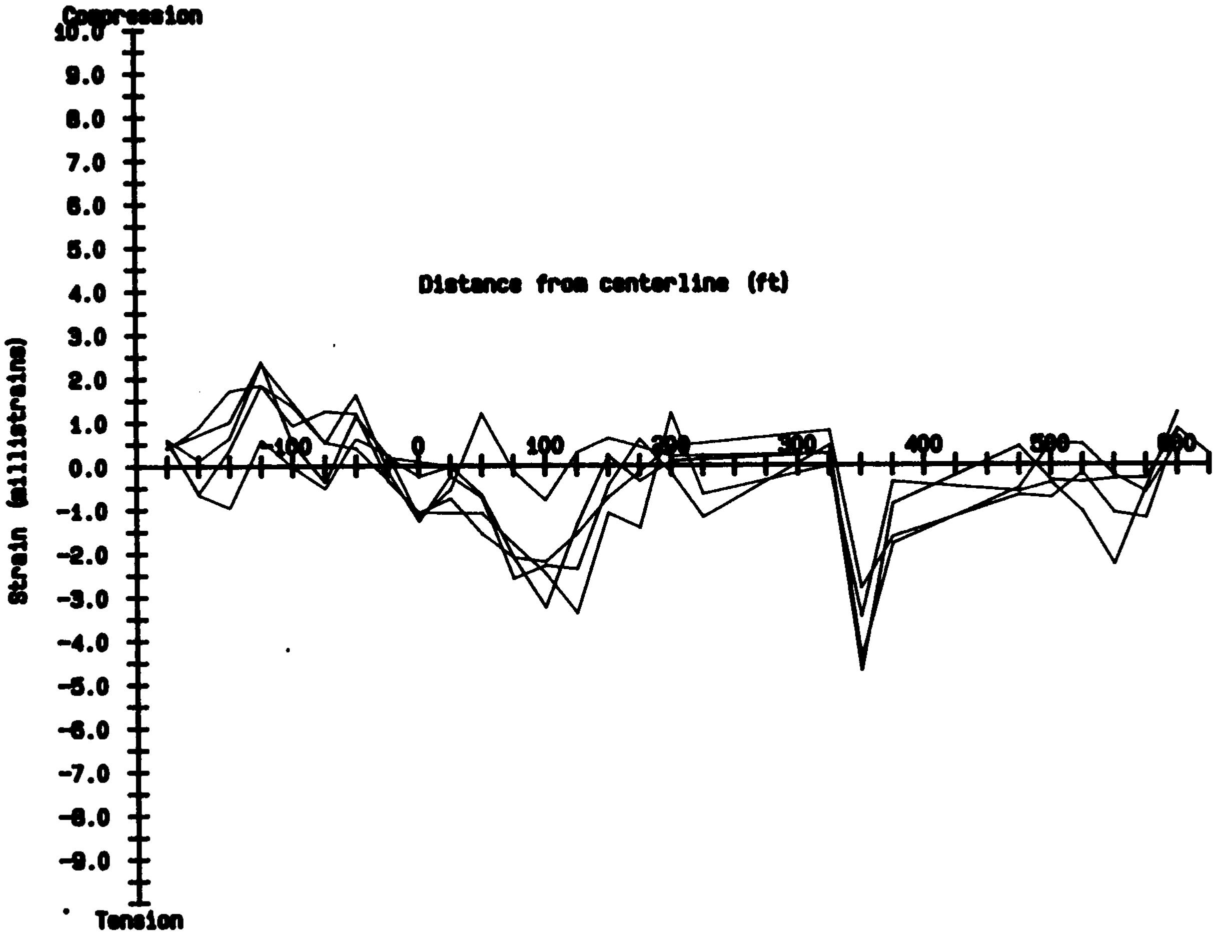

Figure C.13. Transverse Strain Profiles for Case Study RUVA-VT1.

The development of the subsidence profile in this case was very rapid. The final profile was observed 3-4 weeks after mining had been completed. Later surveys did not indicate any significant change due to residual subsidence.

C.4. Case Study RUVA-VT2

C.4.1. Site Description

Case Study RUVA-VT2 was a room and pillar mine located in Wise County, Virginia. The average depth was 315 feet. The terrain was covered by dense forest and the area above the panel was rolling with average grades.

The mine was operating in the Clintwood seam, having an average mining height of 5 feet. Figure 4.4 shows a typical geological column for the strata above the mine.

The extraction ratio varied between 85% and 50%.

C.4.2. Mine Description and Instrumentation

The mine selected for monitoring was a relatively small operation in a shallow seam. The monitoring lines were positioned above a section consisting of three panels. This section was lying under two ridges and mining was initially planned to extend as close to the outcrop as possible.

The initial plan consisted of three panels, each having 6-7 entries, 20 feet wide at 70 feet centers with crosscuts at 70 feet centers. It was also planned that all pillars, with the exception of those left around the final excavation for ventilation purposes, would be extracted. However, due to roof or bottom problems, the initial plan was modified. Two monitoring lines were installed above the panels (Figure 3.8). They were positioned according to its planned shape. The longitudinal line was placed above the second (middle) panel (points 234-286). The first point (234) is located well beyond the area of influence. On the other end (point 286) the monitoring line was terminated within the limits of the excavation because of steep grades and because the coal seam outcropped. The transverse line started well beyond the area of influence (point 233) and at the other end (point 186) it was contained within the panel boundaries because of steep grades.

The spacing of monuments was 25 feet. Two lengths of monuments were used, five feet and two feet, at a ratio of one to three.

In total 101 monitoring monuments were used. Three bench marks and a number of control points were established.

C.4.3. Monitoring

The monuments were installed during the development of the first panel. Two surveys were conducted in cooperation with the mine company surveyors in order to tie the system of monuments to the mine. After the monuments were installed, two surveys were run to determine the coordinates and elevation of each monument.

Each survey, i.e. taking two initial back-sights, moving the instrument to six stations, and taking 101 measurements, was competed within less than three hours.

The accuracy of these surveys was checked, regarding elevations, with the use of a precision level.

After the extraction of pillars was initiated the monument lines were scheduled to be surveyed every seven to ten days. However, since rapid development of subsidence was observed, several surveys were spaced within 4-5 days. After the mining had ceased, surveys were conducted at the same frequency until ground movement slowed down and the time span between subsequent surveys was gradually expanded to three months. The latest survey (3/1/85) was taken twelve months after the completion of mining of the third panel. A number of monuments have been removed or covered during the first two months of 1985 by the development of a nearby strip mine. In total, twenty three surveys were conducted. Table C.8 is a sample of the results calculated after each survey.

Figures C.14 trough C.17 show the data obtained during this monitoring program.

C.5. Case Study RUVA-VT3

C.5.1. Site Description

Case Study RUVA-VT3 was a room and pillar mine located in Wise County, Virginia The average depth was in the range of 200 feet. The terrain was covered by dense forest and the area above the panel was rolling with average to steep grades.

The mine was operating in the Clintwood seam, having an average mining height of 5 feet and the geologic column was similar to Case Study RUVA-VT2.

This mine was adjacent to the one of Case Study RUVA-VT2, which has already been reported. The panel under consideration was separated from the first panel of Case Study RUVA-VT2 by a distance of approximately 100 feet.

Table C.8. Subsidence and Strain Measurements for Case Study RUVA-VT2.

INITIAL SURVEY FILE: <PA081983 >
CURRENT SURVEY FILE: <PA091784 >

Total number of measured points 88

Pt#	Subsidence	Strain
187	-.73	-999
188	-1.41	-2.40670821297E-3
189	-2.01	-7.61442176491E-3
190	-2.11	-3.81455515526E-3
191	-2.07	-1.9594729118E-3
192	-2.01	8.01696431955E-4
193	-1.98	-999
195	-1.91	-999
196	-1.88	-7.98423097868E-4
197	-1.86	-999
199	-1.9	-999
200	-1.92	1.59616817882E-3
201	-1.94	.000199940012
202	-1.97	1.98138078765E-4
203	-1.96	8.01459968739E-4
204	-2.05	-999
206	-2.05	-999
207	-2.09	-7.95458071305E-4
208	-2.06	1.19717861006E-3
209	-2.04	1.79737944233E-3
210	-2.03	-1.96245366274E-4
211	-1.98	-1.37780365792E-3
212	-1.93	-7.21413285347E-6
213	-1.92	-1.77479827343E-3
214	-1.88	-1.97750909385E-4
215	-1.87	-4.04036158297E-4
216	-1.83	-5.97480653368E-4
217	-1.85	5.98483679761E-4
218	-1.84	1.40423127584E-3
219	-1.92	-8.03858228103E-4
220	-1.9	-2.99032729357E-3
221	-1.87	-2.19408793349E-3
222	-1.56	-2.79549115996E-3
223	-.94	3.01066374756E-3
224	-.32	7.38539434135E-3
225	-.31	-999
227	-.1	-999
228	-.1	3.96604291466E-4
229	-.07	8.57416287254E-4
230	-.18	-999
231	-.03	-999
232	-.04	-999

Table C.8. (continued)

Pt#	Subsidence	Strain
236	-.01	-999
238	-.04	-999
239	-.05	-8.03372425931E-4
240	-.05	1.19019636676E-3
241	999	1.19275042211E-3
242	-.06	-5.85339981869E-4
243	-.05	-5.99472352518E-4
244	-.08	7.86781939514E-4
245	999	1.3969956328E-3
246	-.11	-2.05441612286E-4
247	-.11	-1.36990932127E-3
248	-.19	9.92144532308E-4
249	-.3	2.6394226513E-3
250	-.43	2.4376808103E-3
251	-.61	1.20152182619E-3
252	-.86	2.40950677121E-3
253	999	-1.98634659791E-4
254	-2.06	-4.31094471293E-3
255	-2.18	-2.5920178658E-3
256	-2.13	-2.05675805197E-3
257	-2.1	2.00254128046E-3
258	-2.04	-999
260	-2.04	-999
261	-2.03	9.16589514144E-4
262	-2.01	-1.25286277776E-5
263	-1.94	6.01651017699E-4
264	-1.88	1.01354679302E-3
265	-1.86	1.19914029591E-3
266	-1.77	2.00491029524E-3
267	-1.75	2.14709317918E-6
268	-1.66	-5.945674208 34E-4
269	-1.68	-1.97218177968E-4
270	-1.63	1.14408317642E-3
271	999	-2.03592745026E-4
272	-1.6	-1.42737432019E-3
273	-1.63	6.04649070229E-4
274	-1.6	1.00034207291E-3
275	-1.62	9.98421556481E-4
276	-1.69	1.22508955538E-3
277	-1.86	5.74530579768E-4
278	-2.15	9.56350309333E-4
279	999	1.40684691773E-3
280	-2.52	-999

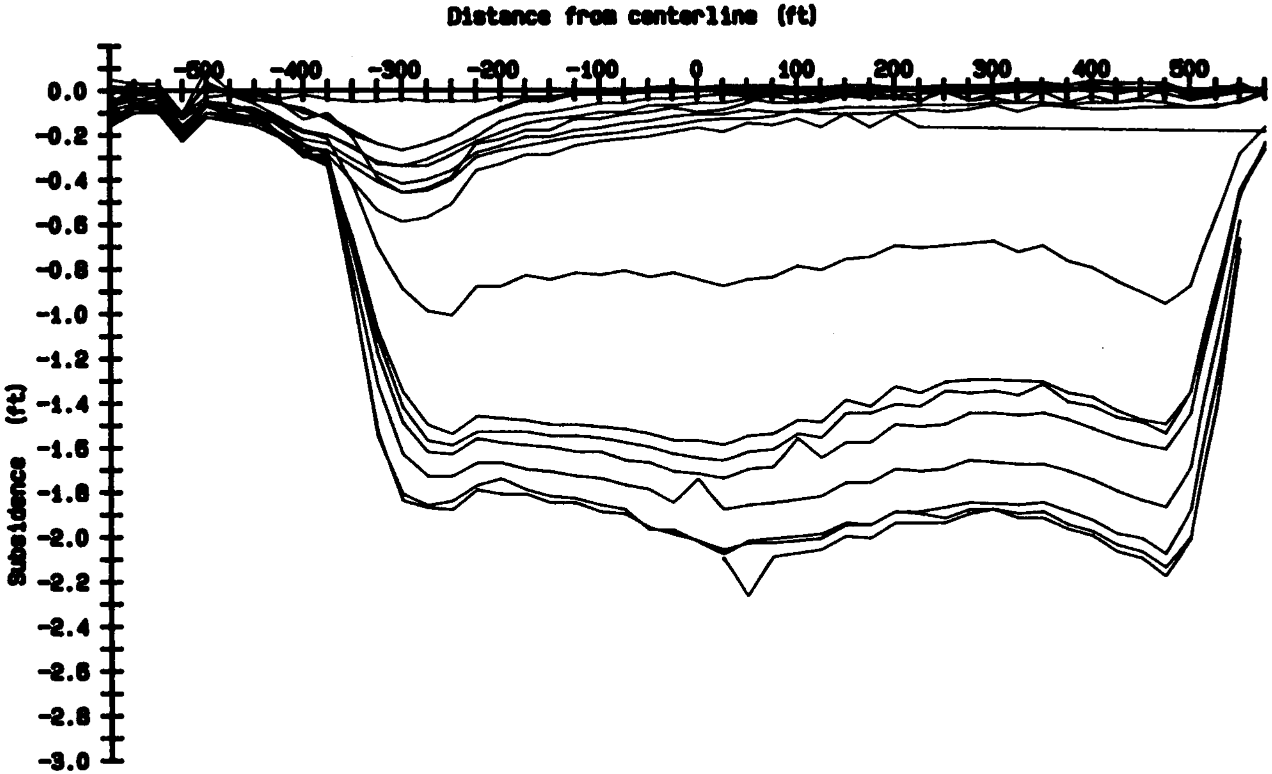

Figure C.14. Longitudinal Subsidence Profiles for Case Study RUVA-VT2.

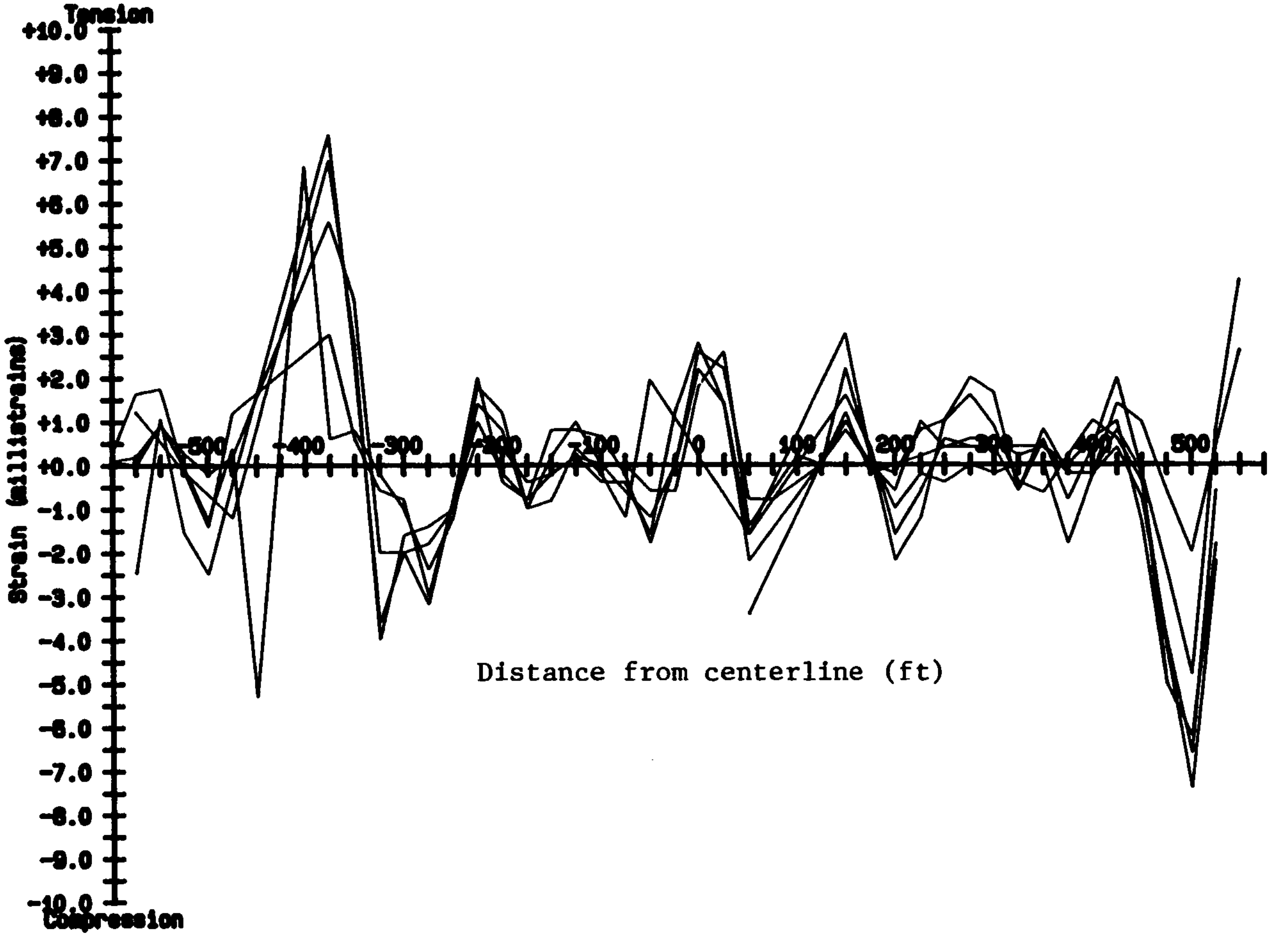

Figure C.15. Longitudinal Strain Profiles for Case Study RUVA-VT2.

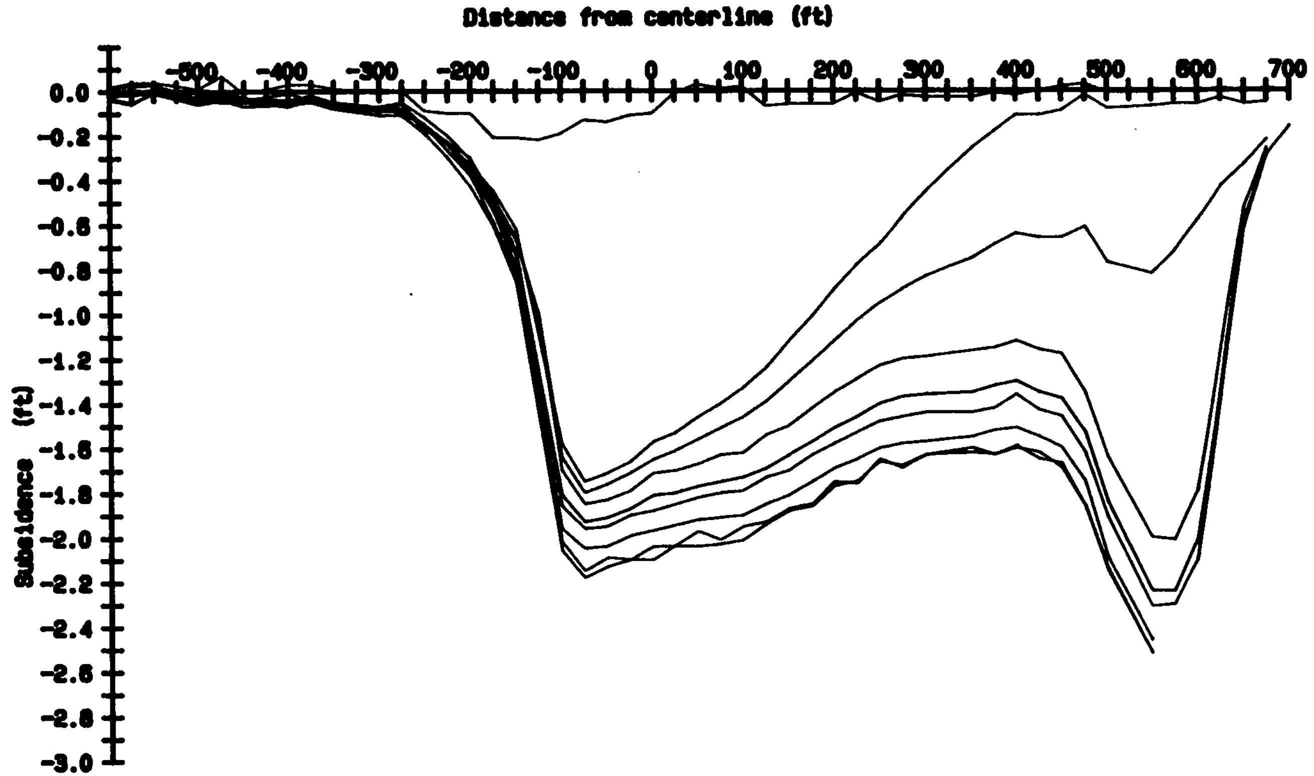

Figure C.16. Transverse Subsidence Profiles for Case Study RUVA-VT2.

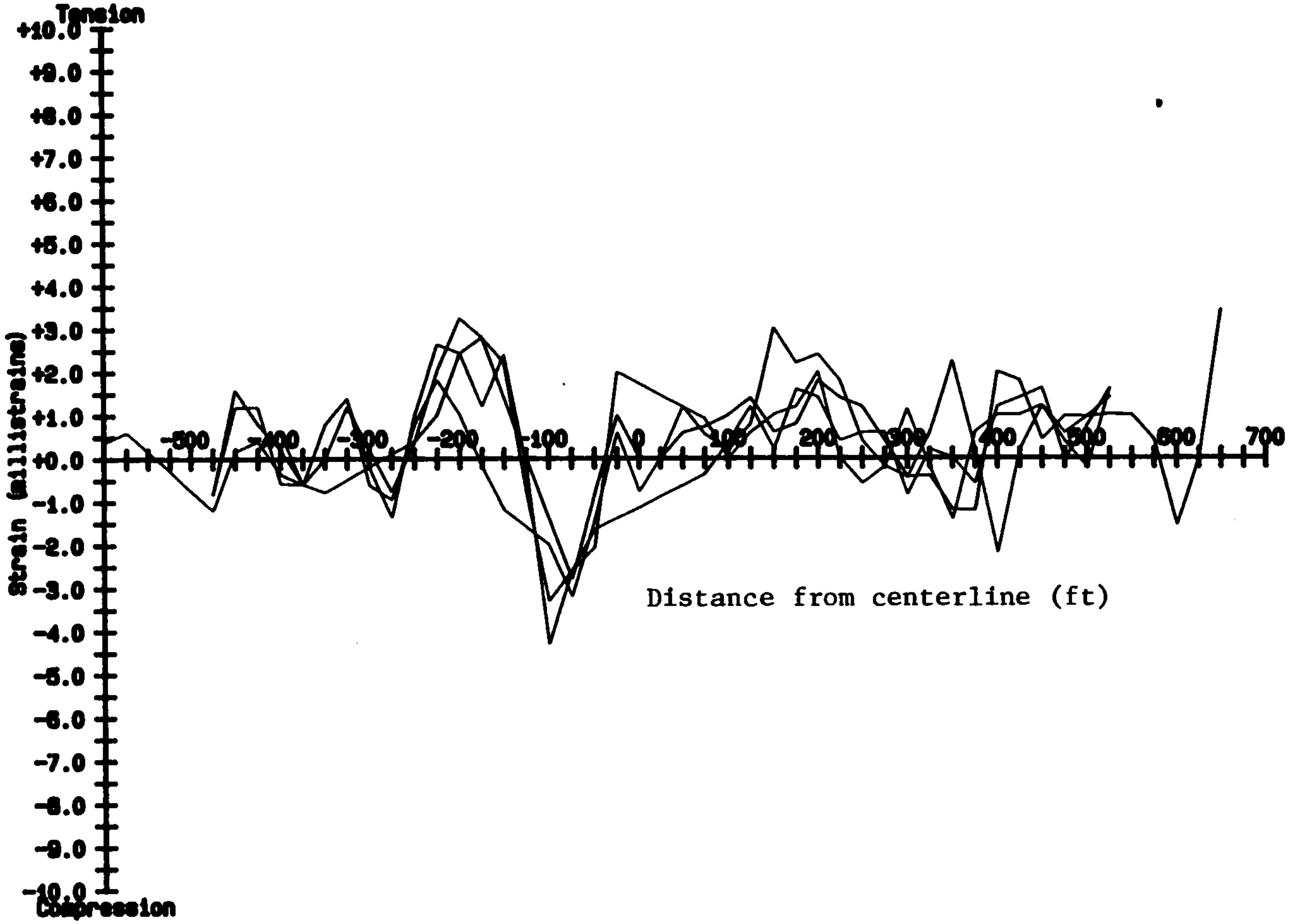

Figure C.17. Transverse Strain Profiles for Case Study RUVA-VT2.

The extraction ratio was about 85%.

C.5.2. Mine Description and Instrumentation

The mine selected was a relatively small operation in a shallow seam. The panel which was instrumented was planed in order to mine the coal lying between the neighboring mine and the outcrop, and therefore it was not of a rectangular shape.

Entries were driven at 60 feet centers. The number of entries varied in the plan, but their span was kept to 20 feet. Crosscuts were at 70 feet centers. The initial plan had to be modified because of difficult ground control conditions. As a result, the position of the longitudinal monitoring line shifted almost above the edge of the final excavation. In addition, four pillars were left in place for roof control purposes.

Figure 3.9 shows the mining layout and the position of the monitoring lines. Both lines, longitudinal and transverse were extended well beyond the area of influence.

The spacing of monuments was 25 feet. Two lengths of monuments were used, five feet and two feet, at a ratio of one to three.

In total 155 monitoring monuments were used. Two bench marks and two control points were also established, well beyond the area of influence.

C.5.3. Monitoring

The monuments were installed before the development of the panel. One survey was conducted in cooperation with mine company surveyors in order to tie the system of monuments to the mine. After the monuments were installed, two surveys were run to determine the coordinates and elevation of each monument.

The accuracy of these surveys was checked, regarding elevations, with the use of a precision level.

After the extraction of pillars was initiated the monument lines were scheduled to be surveyed every seven to ten days. Surveys were conducted at the same frequency, even after mining had been finished, until ground movement slowed down. At that time the time span between subsequent surveys was increased to three months. The latest survey (6/19/85) was taken seventeen months after the completion of mining. A number of monuments were removed or covered, during the first two months of 1985, by the development of a nearby strip mine. In total, twenty three surveys were conducted. Table C.9 and Figures C.18 and C.19 present typical results calculated after each survey. The effect of a number of pillars left in place was illustrated on the hump of the transverse subsidence and strain profiles. It should be noted that the subsidence and strain values were higher on one side of the panel due to shallower depth at that location.

The analysis of the data for Case Study RUVA-VT3 indicated, as for Case Study RUVA-VT2, the problem with the empirical prediction methods when extrapolated to include different mine parameters and conditions. The original prediction was based on certain case studies and does not cover cases of extreme values of hardrock content in the overburden at very shallow depths.

Table C.9. Subsidence and Strain Measurements for Case Study RUVA-VT3.

INITIAL SURVEY FILE: <VICINTn >
CURRENT SURVEY FILE: <VP030185 >

Total number of measured points 43

Pt#	Subsidence	Strain
155	12.25	-999
158	.03	-999
159	.05	-2.73697631889E-3
160	.04	-8.85393509463E-4
161	.05	1.14662942204E-3
162	.05	5.28553896216E-4
163	.07	-3.98430040142E-3
164	.09	-3.02342485192E-3
165	.02	1.350565144E-4
166	.03	-2.86898514545E-3
167	-.01	-1.02610524315E-3
168	-.01	4.89476431516E-4
169	-.15	1.3686463806E-3
170	-.34	5.25140425583E-3
171	-.77	8.86913721605E-3
172	-.99	3.64794578867E-3
173	-1.32	-1.84078279083E-3
174	-1.68	-999
176	-1.86	-999
177	-1.94	-3.01605722565E-4
178	-1.85	-1.75754807861E-3
179	-1.8	-9.58025390043E-4
180	-1.73	4.95761347127E-4
181	-1.77	4.84328792861E-3
182	-1.69	5.05422076436E-3
183	-1.63	2.99663801919E-6
184	-1.57	7.56021795634E-4
185	-1.54	3.35974548514E-3
186	-1.58	4.56974722267E-3
187	-1.61	7.84007210639E-3
188	-2.21	4.25974807606E-4
189	-2.55	-6.72462113912E-3
190	-2.53	-1.33202037983E-3
191	-2.58	-999
193	-2.56	-999
194	-2.52	-999
195	-2.35	-999
196	-1.68	-999
198	-.16	-999
199	-.08	-999
200	0	-999

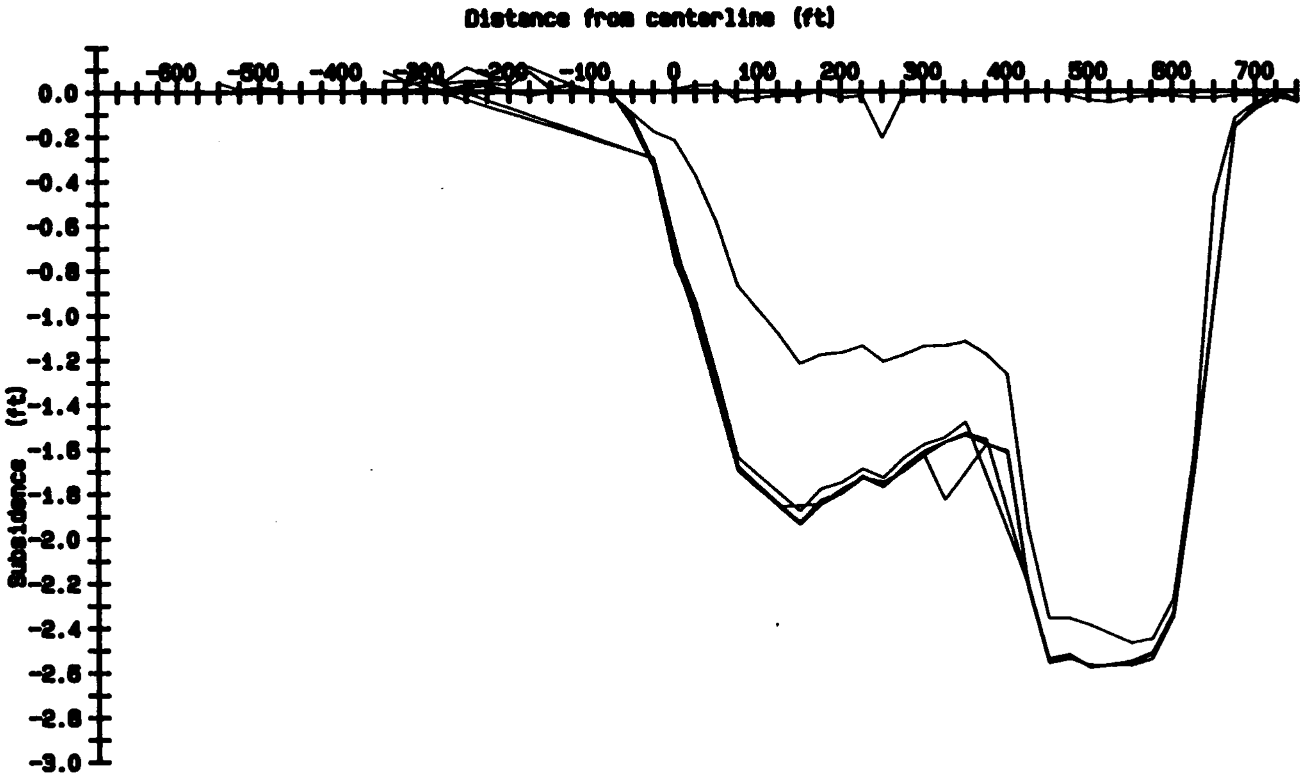

Figure C.18. Transverse Subsidence Profiles for Case Study RUVA-VT3.

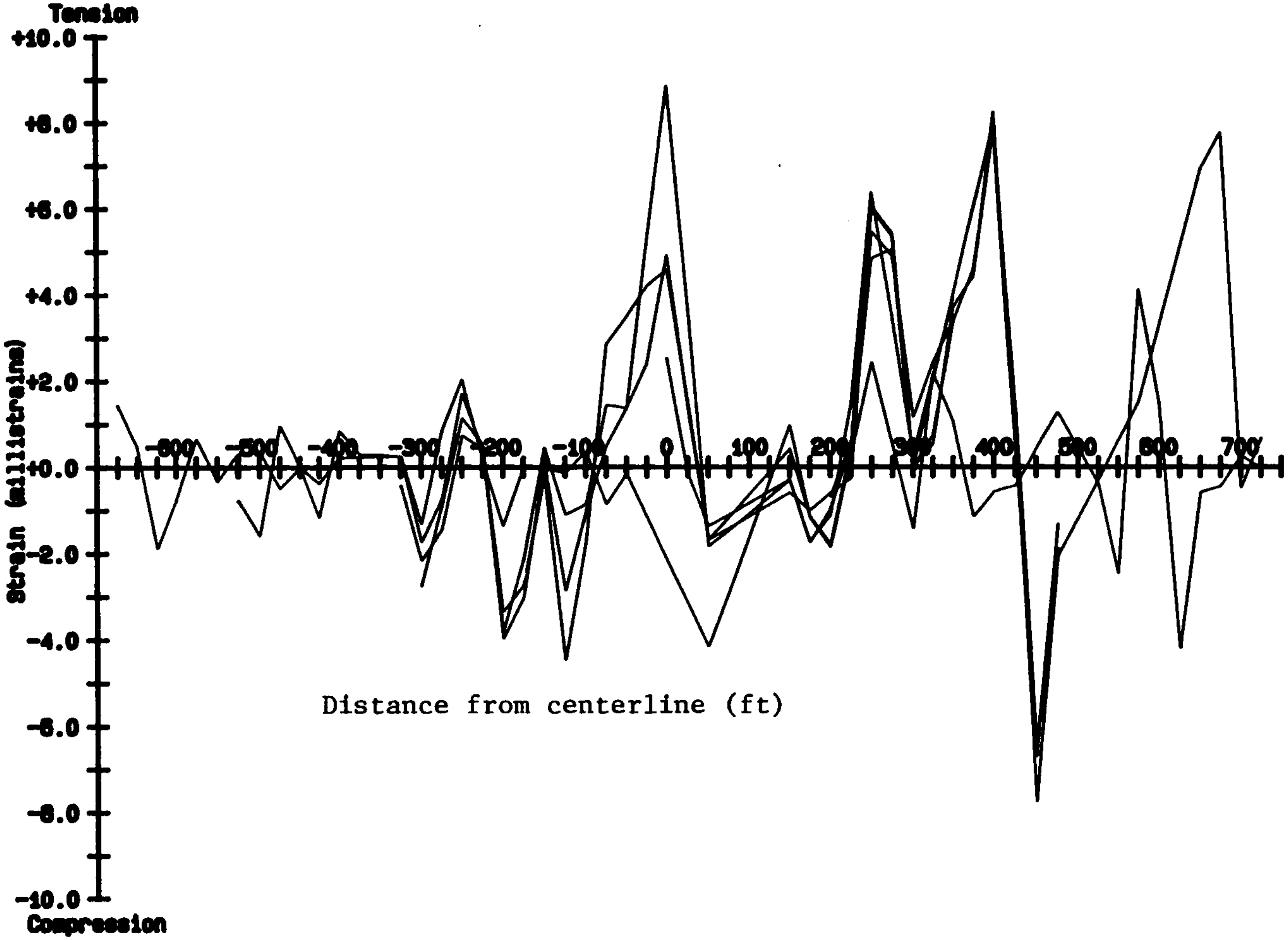

Figure C.19. Transverse Strain Profiles for Case Study RUVA-VT3.

C.6. Case Study RUVA-VT4

Case Study RUVA-VT4 was a room and pillar section selected for its geologic similarity to the longwall mine of Case Study LUVA-VT1. However due to roof problems only a small number of pillars were extracted, without noticeable movement on the surface.

C.7. Case Study RUVA-VT5

C.7.1. Site Description

Case Study RUVA-VT5 was a room and pillar mine located in Buchanan County, Virginia . The average depth was in the range of 400 to 790 feet. The terrain was covered by dense forest and the area above the panel was rolling with steep grades.

The mine was operating in the Red Ash seam, having an average mining height of 3.5-4 feet. The amount of hardrock in the overburden was ranging from 47 to 60 percent.

The average recovery at the mine was 85 percent.

C.7.2. Mine Description and Instrumentation

The mine plan consisted of a series of eight panels, each having six to seven 20 feet wide entries, with varying configuration of pillar sizes. It was originally planned that all pillars would be fully extracted, with the exception of those left around the final excavation for ventilation purposes. However, during mining, a number of pillars were left in place, which, therefore, resulted to a varying extraction ratio over the section under consideration. In addition, pillars were also extracted from the surrounding development works.

Monuments were installed during the development of the fourth panel. Therefore, measurements for the last five panels and surrounding development works were conducted. Four monitoring lines were installed covering these five panels (Figure 3.10). A transverse line (points 131 to 200) was extended from outside the expected area of influence to the center of the forth panel. Three longitudinal lines were installed. The first (points 223-280) was positioned between panels #4 and #5, extending beyond the mining section at both ends. The second (points 49-23) was positioned above panel #6 and extended from the transverse line to beyond the panel limit. The third (points 50-75) was positioned above panel #7 and extended from the transverse line to beyond the panel limit.

The spacing of monuments was 33.33 feet. Two lengths of monuments were used, three and four feet, at a ratio of one to two.

In total 181 monitoring monuments were used over 6100 feet of lines. Three bench marks and a number of control points were also established. Due to the extent of the monitoring system and the difficult topography, a complete monitoring required two surveys, each starting from different stations.

C.7.3. Monitoring

Two surveys were conducted in cooperation with the mine company surveyors in order to tie the system of monuments to the mine. After the monuments were installed, a number of surveys were run to determine the coordinates and elevation of each monument.

After the extraction of pillars was initiated the monument lines were scheduled to be surveyed every seven to ten days. After the mining had ceased, surveys were conducted at the same frequency until ground movement slowed down and the time span between subsequent surveys was gradually expanded to two months. The latest surveys (4-29-86 and 5-2-86) were taken five months after the completion of mining of the eighth (last) panel. A number of monuments have been removed or covered during maintenance work on local unpaved roads. In total, 39 surveys were conducted.

Figures C.20 trough C.27 show the data obtained during this monitoring program.

C.8. Case Study RUVA-VT6

C.8.1. Site Description

Case Study RUVA-VT6 was also a room and pillar section located in Buchanan County, Virginia. The average depth was in the range of 490 feet. The terrain was covered by dense forest and the area above the panel was rolling with steep grades.

The mine was operating in the Red Ash seam, having an average mining height of 3.2-3.9 feet. The amount of hardrock in the overburden was in the range of 50 percent.

The maximum recovery at the mine was 85 percent.

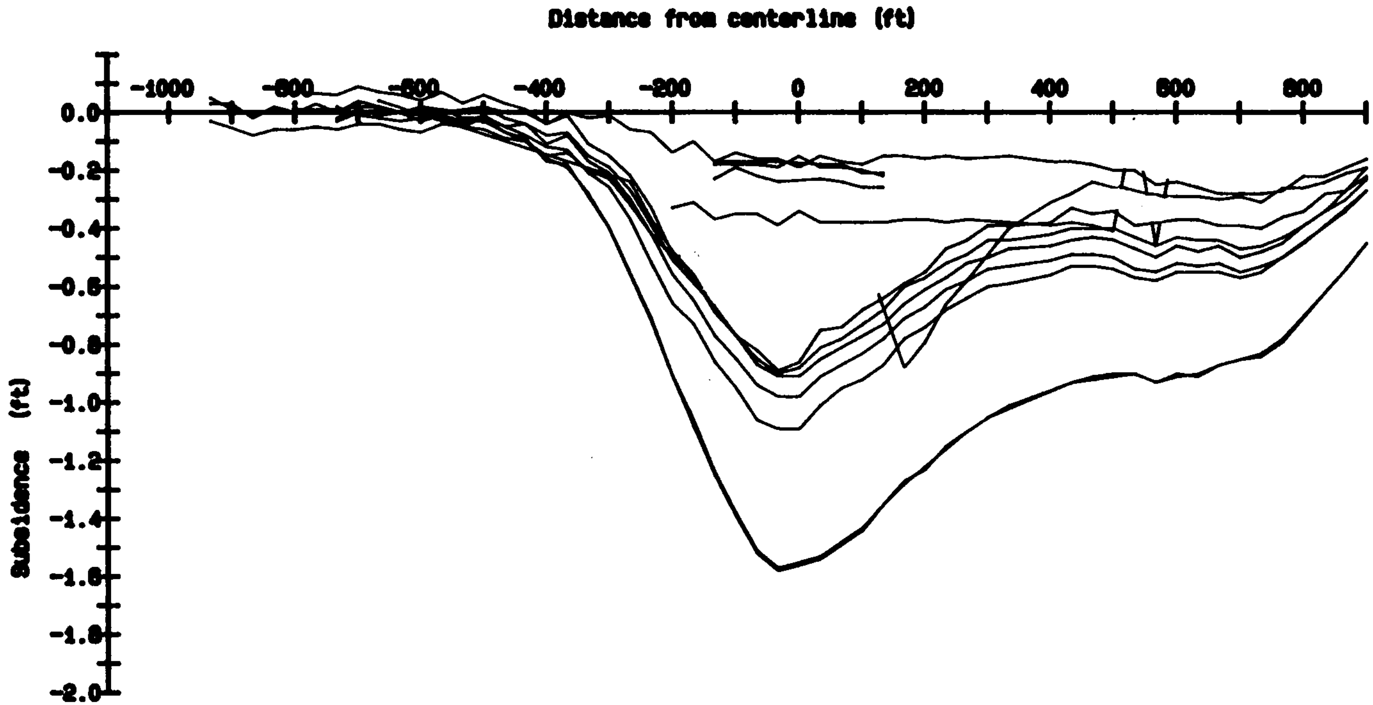

Figure C.20. Longitudinal (L1) Subsidence Profiles for Case Study RUVA-VT5.

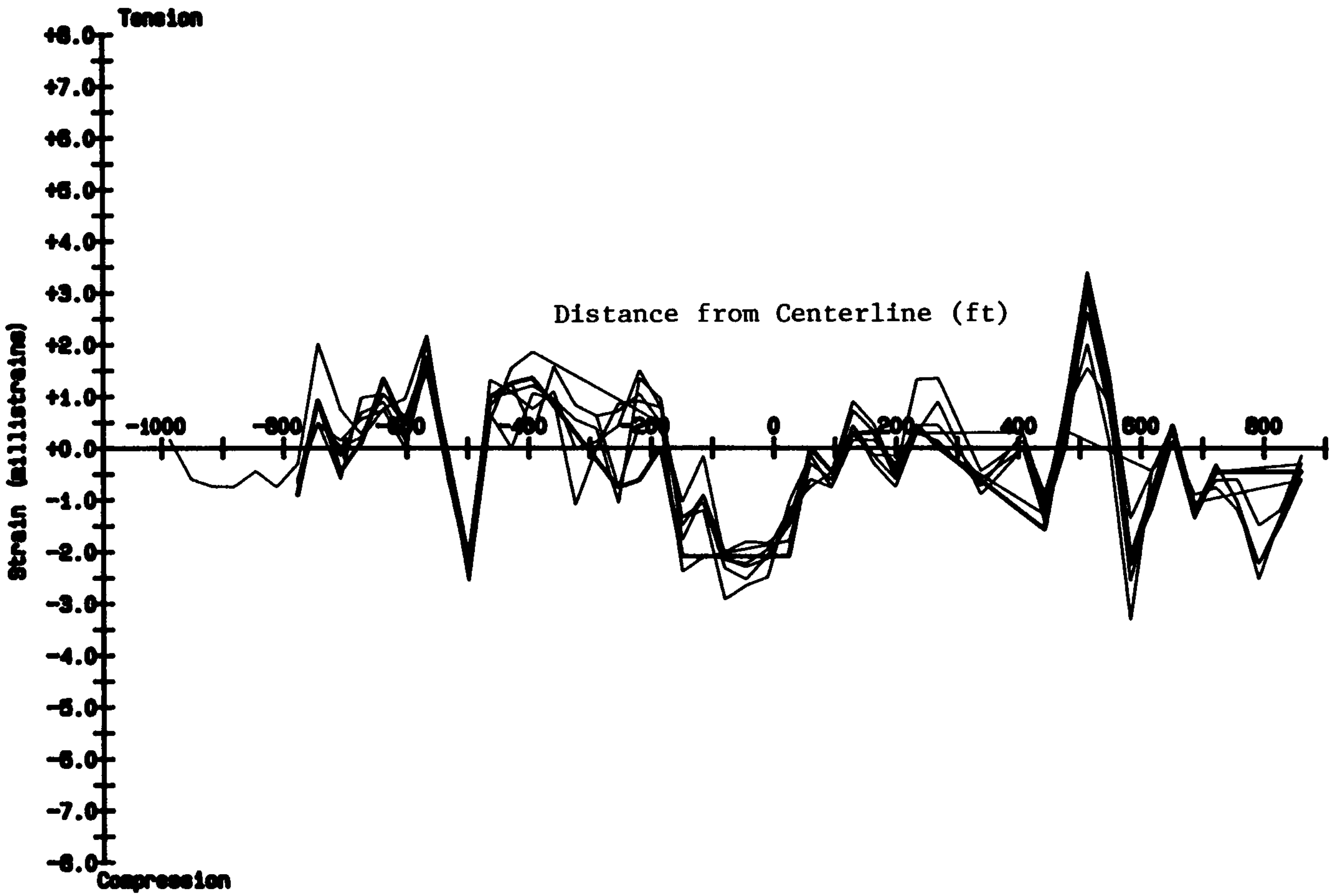

Figure C.21. Longitudinal (L1) Strain Profiles for Case Study RUVA-VT5.

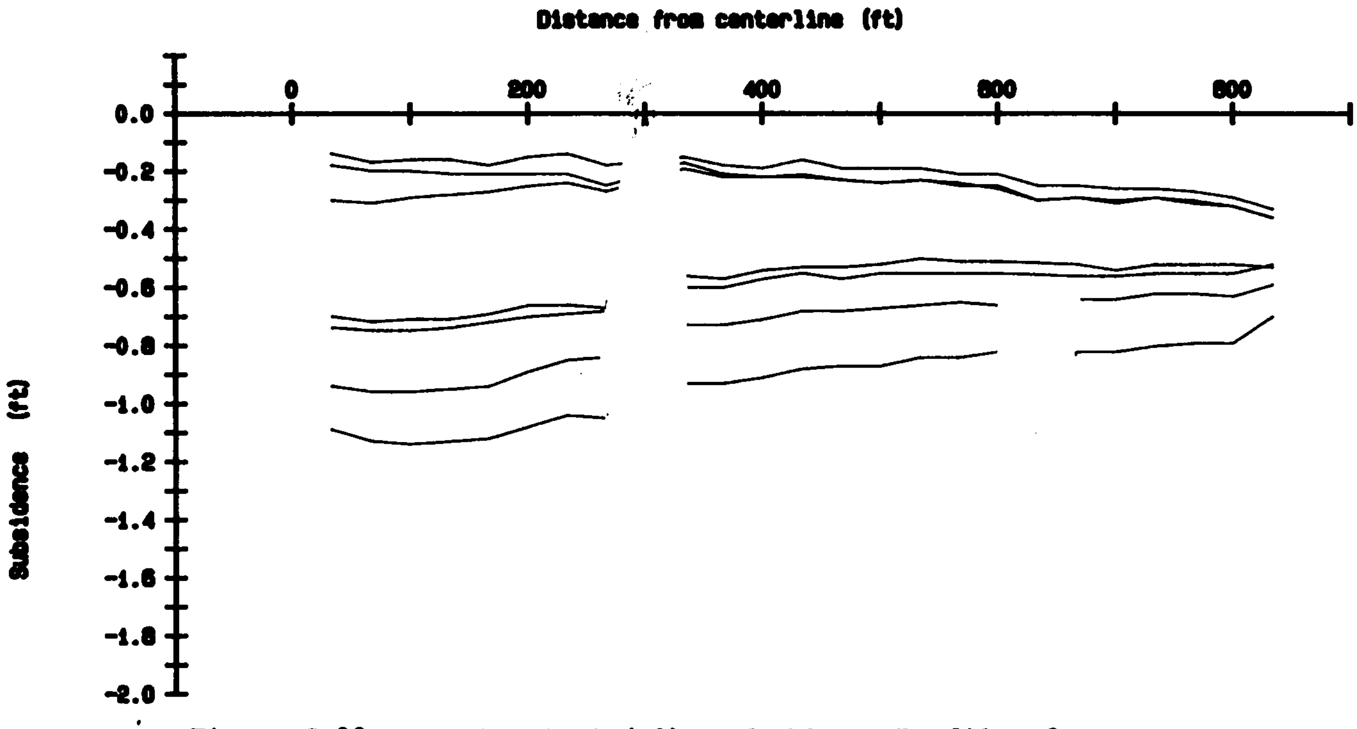

Figure C.22. Longitudinal (L2) Subsidence Profiles for Case Study RUVA-VT5.

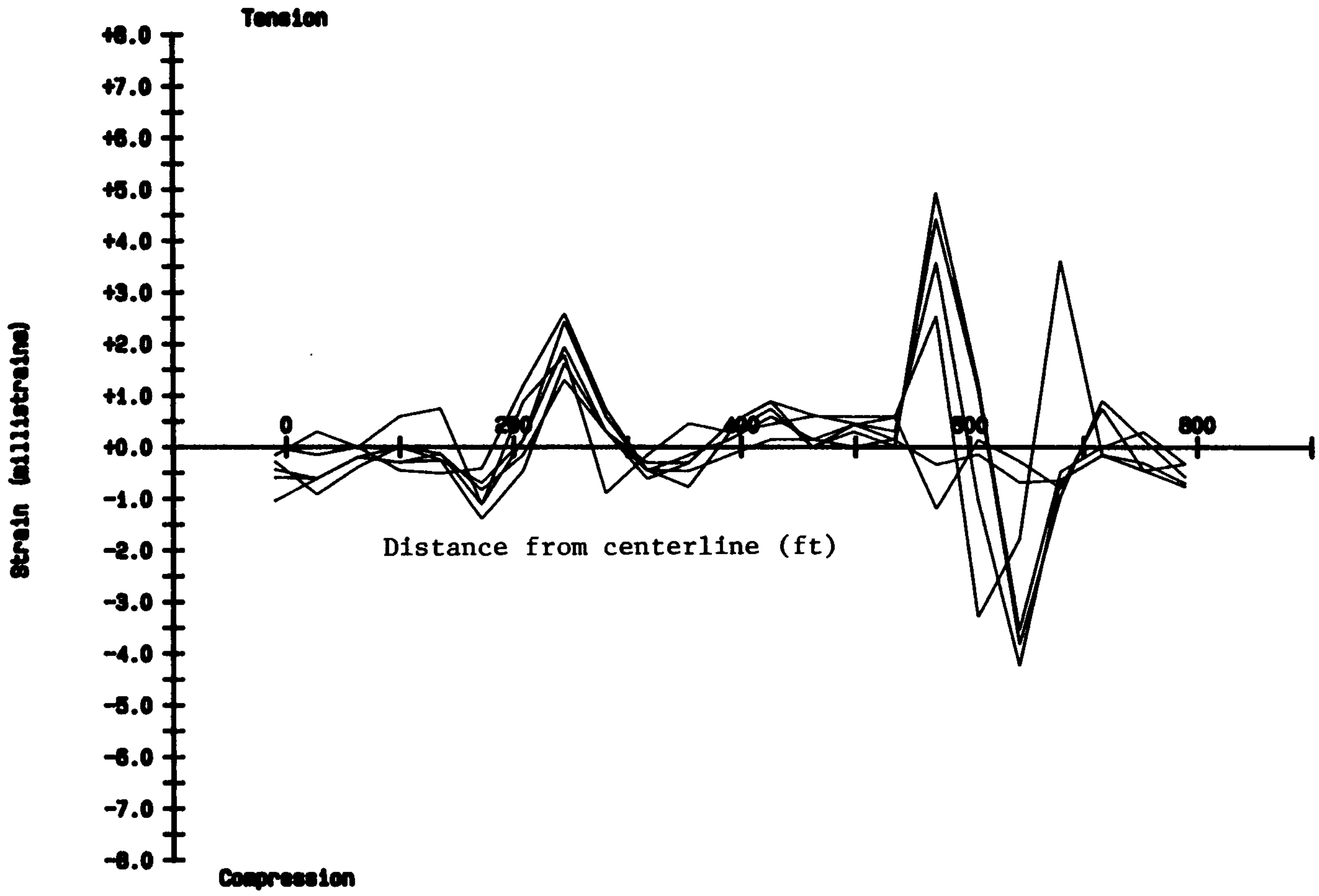

Figure C.23. Longitudinal (L2) Strain Profiles for Case Study RUVA-VT5.

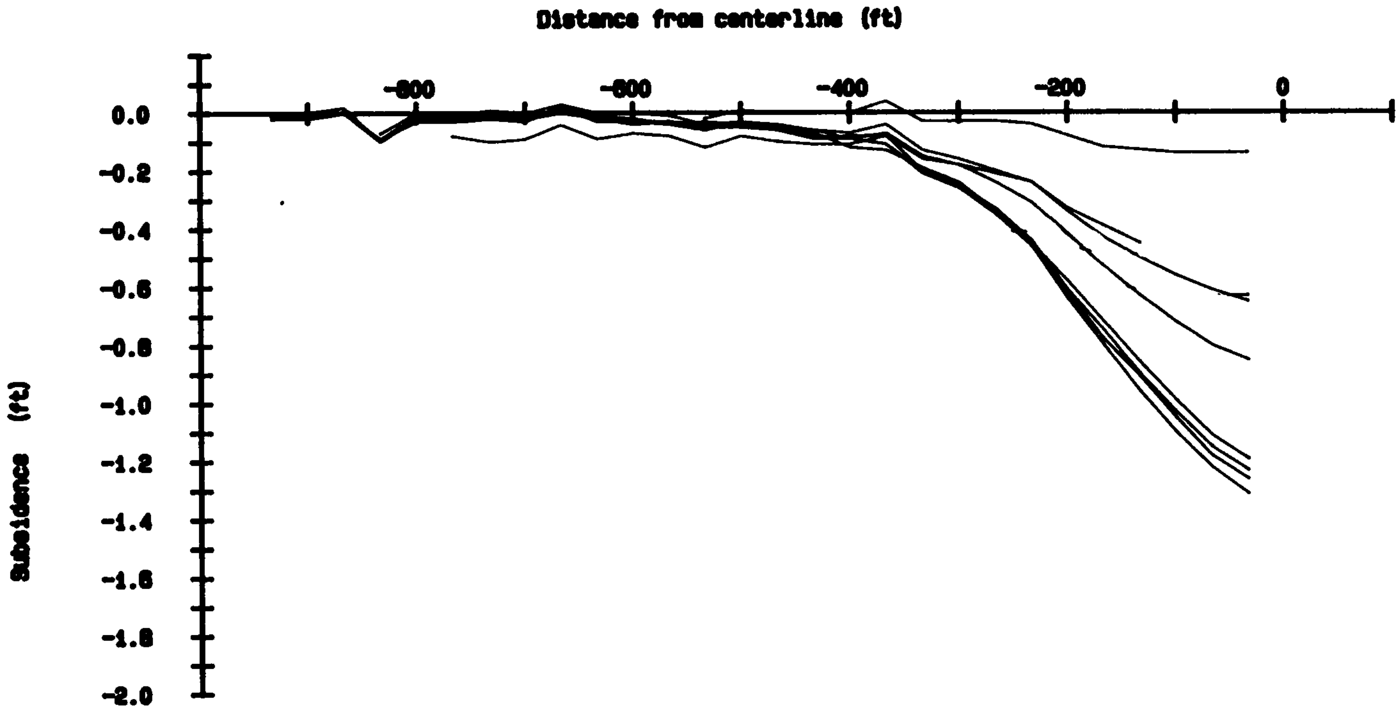

Figure C.24. Longitudinal (L3) Subsidence Profiles for Case Study RUVA-VT5.

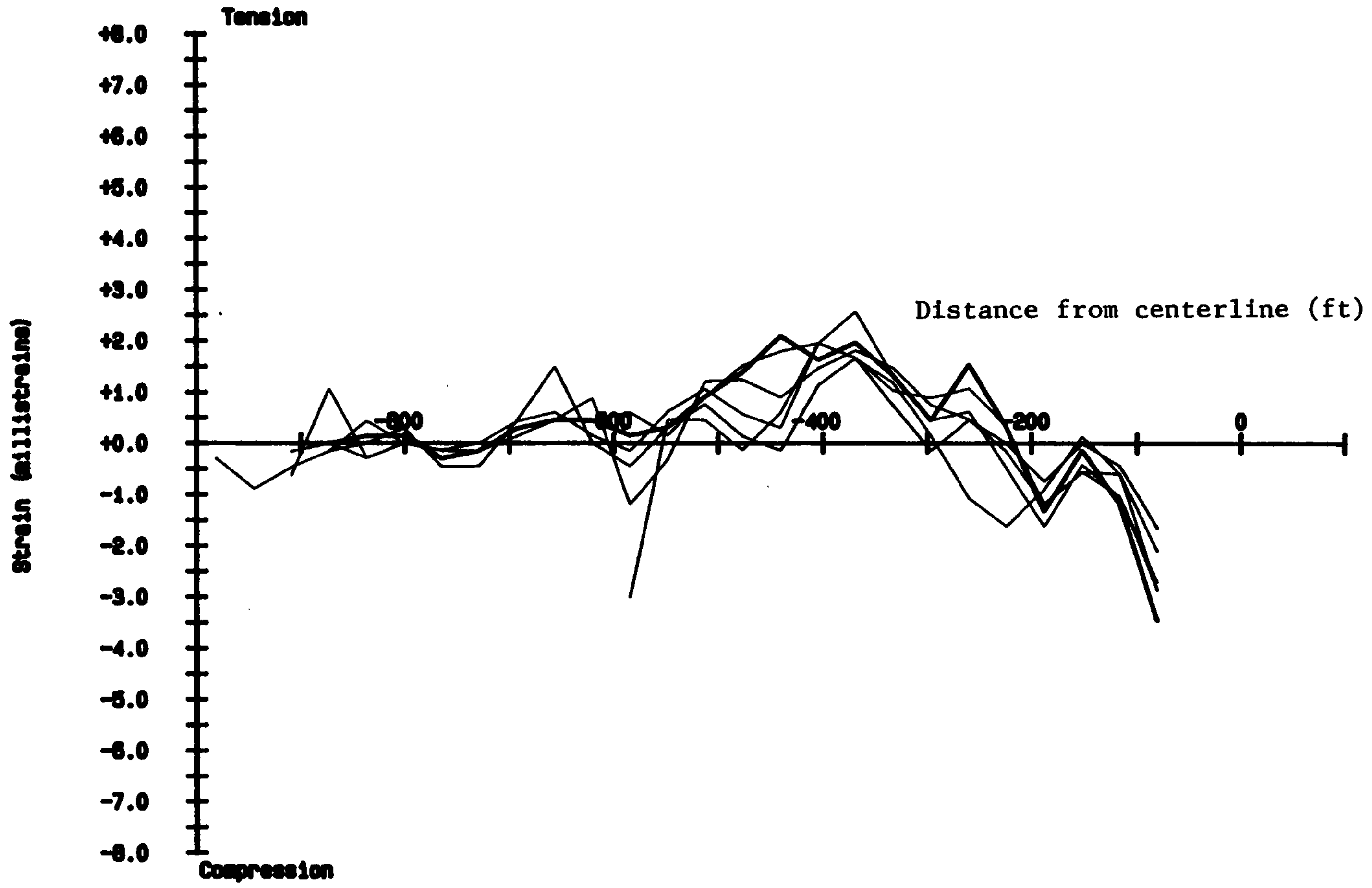

Figure C.25. Longitudinal (L3) Strain Profiles for Case Study RUVA-VT5.

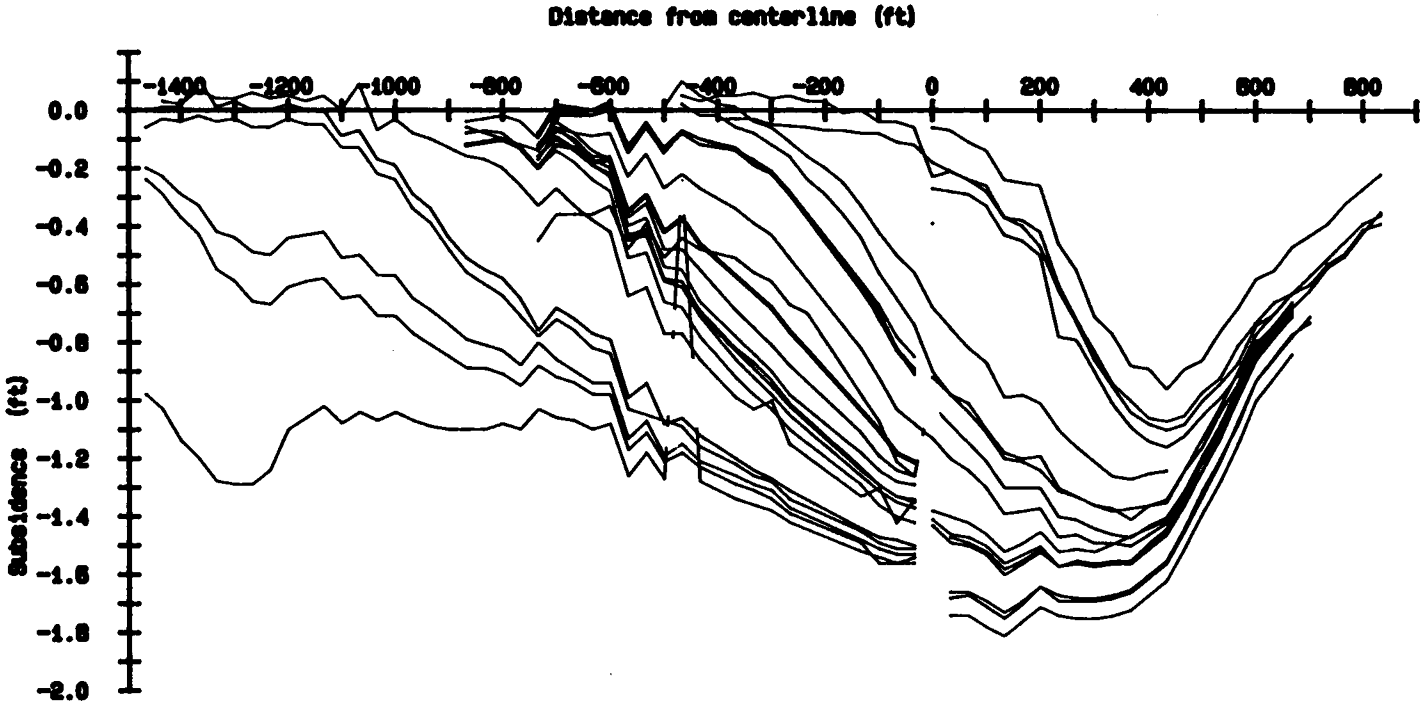

Figure C.26. Transverse Subsidence Profiles for Case Study RUVA-VT5.

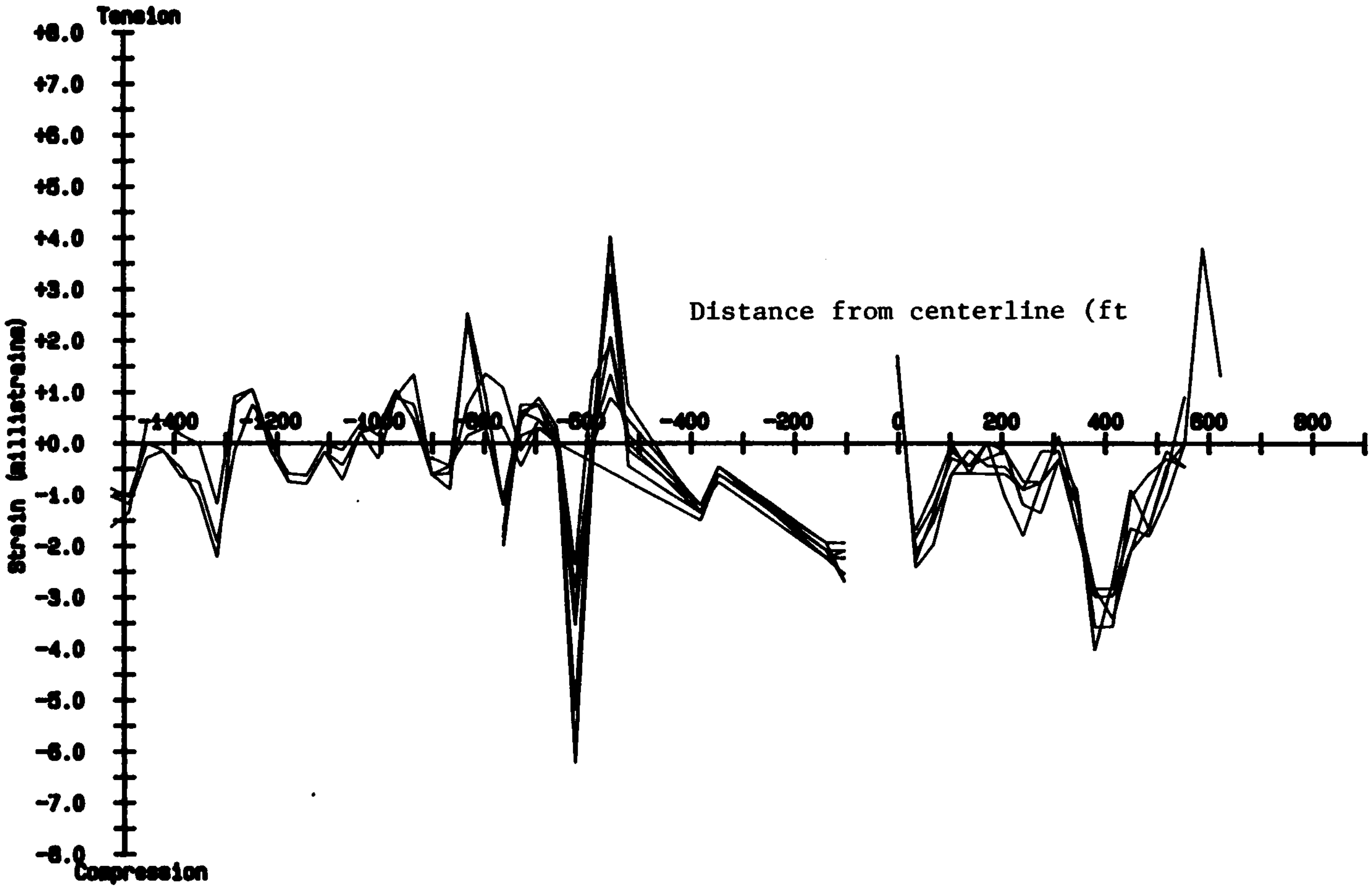

Figure C.27. Transverse Strain Profiles for Case Study RUVA-VT5.

C.8.2. Mine Description and Instrumentation

The mine plan consisted of a series of four panels, each having seven 20 feet wide entries at 60 feet centers. It was originally planned that all pillars would be fully extracted, with the exception of those left around the final excavation for ventilation purposes. However, during mining, a number of pillars were left in place, which, therefore, resulted in a varying extraction ratio over the section under consideration. In addition, pillars were also extracted from the surrounding development works. On the other side of the development works lay a previously extracted section. This fact was also indicated by the observation of the inflection point, almost above the boundary of the currently extracted area.

Monuments were installed during the development of the second panel. Therefore, measurements for the last three panels and surrounding development works were conducted. Two monitoring lines were installed. A transverse line was extended from outside the expected area of influence to the center of the first panel which had been fully extracted. The longitudinal line was located above the third panel and was extended over the older section.

The spacing of monuments was 33.33 feet. Two lengths of monuments were used, three and four feet, at a ratio of one to two.

C.8.3. Monitoring

Two surveys were conducted in cooperation with the mine company surveyors in order to tie the system of monuments to the mine. After the monuments were installed, a number of surveys were run to determine the coordinates and elevation of each monument.

After the extraction of pillars was initiated the monument lines were scheduled to be surveyed every seven to ten days. After the mining had ceased, surveys were conducted at the same frequency until ground movement slowed down and the time span between subsequent surveys was gradually expanded to two months. The latest surveys were taken several months after the completion of mining of the forth (last) panel.

Figures C.28 trough C.31 show the data obtained during this monitoring program.

C.9. Case Study RUVA-VT7

Case Study RUVA-VT7 was a room and pillar section located in Buchanan county, Virginia. One transverse and two longitudinal monument lines were installed in order to monitor surface movements over three panels. The lines were installed during the development of the first panel. However, due to the change of the production plans of the mine extraction of pillars has not been initiated.

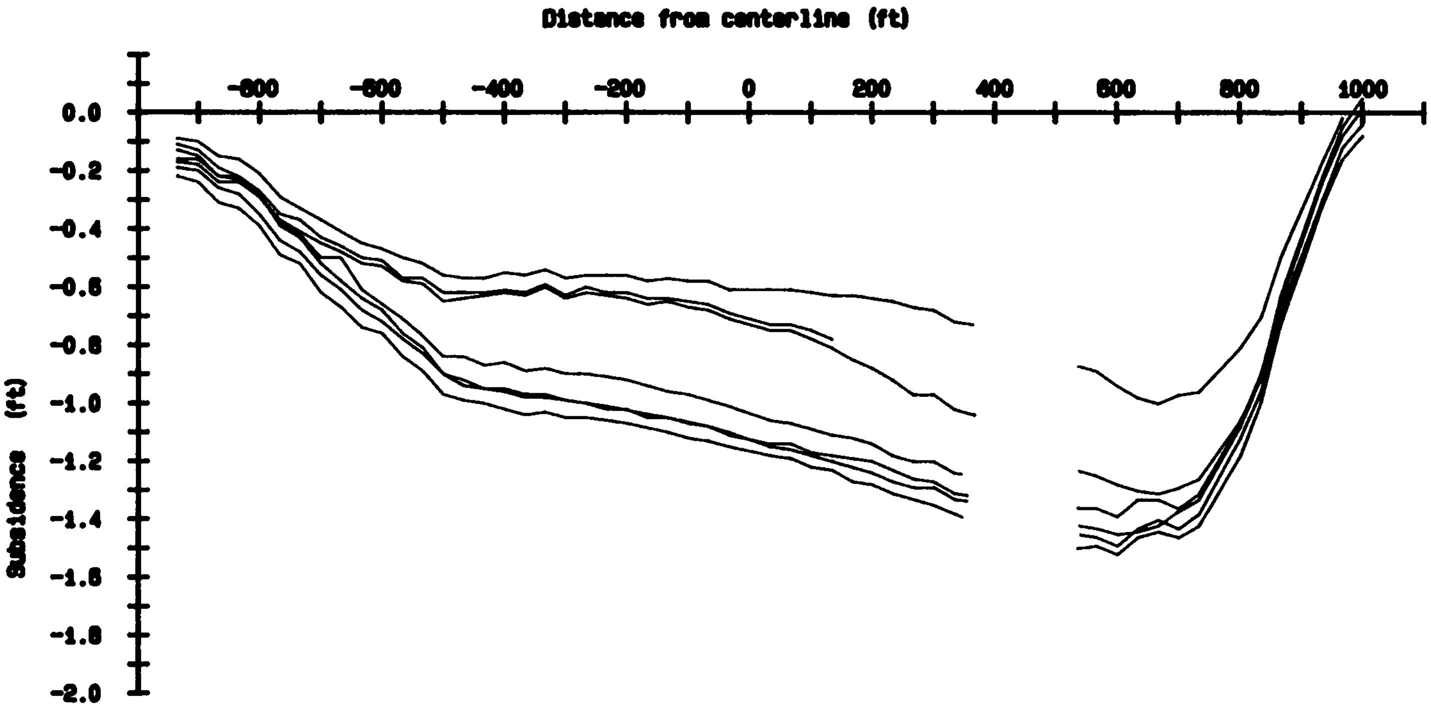

Figure C.28. Longitudinal Subsidence Profiles for Case Study RUVA-VT6.

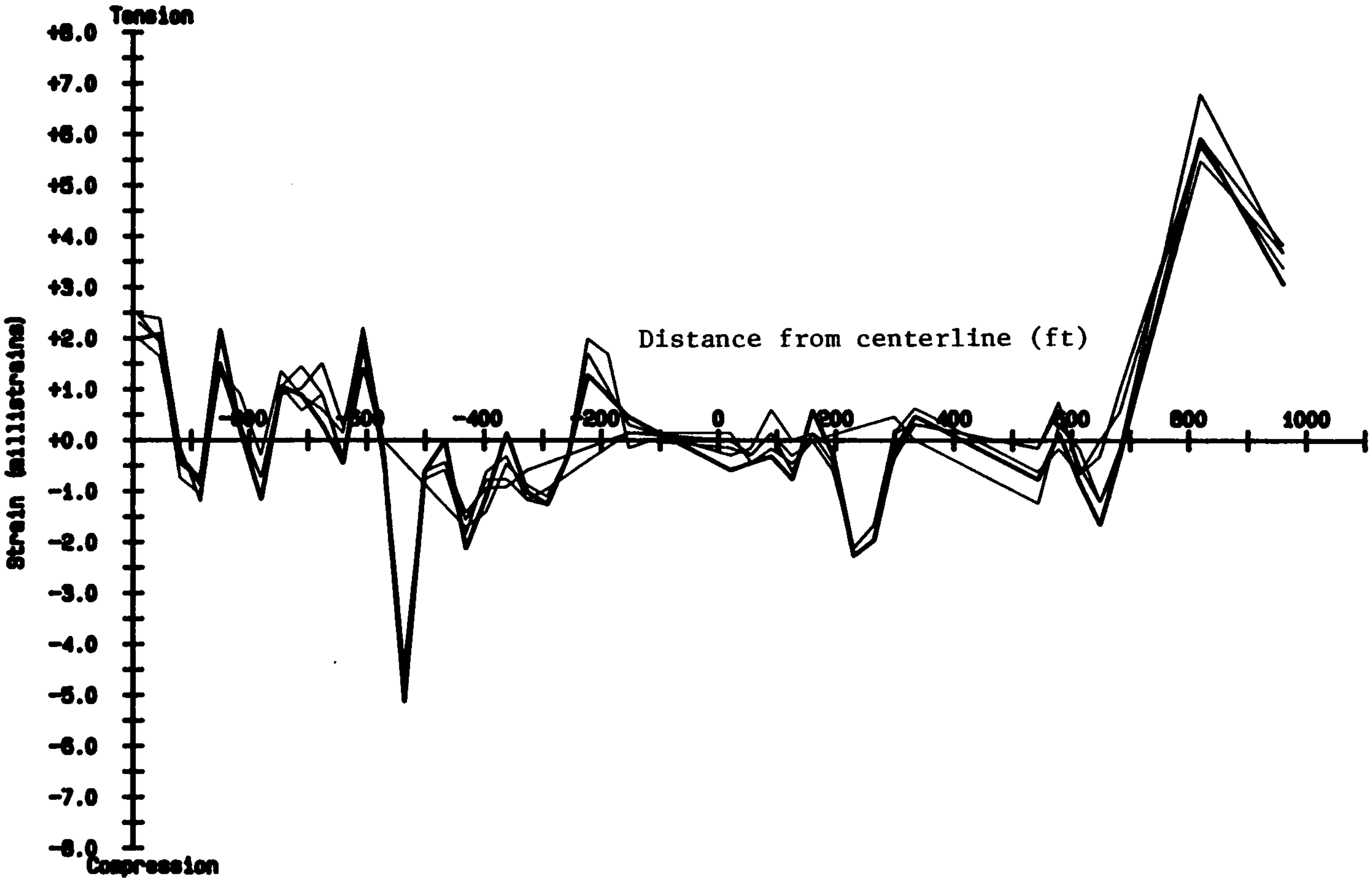

Figure C.29. Longitudinal Strain Profiles for Case Study RUVA-VT6.

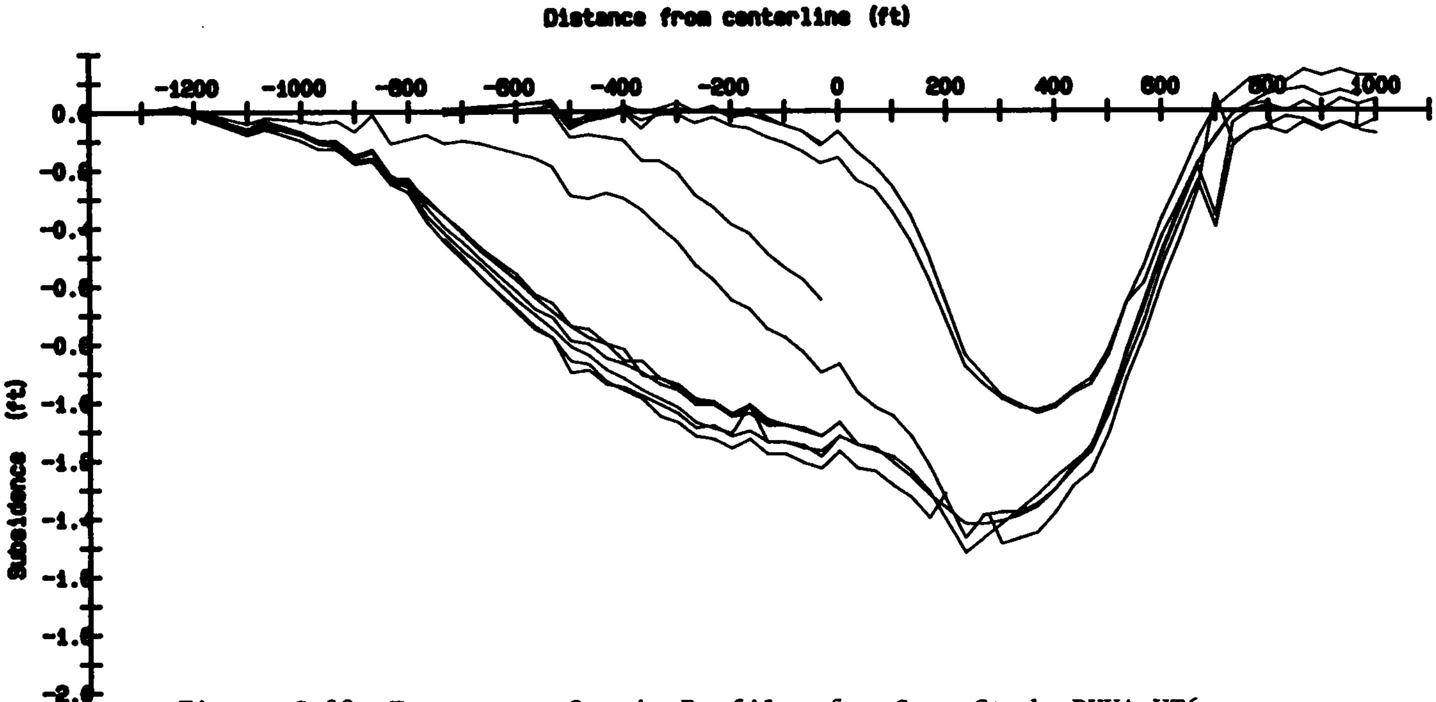

Figure C.30. Transverse Strain Profiles for Case Study RUVA-VT6.

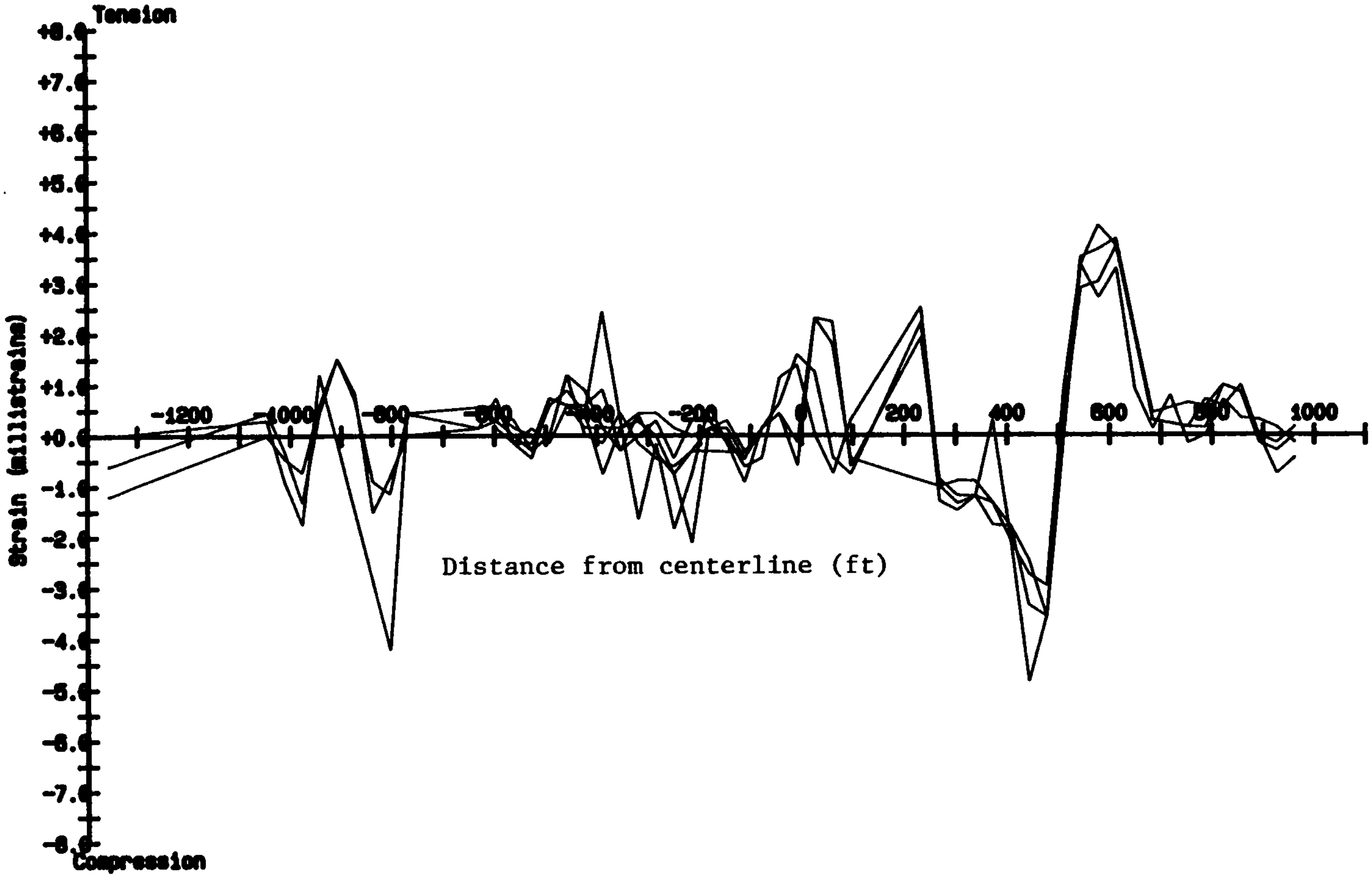

Figure C.31. Transverse Strain Profiles for Case Study RUVA-VT6.

APPENDIX D

Reference Index and Source of All Longwall Case Studies

Listing of All Subsidence Case Studies - Longwall Mines

Case Study Identification	References
LPAL 1	Park (1985)
LPAL 2	ibid.
LPOH 1	Roscoe (1981)
LPOH 2	Adamek (1981); Tandanand & Powell (1984)
LUPA 1	---
LPPA 2	Tandanand & Powell (1984)
LPPA 3	Tandanand & Powell (1982)
LPPA 4	ibid.
LPPA 5	ibid.
LPPA 6	Grayson & Mishra (1982)
LPPA 7	Tandanand & Powell (1982)
LPWV 1	Adamek (1981); Tandanand & Powell (1984); Tandanand & Powell (1982)
LPWV 2	Tandanand & Powell (1984)
LUWV 3	---
LUWV 4	---
LPWV 5	Dahl & Choi (1975); Tandanand & Powell (1984)
LPWV 6	Choi & McCain (1979)
LPWV 7	Adamek (1981); Tandanand & Powell (1984)
LPWV 8	Tandanand & Powell (1984)
LPWV 9	Triplett (1983)
LPWV 10	von Schonfeldt (1980); Dahl & von Schonfeldt (1976)
LPWV 11	Kohli & Jones (1986)
LPWV 12	Peng, et al. (1986)
LPVA 1	von Schonfeldt, et al. (1980)
LUVA-VT1	---
LUVA-VT2	---

Note: --- indicates unpublished data.

APPENDIX E

Reference Index and Source of All Room and Pillar Case Studies

Listing of All Subsidence Case Studies - Room and Pillar Mines

Case Study Identification	References
RUAL1	---
RPMD1	Committee on Ground Movement & Subsidence (1926)
RPMD2	ibid.
RPMD3	ibid.
RPPA1	Moebs (1979)
RPPA2	ibid.
RPPA3	ibid.
RPPA4	ibid.
RPPA5	Kohli and Peng (1980)
RPPA6	ibid.
RPPA7	ibid.
RPPA8	Greenwald,et al. (1937)
RPPA9	Maize, et al. (1939; 1941)
RPPA10	Maize, et al. (1940)
RPPA11	Maize, et al. (1941)
RPPA12	Rayburn (1930)
RPPA13	Committee on Ground Movement & Subsidence (1926)
RPPA14	ibid.
RPPA15	ibid.
RPPA16	ibid.
RPPA17	ibid.
RPPA18	ibid.
RPPA19	ibid.
RPPA20	ibid.
RPPA21	ibid.
RPPA22	ibid.
RUPA23	---
RUPA24	---
RPPA25	Draper (1964)
RUPA26	---
RUPA27	---
RUPA28	---
RUPA29	---
RUPA30	---
RUPA31	---
RPPA32	Newhall and Plein (1933)
RPPA33	Dahl and Choi (1975)
RUPA34	---
RPWV1	Choi and Dahl (1974)
RPWV2	Jones and Kohli (1984; 1985)
RPWV3	Bruhn (1985)
RUWV4	---
RUVA-VT1	---
RUVA-VT2	---
RUVA-VT3	---
RUVA-VT4	---
RUVA-VT5	---
RUVA-VT6	---
RUVA-VT7	---

Note: --- indicates unpublished data.

APPENDIX F

Listing of Program and Printout

F.1. Program Listing

```
10 CLS
20 'subsidence distribution using the profile function method
30 'P. Schilizzi, M.Karmis, VA TECH, 12-16-1986
40 '**********************************************
60  DIM S(51), X(51)
70 '**********************************************
80 '
90  PRINT "                Subsidence  Prediction"
100  PRINT "          Hyperbolic Tangent Profile Function"
110  PRINT "                 Developed at VA TECH"
120  PRINT: PRINT: PRINT: PRINT
130  PRINT "Input of Parameters:"
140  PRINT "Mining system (R for room and pillar - L for longwall):"
150  INPUT MS$
160    IF MS$="r" THEN MS$="R"
170    IF MS$="l" THEN MS$="L"
180    IF MS$="R" THEN 200
190    IF MS$<>"L" AND  MS$<>"R" THEN 140
200  PRINT "Input seam thickness (m):": INPUT M
210  PRINT "Input panel width (W) (0.5<W/H):": INPUT W
220  PRINT "Input depth of excavation:": INPUT H
230  PRINT "Input percent hardrock in the overburden:": INPUT HR
240  RF=1
250    IF MS$="R" THEN 260 ELSE 290
260  PRINT "Input extraction ratio (%) (R):": INPUT R
270  RF=.855*R/100  'Adjustment for room and pillar mines
280 '**********************************************
290  PRINT: PRINT: PRINT: PRINT
300  PRINT "Input Parameters:"
310  PRINT "Seam thickness (m):": PRINT M
320  PRINT "Panel width (W):": PRINT W
330  PRINT "Depth of excavation:": PRINT H
340  PRINT "Percent hardrock in the overburden:": PRINT HR
350  IF MS$="R" THEN 360 ELSE 380
360  PRINT "Extraction ratio (%) (R):": PRINT R
370 '**********************************************
380 HRC=(.12+.66*EXP(-(.00034*HR*HR)))/.78*RF
390 SMAX=(.6636-.121/((W/H*10-18)/20)+.13)*HRC
400 '**********************************************
410 '**********************************************
420 D=.29-.058/(W/H-.5 ) 'distance from inflection point to rib
430          IF D>=.21 THEN D=.21   'ASSYMPTOTIC CONDITIONS
440          IF H>1095 THEN D=230/H 'd WITHIN DATA BANK RANGE
450          IF W/H>= 1.3 THEN C=1.8    ' c INCREASES GRADUALLY
460          IF W/H=1.2 THEN C=1.7      ' TO AVOID DISCONTINUITY
470          IF W/H=1.1 THEN C=1.5      ' FROM SUBCRITICAL TO
480          IF W/H<=1 THEN C=1.4       ' SUPERCRITICAL
```

```
490        IF W/H> =1.2 THEN B=.6*H-D ELSE B=W/2-D
500 '**************************************************
510 PRINT "CALCULATED PARAMETERS"
520 PRINT "Smax=";SMAX*M
530 PRINT "   d=";D
540 PRINT "   B=";B
550 IF W/H>1.2 THEN PRINT "Panel is supercritical"
560 IF W/H=1.2 THEN PRINT "Panel is critical"
570 IF W/H<1.2 THEN PRINT "Panel is subcritical"
580 '**************************************************
590 W2=W/2
600 C1=C/B: W2=.5*W
610 X0=(0-W2+D)*C1
620 E1=EXP(X0): E2=EXP(-X0): E3=E1+E2: E4=E1-E2
630 'PRINT X1,E1,E2,E3,E4
640 S0=.5*SMAX*(1-E4/E3)'STOP
650  SMAX1=SMAX*SMAX/S0*M 'adjustment for s=smax at center
660 '**************************************************
670 AIN=INT((W2+.8*H)/100)*100  'CALCULATING RANGE FOR S=0
680 INCR=AIN/50 'DISTANCE INCREMENT
690 '**************************************************
700 FOR I=1 TO 51 STEP 1
710 XX=(I-1)*INCR
720 X(I)=XX
730 X1=(XX-W2+D)*C1
740 E1=EXP(X1): E2=EXP(-X1): E3=E1+E2: E4=E1-E2
750 S(I)=.5*SMAX1*(1-E4/E3)
760 'PRINT X(I),S(I)
770 NEXT I
780 '**************************************************
790  PRINT "       Distance (X) from panel center"
800  PRINT "       X      Subsidence          X      Subsidence"
810     A$="    ####       #.#            ####        #.#   "
820 FOR I=1 TO 26
830 PRINT USING A$; X(I),S(I),X(I+25),S(I+25)
840 NEXT I
850 '**************************************************
860 PRINT "Do you want a printout [Y/N]": INPUT A1$
870 IF A1$< >"y" AND A1$< >"Y" THEN 1170
880 LPRINT: LPRINT: LPRINT: LPRINT: LPRINT
890  LPRINT "                    Subsidence  Prediction"
900  LPRINT "                Hyperbolic Tangent Profile Function"
910  LPRINT "                     Developed at VA TECH"
920  LPRINT: LPRINT:
930  LPRINT "        INPUT PARAMETERS:": LPRINT
940  LPRINT "        Seam thickness (m):"; M
950  LPRINT "        Panel width (W):"; W
960  LPRINT "        Depth of excavation:";H
970  LPRINT "        Percent hardrock in the overburden:"; HR
980  IF MS$="R" THEN 990 ELSE 1000
990  LPRINT "        Extraction ratio (%) (R):"; R
```

```
1000 '*********************************************
1010 LPRINT: LPRINT
1020 LPRINT "        CALCULATED PARAMETERS": LPRINT
1030 LPRINT "        Smax=";SMAX*M;"ft"
1040 LPRINT "          d=";D*H;"ft
1050 LPRINT "          B=";B;"ft"
1060 IF W/H> 1.2 THEN LPRINT "       Panel is supercritical"
1070 IF W/H= 1.2 THEN LPRINT "       Panel is critical"
1080 IF W/H< 1.2 THEN LPRINT "       Panel is subcritical"
1090 '*********************************************
1100 LPRINT: LPRINT: LPRINT
1110 LPRINT "      Distance (X) from panel center": LPRINT : LPRINT
1120  LPRINT "     X     Subsidence          X      Subsidence"
1130    A$="    ####      #.#          ####      #.#   "
1140 FOR I=1 TO 26
1150 LPRINT USING A$; X(I),S(I),X(I+25),S(I+25)
1160 NEXT I
1170 '*********************************************
1180 PRINT "Do you want to store results on disk [Y/N]": INPUT A1$
1190 IF A1$<>"y" AND A1$<>"Y" THEN 1470
1200  INPUT "ENTER FILENAME";F$
1210  OPEN "o",1,F$
1220  PRINT #1, "                 Subsidence  Prediction"
1230  PRINT #1, "             Hyperbolic Tangent Profile Function"
1240  PRINT #1, "                  Developed at VA TECH"
1250 PRINT #1, "     INPUT PARAMETERS:"
1260 PRINT #1, "     Seam thickness (m):"; M
1270 PRINT #1, "     Panel width (W):"; W
1280 PRINT #1, "     Depth of excavation:";H
1290 PRINT #1, "     Percent hardrock in the overburden:"; HR
1300  IF MS$="R" THEN 1310 ELSE 1320
1310 PRINT #1, "     Extraction ratio (%) (R):"; R
1320 '*********************************************
1330 PRINT #1, "     CALCULATED PARAMETERS" : PRINT #1,
1340 PRINT #1, "     Smax=";SMAX*M
1350 PRINT #1, "       d=";D
1360 PRINT #1, "       B=";B
1370 IF W/H> 1.2 THEN PRINT #1, "      Panel is supercritical"
1380 IF W/H= 1.2 THEN PRINT #1, "      Panel is critical"
1390 IF W/H< 1.2 THEN PRINT #1, "      Panel is subcritical"
1400 '*********************************************
1410  PRINT #1, "      Distance (X) from panel center"
1420  PRINT #1, "      X      Subsidence          X      Subsidence"
1430    A$="    ####      #.#          ####      #.#   "
1440 FOR I=1 TO 26
1450 PRINT #1,, USING A$; X(I),S(I),X(I+25),S(I+25)
1460 NEXT I
1470 END
```

F.2. Typical Printout

Subsidence Prediction
Hyperbolic Tangent Profile Function
Developed at VA TECH

INPUT PARAMETERS:
Seam thickness (m): 5 ft
Panel width (W): 560 ft
Depth of excavation: 600 ft
Percent hardrock in the overburden: 50
CALCULATED PARAMETERS

Smax = 2.37 ft
d = .16 ft
B = 279.84 ft
Panel is subcritical
Distance (X) from panel center

X	Subsidence	X	Subsidence
0	2.4	350	0.8
14	2.3	364	0.8
28	2.3	378	0.7
42	2.3	392	0.6
56	2.3	406	0.6
70	2.2	420	0.5
84	2.2	434	0.4
98	2.2	448	0.4
112	2.1	462	0.3
126	2.1	476	0.3
140	2.0	490	0.3
154	2.0	504	0.2
168	1.9	518	0.2
182	1.8	532	0.2
196	1.8	546	0.2
210	1.7	560	0.1
224	1.6	574	0.1
238	1.5	588	0.1
252	1.4	602	0.1
266	1.3	616	0.1
280	1.3	630	0.1
294	1.2	644	0.1
308	1.1	658	0.1
322	1.0	672	0.0
336	0.9	686	0.0
350	0.8	700	0.0

APPENDIX G

List of Symbols

The following internationally accepted symbols have been used throughout this research.

Mining Parameters	*Symbol*
Depth	h
Extraction Ratio	R
Mining Height	m
Opening Width	W_o
Panel Width	W
Percent Hardrock	%HR
Pillar Width	W_p

Subsidence Parameters	
Angle of Draw	γ
Curvature	K
Horizontal Displacement	U
Horizontal Strain	E
Inflection Point	I.P.
Maximum Subsidence	S_m or S_{max}
Position of I.P. from the Rib	d
Ribside Subsidence	S_r
Slope	T
Subsidence at any Point	s or S
Subsidence Factor	a

Profile Function Parameters

Position of I.P. from S_{max}	B
Profile Function Constant	c

Influence Function Parameters

Angle of Principal Influence	β
Radius of Influence	r
Strain Parameter	B

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