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UNITED STATES DEPARTMENT OF THE INTERIOR

BUREAU OF MINES

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	min	minute
m	meter	psi	pound (force) per square inch
m^2	square meter	psi/ft	pound (force) per square inch per foot

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CALCULATION OF VERTICAL STRESS EXERTED BY TOPOGRAPHIC FEATURES

By Valois R. Shea-Albin,[1] Dennis R. Dolinar,[2] and Douglas C. Peters[2]

ABSTRACT

An accurate assessment of the vertical stress on a coal seam at depth is important for mine design. Vertical stress calculation techniques presently available either are not sufficiently accurate or cannot handle complex surface topography. Therefore, the U.S. Bureau of Mines developed a computerized method to calculate vertical stress exerted on surfaces at depth that includes the effect of topography. Two input data sets are required: a digital elevation model containing topographic elevations and a coal seam file defining coal seam elevations at depth. Boussinesq's equation then quantifies the vertical stress resulting from topography.

The computerized method was tested on a coal seam overlain by a complex topography where a vertical stress map encompassing several square miles was produced. Results show that depth mitigates the affects of surface topography, while the coal seam topography has a direct effect on the vertical stress. In comparison to the computerized method, the direct stress method overestimates stress under hills and underestimates stress under valleys. The largest difference between the two methods occurs under the steepest topographic relief. A limitation of the computerized method is that stresses cannot be accurately determined near an outcrop.

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INTRODUCTION

Ground control problems are inherent to mine development. Mine planning attempts to alleviate or avoid obvious hazardous areas that would cause unstable ground conditions during mining. Problems are encountered when mine entries intersect hazardous areas that were unforeseen prior to mining. Vertical (gravitational) stress is an important factor contributing to unstable ground surrounding mine entries. The distribution of vertical stress at the mining level is influenced by the overlying topographic features. Because of the rugged topography present in many coal-bearing regions, there was a need to develop a method to calculate the stress on a coal seam surface induced by the effect of topographic features overlying the coal seam.

When a coal seam is located in an area in which the topography is rugged with steep mountains, plateaus, or ridges, the abrupt change in overburden thickness above the coal affects the stress induced on a coal seam surface. When the coal seam is mined, stress and changes in stress will have to be considered in the design of the mine entries and the strata control plan. A method of assessing the stress at the level of the coal seam surface resulting from changes in topography would aid in identifying high stress areas and stress gradients before they are encountered in mining and could provide a helpful tool in effective mine design. As part of its program to improve mining safety, the U.S. Bureau of Mines has developed a method to calculate the vertical stress on a surface at depth that takes into account the variation of the overlying topography.

Hooker (*1*)[3] and Savage (*2-3*) investigated methods for calculating gravitational stresses induced by topographic features. Savage (*2-3*) developed models describing the effects of gravitational stresses induced by long symmetric ridge and valley topography. Hooker (*1*) developed a model for mountainous topography. Both of these methods use a cross-sectional plane through the topographic feature in question to calculate the stress effects of the feature at depth. These methods, therefore, cannot be used effectively in areas of more complex topography. The calculation method discussed in this report differs from the previous approaches by including in the stress calculation the effects of topographic features extending in two dimensions along the surface of the earth rather than a cross-sectional plane through the feature. Another advantage of this proposed method is that the topographic features do not have to match any specifications for symmetry or form. This technique allows for the evaluation of the vertical stress and topography for areas encompassing several square miles.

STRESS CALCULATION METHODOLOGY

The objective of the stress program is to calculate the distribution of stresses induced by a topographic feature upon a surface at depth at points that are located at varying horizontal distances away from the topographic feature. The accomplishment of this objective requires a method to quantify the magnitude of a stress vector from any point of origin on the topographic surface to any point of termination on the coal seam surface. Such a method is supplied by Boussinesq, who designed a model for continuous stress distribution from a vertical load to horizontal surfaces located beneath the load (*4*).

BOUSSINESQ'S EQUATION

Theory

Boussinesq's theory applies to the effect that a concentrated vertical load (Q) has on point N at depth. As shown in figure 1, Q is resting on the surface of a semi-infinite mass and induces a vertical stress (dP_v) at point N within the mass. dP_v is quantified by Boussinesq to be

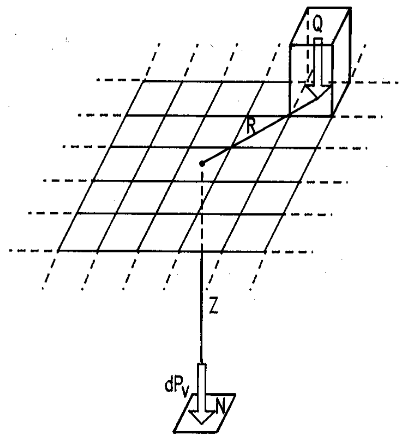
$$dP_v = \frac{3Q}{2Z^2}\left[\frac{1}{1+(R/Z)^2}\right]^{(5/2)}, \qquad (1)$$

where Z = vertical distance between point N and surface mass,

and R = horizontal distance from applied load to a point at depth within mass.

A topographic feature can be represented as a distributed load (q) resting on a semi-infinite surface of a mass. This is analogous to having a footing with q lying on the surface. The distribution of stress throughout the material underlying such a footing takes the configuration of a bulb-shaped stress dome as shown in figure 2. The area affected by the footing increases in horizontal extent with

[3] Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.



KEY

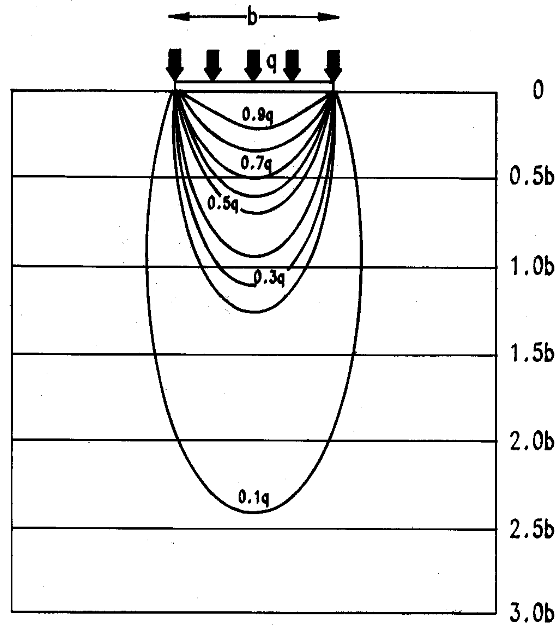
dP_V Vertical stress induced at point N

Q Load applied to a point

R Horizontal distance from load to point N at depth

Z Vertical distance between point N and surface mass

Figure 1.—Stress exerted at point N at depth by Q resting on semi-infinite horizontal surface.



KEY

b Footing width

q Distributed load

Figure 2.—Contours of vertical stress distribution underlying distributed load resting on semi-infinite surface. [From Adler (*4*)]

depth from the elevation of the applied load. As a result, the amount of load at any point on a horizontal surface within the stress dome decreases with depth so that the total stress remains constant and equal to that of the applied load (*4*). To calculate the vertical stress induced by the footing, the point load theory is used at distances into the medium greater than three times the footing width (b), while inside this distance, the loads must be integrated over the footing surface. Because of the horizontal extent of topographic features, the area of interest, in general, is less than twice the width of the feature, and therefore, the surface loads must be integrated.

To integrate, the surface area A bearing q produced by the topographic feature can be divided into smaller incremental areas (dA's) each with a q. These q's can be replaced by Q at the center of each incremental area where the concentrated load is $Q = q \cdot dA$. Equation 1 can then be used to calculate the vertical stress (dP_v) caused by each point load at a point N within the mass. Equation 1 becomes

$$dP_{vi} = \frac{3Q_i}{2Z^2}\left[\frac{1}{1 + (R_i/Z)^2}\right]^{(5/2)}, \qquad (2)$$

where $Q_i = q_i \cdot dA$,

$= $ vertical point load applied to dA,

$i = $ identity of given dA,

$R_i = $ horizontal distance from dA to point of calculation in mass,

and $dP_{vi} = $ vertical stress induced at a point within mass by Q on dA.

The total vertical stress at a point at depth caused by the topography (P_v) can be determined by summing each dP_v induced from all the point loads applied to the surface.

$$P_v = \sum_{i=1}^{n} dP_{vi} = \sum_{i=1}^{n} \frac{3Q_i}{2Z^2}\left[\frac{1}{1 + (R_i/Z)^2}\right]^{(5/2)}, \qquad (3)$$

where $n = $ total number of dA's.

The limitation still exists where the stress within the mass cannot be evaluated within a depth from a point load equal to three times the width of the dA.

Boussinesq's equation applies to load-bearing masses that are homogeneous, elastic, and isotropic, and extend infinitely in all directions below the level at which the mass rests. This application of Boussinesq's equation involves the calculation of only vertical stresses. It has been established that the distribution of vertical stresses throughout the substrata is independent of the physical properties of the substrata (5). These assumptions will, therefore, hold true for the distribution of vertical stresses through coal-bearing strata.

Calculation Surface

Three surfaces are required for the calculation of P_v due to a topographic feature. These are the coal seam, topographic, and calculation surfaces. The coal seam surface is the surface on which P_v will be calculated at various points, while the topographic surface is the terrain of the earth overlying the coal seam. The calculation surface is a semi-infinite plane upon which the vertical load due to the topography rests. The calculation surface extends parallel to a flat earth surface and lies between the coal seam and topographic surfaces. The vertical load distribution on this plane can be approximated as columns that have square bases equal to dA and have a height equal to the difference in elevation between the topographic and calculation surfaces.

In this application of Boussinesq's theory, the dA's correspond to the 30- by 30-m[4] grid cells containing the topographic elevations and the coal seam elevations. The surface topographic features, represented as various elevation values distributed within the grid pattern, are considered to rest upon the calculation surface. The 30- by 30-m grid is also projected onto the calculation surface. The elevation values assigned to the grid cells on the calculation surface are all the same value because, by definition, the calculation surface is a surface of constant elevation. The thickness of overburden above the calculation surface at each 30- by 30-m grid cell can be calculated by subtracting the elevation value within each grid cell from the surface topography elevations in the overlying grid cells. From this overburden thickness and the density of the material, the stress exerted by each column of overburden over each grid cell of the calculation surface can be determined.

Stress induced on points lying on the top of the coal by overlying topographic features can be calculated using this concept of a calculation surface. The body of distributed mass is the topographic feature, such as a mountain or ridge, resting on the horizontal calculation surface. Ideally, the calculation surface should be at the highest possible elevation. The plane of highest elevation over which the topographic features of the study area are considered to distribute their load is a plane lying at the same elevation as the topographic low for the study area. The point N upon which the stress is induced exists on the surface of a coal seam lying at depth. The dA's in this application are grid cells corresponding to the grid cells of the surface topography file, sectioned into 30- by 30-m squares as measured along the calculation surface. Because the dA's are square cells, the total area bearing the load is a square, rather than a circular area. The stress on each grid cell is assumed to be a point load located at the center of each grid cell. The stress directed toward point N on the coal seam surface, corresponding to the center cell of the grid, is calculated by summing all the stress vectors originating from each dA. The number of dA's or grid cells involved in the summation is determined through regression analysis of the asymptotic relationship between calculated stress and an increasingly larger area of the topographic surface included in the calculation. The topographic surface area is measured in grid cells away from the point on the surface topography that directly overlies the point on the coal seam surface corresponding to point N, the point bearing the stress. Equation 3 can be used to calculate the stress for cells up to a given distance from the point of calculation:

$$P_v = \sum_{i=1}^{(H \cdot 2 + 1)^2} \frac{3Q_i}{2Z^2} \left[\frac{1}{1 + (R_i/Z)^2} \right]^{(5/2)}, \quad (4)$$

where H = half width of surface load application area, the shortest horizontal distance in grid cells from dA where P_v is to be calculated to perimeter of square area over which dP_v is calculated for each cell.

For a distance of H grid cells away from the center point, the total load-bearing area is $(H \cdot 2 + 1)^2 \cdot 900\ m^2$. Figure 3 illustrates the spatial relationships described.

[4]Thirty-meter-square grid cells are used because that is the standard spatial distribution for digital elevation model (DEM) data.

Because the configuration of the calculation surface and the point at depth resembles that of an inverted pyramid and each point on the calculation surface influences the stress on the point at depth, the arrangement is called "the pyramid of influence."

TEST TOPOGRAPHY AND COAL SEAM SURFACES

The stress calculation program was tested first with a flat semi-infinite topographic surface overlying a flat coal seam top. Because there was no variation in topography, the total stress at any point on the coal seam could be calculated as direct stress (also known as "tributary area" method) using the standard average value of 1.1 psi/ft of overburden depth for coal-bearing strata. For this study, direct stress was defined as the stress at a point on the coal seam exerted by the topographic elevation lying directly above it. Direct stress did not take into account any stresses exerted by topographic features lying at a distance away from the point directly above.

The flat test surface lay at an elevation of 600 ft above sea level, with the calculation surface located at 200 ft above sea level. The coal seam lay at an elevation of 400 ft below sea level, creating an overburden thickness of 1,000 ft. The stress calculation was performed on the same point on the coal seam surface with increasingly larger pyramid bases, thus encompassing an increasingly larger topographic area surrounding the point at depth. Table 1 lists the calculated stresses with the number of grid cells defining the half width of the pyramid base used in each calculation. The direct stress value of 1,100 psi is the total stress to which the calculated values were compared. The stress calculation values approached total stress quickly at first with increasing pyramid base sizes. After an initial rapid approach to total stress, the calculated stress increased more slowly toward the total stress value. Figure 4 is a graph illustrating the percentage of total stress calculated using increasingly larger pyramid half widths. As the pyramid base grew larger, more cells were added to the perimeter and were included in the summation of point stresses. Even though more point loads were being included, they were progressively farther away from the center point of the pyramid, and each cell contributed a lesser amount of stress to the total stress. As the curve illustrates, the stress values calculated with larger and larger pyramid bases approached total stress asymptotically. Total stress would be achieved only with an infinite pyramid base.

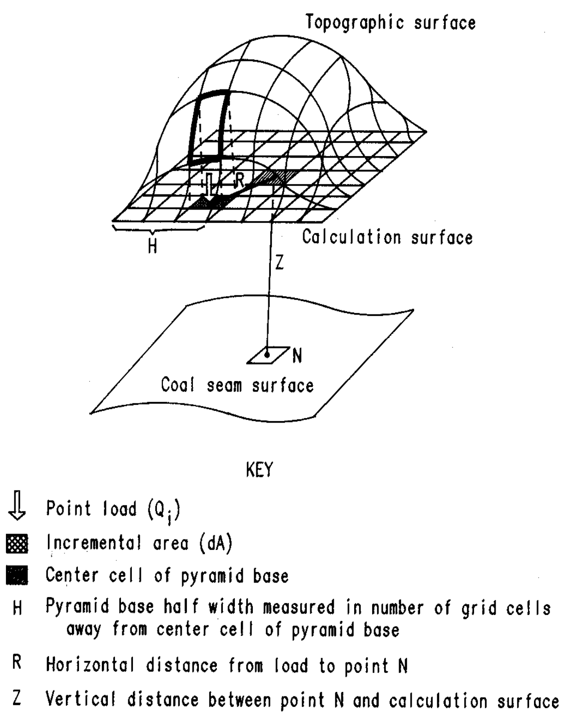


Figure 3.—Pyramid of influence showing topographic feature represented as collection of point loads resting on calculation surface exerting stress at point N at depth.

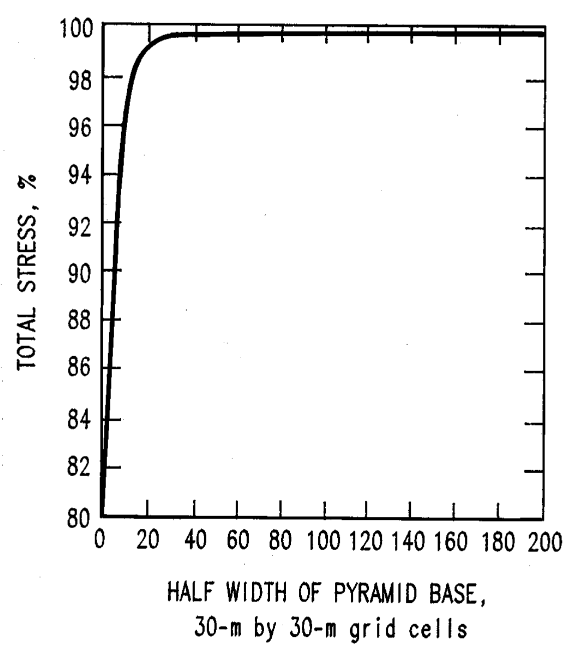


Figure 4.—Percentage of calculated stress versus number of grid cells comprising half width of pyramid base.

Table 1.—Stress values calculated for point on flat test surface with increasing pyramid base sizes, in pounds (force) per square inch

Pyramid base half width[1]	*Calculated stress*	*Pyramid base half width*[1]	*Calculated stress*
1	893.6	70	1,099.6
10	1,058.8	80	1,099.6
20	1,091.5	90	1,099.7
30	1,097.1	100	1,099.7
40	1,098.7	150	1,099.7
50	1,099.3	200	1,099.7
60	1,099.5		

[1]Half width measured in number of grid cells away from center cell of pyramid base.

NOTE.—Topographic elevation = 600 ft above sea level; calculation surface = 200 ft above sea level; coal seam elevation = 400 ft below sea level; and total stress = 1,000 ft overburden × 1.1 psi/ft overburden = 1,100 psi.

CALCULATION OF VERTICAL STRESS FOR A COAL MINE

When topographic variations occur as in the case of an actual coal mine, the total stress which the calculated stress approaches asymptotically is unknown. Once there are topographic variations at the surface, the direct stress method does not calculate the correct stress values at an underlying point. Using the relationship established with the flat test surface, the total stress can be estimated even though it is unknown. The calculated stresses follow the same relationship as before, approaching asymptotically a maximum value for stress. This maximum can be estimated through regression analysis techniques.

Given the relationship between the pyramid base size and the calculated stress observed at the test points using a flat topographic test surface, it is possible to estimate the total topographic stress at a point for a flat surface by developing an equation that will predict the amount of stress contributed by the topographic load beyond a selected base size of the inverted pyramid of influence. Rewriting equation 1 yields

$$dP = \frac{3QZ^3}{2}\left[R^2 + Z^2\right]^{(-5/2)}. \qquad (5)$$

If Z is held constant, and R gets much greater than Z, then equation 5 becomes

$$dP = \frac{3QZ^3}{2}\left[R^{-5}\right]. \qquad (6)$$

Equation 6 provides an approximation for the stress induced by a point load located beyond the bounds of the pyramid base and, therefore, is not included in the stress calculations. Figure 5 shows a square perimeter consisting of a single row of cells that is centered around but lies beyond the pyramid base. The stress induced beneath the center of the pyramid base by a cell in this perimeter can be written in terms of the perimeter dimensions. The distance from the center of the pyramid to the cell is

$$R_i = (W^2 + l^2)^{0.5}, \qquad (7)$$

where W = half width of extended perimeter load application, the horizontal distance from center of pyramid to load application point of nearest extended perimeter cell,

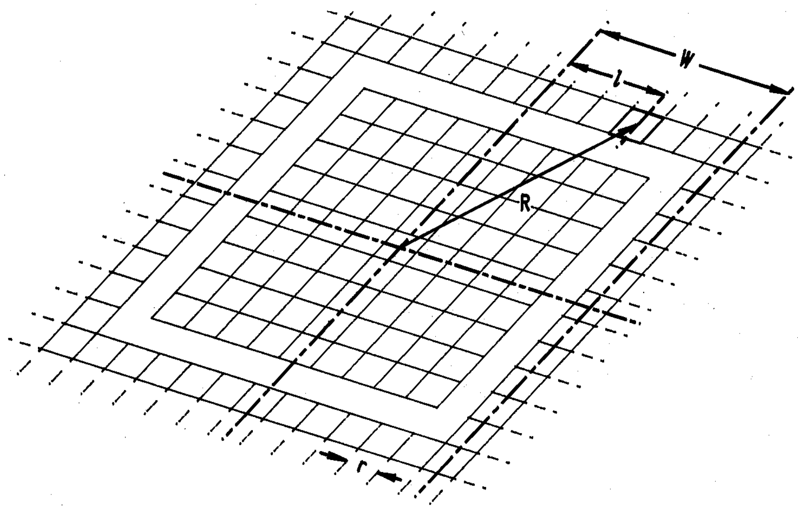
and l = distance in meters from middle of center cell of perimeter side to middle of another cell along same perimeter side.

Rearranging terms in equation 7,

$$R_i = W\cdot(1 + l^2/W^2)^{0.5}. \qquad (8)$$

Writing the distances inside the parentheses in terms of an individual cell width dimensions,

$$R_i = W\cdot(1 + (j\cdot r)^2/(h\cdot r)^2)^{0.5}, \qquad (9)$$



KEY

-·-·- Centerlines of cells

l Distance from middle of center cell of a perimeter side to middle of selected cell along same perimeter side

R Horizontal distance from applied load to a point within the mass

r Width of individual grid cells

W Half width of extended perimeter

Figure 5.—Square perimeter surrounding pyramid base.

where r = width of individual cell,

j = l/r,

= distances in number of grid cells from middle of center cell of perimeter side to middle of another cell along same perimeter side,

and h = W/r,

= half width of perimeter in number of grid cells.

Canceling terms in equation 9,

$$R_i = W(1 + j^2/h^2)^{0.5}. \qquad (10)$$

Substituting equation 10 into equation 6,

$$dP_i = \frac{3Q_iZ^3}{2}(W^{-5})\left[\left(1 + \frac{i^2}{h^2}\right)^{-5/2}\right]. \qquad (11)$$

Because the load applied to each incremental cell (Q_i) does not vary for a flat surface, this incremental load can be replaced by one constant load. Equation 11 becomes

$$dP_i = \frac{3PZ^3}{2}(W^{-5})\left[\left(1 + \frac{i^2}{h^2}\right)^{-5/2}\right], \qquad (12)$$

where P = constant vertical load applied to each dA.

The stress at the point at depth due to the perimeter cells can be determined by summing up the stress due to the individual cells along the perimeter. From a center cell to a corner cell along a perimeter side, the summation is

$$P_{p1} = \frac{3PZ^3}{2}(W^{-5})\left[\sum_{i=0}^{h}\left(1+\frac{i^2}{h^2}\right)^{-5/2}\right], \quad (13)$$

where P_{p1} = vertical stress at point at depth due to cells from center cell to corner cell of perimeter side.

For the adjacent side, the stress due to elements from the cell next to the corner cell to the perimeter side center cell is

$$P_{p2} = \frac{3PZ^3}{2}(W^{-5})\left[\sum_{i=1}^{h-1}\left(1+\frac{i^2}{h^2}\right)^{-5/2}\right], \quad (14)$$

where P_{p2} = vertical stress at point at depth due to cells beginning with cell adjacent to corner cell through center cell of perimeter side.

Equations 13 and 14 must be multiplied by 4, then added together to calculate the total stress at the point at depth due to the perimeter.

$$P_v = \frac{3PZ^3}{2}(W^{-5})\left[4\sum_{i=0}^{h}\left(1+\frac{i^2}{h^2}\right)^{-5/2} + 4\sum_{i=1}^{h-1}\left(1+\frac{i^2}{h^2}\right)^{-5/2}\right], \quad (15)$$

where P_v = total vertical stress at point at depth due to all cells around perimeter.

Multiplying both numerator and denominator by 8 m, the number of cells along the perimeter, equation 15 becomes

$$P_v = \frac{3PZ^3(W^{-5})}{2}\,8h\,\frac{\left[4\sum_{i=0}^{h}\left(1+\frac{i^2}{h^2}\right)^{-5/2} + 4\sum_{i=1}^{h-1}\left(1+\frac{i^2}{h^2}\right)^{-5/2}\right]}{8h}. \quad (16)$$

Each summation in equation 16 divided by h in the denominator can be calculated for a given perimeter width. Table 2 shows these values for various perimeter widths and illustrates that the summations converge. An average distance can be used for all perimeter cells. Replacing the summations in equation 16 by the number on which the summations converge yields

$$P_v = \frac{3PZ^3W^{-5}}{2}\,8h\,\frac{[4(0.59) + 4(0.59)]}{8h}. \quad (17)$$

Table 2.—Summation of cell distances according to increasing perimeter widths

Width of perimeter (in grid cells)	$\sum_{i=0}^{h}$	$\sum_{i=1}^{h-1}$
100	0.595	0.583
150	.593	.585
200	.592	.586
500	.590	.588
1,000	.590	.589
10,000	.589	.589
20,000	.589	.589

h Half width of perimeter in number of grid cells.

Replacing h by W/r and canceling terms in equation 17 gives

$$P_v = \frac{3PZ^3W^{-4}}{r}[(4)\ (0.59)]. \quad (18)$$

Combining the constants in equation 18 yields

$$P_v = CW^{-4}P, \quad (19)$$

where $C = \frac{3Z^3(4)(0.59)}{r}$,

= a constant.

The summation terms represent the distance to each small square along the perimeter. Dividing through by 8 h, the number of grid cells along the perimeter will result in an average distance for each square along the perimeter. The total stress beyond the pyramid of influence can be calculated by integration of equation 19 from the pyramid load application half width to infinity:[5]

$$S_B = \int_H^{\infty} C\, W^{-4}\, dW\, P, \tag{20}$$

where S_B = stress at point of calculation due to topography beyond zone of influence.

Integration of equation 20 yields

$$S_B = C\, H^{-3}\, P. \tag{21}$$

The total stress due to topography at the point of calculation can be calculated by adding together the stress calculated from the pyramid of influence and the stress beyond the pyramid (equation 22).

$$S_t = S_H + S_B, \tag{22}$$

where S_t = total stress from topography above calculation surface,

and S_H = stress calculated from pyramid of influence.

Substituting equation 21 into equation 22 and rearranging the terms yields

$$S_H = S_t - C\, H^{-3}\, (P). \tag{23}$$

Although the equation was originally applied to a flat surface, when the pyramid of influence is large, the variation of the loads beyond the pyramid width will not have a large effect on the stresses at the point of calculation. The number of cells beyond the pyramid base is very large, but because the stress value that each would contribute is very small, an average load for each cell can be used. This average load (Q_a) is the total sum of the applied loads on the dA's divided by the total number of cells beyond the pyramid of influence. Equation 23 can then be written in terms of a new constant (K).

$$S_H = S_t - K\, H^{-3}, \tag{24}$$

[5]There is a difference of one grid cell between the width of the pyramid base and the width of the area where the point loads are applied, the load application width. This occurs because the point loads are applied at the center of the grid cells with no loads actually being applied at the perimeter.

where $K = C\, Q_a$,

and Q_a = average load that can be applied to each dA beyond pyramid of influence.

By calculating the various values of the stress from topographic features within different sizes of pyramid bases, a regression analysis can be performed to calculate the total stress from equation 24. Through the regression analysis, the variation of topography within the zone of the pyramid is used to determine the stress due to topography beyond the pyramid of influence. Essentially, an assumption is made that the same type of topographic variation exists both inside and outside the pyramid of influence. Even if this assumption is not entirely correct, the error is greatly mitigated by the large distances between these topographic variations outside the pyramid zone and the point of calculation at depth. Because of the assumptions made in developing the equation, it is not accurate for H values for pyramid base widths less than twice the distance from the calculation surface to the coal seam surface. Further, to provide a good estimate of the total stress from the regression analysis, the H values should range from at least 3 to 10 times the distance from the calculation surface to the point of calculation on the coal seam surface.

LOCATION OF STUDY AREA

The study area includes the Jim Walters Resources, Inc., No. 5 Mine in the Black Warrior Basin of Alabama. The No. 5 is an underground mine in Tuscaloosa County extracting the Mary Lee coal seam. The mine property boundaries and the study area encompass portions of six 7.5- by 7.5-min quadrangles as shown in figure 6.

The Black Warrior Basin is located within a subdivision of the Appalachian Plateau Province, called the Cumberland Plateau. The sedimentary strata within this province are predominately flat lying, showing only minor structural deformation (*6-7*). The Cumberland Plateau, however, has been highly dissected by erosion into a configuration of isolated, flat-topped plateaus separated by deep valleys displaying large vertical relief, making the location a good study area for analyzing the stress effects of steep topography.

ELEVATION DATA

Surface Topography Elevations

The surface topography elevations for the study area are provided by DEM's. A DEM consists of profiles or arrays of topographic elevation values corresponding to regularly spaced ground positions every 30 by 30 m. Each

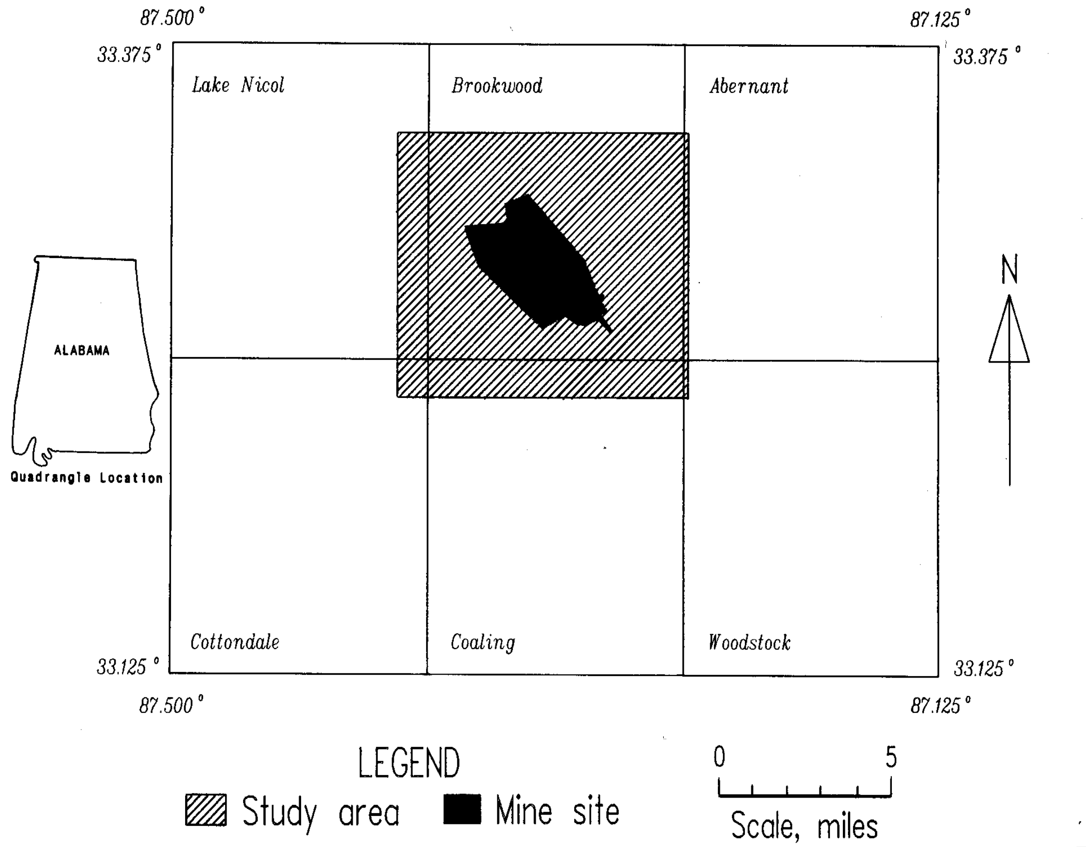


Figure 6.—Study area map of Jim Walter Resources, Inc., No. 5 Mine in Black Warrior Basin, Tuscaloosa County, AL.

DEM provides coverage for a 7.5- by 7.5-min block corresponding to the standard U.S. Geological Survey (USGS) 1:24,000 scale map series quadrangles.

In the DEM file, the elevation values are contained in profiles, which are one-dimensional arrays containing a series of elevation values, called nodes. The first node in the profile is the elevation of a point at the south edge of the quadrangle. The subsequent values represent elevations at successive points to the north, spaced 30 m apart. The profiles are listed in the file in order from east to west. Each profile begins with header information describing the profile. The profiles within each DEM do not have the same number of elevations. Because there is an angle of varying size between true north and the north direction of the Universal Transverse Mercator (UTM) grid, the 7.5-min quadrangle boundaries clip profiles, which parallel the UTM grid system at some angle to true north.

The elevation data contained in a DEM are produced in 7.5- by 7.5-min blocks either by digitizing contour maps or scanning high-altitude photographs. The data are then processed and formatted in a 30- by 30-m grid. Additional information on DEM data collection and file format is included in the "Data Users Guide 5" entitled "Digital Elevation Models" provided by the USGS National Mapping Program (*8*).

To obtain the coverage of elevation values for the study area, computer programs were developed to extract from each DEM file only the elevation values falling within the boundaries of the study area. The header information for each profile provides the UTM northing and easting of the first point in the profile and the number of elevations contained in each profile. The easting of the profile is compared with the minimum (westernmost) and maximum (easternmost) easting of the study area. Once a profile is determined to be within the easting range of the study area, the program calculates the northing of each elevation point and extracts only the points falling within the northing range of the study area.

Because of the size of each DEM file and the fact that it was necessary to read in six files to obtain the coverage for the study area, it was more expedient to separate the process into two steps. One program extracts the elevation from one DEM file at a time and saves the extracted elevations to a smaller file. Then, a second program reads in the six smaller files and combines them to provide the one large study area file. Because the UTM coordinate system is not parallel to the boundaries of the 7.5-min quadrangle, DEM profiles vary in length. It is, therefore, necessary to keep track of the northing and easting values of the first point in each of the extracted profiles to match them properly with adjacent profiles in the contiguous cut files. The resulting elevation coverage for this study area is a file of 445 by 445 elevation points arranged in the 30- by 30-m grid pattern of the original DEM. The elevation points are ordered from east to west in rows, with the rows ordered from north to south, as illustrated in figure 7. This format was chosen to be compatible with the display program used for remote sensing data.

The study area extends from 463,515 m easting in the west to 476,865 m easting in the east. The southern boundary is at 3,676,035 m northing, and the northern boundary is 3,689,385 m northing. The maximum surface elevation is 800 ft above mean sea level, and the minimum elevation is 187 ft. (Feet, instead of meters, were chosen for the unit of measure of elevation in the data files to be compatible with the coal seam elevation values, which were in feet, and to facilitate comparison to topographic maps.)

Coal Seam Top Elevations

The mining company provided logs of drill holes throughout the mine property. Coal seam and overburden strata elevations were entered into a personal computer (PC) data base along with the geographical (northing and easting) coordinates for each drill hole location. The

0 m	30 m	60 m	90 m	120 m	150 m	180 m	210 m	240 m	270 m	300 m
30 m	1 429.7	2 449.4	3 465.8	4 485.4	5 501.8	6 515.0	7 515.0	8 508.4	9 492.0	10 485.4
60 m	306 426.4	307 436.2	308 449.4	309 472.3	310 492.0	311 505.1	312 498.6	313 492.0	314 475.6	315 475.6
90 m	611 449.4	612 459.2	613 475.6	614 485.4	615 488.7	616 501.8	617 488.7	618 485.4	619 469.0	620 469.0
120 m	916 452.6	917 452.6	918 469.0	919 472.3	920 469.0	921 478.9	922 462.5	923 465.8	924 455.9	925 455.9
150 m	1,221 462.5	1,222 452.6	1,223 459.2	1,224 462.5	1,225 452.6	1,226 455.9	1,227 442.8	1,228 452.6	1,229 462.5	1,230 452.6
180 m	1,526 449.4	1,527 439.5	1,528 449.4	1,529 449.4	1,530 436.2	1,531 436.2	1,532 423.1	1,533 433.0	1,534 446.2	1,535 436.2
210 m	1,831 429.7	1,832 426.4	1,833 439.5	1,834 446.1	1,835 429.7	1,836 423.1	1,837 413.3	1,838 413.3	1,839 419.8	1,840 429.7
240 m	2,136 410.0	2,137 413.3	2,138 423.1	2,139 429.7	2,140 410.0	2,141 410.0	2,142 403.4	2,143 396.9	2,144 400.2	2,145 419.8
270 m	2,441 400.2	2,442 410.0	2,443 410.0	2,444 406.7	2,445 406.7	2,446 419.8	2,447 413.3	2,448 396.9	2,449 393.6	2,450 413.3
300 m	2,746 380.5	2,747 390.3	2,748 390.3	2,749 387.0	2,750 400.2	2,751 419.8	2,752 429.7	2,753 419.8	2,754 416.6	2,755 433.0

KEY

1	Point number
429.7	Elevation value, ft

N

Figure 7.—Format of input file containing topographic elevations.

data base structure expedites the storage and extraction of geographically referenced drill log information. A file containing only geographical coordinates of the drill logs and the elevation of the top of the Mary Lee coal seam was created within the data base and entered into a gridding program to interpolate regularly spaced coal seam top elevation points between the irregularly spaced drill log locations. The gridding program used was Gridzo, a product of RockWare, Inc.[6]

The coal seam elevation coverage for the study was too large for the Gridzo gridding program to handle as one file. The area was divided into four contiguous areas, each gridded separately by the Gridzo gridding program and stored as separate grid files. The files were transferred from the PC to a Prime 6350 super-minicomputer and merged into one large file containing the coal seam elevation coverage for the study area.

[6]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

The Gridzo gridding program provides a number of algorithms to interpolate between irregularly spaced data points. The method chosen for this study was the triangulation method, because it uses the points outside the designated grid boundaries to interpolate up to the boundaries and, therefore, acted to "link together" the four areas that were gridded separately.

The resulting coverage containing the Mary Lee coal seam top elevations for the study area extends from 465,615 m easting on the west side to 474,765 m easting on the east side. The southern boundary is 3,678,135 m northing, and the northern boundary is 3,687,285 m northing. The maximum coal seam elevation within the study area is -1,305 ft below mean sea level, and the minimum elevation is -1,641 ft. The grid cell coordinates for both the topographic elevation coverage and the Mary Lee coal seam top coverage were designed to correspond geographically. An example of the file is shown in figure 8.

0 m 30 m 60 m 90 m 120 m 150 m 180 m 210 m 240 m 270 m 300 m

	1 -1,434	2 -1,434	3 -1,434	4 -1,434	5 -1,434	6 -1,434	7 -1,434	8 -1,434	9 -1,434	10 -1,434
30 m	306 -1,434	307 -1,434	308 -1,434	309 -1,434	310 -1,434	311 -1,434	312 -1,434	313 -1,434	314 -1,434	315 -1,434
60 m	611 -1,434	612 -1,434	613 -1,434	614 -1,434	615 -1,434	616 -1,434	617 -1,434	618 -1,434	619 -1,434	620 -1,434
90 m	916 -1,434	917 -1,434	918 -1,434	919 -1,434	920 -1,434	921 -1,434	922 -1,434	923 -1,434	924 -1,434	925 -1,434
120 m	1221 -1,434	1222 -1,434	1223 -1,434	1224 -1,434	1225 -1,434	1226 -1,434	1227 -1,434	1228 -1,434	1229 -1,434	1230 -1,434
150 m	1526 -1,434	1527 -1,434	1528 -1,434	1529 -1,434	1530 -1,434	1531 -1,434	1532 -1,434	1533 -1,434	1534 -1,434	1535 -1,434
180 m	1831 -1,434	1832 -1,434	1833 -1,434	1834 -1,434	1835 -1,434	1836 -1,434	1837 -1,434	1838 -1,434	1839 -1,434	1840 -1,434
210 m	2,136 -1,434	2,137 -1,434	2,138 -1,434	2,139 -1,434	2,140 -1,434	2,141 -1,434	2,142 -1,434	2,143 -1,434	2,144 -1,434	2,145 -1,434
240 m	2,441 -1,434	2,442 -1,434	2,443 -1,434	2,444 -1,434	2,445 -1,434	2,446 -1,434	2,447 -1,434	2,448 -1,434	2,449 -1,434	2,450 -1,434
270 m	2,746 -1,434	2,747 -1,434	2,748 -1,434	2,749 -1,434	2,750 -1,434	2,751 -1,434	2,752 -1,434	2,753 -1,434	2,754 -1,434	2,755 -1,434
300 m										

KEY

1	point number
-1,434	elevation value, ft

N

Figure 8.—Format of input file containing coal seam top elevations.

RESULTS

A number of test points were selected within the study area to determine the size of the pyramid of influence from the regression analysis. The test points included the minimum and maximum topographic elevations, the minimum and maximum coal seam elevations, the minimum and maximum overburden thickness, the center point of the study area, and the center points of each quadrant of the study area. The maximum topographic elevation in the study was 800 ft above sea level. The minimum elevation and, therefore, the elevation of the calculation surface was 187 ft. The minimum and maximum coal seam elevations were 1,641 and 1,305 ft below sea level, respectively.

The stress at each test point was calculated at increasingly larger half width values to establish a relationship between the half width of the pyramid base and the calculated stress value. Through regression analysis, the half width and stress values were used to extrapolate the total stress at each test point. The half width values calculating 99% total stress at each test point were examined, and the maximum half width value was selected as the half width for the entire study area. A half width value calculating 95% total stress was also selected.

The half width value for the pyramid base calculating 99% total stress for this study area was determined to be 70 grid cells. The base of the pyramid encompassed 141 by 141 grid cells. A half width yielding 95% total stress calculation was 42 grid cells, forming a pyramid base of 85 by 85 grid cells.

The stress calculation was run twice, once with the pyramid base width set to calculate 95% total stress and once with the pyramid base width set to calculate 99% total stress. For comparison, direct stress was calculated for the study area, which used only overburden thickness directly above the coal seam grid cell, multiplied by the approximate value of 1.1 psi/ft of overburden to calculate vertical stress. An example of the format of the output files resulting from these three calculations is included in figure 9. The output files were converted by contouring programs into contour maps representing stress values, allowing the data files to be more easily analyzed and compared.

The comparison of the 99% and 95% total stress calculations, represented in both the stress contour maps in figures 10 and 11, respectively, and the test points in table 3, shows only minimal difference in P_v values calculated for each point. The savings of computer time warrants the decrease in accuracy involved in calculating only 95% total stress. In comparing the direct stress map (fig. 12) to the other two stress maps, it can be seen that the direct stress method creates artificial zones of abrupt stress change across relatively small horizontal distances. The abrupt stress changes, if they were real, would indicate great stress differentials in these zones that might cause ground control problems in an underground mine workings intersecting these zones. The abrupt stress changes are not observed in the maps produced from the pyramid of influence calculation method for two reasons. The first reason is that this method takes into account the effect of stress from topographic features lying adjacent to a point directly overlying a point on the coal seam. Because the calculation involves several topographic elevation cells and assigns the final value to one stress cell, the calculation acts as a filter to the effects of abrupt changes in topographic elevation. The second reason is that Z is directly dependent on the coal seam elevation values. The calculated stress contour maps, therefore, more closely resemble the patterns of the coal seam elevation map (fig. 13) than those of the topographic elevation map (fig. 14).

Table 3.—Stress values calculated at study area test points, in pounds (force) per square inch

Test point	Direct stress[1]	Total stress[2]	99% total stress	95% total stress
Topographic elevation:				
Minimum	1,917.6	2,084.3	2,082.0	2,072.7
Maximum	2,520.0	2,429.2	2,423.3	2,400.0
Coal seam elevation:				
Minimum	2,414.3	2,416.4	2,412.3	2,396.1
Maximum	2,233.2	2,191.5	2,186.0	2,164.0
Overburden thickness:				
Minimum	1,913.1	2,089.1	2,086.7	2,077.1
Maximum	2,623.8	2,589.3	2,583.5	2,560.4
Center point:				
Study area	2,228.2	2,284.5	2,280.2	2,262.9
Northwest quadrant	1,945.0	2,098.8	2,095.6	2,083.0
Northeast quadrant	2,318.0	2,237.2	2,231.9	2,210.4
Southwest quadrant	2,269.1	2,274.6	2,271.1	2,257.0
Southeast quadrant	2,366.9	2,255.4	2,251.6	2,236.4

[1]1.1 psi/ft × overburden.
[2]Based on equation 22.

As seen by comparing stress values for the test points in table 3, the direct stress method overestimates vertical stress values at some points and underestimates stress values at others. Figure 15 is a contour map showing the difference between the direct stress and the pyramid of influence methods for the Alabama site. On the map, the stress calculated from the pyramid of influence method is subtracted from the stress calculated from the direct stress method. The direct method overestimates the vertical stress under hills and ridges, resulting in a positive stress differential, and underestimates the stress under valleys and drainages, resulting in a negative stress differential.

0 m 30 m 60 m 90 m 120 m 150 m 180 m 210 m 240 m 270 m 300 m

	1 20.94	2 20.94	3 20.93	4 20.93	5 20.94	6 20.94	7 20.94	8 20.95	9 20.95	10 20.96
30 m	306 20.98	307 20.97	308 20.97	309 20.96	310 20.96	311 20.96	312 20.96	313 20.96	314 20.99	315 20.97
60 m	611 21.02	612 21.01	613 21.00	614 21.00	615 29.99	616 20.99	617 20.99	618 20.99	619 20.99	620 20.99
90 m	916 21.07	917 21.06	918 21.05	919 21.04	920 21.03	921 21.03	922 21.02	923 21.02	924 21.01	925 21.01
120 m	1,221 21.12	1,222 21.10	1,223 21.09	1,224 21.08	1,225 21.07	1,226 21.06	1,227 21.06	1,228 21.05	1,229 21.04	1,230 21.03
150 m	1,526 21.12	1,527 21.15	1,528 21.14	1,529 21.13	1,530 21.12	1,531 21.11	1,532 21.10	1,533 21.08	1,534 21.07	1,535 21.06
180 m	1,831 21.22	1,832 21.21	1,833 21.19	1,834 21.18	1,835 21.17	1,836 21.15	1,837 21.14	1,838 21.12	1,839 21.11	1,840 21.09
210 m	2,136 21.27	2,137 21.26	2,138 21.24	2,139 21.23	2,140 21.21	2,141 21.20	2,142 21.18	2,143 21.16	2,144 21.15	2,145 21.13
240 m	2,441 21.32	2,442 21.31	2,443 21.29	2,444 21.28	2,445 21.26	2,446 21.24	2,447 21.22	2,448 21.20	2,449 21.19	2,450 21.17
270 m	2,746 21.37	2,747 21.36	2,748 21.34	2,749 21.33	2,750 21.31	2,751 21.29	2,752 21.27	2,753 21.25	2,754 21.23	2,755 21.20
300 m										

KEY

1	point number
20.94	stress value, psi

N

Figure 9.—Format of output file containing calculated stress values related to locations within study area.

The differential stress contours tend to follow the valley, hill, and ridge pattern (compare with figures 12, 14, and 15). The greatest stress differential exists in the areas such as the stream channels, where the most rapid change in topography within the study area occurs. Essentially, the greater the change in elevation for a given horizontal distance, the greater the stress differential. The average absolute difference in stress for all the cells is 28 psi per cell. This number indicates that over much of the map there is not a large difference in the stresses calculated by the two methods. The algebraic maximum and minimum stress differences are 146 and -187 psi and are located in those areas on the map that are enclosed by the +100- and -100-psi contours. The minimum stress difference of -187 psi is located in the valley, while the maximum stress difference of 146 psi is located on a hill. At the Alabama site, the pyramid of influence method could, therefore, be used with the greatest benefit in those areas where the largest and most rapid change in topography occurs, in the drainage systems and around the highest hills. For the rest of the area, where the change in topography is less steep, the direct stress method could be used without a large error. The pyramid of influence method is still useful to check the stress from overburden at any point to determine if the direct method is sufficiently accurate. However, the overburden stress pattern established by the direct method is very different from the stress pattern developed from the pyramid of influence method. If any mine design decisions are based on the pattern of overburden stress and not just the magnitude of the stress, the pyramid of influence method must be used to establish the most accurate pattern.

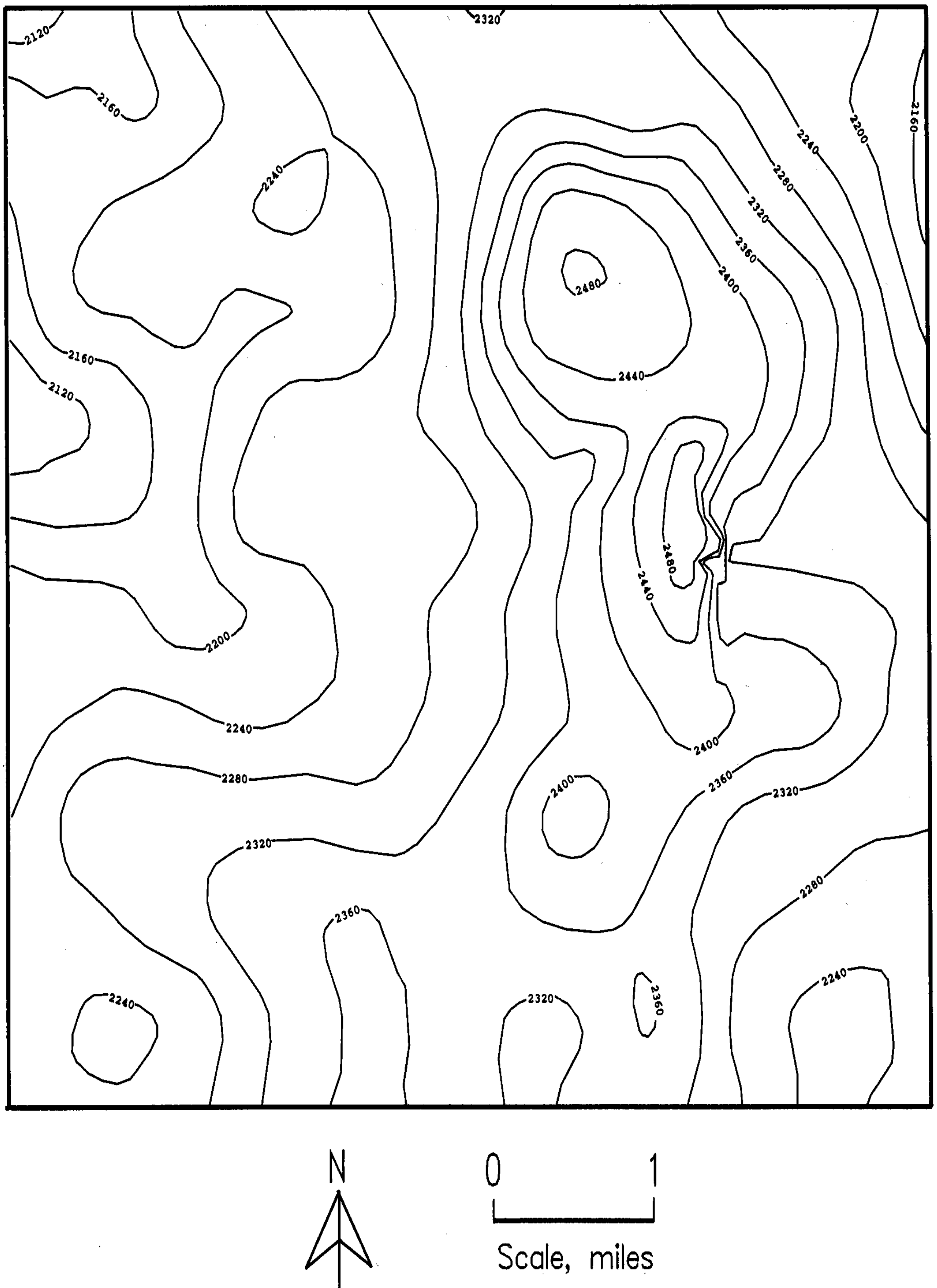


Figure 10.—Contour map of 99% total stress in study area (contour interval, 40 psi).

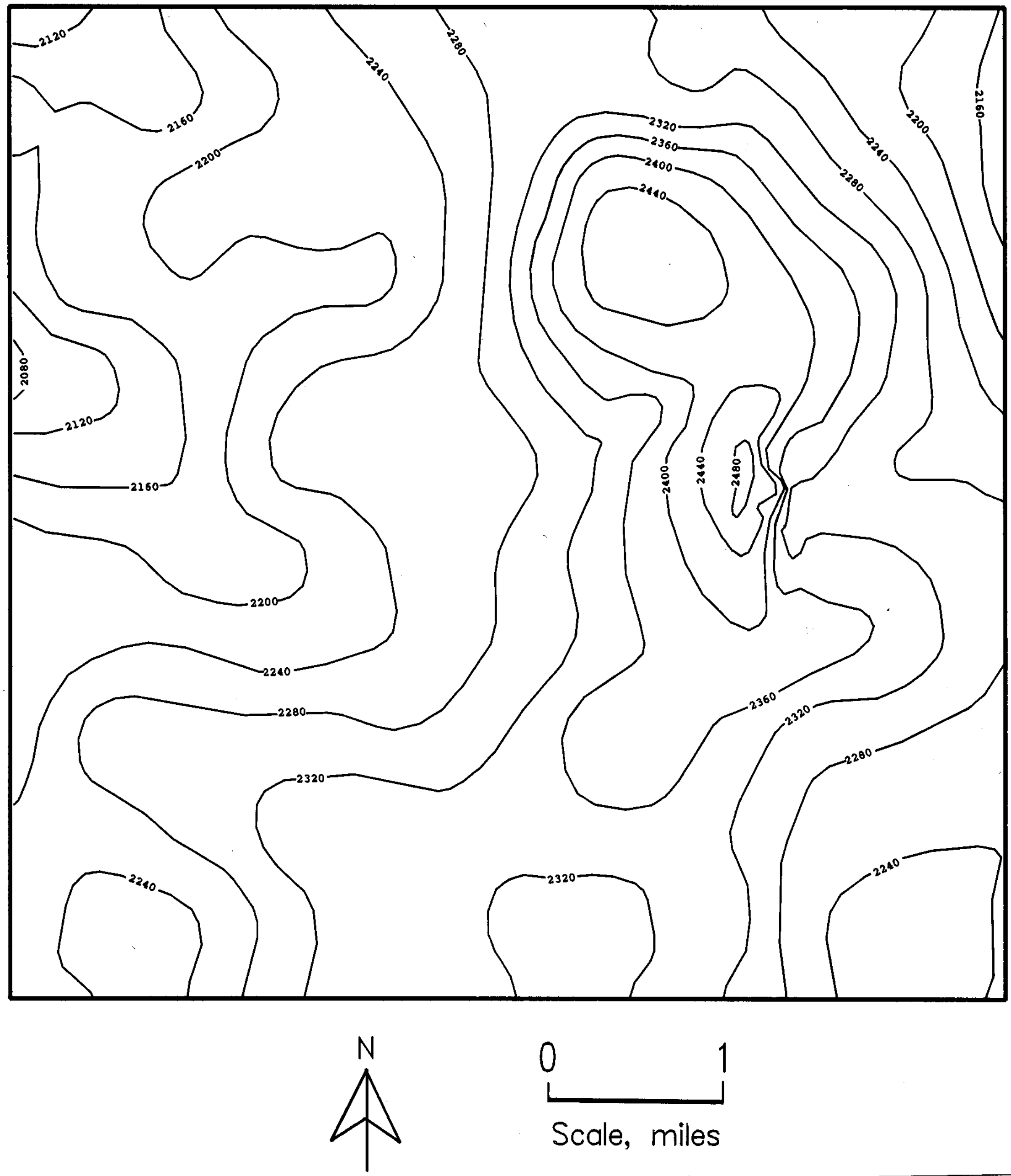


Figure 11.—Contour map of 95% total stress in study area (contour interval, 40 psi).

Figure 12.--Contour map of direct stress in study area (contour interval, 100 psi).

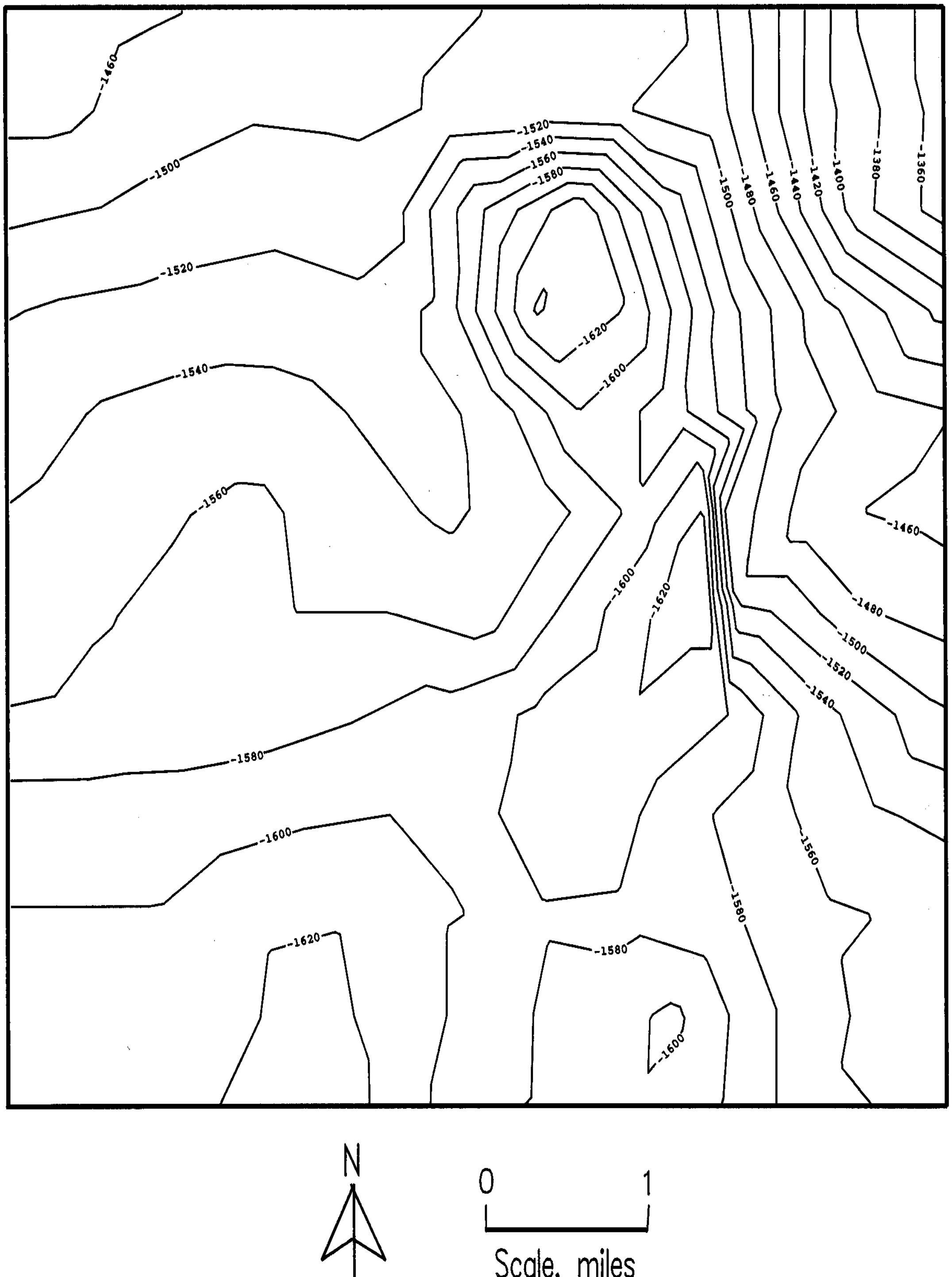


Figure 13.—Contour map of coal seam top elevations in study area (contour interval, 20 ft).

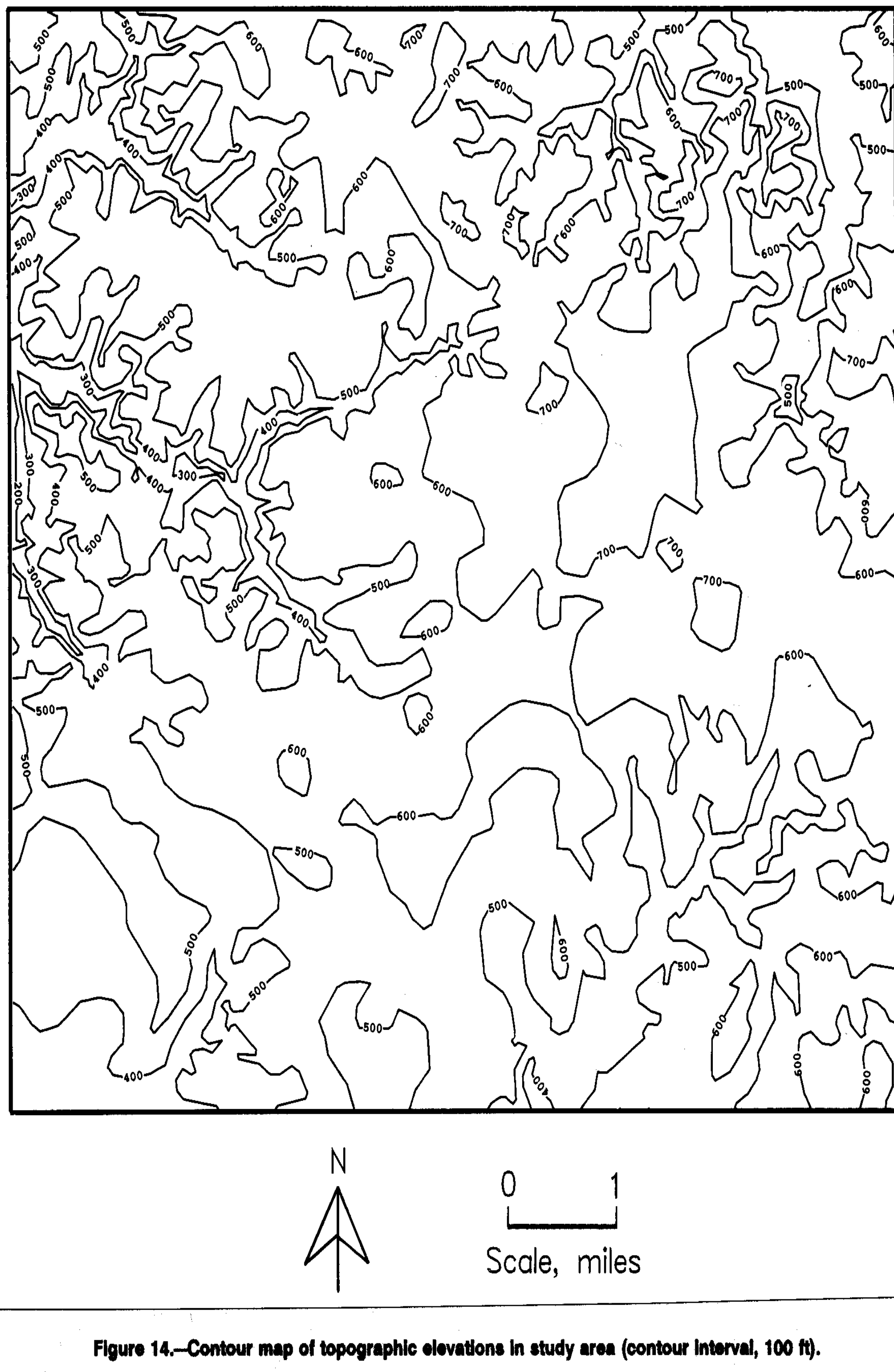


Figure 14.—Contour map of topographic elevations in study area (contour interval, 100 ft).

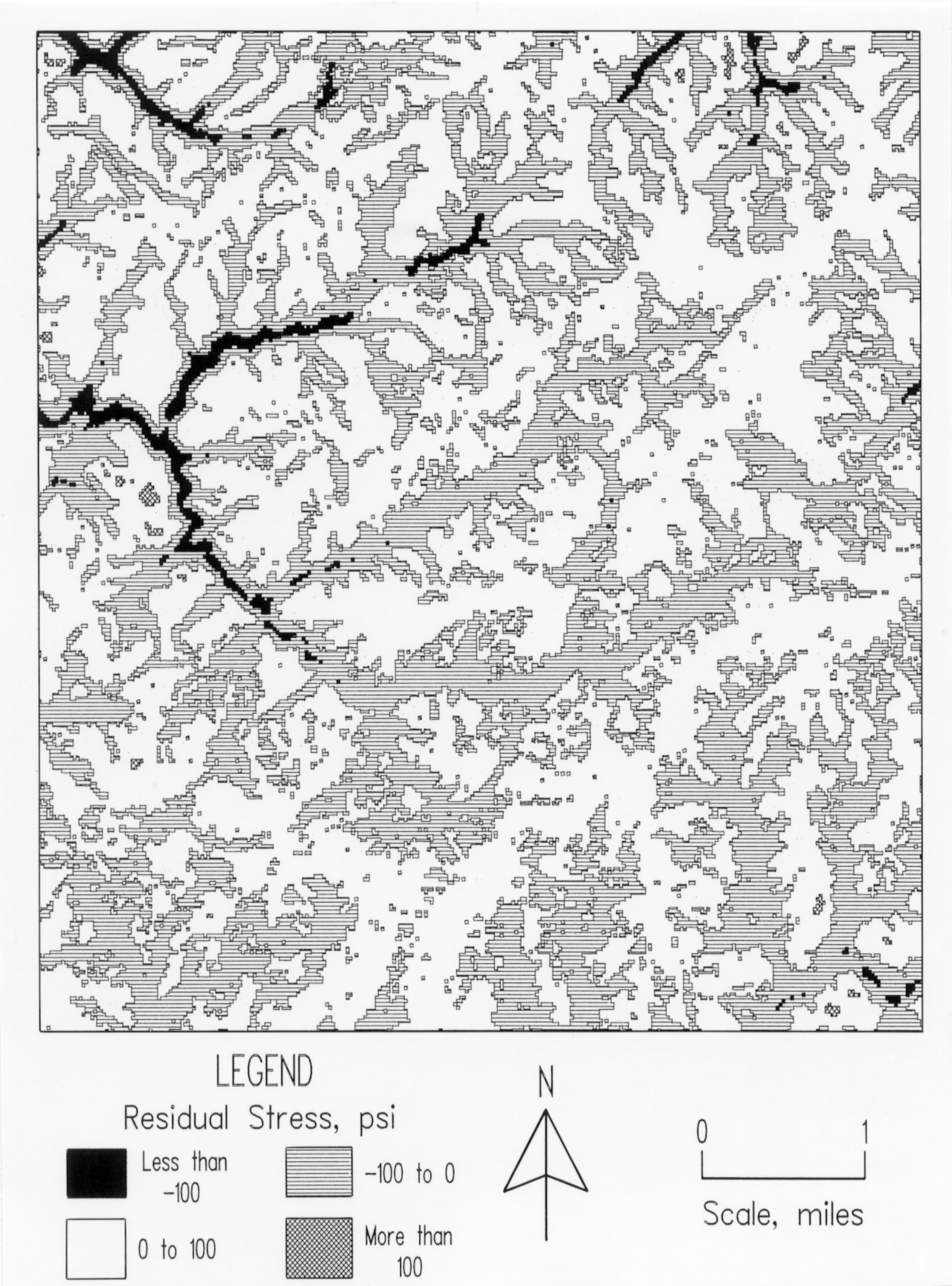


Figure 15.—Contour map of direct stress values minus calculated stress values over study area.

RESTRICTIONS PLACED ON STRESS CALCULATION METHODOLOGY

Boussinesq's equation calculates the stress distribution for a point load acting on the flat surface of a semi-infinite solid. Where an outcrop of the calculation surface or the surface at depth exists, the solid cannot be considered infinite in the outcrop direction. Theoretically, the stress distribution given by equation 1 no longer holds true because of the different boundary conditions imposed by the outcrop. From a practical standpoint, however, the calculation method can be used to within a certain distance of the outcrop without serious error. This distance is directly related to the size of the pyramid of influence used to calculate a given percentage of P_v. At a point, to determine a certain percentage of P_v requires a pyramid of influence of a specific size. The pyramid of influence is centered around the point of calculation. If the point is close to an outcrop where the pyramid of influence extends beyond the outcrop, the stress calculated at the point will be less than the predicted percentage of stress because no P_v is being calculated from that portion of the pyramid that is beyond the outcrop. The greater the portion of the pyramid of influence beyond the outcrop, the smaller the calculated P_v. An example for the test case given previously in the report, where the topography was flat and the overburden thickness was 1,000 ft with a resulting stress of 1,100 psi, a pyramid base with a half width of 100 30- by 30-m cells will result in a stress of 1,099.7 psi (table 2) being determined, of which 660 psi is direct overburden and 339.7 psi is calculated based on the topography. If an outcrop is parallel to a side of the pyramid base and is located 100 cells (3,000 m) from the cell where the stress is to be calculated, the resulting stress at the point will still be 1,099.7 psi. For an outcrop that passes next to the point with half the pyramid of influence beyond the outcrop, the calculated stress will be approximately 880 psi. The stress at the point is still 1,100 psi, where only 220 psi is calculated based on the pyramid of influence or 50% of the actual value (440 psi), since no stress is being calculated from half the pyramid of influence. The pyramid of influence can therefore touch, but should not go beyond, the outcrop to calculate a stress at a known percentage of the actual value. (The closest distance a point of calculation can be to an outcrop is then either half the pyramid base width or the square root of two times half the pyramid base width.)

The shape of the outcrop and how the pyramid base edge lines up with the outcrop will determine the appropriate distance to be used. For computational purposes, it is possible that an average distance could be used without incorporating a large error into the calculation results. If the distance between the calculation surface and the surface at depth is decreased, the size of the pyramid base required to calculate the stress at a point is also decreased. By artificially decreasing this distance, the stress at points closer to the outcrop can be calculated. As this distance is reduced, however, the calculated stress approaches the stress determined by the direct or tributary method. There will be some loss in the accuracy of the calculated stress. If the decrease in distance between the surface at depth and the calculation surface occurs as a natural phenomenon (for example, a steeply dipping coal seam approaching the calculation surface), the change in distance between the two surfaces does not pose a problem. The closest distance between the calculation surface and the surface at depth should not be less than three times the width of dA or square grid cell at which the load is applied (approximately 100 ft when a DEM file area 30 by 30 m is used). At less than this distance, the difference between q and Q is no longer minimal. If the grid cell size is reduced, the minimum required distance between the two surfaces can be reduced accordingly, and the calculations surface and the surface at depth could be even closer to the outcrop. However, because more grid cells would be required to cover the study area, more computational time would be required for the stress calculation. As the outcrop is approached, it may be more practical at some point to use the direct stress calculation method. For the best results, the calculation surface should be as far from the surface at depth as possible without violating the outcrop condition. For this reason, the location of the calculation surface in the Alabama study area was the minimum topographic elevation.

CONCLUSIONS

The stress calculation program appears to provide an effective method to calculate vertical stress values induced on a surface at depth by overlying topography. This calculation method is more reliable than a direct overburden stress calculation method because it takes into account the influence of adjacent topographic features overlying the coal seam. The effect that changes in topography have on P_v at the surface below is mitigated with depth, which the direct stress method does not take into account. The variation of the coal seam topography has a more direct influence on the calculated P_v than the surface topographic features, the influence of which is modified by the distance to the calculation surface.

The stress calculation program also offers advantages over the methods of Hooker (*1*) and Savage (*2-3*) by allowing calculation of topographic features in two dimensions along the surface of the earth rather than along a profile representing a cross section of the topography and by permitting analysis of real, asymmetrical topography. Another advantage is that P_v can be calculated over large areas encompassing several square miles. Thus, P_v maps can easily be developed for an entire coal mine and adjacent regions.

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APPENDIX.—USER'S GUIDE FOR RUNNING COMPUTER PROGRAMS TO CALCULATE VERTICAL STRESS ON A COAL SEAM

RUNNING THE PROGRAMS

As discussed in the text, the purpose of this computer program is to calculate P_v on a coal seam surface induced by the weight of the overlying rock mass. The program STRESS accomplishes this by calculating a number of dP_v vectors originating from various points within a square area of the topographic surface. These stress vectors are summed to create a P_v value at a point on the coal seam surface below. This procedure is performed for a number of points on the coal seam surface. The end result is an array of P_v values that represent the vertical stress induced by overburden at regularly spaced points along the coal seam surface. The configuration described has been named the pyramid of influence, which is discussed in the main text in the section entitled "Calculation Surface" and illustrated in figure 3.

The size of the pyramid of influence necessary to calculate the P_v varies for different topographic and coal seam configurations. To determine the size of the pyramid needed for a given minesite, program WIDTHCALC is run. In program WIDTHCALC, pyramids of progressively larger sizes are used to calculate P_v at a number of test points. This information is given to a regression analysis subroutine to determine the size of pyramid required to calculate 99% and 95% of the total P_v. The two percentages are included to give the user the option for calculating only 95% of the stress to reduce computer run time. The size of the pyramid is determined by the "radius" value, which represents the half width of the pyramid base in number of grid cells.

Before running the programs WIDTHCALC and STRESS, two American Standard Code for Information Interchange (ASCII) input files must be available and in the correct format. The first file contains topographic elevation values of the ground surface overlying the mine. The second file contains coal seam top elevations. The input files are discussed in detail in the main text in the section entitled "Elevation Data."

WIDTHCALC prompts the user for the names of the two input files. After reading the two files, sorting through elevation values, and calculating overburden thickness at each point, WIDTHCALC determines six test points. The test points include the minimum and maximum topographic elevations, the minimum and maximum coal seam elevations, and the locations of minimum and maximum overburden thickness in the area of interest. The coordinates for each test point are listed on the screen. It is helpful for the user to make note of the coordinates for each test point for input into the program. The program then prompts the user for the coordinates of each test point. In addition to the six selected test points, the user has the option to enter the coordinates of any additional points of particular interest in the study area. As the coordinates for each test point are entered, the program calculates P_v for radius values from 10 to 120 in increments of 10 to create a series of progressively larger pyramids. After calculating the stress for 12 progressively larger pyramids, the stress values are passed to the regression analysis subroutine, REGRESS. In the subroutine, the stresses calculated for each radius value are entered into a regression analysis algorithm, which calculates radius values for which 95% and 99% stress would be calculated for these topographic and coal seam top files. The radius values are listed on the screen and are written to a user-named output file. Once all test points of interest have been entered, the user exits the program. After the user looks at the output file, the largest radius for either 95% or 99% total stress is selected to include in program STRESS. Calculating only 95% stress will save computer time as compared with calculating 99% stress.

Program WIDTHCALC will need to be edited for each study area. The values that might require editing include names and array dimensions for the input and output files and variables OFFSET, ROWS, and COLS. These variables are noted by comments in the FORTRAN code. ROWS and COLS are the number of rows and columns, respectively, in the coal seam top file. The topography file is larger than the coal seam file because a buffer zone is included in the topographic surface around the outside of the mine boundaries to accommodate the base of the pyramid of influence. The size difference of the topographic and coal seam files is accounted for by the OFFSET value. OFFSET = 1/2·(number of ROWS in topographic file - number of ROWS in coal seam file).

After running WIDTHCALC and selecting the maximum radius value to calculate either 95% or 99% P_v, edit program STRESS to input the radius value. Other values that may require editing for a particular study include input file and output file names and array dimensions, input and output file names, ROWS, COLS, and OFFSET. These variables are noted by comments in the FORTRAN code.

Because the STRESS program will run a long time, it might be best to run it as a batch file.

The output file is an ASCII file containing a list of stress values in pounds (force) per square inch. The format resembles that of the coal seam file in dimensions and data point spacing. Processing the stress values with a contouring package will present the data in a more visible format. The list of stress values can be observed as stress value contours, which is more easily comprehended by the user.

The specifics of generating the input files are not discussed in this report. Since the files are large, to save space, the X and Y coordinates are omitted and only the Z values, or elevation values, are included in the files. As described in the main text, the first point in the file corresponds to the northwestern-most point in the study area, and subsequent values are arranged point-wise at 30-m increments from west to east in rows arranged from north to south in 30-m increments. The topography, coal seam, and output stress files each follow this format. To reformat the files to include X and Y values, it is necessary only to know the coordinates of the northwest corner of the study area and to assign the rest of the coordinates in order based on the 30-m increments.

FORTRAN CODE LISTING

```
      PROGRAM STRESS
C*****************************************************
C PROGRAM TO CALCULATE PYRAMID OF INFLUENCE OVER A COAL SEAM
C PROGRAMMER:     VALOIS R. SHEA-ALBIN
C                 BUREAU OF MINES
C                 DENVER RESEARCH CENTER
C                 BUILDING 20, DENVER FEDERAL CENTER
C                 DENVER, COLORADO 80225
C                 (303)-236-0775
C PROGRAMMING LANGUAGE: FORTRAN 77
C       Rev. T2.1-22.1 Copyright (c) 1990
C       Prime Computer, Inc.
C COMPILED ON PRIME 6350, PRIMOS OPERATING SYSTEM, Rev. 22.1.2
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C special, consequential, or other similar damages arising out of or
C in any way connected with the use of the software contained herein.
C*****************************************************
       CHARACTER*11 TOPOIN,COALIN,TOTOUT
       REAL TOPO, COAL
       INTEGER RADIUS, ROWS, COLS, ERSTAT,
     C OUTFIL, ROW, COL, YCOORD, XCOORD, IOSTAT, CCNTRY, CCNTRX,
     C TCNTRY, TCNTRX, CONROW, CONCOL, TOPROW, TOPCOL, COALRW,
     C COALCL, OFFSET
       REAL MINEL, MAXEL, INTBDN, P1, Z1, R1, CUMVEC, PI, VECTOR, SUM
       DIMENSION PYRMID(100,100), TOPO(253,230), COAL(163,140)
       COMMON/COALBL/COAL
       COMMON/TOPOBL/TOPO
       PARAMETER (PI=3.1415926536)
      MINEL = 100000.00
      ROWS=163
      COLS=140
```

```
C user edits values
    RADIUS=45
    OFFSET=45
C topographic file name
    TOPOIN='THREE.TOPO'
C coal seam file name
    COALIN='THREE.COAL'
C output file name
    TOTOUT='THREE.STRESS'
10  FORMAT (A45)
C READ COAL SEAM ELEVATION FILE INTO ARRAY
    PRINT (10), 'READING COAL SEAM TOP ELEVATION FILE'
    OPEN (UNIT=101, FILE=COALIN, STATUS='OLD', ERR=20,
   C IOSTAT=ERSTAT, ACTION='READ')
IF (ERSTAT.EQ.0) GOTO 30
20      PRINT '(A50)', 'PROBLEM WITH OPEN FOR COAL TOP FILE'
30      CONTINUE
     DO 200, COALRW=1, ROWS
         DO 100, COALCL=1, COLS
             READ (101, 201) COAL(COALRW, COALCL)
100        CONTINUE
200    CONTINUE
201    FORMAT(F9.2)
       CLOSE (101)
C
C
C READ IN TOPOGRAPHY ARRAY & DETERMINE MINEL
     PRINT (10),'READING TOPO ELEVATION FILE'
C
     OPEN (102, FILE=TOPOIN, STATUS='OLD', ERR=202,
   C IOSTAT=ERSTAT, ACTION='READ')
       IF (ERSTAT.EQ.0) GOTO 210
202     PRINT '(A50)', 'PROBLEM WITH OPEN FOR TOPO FILE'
210     CONTINUE
     DO 400, TOPROW=1, ROWS + (OFFSET * 2)
         DO 300, TOPCOL=1, COLS + (OFFSET * 2)
           READ(102,201) TOPO(TOPROW, TOPCOL)
           IF (TOPO(TOPROW,TOPCOL) .LT. MINEL) THEN
             MINEL=TOPO(TOPROW,TOPCOL)
           ENDIF
300        CONTINUE
400    CONTINUE
       CLOSE (102)
    PRINT '(A6,F7.2)','MINEL=',MINEL
C
C
      PRINT '(A40)','BEGIN STRESS CALCULATIONS'
C OPEN OUTPUT FILE
     OPEN(103,FILE=TOTOUT, STATUS='UNKNOWN')
C
C*******************************************************
C
```

```
C     BEGIN CALCULATING PYRAMID
C
C*************************************************************
C
C     CCNTRY=CENTER CELL IN COAL SEAM TOP GRID (Y CONTROL)
C     CCNTRX=CENTER CELL IN COAL SEAM TOP GRID (X CONTROL)
C     TCNTRY=CENTER CELL IN TOPOGRAPHY GRID (Y CONTROL)
C     TCNTRX=CENTER CELL IN TOPOGRAPHY GRID (X CONTROL)
C     CONROW=PYRAMID OF INFLUENCE Y GRID CELL CONTROL
C     CONCOL=PYRAMID OF INFLUENCE X GRID CELL CONTROL
C
      DO 3000,CCNTRY=1, ROWS
        DO 2000,CCNTRX=1, COLS
C
        TCNTRY=CCNTRY+OFFSET
        TCNTRX=CCNTRX+OFFSET
C
C BEGIN PYRAMID
C          PRINT '(A30,I6)', 'CENTER COAL CELL Y CRD =',CCNTRY
C          PRINT '(A30,I6)', 'CENTER COAL CELL X CRD =',CCNTRX
C          PRINT '(A30,I6)', 'CENTER TOPO CELL Y CRD =',TCNTRY
C          PRINT '(A30,I6)', 'CENTER TOPO CELL X CRD =',TCNTRX
C FILL PYRAMID WITH ZEROES
     DO 1000, CONROW=1,RADIUS*2+1
         DO 900, CONCOL=1,RADIUS*2+1
            PYRMID(CONROW,CONCOL)=0
900      CONTINUE
1000  CONTINUE
C FILL PYRAMID WITH TOPOGRAPHIC VALUES
     CONROW=1
     DO 1200, TOPROW=(TCNTRY-RADIUS),(TCNTRY+RADIUS)
         CONCOL=1
         DO 1100, TOPCOL=(TCNTRX-RADIUS),(TCNTRX+RADIUS)
           PYRMID(CONROW,CONCOL)=TOPO(TOPROW,TOPCOL)
           CONCOL=CONCOL+1
1100      CONTINUE
          CONROW=CONROW+1
1200  CONTINUE
C
C     CALCULATE INTERBURDEN THICKNESS FOR CENTER CELL
C
      Z1 = FLOAT(MINEL - COAL(CCNTRY,CCNTRX))
C
C     CALCULATE STRESS DUE TO INTERBURDEN THICKNESS
C
      INTBDN = Z1 * 1.1
C
C     INITIALIZE TOTAL STRESS COUNTER
C
      CUMVEC=0
C
C     BEGIN ISOLATING AND CALCULATING STRESS VECTORS
```

```
C
      DO 1500,CONROW=1,RADIUS*2+1
       DO 1400,CONCOL=1,RADIUS*2+1
C
C*****************************************************************
C     BOUSSINESQ'S EQUATION
C*****************************************************************
C
C          P1 = (column height) * (1.1 psi/vertical ft) * area
          P1=(PYRMID(CONROW,CONCOL)-MINEL)*1.1*((98.4)**2)
     R1=SQRT((CONROW - (RADIUS + 1.0))**2 + (CONCOL -
    C (RADIUS + 1.0))**2) * (98.4)
     VECTOR=(P1/(Z1**2))*((3/(2*PI))/((1+((R1/Z1)**2))**(5.0/2.0)))
C
C     ACCUMULATE STRESS COMPONENTS FROM PYRAMID
C
      CUMVEC = CUMVEC + VECTOR
C
1400     CONTINUE
1500  CONTINUE
C
C     ADD STRESS DUE TO INTERBURDEN TO TOTAL STRESS FROM PYRAMID
C
      SUM = CUMVEC + INTBDN
C
C     WRITE TOTAL STRESS FROM PYRAMID OF INFLUENCE TO OUTPUT FILE AT POINT
C     CORRESPONDING TO CENTER OF PYRAMID CELL TO WHICH THE STRESS IS
C     DIRECTED ON COAL SEAM TOP
C
      WRITE (103,1501) SUM
1501  FORMAT (F12.2)

2000     CONTINUE
3000  CONTINUE
      CLOSE (103)
      END

     PROGRAM WIDTHCALC
C*****************************************************************
C PROGRAM TO CALCULATE A PROGRESSIVELY LARGER PYRAMID BASE AROUND A
C CENTRAL POINT LOCATED ON THE TOP OF THE UNDERLYING COAL SEAM, THEN
C PASSES RADIUS VALUES AND RESPECTIVE TOTAL STRESS VALUES TO THE
C                    REGRESSION ANALYSIS SUBROUTINE
C PROGRAMMER:    VALOIS R. SHEA-ALBIN
          BUREAU OF MINES
          DENVER RESEARCH CENTER
          BUILDING 20, DENVER FEDERAL CENTER
          DENVER, COLORADO  80225
          (303)-236-0775
C PROGRAMMING LANGUAGE:  FORTRAN 77
      Rev. T2.1-22.1 Copyright (c) 1990
      Prime Computer, Inc.
```

```
C COMPILED ON PRIME 6350, PRIMOS OPERATING SYSTEM, Rev. 22.1.2
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
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C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      CHARACTER*11 TOPOIN,COALIN
      CHARACTER*15 OUTPUT
      CHARACTER*6 PTNAME
      INTEGER TOPROW, TOPCOL, COALRO, COALCL, RADIUS, MIDROW, MIDCOL,
     C PYRROW, PYRCOL, REPLY, ROWS, COLS, OFFSET,
     C COUNT, TMXROW, TMXCOL, TMNROW, TMNCOL, CMXROW, CMXCOL, CMNROW,
     C CMNCOL, OBMXRO, OBMXCL, OBMNRO, OMNCOL
      REAL COAL, TOPO, COALMN, COALMX, TOPOMN, TOPOMX, PYRBAS, ARRAY,
     C MINEL, OBDNMN, OBDNMX, INTBDN, Z1, R1, P1, VECTOR, CUMVEC, OBDN
C edit array dimensions
      DIMENSION COAL (163,133), TOPO(463,433), ARRAY(12,2)
      PARAMETER (PI=3.14159)
      COMMON/BCOAL/COAL
      COMMON/BTOPO/TOPO
      COMMON/PYRMID/PYRBAS
C fill array with radius values
      DATA (ARRAY(COUNT,1),COUNT=1,12)/10.0,20.0,30.0,40.0,50.0,60.0,
     C 70.0,80.0,90.0,100.0,110.0,120.0/
C these values will be calculated in program
      COALMN=10000.0
      MINEL=10000.0000
      TOPOMN=10000.0
      COALMX=-10000.0
      TOPOMX=0.0
      OBDNMN=10000.0
      OBDNMX=0.0
C edit these values
      OFFSET=120
      ROWS=163
      COLS=133
C these variables will be input by user
C     TOPOIN
C     COALIN
C     OUTPUT
C prompt for output file name
      PRINT '(A45)','ENTER OUTPUT FILE NAME (max 15 characters):'
      READ (1,'(A15)') OUTPUT
      OPEN (UNIT=103, FILE=OUTPUT, STATUS='UNKNOWN')
```

```
C prompt for topography file name
10  PRINT '(A30)','ENTER TOPOGRAPHY FILE NAME:'
    READ (1,'(A11)') TOPOIN
C open topography file
    PRINT '(A20)','OPENING TOPO FILE'
    OPEN (UNIT=101, FILE=TOPOIN, ACTION='READ', ERR=20)
    GOTO 30
20  PRINT '(A45)','PROBLEM WITH OPENING FILE; CHECK FILE NAME.'
    GOTO 10
C prompt for coal seam file name
30  PRINT '(A30)','ENTER COAL SEAM FILE NAME:'
    READ (1,'(A11)') COALIN
C open coal seam file
    PRINT '(A20)','OPENING COAL FILE'
    OPEN (UNIT=102, FILE=COALIN, ACTION='READ', ERR=40)
    GOTO 50
40  PRINT '(A45)','PROBLEM WITH OPENING FILE; CHECK FILE NAME.'
    GOTO 30
C read topo file into array, and determine test points
50  PRINT '(A30)','READING TOPO FILE'
    DO 200, TOPROW=1, ROWS + (OFFSET * 2)
        DO 100, TOPCOL=1, COLS + (OFFSET * 2)
         READ (101,201) TOPO(TOPROW,TOPCOL)
         IF (MINEL .LT. TOPO(TOPROW,TOPCOL)) GOTO 60
         MINEL=TOPO(TOPROW,TOPCOL)
60  IF ((TOPROW .GT. OFFSET) .AND. (TOPROW .LT. ROWS+OFFSET))
   C GOTO 70
          GOTO 100
70  IF ((TOPCOL .GT. OFFSET) .AND. (TOPCOL .LT. COLS+OFFSET))
   C GOTO 80
          GOTO 100
80          IF (TOPOMN .GT. TOPO(TOPROW,TOPCOL)) GO TO 90
         GOTO 91
90            TOPOMN=TOPO(TOPROW,TOPCOL)
            TMNROW=TOPROW
            TMNCOL=TOPCOL
91        IF (TOPOMX .LT. TOPO(TOPROW,TOPCOL)) GOTO 93
92        GOTO 100
93            TOPOMX=TOPO(TOPROW,TOPCOL)
            TMXROW=TOPROW
            TMXCOL=TOPCOL
100       CONTINUE
200  CONTINUE
201  FORMAT (F9.2)
     CLOSE (101)
     PRINT '(A6,F12.4)','MINEL=',MINEL
     PRINT (202),'TOPOMN=',TOPOMN,' AT ROW=',TMNROW,' COL=',TMNCOL
     PRINT (202),'TOPOMX=',TOPOMX,' AT ROW=',TMXROW,' COL=',TMXCOL
202  FORMAT (A7,F10.2,A8,I6,A5,I6)
C read coal file into array, determine test points
     PRINT '(A30)','READING COAL FILE'
     DO 400, COALRO=1,ROWS
      DO 390,COALCL=1,COLS
         READ (102,401) COAL(COALRO,COALCL)
```

```
310        OBDN=TOPO(COALRO+OFFSET,COALCL+OFFSET)-COAL(COALRO,COALCL)
          IF (OBDNMN .GT. OBDN) GOTO 320
          GOTO 330
320          OBDNMN=OBDN
            OBMNRO=COALRO+OFFSET
            OMNCOL=COALCL+OFFSET
330        IF (OBDNMX .LT. OBDN) GOTO 340
          GOTO 350
340          OBDNMX=OBDN
            OBMXRO=COALRO+OFFSET
            OBMXCL=COALCL+OFFSET
350        IF (COALMN .GT. COAL(COALRO,COALCL)) GO TO 360
          GOTO 370
360          COALMN=COAL(COALRO,COALCL)
            CMNROW=COALRO+OFFSET
            CMNCOL=COALCL+OFFSET
370        IF (COALMX .LT. COAL(COALRO,COALCL)) GOTO 380
          GOTO 390
380          COALMX = COAL(COALRO,COALCL)
            CMXROW=COALRO+OFFSET
            CMXCOL=COALCL+OFFSET
390     CONTINUE
400   CONTINUE
401   FORMAT (F9.2)
      CLOSE (102)
      PRINT (202),'COALMN=',COALMN,' AT ROW=',CMNROW,' COL=',CMNCOL
      PRINT (202),'COALMX=',COALMX,' AT ROW=',CMXROW,' COL=',CMXCOL
      PRINT (202),'OBDNMN=',OBDNMN,' AT ROW=',OBMNRO,' COL=',OMNCOL
      PRINT (202),'OBDNMX=',OBDNMX,' AT ROW=',OBMXRO,' COL=',OBMXCL
498    CONTINUE
         PRINT '(A30)','ENTER TEST POINT NAME:'
         READ (1,'(A6)') PTNAME
         PRINT '(A30)','ENTER CENTER CELL COORDINATES'
         PRINT '(A4)','ROW='
         READ (1,'(I6)') MIDROW
         PRINT '(A4)','COL='
         COUNT=0
         READ (1,'(I6)') MIDCOL
         PRINT '(A7,F9.2)','TOPOEL=',TOPO(MIDROW,MIDCOL)
      PRINT '(A7,F9.2)', 'COALEL=',COAL(MIDROW-OFFSET,MIDCOL-OFFSET)
         Z1=MINEL-COAL(MIDROW-OFFSET,MIDCOL-OFFSET)
         INTBDN = Z1 * 1.100000
499     CONTINUE
     DO 800, COUNT=1,12
         CUMVEC=0
     RADIUS=INT(ARRAY(COUNT,1))
     PRINT '(A32,I3)','CALCULATING STRESSES FOR RADIUS=',RADIUS
     DO 600, PYRROW=MIDROW-RADIUS,MIDROW+RADIUS
         DO 500, PYRCOL=MIDCOL-RADIUS,MIDCOL+RADIUS
C CALCULATE STRESS VECTOR FROM EACH TOPOGRAPHY CELL DIRECTED TO THE
C CENTRALLY LOCATED POINT ON THE COAL SEAM SURFACE
```

```
C        P1 = (column height) * (1.1 psi/vertical ft) * area
         P1=(TOPO(PYRROW,PYRCOL)-MINEL)*1.1000*((98.400)**2.0)
         R1=SQRT((FLOAT(PYRROW-MIDROW)**2)+
   C (FLOAT(PYRCOL-MIDCOL)**2)) * 98.4
    VECTOR=(P1/(Z1**2))*((3/(2*PI))/((1+((R1/Z1)**2))**(5.0/2.0)))
C KEEP A RUNNING TOTAL OF VECTOR VALUES
         CUMVEC=CUMVEC+VECTOR
500      CONTINUE
600   CONTINUE
601   FORMAT (A7,F12.2)
      SUM = CUMVEC + INTBDN
C STORE SUM OF ALL VECTORS AND RADIUS VALUE TO ARRAY
C     ARRAY(COUNT,1)=RADIUS
      ARRAY(COUNT,2)=CUMVEC
      PRINT '(A19,F9.2)','STRESS FOR PYRAMID=',ARRAY(COUNT,2)
602   FORMAT (A6,F9.2,A8,I3)
603   FORMAT (A15,F15.4,A14,F15.4)
800      CONTINUE
805   CONTINUE
      CALL REGRES(ARRAY,INTBDN,PTNAME)
      PRINT '(A45)','IF YOU WISH TO CHANGE TEST POINT, ENTER 1'
      PRINT '(A45)','IF YOU WISH TO EXIT PROGRAM, ENTER 2'
      READ (1,'(I1)') REPLY
      IF (REPLY .EQ. 1) GOTO 498
      CLOSE (103)
      PRINT '(A3)','BYE'
      END
      SUBROUTINE REGRES(VALUES,IBSTRS,TESTPT)
C THIS IS A LEAST SQUARES PROGRAM TO FIT THE CURVE Y= B0 + B1 * X**(-3)
C AS A STEP IN DETERMINING THE OPTIMUM RADIUS FOR THE PYRAMID OF INFLUENCE
C              FOR THE TOPOGRAPHY OF THE STUDY AREA
C
C THE DUMMY ARGUMENT 'VALUES' CONTAINS TWELVE RADIUS VALUES AND
C        CORRESPONDING TOTAL STRESS VALUES FOR TEST POINT
C  THE LAST 8 VALUES ARE USED IN THE REGRESSION ANALYSIS
C
C THE OUTPUT IS TABLE OF INTERCEPT VALUES, SLOPE VALUES, AND A RADIUS
C     VALUE AT WHICH 99% TOTAL STRESS IS CALCULATED
C
      INTEGER COUNT,RADIUS,NUM
      REAL IBSTRS,STRESS,X1,X2,Y1,YX,SY,SE,RSQU,B095,B099,L,X95,X99
      CHARACTER*15 OUTPUT
      CHARACTER*6 TESTPT
      DIMENSION VALUES(12,2)
      COMMON/ARGS/ARRAY,INTBDN,PTNAME
      X1=0
      X2=0
      Y1=0
      YX=0
      SY=0
      SE=0
      NUM=8
```

```
C  RADIUS=PYRAMID RADIUS(VALUES(COUNT,1))
C  STRESS=TOTAL STRESS CALCULATED FOR GIVEN RADIUS(VALUES(COUNT,2))
C  X1=SUM OF X**(-3)
C  X2=SUM OF X**(-6)
C  Y1=SUM OF Y
C  YX=SUM OF YX**(-3)
C  SE=RESIDUAL MEAN SQUARE
C  SY=CORRECTED MEAN SUM OF SQUARES
C CALCULATE NECESSARY SUMS
     DO 100 COUNT=5,12
       Y1=Y1+VALUES(COUNT,2)
       X1=X1+VALUES(COUNT,1)**(-3)
       X2=X2+VALUES(COUNT,1)**(-6)
       YX=YX+VALUES(COUNT,2)*VALUES(COUNT,1)**(-3)
100  CONTINUE
C CALCULATE B0, THE INTERCEPT, AND B1, THE SLOPE OF THE EQUATION
C D, D0, AND D1 ARE 2x2 DETERMINANTS
      D=X1*X1-NUM*X2
      D0=X1*YX-Y1*X2
      D1=Y1*X1-NUM*YX
C B0, THE INTERCEPT, IS THE ESTIMATE OF THE FULL TOPOGRAPHIC LOAD
      B0=D0/D
      B1=D1/D
C CALCULATE A CORRELATION COEFFICIENT SQUARED  (RSQU)
      DO 300, COUNT=5,12
      SE=SE+((VALUES(COUNT,2)-(B0+B1*VALUES(COUNT,1)**(-3)))**2)/
    C (NUM-2)
      SY=SY+((VALUES(COUNT,2)-Y1/NUM)**2)/(NUM-1)
300  CONTINUE
C THE CORRELATION COEFFICIENT SQUARED
      RSQU=1-SE/SY
      PRINT (301),'ESTIMATED STRESS=',B0,' PSI'
      PRINT (302),'SLOPE=',B1
      PRINT (303),'CORRELATION COEFFICIENT SQUARED=',RSQU
301  FORMAT (A17,F8.2,A4)
302  FORMAT (A6,F13.2)
303  DO 300, COUNT=5,12
      SE=SE+((VALUES(COUNT,2)-(B0+B1*VALUES(COUNT,1)**(-3)))**2)/
    C (NUM-2)
      SY=SY+((VALUES(COUNT,2)-Y1/NUM)**2)/(NUM-1)
300  CONTINUE
C THE CORRELATION COEFFICIENT SQUARED
      RSQU=1-SE/SY
      PRINT (301),'ESTIMATED STRESS=',B0,' PSI'
      PRINT (302),'SLOPE=',B1
      PRINT (303),'CORRELATION COEFFICIENT SQUARED=',RSQU
301  FORMAT (A17,F8.2,A4)
302  FORMAT (A45,F8.6)
C CALCULATE PYRAMID SIZE THAT WILL PROVIDE 95% AND 99% OF TOTAL STRESS
      B095=(0.95)*(B0)
      B099=(0.99)*(B0)
      L=1.0/3.0
      X95=((B095-B0)/B1)**(-L)
      X99=((B099-B0)/B1)**(-L)
```

```
      PRINT (304),'RADIUS SIZE FOR 95% TOTAL STRESS=',NINT(X95)
      PRINT (304),'RADIUS SIZE FOR 99% STRESS=',NINT(X99)
304   FORMAT (A35,F6.1)
      WRITE (103,'(2A12)') 'TEST POINT=',TESTPT
      PRINT '(A40)','WRITE INTERCEPT SLOPE CORRELATION DATA'
      WRITE (103,FMT=405) 'INTERCEPT SLOPE CORRELATION'
      WRITE (103,FMT=405) '             '
      WRITE (103,FMT=406) '    B0       B1',
     C'       R**2     95%B0      RADIUS     99%B0      RADIUS'
      WRITE (103,FMT=407) B0,B1,RSQU,B095,X95,B099,X99
400   CONTINUE
405   FORMAT (A50)
406   FORMAT (A15,A60)
407   FORMAT (F7.2,F12.2,F9.2,2F12.2,2F11.2)
      WRITE (103,FMT=405) '  '
      WRITE (103,FMT=405) '  '
      PRINT '(A40)','WRITE STRESS TABLE DATA'
      WRITE (103,FMT=501) 'STRESS TABLE'
      WRITE (103,FMT=405) '      '
      WRITE (103,FMT=501)
     C'          CALCULATED STRESS   ESTIMATED STRESS'
      WRITE (103,FMT=502) 'RADIUS          FROM PYRAMID',
     C'     FROM PYRAMID       TOTAL STRESS'
     C'  ESTIMATED STRESS       TOTAL STRESS'
       DO 500, COUNT=1,12
       WRITE (103,FMT=503) VALUES(COUNT,1),VALUES(COUNT,2),B0,
     C B0+IBSTRS
500   CONTINUE
501   FORMAT (A50)
502   FORMAT (A27,A37)
503   FORMAT (I5,3F19.2)
      END
```