A SIMPLE APPROACH TO SUBSIDENCE PREDICTION
ABOVE LONGWALL MINES

by

Trevor P. Hawkes

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Trevor P. Hawkes

The Project of Trevor P. Hawkes is acceptable in its final form including (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory and ready for submission.

This project has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

________________________________________
Date
Paul W. Richards, Chair

________________________________________
Date
Steven E. Benzley

________________________________________
Date
Kyle M. Rollins

Accepted for the Department of Civil and Environmental Engineering

________________________________________
Date
E. James Nelson
Graduate Coordinator
ABSTRACT

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Trevor P. Hawkes
Department of Civil and Environmental Engineering
Master of Science

Mining engineers and other interested parties are seeking for better ways to predict subsidence above underground coal mines. Accurate, inexpensive prediction methods may lead to an increase in mine safety and prevention of detrimental affects to surface and subterranean features.

The following study briefly summarizes a few of the key concepts of widely accepted subsidence theory. One of these concepts is the influence function. Influence functions enable subsidence prediction over irregularly shaped mines with varying surface topography. A new influence function is proposed. The simplicity of this new function increases the computational efficiency of subsidence prediction procedures.

A step-by-step algorithm is also proposed which outlines all of the elements of a subsidence prediction procedure. This algorithm is presented in a way which will facilitate its implementation in computer programs.

Deer Creek Mine in central Utah is used as a case study for the subsidence prediction procedure presented herein. The influence function and subsidence prediction algorithm are utilized to generate predicted subsidence over a study area which consists of 12 longwall panels mined in 2 coal seams of varying depth and thickness below mountainous surface topography. A comparison of predicted and measured subsidence at Deer Creek Mine shows surprisingly close agreement considering the empirical nature of the model and the inherent uncertainties involved.

Keywords: Utah, Deer Creek, coal, mining, longwall, subsidence
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# TABLE OF CONTENTS

LIST OF TABLES ............................................................................................................. vii

LIST OF FIGURES ........................................................................................................... ix

1  BACKGROUND .............................................................................................................. 1
   1.1 Longwall Mining ........................................................................................................ 1
   1.2 Subsidence Theory .................................................................................................... 2
   1.3 Illustrations of Parameters ........................................................................................ 6

2  INFLUENCE FUNCTIONS ............................................................................................ 9

3  SUBSIDENCE PREDICTION PROCEDURE ................................................................. 15
   3.1 Input from ArcGIS ...................................................................................................... 15
   3.2 Single-Value Input ..................................................................................................... 16
   3.3 Output ........................................................................................................................ 16
   3.4 Data Processing ......................................................................................................... 16
   3.5 Subsidence Prediction Algorithm .............................................................................. 17
      3.5.1 Adjustments for Efficiency ................................................................................ 18
      3.5.2 Adjustments for Accuracy ................................................................................ 19
   3.6 Benefits of the Subsidence Prediction Procedure ..................................................... 21
   3.7 Recommendations to Users ..................................................................................... 21

4  SUBSIDENCE AT DEER CREEK MINE ....................................................................... 23
   4.1 Predicted Subsidence ............................................................................................... 26
   4.2 Measured Subsidence ............................................................................................... 37
   4.3 Conclusions ............................................................................................................... 39

REFERENCES .................................................................................................................. 41

APPENDIX A. VISUAL BASIC CODE ........................................................................... 43
LIST OF TABLES

Table 2-1: Comparison of Influence Functions .................................................................11
Table 4-1: Single-Value Input Parameters ........................................................................32
Table 4-2 Subsidence Results Summary ...........................................................................36
LIST OF FIGURES

Figure 1-1: Illustration of longwall mining .................................................................2
Figure 1-2: Illustration of parameters: Subcritical extraction .................................6
Figure 1-3: Illustration of parameters: Critical extraction .......................................7
Figure 1-4: Illustration of parameters: Supercritical extraction ...............................8
Figure 2-1: Comparison of subsidence troughs .......................................................13
Figure 3-1: Illustration of a case of under-prediction ............................................20
Figure 4-1: Deer Creek Mine location and terrain ...............................................24
Figure 4-2: Mine workings in the Blind Canyon seam ............................................25
Figure 4-3: Mine workings in the Hiawatha seam ...................................................26
Figure 4-4: Height of overburden: Blind Canyon seam ........................................27
Figure 4-5: Height of overburden: Hiawatha seam ...............................................28
Figure 4-6: Mined coal thickness: Blind Canyon seam .........................................29
Figure 4-7: Mined coal thickness: Hiawatha seam ................................................30
Figure 4-8: Slope at Deer Creek Mine ..................................................................31
Figure 4-9: Predicted subsidence due to mining in the Blind Canyon seam ..........34
Figure 4-10: Predicted subsidence due to mining in the Hiawatha seam ...............35
Figure 4-11: Total predicted subsidence ...............................................................36
Figure 4-12: Measured subsidence ......................................................................38
Figure 4-13: Measured subsidence minus predicted subsidence ...........................39
Figure B-1: Spreadsheet used to predict subsidence ............................................48
Figure B-2: Spreadsheet showing measured and predicted subsidence in profile ....48
1 BACKGROUND

1.1 Longwall Mining

Coal mines have been operating for many centuries. The World Coal Institute (2005) estimates that coal is currently the source of 40% of the world’s electricity production. An estimated 984 billion metric tons of economically recoverable coal is available worldwide.

Until the late 1900’s, the prevailing method of deep coal mining was room-and-pillar mining (Energy Information Administration 1995). In this method, coal is extracted as voids are created in the coal seam. A large fraction of the coal is left undisturbed in order to keep the mine from caving in due to the weight of the overburden above the mined seam.

In recent years, a method of coal extraction called longwall mining was developed and has become widely used (Energy Information Administration 1995). In longwall mines, no effort is made to prevent the overburden from caving in after coal has been extracted. Large, moveable equipment is used to hold up the roof of the mine next to the face of the seam as coal is extracted, but as coal is extracted and the cut face moves, the supporting equipment is moved, leaving the roof unsupported and prone to caving. See Figure 1-1.
Figure 1-1: Illustration of longwall mining (Arch Coal 2008, used without permission).

1.2 Subsidence Theory

When the weight of the overburden above a mine causes caving, displacement of the overburden material usually results in measurable movement, or subsidence, at the ground surface above the mine. The shape of the disturbed ground surface above a collapsed mine is called a subsidence trough. In this paper, the term “subsidence” refers only to the vertical displacement of the ground surface, although horizontal movement is also measurable and has been treated elsewhere (Dunrud 1976).

Subsidence above coal mines can be more accurately predicted where longwall mining has occurred as opposed to room-and-pillar mining, because it is more reasonable to assume that the mined cavities will collapse within a short time after mining activity has ceased.
The authors of studies on subsidence theory nearly always agree on a few factors that are important in subsidence prediction methods. Two of these parameters are directly measurable, geometric properties of the coal seam and the mine of interest. They are (1) the thickness of the coal that is extracted and (2) the vertical distance between the mined seam and the ground surface. Here, these parameters will be symbolized and defined as:

- \( m \): mined coal thickness
- \( h \): height of overburden

Two other important parameters are also dependent on the location of the mine. They are empirical in nature and, when used in a predictive method, are often assumed to be equal to values back-calculated from similar, nearby mines. The first is referred to as the subsidence factor. This factor is used to determine another derived parameter (see below). The second is called the angle of draw. The angle of draw is the angle of the line, measured from horizontal, from the outer edge of a mined area to the outer edge of the subsidence trough. These two parameters will be symbolized and defined as:

- \( a \): subsidence factor
- \( \gamma \): angle of draw

Most studies on subsidence theory also refer to two other derived parameters. One is the maximum predicted subsidence. This value depends on both the mined coal thickness and the subsidence factor. It represents the amount of subsidence (in units of length) which would be expected above a large mined area. The second derived parameter is called the critical radius. These last two parameters are symbolized and defined below and in Equation (1-1) and Equation (1-2).
- \( S_{\text{max}} \): maximum predicted subsidence

\[
S_{\text{max}} = a \cdot m
\]  

(1-1)

- \( B \): critical radius

\[
B = \frac{h}{\tan \gamma}
\]  

(1-2)

To understand the critical radius, consider a horizontal coal seam extending infinitely in all directions below a horizontal ground surface. Imagine that half of the seam is extracted to one side of a straight line and the other half is left undisturbed. The surface above the extracted portion (far from the dividing line) could be expected to subside a distance equal to \( S_{\text{max}} \). The surface above the undisturbed portion (far from the dividing line) would not be expected to subside at all. Close to the dividing line, however, the surface would likely be disturbed. The extent of the disturbance is quantified by the critical radius. Moving perpendicularly away from the dividing line, subsidence would be expected to become uniform (either zero or \( S_{\text{max}} \)) at one critical radius from the dividing line.

To further illustrate the concept of a critical radius, consider two scenarios: (1) subsidence above a very small extraction area, and (2) subsidence above a very large extraction area. Assuming that the overburden material causes caving in both scenarios, the small extraction area would result in a maximum measured subsidence equal to some small fraction of \( S_{\text{max}} \). The large extraction area would result in an extensive subsidence trough with uniform subsidence equal to \( S_{\text{max}} \) above most of the extraction area. The distinction between the two scenarios is defined by the critical radius; specifically, the critical radius is half of the dimension
of an extraction area which would result in a subsidence trough where the largest subsidence value equals the calculated value of $S_{\text{max}}$ at one and only one point. Extraction areas larger than the critical radius will be referred to as supercritical, while extraction areas smaller than the critical radius will be referred to as subcritical.

One recent study has suggested that surface slope be considered as a variable influencing the magnitude of subsidence (Platt 2009). The effect of slope has been quantified only empirically, as the mechanics involved are not yet clear, but in general, steeper slopes have been found to decrease the magnitude of subsidence. Platt suggests that the predicted subsidence obtained from the input described above be adjusted according to the slope at each point. Equation (1-2) defines a factor related to slope which may be multiplied by each preliminary predicted subsidence value to obtain the final predicted subsidence. The parameters relating to slope are symbolized and defined below.

- $D$: global slope factor
- $z'$: slope
- $\zeta$: local slope factor

\[
\zeta = 1 - D \cdot z'
\]  

The global slope factor is assumed to be constant for a particular mine. After more investigation, this factor may be found to be constant for all mines. The local slope factor is the value multiplied by each preliminary subsidence prediction point to obtain final subsidence prediction values. For simplicity, slope will not be represented in the illustrations in the remainder of this chapter, but will be revisited in the procedure described in Chapter 3.
1.3 Illustrations of Parameters

The 3 figures below illustrate the parameters and concepts described above. All three figures present a horizontal coal seam below a horizontal ground surface. Only two dimensions are considered. A portion of the coal seam has been extracted, resulting in a subsidence trough at the surface. For simplicity, the parameters \( m \) and \( h \) (and consequently the parameters \( S_{\text{max}} \) and \( B \)) are taken as constants in each figure. The subsidence factor, \( a \), is taken to be 1.0 so that the calculated maximum subsidence, \( S_{\text{max}} \), is equal to the mined coal thickness, \( m \).

The first schematic (Figure 1-2) represents a subcritical extraction area where the extracted width is less than \( 2\cdot B \). The maximum amount of subsidence is somewhat less than the calculated value of \( S_{\text{max}} \) as calculated in Equation (1-1).

![Diagram showing subsidence trough and coal seam](image)

**Figure 1-2: Illustration of parameters: Subcritical extraction.**
The second schematic (Figure 1-3) represents a critical extraction area, where the extracted width is equal to $2 \cdot B$. The maximum amount of subsidence is equal to the calculated value of $S_{\text{max}}$ from Equation (1-1) at exactly one point.

Figure 1-3: Illustration of parameters: Critical extraction.

The third schematic (Figure 1-4) represents a supercritical extraction area where the extracted width is greater than $2 \cdot B$. The maximum amount of subsidence is equal to the calculated value of $S_{\text{max}}$ from Equation (1-1) over a finite distance above the center of the extraction area, beginning at a distance $B$ from the edge of the extraction area.
Figure 1-4: Illustration of parameters: Supercritical extraction.
2  INFLUENCE FUNCTIONS

Influence functions make it possible to divide the extraction area into small extraction elements. The subsidence at a surface point can be predicted by summing the value of the influence functions from all nearby extraction elements. Mathematically, the size of each element can approach zero to obtain exact results through integration. However, in practical purposes where input data are measured at finite intervals and the values of $m$ and $h$ are not constant, extraction elements have finite dimensions.

The dependent variable in any influence function is $r$, the horizontal distance from the extraction element. Other arguments usually include the values $S_{\text{max}}$, and $B$. Many functions exist in literature, and other arguments have been suggested (Brauner 1973). Three functions have been chosen as examples for comparison in this paper. Two are presented in Brauner’s document, while the third was developed by the author. The functions are compared and contrasted in the following section. Equations (2-1), (2-2), and (2-3) are the three equations considered.

$$P(\,r\,) = \frac{3 \cdot S_{\text{max}}}{\pi \cdot B^2} \left[ 1 - \left( \frac{r}{B} \right)^2 \right]^2 \text{ for } 0 \leq r \leq B \tag{2-1}$$

$$P(\,r\,) = \frac{S_{\text{max}} (B \cdot \tan \gamma)^3}{\pi \cdot r \left( \sin \gamma \cdot \cos \gamma + \frac{\pi}{2} - \gamma \right)} \left[ r^2 + (B \cdot \tan \gamma)^2 \right]^{\frac{3}{2}} \tag{2-2}$$
\[ P(r) = \frac{3 \cdot S_{\text{max}}}{\pi \cdot B^2} \left(1 - \frac{r}{B}\right) \quad \text{for } 0 \leq r \leq B \]  

In the following table (Table 2-1), the three equations are presented in parallel. First, each equation is plotted in 2 dimensions. The abscissa is the dimensionless ratio \( r/B \). The ordinate is the dimensionless ratio \( PB^2/S_{\text{max}} \). Note that the parameter \( P \) has units of inverse length such that the double integral of \( P \) results in a subsidence value with units of length. Next, each equation is plotted in 3 dimensions. The last row of Table 2-1 presents the volume under the influence function. Because each function has units of inverse length, the volume under the function has units of length.
Table 2-1: Comparison of Influence Functions

<table>
<thead>
<tr>
<th>Equation (2-1)</th>
<th>Equation (2-2)</th>
<th>Equation (2-3)</th>
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</table>

Volume varies with $\gamma$

Volume $= a \cdot m$

Volume $= a \cdot m$
An extracted coal element should result in a subsidence trough with a volume equal to the volume of the extraction element times the subsidence factor, \( a \). An infinitesimal extraction element should produce a subsidence volume of \( a \cdot m \), as the two horizontal dimensions approach zero. The subsidence volume can be calculated by integrating over the entire influence function. This is easily achieved using cylindrical coordinates and integrating over the solid of revolution defined by the influence function as shown in Equation (2-4) below.

\[
V = 2 \cdot \pi \int_{0}^{e} P(r) \cdot r \, dr
\]  

(2-4)

The influence function presented in Equation (2-1) is smooth and meets the criterion that the volume under the function is equal to \( a \cdot m \). The influence function presented in Equation (2-2) is also smooth except at \( r = 0 \) where the function is infinite. The function extends infinitely in the horizontal dimensions and never reaches a value of zero. This characteristic is undesirable because an influence function extending infinitely in all directions, when integrated, results in a subsidence trough that extends infinitely beyond the edges of the extraction zone, rather than one critical radius. The third function represented by Equation (2-3) is smooth except at \( r = 0 \) and at \( r = B \). For practical application, however, the function is desirable because of its simplicity. It is computationally inexpensive compared to the other two functions.

Equation (2-2) will not be treated further. It is deemed impractical for predictive purposes. Equation (2-1) may seem better than Equation (2-3) due to its natural shape. However, it should be remembered that the influence function does not represent actual subsidence; rather, it represents the effect of an extraction element on a point at some distance away. The subsidence troughs predicted by integrating the two functions are actually quite similar. For comparison, Figure 2-1 below shows the subsidence profile predicted using the two
equations. The profiles span from one critical radius to the left of the edge of a mined area to one critical radius to the right of the edge of the mined area.

Figure 2-1: Comparison of subsidence troughs.

Because the subsidence profiles obtained by integrating Equations (2-1) and (2-3) are so similar, Equation (2-3) was chosen for use in the development of a practical subsidence prediction application described in Chapter 3. The main benefit of this equation over others is its simplicity and computational efficiency.
3 SUBSIDENCE PREDICTION PROCEDURE

In this chapter, a step-by-step procedure for predicting subsidence is described. Input to the procedure includes data representing the parameters described in Chapter 2 for a particular mine. The output consists of data representing the predicted subsidence at the surface above the mine.

3.1 Input from ArcGIS

ArcGIS is a package of sophisticated mapping software. The input to the subsidence prediction procedure is easily created, viewed, manipulated, and stored as rasters in ArcGIS. “In its simplest form, a raster consists of a matrix of cells (or pixels) organized into rows and columns (or a grid) where each cell contains a value representing information (from ArcGIS documentation).” The information stored as rasters and used as input to the subsidence prediction procedure includes the following:

1. Mined seam thickness ($m$)
2. Overburden ($h$)
3. Slope ($z'$)

Care must be taken to ensure that each of the above rasters lines up horizontally with the others. The linear distance represented by one cell width in each raster must also be included in the input to the subsidence prediction procedure.
3.2 Single-Value Input

The other values required to begin the procedure include:

1. Subsidence factor ($a$)
2. Angle of draw ($\gamma$)
3. Global slope factor ($D$)

These location-dependent values should be obtained by consulting with qualified personnel at the mine of interest whenever possible. The global slope factor has not been widely used; a value must be assumed.

3.3 Output

The output from the subsidence prediction procedure is a raster representing predicted subsidence. Where subsidence has been measured and is available, predicted subsidence can be compared to measured subsidence by manipulating two rasters in ArcGIS.

3.4 Data Processing

While the input and output to the subsidence prediction procedure involve ArcGIS rasters, the data processing required to generate the output can be performed outside of the ArcGIS environment. For example, rasters can be manipulated in Microsoft Excel by exporting from ArcGIS. All data may be available in spreadsheet form, in which case ArcGIS may not be necessary for subsidence prediction. Any application or programming language may be used to perform the data processing required in this procedure. See Appendix B for examples of spreadsheets developed to aid in and carry out subsidence prediction.
3.5 **Subsidence Prediction Algorithm**

This section describes the computations required to arrive at the output once the input to the subsidence prediction procedure has been gathered. The procedure requires nested loops in order to sum the influence of multiple extraction elements on each subsidence raster cell. The following steps outline the algorithm conceptually.

- The outer loop: each raster cell (referred to as the source cell) is evaluated for possible influence on surrounding cells (referred to as target cells).
  - The inner loop: the preliminary predicted subsidence of each target cell is incremented by the influence of the current source cell.
    - The distance \( r \) between the target cell and the source cell is computed using the Pythagorean Theorem.
    - The critical radius \( B \) is computed according to Equation (1-2).
    - If \( r \) is less than \( B \), then the source cell is close enough to the target cell to influence subsidence at the target cell. The influence of the source cell on the target cell is computed according to Equation (2-3) multiplied by the area represented by each raster cell.
- Subsidence values are adjusted for slope.
  - The local slope factor is determined according to Equation (1-3).
  - Final predicted subsidence values are computed by multiplying each preliminary predicted subsidence value by the corresponding local slope factor.
The algorithm has been coded in Microsoft Visual Basic and is presented in Appendix A section A.1. Indentation and comments have been added for clarity. The code was written for use with Microsoft Excel, where each input raster has been converted to spreadsheet format.

### 3.5.1 Adjustments for Efficiency

While very straightforward, the algorithm presented in this chapter can be quite time-consuming. The computation time can be decreased by making two adjustments.

First, the above algorithm ignores the fact that if the mined area under consideration is very large (represented by many raster cells), then for each source cell considered in the outer loop, the distance to every other cell must be computed to determine whether the target cell is close enough to be influenced by the source cell. Where the mined area is large, each source cell will influence only a small percentage of the potential target cells. To avoid these unnecessary computations, a subset of target cells that are close to the source cell can be tested rather than checking every cell in the considered area. This is done by calculating the critical radius and dividing by the size of a single cell. The inner loop is then confined to a square stretching one critical radius in each direction from the source cell.

The second adjustment involves removing any redundant or otherwise unnecessary calculations. The following steps can be taken to reduce the number of computations:

- Before calculating the increase in subsidence at the target cell from Equation (2-3), check the value of the mined thickness \( m \) at the source cell. If the value is zero, then no increase need be computed.

- Eliminate the repeated computation of values that are constant. Some constants may be computed before entering the outer loop of the algorithm. Equation (2-3)
contains the factor $3-a/\pi$, which is constant over the entire area of interest. Other values are not constant over the entire area of interest, but are constant for any particular source cell. The critical radius is one of these; it may be computed outside of the inner loop. Once the critical radius ($B$) is calculated but before entering the inner loop, the constant $3-a/\pi$ may be divided by $B^2$.

### 3.5.2 Adjustments for Accuracy

Other adjustments improve the accuracy of the predictive algorithm. Just as the extraction elements represented by rasters must be of finite dimensions, the value of the influence function must be determined at finite intervals, governed by the cell size. Inaccuracy is introduced because the center of the target cell does not generally represent the average value of the influence function (centered on the source cell) over the area represented by the target cell. Three adjustments to the algorithm help to reduce this inaccuracy.

- Where the distance $r$ equals zero (where the target cell and the source cell are the same), the value of the influence function is the value at the apex of the cone represented in the third column of Table 2-1. When this value is used to increase subsidence at the cell of interest, subsidence is over-predicted because the peak value is always higher than the average value considering a cell directly below the peak. An assumption was made that the average value above the square cell is equal to the value at a distance $r$ equal to one quarter of the cell size away from the center of the influence function. The adjustment requires an if statement inside of the inner loop.
• Where subsidence is over-predicted, the values are reduced to $S_{max}$ before adjusting for slope. This is achieved by looping through the preliminary subsidence values, calculating $S_{max}$, and using an if statement to check for the need to reduce subsidence values.

• Occasionally, subsidence is under-predicted. Shallow mines and high angles of draw both tend to result in under-prediction. Whenever the cell size is greater than $B$, each source cell influences only one target cell, and the source and target cells are the same. However, the influence function may extend beyond the extents of the cell of interest. See Figure 3-1. In the figure, the source cell is green. The circle has a radius $B$ and represents the extent of the influence function centered over the target cell. The surrounding cells represent potential target cells that are not influenced by the source cell because their centers fall outside of the critical radius. Because of this problem, the predicted subsidence is simply increased to $S_{max}$ when this condition occurs. $S_{max}$ can be calculated as represented by Equation (1-1).

![Figure 3-1: Illustration of a case of under-prediction.](image-url)
The adjusted code reflecting the changes described above is included in Appendix A section A.2. Indentation and comments have been added for clarity.

3.6 **Benefits of the Subsidence Prediction Procedure**

The procedure described in this chapter makes subsidence prediction a much more approachable task. It also increases the accuracy of subsidence prediction as compared with overly simplified methods that have been suggested by others. This section lists some clear benefits of the procedure.

1. Subsidence is predicted over an area rather than along a line.
2. Mine geometry and orientation are not limited.
3. Mined thickness and overburden are allowed to vary over the mined area.
4. The effect of slope on subsidence is quantified and accounted for.

3.7 **Recommendations to Users**

Engineers and others interested in predicting subsidence over mined areas should take particular care when preparing the input to the subsidence prediction procedure. A thorough understanding of the concepts involved, assumptions made, and inherent limitations is necessary in order to obtain accurate results.

An important parameter which must be determined by the user is the cell size of the rasters used as input. The smaller the cell size, the higher the accuracy and resolution of the results. Unfortunately, models with small cell sizes require considerable time to analyze using the subsidence prediction procedure. A good rule of thumb is that the cell size be no smaller than the distance between sample points in the raw data representing mined thickness,
overburden, or slope. The coarseness of these data sets can be increased as desired by interpolation when a larger cell size is chosen. On the other hand, where overburden depth is small and/or the angle of draw is high, it may be necessary to decrease the cell size such that the subsidence at each cell will result from the influence of several source cells. This may require that the resolution of the input rasters be artificially increased by interpolating between raw data sample points.

Many mined coal seams lie vertically above or below other mined coal seams. When this is the case, the principle of superposition applies (Brauner 1973). The predicted subsidence may be determined for each mine separately and then added together. Superposition assumes that the subsidence resulting from one mined seam is independent (not affected) by mining in overlapping seams.
4 SUBSIDENCE AT DEER CREEK MINE

This chapter presents the results of the subsidence prediction procedure applied above a portion of Deer Creek Mine in central Utah. The period of interest in this paper is between 1999 and 2004. Figure 4-1 shows the general area of the mine. Figure 4-2 and Figure 4-3 show longwall mining panels from the Hiawatha and Blind Canyon seams, respectively, overlaid on aerial photographs. Each panel is labeled with the year in which it was mined. The Blind Canyon seam lies above the Hiawatha seam, and the two seams are separated by between 60 and 110 ft of material in the vicinity of the mined panels.
Figure 4-1: Deer Creek Mine location and terrain.
Figure 4-2 Mine workings in the Blind Canyon seam.
Subsidence is expected to occur where the overburden material caves in. This is assumed to occur at all longwall panels shown in the previous figures, regardless of the year in which mining took place. Mine workings excavated for access to the mined panels are assumed to remain intact; therefore, subsidence is not influenced by these workings.

4.1 Predicted Subsidence

The following figures represent input rasters to the subsidence prediction procedure. Figure 4-4 and Figure 4-5 represent overburden for the Blind Canyon and Hiawatha seams,
respectively. Figure 4-6 and Figure 4-7 represent mined thickness for the Blind Canyon and Hiawatha seams, respectively. Figure 4-8 represents surface slope. Data obtained from Deer Creek mine personnel include seam elevations and mined thickness. Surface elevation data was obtained from the United States Geological Survey website (accessed 2010). Overburden was determined by subtracting seam elevations from surface elevations. Slope was determined on a cell-by-cell basis using ArcGIS tools.

![Image: Height of overburden: Blind Canyon seam.](image-url)

**Figure 4-4: Height of overburden: Blind Canyon seam.**
Figure 4-5: Height of overburden: Hiawatha seam.
Figure 4-6: Mined coal thickness: Blind Canyon seam.
Figure 4-7: Mined coal thickness: Hiawatha seam.
Mining activity in each seam resulted in a small extraction area with very low overburden depth. Due to errors either in the data reported by mine personnel or in precisely aligning seam elevation points with surface elevation, small portions of each overburden raster contain negative values (30 cells in the Hiawatha seam and 40 cells in the Blind Canyon seam). Negative values imply that the mined coal was above the ground surface, which is, of course, impossible.

Elevation data were downloaded with a cell size of 30 ft. Data representing mined thickness were provided along lines spanning each panel (north to south) with points spaced at approximately 60 ft intervals. The distance between each line of sample points varied from 150
to 1200 ft. Due to the irregularity in the data points, mined thickness values were simply averaged for each panel. Data representing seam elevation were provided at fairly regular intervals of approximately 100 ft around the perimeter of each mined panel. This data was subtracted from elevation data and interpolated to achieve a smooth surface. The input rasters were prepared with a cell size of 50 ft. This was accomplished through ArcGIS interpolation tools. Specifically, the values of each input raster cell were determined based on inverse distance weighting. “Inverse Distance Weighted (IDW) is a method of interpolation that estimates cell values by averaging the values of sample data points in the neighborhood of each processing cell. The closer a point is to the center of the cell being estimated, the more influence, or weight, it has in the averaging process (from ArcGIS documentation).”

Table 4-1 summarizes the single-value parameters of the input to the subsidence prediction procedure applied at Deer Creek Mine.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subsidence factor</td>
<td>$a$</td>
<td>0.9</td>
</tr>
<tr>
<td>Angle of draw</td>
<td>$\gamma$</td>
<td>45°</td>
</tr>
<tr>
<td>Global slope factor</td>
<td>$D$</td>
<td>0.3</td>
</tr>
<tr>
<td>Cell size</td>
<td></td>
<td>50 ft</td>
</tr>
</tbody>
</table>

The subsidence factor was recommended by engineers at Deer Creek Mine. Various angles of draw were provided in subsidence reports compiled by Deer Creek personnel. The value assumed here was used by Platt and assumed to be constant (2009). The global slope
factor was chosen by comparing actual subsidence to predicted subsidence in an attempt to minimize total error.

Predicted subsidence at Deer Creek Mine due to mining in the Blind Canyon and Hiawatha seams, respectively, is represented in Figure 4-9 and Figure 4-10. Superimposed results are shown in Figure 4-11. Table 4-2 provides minimum, maximum, and average predicted subsidence in each seam and considering the superposition of the 2 seams. These data consider only the areas where subsidence is predicted to be greater than zero. A close examination of these figures shows that the results from the subsidence prediction procedure generally vary as expected with respect to overburden height, mined thickness, and slope.
Figure 4-9: Predicted subsidence due to mining in the Blind Canyon seam.
Figure 4-10: Predicted subsidence due to mining in the Hiawatha seam.
Figure 4-11: Total predicted subsidence.

Table 4-2 Subsidence Results Summary

<table>
<thead>
<tr>
<th></th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blind Canyon</td>
<td>7.9 ft</td>
<td>4.5 ft</td>
</tr>
<tr>
<td>Hiawatha</td>
<td>7.5 ft</td>
<td>3.8 ft</td>
</tr>
<tr>
<td>Total</td>
<td>15.0 ft</td>
<td>7.5 ft</td>
</tr>
</tbody>
</table>
4.2 Measured Subsidence

Subsidence at Deer Creek has been monitored annually by aerial surveying. Subsidence over any number of years can be obtained by subtracting elevations at the beginning of the period of interest from elevations at the end of the period of interest. Elevations at Deer Creek Mine were obtained using photogrammetry. Aerial photographs taken from different locations enable surveyors to determine the location of a fixed surface point in 3-dimensional space. When the same surface feature is used as a survey point in 2 annual surveys, a reliable measured subsidence value is obtained. With a sufficient number of subsidence data points, interpolation between points makes it possible to plot subsidence in raster format.

Survey data made available by Deer Creek Mine reference 1999 as the base year. Measured subsidence is given for the year 2006. Mining began in 1999 and ended in 2004, so the data range spans all mining activity. The time between the end of mining activity and the final survey is assumed to be sufficient for caving and subsidence to have occurred.

Figure 4-12 shows a measured subsidence raster produced using IDW interpolation. Considering the large subsidence values around the edges of the surveyed area, it appears likely that some surface features used as survey points were influenced by movements not caused by mining, such as rock slides. The survey data may reflect human error and the limitations of the aerial survey as well.
Figure 4-12: Measured subsidence.

Measured and predicted subsidence are compared in Figure 4-13. The figure shows error, computed as measured subsidence minus predicted subsidence. The region of comparison was limited to the cells in which non-zero subsidence was predicted.
4.3 Conclusions

The results of the subsidence prediction algorithm applied at Deer Creek Mine differ from actual subsidence. Of the cells in which non-zero subsidence was predicted, 83% were within 3 ft of measured subsidence and 35% were within 1 ft of measured subsidence. The cells with predicted values which differed by more than 3 ft (17%) are largely found around the edges of the area of interest. This suggests that the extracted areas have more influence on distant
surface points than was assumed. Error near the edges might be minimized by selecting a larger angle of draw.

Having laid out the limitations of this particular subsidence prediction application, it should be noted that measured and actual subsidence at Deer Creek Mine are actually in surprisingly good agreement in most places. The fact that practically nothing is known about the soil and rock constituting the overburden has not prohibited the calculation of predicted subsidence. Empirical parameters are adequate to produce satisfactory results. Future improvements to subsidence prediction methods may yield even better results by more accurately quantifying relationships between input and output variables and by considering additional parameters as influential to subsidence.
REFERENCES


APPENDIX A. VISUAL BASIC CODE

The following is the actual Visual Basic code used to predict subsidence at Deer Creek Mine. Indentation is for clarity only. Comments are colored green and set off with apostrophes ('). Keywords specific to the programming language are colored blue.

A.1 Unadjusted Code

Const pi As Double = 3.14159265358979

Function subsidence(m, h, z_prime, cellsize, a, gamma, D)

'Input:
' Arrays:
'  m: mined seam thickness
'  h: overburden thickness
'  z_prime: slope
' Scalars:
'    cellsize: distance represented by each cell
'    a: subsidence factor
'    gamma: angle of draw
'    D: global slope factor

'Intermediate variables:
Dim i1 As Integer, j1 As Integer
Dim i2 As Integer, j2 As Integer
Dim ni As Integer, nj As Integer

'Initial calculations:
ni = m.Rows.Count
nj = m.Columns.Count

'Array variable to store subsidence prediction values:
ReDim s(1 To ni, 1 To nj) As Double

'Outer loop
For i1 = 1 To ni
   For j1 = 1 To nj
'Inner loop:
For i2 = 1 To ni
    For j2 = 1 To nj
        r = Sqr((i1 - i2) ^ 2 + (j1 - j2) ^ 2) * cellsize
        B = h(i1, i2) / Tan(gamma)
        If r < B Then
            s(i2, j2) = s(i2, j2) + 3 * a * m(i1, j1) / (pi * B ^ 2)
            * (1 - r / B) * cellsize ^ 2
        End If
    Next j2
Next i2
Next j1
Next i1

'Adjust for slope
For i1 = 1 To ni
    For j1 = 1 To nj
        If m(i1, j1) <> 0 Then
            Smax = a * m(i1, j1)
        End If
        zeta = 1 - D * z_prime(i1, j1)
        s(i1, j1) = zeta * s(i1, j1)
    Next j1
Next i1

'Set the output equal to the 's' array
subsidence = s

End Function

A.2  Adjusted Code

Const pi As Double = 3.14159265358979

Function subsidence(m, h, z_prime, cellsize, a, gamma, D)

'Input:
'  Arrays:
'    m: mined seam thickness
'    h: overburden thickness
'    z_prime: slope
'  Scalars:
'    cellsize: distance represented by each cell
'    a: subsidence factor
'    gamma: angle of draw
'    D: global slope factor

'Intermediate variables:
Dim il1 As Integer, j1 As Integer
Dim i2 As Integer, j2 As Integer
Dim ni As Integer, nj As Integer
Dim cl As Double, c2 As Double
Dim Smax As Double
Dim avgm As Double
Dim ninf As Integer, ncells As Integer
Dim x1 As Integer, x2 As Integer, y1 As Integer, y2 As Integer

'Initial calculations:
ni = m.Rows.Count
nj = m.Columns.Count
c1 = 3 * a * cellsize ^ 2 / pi

'Array variable to store subsidence prediction values:
ReDim s(1 To ni, 1 To nj) As Double

'Outer loop
For i1 = 1 To ni
    For j1 = 1 To nj
        B = h(i1, j1) / Tan(gamma)
        Smax = a * m(i1, j1)

        'Check for small critical radius
        If cellsize > 2 * B Then
            If m(i1, j1) <> 0 Then
                s(i1, j1) = Smax
            End If
            GoTo next_target_cell
        End If

        'Determine bounds on the inner loop
        ninf = Int(B / cellsize)
        x1 = j1 - ninf
        If x1 < 1 Then
            x1 = 1
        End If
        x2 = j1 + ninf
        If x2 > nj Then
            x2 = nj
        End If
        y1 = i1 - ninf
        If y1 < 1 Then
            y1 = 1
        End If
        y2 = i1 + ninf
        If y2 > ni Then
            y2 = ni
        End If
        c2 = c1 / (B ^ 2)

        'Inner loop:
        For i2 = y1 To y2
            For j2 = x1 To x2
                If m(i1, j1) <> 0 Then
                    r = Sqr((i1 - i2) ^ 2 + (j1 - j2) ^ 2) * cellsize
                    If r < B Then

next_target_cell:
'Check for the case where the target cell and source cell are the same
If \( r = 0 \) Then
    \( r = \text{cellsize} / 4 \)
End If
\[
s(i2, j2) = s(i2, j2) + c2 * m(i1, j1) * (1 - r / B)
\]
End If
Next j2
Next i2

Next target cell:
Next j1
Next i1

'Adjust for slope
For \( i1 = 1 \) To \( ni \)
    For \( j1 = 1 \) To \( nj \)
        If \( m(i1, j1) <> 0 \) Then
            \( S_{\text{max}} = a * m(i1, j1) \)
            If \( s(i1, j1) > S_{\text{max}} \) Then
                \( s(i1, j1) = S_{\text{max}} \)
            End If
        End If
        \( zeta = 1 - D * z_{\prime}(i1, j1) \)
        \( s(i1, j1) = zeta * s(i1, j1) \)
    Next j1
Next i1

'Set the output equal to the 's' array
\( \text{subsidence} = s \)

End Function
APPENDIX B. SPREADSHEET TOOLS

This appendix shows screen images of spreadsheets developed to aid in and carry out the subsidence prediction procedure. Figure B-1 presents a compressed version of the spreadsheet used to run the subsidence prediction procedure on the data from Deer Creek Mine. A sample of input data is shown and has been colored using Microsoft Excel’s conditional formatting. Figure B-2 shows a spreadsheet used to compare measured and predicted subsidence. The graphs in the figure represent subsidence through a profile rather than over the entire mine area. This tool facilitates comparison and highlights areas of concern.
Figure B-1: Spreadsheet used to predict subsidence.

Figure B-2: Spreadsheet showing measured and predicted subsidence in profile.