Multiple-Seam Mining Interactions in Underground Coal Mines: Regulations and Technical Studies

Final Report

Report Period: May 16 – August 15, 2013

Submitted to

MISTTI Project
Center for Educational Technologies
Wheeling Jesuit University

by

Yi Luo, Ph.D., P.E.
Associate Professor
Department of Mining Engineering

Gary L. Winn, Ph.D.
Professor
Department of Industrial and Management Systems Engineering

Statler College of Engineering and Mineral Resources
West Virginia University

August 28, 2013
# TABLE OF CONTENTS

EXECUTIVE SUMMARY .................................................................................................................. 1

INTRODUCTION ................................................................................................................................. 3

MINING DIFFERENCES BETWEEN US AND OTHER COUNTRIES ....................................................... 4
  Regulations Regarding Mining Rights ............................................................................................... 4
  Emphasis on Mining Research ........................................................................................................... 7

TECHNICAL STUDIES OF MSM INTERACTIONS .............................................................................. 7
  Direct MSM Interactions .................................................................................................................. 7
  Indirect MSM Interactions ............................................................................................................. 8
  Rationale for Applying Subsidence Theories to Study MSM Interactions ........................................ 8

SUBSURFACE SUBSIDENCE PREDICTION MODELS ......................................................................... 9
  First Version of Subsurface Subsidence Prediction Model ............................................................... 9
  Enhanced Subsurface Subsidence Prediction Model ........................................................................ 11
  Demonstration of Subsurface Subsidence Prediction Model ............................................................ 14

METHODS TO STUDY DIRECT MSM INTERACTIONS .................................................................... 20
  Method to Assess Overall MSM Interactions ................................................................................ 22
  Pillar Stability under MSM Influence ............................................................................................ 23
    Pillar Load Determination ............................................................................................................ 23
    Pillar Strength Determination ...................................................................................................... 23
    Pillar Stability Factor ................................................................................................................... 27
  Roof Stability under MSM Influence ............................................................................................. 28
    MSM Influence to Roof Cracks .................................................................................................... 29
    MSM Influences to Cutter Roof .................................................................................................. 29
  Floor Stability under MSM Influences .......................................................................................... 29
    MSM Influences to Mine Floor Cracks ........................................................................................ 30
    MSM Influences to Mine Floor Heave ......................................................................................... 30

STUDIES OF INDIRECT MSM INTERACTIONS ............................................................................. 31
  Inteburden Stability ...................................................................................................................... 32
  Case Demonstrations .................................................................................................................... 33
    Case Demonstration No. 1 ........................................................................................................... 33
    Case Demonstration No. 2 ............................................................................................................ 37
  Assessment of MSM Interaction on Water Leakage .................................................................... 44
  Assessment of MSM Interaction on Gas Leakage ......................................................................... 51
  Assessment of MSM Interaction on Spontaneous Combustion ..................................................... 51

CONCLUSIONS .................................................................................................................................... 52

REFERENCES ...................................................................................................................................... 53
EXECUTIVE SUMMARY

Multiple-seam mining (MSM) operations refer to the mining operations conducted by one or more mine operators in closely-spaced multiple coal seams. Unlike more conventional mining operations conducted in single-seam situation, these MSM operations and their interactions could bring some unique technical, safety and regulatory issues to the attention of mine regulators, operators and engineers. This report primarily addresses the technical issues and mining best-practice surrounding MSM, but also discusses the safety and regulatory concerns associated with MSM.

Technical Difficulties with MSM Operations:

If not well coordinated, MSM operations can cause many unexpected consequences to active and inactive mines in the influence ranges – MSM interactions. Among the various MSM interactions, the interactions caused by the large strata movements and deformations in the ground subsidence process in the overburden strata, and especially the interburden (in-between) strata, must be critically examined. When large deformations are concentrated in neighboring areas, they can form leakage paths for water, gas and air to flow between the coal seams in addition to disturbances to mine structures in the mines. The flow of these liquid and gases from previous mines to active mine can cause significant ventilation and safety problems such as inundation (e.g., the accident at Quecreek), or gas explosions as may have happened at Upper Big Branch.

Using Computer Models to Accurately Predict Subsidence:

Numerical modeling techniques have been developed and applied to study the MSM interactions. However, most of the modeling methods assume continuity in media that deviated from the coal measure rock strata that contains various preexisting and mining induced horizontal bedding planes, vertical or sub-vertical fractures. Because of this, these methods have difficulty in accurately assessing the MSM interactions associated with large-movements and large deformations strata subsidence process. On the other hand, subsidence theories, well suited for dealing with large strata movements deformations caused by mining operations, can be applied to study the MSM interactions. **Recommendation: Future research should concentrate on improved computer models which consider issues involved in MSM operations including large seam displacements, jointed and refractive strata and softwares developed for use in known MSM operations.**
Coordinating the Legal Rights to Multi-Seam Operations:

In countries outside the U.S., the mine owner typically owns the rights to all of the coal reserves which may be located in a single seam, or in overlying seams. Because there is no issue of “who owns what”, coordination operations is an important matter. But in the U.S., however, one owner often owns rights to a particular seam, but not the rights to an overlying or underlying seam. Coordinating mining operations becomes a central issue, and this is even more important when old mine workings are found in a different seam or the old workings have poor maps. Even though as early as 1883, mine maps were required to be provided to the state of West Virginia, many mines were abandoned without proper historical maps. Since the passage of mine map legislation on both state and federal levels, the agencies involved including U.S. Department of Interior, Office of Surface Mining and the West Virginia Office of Miners' Health, Safety and Training and the WV Geological and Economic Survey, plus West Virginia University have worked in cooperation to acquire maps and to index and digitize them. Currently, over 60,000 images have been digitized and indexed for West Virginia mines (WV Office of MHST, 2013). **Recommendation:** For future research, a coordination and archiving project ought to be undertaken to voluntarily share or even force sharing information about ownership rights but also scheduling, design, and planning of MSM mines.

Updating Permitting Procedures:

Federal and State regulatory agencies require a complete set of engineering, safety and environmental designs to be approved prior to undertaking mining activity. Unfortunately, multi-seam mining and the possible seam or ownership interactions are not considered or not sufficiently considered in the permitting process. While future research could easily pinpoint situations when failure to consider MSM interactions have had harmful consequences, this recommendation must be properly aimed at the regulatory agencies and perhaps legislative bodies in order to make it a priority to consider MSM variables in the permitting process. **Recommendation:** state and federal regulatory agencies should follow the lead of Congress and/or the State legislature in causing the promulgating of rules to require the consideration of MSM operations early in the mine permitting process.

Summary:

While technical understanding of the MSM process has improved significantly in recent years, and while a good amount of research has been performed and some numerical-modeling based design tools have been developed for dealing with the load transfer MSM interactions, problems persist. In particular, problems with MSM operations need to update computer subsidence models they currently use to include large displacement algorithms, for example. Second, MSM operators and state and federal regulatory agencies need to coordinate the use of
maps especially, but also and general information about scheduling and methods in order to coordinate activities and not act in secret as is done now. Finally, acting on the lead by Congress and/or state regulatory agencies, the permitting process must have rules promulgated to include the consideration of MSM operations. All of these would work to improve MSF safety.

INTRODUCTION

Coal reserves generally exist in multiple seam formations, that is, one seam overlays another seam. About 156 billions tons of US coal reserve is subject to multiple seam mining influences (Singh and Dunn, 1981). Depending on coal fields, these multiple coal seams might be closely spaced such as those in the Central Appalachian and Western coal fields and the others could be spaced in larger distances such as that in the Northern Appalachian, Illinois and Alabama coal fields. Mining operations in closely spaced multiple coal seams (MSM) can cause significant interactions and considerably more potential problems to mining operations and to miner safety than mining conducted in a single coal seam or in far-spaced coal seams.

Figure 1 Five Major Underground Coal Mining Regions in US (Mark, et al., 2007)

The most common safety problems associated with multi-seam mining (MSM) operations are: water inundations, sudden methane inrushes, spontaneous combustions, large-scale roof falls, and coal bumps. The first three types of problems are related to subsidence-induced
fracture zones in the interburden strata that connect the active mine to old mine workings or previously sealed mines. The last two types of problems are related to mining-induced stress redistribution in the surrounding strata. Fortunately, not all of the MSM situations results in hazardous conditions. Coincidentally, most MSM operations in the US are conducted in the Central Appalachian coal field because of the high quality coal. This area also has the most mining accidents and disasters in the history of U.S. coal industry. For example, thirteen (green shaded cases) out of 21 coal mine disasters (defined as five or more fatalities in an accident) have occurred in the Central Appalachian coal field since 1970. More recently, MSM interactions heavily contributed to the Upper Big Branch mine explosion in West Virginia. Prior to this accident, a large amount of water leaked, through possibly subsidence-induced fracture zone, from an overlying abandoned coal mine has partially blocked the ventilation airways. Methane leaked from an underlying coal seam or abandoned mine through mining induced ground cracks into the longwall face started the flame and consequently the methane explosion and coal dust explosion (MSHA, 2012).

**MINING DIFFERENCES BETWEEN US AND OTHER COUNTRIES**

It should be noted that US is the leader in the world in many aspects of mining research and regulations in the fields of extraction technology, equipment development, mine safety and health, coal utilization. Because of these, the US coal industry is one of the safest and most productive ones among the coal producing countries. However, the safety with coal mining operations in closely spaced multiple seams in the US still remains to be an area deserving significant improvement as previously mentioned.

**Regulations Regarding Mining Rights**

Unlike many other major coal producing countries, the high degree of privatization of coal reserves in most U.S. coal fields often limits a company’s mining right to only one single coal seam. If the coal seams are spaced in sufficient distances, it is simple to lay out a mine and is safe to conduct mining operations in one single coal seam. However, the U.S. coal mining operations in closely spaced multiple seams are often conducted in an uncoordinated manner by different mining companies without due consideration of potential interactions to mining operations in adjacent coal seams. The MSM interactions could cause significant difficulties to mining operations and produce unsafe mining conditions.

In many other major coal producing countries such as China, Germany, Britain, Russia, etc., the mining companies normally obtain their mining rights from the central or local gov-
ernments. In such case, a mining company normally owns the mining rights of all coal seams located directly under its surface property boundary. For the sake of smooth production and mine safety, the mining company and its engineers will carefully coordinate its mine design and operation schedule to avoid significant mining interactions. If the coal seams under a common surface property has to be permitted to two or more coal mines, sufficient space not induce significant MSM interactions should be left between the mines.

<table>
<thead>
<tr>
<th>Year</th>
<th>Day</th>
<th>Mine</th>
<th>Location</th>
<th>Type</th>
<th>Deaths</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>4/5</td>
<td>Upper Big Branch Mine, Massey Energy</td>
<td>Raleigh County, West Virginia</td>
<td>Explosion</td>
<td>29</td>
</tr>
<tr>
<td>2007</td>
<td>8/6</td>
<td>Crandall Canyon Mine, Genwal and Murray Energy Corporation</td>
<td>Huntington, Utah</td>
<td>Collapse</td>
<td>6</td>
</tr>
<tr>
<td>2006</td>
<td>5/20</td>
<td>Darby Mine No. 1, Kentucky Darby LLC</td>
<td>Holmes Mill, Kentucky</td>
<td>Explosion</td>
<td>5</td>
</tr>
<tr>
<td>2006</td>
<td>1/2</td>
<td>Sago Mine, International Mines Corp.</td>
<td>Tallmansville, West Virginia</td>
<td>Explosion</td>
<td>12</td>
</tr>
<tr>
<td>2001</td>
<td>12/07</td>
<td>No. 5 Mine, Jim Walter Resources, Inc.</td>
<td>Tuscaloosa County, Brookwood, Alabama</td>
<td>Explosions</td>
<td>13</td>
</tr>
<tr>
<td>1989</td>
<td>09/13</td>
<td>William Station No. 9 Mine, Pyro Mining Co.</td>
<td>Union Co., Wheatcroft, Kentucky</td>
<td>Explosion</td>
<td>10</td>
</tr>
<tr>
<td>1986</td>
<td>02/06</td>
<td>Loveridge No. 22, Consolidation Coal Co.</td>
<td>Marion Co., Fairview, West Virginia</td>
<td>Suffocation (surface stockpile)</td>
<td>5</td>
</tr>
<tr>
<td>1984</td>
<td>12/19</td>
<td>Wilberg Mine, Emery Mining Corp.</td>
<td>Emery Co., Orangeville, Utah</td>
<td>Fire</td>
<td>27</td>
</tr>
<tr>
<td>1982</td>
<td>01/20</td>
<td>No. 1 Mine, RFH Coal Co.</td>
<td>Floyd Co., Craynor, Kentucky</td>
<td>Explosion</td>
<td>7</td>
</tr>
<tr>
<td>1981</td>
<td>12/08</td>
<td>No. 21 Mine, Grundy Mining Co.</td>
<td>Marion Co., Whitwell, Tennessee</td>
<td>Explosion</td>
<td>13</td>
</tr>
<tr>
<td>1981</td>
<td>12/07</td>
<td>No. 11 Mine, Adkins Coal Co.</td>
<td>Knott Co., Kite, Kentucky</td>
<td>Explosion</td>
<td>8</td>
</tr>
<tr>
<td>1981</td>
<td>03/15</td>
<td>Dutch Creek No. 1, Mid-Continent Resources, Inc.</td>
<td>Pitkin Co., Redstone, Colorado</td>
<td>Explosion</td>
<td>15</td>
</tr>
<tr>
<td>1978</td>
<td>04/04</td>
<td>Moss No.3 Portal A, Clinchfield Coal Co.</td>
<td>Dickinson Co., Duty, Virginia</td>
<td>Suffocation (oxygen deficient air)</td>
<td>5</td>
</tr>
<tr>
<td>1977</td>
<td>03/01</td>
<td>Porter Tunnel, Kocher Coal Co.</td>
<td>Schuykill Co., Tower City, Pennsylvania</td>
<td>Flood</td>
<td>9</td>
</tr>
<tr>
<td>1976</td>
<td>03/9-11</td>
<td>Scotia Mine, Blue Diamond Coal Co.</td>
<td>Letcher Co., Oven Fork, Kentucky</td>
<td>Explosion</td>
<td>26</td>
</tr>
<tr>
<td>Year</td>
<td>Date</td>
<td>Location</td>
<td>Cause</td>
<td>Number</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td>-----------------------------------------------</td>
<td>---------------</td>
<td>--------</td>
<td></td>
</tr>
<tr>
<td>1972</td>
<td>12/16</td>
<td>Itmann No. 3 Mine, Itmann Coal Co.</td>
<td>Explosion</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>1972</td>
<td>07/22</td>
<td>Blacksville No. 1, Consolidation Coal Co.</td>
<td>Fire</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>1970</td>
<td>12/30</td>
<td>Nos. 15 and 16 Mines, Finley Coal Co.</td>
<td>Explosion</td>
<td>38</td>
<td></td>
</tr>
</tbody>
</table>
Emphasis on Mining Research

It should be mentioned that most of U.S. mining research efforts have been directed to mining operations in single coal seam. For example, various pillar design formulae for longwall mine and room and pillar mine are all for mining operations conducted in single coal seams. These formulae are relatively simple to apply and have been widely and successfully used by mining engineers in their mine design works.

Currently, two program packages, LaModel and AMSS, are available in US for designing mines operating in multiple coal seams. The LaModel program developed using boundary element method by Heasley has the capability to model the stresses in large areas of single and multiple coal seam mines and to help in designing adequate pillar sizes (Heasley and Agioutantis, 2001). Laminated and continuity media model is used in the numerical analysis. Though LaModel could provide a 3-D and comprehensive analysis, the long time required for the user to build a realistic mine model, hours to days, could make it difficult to be widely applied by mines, especially small mines facing potential MSM interactions. This program is still being improved (Heasley, 2011) and calibrated with field data.

Mark et al, (2007) developed another program package called Analysis of Multiple Seam Stability (AMSS) for analyzing the stability of the mine structures for MSM operations. The program uses a shortened version of the LaModel (LaM2D) to determine the stress distribution and empirical models to determine the stability factors for the mine structures. In this program, MSM interaction effects due to different vertical mining sequence (i.e., undermining and over-mining) are considered in the process. However, since it is only capable of performing analysis in 2-D conditions, it would be difficult to deal with multiple seam mining problems with complex mining geometries.

TECHNICAL STUDIES OF MSM INTERACTIONS

As mentioned previously, the interactions caused multi-seam mining operations in coal mines could be divided into two following types:

Direct MSM Interactions

In this type of MSM interactions, the load transfers from remnant structures in overlying or underlying mines can create concentrated high stress zones in the active mine. Such localized high stresses
can overcome the strengths and cause ground failures of mine roof, pillars, ribs and floor. In more severe cases, the highly stressed coal pillars can fail in rapid and violent manner and induce coal bumps.

It should be noted that the strata movements and deformations in the load transfer process is normally small. Numerical analysis can well suit for such load transfer induced MSM interactions. Therefore, the direct type of MSM interactions can be adequately studied using the LaModel and AMSS in both numerical analysis techniques are used to determine the stress distributions in the strata domain. Since the direct type of MSM interactions have been intensively studied by various ground control researchers, there is no need to repeat the direct MSM interactions in this report.

**Indirect MSM Interactions**

This type of MSM interactions are normally associated with large strata movements and deformations induced by the ground subsidence process in the overburden strata, particularly interburden strata. Holland (1951) stated that trough subsidence is responsible for most of the interaction effects on overlying seam. The large deformations, especially the expansive volumetric strain (also called as void intensity), concentrated in contiguous areas, could form leakage paths for water, gas and air to flow between the coal seams. The flow of these liquid and gases from previous mines to active mine can cause significant ventilation and safety problems. The large strata deformations can also reduce the confinement to and the strength of mine structures and consequently could cause the direct type of MSM interactions. The numerical analysis techniques developed based on continuity media approach, commonly employed for mining applications, are inadequate for study the large deformation ground control problems.

**Rationale for Applying Subsidence Theories to Study MSM Interactions**

It should be noted that a very strong mine subsidence research program has been built in the Department of Mining Engineering of West Virginia University (WVU). Mathematical models have been developed for various subsidence processes and calibrated with numerous collected surface and subsurface mine subsidence cases. The final and dynamic subsidence prediction programs developed from the research produce very accurate estimates of static and time-dependent movements and deformations. Due to such high prediction accuracy, the subsidence theories developed and prediction programs have been successfully applied to numerous subsidence projects involving mine design, public safety, surface structures and environment.

All these subsidence prediction models have been developed using the stochastic influence function method. The stochastic model is well capable of handling geo-mechanical prob-
lems associated with large strata movements and deformations. Added with the proven accuracy in predicted movements and deformations, the subsidence theories have great application potentials for many ground control problems. Therefore, this research will focus on the development of approaches and methodologies that can be used to study the indirect and direct MSM interactions so that easy and accurate tools can be developed.

**SUBSURFACE SUBSIDENCE PREDICTION MODELS**

In order to study the MSM interactions, the strata movements and deformations should be accurately predicted first. This calls for theoretically sound and versatile subsurface subsidence prediction models that can take stratification changes into account.

As coal seam is mined with total extraction (longwall) or high extraction (room and pillar mining with depillaring operations), the large sized mine gob will induce the overburden strata to move toward the gob so a new equilibrium can be reached. The strata movements will propagate upwards vertically while spread laterally outwards from edges of the mine gob. As the mine gob expands along its mining direction, the overburden strata located within a small angle ahead and some angle behind the moving working face would experience a time-dependent dynamic subsidence process. In area with sufficient distance behind the working face, the new equilibrium has been reached in the overburden strata certain distance and subsidence is static or final. Apparently, the propagation of strata movements will be influenced by stratification changes in the overburden. For example, a thick strong rock stratum (e.g. sandstone) can overhang a distance over the underlying weak strata and change the strata movement distribution above it.

Since the strata movements are normally not distributed uniformly, the differential movements will cause various deformations. The strata deformations that could impact the integrity and stability of overburden strata and mine structures are normally the horizontal, vertical and total strains. Among them, the total strain is defined as the volumetric change of strata during and after the subsidence. The expansive type of total strain is the most useful deformation for assessing the indirect and direction MSM interactions.

**First Version of Subsurface Subsidence Prediction Model**

One method for predicting final and dynamic subsurface subsidence over full extraction mining methods have been developed by Luo and Peng (2000) using a large amount of surface
and subsurface subsidence data over longwall panels. This method is an expansion of the previous surface subsidence prediction model but it unable to consider the stratification changes. The final subsurface subsidence and horizontal displacement at a point of interest \((x, h)\) as shown in Fig. 2 can be determined by the following two equations. In these equations, \(W\) and \(m\) are the panel width and mining height, respectively. The final subsidence parameters, \(a\), \(R\) and \(d\) are the subsidence factor, radius of major influence and offset of inflection point, respectively. These final subsidence parameters depend on the vertical distance between the point of interest and the mined coal seam. They are determined from empirical formulae derived from collected surface and subsurface subsidence data. Subsurface deformations are various forms of derivatives of the two equations.

\[
S(x, h) = \frac{am}{R} \int_{d-x}^{w-d-x} e^{-\pi \left(\frac{\zeta}{R}\right)^2} d\zeta \tag{1}
\]

\[
U(x, h) = \frac{amR}{h} \left[ e^{-\pi \left(\frac{d-x}{R}\right)^2} - e^{-\pi \left(\frac{W-d-x}{R}\right)^2} \right] \tag{2}
\]

![Diagram](image.png)

Figure 2 Schematic for influence function method (Luo and Peng, 2000)
Similar approach has also used to develop the dynamic subsurface subsidence prediction model. The dynamic subsurface dynamic subsidence model is used to predict the subsurface time-dependent strata movements and deformations.

**Enhanced Subsurface Subsidence Prediction Model**

The overburden stratification plays a significant role in the propagation of the subsurface subsidence. For example, a thick hard rock layer could significantly alter the distribution of subsurface and surface subsidence. However, the means to reflect the presence and effects of such hard layer are missing in the previous subsurface subsidence prediction models.

In order to build the capability of considering the stratification changes, an enhanced subsurface subsidence prediction model has been proposed (Luo and Qiu, 2012). In this new model, the overburden strata over a longwall gob are divided into a finite number \( n \) of layers of equal thickness. The layers are numbered from the immediate roof stratum to the surface by 1, 2, ..., \( n \) as shown in Fig. 3. The subsidence on the top surface of a given layer can be determined in the following procedure: (1) transforming the overburden load above it into a uniform equivalent load on the layer; (2) defining the subsidence influence function at a prediction point using the equivalent load, layer thickness, percent of hard rock in the layer and vertical movement at the layer bottom directly under the prediction point, (3) integrating the influence function within a proper horizontal interval for the final subsidence on the top of the layer. This procedure is repeated from the mining horizon, layer by layer upwards, until the ground surface is finally reached.

![Figure 3 Enhanced subsurface subsidence prediction model](image-url)
The first step to apply the influence function method for determining strata movements at a given point on the top surface of the ith layer is to define the influence functions for vertical and horizontal displacement, respectively. The influence function for subsidence along a major cross-section is shown in the Eq. 3.

\[ f_1(x', z_i) = \frac{S(x + x', z_{i-1}) \cdot a_i \cdot e^{-\left( \frac{x'}{R_i} \right)^2}}{R_i} \quad i = 1, 2, \ldots, n \]  

In this equation, \( x \) is the horizontal distance between the left panel edge and the prediction point while \( z_i \) is the vertical distance between the top surface of the ith layer and the mined coal seam as shown in Fig. 4. The term \( S(x + x', z_{i-1}) \) is the predicted final subsidence on top surface of the underlying layer located \( x' \) distance on the left of the prediction point. For the first layer immediately above the mined coal seam, the mining height, \( m \), should be used in the place of \( S(x + x', z_{i-1}) \) in the influence functions. Final subsidence parameters \( a_i \) and \( R_i \) are the subsidence factor and radius of major influence for the ith layer, respectively. Coordinate \( x' \) is the horizontal distance between the point of “influence” to cause subsidence and the prediction point on the top surface of the layer.

![Figure 4 Schematic for influence function method](image)

Based on the focal point theorem, the influence function for horizontal displacement along a major cross-section is derived from the influence function for subsidence (Eq. 3) as shown in the following equation. In the equation, \( h \) is the overburden depth.

\( h \) - overburden depth; \( m \) - mining height; \( W \) - panel width; \( n \) - number of overburden layers
\[ f_i(x', z_i) = -2\pi \frac{S(x + x', z_{i-1}) \cdot a_i \cdot n}{R_i \cdot h} x' e^{-\pi \left(\frac{x'}{R_i}\right)^2} \quad i = 1, 2, \ldots, n \] (4)

The final subsurface subsidence and horizontal displacement at a prediction point are determined by integrating the respective influence functions between the left and right inflection points as shown in Figs. 5 and 6, respectively. In the following two equations, \(d_{i1}\) and \(d_{i2}\) are the offset distances of inflection points on the left and right sides of panel for the ith layer, respectively. The final subsidence parameters \((a_i, R_i, d_{i1}, d_{i2})\) are dependent of the layer thickness, percent of hard rock (i.e., limestone and sandstone) in each layer and the distance above the mined coal seam.

\[ S(x, z_i) = \frac{a_i}{R_i} \int_{d_{i1}-x}^{w-d_{i2}-x} S(x + x', z_{i-1}) \cdot e^{-\pi \left(\frac{x'}{R_i}\right)^2} dx' \quad i = 1, 2, \ldots, n \] (5)

\[ U(x, z_i) = \frac{a_i \cdot n \cdot R_i}{h} \int_{d_{i1}-x}^{w-d_{i2}-x} S(x + x', z_{i-1}) \cdot e^{-\pi \left(\frac{x'}{R_i}\right)^2} dx' \quad i = 1, 2, \ldots, n \] (6)

The differential strata movements in both horizontal and vertical directions will cause deformations in the subsurface strata. In surface subsidence studies, the surface deformations are traditionally described by slope, strain and curvature. However, for applications dealing with subsurface subsidence, the distributions of horizontal, vertical and total strains in the overburden strata could be much more valuable for assessing the subsidence influences to subsurface structures, hydrological system and gob well degasification operations.

The horizontal strain \((\varepsilon_x)\) is defined as the first derivative of horizontal displacement with respect to \(x\) (Eq. 7). Sufficient horizontal strain could cause vertical fractures or even cracks in the strata. The vertical strain \((\varepsilon_z)\) is defined as the first derivative of subsurface subsidence with respect to \(z\) (Eq. 8). Sufficient vertical strain could cause bed separations along the strata bedding planes or even step cracks. The total strain \((\varepsilon_t)\), defined in Eq. 9, is an indicator of the severity of expansion or shrinkage of a volume of rock strata under the influence of subsidence process. It should be noted that the expansive type of total strain (in positive value), reflecting the intensity of voids, is an indicator of the increase in porosity and permeability for seepage flows of gases or water in the subsurface strata. For simplicity, the expansive total strain is also called void intensity. The approaches and methodologies developed to use the predicted subsurface deformations in assessing the stabilities of mine structures and the indirect MSM interactions are shown in the later sections.
\[
\varepsilon_x(x, z) = \frac{dU(x, z)}{dx} 
\]
(7)

\[
\varepsilon_z(x, z) = \frac{dS(x, z)}{dz} 
\]
(8)

\[
\varepsilon_t(x, z) = \varepsilon_x + \varepsilon_z + \varepsilon_x \cdot \varepsilon_z 
\]
(9)

**Demonstration of Subsurface Subsidence Prediction Model**

A longwall mine case in which both surface and subsurface subsidence has been monitored is selected for demonstrating the proposed mathematical model and the computer program. The site is located in the northern Appalachian coal fields.

The longwall panel of the study area is 437 m (1,433 ft) wide and the overburden depth is 187 m (612 ft). A mining height of 2.3 m (7.7 ft) is used in the prediction. Table 3 shows the geological column of the overburden strata. To perform the subsurface subsidence prediction with the program, the overburden is divided into 20 equal horizontal layers, and the determined percent of the hard rock in each layer is shown in Fig. 5. Two layers with high percentages of hard rock strata (99% and 100%) are presented at 65 and 121 m (214 and 398 ft) below the ground surface.

### Table 2 Geological column of the overburden

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Thickness(m)</th>
<th>Depth(m)</th>
<th>Rock Type</th>
<th>Thickness(m)</th>
<th>Depth(m)</th>
<th>Rock Type</th>
<th>Thickness(m)</th>
<th>Depth(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Soil</td>
<td>4.3</td>
<td>4.3</td>
<td>Sandstone</td>
<td>12.7</td>
<td>78.1</td>
<td>Sandstone</td>
<td>0.6</td>
<td>159.4</td>
</tr>
<tr>
<td>Shale</td>
<td>15.0</td>
<td>19.4</td>
<td>Shale</td>
<td>4.1</td>
<td>82.1</td>
<td>Shale</td>
<td>1.2</td>
<td>160.6</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1.3</td>
<td>20.7</td>
<td>Coal</td>
<td>1.1</td>
<td>83.2</td>
<td>Coal</td>
<td>0.2</td>
<td>160.8</td>
</tr>
<tr>
<td>Shale</td>
<td>2.6</td>
<td>23.2</td>
<td>Shale</td>
<td>2.0</td>
<td>85.2</td>
<td>Shale</td>
<td>1.4</td>
<td>162.3</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1.8</td>
<td>25.0</td>
<td>Sandstone</td>
<td>5.5</td>
<td>90.7</td>
<td>Limestone</td>
<td>9.9</td>
<td>172.2</td>
</tr>
<tr>
<td>Shale</td>
<td>4.0</td>
<td>29.0</td>
<td>Limestone</td>
<td>0.7</td>
<td>91.4</td>
<td>Shale</td>
<td>1.2</td>
<td>173.4</td>
</tr>
<tr>
<td>Coal</td>
<td>0.5</td>
<td>29.5</td>
<td>Shale</td>
<td>3.5</td>
<td>94.9</td>
<td>Limestone</td>
<td>2.3</td>
<td>175.7</td>
</tr>
<tr>
<td>Shale</td>
<td>9.9</td>
<td>39.4</td>
<td>Sandstone</td>
<td>15.9</td>
<td>110.8</td>
<td>Shale</td>
<td>1.1</td>
<td>176.8</td>
</tr>
<tr>
<td>Sandstone</td>
<td>3.2</td>
<td>42.6</td>
<td>Shale</td>
<td>2.1</td>
<td>112.9</td>
<td>Limestone</td>
<td>0.6</td>
<td>177.4</td>
</tr>
<tr>
<td>Shale</td>
<td>1.9</td>
<td>44.5</td>
<td>Limestone</td>
<td>3.1</td>
<td>116.0</td>
<td>Shale</td>
<td>5.0</td>
<td>182.3</td>
</tr>
<tr>
<td>Coal</td>
<td>0.3</td>
<td>44.8</td>
<td>Sandstone</td>
<td>2.0</td>
<td>118.0</td>
<td>Coal</td>
<td>0.1</td>
<td>182.4</td>
</tr>
<tr>
<td>Shale</td>
<td>3.8</td>
<td>48.6</td>
<td>Shale</td>
<td>1.8</td>
<td>119.8</td>
<td>Shale</td>
<td>0.2</td>
<td>182.6</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1.1</td>
<td>49.7</td>
<td>Limestone</td>
<td>14.7</td>
<td>134.5</td>
<td>Coal</td>
<td>0.4</td>
<td>183.0</td>
</tr>
<tr>
<td>Shale</td>
<td>9.5</td>
<td>59.3</td>
<td>Shale</td>
<td>2.1</td>
<td>136.6</td>
<td>Shale</td>
<td>3.2</td>
<td>186.2</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.6</td>
<td>59.9</td>
<td>Limestone</td>
<td>10.5</td>
<td>147.1</td>
<td>Coal</td>
<td>0.2</td>
<td>186.4</td>
</tr>
<tr>
<td>Shale</td>
<td>1.0</td>
<td>60.9</td>
<td>Shale</td>
<td>8.9</td>
<td>156.0</td>
<td>Shale</td>
<td>0.1</td>
<td>186.5</td>
</tr>
<tr>
<td>Coal</td>
<td>0.4</td>
<td>61.3</td>
<td>Coal</td>
<td>1.7</td>
<td>157.7</td>
<td>Coal</td>
<td>2.3</td>
<td>188.9</td>
</tr>
<tr>
<td>Shale</td>
<td>4.1</td>
<td>65.4</td>
<td>Shale</td>
<td>1.1</td>
<td>158.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The program determines the final subsidence parameters for each layer based on the proposed empirical equations. The profiles of the predicted final subsurface subsidence on the top surface of the layers are plotted in Fig. 6. In the plotting, the vertical subsidence is exaggerated by 10 times so that the displacements can be visually observable. The percentage of the hard rocks in each layer is also plotted beside the predicted subsidence. Due to the symmetrical features of the subsidence profiles, only the subsidence profiles over one half of the longwall panel are plotted in the figure. It shows that the subsidence profiles formed at all layers exhibits the super-critical nature with a flat basin bottom. This agrees well the high width/depth ratio of 2.34 which is significantly higher than the width/depth ratio of value 1.2 for a critical subsidence basin in the same region. Figure 6 also shows that the flat bottom portion in a lower layer is wider than that in an upper layer as expected. Though not very easily discernible from the plot, there is a significant differential subsidence a strong layer and its underlying weak layers.

![Diagram](image)

**Figure 5** Percent of hard rock in the overburden layers
In order to calibrate the subsurface subsidence prediction model, the data from three extensometer monitoring holes drilled over the longwall panel have been collected. Extensometers have been used in various research projects to measure the lowering of the subsurface strata in relation to the ground surface. With the measured surface subsidence at the top of the extensometer borehole, the subsurface subsidence along the borehole at different strata levels above the mined coal seam can be determined. The general information about each of the data collection sites is shown in Table 4. The three sites were located at the panel edge, at a quarter of panel width to the edge and at the panel center, which are about 0 m (0 ft), 106.7 m (350 ft) and 213.4 m (700 ft) from the panel edge respectively. In each borehole, 18 anchors were installed in different levels over the coal seam. The lowest anchors were located about 64.6 m (212.0 ft) above the coal seam while the uppermost anchors were located about 178.0 m (584.0 ft) from the mining level.

The borehole extensometer monitoring results were analyzed in comparison with the prediction results from the new subsurface subsidence prediction program. Due to some installation problems and adverse strata movements, the section 1 of borehole 1 and section 1, 2 of borehole 2 were damaged, and the results were unreliable. The comparison of the final subsurface subsidence prediction results and borehole extensometer monitoring results were shown in Table 4. The errors of prediction are also listed in this table. It shows that the final
surface subsidence prediction for the three borehole locations matches the borehole extensometer monitoring results well.

### Table 3 Subsurface subsidence monitoring site anchor locations*

<table>
<thead>
<tr>
<th>Anchor Number</th>
<th>Borehole 1</th>
<th>Borehole 2</th>
<th>Borehole 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>17</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>16</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>15</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>14</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>13</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>12</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>11</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>10</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>9</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>8</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>7</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>6</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>5</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>4</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>3</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>2</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
<tr>
<td>1</td>
<td>0.122</td>
<td>0.210</td>
<td>0.206</td>
</tr>
</tbody>
</table>

*Vertical distance above the coal seam, m

### Table 4 Comparison of subsurface subsidence prediction and field monitoring results

<table>
<thead>
<tr>
<th>Anchor Number</th>
<th>Borehole 1</th>
<th>Borehole 2</th>
<th>Borehole 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>17</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>16</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>15</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>14</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>13</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>12</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>11</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>10</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>9</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>8</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>7</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>6</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>5</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>4</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>3</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>2</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
<tr>
<td>1</td>
<td>0.210</td>
<td>0.210</td>
<td>0.210</td>
</tr>
</tbody>
</table>
To calibrate the subsurface dynamic subsidence prediction model, the measured subsurface subsidence and surface subsidence at the location of borehole 3 is plotted against the distance that the longwall face has passed the extensometer boreholes in Fig. 7. The subsidence process at all the subsurface and surface points develops when the face is about 27.4 m (90 ft) inby the borehole location. Then the subsidence process accelerated before the longwall face reached a distance between 12.2 and 18.3 m (40 and 60 ft) outby the borehole locations. Figure 3.14 also shows that the lower level strata subside earlier and more than the upper strata.

![Figure 7 Subsidence development curves at borehole 3](image)

This case shows that the subsurface subsidence prediction model is accurate. As any methods to study the subsurface ground control problems associated with large-movement and large-deformation, the first step of success is to obtain accurate information about the ground movements. After that accurate deformations in the subsurface strata can be obtained from the predicted movements by using proper differentiation techniques.

Figures 8 and 9 show the contour plots of the predicted final vertical and total strain, respectively. Because of the differential strata movements in both horizontal and vertical directions, deformations are induced in the subsurface strata. In these plots, the strain distribution, especially that of the total strain, changed the patterns considerably in the level with harder rock layers at the depths of 65 and 121 m (214 and 398 ft). The presence of the thick hard rock layers will reduce the peak total strains above them but spread them in a larger area.
Figure 8 Contour plot of final subsurface vertical strain above the longwall panel

Figure 9 Contour plot of final subsurface void intensity above the longwall panel
METHODS TO STUDY DIRECT MSM INTERACTIONS

As mentioned in the previous section, the large-movement and large-deformation induced MSM interactions can be in the direct form causing failure of mine structures. This type of interactions can affect mining operations, and in severe case can induce coal bumps as a serious safety hazard. For example as shown in Fig. 10, Stemple (1956) reported that the most common phenomenon observed in the upper seam mining operation affected by lower seam mining was cracking or horizontal parting of the overlying strata. The upper seam was often displaced vertically from a fraction of an inch to as much as a few feet. This bed separation caused either the floor to drop away from the coal or the coal to separate from the roof. Other disturbances caused by the extraction of the lower seam were roof falls, floor heaves, and pillar crushing or squeezing, which may be observed with single seam mining but are aggravated by overmining. Stemple also noted that maximum disturbance in the upper seam was generally observed when isolated pillars, groups of pillars, or solid coal (barrier pillars, chain pillars) were left in the lower seam. This caused the upper seam to shear along the coal line in the lower seam. However, Stemple reported that the maximum damage area often did not lie immediately over the edge of the coal but at a distance of 100 to 300 feet away, on the gob side.

Figure 10 Disturbance in a superjacent seam (Stemple, 1956)
The severity of MSM interactions heavily depend on the interburden characteristics, mining sequence, seam heights and mining methods applied, time interval between the mining activities in neighboring seams and sometimes local topographic and hydrographic features. Among these factors, the interburden characteristics are the most critical factors in determining the potential for severe MSM interactions. The interburden characteristics include thickness, rock type, the number of layers and percentage of hard rock. Within the interactive distance, typically about 10 times of the mining height in the lower seam, interburden thickness determines the intensity and types of interaction. The intensity of the MSM interaction generally is inversely proportional to the thickness of the interburden. Strata in the interburden that have high elastic modulus, such as sandstone and limestone are stiffer and tend to bridge. Therefore, the interactive distance decreases with increasing percentage of hard rocks (i.e., sandstone and limestone) in the interburden.

Typical surface and subsurface subsidence formed over a full or high extraction panel is shown in Fig. 11. The major strata deformations occur in a zone with it outer limit defined by the angle of draw and inner limit by an angle of full subsidence. The major influence zone is also divided by the line of inflection point that is actually located over the mined-out panel. In the part of major influence zone outside the line of inflection point, the overburden strata are subject to tension. Inside the line of inflection point, the ground is in compression.

![Diagram of subsidence](image.png)

Figure 11 Formation of subsidence trough above mined-out panel (Haycocks et al., 1982)
Method to Assess Overall MSM Interactions

A multi-seam mining interaction analysis software program, UGLY (Upper seam Gateroad Longwall Stability), was developed by Luo et al., (1997) and Kaniganti, (1996) to determine the amount of damage in the upper seam when the lower seam had been mined out previously. The program is applicable to both room-and-pillar mining and longwall mining. The damage rating is defined by

$$DR = 1.69 \left[ \frac{3m_{\text{lower}}(HR)h}{H_{\text{in}}} \right]^{0.05} e^T 0.07$$

where, $DR$ - damage rating
$m_{\text{lower}}$ - lower seam mining height.
$h$ - overburden thickness (ft).
$H_{\text{in}}$ - interburden thickness (ft).
$HR$ - percentage of hard rock in interburden (%).
$e$ - extraction ratio of lower seam.
$T$ - time delay between mining of the upper and lower seams (year).

The expected mine damages for the determined damage rating are shown in Table 5.

<table>
<thead>
<tr>
<th>Damage Rating</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.12 -- No Damage</td>
<td>Normal conditions; conditions no worse than mining in undisturbed areas.</td>
</tr>
<tr>
<td>1.56 -- Negligible Damage</td>
<td>Fractures present in upper seam, but no associated roof problems; no displacements; no difficulty of mining due to the lower seam extraction.</td>
</tr>
<tr>
<td>2.00 -- Moderate Damage</td>
<td>Fractures with visible movement; occasional broken roof and/or coal; water entering; mined with minimum or no extra support.</td>
</tr>
<tr>
<td>2.44 -- Considerable Damage</td>
<td>Roof problems encountered; seam broken; some bottom heaves and pillar spalling; mined with increased timber support and slate work; occasional loss of coal.</td>
</tr>
<tr>
<td>2.88 -- Severe Damage</td>
<td>Major roof problems encountered; entire entry caved; bottom heaved; top broken; coal crushed or cut out; mined with heavy support or certain amount of coal lost.</td>
</tr>
<tr>
<td>3.32 -- Very Severe Damage</td>
<td>Coal abandoned; mining too dangerous or too costly to continue; large amount of coal lost.</td>
</tr>
</tbody>
</table>
Pillar Stability under MSM Influence

The stability of a mine pillars located in the subsidence zone caused by mining in the underlying coal seam could be affected. The subsidence in the overburden strata not only changes the loads on the pillars and but also the pillar strength. This section provides the methods to link the predicted subsurface deformations to the pillar load and strength.

Pillar Load Determination

Change in the pillar load can be related to the differential subsidence between the roof and floor line of the pillar, or the vertical strain. The pillar load under the influence of subsurface subsidence, \( \sigma_p' \), can be estimated by the following equation. In this equation, \( \sigma_p \) is the pillar load prior to the subsurface subsidence influence which is normally determined using the tributary load method, \( E_c \) is the Young’s modulus of the coal pillar, and \( \varepsilon_v \) is the subsidence-induced vertical strain at the location of pillar which can be predicted using the subsurface subsidence prediction model.

\[
\sigma_p' = \sigma_p - E_c \cdot \varepsilon_v
\]  

(11)

Pillar Strength Determination

The strength of a coal pillar increases with the confinement pressure that is subject to. In single seam mining sitting, the pillar confinement is reflected by the pillar width \( W_p \) to height \( H_p \) ratio. The pillar strength in single-seam mining condition, \( S_p \), is estimated using the popular Bieniawski’s formula as shown in Eq. 12. For most US coal mines, a value of 900 psi is normally used for in-situ coal strength \( \sigma_1 \) in Eq. 12. Smaller \( \sigma_1 \) values are used for some special cases. For example, if the overburden cover is small, \( \sigma_1 = 800 \) psi has been used by some mining companies when they are mining in shallow area. When mine floor is weak and water sensitive such as that in Illinois coal field, \( \sigma_1 = 600 \) psi is even used.

\[
S_p = \sigma_1 (0.64 + 0.36 \frac{W_p}{H_p})
\]  

(12)

Under the subsidence influence caused by an underlying mining operation, the confinement to the pillars can be further affected by subsidence-induced void intensity. Therefore, the pillar strength should be modified to consider the subsidence influence. Equation 13 is proposed to determine the pillar strength under the influence of subsurface subsidence, \( S_p' \). In this equation, \( \lambda \) is the pillar strength reduction factor and the method to determine it is discussed in the following section.
Multiple Mining Interactions Final Report

\[ S_p' = \lambda S_p \]  

(13)

In order to account for the effects of subsurface subsidence on the pillar strength, the Hoek-Brown failure criterion is adopted here to evaluate the pillar strength. The generalized Hoek-Brown (1997) failure criterion for jointed rock masses is defined by Eq. 14. The \( m_b \), \( s \) and \( a \) in this equation are material constants. In this equation, \( \sigma_1' \) and \( \sigma_3' \) are the major and minor effective principal stresses at failure, respectively. The \( \sigma_{ci} \) is the uniaxial compressive strength of the intact rock material.

\[ \sigma_1' = \sigma_3' + \sigma_{ci} \left( m_b \frac{\sigma_3'}{\sigma_{ci}} + s \right)^a \]  

(14)

When considering the strength of a pillar, it is useful to have an estimate of the overall strength of the pillar rather than a detailed knowledge of the extent of fracture propagation in the pillar. This leads to the concept of a global “rock mass strength” that could be estimated by the following Mohr-Coulomb relationship as proposed by Hoek and Brown Criterion 2002 (Hoek et al, 2002). In Eq. 15, \( c' \) is the cohesion and \( \phi' \) is the angle of internal friction.

\[ S_p = \frac{2c' \cos \phi'}{1 - \sin \phi'} \]  

(15)

Equation 15 can be further derived into Eq. 16 in the stress range of \( \sigma_1' < \sigma_3' < \sigma_{ci}/4 \). The relationship between \( k \) and the material constants (i.e., \( m_b \), \( s \) and \( a \)) are shown in Eq. 17. The pillar strength reduction factor, \( \lambda \), is shown Eq. 18.

\[ S_p' = k \sigma_{ci} \]  

(16)

\[ k = \frac{[m_b + 4s - a(m_b - 8s)](m_b / 4 + s)^{a-1}}{2(1 + a)(2 + a)} \]  

(17)

\[ \lambda = \frac{S_p'}{S_p} = \frac{k' \sigma_{ci}}{k \sigma_{ci}} = \frac{k'}{k} \]  

(18)

In Eq. 18 for the pillar strength reduction factor, the last part \( K'/K \) reflects the ratio of pillar strengths when the pillar is disturbed and undisturbed by subsidence from mining the underlying coal seam, respectively. The reduced material constant, \( m_b \), is a function of the material constant, \( m_i \) in the original condition, the rock’s geological strength index (GSI) and the degree of disturbance (\( D \)) as shown in Eq. 19. The coefficients \( s \) and \( a \) for the rock mass are determined by Eqs. 20 and 21, respectively.
\[ m_b = m_i \cdot e^{\frac{GSI-100}{28-14D}} \]  

(19)

\[ s = e^{\frac{GSI-100}{9-3D}} \]  

(20)

\[ a = \frac{1}{2} + \frac{1}{6}(e^{-GSI/15} - e^{-20/3}) \]  

(21)

In these equations, coefficient \( D \) is a factor reflecting the degree of disturbance to which the rock mass has been subjected by blasting damage and stress relaxation. It varies from 0 for undisturbed in situ rock masses to 1 for very disturbed rock masses. The significance of the parameters and their values can be found in a publication by Hoek (2004).

The Geological Strength Index (GSI) provides a system for estimating the reduction in rock mass strength for different geological conditions. The GSI takes into account of the geometrical shape of intact rock fragments as well as the condition of joint faces. For underground structures such as tunnels, slopes and mine openings that are easy to access and observe the geological conditions, the GSI is determined using the method proposed by Hoek and Brown (1997). However, in this research, the geological conditions of the subsurface structures under the disturbance of the subsurface subsidence are very hard to be observed directly. The subsurface total strain in the rock mass can be considered as a mining-induced geological condition of the rock mass. An empirical formula is established here to estimate the GSI for the subsurface structures based on the subsurface total strain (\( \varepsilon_t \)) distribution.

\[ GSI = 75 - 0.95(\varepsilon_t \cdot 10^3) \]  

(22)

In order to calibrate the empirical formula, numerical simulations are also performed. The Fast Lagrangian Analysis of Continua (FLAC) program package, capable for elasto-plastic analysis of rock excavations with strain softening using the linear Mohr-Coloumb failure criterion, is used in the simulation. A FLAC3D model is developed to study the coal pillar strength under the influence of subsurface subsidence. The model consists of 8 ft coal seam, 30 ft thick roof strata and 36 ft thick floor strata as shown in Fig. 12. The 20-ft entry and crosscut are used in the modeling.

Elastic perfectly plastic Mohr-Coulomb model is assigned for the rock strata. Strain softening Mohr-Coulomb model is assigned for the coal seam. Roller boundary conditions were assigned along the sides and bottom of the model. In order to establish the peak load for the pillar to carry, the velocity of the vertical displacement on top of the model is fixed at a constant value of \(-1\times10^{-5}\) ft/sec. The sum of the reaction forces at the base of the model is obtained via a FISH function (Itasca, 2006) to estimate the average vertical stress developed in
the pillar. Four pillar widths of 24, 40, 56, and 80 ft reflecting the pillar width to height ratio (W/H) of 3, 5, 7 and 10 are simulated. The resulting stress strain relationships are plotted in Fig. 13.

![3D discretized view of quarter pillars](image)

**Figure 12** 3-D discretized view of quarter pillars (W/H=5)

![Stress strain curves under different W/H ratios](image)

**Figure 13** Stress strain curves under different W/H ratios

In order to simulate the subsurface subsidence effect on the pillar strength, the horizontal and vertical strains are simulated by applying the displacements on the side and the
top of the model respectively at a constant value of \(-1 \times 10^5\) ft/sec. Different subsurface deformation values are simulated with this model. The numerical simulation results are compared to the results of the previous analytical model (Eq. 13) for validation purpose in Fig. 14. It shows the proposed pillar strength formula to consider the subsurface subsidence effects agree well with the numerical simulation results.

![Graph showing comparison between pillar strength formula and FLAC modeling results](image)

**Figure 14** Comparison between proposed pillar strength formula and FLAC modeling results

Figure 14 shows that the pillar strength would decrease with the confinement pressure that is related to the increased void intensity caused by the subsurface subsidence process. However, the formula derived based on the Hoek-Brown (1997) failure criterion for jointed rock masses to link the subsurface void intensity to the pillar strength (Eq. 13) is complicated to use. For simplicity and accuracy, Eq. 23 is proposed to determine the pillar strength under multi-seam mining influence. In this equation, \(\varepsilon_t\) is the total strain, \(S_p\) is the strength of the pillars without multi-seam mining influence, \(S'_p\) is the strength of the pillars with multi-seam mining influence. The strength reduction coefficient, \(a\), can be determined based on regression studies of case data, it is recommended to be in the range of \(-30\) to \(-10\) for the coal mines in the eastern US.

\[
S'_p = S_p e^{a\varepsilon_t}
\]  \hspace{1cm} (23)

**Pillar Stability Factor**

The pillar stability factors under multi-seam influence, \(SF'\), defined by Eq. 24, can be assessed based on the determined pillar load (\(\sigma'_p\)) and pillar strength (\(S'_p\)). If the pillar stability
factor under the disturbance of mine subsurface subsidence is less than a critical value, the pillar could fail. Based on the published investigation cases (Morsy et al., 2006; Mark and Barker, 2012), it is proposed that a critical stability factor for pillars to fail in a large area is 1.0. When the failure of the pillars occurs in a sufficiently large contiguous area, it could induce additional subsurface and surface subsidence other than that caused by the active mine alone.

\[
SF' = \frac{S'}{\sigma_p}
\]  

(24)

Roof Stability under MSM Influence

Roof falls have been the No. 1 safety threat to underground miners. Common roof falls in coal mines are resulted from roof tensile failures and roof cutters. Except for the geologic effects, the induced stress by surface sharp valley and multi-seam mining is the main cause of roof instability (Moebs and Stateham, 1986). In multi-seam mining operations, when an underground coal mine is affected by mining activities conducted in the underlying coal seam, the originally stable mine roof could become unstable. Roof tension cracks could be induced in zones with high tensile strain (Fig. 15). Roof cutters are more likely to occur in zones with high shear stress at the corner of the mine entries. Roof tension cracks and cutters do not always lead to roof falls. Many roof tension cracks and cutters stayed the same throughout the whole entry/crosscut life as they were found, while others progressed to various stages and stopped. The rate of propagation of tension cracks and cutters from stage to stage also varies (Peng, 2007).

Figure 15 Roof cracks caused by MSM interactions and standing supports employed
MSM Influence to Roof Cracks

The changes of the strains on the roof of the upper seam panels caused by subsurface deformations can be predicted by the previous described subsurface subsidence prediction model. The predicted horizontal strain, instead of commonly stress, of the roof rock strata can be used to assess the stability of the roof. Based on the numerous subsidence cases, a tensile strain higher than $2 \times 10^{-3}$ ft/ft is normally capable of causing hairline cracks in the immediate mine roof if it is made of shale type rock (Luo and Qiu, 2012b). Table 6 shows the physical and mechanical properties of four common coal measure rocks. The tensile strain at failure for two types of rocks, sandstone and mudstone, are shown in the last column of the table. It should be noted that the maximum subsurface tensile strain can easily exceed the critical strains. Therefore, similar to subsidence damages to surface structures, subsurface tensile strain caused by mining in underlying coal seam should also be the No. 1 causes to roof falls. Once hairline cracks are developed in the mine roof, adequate efforts should made to prevent the cracked roof from potentially developing into massive roof falls.

Table 6 Physical and Mechanical Properties of Coal Measure Rocks in Dry Condition (Zhao)

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>Dry Density, lbs/ft$^3$</th>
<th>UCS Strength, psi</th>
<th>Tensile Strength, psi</th>
<th>Young's Modulus, psi</th>
<th>Poisson's Ratio</th>
<th>Strain at Failure, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>max</td>
<td>Min</td>
<td>max</td>
<td>Min</td>
<td>max</td>
</tr>
<tr>
<td>Sandstone</td>
<td>119</td>
<td>161</td>
<td>2,900</td>
<td>24,650</td>
<td>580</td>
<td>3,625</td>
</tr>
<tr>
<td>Shale</td>
<td>125</td>
<td>150</td>
<td>725</td>
<td>14,500</td>
<td>290</td>
<td>1,450</td>
</tr>
<tr>
<td>Mudstone</td>
<td>113</td>
<td>168</td>
<td>1,450</td>
<td>14,500</td>
<td>725</td>
<td>4,350</td>
</tr>
<tr>
<td>Limestone</td>
<td>167</td>
<td>170</td>
<td>4,350</td>
<td>36,250</td>
<td>870</td>
<td>3,625</td>
</tr>
</tbody>
</table>

MSM Influences to Cutter Roof

It is clear that the cutter roof problems normally developed at the pillar-roof corner areas are caused by high shear strain. Despite of numerical modeling attempts, reliable methods to assess the potential and severity of roof cutter problems are yet to develop. Using the subsidence theory approach, the compressive type of total strain or a new deformation term derived from the predicted subsurface movements, added with location and property of mine pillar, could be a good indicator for MSM induced roof cutters. However, additional research should be conducted to study the mechanism and develop the method for assessing cutter roof potentials when MSM interactions are involved.

Floor Stability under MSM Influences

The mine subsidence caused by the extraction of the underlying coal seam could also destabilize the floors of the mine entries in the upper seam mine operations. Unstable mine
floors are mainly shown in floor cracks in high tension and high convex bending zones and floor heaves in high compression zones.

**MSM Influences to Mine Floor Cracks**

The mechanism for strata subsidence to cause floor cracks should be similar to that cause roof crack, that is, the subsidence-induced tensile strain could cause cracks in mine floor if the tensile strain is larger than the critical strain for the floor rock. It should be noted that the maximum tensile strain induced by full or high extraction mining operation in underlying coal seam is generally full capable of creating floor cracks. The subsidence-induced curvature could also cause cracks on brittle floor rock layer. Since the point of maximum tensile strain ($\varepsilon_{h, \text{max}}$) and the point of maximum convex curvature ($k_{\text{max}}$) induced by a subsidence event generally occur at the same point, the maximum strain on the top surface of the floor layer ($\varepsilon_{\text{max}}$) can be determined by Eq. 25. In the equation, $b$ is the thickness of the rock layer. The resulting maximum strain can be checked against the tensile strain at failure shown in Table 6.

$$\varepsilon_{\text{max}} = \varepsilon_{h, \text{max}} + \frac{b}{2} k_{\text{max}}$$

(25)

When the floor cracks are large and deep enough to connect any pressurized water and gas sources in underlying abandoned coal mines or reservoirs, sudden release of gas and/or water from these sources could occur. In such cases, hazardous conditions could be induced by indirect MSM interactions. The size and distribution of these floor cracks depend on the tensile strains on the floor strata and the geological properties.

**MSM Influences to Mine Floor Heave**

For mining in single coal seam, two common types of mine floor heaves are encountered both involving soft and weak floor strata as shown in Fig. 16. In the first type, the immediate mine floor is made up with thick weak strata such as weak shale or claystone. The weak floor, being a low modulus material, could result in “hump-like” floor heaves under high compressive total strain and high pillar load.

However, if a relatively thin layer of strong immediate mine floor, such as sandstone and limestone, sits on thick weak and soft strata, a “buckling” type floor heave may result (Matetic et al., 1987). Under the compressive total strain and pillar load, the underlying soft strata would flow toward the less confined area of mine entry. The harder surface rock layer above the deformed soft strata can be easily bent and broken in area with convex curvature.
The subsidence-induced compressive type of total strain could further intensify the floor heave problems. Though severe floor heaves could cause significant problems to mining operations, they rarely create conditions hazards to mine safety. Therefore, the MSM induced floor heave problems are not discussed in details in the report.

**STUDIES OF INDIRECT MSM INTERACTIONS**

In the second type or indirect Interactions, subsidence-induced fracture zones in the interburden strata connect the active mine to old mine workings or previously sealed mines. In such case, leakage paths are formed for water, gases and air to flow between the old mine and active mine. More severe safety problems than the problems caused by direct MSM
interactions, such as water inundations, sudden methane inrushes, and spontaneous combustions, can occur. These problems can seriously disrupt mining operations and threaten the safety of miners.

**Interburden Stability**

In both undermining and overmining cases, the previously mined gob could be flooded or filled with explosive gases. The mine subsidence caused by the full or high extraction mining in the lower seam could induce zone of fractures in the interburden near panel edges. The connected fracture zone between the mined coal seams induced by subsurface subsidence process could channel the accumulated methane or water in the sealed mine areas to rush into the active working to create a hazardous condition. The flow rate of water and/or gases depends mainly how permeable these zones of fractures are to the water and gases. Since the subsurface subsidence prediction model can predict the magnitude and distribution of various subsurface deformations, the model can be used to guide mine design to avoid excessively disturbed zones and to plan ahead of any mitigation measures to minimize such influences.

The subsurface subsidence process produces localized deformation zones in the interburden strata. For example, a zone of expansive total strain (void intensity) will be created in the interburden near the edge of the panel on each side. The maximum void intensity at a given level above the mine gob is located a short distance inside the panel edge. Separated by the neutral zone, a zone of compressive total strain will be located further inward from the expansion zone. Depending on size of the panel, the total strain in the interburden over the central portion of the panel could vary from minor expansive at the lower level to minor compressive at upper level. In the zones of expansive total strain, the permeability of the interburden strata to gas and water flows will increase, whereas, the permeability will decrease in the compression zones. Potential leakage paths for water and/or gas due to significantly increased permeability are formed in contiguous zones with sufficient expansive total strain. Therefore, the main effort for studying the indirect MSM interactions is concentrated on to link the predicted subsurface strata deformations to the changes in permeability. The following equation has been derived to evaluate the subsurface subsidence influence on the permeability change in the interburden strata (Qiu and Luo, 2013).

\[
K = K_0 \left( \frac{1 + \epsilon_f}{\phi_0} \frac{\phi_0}{1 + \epsilon_i} \right)^3
\]

(26)

where, \( K \) - rock permeability under subsidence influence.
$K_0$ - rock initial permeability without subsidence influence.
$\varepsilon_t$ - total strain caused by mine subsidence.
$\phi_0$ - initial porosity of the rock.

**Case Demonstrations**

Two cases involving mining operations in closely spaced two coal seams are shown in this section to demonstrate the methodology and capability to apply the subsurface subsidence prediction in studying the MSM interactions. A program based on the subsurface subsidence prediction model and MSM interactions, CISPM-MS, is applied in these cases to facilitate the computations involved.

**Case Demonstration No. 1**

In this case, the program CISMP-MS is used to simulate the mechanisms involved in the damages to subsurface mine structures and to surface structures in a multi-seam mining case as shown in Fig. 17.

![Figure 17 Spatial relationships among surface structures and mains in the mines in the Sewickley and Pittsburgh Seams](image)
In the case, the active mine was in the upper Sewickley coal seam and an abandoned coal mine was in the lower Pittsburgh coal seam. The interburden between the two seams was about 27.4 m (90 ft). The Pittsburgh seam had been mined in the 1960’s using the room and pillar method and closed afterwards. Pillars in a portion of mine were extracted as shown in Fig. 17. The boundary between the pillared area and the area with development mining only in the Pittsburgh seam are also shown in this figure. To protect an active gas well, a large support area was left in the Pittsburgh coal seam. The irregularly shaped support area was about 76.2 m (250 ft) long and 45.7 m (150 ft) wide. The contour lines of the floor elevation in the lower seam are also plotted in Fig. 17. The coal seam dipping direction is toward the west.

The active room and pillar mine in the upper Sewickley coal seam was developing its main entries as shown in Fig. 17. The spatial relationship between the two residential structures (a house and a workshop) is also shown in the figure.

Based on the mine closure agreement, the mine water level in the abandoned mine in the lower seam was continuously monitored even it had been closed. When the mine water level reached the area passing the large support area for the gas well, severe damages of mine structures occurred in the active mine and damages were observed on the two surface structures.

On the ground surface, a ground crack and a depression zone were observed near the surface structures. Underground observations made in the active mine indicate that rib spall and cutters are more prevalent in the area around the boundary line between pillared and unpillared areas in the Pittsburgh seam. Massive roof falls were observed in the entries in the active mine appeared to coincide with the edge of the support pillar area with the west end of the roof fall extended further away from the support area.

In order to study the subsurface subsidence effects of the Pittsburgh seam on the Sewickley seam mine pillars and entries, predictions are performed along the cross-section A-A’ and in a rectangular area of BCDE as shown in Fig. 17. The predicted subsurface subsidence and subsurface void intensity distribution in the Sewickley seam in the specified rectangular area of BCDE are plotted in Figs. 18 and 19, respectively. The subsurface subsidence along the prediction line A-A’ at the Sewickley seam around the support pillar area of the Pittsburgh seam is predicted using CISMP-MS and the results are shown in Fig. 20. It is assumed that the weak mine roof strata immediately above the Pittsburgh coal seam was considerably weakened and caused failure of the remnant pillars in the pillared area. In the prediction, the failure of the remnant pillar in large area was the cause of the ground subsidence.
Figure 18 Predicted subsurface subsidence in the Sewickley seam in rectangular area BCDE

Figure 19 Predicted subsurface void intensity in the Sewickley seam in rectangular area BCDE
Using the methods developed previously, the subsurface subsidence prediction indicates that the subsurface deformation can reduce the average safety factor of mine pillars in the upper Sewickley seam by 11.68%. The original pillar safety factor for the Sewickley seam mine was about 8.56 supposedly for the long stability of the main entries. With the subsidence induced reduction, the pillar safety factor under the subsurface subsidence influence is still 7.56. This finding agrees well with fact that no pillar failure had been observed in the active mine. This strongly suggested that the mining operation in the Sewickley seam is not the cause for the reported surface subsidence events. However, the reported subsidence events and the mine structure failures were strongly related with the moving water front in the Pittsburgh seam.

As shown in Figure 20, the maximum strain of the mine roof in the Sewickley seam at the location near the edge of the support pillar is 1.96×10⁻² m/m (for t/ft). This is significantly higher than the proposed critical tensile strain for roof cracking, 2×10⁻³ m/m (ft/ft) and more than sufficient to cause the roof failure in the active mine. Figure 19 shows the most of the observed massive roof falls (in cross hatch pattern) and roof cracks in the active mine in the Sewickley coal seam are located in the zones of high void intensity.
Case Demonstration No. 2

The site of the second case study was not too far away from the one in the first case. Again, the lower Pittsburgh coal seam was mined previously using longwall mining method in the late 1980’s (about 14 years before this investigation). Room and pillar mining method was conducted in the upper Sewickley seam. The interburden was about 25.9 m (85 ft). Significant ground control problems were encountered in the upper seam mine in areas affected by previous longwall subsidence.

In the active mine in the Sewickley seam, the main entry system was consisted of 8 entries when it was at the right side of the Pittsburgh seam longwall panel, and were consisted of 6 entries when it was above and at the left side of the Pittsburgh seam longwall panel (Fig. 21). The pillars used in the mains were 18.3 m (60 ft) wide and 18.3 to 36.6 m (60 to 120 ft) long. The pillars used in the panels were 13.7 m × 24.4 m (45 ft × 80 ft). Entries and cross-cuts were 5.5 m (18 ft) wide. The overburden above the Sewickley seam in the studied area ranges from 121.9 to 243.8 m (400 to 800 ft). The thickness of Sewickley seam was 1.5 m (5 ft).

![Figure 21 Mine layout and topographic map at study site](image)

In the longwall mine in the lower seam, the thickness of the Pittsburgh seam was 2.4 m (8 ft). At the study area, 3-entry gateroad system (stiff-yield) pillar design was implemented for the Pittsburgh seam longwall panel gateroad where the stiff pillar dimensions were 21.3 m × 51.8 m (70 ft × 170 ft) while the yield pillars were 10.7 m × 19.8 m (35 ft × 65 ft). Entries and
crosscuts were 6.1 m (20 ft) wide. The panel width was 172.5 m (566 ft) wide. Two barrier pillars of 23.8 m (78 ft) and 73.2 m (240 ft) wide were left to separate the longwall panel from the right and left side room-and-pillar panels in the Pittsburgh seam respectively. The room-and-pillar section utilized an 8-entry mains system for Pittsburgh seam (Fig. 21). The pillars used in the room-and-pillar panels were 10.7 m × 19.8 m (35 ft × 65 ft). Entries and cross-cuts were 4.9 m (16 ft) wide.

Figure 22 shows a representative geological column at the study site. The inter-burden between Sewickley and Pittsburgh seams was composed of shaly limestone, sandstone and limestone. These strong rocks represent about 41% of the inter-burden. The immediate roof and floor of Sewickley seam were gray shale of 0.5 m (1.76 ft) and 0.4 m (1.4 ft), respectively.

A site investigation was conducted to observed the mine structural failures in the active mine. The field investigation started at intersection #2326 (Fig. 5.15) where the upper seam mains starts to change direction and passes over the lower seam longwall panel. Going inby the mains from intersection #2326 to intersection # 2790, some water came out of the left side rib of entry No. 1. Near the intersection #2326, it was obvious that the entry was dipping downward towards inby the mains (Fig. 23). Based on the measurements, the subsidence of the entries in the Sewickley seam started to dip towards Pittsburgh seam mine gob at about 16.8 m (55 ft) from the panel edge. The roof was bended obviously due to the subsidence caused by the longwall mining in the Pittsburgh seam. At the high tension zone of the subsidence trough, “V” shape cracks were formed on the shoulder of the entries (Fig. 24). Near the intersection of #2358, we were informed by the mine operator that there was a small area of roof fall that occurred in 2008.

![Figure 22 Geological column at study site](image-url)
Figure 23 Subsidence downhill from right to left

Figure 24 Cracks caused by subsidence induced tension
Near the intersection #2364, the floor was dipping upward and it went uphill on solid at about 41.8 m (137 ft) from the panel edge. The investigation ended at the intersection #2790 and switched to the belt entry to go backwards outby the mains. Additional investigations were conducted along this entry. The same subsidence induced roof and floor bend line was observed in the belt entry near the intersection #2365 (Fig. 25). Simultaneously, it was observed that the pillars at the left side of the belt entry were in depression, which was possible to cause pillar failure.

![Figure 25 Subsidence up dip in the belt entry](image)

The results of the field investigation for the mains in the Sewickley seam can be summarized in the following, and they are all marked on the mine map (Fig. 26).

- In the area that the Sewickley seam mains pass over the previously mined Pittsburgh seam longwall panel, more ground control problems occurred there than in other
areas.

- The subsidence caused by the Pittsburgh seam longwall mining induced the roof and floor bending of the entries of the Sewickley seam mains.
- Groundwater came out of the rib of the solid coal side of No. 1 entry.
- The pillars at the left side of the belt entry near the intersection #2365 were in depression, which was possible to cause pillar failure.

![Figure 26 Field investigation results at study site](image)

In order to study the subsurface subsidence effects of the longwall mining in the Pittsburgh seam on the Sewickley seam mine pillars and entries, predictions were performed along the cross-section A-A’ as shown in Fig. 21. The predicted subsurface vertical strain and subsurface void intensity distribution along the cross-section A-A’ are plotted in Figs. 27 and 28, respectively.
Figure 27 Subsurface vertical strain distribution along the cross-section A-A’

Figure 28 Subsurface void intensity distribution along the cross-section A-A’
In Figs 27 and 28, the strain distribution patterns, especially that of the void intensity, varied considerably in locations with harder rock layers overlying the weak layers at the depths of 46 and 122 m (150 and 400 ft), respectively. The presence of the thick hard rock layers will prevent high void intensity developed in the underlying weak layers from propagating directly upwards while spread them in a larger area. The Sewickley seam pillars C, D, G and H are located in the major influence zone of the subsidence basin, which are endangered by severe multi-seam mining interactions.

Table 7 shows the calculations of the stability factors of the pillars A to J at the Sewickley seam mains. And the stability factors of pillars A to J with/without multi-seam mining interactions are plotted in Fig. 29. Due to the longwall mining in the lower seam, the stability factors of pillars D and G were actually increased. This was because of the relief zone created above the longwall of the lower seam. However, the multi-seam mining had negative effects on the stability factors of pillars C, E, F and H. Especially for pillars C and H, the stability factors were reduced from 5.0 to 2.8 and from 5.1 to 2.4 respectively. Through significantly reduced by the multi-seam mining interactions, the stability factors were all still large enough to keep the pillars from failure, which agrees well with the underground observation that the pillars in the active mine were still intact.

**Table 7 Stability factors calculations of the pillars at the upper seam mains**

<table>
<thead>
<tr>
<th>Pillar No.</th>
<th>Dimensions</th>
<th>No Multi-seam Interaction</th>
<th>With Multi-seam Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L (m)</td>
<td>W (m)</td>
<td>h (m)</td>
</tr>
<tr>
<td>A</td>
<td>26.4</td>
<td>18.3</td>
<td>1.5</td>
</tr>
<tr>
<td>B</td>
<td>25.2</td>
<td>18.3</td>
<td>1.5</td>
</tr>
<tr>
<td>C</td>
<td>30.0</td>
<td>18.3</td>
<td>1.5</td>
</tr>
<tr>
<td>D</td>
<td>31.7</td>
<td>18.3</td>
<td>1.5</td>
</tr>
<tr>
<td>E</td>
<td>24.5</td>
<td>18.3</td>
<td>1.5</td>
</tr>
<tr>
<td>F</td>
<td>25.9</td>
<td>18.3</td>
<td>1.5</td>
</tr>
<tr>
<td>G</td>
<td>24.4</td>
<td>18.3</td>
<td>1.5</td>
</tr>
<tr>
<td>H</td>
<td>31.9</td>
<td>18.3</td>
<td>1.5</td>
</tr>
<tr>
<td>I</td>
<td>32.9</td>
<td>18.3</td>
<td>1.5</td>
</tr>
<tr>
<td>J</td>
<td>23.0</td>
<td>18.3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The entry between pillars C and D was located in the high void intensity zone (Fig. 28), where the multi-seam interaction would have had severe effects on the roof of this entry. The maximum strain of the mine roof in the Sewickley seam at the location near the edge of the support pillar was 4.24×10⁻² m/m. This was higher than the proposed critical tensile strain for roof cracking, 2×10⁻⁵ m/m and more than sufficient to cause the roof failure in the active mine. The roof support in this area should be stronger than other areas. This agrees also well with the field investigations that there was a roof fall that occurred at the crosscut between pillars C and D as shown in Fig. 26.
Assessment of MSM Interaction on Water Leakage

Using Eq. 26, the distribution of permeability after a subsidence process in the interburden strata can be determined using the predicted subsurface total strain. This piece of information is essential for any numerical simulation studies to quantify the subsidence influence on subsurface and surface water bodies. One example of studying longwall mining influences to a large surface water reservoir (Qiu and Luo, 2013) is shown in this section to demonstrate the application of this proposed approach though the case is not a MSM interaction case.

Mining operation in one longwall panel is planned to be conducted directly under the tail half of a large reservoir while its earth dam is located beyond the panel over the solid coal as shown in Fig. 30. The longwall panel width is 1,425 ft (434 m). The smallest overburden depth under the reservoir area is about 720 ft (219 m). One of the main concerns for this study is whether water leaked from the reservoir would affect the underground longwall operation. In the study, it is important to find whether contiguous highly-fractured zones will be formed in the overburden strata to connect the surface reservoir and the underground longwall gobs.

The provided core log information from a nearby geological exploration hole is shown in Fig. 31. It shows about 39 ft (12 m) of claystone and shale layer is located right below the reservoir bottom as shown in Fig. 31. After a 7.9-ft (2.4 m) sandstone layer, another 36 ft (11 m) of claystone layer follows. The next 150 ft (46 m) overburden strata contains claystone layers of

Figure 29 Stability factors of the pillars at the upper seam mains with and without multi-seam mining interaction
14, 10, 9 and 28 ft (4.3, 3.0, 2.7 and 8.5 m) thick. Therefore, the impermeable claystone layers account for about 58% of the top 230 ft (70 m) overburden strata. Two layers of sandstone (28 and 60 ft or 8.5 and 18.3 m thick) are located about 240 and 400 ft (73 and 122 m) below the bottom of the reservoir, respectively. It is also important to note that the presence of substantial limestone beds in the roof of the coalbed. From bottom up, the maximum height of the coal seam to be mined is 9.1 ft (2.8 m). Three limestone layers, 30, 120 and 8 ft (9.1, 36.6 and 2.4 m) thick, are located about 40, 90 and 250 ft (12, 27, 76 m) above the coal seam. The limestone is stiffer and stronger than the shale, claystone and siltstone strata.

Figure 30 The reservoir and the longwall panels under it
Using the new subsurface subsidence prediction model, the final movements and deformations in the subsurface strata are predicted. After substituting the predicted final void intensity into Eq. 26, the subsidence influence to the permeability of overburden strata under the reservoir can be determined and the results are plotted in Fig. 32. The bridging effect of the 120-ft (36.6-m) thick limestone layer located about 90 ft (27 m) above the coal seam is clearly shown in the figure. This thick competent rock layer considerably changes the distribution patterns of strata deformations and the permeability below and above it. The prediction shows that the maximum subsidence influence on the strata permeability at the bottom of reservoir is that the initial permeability will be doubled. A zone of high permeability increase occurred in the area a short distance inside the longwall panel edge.
In order to assess the possibility for the reservoir water to leak into the longwall gob in large quantity, a numerical simulation study has been conducted. As shown in Fig. 32, the most possible water leakage path is along the high permeability increase zone from the surface to the mine level near the panel edge. The numerical study will focus on assessing the possibility of the water leakage through this path. One half width of the longwall panel is selected for the numerical simulation. The 2-D numerical model consists of about 2,288 finite elements and simulates a 748 ft (228 m) in width and 738 ft (225 m) in depth of the overburden above the longwall panel as shown in Fig. 33. Element sizes varied, but were selected so that the element size was about 3 ft (0.91 m) in the zone of interest, near the panel edge. Element sizes increase with increasing distance from the area of interest.

In building the numerical model, the ground water elevation at mine gob was set to be zero, and the ground water elevation at surface equaled to the reservoir water elevation minus coal seam elevation (738 ft or 225 m). The vertical boundaries of the model are set to be impermeable. The actual overburden sequence has been simplified, combining lithological layers to represent rock characteristics of primary importance to obtain an average response.
Two numerical models were built to represent the pre-mining and post-mining conditions respectively.

![Figure 33 Post-mining vertical hydraulic permeability distribution over the longwall panel](image)

Figure 33 Post-mining vertical hydraulic permeability distribution over the longwall panel

Table 9 presents the initial hydraulic property of the coal measure rocks used in the numerical simulation, which is determined from published values (Esterhuizen, and Karacan, 2005). The hydraulic permeability of the overburden strata after mining is calculated based on the predicted final total strain distribution and the results are plotted in Fig. 33. It shows that a zone of high permeability is located in the sandstone strata between 200 and 300 ft (61 and 91 m) above the coal seam. The longwall subsidence induces high total strain and high permeability in area located near but inside the longwall panel edge. In this area, the zones with high permeability are limited within the 350 ft (106 m) from the coal seam. Above this
level, the subsidence influence to the permeability is insignificant due to much lower total strain and the low permeability of the claystone strata and thick silt at the bottom of the reservoir. The maximum vertical permeability after mining reaches 0.18 ft/day in the area directly above the longwall panel edge. However, the vertical permeability in most of the other areas is less than 0.09 ft/day.

Table 8 Initial hydraulic property of coal measure rocks

<table>
<thead>
<tr>
<th>Rock Types</th>
<th>Permeability (ft/day)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Horizontal</td>
<td>Vertical</td>
</tr>
<tr>
<td>Soil</td>
<td>2.74E-04</td>
<td>2.74E-04</td>
</tr>
<tr>
<td>Claystone</td>
<td>5.48E-04</td>
<td>5.48E-04</td>
</tr>
<tr>
<td>Shale</td>
<td>2.74E-03</td>
<td>1.37E-03</td>
</tr>
<tr>
<td>Coal</td>
<td>2.74E-03</td>
<td>2.74E-04</td>
</tr>
<tr>
<td>Limestone</td>
<td>5.47E-03</td>
<td>5.47E-03</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2.74E-02</td>
<td>2.74E-02</td>
</tr>
</tbody>
</table>

The distribution of the simulated post-mining ground water pressure head in reference to the mine level is plotted in Fig. 34. In the zone where the significantly increased permeability and water flow are induced by mine subsidence, the water head contour lines bent upward. It shows that the head at a point has decreased from its original level. The vectors of water flow velocity in the overburden strata after subsidence are also plotted in Fig. 34. The zone with higher flow velocities is located in a short distance inside the panel edge. Based on the simulation, the water leakage rate from the surface reservoir to the mine gob is about 1.42 ft³/day per foot (0.132 m³/day per meter) of distance along the panel longitudinal direction. From Fig. 12, the equivalent average width of the reservoir water surface along the panel longitudinal direction is determined to be 83.8 ft (25.5m). The daily water leakage from the reservoir to underground longwall gob is estimated to be 119 ft³/day (3.4 m³/day). For the underground mining operation, the increased in-flow of water (0.62 gallons/min or 0.0024 m³/min) to the mine from the surface reservoir is very insignificant to the mine pumping system. Therefore, the water leaked from the reservoir to the underground mine through the subsidence-disturbed overburden strata should not create a safety concern.

However, for mining operations conducted in closely spaced multiple coal seams with interburden smaller than 100 ft, the water leakage should be much large than that predicted in this case study. Therefore, the potential water leakage through the subsidence induced leakage paths could present very severe safety threat to mining operations in underlying coal seam.
It should be noted that the same approach could also be applied for overmining cases where active mine is laid over abandoned mines filled with pressurized mine water. The previous mining in the lower coal seam could have also created zones with high void intensity. If the underlying mine is not properly dewatered, the active mine in the upper seam could face the danger to be flooded.

The approach presented previously provides the means to quantitatively assess the indirect MSM interaction to water bodies. However, it is a very complicated process and may not be readily applied by many field engineers. An empirical approach can be also used to qualitatively assess the potential of significant water leakage in MSM cases. This approach
involves with the determination of a critical void intensity for significant water leakage. In other words, if a contiguous fracture zone with void intensity higher than the critical one can penetrate into the old water-filled mine, significant water leakage could pass through this zone. Luo and Peng (2010) analyzed the data from water pumping tests conducted over many Chinese longwall mines and found that a conservative critical void intensity for significant water leakage is $4.1 \times 10^{-2}$ ft/ft. The top location of this determined critical void intensity for US longwall mines agrees well with the reported heights of the top surface of fracture zone formed over a longwall gob. To use this simpler approach, the predicted total strain in the overburden strata using the new subsurface subsidence prediction model is plotted. From the total strain distribution map, the potential water leakage paths, bounded with the critical void intensity of $4.1 \times 10^{-2}$ ft/ft, can be delineated. If the paths connect the active and old mine voids, water leakage could form a safety hazard.

**Assessment of MSM Interaction on Gas Leakage**

Highly concentrated methane in sealed mine areas or abandoned mine overlying or underlying the active mine could become the most serious hazard to the mining operation if it can travel through the subsidence-induced fracture zones into active mine. The mechanism of the gas leakage through the interconnected leakage paths should be the same as that of water leakage. Again, the resulting void intensity from the subsurface subsidence prediction can be used to determine the distribution of the permeability in the interburden strata. However, it should be noted that the gas flows through the narrow leakage paths differently from water. The critical void intensity for delineating the gas leakage paths should be established. Practically, an unsafe mining condition is already formed once the active mine is connected to the mine space filled with high concentration methane. However, computational fluid dynamics (CFD) modeling should be performed to further quantify the gas flow rate and the time effects.

**Assessment of MSM Interaction on Spontaneous Combustion**

For coals with moderate to high propensity of spontaneous combustion, the subsidence-induced leakage paths allow mine air to enter from the active mine into the abandoned mine space. The paths will provide oxygen to the coal debris for oxidation but will prevent the generated heat from dissipating which forms an ideal condition for coal spontaneous combustion in the abandoned mine space. The smoldering or even flame fires in the abandoned mine space caused by spontaneous combustion can present serious mine safety problems to the active mines. There are many such spontaneous combustion cases in Chinese coal mines where mining operations are conducted in closely spaced multiple coal seams. A
large number of mine fire and explosion cases due to such MSM induced spontaneous combustion have occurred in Chinese coal industry. In the US, the propensity for spontaneous combustion of the coals in the central Appalachian coal fields, the area with most intensive multiple seam mining operations, is generally low and reported spontaneous combustion cases are rare. However, in the Western coal fields (Fig. 1), also an area with multiple seam mining operations, the propensity of spontaneous combustion is often moderate. The potential for MSM interactions to cause spontaneous combustion should be closely watched.

Again, the hazards of MSM induced spontaneous combustion is heavily related to the air leakage paths caused by mine subsidence. The method mentioned previously can also be directly applied to assess the potential for this type of indirect MSM interactions.

**CONCLUSIONS**

Direct and indirect interactions caused by mining operations in closely spaced multiple coal seams could produce much more ground control and mine safety problems them mining operations in single seam. This is evidenced by the fact that more frequent coal mine disasters have occurred in the central Appalachian coal fields where multi-seam mining (MSM) operations are intensely practiced than other US coal mining regions. Published and unpublished cases also show that operational difficulties caused by MSM interactions in this region are significantly more and severer. Due to the relatively maturity of mining technology in single seam settings, more mining research and regulatory efforts should be made to improve the mine safety in multiple seam mining conditions.

Due to much higher degree of privatization in mineral rights than other major coal producing countries, each of the US coal mines that operates in MSM conditions generally has its mining right limited to one single coal seam. Accordingly, a mine often designs the time and conducts its operations in single seam mining setting without full knowledge about and careful coordination with other past and current mining activities in the overlying and underlying coal seams. Therefore, the federal and state regulatory agencies should increase their roles: (1) to inform the mining companies involved about the past and current mining activities in the underlying and overlying coal seams, and (2) to check whether the potential MSM interactions have been fully considered in the submitted mine permit documents.

On technical research side, the MSM interactions can be classified into problems caused by load transfer or by strata subsidence. The load transfer MSM interactions are produced by the locally concentrated stress zones transferred from isolated remnant pillars in the neighboring coal seams. A good amount of research has been performed and some numerical-
modeling based design tools have been developed for dealing with the load transfer MSM interactions.

The full (longwall) or high (room and pillar with depillaring operations) extraction mining methods will induce subsidence in the overburden strata with significantly larger strata movements and deformations than those expected from load transfer MSM interaction cases. The subsidence process creates not only the direct MSM interactions to mine structures (i.e., mine pillars, roof and floor) but also the indirect MSM interactions to interburden strata. The indirect MSM interactions could potentially produce much more significant mine safety problems in terms of mine water, gases and spontaneous combustion. However, due to the limitations for most of the numerical analysis tools to deal with large movements and deformations commonly seen in subsidence process, research and tools are still lagging in dealing with the MSM interactions created with subsidence process. The authors have started some pinioning research work to apply the subsidence theories to the studies of large-movement and large-deformation MSM interactions. Some of the research works are presented in this report.

REFERENCES


Itasca Consulting Group, Inc., 2006, *Flac 3D Version 3.1 Example Applications*, Minneapolis, MN, pp. 2-1 to 2-17


Zhao, J., Rock Mechanics for Civil Engineers, Lecture Notes, Swiss Federal Institute of Technology, Lausanne, Switzerland