A Metamodel-Based Monte Carlo Simulation Approach for Responsive Production Planning of Manufacturing Systems

Minqi Li

Follow this and additional works at: https://researchrepository.wvu.edu/etd

Recommended Citation
https://researchrepository.wvu.edu/etd/6071

This Dissertation is brought to you for free and open access by The Research Repository @ WVU. It has been accepted for inclusion in Graduate Theses, Dissertations, and Problem Reports by an authorized administrator of The Research Repository @ WVU. For more information, please contact ian.harmon@mail.wvu.edu.
Implementing the Local Mine Stiffness Calculation in LaModel

Kaifang Li

Dissertation submitted
to the Benjamin M. Statler College of Engineering and Mineral Resources
at West Virginia University

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in
Mining Engineering

Keith A. Heasley, Ph.D., Chair
Yi Luo, Ph.D.,
Brijes Mishra, Ph.D.,
Aaron Noble, Ph.D.,
Department of Mining Engineering
West Virginia University

Ihsan Berk Tulu, Ph.D.,
Office of Mine Safety and Health Research
National Institute for Occupational Safety and Health

Morgantown, West Virginia
2016

Keywords: Local Mine Stiffness, Strain Softening, LaModel, Pillar bumps, Pillar Run, Ground Control
Copyright 2016 Kaifang Li
ABSTRACT
Implementing the Local Mine Stiffness Calculation in LaModel
Kaifang Li

Catastrophic failure of mine structures, such as coal/rock bumps and cascading pillar failures, is a difficult and longstanding ground control issue which has presented serious safety problems in coal, metal and nonmetal mines. Although various approaches for analyzing this issue have been proposed, it is still hard to predict and/or to eliminate these violent pillar failures due to the poor understanding of the exact mechanism.

The local mine stiffness criterion had been recognized as a promising approach for analyzing the issue of dynamic underground pillar collapses. This criterion was initially hypothesized and tested with laboratory experimentation, but with the advent of appropriate numerical models, it can be extended to analyze the stability of the field pillar. To successfully use the local mine stiffness criterion, the post-failure pillar stiffness and the local mine stiffness need to be accurately calculated. Previous research has roughly determined the relationship between pillar stiffness and pillar geometry, but those results were primarily based on the analysis of specimens in the laboratory, which may certainly have the different scale and stress conditions than real pillars in the field.

The objective of this thesis is to fully implement the local mine stiffness calculation into LaModel. Also, as an integral part of this implementation, an improved method for generating strain-softening pillar behavior based on extensive field data was developed and updated. The implementation of the local mine stiffness and strain-softening coal properties will be validated with a number of test models, and then the practical utility of using the local mine stiffness criterion will be evaluated with the back-analysis of a couple of actual case histories.

Keywords
LaModel, Local Mine Stability Criterion, Strain Softening Behavior, Pillar Stiffness, Local Mine Stiffness.
Acknowledgments

Without the support of my advisor, colleagues, friends and family, the completion of this thesis would have never been possible.

First of all, I would like to express my gratitude to my supervisor Dr. Keith A. Heasley. He is more of a mentor than a professor throughout my graduate study. I want to thank him for his unending patience, guidance and assistance during my time at West Virginia University.

I would like to thank my committee members Dr. Yi Luo, Dr. Brijes Mishra, Dr. Aaron Noble and Dr. Ihsan Berk Tulu for their supports and invaluable suggestions during this research.

This work was performed under a project sponsored by the National Institute for Occupational Safety and Health (NIOSH). I would like to thank them for their support and funding.

I would like to give my best thanks and wishes to my friends in the Department of Mining Engineering at WVU.

More importantly, I want to thank my lovely wife, Rui Bao, for encouragement, patience and support. Finally, thanks to daughter, Bella Li, for bringing happiness to my work and study.
# Table of Contents

Abstract ........................................................................................................................................ ii

Keywords ..................................................................................................................................... ii

Acknowledgments ......................................................................................................................... iii

Table of Contents .......................................................................................................................... iv

List of Figures ............................................................................................................................... vii

List of Tables ................................................................................................................................ xi

Chapter 1 Introduction .................................................................................................................... 1

1.1 Background .............................................................................................................................. 1

1.2 Statement of Problem .............................................................................................................. 2

1.3 Scope of work ......................................................................................................................... 3

Chapter 2 Literature Review .......................................................................................................... 5

2.1 Dynamic Pillar Failure .......................................................................................................... 5

2.1.1 Coal bumps ....................................................................................................................... 5

2.1.2 Cascading pillar failure .................................................................................................. 7

2.2 Local Mine Stability Criterion ............................................................................................ 9

2.3 Local Mine Stiffness .............................................................................................................. 11

2.3.1 Determination ................................................................................................................ 11

2.3.2 Properties of the local mine stiffness ............................................................................ 15

2.4 Post-Peak Stiffness of Pillar ................................................................................................. 19

2.4.1 Properties of the strain-softening behavior ................................................................. 19

2.4.2 Post-failure pillar stiffness determination .................................................................. 26

2.5 Summary .............................................................................................................................. 28

Chapter 3 Parameterizing the Strain Softening Behavior .............................................................. 29
3.1 Introduction ......................................................................................................................... 29
3.2 Measurement Instruments ................................................................................................. 30
3.3 Study Sites .......................................................................................................................... 31
  3.3.1 Study sites in U.S. coal mine ......................................................................................... 31
  3.3.2 Study sites in Australia ................................................................................................. 33
3.4 Developing the Residual Stress Formula ............................................................................. 35
  3.4.1 Data Collection ................................................................................................................ 35
  3.4.2 Data Calibration ............................................................................................................. 36
  3.4.3 Best-Fitting .................................................................................................................... 37
  3.4.4 Parameterizing ............................................................................................................... 39
  3.4.5 Characteristics of Strain-softening of pillar ................................................................. 40
3.5 Summary ............................................................................................................................. 43

Chapter 4 Local Mine Stiffness Calculation in LaModel ......................................................... 44
  4.1 Introduction ......................................................................................................................... 44
  4.2 The LaModel Program ....................................................................................................... 44
  4.3 Strain-softening in LaModel ............................................................................................. 45
    4.3.1 Strain-softening behavior of element and pillar ......................................................... 45
    4.3.2 Strain Softening Wizard in LamPre ........................................................................... 48
    4.3.3 Post-failure stiffness Output ....................................................................................... 56
  4.4 Local Mine Stiffness in LaModel ....................................................................................... 58
    4.4.1 Local Mine Stiffness Calculation Wizard ................................................................... 58
    4.4.2 Local Mine Stiffness Output ...................................................................................... 60
  4.5 Summary ............................................................................................................................. 61

Chapter 5 Parametric Evaluation on LMS Criterion in LaModel ........................................... 62
List of Figures

Figure 2.1 Coal bumps events, injuries and fatality trends from 1930 to 2014 ......................... 6
Figure 2.2 Stable, nonviolent failure versus unstable, violent failure .................................... 10
Figure 2.3 Illustration of the local mine stiffness concept ......................................................... 13
Figure 2.4 Illustration of the two-step method to evaluate the local mine stiffness ............... 14
Figure 2.5 Mining patterns for panel stiffness calculation ....................................................... 15
Figure 2.6 Decrease in mine stiffness at the pillar with increasing room number .......... 16
Figure 2.7 Pillar layout used in Ozbay analysis ......................................................................... 17
Figure 2.8 Variation of minimum stiffness of pillar with span/depth ratio ............................ 18
Figure 2.9 Post-failure stress-stain behavior of coal against the w/h ratio ....................... 21
Figure 2.10 Simplification of strain softening behavior form curve to piecewise line .... 22
Figure 2.11 Three points Strain-Softening behavior of Element ........................................ 23
Figure 2.12 Two points Strain-Softening behavior of Element in Lamodel ......................... 25
Figure 2.13 Parameter input form of strain softening Wizard in LaMPre ............................... 25
Figure 2.14 Post-failure modulus data for full-scale coal pillar and laboratory specimens .. 27
Figure 3.1 Part of mine layout of Pocahontas No.3 Coalbed in the U.S ................................. 32
Figure 3.2 Cell pressure changes in a single pillar with mining face advance .................... 35
Figure 3.3 Relationship of the residual stress and the distance into pillar .......................... 38
Figure 3.4 Upper and Lower bounds for A and B ................................................................. 40
Figure 3.5 Post-failure behavior of coal with different A and B ............................................ 41
Figure 3.6 Pillar model and complete stress strain curve with different A and B .............. 42
Figure 3.7 Comparison of two different residual stress comparisons ............................... 43
Figure 4.1 Corner Elements and Side Elements ..................................................................... 46
Figure 4.2 Schematic of strain-softening behavior ............................................................... 46
Figure 4.3 Compositing the pillar behavior from elements .......................................................... 48
Figure 4.4 In-Seam Material Definition Form ............................................................................ 49
Figure 4.5 Strain Softening Definition Wizard with Default Value Option ............................. 52
Figure 4.6 Strain Softening Definition Wizard with Calculated Value Option ......................... 52
Figure 4.7 Strain Softening Definition Wizard with Specified Value Option ......................... 53
Figure 4.8 Summary of the strain softening material in LaMPre .............................................. 55
Figure 4.9 Calculated Strain Softening Behavior in Input File ................................................ 56
Figure 4.10 Stress/Strain Value of an Entire Pillar in LaModel Output File ............................... 57
Figure 4.11 Stress Strain curve and Stiffness Curve ................................................................ 58
Figure 4.12 Local mine stiffness calculation option in LaMPre ................................................ 59
Figure 4.13 Local mine stiffness calculation wizard in LaMPre ............................................... 59
Figure 4.14 Local Mine Stiffness Calculation Process in output file ...................................... 61
Figure 4.15 Local Mine Stiffness Calculation Result ............................................................... 61
Figure 5.1 Scenarios of residual point affecting the relationship of \( K_{LMS} \) and \( K_P \)............. 64
Figure 5.2 Parameters Calibration Model ................................................................................. 65
Figure 5.3 Lamination thickness vs. local mine stiffness of central pillar ............................... 66
Figure 5.4 Local mine stiffness behavior as a function of mine geometry ............................... 67
Figure 5.5 Mine stiffness with different \( t \) and \( D \) .............................................................. 67
Figure 5.6 Mine stiffness with different \( t \) and \( D \) .............................................................. 68
Figure 5.7 Pillar stress strain curve with varying \( A \) and Constant \( B \) ................................. 69
Figure 5.8 Maximum post failure pillar stiffness with varying \( A \) and Constant \( B \) .......... 69
Figure 5.9 Pillar stress strain curve with varying \( B \) and Constant \( A \) ................................. 70
Figure 5.10 Maximum post failure pillar stiffness with varying \( B \) and Constant \( A \) ....... 70
Figure 5.11 Stress strain curve with different \( A \) and \( B \) .................................................... 71
Figure 6.25 Step 28 in Harlan Model........................................................................................................... 94
Figure 6.26 Step 36 in Harlan Model........................................................................................................... 94
Figure 6.27 Pillar Geometry at Cutting Step 36............................................................................................ 95
Figure 6.28 Stress Strain Curve of Pillar and Minimum Post Peak Pillar Stiffness .................. 96
Figure 6.29 Comparisons of the Pillar Stiffness and Local Mine Stiffness................................. 96
List of Tables

Table 3.1 Geologic Information of three measurement sites in U.S coal mine ................................ 33
Table 3.2 Geologic Information of three measurement sites in Australia coal mine .................. 34
Table 3.3 Stress change of BPFs in U.S. coal mine ................................................................. 36
Table 3.4 Stress change of BPFs in Australian coal mine ......................................................... 36
Table 3.5 Calibrated peak and residual stresses in U.S coal mine ........................................ 37
Table 3.6 Calibrated peak and residual stresses in Australian coal mines ............................... 37
Table 5.1 Default Value of input Parameters ............................................................................ 65
Table 6.1 Strain softening behavior of each different element ................................................ 81
Table 6.2 Timing, Location, and Circumstances of Coal Bumps ............................................ 90
Table 6.3 Strain softening behavior of each different element (1435 psi) ............................... 95
Chapter 1 Introduction

1.1 Background

Coal bumps and cascading pillar failures (progressive pillar failures, massive pillar collapses or pillar runs) are two kinds of longstanding engineering problems associated with underground mining activities. These kinds of instabilities have presented some serious safety problems that have historically resulted in injuries and fatalities. Over the past 20 years, the increasing overburden depth of the underground mine seam and the widespread utilization of the longwall mining technology in the United States further increased the possibility of the catastrophic failures (Mark and Gauna, 2015).

The former Bureau of Mines (now NIOSH) and other institutions have assembled a wealth of technical information on pillar bumps and attempted to understand, control, and/or eliminate pillar bumps (Iannacchione, 1995). Significant strides have been made on understanding these dynamic failures and on developing techniques for mitigating these violent pillar failure issues. However, the complicated mechanisms of these catastrophic failures of mine structure are still unclear and being studied and debated today (Iannacchione, 1995; Iannacchione and Zelanko, 1994; Maleki, Wopat, and Repshe, 1995). The increasing pillar bump events urgently require accurate approaches and efficient tools to analyze and/or predict dynamic pillar failures timely. Currently, three techniques are commonly used to evaluate a dynamic pillar failure event: energy release rate calculation, seismic monitoring and local mine stiffness calculation (Ellenberger and Heasley, 2000; Garvey and Ozbay, 2012; Salamon, 1984; Sears, 2009; Sears and Heasley, 2009; Zipf, 1999). These approaches, combined with the advanced computer technology, provide potential numerical tools for analyzing dynamic failures timely.

The local mine stiffness criteria was originally developed by Salamon (1970) in a rigorous mathematical to evaluate the stability of a mining situation and the potential for dynamic failure. This criterion has been used over the intervening years (Ozbay, 1989; Morsy and Peng, 2002; Zipf, 1992, 1999), however, it is still difficult to calculate accurate results due to the challenge of accurate determining the post-failure stiffness and the mine stiffness of a pillar or pillars.
1.2 Statement of Problem

The local mine stiffness criterion has been recognized as a promising approach for analyzing pillar bumps. The advantage of this criterion includes two truly calculated values, the post-failure stiffness and the mine stiffness, for comparing and then determining the pillar failure manner. However, a significant gap exists in our abilities to use the local mine stiffness criterion expertly in practice because of limited analysis techniques that determine two stiffness values accurately and efficiently.

Intrinsically, the local mine stiffness calculation compulsively requires pillars in the strain-softening material model. The strain softening behavior has been widely investigated on rock/coal specimens in the laboratory; however, the coal specimen and real pillar have different scales and stress conditions. It is not clear how well the laboratory results are able to describe real pillar behavior. Besides, the field measurements actually observed the strain softening behavior on pillars. In numerical modeling, it is better to simulate pillar behavior by using the measured strain softening behavior directly from filed than from laboratory; however, it is an expensive and long-term project to conduct the field measurement in pillars to measure the strain-softening behavior. Especially, some uncontrolled factors during measurements always interrupt field monitoring processes, such as instruments damage, etc...Therefore, the strain-softening behavior of field pillar is rarely mentioned due to the lack of comprehensive field measurement data. In the current LaModel program, the parameter selection method for the strain softening parameters uses the Mark-Bieniawski stress gradient for determining the peak stress (Mark, 2000) and the published formulas by Karabin and Evanto (1999) for determining the residual stress of a specified pillar. However, Karabin and Evanto’s residual stress was developed by analyzing only a couple of cases and the data could be greatly expanded.

The mine stiffness determination of a pillar is another complicated problem when using the local mine stiffness criterion. Previous research gave the analytical and numerical approaches; however, the analytical approach in a large mine analysis requires complicated matrix calculation which is a hard and time-consuming process. Besides, the frequently-used numerical models lack the user-friendly plug-in and/or GUI which can help users to calculate the mine stiffness efficiently. Therefore, previous research truly did not provide an efficient tool to calculate the mine stiffness. Further, the calculation of the mine stiffness surrounding a pillar is
not an isolated but a comprehensive process that needs to be considered not only the characteristics of the specified pillar but also the properties of the surrounding pillars and the rock mass. However, previous research did not give sufficient information about the effect of the surrounding structures on the mine stiffness calculation of pillar. In the past, the local mine stiffness criterion was utilized in cases on some specified mine sites (Morsy and Peng, 2002; Y Pen and Barron, 1994; Zipf, 1992, 1999; Zipf and Mark, 1997). The local mine stiffness criterion was variably satisfied in those pillar bumps. But those studies did not further investigate failed reasons of using the local mine stiffness criterion in pillar bump events.

1.3 Scope of work

The goal of this research is to enhance coal mine safety and improve pillar design through analyzing and/or predicting the potential violent pillar failure with the local mine stiffness calculation. To fulfill this goal, the local mine stiffness calculation is implemented into LaModel as a tool. Correlatively, the strain-softening behavior of coal in LaModel is improved with field measurements. The local mine stiffness calculation and the strain-softening material model in LaModel is validated and evaluated. Three objectives are included in this goal.

The first objective is to implement the local mine stiffness calculation in LaModel. The implementation includes building a user-friendly mine stiffness calculation form and writing the related algorithm. The form is designed concisely and requires minimum input parameters. With the help of the correspondent well-designed algorithms, the calculation form should have the function that locates the designated pillar’s location in mine layout easily by just using the coordinate of any element in pillar.

The second objective is to improve the accurate determination of the parameters to use with the strain-softening coal material in LaModel. To fulfill this objective, a number of additional sets of field stress measurements are collected, and analyzed from the past publications. An improved residual strength calculation to more accurately quantify the post-failure behavior of coal pillars is developed. The new residual strength has the same format as the peak strength that mainly relies on the coal strength and the pillar geometry. In order to exhibit the different behavior with changing pillar geometry, the new residual strength should add some variables which enhance the flexibility that changing of variables in the quantified range should change the pillar behavior from strain-softening to elastic-plastic and reach to strain-hardening. By using the
improved residual stress, the strain softening wizard in LaMPre is updated more functionally. The new residual strength will be programmed and a multi-options strain softening wizard will be redesigned into LaModel. The multi-option function wizard should give users a flexible choice to define their own expected pillar behavior.

The Third objective is to validate the model and investigate the various critical input parameters that affect the post-failure pillar stiffness and local mine stiffness. Initially, the effect of the critical input parameters will be tested and evaluated with some simple models of these factors is possible providing an efficient method for determining the appropriate input parameters in future. Ultimately the utility of using the new local mine stiffness calculations and strain softening behavior will be investigated through case studies.
Chapter 2 Literature Review

2.1 Dynamic Pillar Failure

Catastrophic failures of mine structures have been one of the most difficult and longstanding ground control issues for more than 90 years (Iannacchione and Tadolini, 2015). The early phases of research into this area revealed that unstable mine structure failures are complex problems associated with coal mine deformation and geologic features. In practice, the common hazardous or devastating structure failures in room-and-pillar mines include coal bumps (or rock bursts) and cascading pillar failures.

Essentially, effectively analyzing, predicting and eliminating the dynamic failure in room-and-pillar mine rests with clearly understanding the mechanism of these unstable failures. However, the mechanism of the unstable coal failure is complicated that the underlying mechanism of the pillar bump is completely different from that of the cascading pillar failure.

2.1.1 Coal bumps

Coal bumps are violent, spontaneous, and sometimes catastrophic expulsions of coal from the mine ribs, faces, and floors at lethal speeds that can extremely hazard to miners and mine equipment.

Coal bump issues have been investigated for a long time. Holland and Thomas (1954) examined 177 instances of coal bursts occurring from 1925 to 1950 and finally recommended some method of preventing bumps. Campoli et al., (1987) analyzed the records of burst events from 1950 until 1984 and found 28 fatalities, 14 in the eastern U.S. and 14 in the western U.S. They concluded that bumps occurred as a result of the extensive use of continuous mining machines. Iannacchione and Zelanko (1995) analyzed more than 170 events coal bursts and included them in a database, which included 87 fatalities and 163 injuries. This database was constructed from U.S. Bureau of Mines (USBM) and Mine Safety and Health Administration (MSHA) accident and incident reports from Oct. 12, 1936, to Jan. 21, 1993. They found that bumps occurred when complex arrangements of geology, stress, and mining conditions interact to interfere with the orderly distribution of stress. They also noticed that although some bump-control design techniques have mostly successful, these techniques have not been applied over a wide range of geologic and mining conditions. Iannacchione and Tadolini (2015), based on the
MSHA Data Retrieval System, examined and verified 337 coal bursts events which occurred in 77 mines located in six states from 1983 to 2013. This database included 240 injuries, 20 of which were fatalities. Summarizing those recorded pillar bump events, Figure 2.1 shows the changes of total coal bumps, and coal burst injuries and fatalities from 1930 to 2014. Clearly, there is a general downward trend in the number of fatalities over the past 80 years. However, there was also a significant increase in the number of events and injuries in the 1990s and 2000s.

![Figure 2.1 Coal bumps events, injuries and fatality trends from 1930 to 2014](image)

As early as the 1930's, the U.S. Bureau of Mines began to research causes and a potential mechanism to avoid bumps in coal mines. Traditionally, coal bumps occurred in seismically active mines. Therefore, coal bumps were widely recognized as a subset of a much larger set of mining induced seismic events (Zipf and Mark, 1997). However, not every potentially hazardous coal bump generates a regional seismic event and not every mine-induced, regional seismic event manifest itself as coal outburst at the seam level. The further research stated that burst-prone environments are almost universally associated with the presence of highly stressed coal which was represented by the fact that bumps occur mostly at depths greater than 300 m (1,000 ft) (Ellenberger and Heasley, 2000). Pillar design or multiple seam interactions can also concentrate
stresses in distinct locations. Geologic features (Iannacchione, 1995; Rice, 1935; Zelanko and Heasley, 1995), including sandstone channels, faults, have been associated with the coal bump events. Certain mining layouts and excavation sequences, which can cause rapid stress increases on pillar over a short distance, is also the potential to result in pillar bump events (Maleki et al., 1995). Laboratory tests have given evidence regarding the influence of confining stresses (Babcock, 1986) and post-failure characteristics of coal pillars in producing violent failure. Iannacchione (1994) summarized the mechanism of coal bumps, which included (1) excessive pressure, (2) seismic shock, and (3) loss of confinement.

2.1.2 Cascading pillar failure

Cascading pillar failure in room-and-pillar mines has other names such as "progressive pillar failure", "massive pillar collapse", "domino-type failure", or "pillar run". Compared with coal/rock bump in practice, pillar run is a similar but more severe event. Cascading pillar failure is a rapid failure process that poses a catastrophic effect on the health of miners and safety risk on the underground environment. The cascading pillar failure can induce a devastating air blast due to the displacement of air from the collapse area; the induced air blast can totally disrupt the ventilation system at a mine by destroying ventilation stoppings, seals, and fan housings. Flying debris in cascading pillar failure can seriously injure or kill mining personnel. Cascading pillar failure might also fracture a large volume of rock in the pillars and immediate roof and floor. This fragmentation can lead to the sudden release of large quantities of methane gas into the mine atmosphere which might cause a methane explosion. After cascading pillar failure, the openings in the affected mine workings would typically be completely sealed.

Compared to coal bumps, the mechanism of cascading pillar is more complicated. The simple explanation of the mechanism of cascading pillar failure is the rapid load transformer. When the strength of one pillar (or a few pillars) in a room-and-pillar mine is exceeded, the pillar (or pillars) fails and sheds its (their) strength rapidly and transfer the additional load on the neighboring pillars causing these pillars to fail rapidly, and so forth. This failure mechanism can result in the rapid pillar collapse in large mine areas that a few tens of pillars in a mild situation or hundreds, even thousands of pillars in extreme condition. However, the underlying mechanics of cascading pillar failure are more complex (Zipf, 1997). The nature of the cascading pillar failure depends on the related properties of the rock mass and the pillars, such as the geological conditions of the
rock mass, mining sequence, pillar geometry, the post-failure stiffness and strength of the remnant pillars and etc. For example, slender pillars with a low width-to-height (w/h) ratio shed load rapidly when they fail and transfer weight to overload adjacent pillars and a rapid "domino" failure of adjacent pillars; while, squat pillars with a large w/h ratio retain most of their load even after failure and pillars squeeze slowly, rather than collapsing.

Many case studies exist of cascading pillar failure in coal mines. The most infamous example (Bryan, Bryan, and Fouche, 1966) is the Coalbrooke Colliery in South Africa where 437 miners perished when 2 km² of the mine collapsed within a few minutes on January 21, 1960. Chase et al. (1995) documented cases of cascading pillar failure in U.S. coal mines. Cascading pillar failure has also happened in many metals and nonmetal mines in the U.S. Straskraba and Abel (1994) describe the failure of a large room-and-pillar copper mine, and Swanson and Boler (1995) analyzed the failure of a room-and-pillar evaporate mine. In addition, there are examples of cascading pillar failure in gold, limestone, potash and other industrial minerals. Zipf (1997) summarized a total of 13 cases of the rapid pillar collapse in U.S. coal mine from the 1980s to 1990s. These collapses happened suddenly, or without significant warning, and were associated with a cascading pillar failure mechanism. The most pillar bumps occurred at Crandall Canyon Mine on August 6th, 2007 (Heasley, 2009), in which dozens of pillar collapsed in a short time and killed six miners working in the active section, and a subsequence bump killed three and injured six rescue workers.

Previous research (Chase et al., 1995; Zipf, 2001; Zipf and Mark, 1997) concluded several important commonalities of the cascading pillar failure in mines. (1) Depths cover the full range of mining conditions; (2) Extraction ratios are usually more than 60%. A high extraction ratio will put pillar stress close to peak strength and provide ample expansion room for the failed pillar material; (3) Width-to-height (w/h) ratio of pillars is always less than 3 in coal mine. A low w/h ratio ensures that the failed pillar material can easily expand into the surrounding openings and that the failed pillar will have little residual load-bearing capacity; (4) The stability factor for the pillar is less than 1.5 using the Mark-Bieniawski pillar strength formula in the Analysis of Retreat Mining Pillar Stability (ARMPS) method (Mark et al., 1995); (5) The number of pillars across the panel width is always at least 5 and usually more than 10, which typically ensures that pillar reached their full tributary area load; (6) The roof rock is stiff, massive, and can bridge
wide spans without caving; (7) cascading pillar failure causes significant damage, the collapse area is at least 15,000 m² (4 acres) with a minimum dimension of at least 100 m (350 feet).

2.2 Local Mine Stability Criterion

Cook and Hojem (1966) first noticed that rock specimens in the laboratory tested violently or crushes gradually depended on the “stiffness” of the testing system. The popular explanation of this phenomenon is that a “soft” testing structure has an ability to store more induced elastic energy which will be rapidly released into the specimen in the vicinity of the maximum load, and the suddenly released energy causes the rock specimen failure violently. While, a “stiff” testing machine, which has a gigantic strain modulus, prevents the testing structure to store overmuch or any elastic energy, the force from the load system is exerted on the rock specimen directly through the stiff testing machine. Therefore, a “stiff” testing machine can cause the rock specimen failure gradually due to the absence of a sudden energy release.

As the underground structure of the pillar and its loading system is similar to the coal specimen and the testing system in the laboratory, there is a direct analogy between the underground pillar and the rock specimen. Based on this, the failure manner of the real pillar in underground mine should be similarly related to the stiffness magnitude of the surrounding loading system (roof and floor).

Starfield and Fairhurst (1968) suggested that the stability of pillar works could be tested with the aid of the concept of ‘local mine stiffness’ of a mine. The concept states that the stable failure of pillar occurs when the stiffness of the mine roof and floor exceeds the post-failure slope of coal pillars, and unstable failure occurs when local mine stiffness is less steep than the pillar post-failure slope.

Salamon (1970), using a spring-specimen system replaces the loading-specimen system in the laboratory, analyzed the work was done by the spring and the rock specimen and originally developed the local mine stability criterion in a rigorous mathematical approach to evaluate the stability of a mining situation and the potential for dynamic failure. Equation 2.1 and 2.2 show the well-known stability criterion and Figure 2.2 illustrates the criterion graphically.

Stable, nonviolent failure occurs when

$$|K_{LMS}| > |K_P|$$  \hspace{1cm} (2.1)
And unstable, violent failure occurs when

$$|K_{LMS}| < |K_P|$$ (2.2)

Where:

$|K_{LMS}| =$ the absolute value of the local mine stiffness;

$|K_P| =$ the absolute value of the post-failure stiffness at any point along the load convergence curve for a pillar.

Figure 2.2 also illustrates the stability criterion from an energy perspective. In Figure 2.2, the allowable input energy to fail the pillar can be indicated by the area under the stress-strain curve (area AA' FE). In Figure 2.2a, the local mine stiffness, $|K_{LMS}|$, is greater than the post-failure stiffness of the pillar, $|K_P|$. Thus, the stored energy in the rock mass (area ACFE in Figure 2.2a) is less than the pillar's failure energy (area AA'FE in Figure 2.2a). In this case, pillar failure would be in a stable, nonviolent manner. On the other hand, the stored energy in a “soft” condition of the rock mass (area ABFE in Figure 2.2b) is larger than the pillar required failure energy (area AA'FE in Figure 2.2b), the pillar failure would be expected to be unstable and violent.

Figure 2.2 Stable, nonviolent failure versus unstable, violent failure

(after Starfield and Fairhurst, 1968)
Since the local mine stiffness and the post-failure pillar stiffness are two critical components which are involved in the Salamon’s stability criteria, the previous research of these two parts should be reviewed individually.

2.3 Local Mine Stiffness

The local mine stiffness, $K_{LMS}$, relates the deformation in the rock mass (in the case of bumps, the convergence of the roof and floor) to the changes in force. Typically, force changes occur as the rock is mined and stresses go from in situ values to zero as the result of mining activity, the associated drop in stress on the rock mass then causes deformation/convergence to also occur in the rock mass. If a given amount of mining (and force change) results in small deformations, the local mine stiffness of the system is relatively stiff; and if the resulting deformations are large, the local mine stiffness of the system is relatively soft. So the value of the local mine stiffness specifies how much deformation will be generated in the rock mass under a certain change in load. The strata with a higher stiffness have less deformation than the rock mass with a smaller stiffness under the same load condition. In practice, we normally examine the local mine stiffness at a particular pillar which is potentially going to bump or trigger a severe structure failure (pillar run). Excepting the previous explained strata stiffness, the local mine stiffness at a pillar location also depends on the stiffness and geometry of all the surrounding pillars. Clearly, stiff surrounding pillars should provide strong supports which prevent the convergence between roof and floor, and compact arrangement of neighbor pillars also give the same ability that reduces the convergence of roof and floor.

2.3.1 Determination

The accurate way to determine the mine stiffness of a pillar is measuring the stress and displacement on the pillar directly and then calculates the value of the mine stiffness of the pillar. However, this kind of in situ test method needs accurate measurement instruments and longtime field operation to obtain sufficient field data. Therefore, this approach is expensive, difficult and time-consuming. Beyond this field measurement method (Pen, 1995), two approaches were used to determine the $K_{LMS}$ of a designated mine pillar, namely: the “analytical method” which was developed by (Salamon, 1970) and the “perturbation method” which was proposed by (Starfield and Wawersik, 1968).
In Salamon’s mathematical analysis (Salamon, 1970), it primary assumes that the strata surrounding the mine workings are linearly elastic and continuous, pillars are confined by the non-linear behavior. Then assume a mine layout which contains ‘n’ pillars and pillar forces $P_i$ (i=1, 2, …n) act at each pillar locations and distribute over the area occupied by surrounding pillars. If the compressive force $P_j$ is applied to the roof and floor of the jth pillar location, the divergence at the position corresponding the i-th pillar can be expressed as $-C_{ij}P_j$ (constants $C_{ij}$ are influenced coefficients and negative sign means convergence is taken positive). The total convergence ($S_i$) of the i-th pillar induced by forces $P_1, P_2, \ldots P_n$ can be obtained by superposition in equation 2.3:

$$S_i = -(C_{i1}P_1 + C_{i2}P_2 + \ldots + C_{in}P_n) \quad (2.3)$$

Equation 2.3 can be simplified in a matrix manner: $S = -CP$. The coefficient of $[C_{ij}]$ is a $n \times n$ symmetric, positive definite matrix. The stiffness coefficient of i-th pillar is the inverse of $C$ ($K=C^{-1}$).

However, this analytical approach has a certain disadvantage when implementing into a numerical model. Many numerical programs do not form $K$ matrix explicitly because of its huge size (commonly on the order of 10,000 by 10,000 or larger) and it is fully populated so that the calculation of the eigenvalues is complicated and time-consuming. Also, this approach is basically only applicable to simple geometric conditions and cannot tell ahead of time where the smallest eigenvalue lies in a particular Model. Typically, knowing which pillar corresponds to a particular $\lambda$ or $K_{LMS}$ may be important if a design engineer wants to alter a mine layout to improve its safety. Therefore, the perturbation method is most commonly used in computer programs for calculating mine stiffness (Brady and Brown, 1981; Ozbay, 1989; Zipf Jr, 1992).

Starfield and Wawersik (1968) introduced a “perturbation method” to determine the local stiffness around a pillar. This perturbation method is popularly used in numerical modeling because it just requires the changes of the stress and displacement of a specified designated pillar, but does not need to define and calculate a stiffness matrix which involved a huge number of pillars. The perturbation method assumes that a pillar in a given geometry is replaced by a hydraulic jack, as shown in Figure 2.3a. Initially, this jack is pressurized enough to be equal to the pillar support and to prevent the convergence of roof and floor. As the jack is de-pressurized, the force imposed on it will drop, then roof sagging and floor heaving will occur at the jack.
location. In this manner, the relationship between the jack force and the roof-to-floor convergence can be obtained and the slope of any point on the curve is essentially the local mine stiffness, as shown in Figure 2.3b.

\[
K_{LMS} = \frac{\Delta P}{\Delta D} = \frac{(S_u - S_p)}{D_u - D_p}
\]  

(2.4)

Where:

\[K_{LMS} = \text{local mine stiffness, psi/in;}\]
\[\Delta P = \text{change in force, psi;}\]
ΔD = change in displacement, in;

S_u = unperturbed stress, psi;

S_p = perturbed stress, psi;

D_u = unperturbed displacement, in;

D_p = perturbed displacement, in;

A = element area, in^2.

Recently, Zipf (1996) and Heasley (1998) implemented the perturbation method into the boundary element programs of MULSIM/NL and LaModel, respectively, to determine the local mine stiffness of specifically designated pillars. In their approach, the perturbation process is simplified by completely removing an individual pillar to create the perturbation (see Figure 2.4). This results in a perturbed stress of zero. In the boundary element calculation, the stress and displacement around a pillar are calculated firstly, giving the unperturbed stresses and displacements (Figure 2.4, step 1). The pillar is then removed, and all of the stresses and displacements are recomputed, giving the so-called perturbed stresses and displacements (Figure 2.4, step 2). The local mine stiffness of the pillar is the slope of the straight line from step 1 to step 2 and the mathematic formula is shown in equation 2.5.

\[
K_{LMS} = \frac{\Delta P}{\Delta D} = \frac{(S_u - 0) \times A}{D_u - D_p}
\]  

(2.5)

Figure 2.4 Illustration of the two-step method to evaluate the local mine stiffness

(after Zipf, 1992)
2.3.2 Properties of the local mine stiffness

Starfield and Fairhurst (1968) discussed the perturbation method and the effects of some important factors on the local mine stiffness calculation, such as the mechanical properties of the roof and floor, the width of the opening, thickness of adjacent pillars, and abutments, the position of the pillar in the room, etc. Starfield and Wawersik (1968) numerically calculated the local mine stiffness of a panel in a model which is shown in Figure 2.5. They supposed that the surrounding rock and the pillars deform in a linearly elastic manner. Pillars and rooms were assumed to be infinitely long such that a plane strain condition was satisfied. A unit displacement disturbance/perturbation was applied for calculation of the stiffness. Using this approach, they found that the mine stiffness at a particular pillar location decreases with an increasing number of rooms in the panel (Figure 2.6) and there should have a critical value of the number of rooms beyond which a further increase room number gave a little reduction in stiffness. This result implies that a sufficiently high modulus of the host rock could safely expand panel width indefinitely. While, they also noticed that if a net tension develops at a potential parting in the hanging, the stiffness at the pillar will depend on the deflection of the loose roof beam.

Figure 2.5 Mining patterns for panel stiffness calculation
(after Starfield and Wawersik, 1968)
Salamon (1970) analytically calculated the critical stiffness of a similar panel layout (Figure 2.5) using a unit load disturbance. His analysis showed that it becomes progressively more difficult to maintain the stability of the panel as the number of pillars increased. It was seen that the panel stability depends on the ability of the yielding pillars to support the immediate roof spanning the panel. As the number of pillars increases, laminated separations or roof fractures would be generated and a net tension was developed at the parting in the overlying layers. At this point, the mine stiffness at the pillar would depend on the deflection of the loose roof beam and the pillar may be driven to complete collapse by the dead weight of this loose slab, if the dead weight stresses the pillar to a value greater than the residual strength of the failed pillar.

Brady and Brown (1981) used a two-dimensional boundary element method with a unit uniformly distributed load disturbance (perturbation) over the width of a pillar to calculate the local stiffness. They kept the extraction ratio constant and used the average convergence over the pillar width as the convergence at the pillar position. They found that the local mine stiffness decreases with the increase of room width and pillar width.
Ozbay (1989) performed a parametric study on a two-dimensional rib-pillar-panel configuration by using a displacement-discontinuity computer program. The layout of the model is shown in Figure 2.7. He assumed that uniformly distributed unit displacement disturbance was applied over the width of a pillar to calculate the stiffness. He reported that the extraction ratio did not have a significant effect on the stiffness of the strata when the number of the pillar in a layout is greater than 5, but in the 3 pillar layout, the strata stiffness increases noticeably with a decrease in extraction ratio. Ozbay also indicated that the stiffness of the strata asymptotically approaches the value of zero with increasing mining span (see Figure 2.8) as the mine span-to-mining depth (L/H) ratio increases. In this situation, the pillar failure will be unstable if the pillar has post-failure stain-softening behavior, as suggested by Salamon’s stability criterion.

Figure 2.7 Pillar layout used in Ozbay analysis
(w=pillar width, l= pillar center-to-center spacing, L= Mine Span) (after Ozbay, 1989)
Zipf (1992) simply added a local mine stiffness calculation loop in MULSIM/NL. He concluded that the magnitude of the local mine stiffness is dominated by the modulus of the surrounding strata. The actual gate road pillar geometry and the position of an element within the panel have no influence on the calculation of the local mine stiffness. No matter which location the pillar occupies in the panel layout, the local mine stiffness decreases initially and then recovers and approaches the same constant value as the pillar converges.
2.4 Post-Peak Stiffness of Pillar

In addition to the local stiffness of the mine, Salamon's stability criterion also equally depends on the post-failure stiffness of the pillar, \(|K_p|\). The requirement of \(|K_p|\) in the stability criterion explicitly requires the pillar to exhibit the softening behavior in its post-peak period. Generally, the post-failure softening behavior of rock swings from the brittle behavior which has the maximum (infinite) of \(|K_p|\) to the perfectly plastic behavior which has the minimum value of \(|K_p|\) (=0). Based on the local mine stiffness stability criterion, if the magnitude of softening approaches to the brittle behavior, pillar should have a higher potential of failure in an unstable manner; otherwise, pillars should fail in a stable manner when the degree of softening close to the perfectly plastic behavior.

2.4.1 Properties of the strain-softening behavior

Before 1960’s, the laboratory test on rock specimen was mostly conducted on the conventional soft testing machine that brittle materials would be disrupted when the load closes the maximum strength of the specimen. When stiff testing machines were introduced in the 60's (Cook and Hojem, 1966; Starfield and Wawersik, 1968), laboratory tests were performed to research the full load-deformation characteristics of materials. Under the stiff testing machine, materials exhibit the softening behavior in the post-peak or post-failure region.

Strain-softening behavior is defined as the process that the rock progressively loses strength as it is strained/compressed beyond its peak strength. This phenomenon has been well documented for many materials, such as concrete, rocks, and some soils. The cause of the strain-softening behavior is the heterogeneity and brittleness of materials. Its mechanism consists of progressively distributed damage, such as dispersed micro cracking, void formation or loss of inter-particle contacts. From laboratory experience, the strain-softening occurs not only in tension but also in compression and shear. In practice, the strain softening behavior has been identified as a reasonable approach to describe the observed stress-strain behavior of coal pillars in the field (Crouch and Faihurst, 1973).

The properties of the strain softening behavior have been researched many years on the specimen in the laboratory and on a real pillar in the field. Rock specimens are easy to prepare in laboratory with various width-to-height ratio and can be exerted on different axial and lateral stress by operating the loading system in laboratory, therefore, most current understanding of the
post-failure softening behavior came from the laboratory testing on the small cylinder or block specimens (Crouch and Faihurst, 1973; Das, 1986; Seedsman and Hornby, 1991). In addition to the inherent material properties, such as young’s modulus, internal friction angle, and joint frequency, etc., of coal, previous research mainly focused on the effects of the specimen/pillar shape, namely the width-to-height (w/h) ratio, on the strain-softerning behavior of coal.

Das (1986) tested 54mm diameter coal specimens in India to study the influence of the width/height (w/h) ratio on the post-failure behavior. He tested a wider range of width/height (w/h) ratio from 0.5 to 13.5 and the stress strain curves illustrated in Figure 2.9. The results showed that coal specimen typically exhibits a greater degree of strain-softerning behavior at low width/height ratio. When the width-to-height ratio is less than 3, the post-failure stresses of the specimen is continuously decreasing as deformation increases and sometimes reaches zero, this behavior presumably happens because of lower confinement of the specimen coal (Das, 1986; Van Heerden, 1975; Wagner, 1974). Besides, the post-failure slope decreases as the width/height ratio increase. When the w/h ratio approaches 10, the post-failure slope is seen to become zero which means the specimen had the elastic-plastic behavior. Further increasing the w/h ratio, the post-failure slope of the specimen becomes positive and goes into the strain-hardening behavior. This phenomenon indicates that at high width/height ratio, the coal specimen loses strength after failure but then gradually recovers strength due to the repacking of the broken pieces of the specimen. When the w/h ratio reaches 13.5, the specimen is seemingly unbreakable. A similar test was also conducted by Seedsman (1991) in Australia. The specimens were from a coal seam with width/height ratio up to about 6. The results were very similar to those obtained by Das.
Figure 2.9 Post-failure stress-stain behavior of coal against the w/h ratio
(after Das, 1986)

However, it is suspicious that extrapolate the specimen behavior observed in the laboratory to the coal pillar in the field due to the different scale and stress conditions between the specimen and the pillar. The extrapolation may be misleading and may lead to erroneous conclusions. For example, Ozbay concluded that a pillar with width/height ratio greater than 5 would have been excluded from bump failure, but it has been reported that even the pillars with a w/h ratio greater than 8 experienced bump failures (Babcock, 1984; Campoli, 1990).

Obviously, the most reliable method to study the softening behavior of real pillar would be to directly load the pillar to failure in the field and obtain the load-deformation curve of the pillar. Even though various difficult, the measurement on full-scale pillars was performed to understand the post failure strain softening behavior of real pillar (Bieniawski, 1968; Cook, Hodgson, and Hojem, 1971; Van Heerden, 1975; Wagner, 1974).

Cook (1967) was the first to point out that a pillar in the field can be tested to obtained the meaningful post-failure as long as the end constraint. He also presented a basic design for such a test. Based on this design, Bieniawski (1968) started a field pillar testing program in South Africa.
Unfortunately, no post-failure information was obtained because of the low stiffness of the loading equipment.

Wagner (1974) conducted the first comprehensive field tests on pillar ranging from 0.6-2.0m side length and width/height ratios from 0.6 to 2.2. The elastic modulus was found to be independent of the size or shape of the pillars, but the post-failure slope was found to be affected remarkable by the pillar width/height ratio. The post-failure slope decreases with the increasing width/height ratio, which indicates that the post-failure behavior is structural or system property rather than an inherent material property. Heerden (1975) performed a test on 1.4 by 1.4 m square pillar and width/height ratio up to 3.5. His results were very similar with those obtained by Wagner (1974).

The results of field measurements revealed that the post-failure behavior of pillar has the same influence factor as the specimen in the laboratory. The softening magnitude of the pillar in the post-peak period decrease as the increase of the pillar width/height ratio.

In numerical modeling, the nonlinear strain softening behavior (left in Figure 2.10) is simplified with multilinear which consists by point of peak stress and peak strain plus points of residual stress and residual strain (right in Figure 2.10). The residual strain must be greater than the peak strain and the final residual stress is assumed to remain constant for strain levels higher than the residual strain.

![Figure 2.10 Simplification of strain softening behavior form curve to piecewise line](image)

Karabin and Evanto (1999) develops strain-softening parameters from field measurements to describe the stress-strain behavior of coal. They used a three point curve to represent the
complete stress-strain curve for a coal element, the points of Peak Stress, First Residual stress, and Second residual stress, see Figure 2.11. The formulas they developed for the peak strength, peak strain, residual strength and residual strain for as a function of distance into the pillar are shown in equations 2.8 to 2.13, and the defined strain softening behavior is illustrated in Figure 2.11.

![Figure 2.11 Three points Strain-Softening behavior of Element](after Karabin and Evanto, 1999)

\[
S_p(i) = S_1 \times \left(0.78 + 1.74 \times \frac{x}{h}\right) \quad (2.8)
\]

\[
\varepsilon_p(i) = \frac{S_p(i)}{E} \quad (2.9)
\]

\[
S_{R1}(i) = S_p(i) \times (0.138\ln(x) + 0.413) \quad (2.10)
\]

\[
\varepsilon_{R1}(i) = 2 \times \varepsilon_p(i) \quad (2.11)
\]

\[
S_{R2}(i) = S_p(i) \times 0.2254\ln(x) \quad (2.12)
\]

\[
\varepsilon_{R2}(i) = 4 \times \varepsilon_p(i) \quad (2.13)
\]

Where:

- \( S_1 \) = in situ coal strength (psi);
- \( x \) = distance from element center to free face (ft);
$h$ = seam height (ft);
$E$ = coal seam modulus of elasticity;
$S_p(i)$ = peak strength of element (psi);
$\varepsilon_p(i)$ = strain at peak strength of element (in/in);
$S_{R1}(i)$ = first residual stress level (psi);
$\varepsilon_{R1}(i)$ = strain at first residual stress (in/in);
$S_{R2}(i)$ = second residual stress level (psi);
$\varepsilon_{R2}(i)$ = strain at second residual stress (in/in).

Heasley (2009; 1998) built upon Karabin and Evanto’s work by implementing a strain-softening wizard in LaMPre (see Figure 2.13). In this strain softening wizard, the default peak stress (strain) and the residual stress (strain) were calculated by the equation 2.14 to equation 2.17, and the strain-softening behavior curve is illustrated in Figure 2.12. The major difference with Karabin and Evanto (1999) and Heasley (2009) is the peak strength formulas for elements. In LaModel, the peak strength is based on Mark-Bieniawski stress gradient formula (as also used in the elastic-plastic wizard in LaModel). According to the unique coal mine geological, the user can define their own strain softening behavior by changing the residual stress factor and residual strain factor, and can also adjust the peak strength of the coal by changing the in-situ coal strength, which default value is 900 psi.

$$S_p(i) = S_1 \times \left( 0.64 + 2.16 \times \frac{x}{h} \right)$$  \hspace{1cm} (2.14)

$$\varepsilon_p(i) = \frac{S_p(i)}{E}$$  \hspace{1cm} (2.15)

$$S_{R}(i) = S_p(i) \times 0.2254\ln(x)$$  \hspace{1cm} (2.16)

$$\varepsilon_{R}(i) = 4 \times \varepsilon_p(i)$$  \hspace{1cm} (2.17)
The problem with these simple models/formulas of strain-softening behavior is that their properties are only “first approximations” and have only been applied to a limited number of case histories for verification. These models need more testing and verification for confident use in modeling (Karabin and Evanto, 1999) and also the residual stress (strain) formula which is used in LaModel, the constant parameter defining the residual stress in this strain softening coal
model ("0.2254" in Equation 2.20) and the constant parameter defining the residual strain value in this strain softening model ("4" in Equation 2.21), need additional research (Heasley, 2009; Karabin and Evanto, 1999)

2.4.2 Post-failure pillar stiffness determination

From the literature review, two approaches, empirical approach, and numerical approach were found to calculate the post-failure stiffness of pillars. For the empirical approach, Zipf (Zipf Jr, 1999), based on the previous field data and laboratory specimen test data, summarized two approximate relationships between the post-failure pillar stiffness and the width-to-height ratio (w/h ratio) of pillars (see Figure 2.14), and the fitted equations was equation 2.18 and equation 2.19.

\[
K_p^{\text{field}} = \frac{E_p \times A}{h} = \frac{(-1750/(w/h) + 437) \times (w \times 1)}{h} = -1750 + 437 \times (w/h) \quad (2.18)
\]

\[
K_p^{\text{lab}} = \frac{E_p \times A}{h} = \frac{(-8000/(w/h) + 1000) \times (w \times 1)}{h} = -8000 + 1000 \times (w/h) \quad (2.19)
\]

where:

- \(K_p^{\text{field}}\) = post failure pillar stiffness of full-scale coal pillar;
- \(K_p^{\text{lab}}\) = post failure stiffness of laboratory specimen;
- \(E_p\) = post failure modulus of pillar or specimen;
- \(A\) = cross section area of pillar or specimen;
- \(h\) = height of pillar or specimen;
- \(w\) = width of pillar or specimen;
- \(l\) = length of pillar or specimen.
This is some very innovative research, but these two equations are rarely used. Their remarkable difference at the low w/h ratios (<4) where pillar had an obvious strain-softening behavior, so these empirical formulas need to verify for using.

Another approach means calculating post failure pillar stiffness from the numerical model. Normally, a pillar is modeled using many tiny elements and each element will have specified behavior. In numerical modeling, the pillar stiffness is calculated from the response of the elements’ behavior. In LaModel, after defining the strain-softening behavior for each element by using peak-stress and residual stress formulas (equations 2.14 to 2.17), the post-failure stiffness of the i-th element at any strain point of post failure section can be obtained from equation 2.20. Then, the post-failure pillar stiffness (Kp) can be calculated by integrated the elements’ stiffness based on their proportion in the pillar to obtain the complete pillar’s stiffness (see equation 2.21).
\[ K_e^i = \frac{E_e^i \times A}{h^i} \]  
(2.20)

\[ K_p = \frac{\sum_{i=1}^{n} (K_e^i \times N^i)}{\sum_{i=1}^{n} N^i} \]  
(2.21)

Where:

- \( K_e^i \) is stiffness of \( i^{th} \) element;
- \( E_e^i \) is post failure modulus of the \( i^{th} \)-element;
- \( h^i \) is thickness of \( i \)-element;
- \( K_p \) is total Pillar Stiffness;
- \( N^i \) is number of \( i \)-element in pillar;
- \( n \) is number of different element types in the pillar;
- \( A \) is element’s area

2.5 Summary

This chapter introduced the pillar bumps and cascading pillar failure in mines. Previous research on pillar bumps and cascading pillar failure events were reviewed. The concept of the local mine stiffness was introduced as a promising approach to analyze dynamic pillar failure events. Related influence factors on the stiffness calculation were also summarized from previous publications. Research stated that the local mine stiffness criterion is a potential tool because this criterion directly compared two specific stiffness values. However, it is still hard to use this criterion successful in practice. Various influence factors, such as the modulus of the country rock, the pillar geometry or arrangement in the underground and the strain-softening behavior of coal, etc., obstructed engineers to determine the mine stiffness and the post-failure stiffness of a designated pillar accurately.
Chapter 3 Parameterizing the Strain Softening Behavior

3.1 Introduction

As mentioned, application of the local mine stiffness stability criterion implies the pillar should have the strain-softening behavior in its post-failure period. Numerous research results, either come from the laboratory or come from the field observation, demonstrate obviously that coal specimen or pillars have the strain-softening characteristic in the post-failure period. However, previous research primarily performed on the rock specimen in the laboratory, and those results merely displayed the softening trend of rock specimen at the post-peak period and proposed an ambiguous relationship between the softening magnitude (modulus) and the width/height (w/h) ratio of the specimen. These results encounter a remarkable head-breaking problem when pillars design in the field. It is indistinct whether appropriate or accurate directly using these results to clarify the strain softening behavior of a real pillar due to the different scale and stress condition between the specimen and the pillar. Nevertheless, the result of the strain-softening pattern from the laboratory gives rise to some significant ideas about how to describe the strain-softening behavior in theory and formulating this behavior in numerical models before sufficiently understanding the softening behavior of the real pillar.

Linearizing the stress-strain curve of rock with connected piecewise lines is a recognized approach to simplify the strain-softening behavior in the numerical model. This curve should be quantified by some significant points to show the relationship of the stress and the strain. The current implemented the strain-softening behavior of coal in LaModel program follows this approach and the strain-softening curve graph is marked by the peak point (peak stress/strain) and the residual point (residual stress/strain). The peak stress is determined by the empirical stress gradient uses in the Mark-Bieniawski coal strength formula (Mark and Chase, 1997; Mark and Iannacchione, 1992) and the residual stress was typically determined from the published equations of Karabin and Evanto (1999). However, this residual stress equation was generated from a couple of case studies and must be verified for accuracy.

The objective of this chapter is best-fitting a residual stress formula through collecting more extensive field stress-change data. The residual stress formula enables LaModel to simulate flexible softening magnitudes under different pillar dimension.
3.2 Measurement Instruments

Underground mining activities trigger redistribution of stress which probably cause potential safety issues. A significant method to forecast and prevent these potential threats is clearly understanding the process of the stress redistribution as the mining advances. Practically, the accurate approach to understanding that is installing a series of stress monitor instruments and recording the changes of a stress condition in rock mass during the mining activities. There are several different methods and devices to measure the stress situation in the field (Peng, 2008). In this dissertation, the devices employed in the stress measurements are either: Vibrating Wire Stressmeters (VWS) or one of the hydraulic pressure cells, the Borehole Pressure Cells (BPC) or the Borehole Platened Flatjack (BPF). All of these stress meters indicate the stress change after installation, not the total in-situ stress.

The VWS consists of a thin wire which is diametrically installed into a thick-walled steel cylinder. The wire is pre-tensioned and to take a measurement, the wire is vibrated by a coil and magnet. The vibration frequency of the wire is proportional to the square root of the wire tension which is related to the wire length. When the VWS is placed into a circular hole, the stress induced deformation of the wall of the borehole also deforms the VWS body. This deformation changes the wire tension and the natural frequency of the vibration. The stress change on the VWS can be determined from the change of the wire frequency.

The BPF (Babcock, 1986) is a tool to record the induced stress. Generally, the design of the BPF is straightforward and includes a flat jack, two platens, enough steel hydraulic tubing, an appropriate pressure gauge and a valve. The flatjack is comprised of two metal sheets placed together, welded around their periphery and connected with the steel hydraulic tubing. Platens allow a minimum clearance between the cell and the borehole during installation. The gauge and valve is assembled to the out by end of the tubing. When using BPF, a borehole with the desired diameter is drilled into the rock. The flatjack and the surrounding platens are then inserted into the borehole to the desired depth and in the desired orientation. Once the flatjack is properly positioned, the flatjack is expanded in the hole to a chosen setting pressure with a hydraulic pump, and the valve is closed. After initial pressurization, any change in the hydraulic pressure of the flatjack corresponds to a change in the stress of the surrounding rock. The BPF used in this research were designed, tested calibrated and manufactured by The Bureau (Heasley, 1989).
Even though the VWS and BPF stressmeters should be calibrated before installing, the accuracy of the gauge reading is largely indeterminate. The measured stress change magnitude can only be an approximate value and not an actual value.

3.3 Study Sites

This research uses some completed and published stress change data and charts (Campoli, Barton, Van Dyke, and Gauna, 1990; Campoli, Barton, Van Dyke, and Gauna, 1993; Colwell, Frith, and Mark, 1999) to catch the expected stress values. In this dissertation, data are collected from 9 different study sites, 3 of them in U.S. and 6 in Australia. These study sites have different geological conditions, different panel, and pillar dimension, etc., so the collected stress change data provide a fairly diverse analysis of the relationship between the residual stress and the pillar geometry.

3.3.1 Study sites in U.S. coal mine

Three study sites in U.S. coal mine located in Pocahontas No.3 Coalbed in Appalachian coal basin, where mining and geologic conditions are conducive for coal pillar bumps (Campoli et al., 1990; Campoli et al., 1993; Yuan Pen, 1995). No.3 coalbed is averaged 5.5 ft in thickness and from 1,200 to 2,200 ft in depth; the coalbed dips 1° from east to west. The immediate roof consists of a widely jointed siltstone overlain by very stiff, massive sandstone. The mine floor consists of a combination of very competent siltstone and sandstone. In the published documents, panel S-6, S-7, S-8, and S-9 (as shown in Figure 3.1) are 600 ft wide and 6,000 ft long.

Three stress measurement sites located at the development entry systems of S-7, S-8 and S-10 (red area in Figure 3.1). The S-7 development and S-8 development entry, which adjoin each other on opposite sides of panel S-7, have different pillar system that provided a unique opportunity for obtaining a better understanding of the strata movements and coal behavior associated with the bump phenomena.
Figure 3.1 Part of mine layout of Pocahontas No.3 Coalbed in the U.S
(after Campoli and Barton, 1990)
The detailed information of three study sites in No. 3 coalbed is listed in Table 3.1.

Table 3.1 Geologic Information of three measurement sites in U.S coal mine

<table>
<thead>
<tr>
<th>Study Site</th>
<th>7 Development study area</th>
<th>8 Development study area</th>
<th>10 Development study area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geological Information</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coalbed Seam</td>
<td>Pocahontas No.3</td>
<td>Pocahontas No.3</td>
<td>Pocahontas No.3</td>
</tr>
<tr>
<td>Seam Thickness (ft)</td>
<td>5.5</td>
<td>5.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Roof</td>
<td>Jointed Siltstone, Sandstone</td>
<td>Jointed Siltstone, Sandstone</td>
<td>Jointed Siltstone, Massive Sandstone</td>
</tr>
<tr>
<td>Floor</td>
<td>Competent Siltstone and Sandstone</td>
<td>Competent Siltstone and Sandstone</td>
<td>Competent Siltstone and Sandstone</td>
</tr>
</tbody>
</table>

Panel and Pillar Geometry

<table>
<thead>
<tr>
<th></th>
<th>7 Development study area</th>
<th>8 Development study area</th>
<th>10 Development study area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel Width (ft)</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Panel Length (ft)</td>
<td>3000</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>Yield Pillar Width (ft)</td>
<td>30</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Yield Pillar Length (ft)</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Abutment Pillar Width (ft)</td>
<td>80</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Abutment Pillar Length (ft)</td>
<td>80</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>Entry Width (ft)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Test Sites Information

<table>
<thead>
<tr>
<th></th>
<th>7 Development study area</th>
<th>8 Development study area</th>
<th>10 Development study area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth of the Site(ft)</td>
<td>1905</td>
<td>2050</td>
<td>2094</td>
</tr>
<tr>
<td>Number of BPF</td>
<td>50</td>
<td>60</td>
<td>47</td>
</tr>
<tr>
<td>Location</td>
<td>Panel S6 - Panel S7</td>
<td>Panel S7 - Panel S8</td>
<td>Panel S9 - Panel S10</td>
</tr>
</tbody>
</table>

3.3.2 Study sites in Australia

Six study sites are located at six different collieries in Australia. Three of them are located in the Bowen Basin Coal Field (Central, Crinum and Kenmare), two collieries are located at the Newcastle Coalfield (Newstan and West Wallsend) and West Cliff Colliery is located at the Southern Coalfield. The overburden depth of those coal mine ranges from 390 to 1575 ft, panel width varies from 443 up to 920 ft and the development height varies from 8.2 to 12 ft. Each
A monitoring site includes an array of hydraulic stress cells to measure the change in vertical stress. The summary information of these study sites in Australia is listed in Table 3.2.

### Table 3.2 Geologic Information of three measurement sites in Australia coal mine

<table>
<thead>
<tr>
<th>Study Site</th>
<th>Central Colliery</th>
<th>Crinum Colliery</th>
<th>Kenmary Colliery</th>
<th>NewStan Colliery</th>
<th>Wallsend Colliery</th>
<th>West Cliff Colliery</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Geological Information</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seam</td>
<td>German Creek Seam</td>
<td>Lilyvale Seam</td>
<td>Aries Seam</td>
<td>West Borehole Seam</td>
<td>West Borehole Seam</td>
<td>Bulli Seam</td>
</tr>
<tr>
<td>Overburden Depth (ft)</td>
<td>869.2</td>
<td>279 ~656.8</td>
<td>426.4</td>
<td>590.4</td>
<td>721.6 ~918.4</td>
<td>1558</td>
</tr>
<tr>
<td>Seam Thickness (ft)</td>
<td>5.9 ~8.8</td>
<td>9.5 ~13.8</td>
<td>11.1 ~13.1</td>
<td>15.7</td>
<td>21.32</td>
<td>8.2</td>
</tr>
<tr>
<td>UCS of Roof (Psi)</td>
<td>7252~11603</td>
<td>2466</td>
<td>1450~2900</td>
<td>3480</td>
<td>3480</td>
<td>1558</td>
</tr>
<tr>
<td>UCS of Floor (Psi)</td>
<td>&lt; 1450</td>
<td>Deteriorated</td>
<td>4061</td>
<td>4061</td>
<td>7251~10152</td>
<td></td>
</tr>
<tr>
<td>CMRR</td>
<td>51</td>
<td>40</td>
<td>46</td>
<td>39</td>
<td>40</td>
<td>48.5</td>
</tr>
<tr>
<td><strong>Panel and Pillar Geometry</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Panel Width (ft)</td>
<td>672.4-770.8</td>
<td>919.5-919.5</td>
<td>672.4-672.4</td>
<td>443.8-443.8</td>
<td>492-492</td>
<td>672-672</td>
</tr>
<tr>
<td>Development Height (ft)</td>
<td>8.2</td>
<td>11.8</td>
<td>10.2</td>
<td>13.8</td>
<td>10.5</td>
<td>8.2</td>
</tr>
<tr>
<td>Chain Pillar Width (ft)</td>
<td>130.9</td>
<td>99</td>
<td>81</td>
<td>85.3</td>
<td>98.7</td>
<td>122</td>
</tr>
<tr>
<td>Chain Pillar Length (ft)</td>
<td>311.3</td>
<td>410.5</td>
<td>393</td>
<td>318.2</td>
<td>318.8</td>
<td></td>
</tr>
<tr>
<td>Crosscut Width (ft)</td>
<td>16.7</td>
<td>15.8</td>
<td>17</td>
<td>16.4</td>
<td>16</td>
<td>15.7</td>
</tr>
<tr>
<td><strong>Test Site Information</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overburden Depth (ft)</td>
<td>869.2</td>
<td>410.5</td>
<td>426.4</td>
<td>590.4</td>
<td>787</td>
<td>1558</td>
</tr>
<tr>
<td>Hydraulic Cell Number</td>
<td>10</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Test Cells Depth in Pillar (ft)</td>
<td>32.8</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>36</td>
<td>32.8</td>
</tr>
<tr>
<td>Test Depth in Rib (ft)</td>
<td>(LW 207) 8.2/14.8/21.3</td>
<td>(LW 2) 9.9/19.7/27.9</td>
<td>(LW 2) 14.8/26/42.6</td>
<td>(LW 11) 16.4/32.8/46</td>
<td>(LW 17) 16.4/32.8/52.5</td>
<td>(LW 24) 8.9/24.9/37.4</td>
</tr>
</tbody>
</table>
3.4 Developing the Residual Stress Formula

3.4.1 Data Collection

Practically, the stressmeters are pre-installed in the pillars or panels when the mining faces were far away from the study sites. These installed stressmeters should experience the whole change process of the original and induced stress and record each changing stress value at each specified monitor point.

In order to best-fit an equation to calculate the residual stress of coal, sets of peak stress and related residual stress are expected from the charts of stress change. However, only certain monitor instruments, which typically near the edge of the pillar, would experience coal failure and then drop to the residual stress level. To locate these critical points, the data from the stress measurement sites were scanned looking for individual stress cells that reached a peak pressure (for example point A in Figure 3.2,) and then subsequently dropped to a lower residual level (point B in Figure 3.2). Further, the location of the cell in the pillar, the behavior of the other cells in the pillar, and the present loading situation on the pillar were also analyzed to verify that the situation was indeed appropriate for the coal at the location of the cell to fail at that point. As shown in Figure 3.2, the stress dropping from point A to B induces the stress increasing of the inner cell from point C to D as the longwall face passing. Therefore, the stress of point A is assumed to indicate the peak cell pressure and the stress of point B is assumed to indicate the residual cell pressure at that location in the pillar.

Figure 3.2 Cell pressure changes in a single pillar with mining face advance  
(after Campoli and Barton, 1993)
Depending on the above collection approach and carefully scanning the entire situations, 19 individual stress cells from 9 measurement sites exhibited suitable behavior to classify them as being subject to both peak and residual stress. 12 of these cells came from the U.S. coal mines and 7 cells came from the Australian mines. The measured peak and residual hydraulic pressure of each cell are listed in Table 3.3 and Table 3.4.

### Table 3.3 Stress change of BPFs in U.S. coal mine

<table>
<thead>
<tr>
<th>Distance into pillar (ft)</th>
<th>Stress Changes in U.S. Coal Mine</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Pillar Height (ft)</td>
<td>5.5</td>
</tr>
<tr>
<td>Field Peak Stress (psi)</td>
<td>4500</td>
</tr>
<tr>
<td>Field Residual Stress (psi)</td>
<td>1800</td>
</tr>
</tbody>
</table>

### Table 3.4 Stress change of BPFs in Australian coal mine

<table>
<thead>
<tr>
<th>Distance into pillar (ft)</th>
<th>Stress Changes in Australia Coal Mines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Pillar Height (ft)</td>
<td>8</td>
</tr>
<tr>
<td>Field Peak Stress (psi)</td>
<td>1348.5</td>
</tr>
<tr>
<td>Field Residual Stress (psi)</td>
<td>928</td>
</tr>
</tbody>
</table>

### 3.4.2 Data Calibration

Even though these expected cell pressure had been collected, these data are raw and discrete and need to calibrate. In LaModel, the peak strength of elements in a pillar model is typically calculated from the widely used Bieniawski stress gradient formula (Bieniawski, 1992; Mark and Iannacchione, 1992) (see equation 2.18). Therefore, in this calibration, the measured peak cell pressure was then adjusted ("calibrated") to equal the calculated Bieniawski stress of the specified point. The same ratio of measured peak pressure to Bieniawski peak stress was then used to determine the calibrated residual stress from the measured residual cell pressure. (In this analysis, knowing the absolute pillar stresses is not nearly as critical as knowing the percent change from the peak to the residual stress. And the given calibration method preserves the percentage changes as observed in the field.) The calibrated peak and residual stresses are given below in
Table 3.5 and Table 3.6.

Table 3.5 Calibrated peak and residual stresses in U.S coal mine

<table>
<thead>
<tr>
<th>Coal strength: 900 psi</th>
<th>Stress Changes in U.S Coal Mine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance into pillar (ft)</td>
<td>5</td>
</tr>
<tr>
<td>Pillar Height (ft)</td>
<td>5.5</td>
</tr>
<tr>
<td>Bieniawski Peak Stress (psi)</td>
<td>2343</td>
</tr>
<tr>
<td>Calibrated Residual stress (psi)</td>
<td>937</td>
</tr>
</tbody>
</table>

Table 3.6 Calibrated peak and residual stresses in Australian coal mines

<table>
<thead>
<tr>
<th>Coal strength: 900 psi</th>
<th>Stress Changes in Australia Coal Mines</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance into pillar (ft)</td>
<td>10</td>
</tr>
<tr>
<td>Pillar Height (ft)</td>
<td>8</td>
</tr>
<tr>
<td>Bieniawski Peak Pressure (psi)</td>
<td>3006</td>
</tr>
<tr>
<td>Calibrated Residual stress( psi)</td>
<td>2069</td>
</tr>
</tbody>
</table>

3.4.3 Best-Fitting

In fact, the calibrated field residual stresses in

Table 3.5 and Table 3.6 can generate various formulas depending on the index of the X-coordinate, for example, the current implemented residual stress formula (see equation 2.12) is calculated with the peak strength of coal (Sp) and the distance into the pillar (x). While, in order to correspond with the peak stress equation used in LaModel (see equation 2.10) which is based on the in situ coal strength (S1) and the distance into the pillar-to-pillar height ratio (x/h), the expected residual stress formula attempts to use the same format that calculate from S1 and x/h. Therefore, the calibrated residual stress data are analyzed against the distance-to-height ratio (x/h) in the pillar. Through some trial-and-error, it was found that the natural log of the normalized distance provided the best fit to the data (see Figure 3.3).
As shown in Figure 3.3, the residual stress equation is equation 3.1 and the R-squared value is 0.8295 which is the highest level in whole probable results:

$$S_r = 1308 \times e^{1.43 \ln(x/h)}$$  \hspace{1cm} (3.1)

In order to exhibit the same format as the peak strength equation in LaModel, equation 3.1 is rearranged and divided 900 from 1308 as the coal strength. The residual stress formula for calculating different elements in pillar is finally shown in equation 3.2.

$$S_r = 900 \times (1.45 \times \left(\frac{x}{h}\right)^{1.43})$$  \hspace{1cm} (3.2)

Where:

- $900$ = in-situ coal strength, (psi);
- $x$ = distance into pillar, (ft);
- $h$ = pillar height, (ft).

![Figure 3.3 Relationship of the residual stress and the distance into pillar](image-url)
3.4.4 Parameterizing

In practice, it is a complicated work to define the behavior of pillar because pillar exhibits different behavior with different geological conditions and pillar dimension. In numerical modeling, some input parameters commonly need to calibrate for matching the expected model results with the field observation. Therefore, this research attempts to add variables into the new developed residual stress formula and then makes the equation more flexibility for matching site-specific coal behavior and easy for modeling calibration. As mentioned above that keeps the residual stress formula having the same format as the peak strength formula, two variables A and B added into the equation 3.2 to replace two default numbers. The parameterized formula is shown in equation 3.3.

\[ S_r = S_1 \times A \times \left( \frac{x}{h} \right)^B \]  

(3.3)

When using this residual stress formula to determine the softening magnitude of coal in LaModel, parameters A and B should be chosen in a boundary. After reviewing the distribution of the stress point, Figure 3.4 illustrate the reasonable upper and lower bound of A and B that A = 1 to 2 and B = 1 to 1.5. It is clear notices that boundary A and B is very satisfaction at the low value of ln(x/h) while the difference between the stress points and the boundary is great at the high level of ln(x/h). The cause of this phenomenon is that most of the collected stress points which experience the peak stress to residual stress locate at the boundary of the pillar which has the low value of distance into a pillar (x).
3.4.5 Characteristics of Strain-softening of pillar

In the given reasonable range of A and B, we should understand the parameters A and B affect the softening behavior of coal and how the residual stress formula affects the strain softening behavior of pillar. Therefore, parameter A and B are given some values and then analyzed the effects of A and B on the strain softening behavior of coal and pillar.

Figure 3.5 show different residual stress trends produced with different values of parameters A and B. The figure also demonstrates the different effect of the two parameters. Increasing parameter A increases every point on the residual stress curve proportional to the point’s distance from the origin. Thus, increasing parameter A essentially swings the curve counter-clockwise about the origin. On the other hand, increasing parameter B causes the coal’s residual strength to increase faster with increasing x/h, essentially simulating a greater increased in residual strength with increasing confinement. Thus, increasing parameter B increases the curvature of the residual stress curve.
Further, in observing Figure 3.5, it needs to be understood that the point where the residual stress equals the peak stress is the point where the material goes elastic, perfectly plastic, and that for any point where the residual stress is greater than the peak strength, the material is then strain-hardening. Therefore, Figure 3.5 also demonstrates how the different values of A and B move the transition point from strain-softening to strain-hardening on the edge of the pillar.

![Graph](image-url)

**Figure 3.5 Post-failure behavior of coal with different A and B**

Figure 3.6 further investigates the behavior of the new residual stress curve by showing the behavior of an entire pillar (60×70×8 ft) modeled with the new residual stress behavior. With the lower values of A and B, the complete stress-strain curve exhibits strain-softening behavior. While increasing parameters A and B will decrease the post-peak modulus of the pillar, and cause the pillar to shift to strain-hardening behavior (see Figure 3.6).
Analyzing Figure 3.6 and Figure 3.7 together shows that when the value of the transition point, from strain-softening to strain-hardening, of the coal, is greater than the half W/H ratio of the pillar, all elements in the pillar have the strain softening behavior and the stress strain curve of the pillar also exhibit strain softening behavior. Otherwise, core elements in the pillar model have strain hardening behavior which begins to transfer the pillar’s behavior from strain softening to strain hardening.

Finally, the new residual stress curve is compared to Karabin and Evanto’s original curve (sees Equation 2.3 and Figure 3.7) in Figure 3.7. This figure shows that the of Karabin and Evanto’s result is essentially equal to one case of the new formula. But, the new equation can also represent a much wider range of behavior.
3.5 Summary

This chapter introduced the development of the residual stress formula and the effects of the new formula on the behavior of coal and pillar. The useful stress change data are collected from 9 different study sites, 3 of them in U.S. and 6 in Australia. Based on this data, a best-fitting formula is developed to determine the residual stress level of coal and then this formula is parameterized with two variables which make the formula more flexible for simulating the behavior of different coal and/or pillar. These two variables actually affect the definition of the softening behavior of coal that parameter An essentially swings the curve counter-clockwise about the origin and B causes the coal’s residual strength to increase faster with increasing x/h. With different A and B, the new developed residual stress formula not only includes the Karabin and Evanto result but also provides a more flexible way for defining the strain softening material model.
Chapter 4 Local Mine Stiffness Calculation in LaModel

4.1 Introduction

Local mine stiffness calculation has been recognized as a promising approach to explore the dynamic pillar failure issues. Using this criterion requires initially determining the local mine stiffness and post failure stiffness of a specified pillar and then comparing to determine the pillar failure in stable or unstable manner. Previous research provided the approach of determining the two values of stiffness. However, current numerical models do not implement a user-friendly plug-in for users to easily and efficiently calculate the stiffness. In order to offset this shortcoming and improve the efficiency, a local mine stiffness calculation utility is implemented into LaModel program with a user-friendly form which guides users using the LMS criterion easily. LaModel has the ability to output the calculation results of two kinds of the stiffness of a designated pillar to users for comparing and analyzing.

4.2 The LaModel Program

The LaModel program (Heasley, K. A, 1997, 1998) is used to simulate the thin tabular deposits such as coal seams by calculating the stresses and displacements on the seam. It uses the displacement-discontinuity (DD) variation of the boundary-element method, and because of this formulation, it is able to analyze large areas of single or multiple-seam coal mines. LaModel is unique among boundary element codes because the overburden formulation includes laminations which give the model a very realistic flexibility for stratified sedimentary geologies and multiple-seam mines. Using the LaModel program, the total vertical stresses and displacements in the coal seam are calculated, and the individual effects of multiple-seam stress interactions and topographic relief can be separated and analyzed individually. LaModel can calculate pillar and element safety factors for analyzing pillar stability and also calculate the surface subsidence resulting from multiple seams, random pillar plans, and pillar failure and gob re-compaction. The LaModel program can analyze a 2000 x 2000 grid with 6 different material models and 52 different individual in-seam materials.

LaModel uses a forms-based operation interface for inputting parameters and a graphical interface for creating the mine grid. LaModel includes a utility referred to as a “Wizard” for automatically calculating coal pillars with Mark-Bieniawski pillar strength and another utility to
assist with the development of “standard” gob properties. The LaModel program is also interfaced with AutoCAD to allow mine plans and overburden contours to be automatically imported into the corresponding seam and overburden grids. Also, the output from LaModel can be downloaded into AutoCAD and overlain on the mine map for enhanced analysis and graphical display.

4.3 Strain-softening in LaModel

Theoretically, the application of the LMS stability criterion implies that pillars should have the softening characteristic in the post failure period because the softening magnitude controls the post-failure stiffness of the pillar. Therefore, the stress-strain curve of the strain-softening behavior of a pillar should be initially generated for obtaining the post-failure softening module. LaModel program has implemented a calculation principle that composites the strain-softening behavior of a pillar based on the defined elements’ behavior and the proportion of each element in this pillar model. Finally, LaModel program can find the minimum value (absolute value) of post-failure pillar stiffness and provide this value in an output file, automatically.

4.3.1 Strain-softening behavior of element and pillar

In LaModel program, pillar model is divided into elements (Figure 4.1) and each element is specified with the unique material model. Even though the elastic-plastic and the strain softening behavior all can be used to describe the behavior of coal in LaModel, this chapter just concerns on the strain-softening behavior because of the usage of the local mine stiffness stability criterion. Figure 4.1 provides a schematic of gridded pillar model which illustrates the element specified with the strain-softening behavior in Figure 4.2.

In LaModel, the strain-softening behavior of element (element i or element j in Figure 4.2) is defined by the calculated value of peak point (peak stress, peak strain) and residual point (residual stress, residual strain). Currently, the peak stress is determined by the stress gradient formula which implied in the Mark-Bieniawski coal strength formula (Equation 4.1), and the associated peak strain level is determined depending on the peak stress and coal elastic modulus (Equation 4.2). The residual stress is determined by the new best-fitted residual formula in chapter 2 (Equation 4.3) and the associated residual strain is calculated by multiplying a strain factor on peak strain (default strain factor is 4 in LaModel) (Equation 4.4).
Figure 4.1 Corner Elements and Side Elements

Figure 4.2 Schematic of strain-softening behavior
\[ S_p(i) = S_1 \times \left( 0.64 + 2.16 \times \frac{x}{h} \right) \]  \hspace{1cm} (4.1)

\[ \varepsilon_p(i) = \frac{S_p(i)}{E} \]  \hspace{1cm} (4.2)

\[ S_R(i) = S_1 \times A \times \left( \frac{x}{h} \right)^B \]  \hspace{1cm} (4.3)

\[ \varepsilon_R(i) = 4 \times \varepsilon_p(i) \]  \hspace{1cm} (4.4)

Where:

- \( S_1 \) = in situ coal strength (psi);
- \( x \) = distance from element center to free face (ft);
- \( h \) = seam height (ft);
- \( E \) = coal seam modulus (psi);
- \( S_p(i) \) = peak stress of element (psi);
- \( \varepsilon_p(i) \) = peak strain (in/in);
- \( S_R(i) \) = residual stress of element (psi);
- \( \varepsilon_R(i) \) = residual strain (in/in);
- \( A \) and \( B \) = residual stress control parameters.

It should be noticed that two kinds of elements, corner element (i-element in Figure 4.1) and side element (j-element in Figure 4.1), exist in the gridded pillar model when calculating the strain softening behavior. These two type elements have an obviously different failure mechanism that the side element has a greater support capacity than the corner element. This difference in LaModel is represented by having a higher peak and residual strength of the side elements than that of the corner elements. Considering the calculation equation 4.1 and equation 4.3, the value of “x”, which means the distance from the center of an element to the nearest free face of the pillar, distinguishes the corner and side element by using \((i - 1 + \frac{1}{2})W\) (where: \(i\) is the element number from the nearest rib \((i=1, 2\ldots)\), \(W\) is the element width) to calculate “x” for corner elements and using \((i - 1 + \frac{1}{2})W\) to calculate a “x” value for side elements. Therefore, each element in pillar model has a unique peak point and residual point to quantify the strain softening behavior.
Against the elements’ behavior, pillar design engineers are more interested in the strain softening behavior of the entire pillar. LaModel program can composite the stress-strain curve of strain softening behavior of pillar from the included elements based on the proportion of each element in the pillar. As shown in Figure 4.3, after knowing the strain softening behavior of each element (such as i, j, k in Figure 4.3), the stress levels of each element ($S_i$, $S_j$, $S_k$ in Figure 4.3) can be calculated at a strain level ($e_a$ in Figure 4.3), then, the stress level of the pillar ($S_a$ in Figure 4.3) at the same strain level ($e_a$) can be determined by averaging the stress of each element in the pillar as shown in Figure 4.3. Along with different strain levels ($e_a$, $e_b$, $e_c$), the LaModel calculate the stress value at each strain level and the stress-stain curve of the entire pillar can be obtained. It should be clarified that this section just explains how does the LaModel composite a strain softening behavior of a full pillar from the behavior of included elements, in face, LaModel does not output the stress-strain curves of pillars but provides a matrix which includes stress values at some specified strain levels on the X-coordinate, as shown in Figure 4.3.

![Figure 4.3 Compositing the pillar behavior from elements](image)

**4.3.2 Strain Softening Wizard in LamPre**

In LamPre, the preprocess suite of LaModel, a user-friendly form of “Strain Softening for Coal” had been implemented into for helping users to define the strain softening behavior through inputting required parameters. LaModel will calculate the post-failure stiffness of a
specified pillar based on these input parameters and output the calculated post-failure stiffness in the output file. The detail is introducing in the following contents.

In LamPre, when the Wizard for Defining In-Seam Material Models dialog window appears, the Strain-Softening for coal wizard tab is the second option (red in Figure 4.4). This form will guide users inputting required parameters for defining the strain-softening material model for coal. The material wizard is designed to automatically generate material properties with respect to the defined yield zone derived from the Mark-Bieniawski pillar strength formula. In Figure 4.4, the Strain-Softening for coal wizard is broken into three groups; 'Geometry Parameters', 'Coal Properties', and 'Yield Zone Definition'. Each of these three groups is described below in more details followed by a short software demonstration for the Strain-Softening Coal Wizard.

![Wizard for Defining In-Seam Material Models](image)

**Figure 4.4 In-Seam Material Definition Form**

'Geometry Parameters' Group: This is the first group displayed in the Strain-Softening for Coal Wizard (area 1 in Figure 4.4). Here the user is presented with information previously defined in the previous 'Seam Geometry Boundary Conditions' dialog window with respect to the displayed seam number and optional pillar width and pillar length.

Current Seam Number: It is important for the user to understand that the seam number displayed, in the associated text box, is the seam for which the generated material properties will apply. For instance, if the seam number displayed is '1', then the wizard defined material properties will be calculated using the appropriate input values from seam '1' and the generated material model will apply to seam'1'. If the seam number displayed is '2', the wizard defined
material properties will be calculated using the appropriate input values from seam '2' and the generated material model will apply to seam '2'. The user can easily toggle between seams using the associated scroll bar.

Extraction Thickness: The value displayed was previously defined by the user as the seam thickness in the 'Project Parameters' form. Therefore, the value cannot be modified in the current form and has been 'grayed out'.

Element Width: The value displayed was previously defined by the user as the Element Width in the 'Project Parameters' form. Therefore, the value cannot be modified in the current form and has been 'grayed out'.

Pillar Width: The value displayed the width of a designated pillar which is given by the user to calibrate the coal strength, parameter A and parameter B (in area 2 of Figure 4.4) for helping users generate the unique strain-softening material. The condition of the textbox is changeable in a different situation and the default value is zero and the associated textbox is locked.

Pillar Length: The value displayed the length of a designated pillar which is given by the user to calibrate the coal strength, parameter A and parameter B (in area 2 of Figure 4.4) for helping users generate the unique strain-softening material. The condition of the textbox is changeable in a different situation and the default value is zero and the associated textbox is locked.

'Coal Properties' Group: This is the second group displayed in Strain-Softening for Coal Wizard form (area 2 in Figure 4.4). Here the user has the ability to input site-specific parameters for the coal material. Modifications can be made to the coal modulus, coal strength, residual strain factor, parameter A and parameter B. The user should recognize that these five parameters are used by the wizard to generate the yield zone materials. All changes must be made before the yield zone is applied by the wizard to have any effect on the model.

Coal Modulus: This value asks the user to define the coal stiffness while in its elastic state given a site-specific modulus respect to the best available data. The program provides a default value of '300,000 psi' which has been globally accepted by the industry. Modifications to this input parameter are not recommended unless the user has a confident value based on adequate knowledge and expertise in rock mechanics and geology.
Coal Strength: Here the user is able to define the site-specific coal strength with respect to the best available data. The program provides a default value of '900 psi' which has been globally accepted by the industry. Modifications to this input parameter are not recommended unless the user has a confident value based on adequate knowledge and expertise in rock mechanics and geology.

Residual Strain Factor: The value displays the relationship between residual strain and peak strain of coal. The program provides a default value of ‘4’ which means the residual strain is 4 times than the peak strain. The number ‘4’ derived from the field data and is commonly used.

Parameter A: This value is used to define strain softening material and the default value is '1.457'. The number '1.457' derived from the field data collection and analysis (see chapter 2). Users can modify this number in the range of 1 to 2. Parameter A can swing the residual stress curve to change the relationship between peak strength and residual strength of coal.

Parameter B: The value is used to define strain softening material and the default value is '1.2799'. The number '1.2799' derived from the field data collection and analysis (see chapter 2). Users can modify this number in the range of 1 to 1.5. Parameter B controls the difference between peak strength and residual strength at a designated x/h ratio. A higher value makes sure a pillar transfer from strain softening to strain hardening behavior quickly, and a lower value of B slows the transformation.

Additional, in the 'Coal Properties' Group, there are three selectable Radio Buttons which are named 'Default Value' 'Calculated Value' and 'Specified Value'. These three Radio Buttons provide three different approaches to users to define the strain softening the material of coal. The details are explained as follow.
Figure 4.5 Strain Softening Definition Wizard with Default Value Option

Default Value: This Radio Button is the first option and this button checked is the default set (see Figure 4.5). In this condition, all the parameters in 'Coal Properties' Group use the recommended default value (coal modulus is 300,000 psi; coal strength is 900 psi; residual strain factor is 4; parameter A is 1.457 and B is 1.2799) to generate the strain-softening material model. However, users can modify the residual strain factor to control the relationship between the post-failure behavior and the relevant strain level.

Figure 4.6 Strain Softening Definition Wizard with Calculated Value Option

Calculate Value: This Radio Button can help users to define strain softening material model follow the specified requirements (see Figure 4.6). In this situation, the textbox of pillar width and pillar length in the 'Geometry Parameters' Group is unlocked and users need to input the
specified pillar dimensions. Meanwhile, in the 'Yield Zone Definition' Group (area 3 in Figure 4.4), users need to give a strength drop percentage value in the textbox of 'Strength Drop Percentage', this number shows the users’ expected difference between the peak strength and the residual strength. Then, the strain-softening material model is calculated based on these input parameters and the 'Coal Strength' 'Parameter A' and 'Parameter B' will be adjusted based on the Mark-Bieniawski peak pillar strength and the users’ expected strength drop percentage.

Figure 4.7 Strain Softening Definition Wizard with Specified Value Option

Specified Value: This Radio Button can help users define strain softening material model follow the specified requirements (see Figure 4.7). In this situation, the textbox of pillar width and pillar length in the 'Geometry Parameters' Group is unlocked and users need to input the specified pillar dimensions. Meanwhile, in the 'Yield Zone Definition' Group (area 3 in Figure 4.4), users need to give a strength drop percentage value in the textbox of 'Strength Drop Percentage', this number shows the users’ expected difference between the peak strength and the residual strength. Then, the strain-softening material model is calculated based on these input parameters and the 'Coal Strength' 'Parameter A' and 'Parameter B' will be adjusted based on the Mark-Bieniawski peak pillar strength and the users’ expected strength drop percentage.

'Yield Zone Definition' Group: This is the final parameter group displayed in the Strain-Softening for Coal wizard form. Here users have the ability to determine the number of sets to be defined as well as the yield zones per set. Each set has an associated number of in-seam materials required which reflects the number of yield zones defined for a given material set. It is important
for the user to plan ahead when building a model such that they are able to define enough materials for use in the preprocessor.

Strength Drop Percentage: The value displayed the difference between the residual stress and peak stress of coal. The number means the drop percentage from the peak strength to the residual stress. Normally, the textbox of 'Strength Drop Percentage' is locked except when the Radio Button of 'Calculate Value' in 'Coal Properties' Group is checked.

Number of Sets to be Defined: Here the user is able to determine the number of material sets defined within the preprocessor. It is often the case that the number of sets is equal to the number of seams defined for a given model. If seam geometries and coal properties between two seams are similar, then it is possible to model both seams using the same material set generated by the wizard.

Current Set Number: This is the second parameter associated with the Yield Zone group. Here users must take caution that the Current Set Number reflects material set necessary for the Current Seam Number displayed. Often users set the current seam and set number equal to each other to ensure that the right in-seam material parameters are correctly defined for their respective seams.

Number of Yield Zones per Set: Here the user can define the width of the yield zone in units of grid elements. The default yield zone width in LaMPre is '1', however it is recommended that for element widths of 10ft and larger, the Number of Yield Zones per Set be defined as '4'. For element widths of 5ft and less, it is recommended that the yield zones per set be defined as '8'.

To the right of the Strain Softening for Coal wizard form (see Figure 4.4), there are five command buttons; 'Material Summary', 'Next Form', 'OK', 'Cancel', and 'Help'. The 'Material Summary' button will open the Summary of Defined Material Models dialog window (see Figure 4.8). Here the user can view all material characteristics; Material Number, Material Character ID, Material, Model Type, Peak Stress, Peak Strain, Plastic Modulus, Poisson's Ratio, and Elastic Modulus from right to left. By selecting the 'OK' command, users will be returned to the Elastic-Plastic wizard form. The 'Next Form' button saves the current input parameter values, closes the current dialog window, and opens the next successive parameter form (Program Controls). The 'Cancel' button will close the dialog window without saving any changes made and return users
to the LaMPre main window. The 'Help' button will bring users back to the Strain Softening Coal wizard section of this on-line users’ manual.

Figure 4.8 Summary of the strain softening material in LaMPre

After saving the LaModel project, there will be a file with “.INP” as the extension generated in the project folder, and the generated strain softening properties for each element were written into this file (see Figure 4.9) which can be read and operated by the LaModel program for further calculation.

There are six columns numbers displayed in the red rectangle area of Figure 4.9. The first column number ‘2’ represents the strain-softening behavior of coal in LaModel (six in-seam material models: 1-Linear Elastic for intact material, 2-Strain Softening for intact material, 3-Elastic Plastic for intact material, 4-Bi-Linear Hardening for gob,5-Strain Hardening for gob,6-Linear Elastic for gob). The second column is the peak strength of element and the third column is the related peak strain values. The forth column is the residual stress of each element and fifth column is the related residual strain values. The sixth column is the Poisson Ratio of coal.
4.3.3 Post-failure stiffness Output

After calculation, LaModel program creates an output file in the same project folder with the “.out” as the extension name. This general output file is used to save all the detail information in the simulation process and includes: formatted input data, lettered mine layout, details of the iterative solution and timing information, etc. If the “local mine stiffness calculation” option is checked in LaMPre and some required parameters for locating the designated pillars have been imputed, LaModel program will calculate the stress values along a series of increasing strain values. These calculated stress with the related strain values write into the output file as shown in Figure 4.10. In this strain and stress group, the strain values are consisted by the peak strain and residual strain of each element as shown in Figure 4.8 (Column #2 and Column #4), and these strain values (left column in Figure 4.10) are sorted in an ascending order and eliminate duplicate values as well as add “0” at the begin and add “1” at the end to make sure developing a full strain-softening behavior of pillar. Then, the pillar stress (right column in Figure 4.10) at each strain level is composited by LaModel automatically based on the proportion of each element in the pillar. After knowing the strain and stress, the maximum post failure modulus of pillar can obtain from the composited stress-strain curve and the maximum post failure stiffness (negative) can be calculated by equation 4.5.
\[ K_P = \frac{E_P \times A}{t} \]  

(4.5)

\( K_P \) = post-failure stiffness of pillar (psi/in);

\( E_P \) = post-failure modulus of coal (psi);

\( t \) = pillar height (in);

\( A \) = pillar area (ft\(^2\)).

<table>
<thead>
<tr>
<th>pillar number 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>0, 0</td>
</tr>
<tr>
<td>0.005520, 1656.00</td>
</tr>
<tr>
<td>0.007320, 2156.43</td>
</tr>
<tr>
<td>0.016320, 3408.07</td>
</tr>
<tr>
<td>0.018120, 3622.88</td>
</tr>
<tr>
<td>0.022080, 3747.64</td>
</tr>
<tr>
<td>0.027120, 3925.57</td>
</tr>
<tr>
<td>0.028920, 3955.47</td>
</tr>
<tr>
<td>0.029280, 3944.76</td>
</tr>
<tr>
<td>0.065280, 3620.87</td>
</tr>
<tr>
<td>0.072480, 3567.25</td>
</tr>
<tr>
<td>0.108480, 3515.78</td>
</tr>
<tr>
<td>0.115680, 3509.12</td>
</tr>
<tr>
<td>1, 3508.51</td>
</tr>
</tbody>
</table>

Figure 4.10 Stress/Strain Value of an Entire Pillar in LaModel Output File

Figure 4.11 shows the stress-strain curve of strain softening behavior of pillar (the blue curve) and also displays the related stiffness curve of the pillar (red curve). The green point on the stiffness curve is the expected minimum value of pillar stiffness. **Please notice, the curve of Figure 4.11 does not appear in the output file but just give the green point value in the output file.**
4.4 Local Mine Stiffness in LaModel

4.4.1 Local Mine Stiffness Calculation Wizard

Currently, a Local Mine Stiffness Calculation form had been built in LaMPre and the code of perturbation method also implemented into LaModel program to help users determining the local mine stiffness around a specified pillar automatically.

When users attempt to use the Local Mine Stiffness Calculation wizard analyzing the potential pillar collapse issues, the checkbox of 'Local Mine Stiffness Calculation' in the 'General Model Information' dialog needs to be checked (Figure 4.12). Then, the Local Mine Stiffness Calculation wizard (Figure 4.13) can be accessed by either clicking 'Next Form' at the bottom of the Program Control Parameters dialog window or by selecting Local Mine Stiffness Calculation from the Edit-Data pull down menu.
When the Local Mine Stiffness Calculation form appears, users will be guided to set four required parameters. These four parameters are used to determine the number of the pillar which will be asked to calculate the local mine stiffness and also used to determine the location of each pillar. The means of each parameter are introduced in following.
Number of Pillar: This input value means how many pillars are expected for the local mine stiffness calculation in LaModel. Currently, the maximum value of this input is '5'. If users input '3', the local mine stiffness around 3 pillars will be calculated during LaModel run.

Current Pillar Number: This value exhibits the number of the current setting pillar. If the 'Number of Pillar' is '5' and the current pillar number is '3', it means that the user is setting the third pillar now.

X,Y Coordinate: These two values are a coordinate of one element in the pillar. LaModel has a function to locate a full pillar by using the coordinate of one element in the pillar. Therefore, the coordinate (X, Y) is used to locate the pillar location in a mine layout.

4.4.2 Local Mine Stiffness Output

Similarly, the detailed calculation processes of the local mine stiffness and results are also written to the output file. As mentioned in chapter 2, two steps involved in the local mine stiffness calculation: pillar in and pillar out. Therefore, the output information displays the result respectively. In Figure 4.14, A and B present the calculation information in these two steps. “LMS Pillar 0” in the red rectangle of Figure 4.14A indicates the first-step calculation that pillar in the mine layout (step 1 in Figure 2.4), and “LMS Pillar 1” in the red rectangle of Figure 4.14B means the second-step calculation that the designated pillar is removed (perturbation) from the mine layout (step 2 in Figure 2.4).

```
Step 1, Seam 1, Level 3 - SOR took 6845 iterations 108 secs to converge
Entering SOR - Step 1, LMS Pillar 0, Seam 1, Level 3

Step 1, LMS Pillar 0, Seam 1, Level 3 - SOR took 1 iterations 0 secs to converge
Entering SOR - Step 1, LMS Pillar 0, Seam 1, Level 2
Step 1, LMS Pillar 0, Seam 1, Level 2 - SOR took 1 iterations 0 secs to converge
Entering SOR - Step 1, LMS Pillar 0, Seam 1, Level 1
Step 1, LMS Pillar 0, Seam 1, Level 1 - SOR took 1 iterations 0 secs to converge
Entering SOR - Step 1, LMS Pillar 0, Seam 1, Level 0
Step 1, LMS Pillar 0, Seam 1, Level 0 - SOR took 1 iterations 1 secs to converge
```

A. Pillar in
B. Pillar out

Figure 4.14 Local Mine Stiffness Calculation Process in output file

The output file also provides the calculation result of the local mine stiffness and post failure stiffness of the specified pillars as shown in Error! Reference source not found.. This information includes model run steps; numbers of the pillar; coordinate of one element in a pillar; initial stress; final stress; initial displacement; final displacement; the maximum value of local mine stiffness and the failure of pillar stiffness.

Figure 4.15 Local Mine Stiffness Calculation Result

4.5 Summary

This chapter briefly introduces the LaModel program, the calculation principle of the strain-softening element behavior in a pillar model, the method of compositing the pillar behavior from elements behavior, the wizard of strain softening definition and local mine stiffness calculation in LaMPre and the output of the calculation result of these two stiffness values in the output file. The user-friendly wizard in LaMPre provides users an efficient way to input the required parameters, and the output file provides users an easy way to find and compare the post failure stiffness and local mine stiffness of the specified pillars.
Chapter 5 Parametric Evaluation on LMS Criterion in LaModel

5.1 Introduction

An efficient and accurate numerical simulation relies on the exact input parameters and a clear understanding the effect of parameters on the simulation process. However, the complicated geologic condition in underground blocks engineers achieving the precise expected parameters. Therefore, the alternative method for accurate numerical modeling is evaluating and understanding how the required parameters impact the modeling results.

This chapter analyzed a carefully designed multifunctional model for evaluating the effects of parameters in LaModel on the usage of the local mine stiffness stability criterion. Through single-parameter analysis and multiple parameters mutual analysis, assessment results enable us understanding the influence magnitude of different parameters on local mine stiffness criterion calculation and help users determining the optimal parameters and then use this criterion in LaModel efficiently.

5.2 Potential Influence Parameters

As the local mine stiffness criterion includes the determination of the post-failure stiffness and mine stiffness of a pillar, the potential influence parameters should be considered from these two aspects that affect the stiffness calculation.

Philosophically, nature determines phenomenon. Therefore, the mathematic background of LaModel program is initially reviewed for seeking the inherent influence parameters. The fundamental second-order, elliptical, partial differential equation (K. A. Heasley, 1998; Salamon, 1963) is presented in equation 5.1.

\[
\frac{\partial^2 S}{\partial x^2} + \frac{\partial^2 S}{\partial y^2} = \frac{2}{E\lambda} \sigma_i \tag{5.1}
\]

In equation 5.1, S is the vertical seam convergence and \( \sigma_i \) is the vertical induced stress in the overburden. E is the elastic modulus of the overburden laminations. \( \lambda \) is a property of the laminated overburden as defined by Equation 5.2. Obviously, the magnitude of \( \lambda \) depends on the strata lamination thickness (t) and the Poisson’s ratio of overburden laminations (\( v \)).
\[ \lambda = \sqrt{\frac{t^2}{12(1 - \nu^2)}} \] (5.2)

In equation 5.1, the induce stress value \( \sigma_i \) for an element is the summation of a number of components which include: the primitive or overburden stress \( \sigma_q \), the seam material or coal stress \( \sigma_c \), multiple-seam interaction stress \( \sigma_m \) and the surface effect stress \( \sigma_s \), and their relationship is shown in equation 5.3.

\[ \sigma_i(S) = -\sigma_q + \sigma_c(S) - \sigma_s(S) - \sigma_m(S) \] (5.3)

Assuming an opening in a seam, either in the simplest condition that just consider the overburden stress or in a complicated situation that considers those four stress components in Equation 5.3, the preliminary induced stress \( \sigma_i \) is equal to the negative of the primitive or overburden stress \( \sigma_q \) and then these four stress components will be calculated with the calculated displacement \( S \) in each iteration. Therefore, the calculation of the displacement \( S \) is mainly controlled by the stiffness of rock mass. Based on equation 5.1 and equation 5.2, the stiffness of the rock mass is primarily determined by the rock mass modulus \( E \) and the rock mass lamination thickness \( t \) in LaModel program (Heasley, K. A; 2009, 1997, 1998). Generally, increasing the modulus or the lamination thickness of the rock mass will increase the stiffness of the overburden. Since changes in either the modulus or lamination thickness cause a similar response in the model, it is most efficient to keep one parameter constant and only adjust the other. When calibrating the rock mass stiffness, it has been found to be most efficient to initially select a rock mass modulus and then solely adjust the lamination thickness for the model calibration.

Beyond this, the geometry/arrangement of underground pillars system also affects the usage of the local mine stiffness stability criterion. Obviously, if mining has a low excavation ratio, pillar should be more stable; while with a high excavation ratio, a pillar should support more overburden load and has a more potential failure in an unstable manner. But we should note that the pillar system is changing along with the mining activities, the induced secondary pillar system has a more important influence on the LMS criterion.

Considering another part in the local mine stiffness criterion, the post-failure stiffness of a pillar is controlled by the softening magnitude in the post-peak period of the pillar. As
introduced in the previous chapter, the strain softening behavior in LaModel is defined by the peak point (strain/stress) and related residual point (strain/stress) on the stress-strain curve of the pillar. Figure 5.1 illustrates three scenarios of varying the residual point on the strain-softening curve and explains how the changing influence the softening magnitude in the post-peak period and how the changing affect the usage of LMS criterion.

In LaModel program, with the maturely quantified peak point, the residual point mainly controls the softening magnitude. However, with limit field date, the determination of the residual strain is still a vacant research area. Therefore, this chapter analyzed the influence from the residual stress equation (Equation 3.3) which was formalized with more extension field stress data. As two variables in equation 3.3 control the magnitude of the residual stress level, parameter A, and B are recognized as two influence parameters which will be evaluated.

Figure 5.1 Scenarios of residual point affecting the relationship of $K_{LMS}$ and $K_p$

Summarily, this chapter will analyze the effect of three factors on the LMS criterion: the lamination thickness (t) (for mine stiffness), the initial and changing geometry/arrangement of pillar system (for mine stiffness); Parameter A and B (for pillar stiffness).

5.3 Parametric Analysis on a Validation Model

5.3.1 Validation Model

In order to evaluate the effect of these possible influence parameters, Figure 5.2 provides a simple but multifunction model which will be simulated in LaModel program to validate, analyze and document the effects on the local mine stiffness criterion.

Figure 5.2 provides a validation model that the pillar dimension is 80×80 ft and the seam is 6ft high with an elastic modulus of 300,000 psi and 600 ft deep. Symbol D is the opening
distance from the central pillar to the surrounding pillars. Different values of D imply the free space (excavation ratio) around the central pillar and D also used to explain the effect of the surrounding pillars on the central pillar. Table 5.1 provides the default (initial) value of each parameter.

![Diagram showing the relationship between the central pillar and surrounding pillars with a distance (D) from the central pillar to the surrounding pillars.]

**Figure 5.2 Parameters Calibration Model**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamination thickness(ft)</td>
<td>50</td>
</tr>
<tr>
<td>Opening Distance (D)(ft)</td>
<td>500</td>
</tr>
<tr>
<td>Parameter A</td>
<td>1.4570</td>
</tr>
<tr>
<td>Parameter B</td>
<td>1.2799</td>
</tr>
</tbody>
</table>

**Table 5.1 Default Value of input Parameters**

---

5.3.2 Lamination Thickness

In order to evaluate the effect of the lamination thickness, in this validation model, the value of lamination thickness varies from the default value 50 ft to a maximum value of 500 ft (50ft, 100 ft, 200 ft, 300 ft, 400 ft, 500 ft). The mine stiffness of the central pillar is calculated along the increasing lamination thickness and results are plotted in Figure 5.3.
Figure 5.3 illustrates that the local mine stiffness of the central pillar decrease (positive value increase) as the increasing lamination thickness. Therefore, based on the local mine stiffness stability criterion, the greater the lamination thickness, the less possibility the pillar failure in the unstable manner of the central pillar.

![Graph showing the relationship between Lamination Thickness and Local Mine Stiffness](image)

Figure 5.3 Lamination thickness vs. local mine stiffness of central pillar

### 5.3.3 Geometry of Pillar System

As mentioned above, the pillar geometry uses index D (distance from central pillar to the surrounding pillar as shown in Figure 5.2) to assess the effect on the local mine stiffness stability criterion. In this evaluation, D varies from 100 ft to 500 ft (100 ft, 200 ft, 300 ft, 400 ft, 500 ft) while other parameters at a constant value. The relationship between the local mine stiffness of the central pillar and the D value is shown in Figure 5.4. Clearly, increasing the opening distance (D) increases (decrease in negative value) the local mine stiffness of the central pillar, but the changing is slight and the value of stiffness keep a high level in this validation model.
Figure 5.4 Local mine stiffness behavior as a function of mine geometry

Considering the lamination thickness and opening distance together in Figure 5.5 and Figure 5.6. Figure 5.5 shows that, increasing the opening distance, the mine stiffness of central pillar changes slightly at low lamination thickness and that change obviously at high lamination thickness. Therefore, as the lamination thickness increase, the opening distance has a more potential influence on the mine stiffness calculation.

Figure 5.5 Mine stiffness with different $t$ and $D$
Figure 5.6 shows that increasing the lamination thickness, the mine stiffness of central pillar changes obviously at a low D level and that change slightly at a high D level. Therefore, as the opening distance increase, the lamination thickness has a decreasing influence magnitude on the mine stiffness calculation.

![Figure 5.6 Mine stiffness with different t and D](image)

### 5.3.4 Parameter A and B

The residual stress level on the stress strain curve of strain softening controls the softening magnitude in the post failure period of a pillar which implies controlling the post failure modulus which indirectly impact the post failure stiffness of pillar. Equation 2.3 indicates that increasing parameter A will swing the curve counter-clockwise about the origin and increase parameter B will increase the curvature of the residual stress curve.

When evaluating the effect of parameter A on the LMS criterion, the value of A varies from 1.1 to 1.9 (1.1, 1.2, 1.5, 1.7, 1.9) and keeps B at a constant value (the default value 1.2799). When evaluating the effects of parameter B on the LMS criterion, the value of B varies from 1.1 to 1.5 (1.1, 1.2, 1.3, 1.4, 1.5) and keeps A at a constant level (default value 1.457). After calculating, the results plotted in Figure 5.7 and Figure 5.8 for parameter A; Figure 5.9 and Figure 5.10 for parameter B.

Figure 5.7 and Figure 5.8 show that increasing the value of A will increase the peak pillar strength slightly and increase the residual strength level which means decreasing the absolute
value of the post-failure modulus of the pillar. Based on the LMS stability criterion, increasing the value of A will have a possible pillar failure in a stable manner.

Figure 5.7 Pillar stress strain curve with varying A and Constant B

Figure 5.8 Maximum post failure pillar stiffness with varying A and Constant B

Figure 5.9 and Figure 5.10 indicate that increasing the value of B slightly impact the peak pillar strength of the pillar but decreases the absolute value of the post-failure modulus of pillar; integrating LMS criterion, increasing the value of B decrease the absolute value of post failure stiffness of pillar which implies the stability of pillar would be stronger.
Figure 5.9 Pillar stress strain curve with varying B and Constant A

Figure 5.10 Maximum post failure pillar stiffness with varying B and Constant A

Furthermore, Figure 5.11 investigates the stress strain behavior of pillar combining different values of A and B. Results states that with the lower values of A and B, the complete stress-strain curve exhibits strain-softening behavior. While increasing parameters A and B will decrease the post-peak modulus of the pillar, and cause the pillar to shift to strain-hardening behavior (see Figure 5.11).
5.5 Summary

This chapter analyzed some effect factors to the using of the local mine stiffness criterion in LaModel program. From the mathematic principle of LaModel and the calculation method of the local mine stiffness criterion, the lamination thickness, geometry of pillar system and two parameters of A and B in the residual stress formula are analyzed. Based on the calculation, the relationship between the lamination thickness and the local mine stiffness is the direct proportion that increasing the lamination thickness should increase the absolute value of the local mine stiffness. The increasing surrounding opening will decrease the absolute local mine stiffness of pillar. Parameters A and B affect the post-failure stiffness of the pillar that increasing A and B will decrease the absolute value of post-failure stiffness of pillar. Therefore, changing of these influence factors will affect the usage of the local mine stiffness stability criterion.

Figure 5.11 Stress strain curve with different A and B
Chapter 6 LMS Criterion in Case

6.1 Introduction

Previous chapters introduced the fundamental principle of the local mine stiffness stability criterion and fitted out the controllable variables for defining the strain-softening behavior of coal as well as analyzed the effects of some critical parameters on the application of the local mine stiffness criterion in LaModel program. However, it is still doubtable for us of using the local mine stability criterion to explore the potential dynamic pillar failure issues, and also problematic whether the analysis results of the parameters can actually guide us choosing the optimal parameters for an accurate simulation. As well known that “Practice is the sole criterion for testing theory”, the research should be verified in case studies.

Back-analyze is a very useful approach in mining engineering and another engineering area. It helps engineers not only determining the accurate input parameters but also providing a guideline for the future work by comparing different working condition. In this chapter, two kinds of dynamic pillar failure issues, pillar bump and cascading pillar failure, are back analyzed to verify the local mine stability criterion and the sensitivity of influence parameters.

6.2 Application of LMS criterion on Crandall Canyon Mine

Previously, Heasley (Heasley, 2009) had performed an excellent back analyze of the pillar collapse accidents in Crandall Canyon mine in LaModel program. He careful calibrated three critical input parameters (rock mass stiffness, modulus for gob, coal strength) and provided the best simulation of what real happened at Crandall Canyon Mine. However, Heasley using Karabin and Evanto (Karabin and Evanto, 1999) formula to confirm the strain softening behavior of coal, which was interpreted from a couple of case studies and the properties are only “first approximations” and must be verified for accuracy.

In this section, the new developed residual strength calculation formula is used to settle the strain softening behavior of coal; the dynamic pillar failure is analyzed to evaluate the flexible of the strain-softening behavior and the rationality of the LMS criterion.
6.2.1 Dynamic Pillar Failure Description

The Crandall Canyon Mine, formerly Genwal Mine, located near Huntington in Emery County, Utah.

On March 7th, 2007, a non-injury coal outburst accident in the north barrier pillar section (Figure 6.1) occurred that knocked miners down, damaged a ventilation control, and caused a delay in mining. These worsening conditions culminated in a March 10th, 2007, outburst accident of sufficient magnitude to cause the north barrier section to be abandoned.

On August 3rd, 2007, another non-injury coal outburst accident occurred as the night shift crew was mining. Coal was thrown into the entries dislodging timbers and burying the continuous mining machine cable. The continuous mining machine operator was struck by coal.

On August 6th, 2007, the pillar collapse in the south barrier section occurred and entrapped six miners. It appeared that a large area of pillars in the Main West and South Barrier sections of the mine had bumped in a brief time period, filling the mine entries with coal from the failed pillars and entrapping the six miners working in the South Barrier section.

On August 16th, 2007, during the heroic rescue effort, another bump occurred thereby killing three of the rescue workers, including one federal inspector, and injuring six other rescue workers.

A few days after the August 16th incident, a panel of ground control experts determined that the Main West area was structurally unstable and underground rescue attempts halted. Subsequently, the mine was abandoned and sealed.

Since both accidents at Crandall Canyon Mine were essentially ground control failures, factors such as geology, mining dimensions, ground support, and mining method have direct or indirect relevance to the accident or implications regarding conditions encountered afterward.
Figure 6.1 Map of Main West Area of Crandall Canyon Mine
6.2.2 Parameters and Simulation Results

The LaModel simulation of the Main West area encompassed all of the concerned areas including the entire Main West, North Barrier, and South Barrier Sections within one grid as shown in Figure 6.1. The boundaries were established to include the full abutment loading from both the northern and southern longwall mining districts for at least a couple of panels.

In the model grid, 10ft wide elements were used and overall dimensions were set at 570 elements in the east-west direction and 390 elements in the north-south direction. The topography grid was developed that was 1500ft wider on all 4 sides than the model grid and used 100ft wide elements on an $87 \times 69$ element grid. The actual mine grid and topography grid was automatically generated from the AutoCAD mine map with the Stability Mapping plug-in.

The lamination thickness was set at 500ft, the final modulus of the north gob (panel 11 and 12 in figure 5.1) was set at 250,000 psi, and the final modulus of the southern gob (panel 13 and 14 in figure 5.1) was set at 160,000 psi. The coal strength in the North and South Barrier sections was set at 1300 psi and coal strength in the Main West was set at 1360 psi. For the strain softening coal behavior, after parametric calibration, parameter A is determined as 1.311504 and B is 1.152089, and the residual stress was 33% reduction from the peak stress.

After calibrating these optimum parameters, an eight-step model was developed and performed to meet the following critical field observations:

1. the Main West Section should be stable in development;
2. the North Barrier Section should be stable in development;
3. the pillar failure in the North Barrier Section;
4. the South Barrier Section should be stable in development;
5. retreat of the South Barrier Section;
6. cascading pillar failure in the South Barrier Section.

After the bump event, pillar failure should cover the middle portion of the South barrier Section and extend out by to crosscut 122 to 124. Also, pillar failure (and pillar bumps) should extend into the face area at least to crosscut 138 with some moderate pillar bumping at crosscut 142 (as indicated by the drill holes).
The simulation results are shown in Figure 6.2 to Figure 6.10. (Please note: the safety factor in the following figures are stress-based pillar safety factor which can easily explain whether a pillar failed or not)

**Figure 6.2 Main West Section stable on development**

**Figure 6.3 North Barrier Section Stable on Development**
Figure 6.4 Retreat North Barrier Section to Crosscut 137-138

Figure 6.5 Pillar Bump at Crosscut 134-135
Figure 6.6 South Barrier Section Stable on Development

Figure 6.7 Retreat Line at Crosscut 142
Figure 6.8 Slab Cuts into the Southern Barrier Section

Figure 6.9 Trigger the Cascading Pillar Failure of August 6th, 2007
Figure 6.10 Element Safety factor after the Pillar Collapse

The model results illustrated in above figures agree reasonably well with the underground observation. Figure 6.2 shows the development of the main west section, the safety factor of this area is between 1.0 and 1.6 which means these pillars are stable. Figure 6.3 shows the development of north barrier section, pillars are stable even though the safety factor close to 1. Figure 6.4 shows the retreat line at crosscut 137-138 where the pillar became unstable and where a couple of pillar rows were then skipped. Figure 6.5 shows after mining a couple of pillars between crosscuts 134 and 135, a bump (pillar failure) occurred that affected: the two rows of pillars inby, a number of pillar ribs and the barriers to the bleeder entry, and one to two rows of pillars outby crosscut 134. At this point, the section was abandoned and sealed shortly after that. Figure 6.6 shows the stable development of the southern barrier section. Figure 6.7 shows the retreat line at the crosscut 142 and three pillars in the working face began to unstable. Figure 6.8 shows slab cut into the southern barrier section when more pillar has a low safety factor. Figure 6.9 simulates the cascading pillar failure on August 6th, 2007. Figure 5.10 shows the individual element safety factors calculated by the model after the South Barrier section was developed and retreated to its final configuration.

As mentioned above, the primary of using LMS criterion is determining the minimum value of post failure pillar stiffness and local mine stiffness around a/some specified pillar(s). Therefore, the following analysis focuses on the two occurred and recorded pillar collapse on Crandall Canyon mine and follows the procedure of determining the post failure pillar stiffness from the composited
stress strain curve of pillar firstly and then, calculated the local mine stiffness of the specified pillar in LaModel with perturbation approach.

6.2.3 LMS Criterion in North Barrier Section

The March 10\textsuperscript{th}, 2007 outburst accident occurred in the Main West northern barrier pillar section (Figure 6.1). North barrier pillar section is a four entries system that average pillar dimension is 60 × 70ft (see Figure 6.11) and entry is 20ft in width. Pillar recovery was retreated from west to east and operations were that two of the three pillars in each row were extracted while the third pillar between the No. 3 and 4 entries was not mined to provide a bleeder entry.

The pillar model of northern pillar section in LaMPre is illustrated in Figure 6.11. The 60 × 70 ft pillar is divided by 10ft element into 6 × 7 grids. With the calibrated coal strength (1300 psi) in the northern barrier section, each element has its own unique strain softening behavior which can be explained by Figure 6.12 and Table 6.1. The composited stress strain curve of strain softening behavior of the pillar and the minimum post failure stiffness of the pillar are shown in Figure 6.13.

![Figure 6.11 Gridded Pillar Model of North Barrier Section](image)

<table>
<thead>
<tr>
<th>Code</th>
<th>Peak Strength ($S_p(i)$) (psi)</th>
<th>Peak Strain ($\varepsilon_p(i)$) (in/in)</th>
<th>Residual Strength ($S_R(i)$) (psi)</th>
<th>Residual Strain ($\varepsilon_R(i)$) (in/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>2002</td>
<td>0.00667</td>
<td>622</td>
<td>0.01335</td>
</tr>
<tr>
<td>N</td>
<td>2587</td>
<td>0.00862</td>
<td>992</td>
<td>0.01725</td>
</tr>
<tr>
<td>M</td>
<td>5512</td>
<td>0.01837</td>
<td>3071</td>
<td>0.03675</td>
</tr>
<tr>
<td>L</td>
<td>6097</td>
<td>0.02032</td>
<td>3518</td>
<td>0.04065</td>
</tr>
<tr>
<td>K</td>
<td>9022</td>
<td>0.03007</td>
<td>5852</td>
<td>0.06015</td>
</tr>
<tr>
<td>J</td>
<td>9607</td>
<td>0.03202</td>
<td>6336</td>
<td>0.06405</td>
</tr>
</tbody>
</table>
Secondary, four pillars near the pillar collapse area are designated as shown in Figure 6.14 to determine the local mine stiffness. After inputting accurate parameters in the “Local Mine Stiffness Calculation” wizard, LaModel finally output the local mine stiffness of these pillars in the “output” file. However, the “output” file just gives the minimum value of local mine stiffness of

Figure 6.12 Strain Softening Behavior of Element

Figure 6.13 Stress Strain Curve of Pillar and Minimum Post Peak Pillar Stiffness

Kp = -601.8 (psi/in)
these specified pillars alone the model run process, in order to understand how the local mine stiffness changing, Figure 6.15 plots the stiffness changing process of these pillars during each perturbation, and Figure 6.15 also includes the entire pillar stiffness from pre-failure to post-failure period.

![Diagram showing four specified pillars for LMS calculation](image)

**Figure 6.14 Four specified pillars for LMS calculation**

![Graph showing comparisons of pillar stiffness and local mine stiffness](image)

**Figure 6.15 Comparisons of the pillar stiffness and local mine stiffness**

Clearly, the analysis result of the northern pillar outburst did not obey the local mine stiffness criterion. The comparison of stiffness in Figure 6.15 indicates that the pillars should be stable due to the absolute value of local mine stiffness of the specified pillars is much greater than the minimum post failure stiffness of pillar ($K_{LMS} > |K_p|$), however, the pillar outburst occurred in the
northern pillar section on March 10, 2007, when mining the first cut of the southernmost pillar from the No. 1 entry between crosscuts 133 and 134.

Initially, it is necessary to explore the possible reasons of causing the pillar outburst in northern pillar section. The increasing of the overburden depth is the first possibility of resulting in the pillar outburst. As shown in Figure 6.1, the overburden depth of the northern pillar section, from east to west is increasing from initial 1600 ft (crosscut 156) to 2000 ft (crosscut 141) to the deepest 2240 ft (crosscut 132) to 2000 ft (crosscut 125) and decrease gradually after crosscut 124. The deepest section is between crosscut 126 and 139 and the pillar bump area, between crosscut 131 and 139, locates the beginning of the deepest part of northern pillar section. The second possibility is the formed cantilever structure in the roof strata. The immediate roof of Crandall Canyon mine typically consists of 0 to 2 ft of interbedded siltstone, shale, and sandstone overlain by bedded sandstone. Normally, strong roof strata do not cave immediately as pillars were removed, especially in this case that the pillar system is too narrow to promote good caving, therefore, resulting in higher stress in the pillars being mined, or even though the immediate roof near the excavation failed, the higher strata may simply sag onto the fallen lower layers forming the cantilever structure that one end falls into the void and other end inserts the inner of the up side of the working face. This cantilever structure transfers the overburden load at either of its ends. This distribution of overburden stress is usually the highest near the excavation and lessens with distance away from the caved area.

Therefore, the possibility of violating the LMS criterion in this scenario is various, including the coal behavior definition, the effect of geological conditions and the limitation of the LaModel program, etc. Firstly, parameter A and B have little effect on the violation in this scenario. After calibrating parameter A and B based on the expected drop percentage of residual stress against the peak stress and then matching the LaModel results with the field observation, A and B are given an appropriate value to quantify the strain softening behavior of elements and then the entire pillar behavior is also determined as well as the immovable minimum post failure stiffness of pillar. Comparing the default value of A and B in this case, the calibrated A and B are smaller that should reduce the minimum post failure stiffness of the specified pillar, but the difference is tiny and does not influence LMS criterion strongly. Secondly, the lamination thickness is possible effect on the violation of the LMS criterion. As mentioned above, the calibrated lamination thickness is 500 ft in
Crandall Canyon Mine model. In fact, 500 ft lamination thickness is really a high value, which means the overlaying strata are very stiffness. The validation model in chapter 4 indicated that, when other influence factors keep constant, increasing the lamination thickness should increases the absolute value of the local mine stiffness and the pillar should fail in stable manner. Therefore, high lamination thickness should violate the LMS criterion easily. Thirdly, the pillar geometry of the northern section is another possible reason of violating the LMS criterion. As shown in figure 5.1, the entry and crosscut is 20 ft, which means the pillar geometry index D has a small value. Depending on the validation model in chapter 4, decreasing D should increases the absolute value of local mine stiffness of pillar and it is more hard using the LMS criterion to explore the unstable, violent pillar failure. The possibility of violating the LMS criterion exists in the perturbation process of the local mine stiffness calculation. In the back analysis of Crandall Canyon mine, the “perturbation method” is total removing the specified pillar directly, then obtains the local mine stiffness by comparing the “displacement and stress” of the specified pillar in and out its location, therefore, as illustrated in figure 5.16, the $|K_{LMS}|>|K_P|$ is probability happening at each perturbation step in this scenario. If just removing one or some elements in pillar for each perturbation step, it may find a “x” step where $|K_{LMS}|<|K_P|$, which is shown in figure 5.16.

![Figure 6.16 A possible perturbation step “x”](image)

**6.2.4 LMS Criterion in South Barrier Section**

This scenario analyzes the cascading pillar failure occurred on **August 6th, 2007** in Crandall Canyon mine. This accident caused a large area of pillar collapsed in short period in the Main
West and South Barrier sections and filled the mine entries with coal from the failed pillars and entrapped six miners.

The south barrier pillar section uses four entries system. The average pillar dimension was 70 × 110ft and the entries and crosscuts were 8ft in height and 18 feet in width. Pillar retreat operations were that two of the three pillars in each row were initially extracted while the third pillar between the No.3 and 4 entries was not mined between crosscuts 149 and 142 to ensure that a minimum 50-foot barrier remained.

The same procedure as analyzing the pillar bump in Northern section, the post failure pillar stiffness should initially be determined and then calculates the local mine stiffness of some designated pillars in the southern pillar section.

As shown in Figure 6.17, the average 60 × 110 ft pillar model of south pillar section is divided by 10ft element width into 6 × 11 grids. With the same strain softening behavior of coal which is shown in Table 6.1 and Figure 6.12. The composited stress strain curve of strain softening behavior of pillar and the minimum post failure stiffness of this pillar are shown in Figure 6.18.

![Figure 6.17 Gridded Pillar Model in South Barrier Section](image-url)
In order to evaluate the LMS criterion based on the pillar collapse on August 6th, 2007, a five-step (Step 1 to 5 in Figure 6.19) sub-model was built and two pillars (red in Figure 6.19) were specified to determine the local mine stiffness. The first step was the extraction of the initial 14 pillars and the slab cut at the end of the section. Then, steps 2 through 3 were successive slab cuts into the southern barrier pillar, and finally, two pillars were removed in steps 4 and 5 at the location of the mining when the collapse occurred.

After simulating, LaModel finally output the local mine stiffness of these pillars in the “output” file. Similarly, “output” file just provides the minimum value of local mine stiffness alone the model run process, in order to understand how the stiffness changing. Figure 6.20 plots the value changing process of two pillars during each perturbation process, and Figure 6.20 also includes the changing process of the pillar stiffness from pre-failure to post-failure.
As seen in the Figure 6.20, during steps 1 to 3, the mine stiffness at the location of Pillar 1 and 2 was relatively stiff. But as slab cut 3 was taken and then the pillar in step 4 was removed, the mine stiffness “decreased” (a decrease in the absolute value) dramatically, until the mine stiffness approached the pillar stiffness curve at mining step 4. At this mining step, even though the number of two stiffness does not obey the LMS criterion strictly, the local mine stiffness is very close to the stiffness of the pillar and LMS theory would suggest that a dynamic failure could possible occur, and we certainly know there was a multiple pillar collapse/bump at the mine at approximately this point in the mining sequence.

Comparing the pillar system of the north and south pillar section of Crandall Canyon mine, pillar dimension in south section is bigger than north section that means a higher support ability of the south section pillar, and furthermore, the trigger location of August 6th pillar bump does not under the deepest overburden depth. However, the cascading pillar failure real happened, therefore, this cascading pillar failure possibly is due to the formed cantilever structure in the roof strata. Another possibility is the failed pillars in the Main West section, Figure 6.8 shows that whenretreating the south pillar section, the safety factor of some pillars in the Main West section is lower than 1 (lowest is 0.2), those failed pillars transferred more overburden load on the south pillar section, especially at the crosscut 139 to 128 where bumps happened.

Besides, these two specified pillar showing an obedience, even though not very strictly, of the LMS criterion is possibly that failed pillars in main west provides a big void space around the
specified pillars in south section. The validation in chapter 5 shows that increasing the value of “D” will reduce the absolute value of the local mine stiffness and approaching the absolute value of the post failure stiffness of a pillar.

6.3 Harlan Model Pillar Bump

This scenario analyzed a pillar bump case named “Harlan Model” which was from the publication of Newman (Newman, 2008).

The Darby seam has been extensively mined in Harlan County, Kentucky (the location of the case studies) since the early 1900’s. The coal in this seam is of metallurgical grade with low sulfur, high BTU, and is suitable as a stoker coal. The coal itself is brittle and strong with in-situ strength of 984 psi, based on physical tests. The Darby seam is also known for coal bumps due to the unique combination of geology, high topographic relief, and stiff overburden/interburden characteristics (Newman, 2008; Sears, 2009).

The immediate roof of Darby seam varies by location, but is typically about 50 ft of competent sandstone. The immediate floor is also competent rock typically consisting of hard shale or sandy shale. Long steep ridges characterize the local topography in the area with relief ranging from 1,800 to 2,000 ft. This means that even though mines typically access the coal seam from the outcrop, overburden depths from 1,000 to 1,500 ft can be reached very quickly.

Multiple seam mining is also practiced in the area and the ability to stack pillars is not typically possible. This situation occurs because different operators who do not wish to divulge proprietary information often conduct mining simultaneously, seams have different mineral owners who wish to maximize their own recovery, or old working may have random pillar layouts with remnant and/or irregularly shaped pillars (Sears, 2009). This means that the contributing mechanisms for coal bumps in the area may be: thick overburden, massive competent formations surrounding the coal seam, and stress concentrations multiple seam mining.

6.3.1 Pillar Bump Occurrence

In this mine, the panels are five entries wide with pillars spaced on $80 \times 90$ ft centers. To provide clearance for mining equipment, the mining height ranges between 4.4 to 5.8 ft with 5.5 ft being the typical mining height. The mining plan is to drive the long panels, from a sub-main, connect to a set of bleeder entries, and retreat mine to the mouth of the panel. Five distinct retreat
mining cut sequences (Newman, 2008) were used at the mine in attempt to overcome operational limitations associated with the reach of the continuous haulage system and later to avoid situations where coal bumps could occur. Over a one-year period, eight bumps occurred as shown in Table 6.2.

Table 6.2 Timing, Location, and Circumstances of Coal Bumps
(after Newman, 2008)

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Section</th>
<th>Cross-cut</th>
<th>Entry</th>
<th>Cover</th>
<th>Plan</th>
<th>Lift</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4/9/2002</td>
<td>5-Lt</td>
<td>57-58</td>
<td>4</td>
<td>1,800'</td>
<td>Close in Middle</td>
<td>?</td>
</tr>
<tr>
<td>2</td>
<td>5/4/2002</td>
<td>4-Lt</td>
<td>66-67</td>
<td>3</td>
<td>1,850'</td>
<td>Close in Middle</td>
<td>?</td>
</tr>
<tr>
<td>3</td>
<td>9/6/2002</td>
<td>3-Lt</td>
<td>81-82</td>
<td>3</td>
<td>1,950'</td>
<td>Close in Middle</td>
<td>9A</td>
</tr>
<tr>
<td>4</td>
<td>1/7/2003</td>
<td>2-Lt</td>
<td>79-80</td>
<td>3</td>
<td>1,950'</td>
<td>Close in Middle</td>
<td>36</td>
</tr>
<tr>
<td>5</td>
<td>2/21/2003</td>
<td>1-Lt</td>
<td>74-75</td>
<td>2</td>
<td>2,000'</td>
<td>Close in # 5</td>
<td>28</td>
</tr>
<tr>
<td>6</td>
<td>3/5/2003</td>
<td>1-Lt</td>
<td>58-59</td>
<td>4</td>
<td>1,400'</td>
<td>Close in # 4</td>
<td>36</td>
</tr>
<tr>
<td>7</td>
<td>4/8/2003</td>
<td>2-Lt</td>
<td>11-12</td>
<td>2</td>
<td>1,750'</td>
<td>Close in # 2</td>
<td>36</td>
</tr>
<tr>
<td>8</td>
<td>4/10/2003</td>
<td>1-Lt</td>
<td>45-46</td>
<td>3</td>
<td>1,950'</td>
<td>Key Cut</td>
<td>29A</td>
</tr>
</tbody>
</table>

In Newman’s research (Newman, 2008), modeling using LaModel was done on the CI3, CI5 and the CI4 with and without the bump cuts. In addition, two methods of taking the bump cuts were modeled including taking the bump cuts in either the outby pillar row or the active pillar row prior to other retreat mining. All of those scenarios were evaluated under high average (1,784 ft) and high (2,000 ft) overburden and for both hanging and non-hanging gob models.

While, analysis in this thesis focuses on the cut sequence of CI4 (see Figure 6.21) to verify the LMS criterion. In this cut sequence, the fifth entry is originally retreated then the entries from 1 to 4 are mined, finishing with the last 2 half pillars around entry 4. The bumps occurred at cutting step 36.
Figure 6.21 Bump Pillar in CI4 retreat plan
(after Newman, 2008).

6.3.2 Model Development and Results

In this modeling, there are 44 steps to simulate each cut sequence of CI4 as shown in Figure 6.21. The mine layout was gridded by 250 ×250 elements with the 5ft element width and there was no topography gridding. The average overburden depth is 2000ft and the retreat height is 4.75ft.

Initially, the lamination thickness used the default value 50ft; the calibrated final modulus of the gob was 30,370 psi; the strain softening properties of each element was defined by the new updated formula with the default value of A (1.457) and B (1.2799), the coal strength was calibrated to 1435 psi (or 2500 psi) which make sure the peak strength of the pillar matching the Mark-Bieniawski strength of pillar.

While, we should notice that the pillar bump in “Harlan model” is obviously different with “Crandall Canyon mine model”, that coal outburst occurred in part of the pillar in Harlan model during cutting the same pillar while pillar bumps occurred was caused by retreating other pillars in
Crandall Canyon mine model. Therefore, in Harlan model, the post failure pillar stiffness and the local mine stiffness of the designated pillars are successively changing due to the changing of the pillar shape, and the local mine stiffness of the bumped pillar is also an interrupted value because of the cutting activities in the pillar.

Based on the above input parameters, the LaModel results (part simulation steps) are shown in the Figure 6.22 to Figure 6.26.

![Figure 6.22 Step1 in Harlan Model](image)
Figure 6.23 Step 20 in Harlan Model

Figure 6.24 Step 26 in Harlan Model
6.3.3 LMS Criterion in Harlan Model

With the same calculation procedure in Crandall Canyon mine, the post failure pillar stiffness of the pillar is determined firstly and then calculate the local mine stiffness of the pillar. In Harlan model, the pillar dimension and geometry of bumped at the step 36 is shown in Figure 6.27.
Figure 6.27 Pillar Geometry at Cutting Step 36

The values of peak point and residual point to define the strain softening behavior in Harlan Model are shown in Table 6.3, and the stress strain curve of strain softening behavior which is composited from the elements is illustrated in Figure 6.28. Figure 6.28 also shows the minimum absolute value of post failure stiffness of the bumped pillar.

Table 6.3 Strain softening behavior of each different element (1435 psi)

<table>
<thead>
<tr>
<th>Code</th>
<th>Peak Strength ($S_p(i)$) (psi)</th>
<th>Peak Strain ($\varepsilon_p(i)$) (in/in)</th>
<th>Residual Strength ($S_R(i)$) (psi)</th>
<th>Residual Strain ($\varepsilon_R(i)$) (in/in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>2005.98</td>
<td>0.0066866</td>
<td>547.21</td>
<td>0.02674639</td>
</tr>
<tr>
<td>H</td>
<td>2549.77</td>
<td>0.0084992</td>
<td>919.46</td>
<td>0.03399691</td>
</tr>
<tr>
<td>G</td>
<td>5268.72</td>
<td>0.0175624</td>
<td>3226.50</td>
<td>0.07024954</td>
</tr>
<tr>
<td>F</td>
<td>5812.51</td>
<td>0.0193750</td>
<td>3751.48</td>
<td>0.07750007</td>
</tr>
<tr>
<td>E</td>
<td>8531.45</td>
<td>0.0284382</td>
<td>6603.84</td>
<td>0.1137527</td>
</tr>
</tbody>
</table>
Figure 6.28 Stress Strain Curve of Pillar and Minimum Post Peak Pillar Stiffness

The local mine stiffness should be determined secondly. For Harlan model, a four-step model which including step 33, 34, 35 36, was built and run in LaModel program for calculating the local mine stiffness of pillar around cut 36. Similarly, Figure 6.29 plots the value changing process of pillar around cut 36, and Figure 6.29 also includes the changing process of the pillar stiffness from pre-failure to post-failure.

Figure 6.29 Comparisons of the Pillar Stiffness and Local Mine Stiffness
Clearly, the result in Figure 6.29 shows the LMS criterion is violated in “Harlan Model”. As the cutting sequence approaching the step 36, the local mine stiffness of the specified pillar increases but stop at and past step 36.

The primary possible reason causing this violation is the pillar geometry. As shown in Figure 6.21, after cutting sequence 1 to 8, the designated pillar (right side pillar) had been cut the right part and the pillar geometry decreased and easy failed because of stress concentration. So, before the bump-happened step (36), the pillar had been actually reach to the post peak period and failed. Even though the following cut sequence continually squashes the pillar, but the failed pillar has tiny convergence which causing a larger value of local mine stiffness that the LMS criterion is easy violated.

6.4 Summary

This chapter investigated three pillar collapse cases in LaModel program with the local mine stiffness stability criterion. The modeling results show that the stability criterion is effective to the cascading pillar failure, but inability to the pillar bumps.
Chapter 7 Conclusions and Suggestion

7.1 Summary and Conclusion

The primary objective of this thesis was to study the effectiveness of implementing the local mine stiffness calculation into the LaModel program for analyzing coal bumps and pillar collapses. This research reviewed the documented pillar bump events in coal mines, and then introduced Salamon’s local mine stiffness criteria as an efficient and reasonable approach to investigate the potential for unstable pillar collapse. As the two primary components of the stability criterion, the local mine stiffness and the post-failure pillar stiffness in previous research was discussed. It was found that the accuracy of using the local mine stiffness stability criterion was very dependent on the accurate definition of the strain-softening behavior of the coal and the material properties of the overburden.

Therefore, as part of this research, stress data from pillars in the field were collected to understand their strain-softening behavior. These data were analyzed, calibrated and used to generate a residual stress formula for calculating the strain-softening behavior of coal. Further, this formula was parameterized to provide more flexibility for defining site-specific strain-softening behavior. By changing the two variables in the residual stress formula, the amount of strain softening in the pillar can be controlled, and in fact, the post failure pillar behavior can be changed from the strain-softening to the strain-hardening. This versatile residual stress formula combines with the Mark-Bieniawski peak stress formula to establish a new strain-softening coal material in LaModel.

To investigate the behavior, accuracy and utility of using the new local mine stiffness calculation in LaModel, initially, a number of simplified parametric models were run and their results analyzed. In these initial models, the LMS calculation was performing as expected. Eventually, three different pillar bump case histories were analyzed in LaModel using the new strain-softening coal material and the new local mine stability calculation on. Several significant results and future research suggestions are concluded in following.

1. The new strain softening coal model in LaModel makes it more accurate and flexible.
2. The local mine stability calculation is a precise approach to analyze whether pillar failures are stable or unstable. This approach has been proven by the laboratory
experience and the energy theory, but is has rarely been used in numerical modeling analysis. The appropriate usage of this approach depends not only on the accuracy of the numerical modeling but also on the accuracy of modeling the true geological condition found in the field. So, the local mine stability calculation is limited that not always right but sometimes is violated where pillar collapse real occurrence.

3. The local mine stiffness calculation is impacted by the lamination thickness and the strain softening behavior of coal in LaModel, and also affected by the pillar geometry in the mine layout.

4. The case histories highlighted a numerical limitation of LaModel that it will not converge to a solution where the mine stiffness is less than the pillar stiffness, since this would be an unstable situation and LaModel converges to a stable equilibrium at each solution step. Therefore, it was concluded that when using LaModel to determine the mine stability, the user should look for a value of the LMS “close” to the peak post-failure modulus of the pillar and/or for excessive pillar yielding/failure associated with a relatively small change in mine geometry to indicate a potential unstable failure.

7.2 Suggestions for Future Research

1. A lot of work in this dissertation was dedicated to determining an accurate value to use for the residual stress; however little effort was given to determining the value of the residual strain. Basically, measurement of the actual pillar strain in the field is extremely difficult and there is little to none field information available. Therefore LaModel fairly arbitrarily sets the residual strain to 4 times the peak strain. Obviously, the value of the residual strain can greatly affect the local mine stiffness calculation and more work can certainly be done to develop an improved method for determining the residual strain in a coal pillar.

2. In LaModel, the same residual stress level is assumed to continue until 100% strain (perfectly plastic behavior); however, in reality, at some strain level, the pillar would start to strain-hardening as the voids are compressed out of the broken coal. Certainly some research into the timing and magnitude of the post-failure, strain-hardening of pillars would be useful for a number of mining problems.

3. Finally, in order to realistically analyze the potential for pillar bumps using LaModel, an allowable safety factor between the calculated local mine stiffness and the post-failure
pillar stiffness needs to determined. This will require the analysis of many more sets of field data and case histories in future in order to develop an empirically valid safety factor.
Reference


Salamon, M. (1963). Elastic analysis of displacements and stresses induced by the mining of seam or reef deposits: part 1-fundamental principles and basic solutions as derived from idealized models. The South African Institute of Mining Metallurgy, 64, 128-149.


Kaifang Li
1325 Stewartstown Rd, Apt A8
Morgantown, WV 26505, USA
(304) 685-2835
likaifang1023@gmail.com

Education

Ph.D  Mining Engineering, GPA- 3.88 out of 4.0, West Virginia University 08/2012 ~ 12/2016
M.S  Mining Engineering, GPA- 83.5 out of 100, XUST, China 09/2006 ~ 07/2009
B.S  Engineering, GPA- 75.6 out of 100, XUST, China 09/2002 ~ 07/2006

Ph.D. Dissertation
Implementing the Local Mine Stability Criterion into LaModel

M.S. Thesis
Failure Mechanism and Bolt Timing in Soft Rock Roadgate under Overlying Aquifer

Eligible to Work

OPT

Software Skill

- AutoCAD
- Matlab
- VB/C++
- ITASCA
- ALPS/ARMPS
- LaModel
- CISPM
- Surfer

Professional Experiences

Graduate Research Assistant - West Virginia University 08/2012 ~06/2016 (4.5 years)

- Lecturer;
- Ground control, Pillar bump/Cascading pillar failure;
- Material Model;
- VB/C/C++;
- Rock mechanical testing on MTS and GCTS;
- Teaching assistant for rock mechanics laboratory class;

Lecturer - CUMT, Yinchuan College, China 09/2009 - 07/2012 (3 years)

- Courses: Ground Pressure & Strata Control, Rock Mechanics, Mining Technology, etc;
- Mine design;
- Bolts and cables support design in entry;
- Mining technology under water and treatment;

Graduate Research Assistant - XUST, China 09/2006 ~07/2009 (3 years)

- Underground water seepage mechanism and control;
- Underground pressure observation and numerical simulation;
- Mine entry and pillar stability analysis;
- Roof support design;
- Report writing with proficient skills of Microsoft Office and AutoCAD;

Professional Societies

- Society for Mining, Metallurgy, and Exploration(SME);
- American Rock Mechanics Association (ARMA);
- International Conference On Ground Control In Mining(ICGCM)

Conferences Attended
31th International Conference on Ground Control in Mining, Aug.1-3, 2012, Morgantown, USA
32th International Conference on Ground Control in Mining, July 31-Aug.2, 2013, Morgantown, USA (presentation)
33th International Conference on Ground Control in Mining, July 29-31, 2014, Morgantown, USA (presentation)
34th International Conference on Ground Control in Mining, July 27-30, 2015, Morgantown, USA (presentation)
48th US Rock Mechanics/Geomechanics Symposium, June 1-4, 2014, Minneapolis, USA (presentation)
49th US Rock Mechanics/Geomechanics Symposium, June 28-July 1, 2015, San Francisco, USA (presentation)
SME 2015 annual meeting, Feb 15-18, 2015, Denver, USA

Internships
- MeiHuaJing Coal Mine, Shenhua Ningxia Coal Industry Group Co., Ltd, China (3 Month)
- QinShuiYing Coal Mine, Shenhua Ningxia Coal Industry Group Co., Ltd, China (3 Month)
- ZaoQuan Coal Mine, Shenhua Ningxia Coal Industry Group Co., Ltd, China (3 Month)
- AiWeiErGou Coal Mine, XinJiang Coke Coal Industry Group Co., Ltd, China (1 Month)
- Black Silver Coal Mine

Publications
- Ang Li, Kaifang Li. “Floor water inrush risk evaluation for mining above confined aquifer in No.5 coal seam of Taiyuan group at Dongjiahe coal mine”. Electronic Journal of Geotechnical Engineering, Vol.21 2016-0157
- Peng Zhang, Heasley, K.A, Kaifang Li. “Multiple seam mining with deep cover and complex mine geometry – a case study” (received by “Journal Central South University of Technology”).