Geology Oriented Loading Approach for Underground Coal Mines

Deniz Tuncay
West Virginia University, dt0036@mix.wvu.edu

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

Part of the Mining Engineering Commons

Recommended Citation
https://researchrepository.wvu.edu/etd/10337

This Dissertation is protected by copyright and/or related rights. It has been brought to you by the The Research Repository @ WVU with permission from the rights-holder(s). You are free to use this Dissertation in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you must obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/or on the work itself. This Dissertation has been accepted for inclusion in WVU Graduate Theses, Dissertations, and Problem Reports collection by an authorized administrator of The Research Repository @ WVU. For more information, please contact researchrepository@mail.wvu.edu.
Geology Oriented Loading Approach for Underground Coal Mines

DENIZ TUNCAY

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

Ihsan Berk Tulu, Ph.D., Chair
Yi Luo, Ph.D.
Brijes Mishra, Ph.D.
Qingqing Huang, Ph.D.
Gabriel Esterhuizen, Ph.D.
Christopher Mark, Ph.D.

Department of Mining Engineering

Morgantown, West Virginia
2021

Keywords: Mining-induced loading, overburden geology, underground coal mines, pillar design

Copyright © 2021 Deniz Tuncay
ABSTRACT

Geology Oriented Loading Approach for Underground Coal Mines

Deniz Tuncay

Mining-induced stresses in underground coal mines play a significant role in pillar and support design, hence in the safety of mining operations. Adequate design of pillars and roof control plans rely on the accurate assessment of the mining-induced loads, as well as the load-bearing capacities of the supports. In pillar design tools frequently used by the underground coal mining industry and Mine Safety and Health Administration (MSHA), overburden loading is estimated by geometric concepts such as the tributary area and the abutment angle method. These methods do not explicitly consider important mechanical responses such as specific overall ground behavior. The mine-specific overburden geology is one of the major influencing factors for these complex mechanical responses.

In this research, to include the effect of geology in the overburden load estimations, a new parameter was defined as the total strong layer thickness \( t_{str} \) that represents the strength and stiffness of the overburden with a single value. This parameter is a function of the strength of overburden layers, thicknesses of strong beds, relative locations of the strong beds in the overburden, and the panel width and overburden depth. In this study, to develop a site-specific \( t_{str} \), 13 field measurement case studies from 12 different U.S. longwall mines with different overburden geologies were used. 2D numerical models of the case studies were verified against the field measurements such as surface subsidence, and stress. After verifying the numerical models, parametric studies were performed to be able to assess the influence of panel dimensions on mining-induced stresses and to simulate different panel conditions such as critical, subcritical, and supercritical. Overburden stress redistribution on the pillar system, gob, and adjacent solid coal is estimated from the modeling results.
Using these results, a regression analysis is conducted for a loading model with the $t_{str}$ as a variable, and a method to estimate the percentages of loads carried by the gob was constructed. The proposed method is used to calculate the percentage of load carried by the gob and was found to have a coefficient of determination ($R^2$) of 85% when compared to the field measurements and the parametric runs. The new methodology was compared against the empirical estimates for the field study cases and was found to give better results.

The method was then tested with field measurement case studies that were not included in the initial analysis. One case was used to test the estimation accuracy and the other cases were tested for LaModel implementation. The percentages of load carried by the gob as estimated by the new method were implemented into the LaModel program by simply entering it into the material wizard and re-calculating the required gob modulus to achieve the desired gob load percentage. The results obtained from LaModel were compared to the available field stress measurements, and the new method, implemented into LaModel, was found to give successful results. This methodology was found to be successful in implementing the effect of site-specific overburden geology into commonly used pillar design tools such as LaModel.
ACKNOWLEDGEMENTS

First, I would like to express my deep and sincere gratitude and appreciation to my supervisor, Dr. Ihsan Berk Tulu for his invaluable supervision and continuous guidance not only in the preparation of this dissertation but also in my professional life and career. His knowledge, dedication, and hard work have been truly inspirational, and I am lucky to have him as a role model. I will forever be grateful to him for believing in me and giving me this opportunity.

I also present my special thanks to Dr. Yi Luo, Dr. Brijes Mishra, Dr. Qingqing Huang, Dr. Gabriel Esterhuizen, Dr. Christopher Mark, and Dr. Keith Heasley for serving on my Ph.D. dissertation committee and for their valuable contributions. I appreciate all their feedback and suggestions which greatly improved this dissertation. I would also like to thank the Alpha Foundation for the Improvement of Mine Safety and Health, Inc. (ALPHA FOUNDATION) for supporting and funding this research. Without their financial support, this study would not have been possible. I must express my special gratitude to my research team member, Haochen Zhao for all his help and contributions to this study. I would also like to thank my friends and colleagues in Morgantown who made my time here fun and full of memories; Emel and Çağrı Kılıç, Özcan Özmen, Mustafa Can Süner, and all the WVU Mining Engineering graduate students. I would also like to thank the faculty, staff, and the students of the WVU Department of Mining Engineering for being so welcoming and supportive.

I also owe my loving thanks to my family, especially my parents Gülçin and Tuğrul Tuncay. Even though they were thousands of miles away, they were always there when I needed them. Without their encouragement and support, it would have been impossible for me to be where I am now. Above all, I would like to thank my beautiful wife and best friend, Deniz Talan for her love and constant support. She has always been by my side and stood by me through it all. She has been my motivation and always kept me on track. I cannot imagine going through all this without her.
To my dear family...
# TABLE OF CONTENTS

ABSTRACT .................................................................................................................................................. ii
ACKNOWLEDGEMENTS ........................................................................................................................ iv
TABLE OF CONTENTS .......................................................................................................................... vi
LIST OF FIGURES ...................................................................................................................................... vii
LIST OF TABLES .......................................................................................................................................... xi

CHAPTER 1 – INTRODUCTION .................................................................................................................. 1
  1.1 Overview ........................................................................................................................................... 1
  1.2 Problem Statement .......................................................................................................................... 4
  1.3 Objectives of the Study ................................................................................................................... 5

CHAPTER 2 – BACKGROUND .................................................................................................................... 7
  2.1 Pillar Design in Underground Coal Mines ......................................................................................... 7
  2.2 Different Pillar Design Methods ....................................................................................................... 9
      2.2.1 Empirical Method ........................................................................................................................ 11
      2.2.2 Boundary Element Method – Laminated Model ..................................................................... 18
      2.2.3 Finite Volume Method – FLAC3D .......................................................................................... 21

CHAPTER 3 – METHODOLOGY ................................................................................................................. 26
  3.1 Database Development ...................................................................................................................... 26
  3.2 Numerical Modeling .......................................................................................................................... 36
      3.2.1 Model Development and Verification ....................................................................................... 36
      3.2.2 Parametric Runs ....................................................................................................................... 38
  3.3 Analysis of the Results ...................................................................................................................... 39
      3.3.1 Analysis of Abutment Stresses ............................................................................................... 39
      3.3.2 Statistical Modeling for Geology Based Loading Estimation ................................................... 41

CHAPTER 4 – RESULTS AND DISCUSSION ............................................................................................. 43
  4.1 Verification of the Numerical Models ............................................................................................... 43
  4.2 Analysis of the Modeling Results ..................................................................................................... 48
      4.2.1 Analysis of Single Panel Abutment Stresses ......................................................................... 48
      4.2.2 Analysis of Multiple Panel Abutment Stresses ..................................................................... 49
  4.3 Statistical Modeling for Geology Based Gob Loading Estimation .................................................... 55
      4.3.1 Analysis of 2-entry yield pillar system ................................................................................... 64
4.4 Method Verification ........................................................................................................ 66
4.5 LaModel Implementation ............................................................................................. 68
  4.5.1 Verification with Case Studies ............................................................................. 69
CHAPTER 5 – CONCLUSIONS AND FUTURE STUDIES ............................................. 75
  5.1 Summary and Conclusions ..................................................................................... 75
  5.2 Suggestions for Future Studies ............................................................................... 76
REFERENCES .................................................................................................................. 77
LIST OF FIGURES

Figure 1.1 Development loading models of a) tributary area theory and b) Pressure arch theory (Mark, 2010) .......................................................... 2
Figure 1.2 The abutment angle concept used to estimate loads for a) supercritical panels and b) subcritical panels (Mark, 2010) ................................. 3
Figure 2.1. Zones of disturbance due to longwall (or retreat room and pillar) mining (Peng, 2008) .......... 9
Figure 2.2. Different analysis methods evaluated and percent of MSHA technical reviews (Gauna and Tyrna, 2011) .......................................................... 11
Figure 2.3. Representation of strength data from large scale in situ tests on coal conducted in South Africa (Bieniawski and Van Heerden, 1975) .......................................................................................... 12
Figure 2.4. Abutment angle concept. (Mark, 1992) ............................................................................. 14
Figure 2.5. ARMPS2010 SF results of the ARMPS2010 shallow cover database using the 21° abutment angle .............................................................................. 16
Figure 2.6. The lamination thickness wizard in LamPre 3.0. ........................................................... 20
Figure 2.7. The gob wizard within the seam material wizard in LamPre 3.0. ........................................ 20
Figure 2.8. Comparison of calibrated coal model pillar strength and the empirical pillar strength equation of Bieniawski (1981) (modified from Esterhuizen et al., 2010) ........................................... 22
Figure 2.9. Stress-strain behavior of the modeled gob ...................................................................... 25
Figure 3.1. Generalized stratigraphic column representation of the case study mines. .................. 27
Figure 3.2. Mine NA-1 panel and chain pillar configuration .............................................................. 28
Figure 3.3. Mine NA-2 panel and chain pillar configuration .............................................................. 29
Figure 3.4. Mine NA-3 panel and chain pillar configuration (modified from Tulu et al., 2018) .......... 30
Figure 3.5. Mine NA-4 close-up of the chain pillar configuration .................................................... 30
Figure 3.6. Mine NA-5 panel and chain pillar configuration (modified from Van Dyke et al., 2020) ...... 31
Figure 3.7. Mine NA-6 panel and chain pillar configuration .............................................................. 32
Figure 3.8. Mine CA-1 4-entry chain pillar configuration (modified from Klemetti et al., 2018) ....... 32
Figure 3.9. Mine CA-2 panel and chain pillar configuration .............................................................. 33
Figure 3.10. Mine CA-3 panel and chain pillar configuration (modified from Campoli et al., 1993) .... 34
Figure 3.11. Mine BW-1 panel and chain pillar configuration (modified from Klemetti et al., 2019b) .... 34
Figure 3.12. Mine W-1 panel and chain pillar configuration ............................................................. 35
Figure 3.13. Mine W-2 panel and chain pillar configuration ............................................................. 36
Figure 3.14. Model extent and boundary conditions ...................................................................... 37
Figure 3.15. 3D representation of a) development b) single panel and c) consecutive panel models 
edemonstration purposes only, actual models are 2D) .......................................................... 37
Figure 3.16. 2D model of Mine CA-3 with five consecutive panels. ........................................ 38
Figure 3.17. Dimensionless (normalized) overburden load calculation for analyzing mining-induced loads for a two-panel model ........................................................................................................ 41
Figure 4.1. Subsidence profiles obtained from the models compared to the field measurements for (a) Mine NA-1 (b) Mine NA-2 (c) Mine NA-3 (d) Mine NA-4 (e) Mine NA-6 (f) Mine W-1 .......... 43
Figure 4.2. Model results compared to the field measurements for Mine CA-1(modified from Klemetti et al., 2019a). ......................................................................................................................... 44
Figure 4.3. Model results showing the average pillar stresses and the sloughing on the pillars for Mine BW-1 instrumentation site (modified from Klemetti et al., 2019b)........................................ 45
Figure 4.4. Model results showing the stress profile along the cross-section AA’ for Mine NA-5 (modified from Van Dyke et al. 2020). ........................................................................................................ 46
Figure 4.5. BPC locations and comparison of measured and modeled results for Mine NA-5 (modified from Van Dyke et al. 2020). ........................................................................................................ 46
Figure 4.6. Stress profiles obtained from the 2D model compared to the field measurements for Mine CA-3. .............................................................................................................................. 47
Figure 4.7. Stress profiles obtained from the 2D model compared to the field measurements for Mine W-2. .............................................................................................................................. 47
Figure 4.8. Subsidence profile obtained from the 2D model of Mine NA-3 .................................. 50
Figure 4.9. Dimensionless overburden load distribution after 1st and 2nd-panel mining for Mine NA-3. 50
Figure 4.10. Subsidence profiles obtained from the FLAC3D model for Mine CA-1b................. 51
Figure 4.11. Dimensionless overburden load distributions approximated by the FLAC3D model for Mine CA-1b after the (a) first panel mined, (b) second panel mined, (c) third panel mined, (d) fourth panel mined, and (e) fifth panel mined ................................................................. 53
Figure 4.12. Calculated S/pw ratios for the overburden layers of mines NA-3 and CA-1.................. 56
Figure 4.13. Relationship between the tstr/pw ratio and the transferred gob load percentage .......... 57
Figure 4.14. Single-panel gob loads with respect to tstr/pw ratio .................................................. 57
Figure 4.15. Comparison of estimated single panel gob loads with the case study model results .......... 59
Figure 4.16. Comparison of estimated active panel gob loads with the consecutive case study model results ...................................................................................................................................... 61
Figure 4.17. Comparison of estimated previous panel gob loads with consecutive case study model results ...................................................................................................................................... 62
Figure 4.18. Comparison of estimated gob load percentages with the case study and parametric model results. ......................................................... 63

Figure 4.19. Comparison of the empirical method and the new gob load estimation method in terms of their success in estimating the field case gob load percentages. ........................................ 64

Figure 4.20. Comparison of estimated active and previous gob load percentages with the consecutive case study model results including Mine W-1. ................................................................. 65

Figure 4.21. Comparison of estimated gob load percentages with the case study and parametric model results including Mine W-1. ................................................................. 66

Figure 4.22. Mine W-3 panel and chain pillar configuration and the location of the field measurement site. ................................................................................................................................................. 67

Figure 4.23. Comparison of estimated gob load percentages for the analyzed database including Mine W-3. ................................................................................................................................................. 68

Figure 4.24. Using gob wizard in LaModel to implement estimated gob load percentages ................. 69

Figure 4.25. Stratigraphic columns for the Australian case studies. ....................................................... 70

Figure 4.26. LaModel gridding for the Australian case studies ................................................................ 71

Figure 4.27. Comparison of maingate and tailgate field stress measurements with LaModel results for Mine AU-1...................................................................................................................... 72

Figure 4.28. Comparison of maingate and tailgate field stress measurements with LaModel results for Mine AU-2...................................................................................................................... 72

Figure 4.29. Comparison of maingate and tailgate field stress measurements with LaModel results for Mine AU-3 ...................................................................................................................... 73

Figure 4.30. Comparison of LaModel results with the field measurements in terms of areas under stress profiles .............................................................................................................................................. 73

Figure 4.31. Comparison of LaModel results with the field measurements in terms of areas under stress profiles for both the default and the new method. ........................................................................... 74
LIST OF TABLES

Table 2.1 Summary of the stress measurement sites used by Mark (1990) ................................................................. 14
Table 2.2. The abutment angle concept suggested by Tulu and Heasley (2012) .............................................................. 17
Table 2.3. Proposed abutment angle equation for H/PW ratios from 0.7 to 3.5. ............................................................... 17
Table 2.4. Hoek-Brown coal model and related interface properties (Esterhuizen et al., 2010). ............................. 22
Table 2.5. Suggested intact rock properties (Tulu et al., 2017). .................................................................................. 23
Table 3.1. Summary of case study mines....................................................................................................................... 26
Table 3.2. List of parametric runs and the respective panel width to depth ratios......................................................... 39
Table 4.1. Numerical modeling results for single panel runs. ....................................................................................... 48
Table 4.2. Mining induced load percentages obtained for Mine NA-5 for the three-panel model. ..................... 53
Table 4.3. Mining induced load percentages obtained for Mine CA-1a for the four-panel model. .................... 54
Table 4.4. Mining induced load percentages obtained for Mine CA-1b for the five-panel model. .................. 54
Table 4.5. Mining induced load percentages obtained for Mine CA-3 for the five-panel model. .................. 54
Table 4.6. Mining induced load percentages obtained for Mine BW-1 for the three-panel model. .............. 54
Table 4.7. Mining induced load percentages obtained for Mine W-1 for the five-panel model. .................. 54
Table 4.8. Mining induced load percentages obtained for Mine W-2 for the four-panel model. .............. 55
Table 4.9. Strong layer thicknesses for each case study overburden geology and calculated t_str/pw ratios 58
Table 4.10. Active panel and previous panel gob load percentages for deep cover consecutive panel models................................................................................................................................. 60
Table 4.11. Gob load percentages obtained from the verified numerical model for Mine W-3. .............. 67
Table 4.12. Gob load percentages estimated using the new methodology for Mine W-3. ............................... 67
Table 4.13. Depths and Panel configurations for the Australian case studies ....................................................... 69
Table 4.14. Gob load percentages estimated using the new methodology for the Australian cases........ 71
CHAPTER 1 – INTRODUCTION

1.1 Overview

In 2019, approximately 38% of the total coal production in the United States was by underground mining (MSHA, 2020a) and 60% of the underground coal production was performed by longwall coal mines. In underground coal mines, ground control plays a significant role in the safety of the operations, especially in high-extraction retreat mines (i.e., longwall and retreat room-and-pillar mines) due to higher mining-induced load concentrations in the vicinity of the gobs. Between 2011 and 2019, fall-of-ground incidents caused almost 30% of the occupational fatalities in underground coal mines, second only to fatalities caused by powered haulage (MSHA 2020b). Of these ground-control-related fatal accidents, 25% of them were in longwall mines. Also, for fatalities related to ground control in longwall mines, 80% of them have occurred even when there was roof support (Sears et al., 2019).

Mining-induced stresses in underground coal mines play a significant role in pillar and support design, hence in the safety of mining operations. It has been more than 50 years since the pillar strength study by Salamon and Munro, which was the first comprehensive study into coal pillar strength in South Africa following the Coalbrook mine disaster in 1960 (Salamon and Munro, 1967). In South African coal mines, Salamon and Munro’s coal pillar design method has been used successfully for decades and was an empirical derivation from an extensive pillar case history database. There have been additions to the database, but the re-analysis of the data did not present sufficient deviation to warrant a change in the original method. However, in a more recent study by Salamon et al. (2006), it was concluded that seam-specific strength formulae would provide a safer and more cost-effective pillar design rather than using a single overall pillar strength formula. In the U.S., the Analysis of Coal Pillar Stability (ACPS) software is the most current tool used for designing longwall coal mine layouts (Mark and Agioutantis, 2019). ACPS software is the new pillar design software that integrates all three of its predecessor software applications namely Analysis of Longwall Pillar Stability (ALPS), Analysis of Retreat Mining Pillar Stability (ARMPS), and the Analysis of Multiple Seam Stability (AMSS) (Mark, 1992; Mark and Chase, 1997; Mark et al., 2007). ALPS marked the beginning of a new era in coal pillar design in the U.S., where abutment loads from full extraction on the longwall panel were used. Also, it was
based on an extensive case history database (Mark and Agioutantis, 2019). In Australia, the University of New South Wales (UNSW) tested the Salamon and Munro method for the Australian database and derived the UNSW formulae that included squat and rectangular pillars (Galvin, 2006). Analysis of Longwall Tailgate Serviceability (ALTS) is also used for designing longwall coal mine layouts, which follows the template of ALPS (Colwell et al., 1999). All these programs determine the adequacy of the design by comparing the estimated loads to the load-bearing capacity of the pillars. To estimate the load-bearing capacity of the pillars, the programs used the Bieniawski (1984) and Mark-Bieniawski (1986) pillar strength formulae that are functions of the pillar’s width-to-height ratio and the in-situ coal seam strength. The in-situ coal strength is suggested to be taken as 900 psi (6.2 MPa) when using these programs for reliable results, according to statistical analysis by Mark and Barton (1997). The programs use “tributary area theory” or “pressure arch theory” for estimating development loads (Figure 1.1) and the “abutment angle” concept together with the square decay stress distribution function to estimate the magnitude and distribution of the mining-induced loads (Figure 1.2).

![Figure 1.1 Development loading models of a) tributary area theory and b) Pressure arch theory](Mark, 2010)
Past and recent research has suggested that very little attention is being paid to mine-specific overburden mechanics such as overburden stiffness, horizontal stress in coal mine strata, bedding weaknesses, and overburden interaction with the pillar system (van der Merwe, 2006; Esterhuizen et al., 2010; Frith and Reed 2017). Frith and Reed (2017) stated that most of the current state-of-the-art pillar design methods use estimated dead-weight of overburden, or if available in-situ stresses, to estimate pillar sizes but ignore the overburden mechanics. These methods overlook important mechanical responses such as specific overburden mechanics, structural competence of the overburden strata, geology, in-situ stresses, and overburden/pillar interactions.

Numerical modeling approaches with the help of field measurements can be used to get some insight into the complex behavior of the sedimentary overburden strata during the mining of the coal seam. This complex behavior is affected by the physiographic province of the mine, the geologic formation of the seam, in-situ stress state of the formation, and operational parameters of the mine (i.e., mining height, panel width, depth, pillar design, etc.), and can change drastically from one coal basin to another.

Surface to seam extensometers might directly measure relative movements of the overburden strata in one dimension. Still, spatial and temporal measurements of relative movements and stress changes are not practical, economical, or even possible. Therefore, no cost-effective method is available to measure or observe complex overburden behavior directly, but surface subsidence, near seam deformation, and stress measurements indirectly show the mechanical response of the
overburden. These measurements can be used to calibrate numerical modeling approaches, which in return give us an idea about the behavior and mechanics of the overburden during mining.

This research investigated the effect of overburden geology on mining-induced loads with the help of field measurements and numerical models and aimed to implement this effect into a practical geology-based load estimation approach to help improve pillar design and mine safety.

1.2 Problem Statement

In addition to panel width and overburden depth, site-specific overburden geology is known to have a considerable impact on the extent and magnitude of the abutment loads, but it is not explicitly included in current pillar design tools. Although the pressure arch loading approach implemented in ARMPS2010 indirectly accounts for the generally stiffer overburden response of narrow and deep panels, it does not include the effect of mine-specific geology on the mechanics of the overburden (Mark, 2010).

The impact of overburden geology on surface subsidence has also been proven by various case studies and is included in different subsidence prediction tools such as the Comprehensive and Integrated Subsidence Prediction Model for Multiple Seam Mining (CISPM-MS) developed at West Virginia University (Luo and Qiu, 2012) and the Surface Deformation Prediction System (SDPS) software developed at Virginia Polytechnic Institute (Karmis et al., 1989; Agioutantis and Karmis, 2017). It can be reasoned that if overburden geology affects surface subsidence, then pillar stresses and deformations are also affected.

Studies showed that while being mostly accurate for shallow mines, empirical methods have been less effective at estimating loads for deeper cover mines (Tulu and Heasley, 2012; Hill et al., 2015; Tuncay et al., 2020). These studies aimed to better estimate abutment loads for deeper cover mines by modifying the abutment angle calculation method to match the field measurements. Although obtaining better results, these studies still did not consider the effect of site-specific overburden geology and overburden mechanics. There are numerical modeling approaches that can simulate the behavior of mine-specific overburden strata by modeling each layer, but these methods require high computation capabilities and long run times and are often not practical. Therefore, this study aims to develop a mechanistic load estimation approach that includes the effect of site-specific overburden geology to be implemented into a practical design tool.
1.3 Objectives of the Study

This research focused explicitly on developing a geology-based loading estimation to better assess the overburden load distribution in underground coal mine ground control design. To accomplish this goal, the following research tasks were targeted and completed during the study:

i. A case study database of longwall coal mines was developed with information on mining geometries, overburden geology, and available field measurements (pillar stress and/or surface subsidence) for each case.

ii. The FLAC3D modeling approach was used to model each case study mine as a 2D cross-section along the panel width. These models were verified against the available field measurements such as surface subsidence and stress change. Consecutive panel mining models were also simulated for deeper mines with narrow panels, where up to five panels were modeled to see the effect of previous panels on the stress and subsidence section. Following the verification of the numerical models, each model was re-run using different panel dimensions to simulate different panel conditions: subcritical, and supercritical.

iii. Abutment stresses were analyzed for all modeled field cases and their parametric counterparts. Due to the nature of the 2D model, development, bleeder, and isolated loading conditions can be simulated. Pillar loads, gob loads, and loads on solid coal were estimated from the modeling results.

iv. A new parameter to represent the strength and stiffness of the overburden was proposed. This case-specific parameter is a function of the strength of the overburden layers, the thickness of strong beds, the relative location of the strong beds in the overburden, and the panel width and overburden depth.

v. Regression analysis of the results from the field measurements and the 2D models was conducted against the new geological parameter and the panel widths.

vi. A new methodology to estimate the mining-induced gob loads was proposed. The new estimation method consists of regression equations that include the geological parameter, and it can be used to calculate the overburden load percentages transferred to the gob.
For the field study cases, the new methodology was compared with the empirical estimates. Gob load percentages calculated using 21° abutment angle and using the new methodology were checked against the percentages estimated from the models.

A field study that was not included in the analyzed database was then used to verify the new methodology for gob load estimation. The estimated results and the results obtained from the field measurements were compared.

Finally, the gob load estimation methodology was introduced into the LaModel program by calibrating the gob modulus according to the geology-based gob load percentage. Using a different set of field measurement case studies, the LaModel results with the new methodology were compared against the results for the traditional gob modulus calibration method.
2.1 Pillar Design in Underground Coal Mines

Over the years, methods for pillar design have constantly been evolving, and essentially there are two main categories: empirical and numerical. While the empirical pillar design methods get their strength from real-life observations and experiments (Mark, 1999), numerical methods rely on the fundamental laws of physics (Heasley, 1998). Both methods have been used extensively throughout the years, and both have their unique advantages and disadvantages in comparison with each other.

Empirical methods are derived from large databases of experiments, field measurements, and observations. These methods aim to determine a statistical “limit value” (design criteria) to minimize the probability of failure within the database domain (Sears, 2013). These methods “compare old with the new” in the decision-making process, and the mechanics involved in the process are usually supplementary information. However, these methods are restricted by the scope of the database they are based on and sometimes fall short when complex mining geometries, stress conditions, or geology not included in the database are encountered.

The numerical methods target to mathematically analyze the mine structure using the geologic material’s physical properties introduced in the model. This makes numerical models more flexible and capable of analyzing more complex problems. The main disadvantage of the numerical models is the selection of these physical properties, the failure criteria, and the post-failure behavior of the materials used in the model. Appropriate geologic parameters for input for the physical behavior in these geologic models are usually difficult to obtain and not always agreed upon (Heasley, 1998).

In general, pillar design methods, both empirical and numerical, have three main components: determining the load-bearing capacity of the pillar, estimating the load on the pillar, and calculating a stability factor that compares the load to the load-bearing capacity (Mark, 1992). Different design methods have different approaches for estimating these components.

The first-ever reported empirical coal strength formula was developed by Bunting in 1911, as reported by Peng (2008). This was a linear function that relates the pillar strength to pillar width.
and height and the strength of the coal. That was followed by the formulas derived by Greenwald et al. (1941), Holland and Gaddy (1957), and Obert and Duvall (1967). These formulas were based on laboratory testing of coal specimens or large-scale in-situ tests in the case of the study by Bieniawski (1968).

The Bieniawski strength formula (1968) was based on the underground in-situ strength tests performed on large-scale coal specimens in the Witbank colliery and was found to be applicable for South African collieries. The specimen sizes ranged from 0.75 inches to 6.6 ft, and the critical specimen size was found to be 5 ft. With specimen sizes larger than 5 ft, the strength reduction was found to be negligible. Bieniawski and Van Heerden (1975) later expressed the formula in its dimensionless form to be generally applicable, not only to the collieries where the in-situ tests were conducted. Back-analysis of different pillar case studies were then used to determine the safety factors to be used in pillar design (Mark and Bieniawski, 1986). The original Bieniawski pillar strength formula assumes a square pillar, or in the case of a rectangular pillar, it assumes additional length does not contribute to the pillar strength. Mark and Chase (1997) later introduced the effect of pillar length to the Bieniawski formula.

For mining-induced load estimation, the tributary area theory is often used for estimating development load. It assumes each pillar only carries the overburden load directly above itself and half of the entries surrounding the pillar (Figure 1.1a). In the case of retreat mining methods, the additional load is transferred onto the pillars from adjacent mined-out panels. When a panel is being retreated, whether it is a longwall mine or retreat room and pillar mine, the bedded strata above the extracted coal starts to converge. As the overlying strata continue to converge towards the empty space, the strata closer to the coal seam breaks and caves. With time, the caved strata further break and fill the void. This caved material is called the gob (or goaf). Peng (2008) identified four zones of disturbance in the overburden strata caused by mining: the caved zone, the fractured zone, the continuous deformation zone, and the soil zone as seen in Figure 2.1.
The load previously carried by the in-situ coal is transferred to the chain pillars, production pillars, gob, and barrier pillars (or solid coal) from the adjacent gob. The loads that are transferred to the adjacent pillars or solid coal are called abutment loads. It can be assumed that the sum of those loads on the gob and the abutments is equal to the dead weight of the strata directly above the panel. Wilson (1982) suggested that the average vertical load prior to mining is conserved, and any stress decrease in an area (gob or entry) must be balanced by an increase in load on adjacent pillars or solid coal. The main unknowns here are the ratio of the load carried by the gob, transferred to the abutments, and the extent the abutment loads reach.

2.2 Different Pillar Design Methods

The most widely accepted pillar design software program in the United States is Analysis of Coal Pillar Stability (ACPS) which is the successor of previous pillar design tools; the Analysis of Longwall Pillar Stability (ALPS), the Analysis of Retreat Mining Pillar Stability (ARMPS), and the Analysis of Multiple Seam Stability (AMSS) (Mark, 1992; Mark and Chase, 1997; Mark et al., 2007; Mark, 2010). These tools are used to check the adequacy of roof control and ground support plans submitted to MSHA. These software packages use empirical equations derived from a large database of case studies and focus on the stability of the pillars. In cases where more complex stress changes are expected, calibrated numerical models are used (Heasley et al., 2010; Tulu et
LaModel is a widely used software in the United States for modeling the stresses and displacements on thin tabular deposits by utilizing the laminated overburden model; it uses a displacement-discontinuity variation of the boundary-element method (Heasley, 1998). Another widely used numerical modeling software is FLAC3D which uses the finite difference method and can be used to model different stratifications of the overburden and their behavior (ITASCA, 2018). Finite element packages such as RS2 (formerly Phase2) from Rocscience and ABAQUS from Dassault Systems are also regularly used for stress analysis in underground mines. The numerical models are based on fundamental laws of physics and approximate the geomechanical behavior of coal and overburden strata. As rock is heterogeneous, the actual response of rock to an excavation rarely matches the theoretical models and therefore must be carefully calibrated for reliable and practical output from the model (Heasley et al., 2010).

Since its inception in 1977, the MSHA Roof Control Division (RCD) has conducted ground control-related technical reviews forwarded from Coal Mine Safety and Health (CMS&H) districts. According to the study by Gauna and Tyrna (2011), the reviews are primarily for pillar recovery design (~53%), followed by designs of development mining (~25%) scenarios. The largest portion of the submitted design reviews was based on NIOSH software packages: Analysis of Longwall Pillar Stability (ALPS) (Mark, 1987; 1992), Analyses of Retreat Mining Pillar Stability – Highwall Mining (ARMPS-HWM) (Zipf, 2005; Mark, 2006), Analyses of Retreat Mining Pillar Stability (ARMPS) (Mark and Chase, 1997; Mark, 2010), Analysis of Multiple Seam Stability (AMSS) (Mark et al., 2007). These empirical design techniques account for 73% of the reviews. Designs based on numerical models account for approximately 14% of the technical reviews and the majority of them are based on LaModel (Heasley, 1998). The overall distribution of the analysis methods is presented in Figure 2.2.
2.2.1 Empirical Method

In 1987, the Analysis of Longwall Pillar Stability (ALPS) program was introduced by Mark and Bieniawski (1987) as a chain pillar design methodology, and it was generally accepted and used by the United States coal mining industry. In 1994, ALPS was modified to include the Coal Mine Roof Rating (CMRR) to consider the effect of roof quality and competence (Mark et al., 1994). Following the success of ALPS, NIOSH developed the Analysis of Retreat Mining Pillar Stability (ARMPS) program for designing retreat mining pillars using a similar approach as ALPS (Mark and Chase, 1997). The ARMPS overburden load prediction algorithm was subsequently improved to better predict the loading of narrow panels with high overburden depths by implementing the pressure arch concept. This new version is called ARMPS2010.

In Australia, the Analysis of Longwall Tailgate Serviceability (ALTS) methodology is used to design pillars developed based on the ALPS methodology (Colwell et al., 1999). It was calibrated for Australian conditions using stress measurement case histories from Australian mines. The original database was sufficient for pillar design purposes, but the methodology was significantly improved in ALTS II which followed the modified ALPS template (Mark et al., 1994). The update allowed it to quantify the interaction between roof quality, primary and secondary roof support, and chain pillar size for tailgate serviceability (Colwell et al., 2003).

Figure 2.2. Different analysis methods evaluated and percent of MSHA technical reviews (Gauna and Tyrna, 2011).
ALTS database has been continually improved and expanded with additional cases, consequently improving the ALTS design methodology (Colwell and Frith, 2009).

These programs compare the strength of pillars with the mining-induced loads to calculate safety factors to be used in pillar design. The Bieniawski pillar strength formula is generally considered to successfully represent the strength of pillars with large width-to-height ratios (Mark and Bieniawski, 1986). Bieniawski and Van Heerden (1975) analyzed 66 large scale (up to 6.5 ft in width) in-situ tests conducted over a period of 8 years, between the years 1966 and 1973 and the results are presented in Figure 2.3.

Figure 2.3. Representation of strength data from large scale in situ tests on coal conducted in South Africa (Bieniawski and Van Heerden, 1975).
Bieniawski and Van Heerden (1975) found that Eq(1) applies to any coal seam provided the value of $S_c$ is known, which is the strength of a critical-sized cubical pillar (Bieniawski, 1968). Bieniawski (1981) also estimated a default $S_c$ of 930 psi to be used for Pittsburgh coal. Later, Mark (1992) estimated the $S_c$ to be 900 psi for the coal pillars in the U.S. after studying 27 unsuccessful and 25 successful pillar case histories.

$$S_p = S_c \left( 0.64 + 0.36 \frac{w}{h} \right)$$

where:

- $w$ = the pillar width
- $h$ = the pillar height
- $S_p$ = the pillar strength
- $S_c$ = the strength of a critical-sized cubical pillar (psi) or in-situ coal strength.

In the U.S., both ALPS and ARMPS utilized the version of the Bieniawski formula modified by Mark (1997); called the Mark-Bieniawski formula (Eq(2)), for the calculation of pillar stability factors (Mark and Chase, 1997).

$$S_p = S_1 \left( 0.64 + 0.54 \frac{w}{h} - 0.18 \frac{w^2}{Lh} \right)$$

where:

- $S_1$ = in-situ coal strength (assumed = 900 psi).
- $L$ = the pillar length

When calculating the loads on the pillars, these programs use the tributary area theory (Figure 1.1a) for development loads and the abutment angle concept for abutment loads (Figure 1.2). The abutment angle ($\beta$) is used to calculate the magnitude of abutment loading adjacent to a gob area. It considers an angle between the vertical plane and the panel roof to calculate the transferred load to the abutments when the panel is mined (Figure 2.4). If the total area above the mined-out panel is the total load to be transferred, the hatched areas in Figure 2.4 constitute the load transferred to the side abutments, and the gob carries the remaining load. The total load to be transferred is calculated as the dead weight of the overburden directly above the mined-out panel.
In 1990, Mark analyzed the abutment stress measurements collected from five different mines. All measurements were conducted using vibrating wire stress meters (VWS). The U.S. Bureau of Mines conducted three of the studies, all of which were conducted in the Pittsburgh seam. The Pennsylvania State University conducted the fourth study in the Lower Kittanning seam, and the U.S. Steel conducted the fifth study at a mine operating in the Harlan seam. Mark (1987, 1992) back-calculated the measured side abutment load by multiplying the load-bearing area of the pillars by the average pillar stresses determined from the array of stress cells inside each pillar. A summary of the panel widths and depths from the case histories used by Mark (1990) to back-calculate the abutment angles from the case histories is shown in Table 2.1.

Table 2.1 Summary of the stress measurement sites used by Mark (1990).

<table>
<thead>
<tr>
<th>Case</th>
<th>Depth (ft)</th>
<th>Panel Width (ft)</th>
<th>Seam</th>
<th>β (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine A:2</td>
<td>520</td>
<td>470</td>
<td>Pittsburgh</td>
<td>21.8</td>
</tr>
<tr>
<td>Mine B:2</td>
<td>650</td>
<td>600</td>
<td>Pittsburgh</td>
<td>25.2</td>
</tr>
<tr>
<td>Mine B:3</td>
<td>600</td>
<td>600</td>
<td>Pittsburgh</td>
<td>10.7</td>
</tr>
<tr>
<td>Mine B:4</td>
<td>455</td>
<td>600</td>
<td>Pittsburgh</td>
<td>17.3</td>
</tr>
<tr>
<td>Mine D:1</td>
<td>760</td>
<td>1,000</td>
<td>Lower Kittanning</td>
<td>18.5</td>
</tr>
<tr>
<td>Mine E:3</td>
<td>630</td>
<td>500</td>
<td>Harlan</td>
<td>20.3</td>
</tr>
</tbody>
</table>

Average 18.97
Originally, a total of 16 stress meter arrays were installed in five different mines, but side abutment measurements were available only from six arrays due to some of the stress meters being destroyed once they were inby. Therefore Table 2.1 only has data from four different mines. Mark (1992) concluded that an average abutment angle of 21° would yield a conservative estimate of the side abutment load, but there was a wide range (10.7° to 25.2°) in the measured values as seen in Table 2.1.

Peng and Chiang (1984) summarized the abutment stress measurements performed before the mid-1980s, and they developed an equation Eq(3) for calculating the maximum extent (influence) of the abutment load (D) as a function of the depth (H).

\[ D = 9.3\sqrt{H} \text{ (in feet)} \] (3)

From the stress measurements at those five mines (Table 2.1), Mark found that a square-decay function Eq(4) fits the measured stress distributions best.

\[ \sigma_a(x) = \frac{3L_s}{D^3} (D - x)^2 \] (4)

where:
- \( \sigma_a \) = the abutment stress level
- \( x \) = the distance from the panel edge
- \( L_s \) = the total side abutment load
- \( D \) = the extent of the abutment stress from Eq(3).

The side abutment loads (\( L_s \) and \( L_{ss} \)) can be calculated according to the appropriate supercritical or subcritical panel formulas using the 21° abutment angle (Mark and Bieniawski, 1986):

\[ L_s = H^2(tan\beta)(\gamma/2) \text{ supercritical} \] (5)

\[ L_{ss} = \left( \frac{H \times PW}{2} - \frac{PW^2}{8 tan\beta} \right) \gamma \text{ subcritical} \] (6)

where \( H \) is the overburden depth, \( PW \) is the panel width and \( \gamma \) is the average unit weight of the overburden.
Mark (1990) recommended an abutment angle of 21° which has been successful in pillar design for mines under shallow cover for more than three decades. Further supporting evidence for this was found through the analysis of the case histories used to develop the ARMPS2010 design criteria. Its database consists of information from 640 different pillar plans from various mining conditions, and these pillar plans are categorized as either a successful pillar or a failed pillar. Of these case histories, 204 are from shallow cover mines (<650 ft). Logistic regression analysis of these cases with respect to calculated stability factor (ARMPS SF) values (using 21° abutment angle) shows an 86% overall classification accuracy using the ARMPS2010 design criteria (Figure 2.5) (Tuncay et al., 2019).

![Figure 2.5. ARMPS2010 SF results of the ARMPS2010 shallow cover database using the 21° abutment angle.](image)

However, for moderate to deep cover mines, several studies have suggested the abutment angle to be lower than 21°. Tulu and Heasley (2012) analyzed stress measurements from different mines and suggested the relationship between abutment angle and overburden depth for deep cover mines in Table 2.2.
Table 2.2. The abutment angle concept suggested by Tulu and Heasley (2012)

<table>
<thead>
<tr>
<th>Overburden Depth, H (ft)</th>
<th>Abutment Angle, β (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H ≤ 900</td>
<td>21°</td>
</tr>
<tr>
<td>900 &lt; H ≤ 2050</td>
<td>21 × (H/900)^{-1.59}</td>
</tr>
</tbody>
</table>

Hill et al. (2015) also analyzed stress measurements from different mines and came up with another predictive formula to be used for estimating abutment angle (Eq(7)). This study also suggested decreasing abutment angles with increasing overburden depths, consistent with previous findings. Another parameter found to influence the abutment angle was the panel width and its ratio to overburden depth. It was found that as the panel width to depth ratio increases, the abutment angle increases.

\[
β = 21.62 - 0.0221H + 0.0725PW - 6.23C
\]  
(7)

where:

\( H \) = overburden depth

\( PW \) = panel width

\( C \) = panel span criticality (\( C = 1 \), when \( PW/H < 0.75 \) and \( C = 0 \), when \( PW/H ≥ 0.75 \))

Finally, in the study by Tuncay et al. (2019), for cases with an overburden depth from 650 to 2050 ft, an abutment angle (\( β \)) that decreases with a continuous function of the \( H/PW \) ratio is proposed (Table 2.3). This equation was derived by performing a least-square error fit to the measured abutment angles above 650 ft overburden depth. Almost all the cases deeper than 650 ft also had a \( H/PW \) ratio of more than 1.

Table 2.3. Proposed abutment angle equation for \( H/PW \) ratios from 0.7 to 3.5.

<table>
<thead>
<tr>
<th>Overburden depth, H (ft)</th>
<th>Abutment angle, β (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H ≤ 650 ft</td>
<td>21°</td>
</tr>
<tr>
<td>650 ft &lt; H ≤ 2050 ft</td>
<td>29.42 × (0.68)^{H/PW}</td>
</tr>
</tbody>
</table>

Using the proposed new abutment angle equation, Tuncay et al. (2019) re-analyzed the cases used to develop ARMPS2010. It was found that for the deep cover cases with barrier pillars, the classification accuracy of ARMPS2010 was improved with the newly proposed abutment angle equation. 88% of the failed cases and 47% of the successful cases were correctly predicted.
compared to using a constant 21° abutment angle which resulted in prediction accuracies of 88% and 34%, respectively. All these studies suggest a different abutment angle calculation but, these studies still did not include the effect of site-specific overburden geology. The fact that all these studies were based on field stress measurements indirectly accounts for the response of the overburden, it is not included exclusively and cannot be modified to be site-specific.

2.2.2 Boundary Element Method – Laminated Model

Salamon (1962) proposed the mathematical basis for the laminated model, and he re-explored the concept in the early ’90s (Salamon, 1991). The laminated model seems naturally more suitable for describing the behavior of stratified coal measure rocks. The model considers the media as a stack of thin plates with cohesionless and frictionless interfaces and calculates the basic displacements and stresses for thin tabular deposits. The model uses “homogeneous stratifications,” meaning the plates have the same elastic modulus (E), Poisson’s ratio (ν), and thickness (t).

The fundamental behavior of the laminated model was investigated across a two-dimensional slot where the slot can be considered as a longwall panel with rigid ribs without any support from the gob. The panel convergence, abutment stresses, remote displacements, and surface subsidence were investigated (Heasley, 1998). The induced vertical stress in the side abutment as a function of the distance (x) from the panel rib is given in Eq (8).

\[
\sigma_l(x) = m q P \sqrt{\frac{2E_s}{E\lambda h}} e^{-\sqrt{\frac{2E_s}{E\lambda h}x}}
\]

where:

\( m \) = the abutment load / total panel load ratio
\( q \) = the in-situ stress
\( P \) = the width of the panel
\( E_s \) = the elastic modulus of the seam
\( E \) = the elastic modulus of the overburden
\( \lambda \) = a stiffness parameter of the laminated model
\( h \) = the seam thickness
In this equation, the laminated model parameter ($\lambda$) is defined as:

$$\lambda = \frac{t}{\sqrt{12(1 - \nu^2)}}$$

(9)

where:

- $t$ = the lamination thickness
- $\nu$ = Poisson’s ratio of the rock mass

The distance ($D_n$) from the panel rib where a certain percentage of the total abutment load ($n$) is carried can be calculated using Eq(10). This equation can also be rearranged to determine the lamination thickness ($t$) for a given abutment distance that is expected for given overburden and seam characteristics.

$$D_n = -\ln (1 - n) \sqrt{\frac{Eht}{2E_s\sqrt{12(1 - \nu^2)}}}$$

(10)

The LaModel program is regularly updated with added new features since its inception and has been evolving following the changes in operating systems and programming languages (Heasley and Agioutantis, 2001; Heasley et al., 2003; Hardy and Heasley, 2006; Sears and Heasley, 2009; Heasley et al., 2010; Sears, 2013). The default parameters used in the lamination thickness wizard and the gob wizard in the program allow users to calibrate their model to match the empirical equations for abutment extent and gob loads from ACPS (Figure 2.6 and Figure 2.7). The user can also manually input known parameters such as rock mass and seam parameters, the abutment extent, and percent gob load to calibrate the model.
Figure 2.6. The lamination thickness wizard in LamPre 3.0.

Figure 2.7. The gob wizard within the seam material wizard in LamPre 3.0.
2.2.3 Finite Volume Method – FLAC3D

The finite difference software FLAC3D can model the mining-induced stresses and the related overburden behavior in terms of displacements. It can also model the strength anisotropy of the bedded coal measure rocks and the weakening of the failed rocks. Furthermore, the built-in FISH coding language allows the user to control the loads and the displacements in the model (Esterhuizen et al., 2010).

The basis of the modeling methodology used in this study was developed in 2010 by Esterhuizen et al. The model includes the 2D slice of a cross-section along the width of the panel, including the chain pillar system. The 2D model employs actual stratigraphy, using all the geological layers as thin as 1 ft. The overburden layers are modeled as strain-softening ubiquitous joint material, which simulates the bedding weaknesses in strongly bedded strata as well as the vertical joints in massive rock types.

Caving in sedimentary strata is mostly governed by the major planes of parting (Singh and Singh 2010). In addition to the model developed by Esterhuizen et al. (2010), interface elements are used to model the interfaces between the geological layers in the overburden. In the study conducted by Bandis et al. (1983), the shear stiffness values observed for 1-m-sized blocks varied from 0.01 and 10 GPa/m, and the ratio of normal stiffness to shear stiffness \( \frac{K_n}{K_s} \) ranged from 10 to 130, with the highest ratios observed under extremely low normal stress. For the interfaces between overburden layers, joint shear stiffness is set to 0.5 GPa/m, which is around average for 1-m block size, and normal stiffness is set to 18.75 GPa/m. As described by Su (1991), the coefficient of friction is set to 0.25 between the overburden layers.

In FLAC Models, the coal material was modeled with a Hoek-Brown coal model based on the model developed at NIOSH by Esterhuizen et al. (2010), with the updated input parameters presented in Table 2.4. The parameters were selected to give matching pillar strength values with the Bieniawski pillar strength formula (Eq(1)). Figure 2.8 shows the comparison of calibrated coal model pillar strength and the empirical pillar strength formula. The interface parameters were set differently for interfaces between overburden layers and between coal and rock. The friction angle on the coal-rock interfaces was set to be 20° to be able to simulate an appropriate stress gradient at the edge of the pillar, and for the interfaces between coal and rock, the shear and normal stiffnesses are set to 2.2×10^6 psi/ft and 4.4×10^6 psi/ft, respectively (Esterhuizen et al., 2010).
Table 2.4. Hoek-Brown coal model and related interface properties (Esterhuizen et al., 2010).

<table>
<thead>
<tr>
<th>Coal properties</th>
<th>Coal-rock interface properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk modulus</td>
<td>Interface friction angle</td>
</tr>
<tr>
<td>290,000 psi</td>
<td>20°</td>
</tr>
<tr>
<td>Shear modulus</td>
<td>Interface cohesion</td>
</tr>
<tr>
<td>175,000 psi</td>
<td>54.4 psi</td>
</tr>
<tr>
<td>m-value</td>
<td>Interface tensile strength</td>
</tr>
<tr>
<td>1.47 (residual: 1.17)</td>
<td>0.0</td>
</tr>
<tr>
<td>s-value</td>
<td>Interface normal stiffness</td>
</tr>
<tr>
<td>0.07 (residual: 0.03)</td>
<td>4.4×10^6 psi/ft</td>
</tr>
<tr>
<td>a-value</td>
<td>Interface shear stiffness</td>
</tr>
<tr>
<td>0.67</td>
<td>2.2×10^6 psi/ft</td>
</tr>
</tbody>
</table>

Figure 2.8. Comparison of calibrated coal model pillar strength and the empirical pillar strength equation of Bieniawski (1981) (modified from Esterhuizen et al., 2010).

Esterhuizen et al. (2010) published suggested overburden rock parameters to be used in large-scale models. Those parameters were later modified by Tulu et al. in 2017 and are presented in Table 2.5. The uniaxial compressive strength (UCS) values in Table 2.5 are laboratory-scale values, and the field UCS values were estimated by reducing the laboratory-scale values to 58% (Hoek and Brown 1980; Esterhuizen et al., 2010). For sandstone and shale, the elastic modulus (E) was estimated using Eq(11), and for limestone, it was estimated using Eq(12) (Tulu et al., 2017; Tulu et al., 2018). These equations were driven from the regression analysis of a large database of UCS tests.
E (GPa) = 0.143 × UCS (MPa) + 6.16 \quad (11)

E (GPa) = 0.1162 \times UCS (MPa) + 15.24 \quad (12)

The friction angles were determined from the database of tri-axial tests (Esterhuizen et al., 2010). The friction values were also assumed to be the same at the laboratory and field scales. The cohesion values listed in Table 2.5 are field-scale values and calculated by using Eq(13).

\[ C = \frac{UCS_{\text{field}} \times (1 - \sin(\emptyset))}{2 \times \cos(\emptyset)} \quad (13) \]

**Table 2.5. Suggested intact rock properties (Tulu et al., 2017).**

<table>
<thead>
<tr>
<th>Intact Rock Properties</th>
<th>Peak Bedding Strength Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UCSlab (psi)</td>
</tr>
<tr>
<td>------------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>Limestone</td>
<td>20.3\times10^3</td>
</tr>
<tr>
<td></td>
<td>14.5\times10^3</td>
</tr>
<tr>
<td></td>
<td>11.6\times10^3</td>
</tr>
<tr>
<td>Sandstone</td>
<td>17.4\times10^3</td>
</tr>
<tr>
<td></td>
<td>14.5\times10^3</td>
</tr>
<tr>
<td></td>
<td>11.6\times10^3</td>
</tr>
<tr>
<td></td>
<td>8.7\times10^3</td>
</tr>
<tr>
<td></td>
<td>5.8\times10^3</td>
</tr>
<tr>
<td>Shale</td>
<td>11.6\times10^3</td>
</tr>
<tr>
<td></td>
<td>8.7\times10^3</td>
</tr>
<tr>
<td></td>
<td>5.8\times10^3</td>
</tr>
<tr>
<td></td>
<td>4.4\times10^3</td>
</tr>
<tr>
<td></td>
<td>2.9\times10^3</td>
</tr>
<tr>
<td></td>
<td>1.5\times10^3</td>
</tr>
<tr>
<td></td>
<td>0.7\times10^3</td>
</tr>
</tbody>
</table>

Using the rock parameters in Table 2.5, bedding strength parameters were derived by Esterhuizen et al. (2010). Bedding tensile strengths were calculated as 10% of field-scale UCS values (0.58*UCS_{lab}). The suggested peak bedding strength properties were also presented in Table 2.5. The bedding cohesion and tensile strength were decreased to residual values that are
10% of their peak values over 5mε of plastic strain (Zipf 2007). The bedding planes were assumed to be elastic perfectly plastic in terms of their stress-strain behavior.

Accurately simulating the gob response is critical to approximate the mining-induced load distribution along the chain pillars, gob, and gateroad entries. Based on the study conducted by Pappas and Mark (1993), the stress-strain response of the caved material they tested followed a strain-hardening curve. The strain-hardening gob response was found to fit the hyperbolic function (Eq(14)) derived by Salamon (1990):

\[
\sigma = \frac{a \times \varepsilon}{b - \varepsilon}
\]

where:

\( \sigma \) = vertical gob stress
\( \varepsilon \) = vertical gob strain
\( b \) = maximum strain parameter (related to void ratio)
\( a \) = gob stress when \( \varepsilon = b/2 \)

The FISH option of the FLAC3D software was used to simulate the strain-hardening gob behavior. It was achieved by updating the elastic modulus of each zone inside the gob with the expected tangent modulus, which can be calculated by taking the derivative of the hyperbolic function (Eq(14)) with respect to vertical strain (Eq(15)) (Tulu et al., 2018).

\[
E(\varepsilon) = \frac{\partial \sigma}{\partial \varepsilon} = \frac{a \times b}{(b - \varepsilon)^2}
\]

In the study by Li et al. (2015), for the numerical analysis of yield pillars, the gob material was modeled assuming a bulking factor of 1.216 resulting in a maximum strain parameter \( b \) of 0.17. The mining height was 20 ft with an assumed caving zone of 90 ft. In another study by Zhang et al. (2017), for a case with a mining height of 21 ft, the bulking factor and maximum strain were estimated as 1.235 and 0.19, respectively. In another recent study, Feng et al. (2019) analyzed the use of irregular yield pillars for gateroad stability. In their numerical modeling approach, they modeled the gob material to follow Salamon’s formula with the bulking factor and maximum strain as 1.31 and 0.24, respectively.

Esterhuizen et al. (2010) examined the gob parameters; \( a \) and \( b \), by matching the model results with subsidence profiles obtained from the Surface Deformation Prediction Software (SDPS)
The maximum strain parameter \( b \) was determined as 0.44, and the “\( a \)” parameter was found to be dependent on the type of rock material in the gob ranging from 856 psi for weak gob up to 3650 psi for very strong gob.

Su (1991) assumed an initial bulking factor of 1.5 for the formation of the gob. This suggests a maximum strain of 0.33 and a caving height of three times the mining height. Su (1991) has applied this approach successfully to various longwall mine cases for estimating subsidence and pillar stresses. Compared to the results obtained by Esterhuizen \textit{et al.} (2010), the stress-strain values obtained from the parameters used by Su (1991) gave similar results for the weak/moderate gob (Tulu \textit{et al.}, 2017). In this study, the gob parameter, \( a \), was selected as 435 psi (3 MPa) except for the mines from the western U.S. where 1,305 psi (9 MPa) was used following the study by Zhao and Tulu (2020) that suggested stiffer gob parameters work better for the western U.S. mines. The \( b \) parameter was selected as 0.33 based on the study by Su (1991) assuming 1.5 bulking factor.

Figure 2.9 illustrates the stress-strain behavior of the gob for weak and strong overburden.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{stress_strain_gob.png}
\caption{Stress-strain behavior of the modeled gob}
\end{figure}
CHAPTER 3 – METHODOLOGY

3.1 Database Development

To truly understand the mechanism of overburden response to mining requires the evaluation of this complex response under a variety of loading, operational, and, most importantly, geologic conditions. The database development task in this thesis consisted of gathering information on various field monitoring cases from mines operating in different physiographic provinces and geological formations.

A database of 13 case studies from 12 different U.S. longwall mines was put together with information on overburden geology and with subsidence or stress measurements to verify the models. Detailed geologic core logs were available for all the mines. Figure 3.1 shows the generalized stratigraphic columns of the case study sites where adjacent thin layers of the same rock types were combined for easier representation. Table 3.1 shows a summary of the cases. The codes given to different mines (NA, CA, BW, W) represent different regions and basins the mines are located: Northern Appalachian, Central Appalachian, Black Warrior, and Western, respectively.

Table 3.1. Summary of case study mines.

<table>
<thead>
<tr>
<th>Case</th>
<th>Seam Name</th>
<th>Seam Height</th>
<th>In-situ Stress Region</th>
<th>Panel Width / Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA-1</td>
<td>Pittsburgh</td>
<td>6.5 ft</td>
<td>Eastern U.S., Northern Appalachia</td>
<td>2.08</td>
</tr>
<tr>
<td>NA-2</td>
<td>Pittsburgh</td>
<td>7.5 ft</td>
<td>Eastern U.S., Northern Appalachia</td>
<td>1.67</td>
</tr>
<tr>
<td>NA-3</td>
<td>Middle Kittanning</td>
<td>7.0 ft</td>
<td>Eastern U.S., Northern Appalachia</td>
<td>2.27</td>
</tr>
<tr>
<td>NA-4</td>
<td>Lower Kittanning</td>
<td>7.0 ft</td>
<td>Eastern U.S., Northern Appalachia</td>
<td>0.91</td>
</tr>
<tr>
<td>NA-5</td>
<td>Pittsburgh</td>
<td>7.0 ft</td>
<td>Eastern U.S., Northern Appalachia</td>
<td>0.82</td>
</tr>
<tr>
<td>NA-6</td>
<td>Pittsburgh</td>
<td>6.5 ft</td>
<td>Eastern U.S., Northern Appalachia</td>
<td>1.45</td>
</tr>
<tr>
<td>CA-1</td>
<td>Pocahontas No.3</td>
<td>6.6 ft</td>
<td>Eastern U.S., Central App.</td>
<td></td>
</tr>
<tr>
<td>CA-2</td>
<td>Pocahontas No.3</td>
<td>4.2 ft</td>
<td>Eastern U.S., Central App.</td>
<td>1.64</td>
</tr>
<tr>
<td>CA-3</td>
<td>Pocahontas No.3</td>
<td>5.5 ft</td>
<td>Eastern U.S., Central App.</td>
<td>0.29</td>
</tr>
<tr>
<td>BW-1</td>
<td>Blue Creek.</td>
<td>7.9 ft</td>
<td>Eastern U.S., Eastern Mid-Continent</td>
<td>0.69</td>
</tr>
<tr>
<td>W-1</td>
<td>Hiawatha</td>
<td>8.0 ft</td>
<td>Western U.S. (Utah)</td>
<td>0.41</td>
</tr>
<tr>
<td>W-2</td>
<td>D coal seam</td>
<td>8.0 ft</td>
<td>Western U.S. (Colorado)</td>
<td>0.42</td>
</tr>
</tbody>
</table>
For the operational parameters, the most influential parameters governing the abutment stresses are usually the panel width, the overburden depth, and their ratios to one another. These parameters are generally the main input parameters for the pillar design tools and are used for estimating the mining-induced loads. The database included cases with $pw/H$ ratios ranging from 0.29 to 2.27. The seam thicknesses ranged from as low as 4.2 ft in a mine operating in the Pocahontas No. 3 coal seam, up to 10 ft in one of the western longwall mines. The case studies utilize either a 3 or 4-entry chain pillar system.

![Generalized stratigraphic column representation of the case study mines.](image)

*Figure 3.1. Generalized stratigraphic column representation of the case study mines.*
**Mine NA-1**

This mine operated in the Pittsburgh coal seam in South Western Pennsylvania. According to the MSHA data retrieval system, the mine produced approximately 6.77 and 6.42 million tons of coal in 2017 and 2018, respectively (MSHA, 2020a). Figure 3.2 shows the panels and the chain pillar system near the field study site. The depth of cover around the studied area was around 650 ft. While the panel widths were around 800 ft in previous districts, currently the mine is operating panels more than 1500 ft wide. They utilize a 3-entry chain pillar system with 80 ft wide pillars (rib-to-rib) and 16 ft wide entries. The mining height is approximately 6.5 ft.

![Figure 3.2. Mine NA-1 panel and chain pillar configuration.](image)

**Mine NA-2**

The second longwall mine from the northern Appalachian region (Mine NA-2) operates in northern West Virginia in the Pittsburgh seam. Figure 3.3 shows the mine outline and the pillar system near the study site. The studied longwall panel was roughly 1170 ft wide with a depth of cover of 700 ft. The gateroad system was a three-entry system with approximately 115 and 100-ft-wide chain pillars (center-to-center) and 16 ft wide entries. The mining height was approximately 7.5 ft. The immediate roof generally consisted of shale, rider coal, claystone, and sandstone or limestone, and the floor was claystone or shale.
The third longwall mine operating in the northern Appalachian region (Mine NA-3) mines the Middle Kittanning coal bed and is located in northern West Virginia. According to the MSHA data retrieval system, the mine produced approximately 3.38 and 3.44 million tons of coal in 2017 and 2018, respectively (MSHA, 2020a). Figure 3.4 shows the outline of the panels near the study site (Tulu et al., 2018). The depth of cover throughout the mine ranged from 500 to 750 ft, and the typical depth was about 520 ft. The longwall panels were roughly 1200 ft wide and 8000 ft long. The gateroad system was a three-entry system with approximately 100-ft-wide chain pillars (center-to-center) with approximately 20 ft wide entries. The mining height was approximately 7 ft. Based on the in-mine mapping, as well as available exploration drill-hole data, the geologic conditions were typical for the Allegheny Formation. The Middle Kittanning coal bed that was mined is overlain by dark gray to carbonaceous clay shale. The clay shale grades upward to gray sandy shale, dark gray sandy shale, or gray sandstone. The gray sandy silt shale and dark gray sandy silt shale beds vary in grain size and sand content, based on their proximity to the laterally correlative gray sandstone beds.
Figure 3.4. Mine NA-3 panel and chain pillar configuration (modified from Tulu et al., 2018).

**Mine NA-4**

This northern Appalachian longwall mine is located in southwestern Pennsylvania and operated in the Lower Kittanning coal seam. Figure 3.5 shows the chain pillar configuration. The depth of cover around the studied area was 650 ft and the longwall panel was roughly 600 ft wide and 2725 ft long. The gateroad system was a three-entry system with approximately 80-ft-wide and 60-ft-wide chain pillars (rib-to-rib) with approximately 20 ft wide entries. The mining height was approximately 4 ft. The information was obtained from confidential consultancy reports.

Figure 3.5. Mine NA-4 close-up of the chain pillar configuration.
Mine NA-5

Located on the border between North Central West Virginia and South Western Pennsylvania, the fifth northern Appalachian longwall mine in our database is operating in the Pittsburgh coal bed. Figure 3.6 shows the outline of the panels and the utilized pillar system near the study site (Van Dyke et al., 2020). The depth of cover at this mine ranges from 400-ft to about 1400 ft. The longwall panels near the study site were 1100-ft-wide and are 12,000 ft long. The gateroad consisted of a small and a large pillar with center-to-center widths of 90-ft and 165-ft-wide. The entry and crosscuts in the gateroads were 18-ft-wide and the mining height was around 7 ft.

![Figure 3.6. Mine NA-5 panel and chain pillar configuration (modified from Van Dyke et al., 2020).](image)

Mine NA-6

The sixth and final northern Appalachian longwall mine in our database (Mine NA-6) is in southwestern Pennsylvania and operates in the Pittsburgh coal seam. The depth of cover around the studied area was around 690 ft, and the longwall panel was roughly 1000 ft wide. The chain pillar system was 3-entries with 85-ft-wide pillars (rib-to-rib) and 17 ft wide entries (Figure 3.7). The mining height was approximately 6.5 ft.
Mine CA-1

The first central Appalachian longwall mine in our database (Mine CA-1) is in Virginia and operates in the Pocahontas No.3 seam. The mine produced approximately 4.9 million tons of low-vol met coal in 2017. Figure 3.8 shows the outline of the panels near the study site (Klemetti et al., 2018). The depth of cover throughout the mine ranged from 1200 to 2300 ft. The longwall panels were roughly 700 ft wide by 10,000 ft long. The gateroad system was a four-entry system with approximately 50-ft-wide yield pillars and 174-ft-wide abutment pillars (center-to-center) with approximately 18 ft wide entries. The mining height was approximately 5.5 ft on average for the studied panel. The typical roof geology consisted of silty to sandy shales, sandstones, and coal. Shales usually dominate the bolted horizon followed by sandstone with an inconsistent shale parting before reaching the Pocahontas No. 4 coal seam (Klemetti et al., 2019a).

Figure 3.7. Mine NA-6 panel and chain pillar configuration.

Figure 3.8. Mine CA-1 4-entry chain pillar configuration (modified from Klemetti et al., 2018).
**Mine CA-2**

The second central Appalachian longwall mine (Mine CA-2) studied in this work was in southern West Virginia and operated in the Pocahontas No. 3 coal bed. Overburden depth around the study area ranged from 447 to 645 ft. The longwall panel studied was 800 ft wide by 5300 ft long. The gateroad system was a four entry with approximately 105-ft-wide center pillars and 40 ft-wide side pillars (rib-to-rib) with approximately 16 ft wide entries. Figure 3.9 shows the outline of the panels near the study site. The mining height was approximately 4.2 ft. Based on the drill logs provided, the rocks in the overburden strata were classified into the following four types: sandstone, shaly sandstone, shale, and sandy shale, and coal. The information was obtained from confidential consultancy reports.

![Figure 3.9. Mine CA-2 panel and chain pillar configuration.](image)

**Mine CA-3**

The third and last central Appalachian longwall mine (Mine CA-3) studied in this work was located in Virginia and operates in the Pocahontas No. 3 seam. The depth of cover throughout the mine ranged from 1200 to 2200 ft, and the depth around the studied area was about 2085 ft. The longwall panels were roughly 600 ft wide by 6000 ft long. The gateroad system was a four-entry with 40-ft-wide yield pillars and 165-ft-wide abutment pillars, center-to-center. The entries were 20 ft wide and Figure 3.10 shows the outline of the panels and the pillar system near the study site (Campoli et al., 1993). The mining height averages approximately 5.5 ft.
Figure 3.10. Mine CA-3 panel and chain pillar configuration (modified from Campoli et al., 1993).

Mine BW-1

The Black Warrior Basin longwall mine (Mine BW-1) studied in this work was located in Alabama. The mine operates in the Blue Creek coal seam. According to the MSHA data retrieval system, the mine produced approximately 4.86 and 5.60 million tons of coal in 2017 and 2018, respectively (MSHA, 2020a). Figure 3.11 shows the outline of the panels and pillar configuration near the study site (Klemetti et al., 2018). The depth of cover throughout the mine changed between 1100 to 2200 ft. The longwall panels were approximately 1000 ft wide and 7000 ft long. They utilize a four-entry chain pillar system with approximately 40-ft-wide yield pillars and 165-ft-wide abutment pillars (center-to-center) with approximately 20 ft wide entries. The mining height was approximately 7.9 ft.

Figure 3.11. Mine BW-1 panel and chain pillar configuration (modified from Klemetti et al., 2019b).
**Mine W-1**

The first western longwall mine studied in this study is in Emery County, Utah. The mine was operated in the Hiawatha coal seam at a depth of 2000 ft (Allgaier, 1988). Four entries were developed through the Main West North Barrier under a depth of cover ranging from 1,500 to 2,240 ft (MSHA, 2007). At Mine W-1, extraction height averages 8.8 ft, and the width of the panel is 550 ft. No previous mining had been conducted above this mine. The longwall panels were roughly 775 ft wide by 4,540 ft long in the west part of mine. A two-entry yield pillar system was used between the panels in Mine W-1 and the dimensions of the pillars were 35 ft by 108 ft (Figure 3.12). The local roof geology consists of sandstones and siltstones. There was a 100 ft thick limestone bed at the surface, followed by about 400 ft of siltstone and sandstone layers.

![Figure 3.12. Mine W-1 panel and chain pillar configuration.](image)

**Mine W-2**

The second western longwall mine, located near Somerset in Gunnison County, CO has used a three-entry abutment pillar design for all gateroads (Figure 3.13). There were different sizes of pillars applied in Mine W-2 depending on the support needs, including 73 ft by 180 ft, 100 ft by 180 ft, and 170 ft by 180 ft. The length of the panels changed from 7000 ft to 9000 ft, and the width of the panels was roughly 780 ft. The coalfield was exposed at a few localities and was buried to a depth of as much as 2,500 ft. The average extraction thickness in Mine W-2 is 8 ft. The
average overburden depth near the instrumentation site was about 2000 ft. Sandstones, sandstones with interbeds of siltstones, and shale were the predominant units. There were also some mudstone layers near the roof and floor, which caused floor heave problems. The information was obtained from confidential consultancy reports.

![Figure 3.13. Mine W-2 panel and chain pillar configuration.](image)

3.2 Numerical Modeling

3.2.1 Model Development and Verification

For each case study, FLAC3D models were constructed and analyzed for a two-dimensional cross-section of the instrumented location of the mine. The overburden model for each mine was developed from actual stratigraphy, using all the geological layers with a minimum layer thickness of 1 ft, from a core hole near the instrumentation sites. The element sizes were selected as 3.28 ft (1 m) in x- and y-direction. The element sizes in z-direction were selected based on the layer thicknesses, still keeping them less than 3.28 ft. The extents of the models were selected to be at least three times the depth on both sides of the outer panels. The side boundaries of the models
were fixed on x- and y-directions and free on z-direction. Figure 3.14 represents the boundary conditions and extents used for the models.

![Figure 3.14. Model extent and boundary conditions.](image)

Each model was solved in successive loading stages, simulating different panels' mining relative to the instrumented site. For all the cases, the first stage was simply the development-mining scenario when all the model entries were mined, followed by complete mining of consecutive panels on the next steps. Figure 3.15 shows the 3D representation of the different models used for the study (demonstration purposes only, actual models are 2D). The single panel models (Figure 3.15b) do not include mining of any prior panels and the consecutive panel models (Figure 3.15c) have at least 2 panels mined sequentially.

![Figure 3.15. 3D representation of a) development b) single panel and c) consecutive panel models (demonstration purposes only, actual models are 2D).](image)

The total number of panels to be mined for the consecutive panel models was determined uniquely for each case to simulate the influence of the consecutive panel mining on instrumented sections. The active panel represents the last panel being mined for each modeling step and the previous panel is the one before that. The shallow mines were modeled as one or two consecutive panel mining, whereas the deeper case studies were modeled with up to five consecutive panels to analyze the effect of the sub-critical loading condition on consecutive panels.
Figure 3.16 is an example of a 2D model with five consecutive panels (Mine CA-3). The zoomed-in section shows the headgate side of the 5th panel with the 4-entry chain pillar system. All the different colored layers represent a stratigraphic layer, modeled using core log information.

![2D model of Mine CA-3 with five consecutive panels.](image)

Figure 3.16. 2D model of Mine CA-3 with five consecutive panels.

After each case study mine model was solved, stresses and displacements computed at the instrument locations were queried and compared with the field monitoring results for model verification.

3.2.2 Parametric Runs

Following the verification of the models with field information, each case was re-run with different panel dimensions, keeping the overburden geology unchanged. The panel dimensions for the parametric runs were selected to test varying panel width to depth ratios, ideally sub-critical, critical, and super-critical. At least two additional parametric runs were conducted even when sub or super-critical conditions could not be achieved with plausible panel widths.
Table 3.2 lists the parametric runs performed for the cases and their respective panel width to depth ratios. However, these parametric runs were conducted for single panel analysis due to time constrain.

Table 3.2. List of parametric runs and the respective panel width to depth ratios.

<table>
<thead>
<tr>
<th>Case</th>
<th>Original pw/H</th>
<th>Parametric #1 pw/H</th>
<th>Parametric #2 pw/H</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA-1</td>
<td>2.10</td>
<td>0.80</td>
<td>1.20</td>
</tr>
<tr>
<td>NA-2</td>
<td>1.68</td>
<td>0.80</td>
<td>1.20</td>
</tr>
<tr>
<td>NA-3</td>
<td>2.28</td>
<td>0.80</td>
<td>1.20</td>
</tr>
<tr>
<td>NA-4</td>
<td>0.91</td>
<td>1.20</td>
<td>1.50</td>
</tr>
<tr>
<td>NA-5</td>
<td>0.82</td>
<td>0.60</td>
<td>1.20</td>
</tr>
<tr>
<td>NA-6</td>
<td>1.45</td>
<td>0.80</td>
<td>1.80</td>
</tr>
<tr>
<td>CA-1a</td>
<td>0.34</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>CA-1b</td>
<td>0.55</td>
<td>0.30</td>
<td>0.70</td>
</tr>
<tr>
<td>CA-2</td>
<td>1.63</td>
<td>1.20</td>
<td>2.00</td>
</tr>
<tr>
<td>CA-3</td>
<td>0.29</td>
<td>0.40</td>
<td>0.60</td>
</tr>
<tr>
<td>BW-1</td>
<td>0.69</td>
<td>0.40</td>
<td>1.00</td>
</tr>
<tr>
<td>W-1</td>
<td>0.41</td>
<td>0.60</td>
<td>0.80</td>
</tr>
<tr>
<td>W-2</td>
<td>0.42</td>
<td>0.50</td>
<td>0.60</td>
</tr>
</tbody>
</table>

3.3 Analysis of the Results

3.3.1 Analysis of Abutment Stresses

Every model run, including the parametric runs was initially analyzed in terms of single panel abutment loading. The total abutment load percentages were calculated for each case. For the original cases with multi-panel runs, detailed analysis including mining-induced loads on the chain pillars and the solid coal of the next panel together with the gob loads were determined.
The loading conditions were restricted to full side abutments due to the models being 2-dimensional. There are five loading conditions used in ALPS for the calculation of pillar safety factors (Mark, 1992):

i. Development loading: The loading on the pillar system before any longwall retreat mining.

ii. Headgate loading: The pillar loading adjacent to the headgate corner of the longwall face, which is equal to the development load plus the first front abutment.

iii. Bleeder loading: The loading on a pillar system adjacent to a mined-out panel, which equals the development load plus the first side abutment.

iv. Tailgate loading: The loading on a double-use gate entry system when it is adjacent to the tailgate corner of the longwall face, equal to the development load plus the first side abutment plus the second front abutment.

v. Isolated loading: The loading on a pillar system located between two mined-out panels, equal to the development load plus two side abutments.

Using the 2D models; only the development, bleeder, and isolated loads can be simulated and estimated since the other loading conditions require a 3D model to simulate different locations of the panel face. For comparable abutment loads for various case studies, dimensionless (normalized) loads were calculated for analysis rather than absolute loads. The percentages of the total panel load transferred to the abutments and carried by the gob were determined using the method shown in Figure 3.17.

The normalized load percentages represent the ratio of the load (side abutment, inter-panel gateroad, or gob) to the single panel tributary area load (TAL). The percentages sum up to 200% in the case of the two-panel model, since it is the ratio of total transferred load (2×TAL) to the single panel tributary area load (TAL).
3.3.2 Statistical Modeling for Geology Based Loading Estimation

To include the effect of geology in statistical modeling, a new parameter that represents the strength and stiffness of the overburden was proposed. This parameter is a function of the strength of the overburden layers, the thickness of strong beds, and the relative location of the strong beds in the overburden. The critical span, which is the self-supporting length of a rock layer, is the main strength component of the geological parameter.
For this study, the elastic thin plate model was selected due to its practicality of calculation compared to other iterative approaches such as the voussoir beam approach. There are also other non-iterative methods to calculate critical span lengths, but the theory of thin plates is also the basis of the laminated model that was used in this study. The elastic thin plate model, which is based on plate theory, was derived by Salamon et al. (1972) and later improved by Galvin (1981) to estimate the span required to break a dolerite sill in the overburden of the South African coal mines. This theory was used by Salamon et al. (1972) to calculate critical panel widths when a very strong geological unit, e.g., a dolerite sill, exists in the overburden. During the derivation of the equations, Salamon et al. (1972) assumed that an elastic thin plate is loaded uniformly with fixed boundary conditions at each side of the plate. According to this theory, the critical (maximum) stress in a sill can be calculated using Eq(16) if the critical span when collapse occurs ($S$) is known (Galvin, 1981).

$$\sigma_c = k\gamma \frac{D_D S^2}{t_D^2}$$

where $\sigma_c$ is the critical stress, $k\gamma$ is the specific weight of the overburden, $D_D$ is the depth to the base of the sill, $t_D$ is the thickness of the sill and $S$ is the critical panel span.

In Eq(16), the critical stress can be replaced with critical failure stress of the rock layer ($f'$) to calculate the critical span for each rock layer on the overburden by using Eq(17).

$$S_i = t_i \sqrt{\frac{f'_i}{k\gamma D_i}}$$

where $S_i$ is the critical span for a rock layer in the overburden, $t_i$ is the thickness of the rock layer, $f'_i$ is critical failure stress or strength of the rock layer, $k\gamma$ is the specific weight of the overburden and $D_i$ is depth to the base of the rock layer. The estimation of the critical failure stress ($f'_i$) values was done for the studied dolerite sills and was a function of $k\gamma$ and the sill’s depth to thickness ratio (Galvin, 1981). The constants in the formula to estimate the critical failure stress were semi-empirically derived from observations of failed and intact sills. For this study, the critical failure stress ($f'_i$) values were selected as the UCS values.
CHAPTER 4 – RESULTS AND DISCUSSION

4.1 Verification of the Numerical Models

After following the systematic procedure explained in section 2.2.3 and running the numerical models, stress changes around the panels and surface displacements were compared to field measurements. For cases where detailed measurements were not available, estimates about maximum subsidence and/or subsidence profiles obtained from SDPS and CISPM-MS were used (Luo, 1989; Luo and Qiu, 2012; Karmis et al., 1989; Agioutantis and Karmis, 2017). These empirical subsidence estimation tools are proven to be successful in predicting subsidence profiles for mines in the Appalachian region, where several cases in their database are located.

Figure 4.1 shows the comparison of the surface subsidence results obtained from the 2D models to the field measurements for case study mines: NA-1, NA-2, NA-3, NA-4, NA-6, and W-1. For mine NA-2 (Figure 4.1b), results from the empirical prediction tool, CISPM-MS, were used for the verification. For mine CA-2, the maximum possible subsidence value was compared with the results obtained from the model. The model approximated the maximum subsidence on the CA-2 mine panel to be 1.99 ft compared to the reported value of 2.04 ft.

Figure 4.1. Subsidence profiles obtained from the models compared to the field measurements for (a) Mine NA-1 (b) Mine NA-2 (c) Mine NA-3 (d) Mine NA-4 (e) Mine NA-6 (f) Mine W-1.
Numerical models for the mines NA-5, CA-1, and BW-1 were conducted under a NIOSH contract. Under the scope of the contract, geological information and the mine maps were used to construct the numerical models and field measurements collected by NIOSH researchers were used to verify the numerical models. The results obtained from the study have been included in the publications (Klemetti et al., 2019a, 2019b; Van Dyke et al. 2020).

For Mine CA-1, average BPC measurements at various locations in yield and abutment pillars were used to compare with the model results and presented in Figure 4.2. Although there were some variations between modeled and measured stress values, the general stress trend computed by the model was comparable to the measurement results (Klemetti et al., 2019a).

*Figure 4.2. Model results compared to the field measurements for Mine CA-1 (modified from Klemetti et al., 2019a).*

For mine BW-1, the model showed comparable results to the instrumentation and monitoring data and field observations. The modeled stress increases were similar for the first panel and slightly greater for the second panel. The model provided reasonable results in terms of pillar rib yielding and yield pillar response to longwall panel retreating as well (Klemetti et al., 2019b). Figure 4.3 shows the rib yielding observed in the model and the calculated average pillar stresses.
Figure 4.3. Model results showing the average pillar stresses and the sloughing on the pillars for Mine BW-1 instrumentation site (modified from Klemetti et al., 2019b).

For Mine NA-5, the 2D model results were compared with the empirical subsidence prediction program, the Surface Deformation Prediction System (SDPS) (Karmis et al., 1989; Agioutantis and Karmis, 2017). The FLAC model approximated the subsidence of the panel with an average overburden depth of 1223 ft, panel width of 1000 ft, and a hard-rock ratio of 25% as 4.75 ft compared to the SDPS prediction of 4.33 ft. Figure 4.4 shows the obtained stress profiles from the 3D model and the results were compared with BPC measurements and shown in Figure 4.5. The BPC installed into the closer pillar was showing less stress compared to the model results but the measurements from the BPC installed in the larger bleeder pillar agreed with the model results (Van Dyke et al. 2020).
Figure 4.4. Model results showing the stress profile along the cross-section AA’ for Mine NA-5 (modified from Van Dyke et al. 2020).

Figure 4.5. BPC locations and comparison of measured and modeled results for Mine NA-5 (modified from Van Dyke et al. 2020).
Verification of Mine CA-3 was carried out using stress measurement data. Borehole Platened Flatjacks were installed into the yield pillars, abutment pillar, and the adjacent coal and the results were published by Campoli et al. (1993). Similarly, the FLAC3D model for Mine W-2 was verified using Borehole Pressure Cell (BPC) measurements obtained from a consultancy report. Comparable to the instrumentation data, stress concentrations closer to the ribs were observed in the model results (Figure 4.6 and Figure 4.7). The variation between the measurements and the model results may be explained by the instrumentation installation as well as the local composition and strength of the material surrounding the pressure cells.

![Stress profiles obtained from the 2D model compared to the field measurements for Mine CA-3.](image)

*Figure 4.6. Stress profiles obtained from the 2D model compared to the field measurements for Mine CA-3.*

![Stress profiles obtained from the 2D model compared to the field measurements for Mine W-2.](image)

*Figure 4.7. Stress profiles obtained from the 2D model compared to the field measurements for Mine W-2.*
4.2 Analysis of the Modeling Results

For each of the 13 field measurement case studies, at least four numerical models were constructed: three single panel models (with the original panel width, plus two parametric panel widths) and a model of consecutive panel (original panel width) mining. Depending on the depth of the mine, the number of panels for the consecutive panel mining models ranged between two and five. For shallow super-critical panels, two panels were modeled since the effect of consecutive panels was found to be negligible. For deeper mines, at least three panels were modeled to investigate the influence of consecutive panels on overburden stress distribution. For all numerical models, total load transfers to the pillar system, the gob, and the adjacent coal were calculated.

4.2.1 Analysis of Single Panel Abutment Stresses

Single panel models include the models with the original panel dimensions as well as the parametric models which have different panel widths. Table 4.1 shows the calculated gob load percentages for each case study mine including the parametric runs. These results represent the calculated loads from a complete single panel extraction model, without any prior panels mined.

<table>
<thead>
<tr>
<th>Case Study Mine</th>
<th>Overburden Depth (ft)</th>
<th>Panel Width (ft)</th>
<th>PW/H</th>
<th>Gob Load (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA-1</td>
<td>647</td>
<td>1,359 (original)</td>
<td>2.10 (original)</td>
<td>68.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>518</td>
<td>0.80</td>
<td>27.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>776</td>
<td>1.20</td>
<td>41.0%</td>
</tr>
<tr>
<td>NA-2</td>
<td>698</td>
<td>1,171 (original)</td>
<td>1.68 (original)</td>
<td>60.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>558</td>
<td>0.80</td>
<td>22.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>838</td>
<td>1.20</td>
<td>47.0%</td>
</tr>
<tr>
<td>NA-3</td>
<td>518</td>
<td>1,181 (original)</td>
<td>2.28 (original)</td>
<td>75.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>414</td>
<td>0.80</td>
<td>39.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>622</td>
<td>1.20</td>
<td>58.0%</td>
</tr>
<tr>
<td>NA-4</td>
<td>651</td>
<td>591 (original)</td>
<td>0.91 (original)</td>
<td>29.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>781</td>
<td>1.20</td>
<td>45.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>977</td>
<td>1.50</td>
<td>55.0%</td>
</tr>
<tr>
<td>NA-5</td>
<td>1224</td>
<td>1,001 (original)</td>
<td>0.82 (original)</td>
<td>44.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>734</td>
<td>0.60</td>
<td>23.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,469</td>
<td>1.20</td>
<td>71.0%</td>
</tr>
<tr>
<td>NA-6</td>
<td>689</td>
<td>1,000 (original)</td>
<td>1.45 (original)</td>
<td>66.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>551</td>
<td>0.80</td>
<td>40.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,240</td>
<td>1.80</td>
<td>73.0%</td>
</tr>
</tbody>
</table>
4.2.2 Analysis of Multiple Panel Abutment Stresses

Following the procedure explained in section 3.3.1, abutment and gob loads were calculated for consecutive panel mining models. These calculations were only done for the original cases since the multi-panel mining scenarios were not included in parametric runs. Detailed results for one of the supercritical and one of the subcritical case studies are presented below.

4.2.2.1 Shallow Cover Example – Mine NA-3

Subsidence profiles of the first and the second panels of Mine NA-3 are supercritical and nearly symmetric (Figure 4.8), which implies the independent response of overburden strata over the adjacent panels. Galvin (2016) indicated that this independent response is seen when the panel width-to-depth ratio is higher than or near 1.2, where it is 1.68 for Mine NA-3. Stress profiles were also estimated as nearly symmetric by the FLAC model.
Figure 4.8. Subsidence profile obtained from the 2D model of Mine NA-3

Figure 4.9 shows the dimensionless mining-induced overburden load distribution on abutments and gobs for Mine NA-3. After the first panel mining, the dimensionless overburden load carried by the gob was calculated as 76.6%, and the remaining load was transferred symmetrically as 11.7% on each side. The difference in loads over the gateroads was due to the difference in pillar layout. After the second panel mining, the load carried by the first gob increased an additional 0.4% to 77.0%, and the load carried by the second gob was calculated as 80.0%. These slight increases of gob loads are due to the extra compression of the gobs near the inter-panel gateroad after the second-panel mining. Overburden loads transferred to the abutments are equal to 10.9% (left) and 11.5% (right), similar to first-panel mining, and the load on the inter-panel gateroad is 20.6%.

Figure 4.9. Dimensionless overburden load distribution after 1st and 2nd-panel mining for Mine NA-3.
4.2.2.2 Deep Cover Example – Mine CA-1b

Figure 4.10 shows the subsidence profiles, and Figure 4.11 shows the dimensionless overburden load distributions approximated by the FLAC3D model for Mine CA-1b for five consecutive panels mined. After the first panel extraction, Figure 4.10 indicates that limited vertical displacement occurred over the first longwall panel, and Figure 4.11a represents the dimensionless overburden load distribution at that stage. The first-panel gob carries 16.6% of the mining-induced overburden loads, and the remaining 83.4% of the loads were carried by the abutments symmetrically. After the first panel mining, the ALPS method calculates 22.3% of the loads on the gob and 77.7% of the loads on the abutments (38.85% on each side). Therefore, empirically calculated loads on the abutments are less than what the model shows.

Extraction of the second panel resulted in a large step increase in subsidence over the first panel as seen in Figure 4.10. Subsidence over the first panel increased from 1.6 ft to 2.7 ft after the second-panel mining. Galvin (2016) referred to this additional subsidence as incremental subsidence. This incremental subsidence over the first panel increased the load on the first gob.
from 16.6% to 28.8%. After the second panel mining, the load carried by the second-panel gob was 20.9%. In addition to increasing loads on the gobs, the loads carried by the outer abutments also increased slightly (to 43.2% and 45.3%), and the model approximated the inter-panel gateroad load as 61.8% (Figure 4.11c). Excavation of the second panel resulted in an asymmetric subsidence profile, stress profile, and load distribution. Incremental subsidence and asymmetric profiles imply that the response of the overburden above the adjacent panels is influenced by consecutive mining of the adjacent panels. Since the ALPS method assumes a perfectly symmetric isolated loading condition, the load on each gob was still calculated as 22.3%, and the load on the inter-panel gateroad was calculated as 77.8%. Therefore, the FLAC3D model approximated the load on the inter-panel gateroad significantly lower than the ALPS method using the 21° abutment angle.

Extraction of the third panel also exhibited similar characteristics and resulted in a large step increase in subsidence over the first and second panels (Figure 4.10). Subsidence over the first panel increased from 2.7 ft to 3.3 ft and over the second panel increased from 2.1 ft to 3.2 ft. This incremental subsidence also increased the loads carried by the first gob from 28.8% to 32.8% and the second gob from 20.9% to 32.5%. The load carried by the third gob was 20.0% at this stage. Loads carried by left abutment increased slightly to 45.1%, and the load carried by the first inter-panel gateroad increased and changed from 61.8% to 67.1%. Load on the second inter-barrier gateroad is 57.5%, again significantly lower than the ALPS estimate (77.8%).

Extraction of the fourth and fifth panels resulted in similar trends in subsidence (Figure 4.10) and the loads as explained below in Figure 4.11d and Figure 4.11e. Incremental subsidence above the first panel continued at a diminishing rate until after the excavation of the fifth panel. Gobs and inter-panel gateroads of the previous panels continue to carry more and more load. The load carried by the gob of the active panel stayed relatively constant during the consecutive panel mining at around 20%. Similarly, the load carried by the inter-panel gateroad of the active panel also stayed relatively constant at around 60%.
Figure 4.11. Dimensionless overburden load distributions approximated by the FLAC3D model for Mine CA-1b after the (a) first panel mined, (b) second panel mined, (c) third panel mined, (d) fourth panel mined, and (e) fifth panel mined.

This detailed analysis of the abutment loads was conducted for all 13 cases and the results were compiled to be used in the statistical analyses. It was observed that the effect of previous panels for super-critical panels can be neglected and the results were similar to the single panel models for those cases. Listed in Table 4.2 through Table 4.8 are the calculated load percentages following the procedure explained in section 3.3.1 for the deep cover models with consecutive panel mining. The yellow cells represent the single-panel gob loads, the magenta cells represent the active panels, and the blue ones are the previous panel gob load percentages. For the gateroads, the red ones represent single-side abutment loads and the blue ones are the inter-panel gateroads with gobs on both sides.

Table 4.2. Mining induced load percentages obtained for Mine NA-5 for the three-panel model.

<table>
<thead>
<tr>
<th>Panels mined</th>
<th>SOLID COAL</th>
<th>Gateroad 1</th>
<th>Panel 1</th>
<th>Gateroad 2</th>
<th>Panel 2</th>
<th>Gateroad 3</th>
<th>Panel 3</th>
<th>Gateroad 4</th>
<th>SOLID COAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.2%</td>
<td>19.3%</td>
<td>43.2%</td>
<td>20.1%</td>
<td>8.7%</td>
<td>0.4%</td>
<td>0.3%</td>
<td>0.1%</td>
<td>-0.3%</td>
</tr>
<tr>
<td>2</td>
<td>7.6%</td>
<td>19.6%</td>
<td>50.6%</td>
<td>48.2%</td>
<td>46.3%</td>
<td>19.0%</td>
<td>8.3%</td>
<td>0.4%</td>
<td>0.1%</td>
</tr>
<tr>
<td>3</td>
<td>6.8%</td>
<td>19.6%</td>
<td>51.3%</td>
<td>49.7%</td>
<td>52.6%</td>
<td>46.8%</td>
<td>46.2%</td>
<td>18.6%</td>
<td>8.4%</td>
</tr>
</tbody>
</table>
### Table 4.3. Mining induced load percentages obtained for Mine CA-1a for the four-panel model.

<table>
<thead>
<tr>
<th>Panels mined</th>
<th>SOLID</th>
<th>COAL</th>
<th>Gateroad 1</th>
<th>Gateroad 2</th>
<th>Gateroad 3</th>
<th>Gateroad 4</th>
<th>SOLID</th>
<th>COAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13.1%</td>
<td>18.4%</td>
<td>30.9%</td>
<td>21.2%</td>
<td>11.6%</td>
<td>1.2%</td>
<td>0.9%</td>
<td>0.7%</td>
</tr>
<tr>
<td>2</td>
<td>14.1%</td>
<td>19.7%</td>
<td>54.8%</td>
<td>42.6%</td>
<td>34.2%</td>
<td>20.0%</td>
<td>11.3%</td>
<td>1.2%</td>
</tr>
<tr>
<td>3</td>
<td>13.5%</td>
<td>20.1%</td>
<td>57.9%</td>
<td>43.7%</td>
<td>56.0%</td>
<td>41.2%</td>
<td>35.2%</td>
<td>20.3%</td>
</tr>
<tr>
<td>4</td>
<td>12.5%</td>
<td>20.5%</td>
<td>60.1%</td>
<td>44.6%</td>
<td>61.4%</td>
<td>44.0%</td>
<td>57.4%</td>
<td>41.8%</td>
</tr>
</tbody>
</table>

### Table 4.4. Mining induced load percentages obtained for Mine CA-1b for the five-panel model.

<table>
<thead>
<tr>
<th>Panels mined</th>
<th>SOLID</th>
<th>COAL</th>
<th>Gateroad 1</th>
<th>Gateroad 2</th>
<th>Gateroad 3</th>
<th>Gateroad 4</th>
<th>Gateroad 5</th>
<th>SOLID</th>
<th>COAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18.1%</td>
<td>19.6%</td>
<td>16.6%</td>
<td>20.3%</td>
<td>16.2%</td>
<td>2.0%</td>
<td>2.0%</td>
<td>0.9%</td>
<td>0.7%</td>
</tr>
<tr>
<td>2</td>
<td>21.7%</td>
<td>21.5%</td>
<td>28.8%</td>
<td>61.8%</td>
<td>20.9%</td>
<td>20.1%</td>
<td>17.2%</td>
<td>2.3%</td>
<td>1.0%</td>
</tr>
<tr>
<td>3</td>
<td>23.0%</td>
<td>22.1%</td>
<td>32.8%</td>
<td>67.1%</td>
<td>32.5%</td>
<td>57.5%</td>
<td>20.0%</td>
<td>20.1%</td>
<td>18.0%</td>
</tr>
<tr>
<td>4</td>
<td>23.0%</td>
<td>22.5%</td>
<td>34.0%</td>
<td>68.0%</td>
<td>36.1%</td>
<td>62.8%</td>
<td>31.6%</td>
<td>58.3%</td>
<td>18.0%</td>
</tr>
<tr>
<td>5</td>
<td>22.2%</td>
<td>22.6%</td>
<td>34.5%</td>
<td>68.7%</td>
<td>37.4%</td>
<td>64.6%</td>
<td>35.1%</td>
<td>63.0%</td>
<td>32.6%</td>
</tr>
</tbody>
</table>

### Table 4.5. Mining induced load percentages obtained for Mine CA-3 for the five-panel model.

<table>
<thead>
<tr>
<th>Panels mined</th>
<th>SOLID</th>
<th>COAL</th>
<th>Gateroad 1</th>
<th>Gateroad 2</th>
<th>Gateroad 3</th>
<th>Gateroad 4</th>
<th>Gateroad 5</th>
<th>SOLID</th>
<th>COAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.9%</td>
<td>20.2%</td>
<td>9.5%</td>
<td>20.2%</td>
<td>16.9%</td>
<td>2.2%</td>
<td>4.1%</td>
<td>1.1%</td>
<td>1.0%</td>
</tr>
<tr>
<td>2</td>
<td>26.6%</td>
<td>26.7%</td>
<td>18.0%</td>
<td>54.9%</td>
<td>15.4%</td>
<td>26.5%</td>
<td>22.0%</td>
<td>2.5%</td>
<td>3.9%</td>
</tr>
<tr>
<td>3</td>
<td>26.4%</td>
<td>26.8%</td>
<td>23.5%</td>
<td>62.6%</td>
<td>27.0%</td>
<td>57.8%</td>
<td>17.3%</td>
<td>26.3%</td>
<td>23.7%</td>
</tr>
<tr>
<td>4</td>
<td>27.4%</td>
<td>28.4%</td>
<td>25.5%</td>
<td>66.6%</td>
<td>32.8%</td>
<td>64.2%</td>
<td>27.4%</td>
<td>57.2%</td>
<td>16.6%</td>
</tr>
<tr>
<td>5</td>
<td>25.7%</td>
<td>27.3%</td>
<td>25.0%</td>
<td>65.4%</td>
<td>33.5%</td>
<td>65.9%</td>
<td>32.6%</td>
<td>64.5%</td>
<td>27.9%</td>
</tr>
</tbody>
</table>

### Table 4.6. Mining induced load percentages obtained for Mine BW-1 for the three-panel model.

<table>
<thead>
<tr>
<th>Panels mined</th>
<th>SOLID</th>
<th>COAL</th>
<th>Gateroad 1</th>
<th>Panel 1</th>
<th>Gateroad 2</th>
<th>Panel 2</th>
<th>Gateroad 3</th>
<th>Panel 3</th>
<th>Gateroad 4</th>
<th>Panel 4</th>
<th>SOLID</th>
<th>COAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.6%</td>
<td>19.0%</td>
<td>35.0%</td>
<td>19.0%</td>
<td>12.4%</td>
<td>0.6%</td>
<td>1.1%</td>
<td>0.2%</td>
<td>0.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>12.1%</td>
<td>20.1%</td>
<td>48.2%</td>
<td>51.9%</td>
<td>34.8%</td>
<td>18.9%</td>
<td>11.9%</td>
<td>0.7%</td>
<td>1.4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10.7%</td>
<td>19.8%</td>
<td>48.8%</td>
<td>53.8%</td>
<td>47.6%</td>
<td>51.2%</td>
<td>35.5%</td>
<td>18.7%</td>
<td>13.8%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4.7. Mining induced load percentages obtained for Mine W-1 for the five-panel model.

<table>
<thead>
<tr>
<th>Panels mined</th>
<th>SOLID</th>
<th>COAL</th>
<th>Gateroad 1</th>
<th>Gateroad 2</th>
<th>Gateroad 3</th>
<th>Gateroad 4</th>
<th>Gateroad 5</th>
<th>SOLID</th>
<th>COAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29.4%</td>
<td>-0.5%</td>
<td>36.6%</td>
<td>-0.5%</td>
<td>27.6%</td>
<td>-0.2%</td>
<td>3.6%</td>
<td>-0.1%</td>
<td>2.0%</td>
</tr>
<tr>
<td>2</td>
<td>34.8%</td>
<td>-0.5%</td>
<td>74.3%</td>
<td>-0.5%</td>
<td>56.6%</td>
<td>-0.5%</td>
<td>28.9%</td>
<td>-0.2%</td>
<td>4.2%</td>
</tr>
<tr>
<td>3</td>
<td>36.1%</td>
<td>-0.5%</td>
<td>84.0%</td>
<td>-0.5%</td>
<td>94.6%</td>
<td>-0.5%</td>
<td>54.8%</td>
<td>-0.5%</td>
<td>27.4%</td>
</tr>
<tr>
<td>4</td>
<td>34.8%</td>
<td>-0.5%</td>
<td>85.3%</td>
<td>-0.5%</td>
<td>103.4%</td>
<td>-0.5%</td>
<td>91.4%</td>
<td>-0.5%</td>
<td>55.6%</td>
</tr>
<tr>
<td>5</td>
<td>34.6%</td>
<td>-0.5%</td>
<td>88.6%</td>
<td>-0.5%</td>
<td>108.8%</td>
<td>-0.5%</td>
<td>103.7%</td>
<td>-0.5%</td>
<td>95.5%</td>
</tr>
</tbody>
</table>
Moving forward, the transferred load percentages on the gobs were selected as the response to be investigated in statistical analysis. The load on the pillars and the adjacent coal was found to be more influenced by the chain pillar system and it was decided that including this effect into the calculation through the gob load percentages would be more practical.

### 4.3 Statistical Modeling for Geology Based Gob Loading Estimation

The statistical relationships between the independent parameters: the geological parameter, overburden depth, and panel width, and the dependent parameter, gob load percentages, were tested. The load percentages carried by the gobs were used as the statistical model response since the pillar loads depend highly on the dimensions of the chain pillar systems. After estimating the gob loads, the pillar loads can easily be calculated using the empirical load distribution function in ACPS or the analytical functions in LaModel.

Mine W-1 was omitted at this stage of the analysis since that is the only mine that utilizes a 2-entry yield pillar system and requires further investigation. Assumed as the most influential parameters, overburden depth and panel width were the variables considered in the analysis together with the critical span \(S_i\) of the overburden layers. For each case study, the critical span of every geological layer was calculated using Eq(17) mentioned in section 3.3.

After examining various plots with different possible geological parameters, a new parameter called the total strong layer thickness \(t_{\text{str}}\) was introduced. The \(t_{\text{str}}\) parameter is the sum of the thickness of all layers with \(S_i/pw\) values larger than 0.1 as seen in Eq(18).

\[
t_{\text{str}} = \sum_{i=1}^{n} \frac{S_i}{pw} \begin{cases} S_i/pw > 0.1 & \frac{S_i}{pw} \\ else & 0 \end{cases}
\]
The cut-off value of 0.1 was initially selected as the best-fit value considering an exponential relationship between the parameter and gob load percentages. Later, the cut-off value of 0.1 was investigated for individual cases considering available geological information. This cut-off allowed us to distinguish known weak overburden mines from the mines with known competent overburden. Mines with thick and strong layers near the seam where those layers are known to withstand the mining-induced loads were also influential in verifying the cut-off value. The layers closer to the surface intrinsically show higher $S_i/pw$ since the span length calculation considers the weight above the layers. These layers might still deform or break, but the cut-off value was mainly selected to better differentiate the layers closer to the seam.

Figure 4.12 shows the calculated $S_i/pw$ values for each stratigraphic layer for Mines NA-3, and CA-1 and the dashed red lines represent the selected cut-off value of 0.1. Mine NA-3 is an example of a supercritical panel with a known weak overburden. The sandstone layers in the overburden are known to cave due to the large panel width. For mine CA-1, there are strong and thick sandstone layers which are known to withstand mining of the panels. The panel widths are designed narrower for deeper mines, to ensure the stability of the strong layers.

*Figure 4.12. Calculated S_i/pw ratios for the overburden layers of mines NA-3 and CA-1*
In the statistical analysis, the ratio “\( t_{str}/pw \)” was found to exhibit a trend with the gob load percentage. It can be seen in Figure 4.13, there is an inverse relationship between the load transferred to the gob and the \( t_{str}/pw \) ratio and this ratio is selected to be used for the statistical analysis. In Figure 4.14, the exponential trend of the single-panel gob loads calculated from the field studies and the parametric runs with their respective \( t_{str}/pw \) ratios can be seen.

**Figure 4.13. Relationship between the \( t_{str}/pw \) ratio and the transferred gob load percentage**

**Figure 4.14. Single-panel gob loads with respect to \( t_{str}/pw \) ratio**
Table 4.9 shows the calculated $t_{str}$ values for each case study geology and the $t_{str}/pw$ ratios for the field study cases and the parametric cases. The $t_{str}$ values for the case studies range from 178.5 ft to 1548.3 ft. The ratio of $t_{str}/pw$ tends to be higher for cases with narrow panels and higher depths of cover.

*Table 4.9. Strong layer thicknesses for each case study overburden geology and calculated $t_{str}/pw$ ratios*

<table>
<thead>
<tr>
<th>Mine</th>
<th>PW/H</th>
<th>$t_{str}$ (ft)</th>
<th>$t_{str}/pw$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA-1</td>
<td>2.10 (original)</td>
<td>317.8</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>512.9</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>395.8</td>
<td>0.51</td>
</tr>
<tr>
<td>NA-2</td>
<td>1.68 (original)</td>
<td>321.9</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>490.8</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>436.0</td>
<td>0.52</td>
</tr>
<tr>
<td>NA-3</td>
<td>2.28 (original)</td>
<td>178.5</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>290.8</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>226.8</td>
<td>0.36</td>
</tr>
<tr>
<td>NA-4</td>
<td>0.91 (original)</td>
<td>586.6</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>571.5</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>1.50</td>
<td>522.0</td>
<td>0.53</td>
</tr>
<tr>
<td>NA-5</td>
<td>0.82 (original)</td>
<td>622.4</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>780.2</td>
<td>1.06</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>474.4</td>
<td>0.32</td>
</tr>
<tr>
<td>NA-6</td>
<td>1.45 (original)</td>
<td>240.2</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>465.6</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>1.80</td>
<td>131.0</td>
<td>0.11</td>
</tr>
<tr>
<td>CA-1a</td>
<td>0.55 (original)</td>
<td>928.5</td>
<td>0.94</td>
</tr>
<tr>
<td></td>
<td>0.30</td>
<td>1230.3</td>
<td>2.28</td>
</tr>
<tr>
<td></td>
<td>0.70</td>
<td>846.5</td>
<td>0.67</td>
</tr>
<tr>
<td>CA-1b</td>
<td>0.34 (original)</td>
<td>1240.2</td>
<td>1.77</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>1112.2</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>1026.9</td>
<td>0.83</td>
</tr>
<tr>
<td>CA-2</td>
<td>1.63 (original)</td>
<td>331.4</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>1.20</td>
<td>418.0</td>
<td>0.71</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>331.4</td>
<td>0.34</td>
</tr>
<tr>
<td>CA-3</td>
<td>0.29 (original)</td>
<td>1067.9</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>769.0</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>680.1</td>
<td>0.54</td>
</tr>
<tr>
<td>BW-1</td>
<td>0.69 (original)</td>
<td>1151.9</td>
<td>1.15</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>1256.9</td>
<td>2.17</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>973.8</td>
<td>0.67</td>
</tr>
<tr>
<td>W-2</td>
<td>0.42 (original)</td>
<td>1548.3</td>
<td>1.86</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>1474.5</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>0.60</td>
<td>1304.5</td>
<td>1.10</td>
</tr>
</tbody>
</table>
The gob load percentage for single-panel mining (Figure 3.15b) was selected as the basis of the estimation methodology. Since single-panel models also included the parametric models, there were more data points from single-panel model results.

The load estimation for consecutive panels was built on top of the single panel estimations calculated by the exponential function presented in Eq(19) which was determined using the least squared error fit.

\[
GOB(\%)_{\text{single}} = e^{-1.15 \times \left( \frac{t_{str}}{pw} \right)}
\]  

(19)

The comparison of estimated single panel gob loads with the case study and parametric model results can be seen in Figure 4.15. The coefficient of determination (R^2) was found to be 78.5%.

![Comparison of estimated single panel gob loads with the case study model results](image)

*Figure 4.15. Comparison of estimated single panel gob loads with the case study model results*

Using the consecutive panel mining models, both the active panel and the previous panel gob loads were examined (Figure 3.15c). Figure 4.11 shows an example of a consecutive panel model with five panels. Figure 4.11a through Figure 4.11e represents different steps of the model whereas Figure 4.11a represents the single panel model. In the second step (Figure 4.11b), the consecutive
panel was mined, and the active panel gob load (load on the 2nd panel) was calculated as 20.9%. The previous panel load, i.e., the load on the first panel increased to 28.8%, which was seen in Figure 4.11a as 16.6% when it was in the single panel stage. Active and previous panel gob loads are calculated for all deep cover consecutive panel models and tabulated in Table 4.10.

Table 4.10. Active panel and previous panel gob load percentages for deep cover consecutive panel models.

<table>
<thead>
<tr>
<th>Panel 1</th>
<th>Panel 2</th>
<th>Panel 3</th>
<th>Panel 4</th>
<th>Panel 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Panel</td>
<td>previous</td>
<td>active</td>
<td>previous</td>
<td>active</td>
</tr>
<tr>
<td>NA-5</td>
<td>43.2%</td>
<td>50.6%</td>
<td>46.3%</td>
<td>52.6%</td>
</tr>
<tr>
<td>CA-1a</td>
<td>30.9%</td>
<td>54.8%</td>
<td>34.2%</td>
<td>56.0%</td>
</tr>
<tr>
<td>CA-1b</td>
<td>16.6%</td>
<td>28.8%</td>
<td>20.9%</td>
<td>32.5%</td>
</tr>
<tr>
<td>CA-3</td>
<td>9.5%</td>
<td>18.0%</td>
<td>15.4%</td>
<td>27.0%</td>
</tr>
<tr>
<td>BW-1</td>
<td>35.0%</td>
<td>48.2%</td>
<td>34.8%</td>
<td>47.6%</td>
</tr>
<tr>
<td>W-2</td>
<td>25.7%</td>
<td>31.6%</td>
<td>26.6%</td>
<td>31.5%</td>
</tr>
</tbody>
</table>

As seen in Table 4.10, the gob load on the active panel increases when there is a previous panel mined. However, this increase is not dependent on the number of panels before the active panel, the increase in the gob load is only observed going from a single panel to the second-panel mining. To estimate the active panel gob loads, a consecutive panel factor ($F_{cons}$) to be multiplied with the single panel estimation is analyzed. Sum of squared error fit with the $t_{str}/pw$ ratio was used to construct Eq(20) which can be used to calculate the consecutive panel factor. The factor can be assumed as 1 when the $t_{str}/pw$ ratio is less than 0.87. This factor can then be introduced into Eq(21) to estimate the active panel gob percentage.

$$F_{cons} = 1.1 \left(\frac{t_{str}}{pw}\right)^{0.7} \quad \text{for } \frac{t_{str}}{pw} > 0.87$$

$$F_{cons} = 1 \quad \text{for } \frac{t_{str}}{pw} \leq 0.87$$

$$GOB(\%)_{cons} = F_{cons} \times GOB(\%)_{single}$$

The gob loads of the active panels estimated with the new method compared to the results obtained from the case studies and the parametric runs showed a coefficient of determination ($R^2$) of 86.1% (Figure 4.16).
After constructing the method for active panel gob load estimation, the next analysis was performed for the gob load percentages of the panel previous to the active one. The calculated gob load percentages for the panels on the tailgate side (Table 4.10) of the active panels were used to construct the equation. The calculated results showed that the major load increase on the gob occurred when the second panel was extracted. The increase in the gob load with consecutive panels after the second panel (3rd, 4th, and 5th panels) was found to be negligible. This can be seen clearly in Table 4.2 through Table 4.8 and in Table 4.10. Equation (22) was found to be the most practical way to calculate the previous panel gob load percentage with an $R^2$ of 86.4% where the $\text{GOB}(\%)_{cons}$ value is calculated using Eq(20) and Eq(21). The comparison of estimated previous panel gob loads with the case study and parametric model results can be seen in Figure 4.17.

$$G O B(\%)_{prev} = 1.35 \times G O B(\%)_{cons}$$  \hspace{1cm} (22)
Figure 4.17. Comparison of estimated previous panel gob loads with consecutive case study model results.

Figure 4.18 further shows all the available data points including the field case studies, parametric models, and consecutive models (both active panel and previous panel). The gob load percentages estimated using the new method were compared against the results calculated from the field measurements and the model runs. The coefficient of determination ($R^2$) was found to be 80.3%
Figure 4.18. Comparison of estimated gob load percentages with the case study and parametric model results.

The gob load percentages for the field cases were also calculated using the empirical method mentioned in Section 2.2.1 and compared with the values estimated using the new method. The abutment angle approach was used to calculate the gob load percentages for the field study mines using a 21° abutment angle. To be consistent with the field studies, the consecutive mining is considered for the new estimation method.

Figure 4.19 represents the percent deviation from the gob loads calculated from the FLAC3D models of the field studies. Mine W-2 and Mine CA-3 were the only cases where the empirical method considerably outperformed the new estimation methodology but overall, the new methodology was found to give more comparable results to the model results.
Figure 4.19. Comparison of the empirical method and the new gob load estimation method in terms of their success in estimating the field case gob load percentages.

4.3.1 Analysis of 2-entry yield pillar system

Special consideration was given to Mine W-1 as they utilized a 2-entry yield pillar system that affected the gob load percentages significantly. Most of the load transferred to the yield pillars is shed to the adjacent gob or solid coal because of the yield pillar design. As shown in Table 4.7, the load transfers to the gateroads are represented as negative since they carry even less load than they originally carry during development after they yield. To take the effect of yield pillars on the load transfer to the gob into account, additional factors are introduced to the Equations (19) through (22) presented in Section 4.2.

For the single panel condition, the calculated gob load for Mine W-1 did not exhibit a significant difference compared to the value estimated using Eq(19). The major difference in load re-distribution was observed for the consecutive panel models compared to other mines that utilize larger pillars.

To estimate the active panel and previous panel load distributions, simple multipliers were selected using the least squared error fit method. Eq(23) and Eq(24) where the $F_{cons}$ parameter is still calculated using Eq(20) can be used to estimate the consecutive active and previous panel gob percentages for these cases.
\[ GOB_{yp}^{(\%)}_{cons} = F_{cons} \times GOB^{(\%)}_{single} \times 1.5 \]  \hspace{1cm} (23)

\[ GOB_{yp}^{(\%)}_{prev} = 1.6 \times GOB_{yp}^{(\%)}_{cons} \]  \hspace{1cm} (24)

The estimated gob loads for Mine W-1 were re-plotted into Figure 4.16 and Figure 4.17, and they are presented in Figure 4.20. Figure 4.21 shows all available data points including Mine W-1 and its parametric runs.

![Figure 4.20. Comparison of estimated active and previous gob load percentages with the consecutive case study model results including Mine W-1.](image-url)
Figure 4.21. Comparison of estimated gob load percentages with the case study and parametric model results including Mine W-1.

4.4 Method Verification

A new field case that was not included in the analyzed database was used to verify the new method of estimation. The new case study is from a longwall mine operating in the western U.S. (Mine W-3) and the panel where the field measurements were taken is 850 ft wide and has a depth of cover of approximately 1,250 ft. One of the important attributes of this mine is that the mine utilizes the 2-entry yield pillar system between the panels. This was an important opportunity to test the adequacy of the method for mines that utilize yield pillars since the analyzed database only included one such case. The yield pillars in this mine are 29 ft wide (rib-to-rib) with 20 ft wide entries. Figure 4.22 shows the panel outlines and the pillar configuration for Mine W-3. The stress measurements were taken at the location presented in Figure 4.22 where borehole pressure cells (BPC) were installed into the yield pillar and the adjacent solid coal. The measurements were compared against the results obtained from the numerical model for verification.
Figure 4.22. Mine W-3 panel and chain pillar configuration and the location of the field measurement site.

The case was modeled in FLAC3D using a similar procedure mentioned in Section 2.2.3 but for this simulation, the model was in 3D to capture the effect of face location. The model was able to simulate the response of the pillar and the adjacent coal successfully. For the scope of this study, the load percentages when the panels were completely mined are used to compare against the values estimated with the new method. The results obtained from the FLAC3D model are presented in Table 4.11.

Table 4.11. Gob load percentages obtained from the verified numerical model for Mine W-3.

<table>
<thead>
<tr>
<th></th>
<th>Single Panel</th>
<th>Previous Panel</th>
<th>Active Panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gob Load (%)</td>
<td>21%</td>
<td>86%</td>
<td>44%</td>
</tr>
</tbody>
</table>

The $t_{sr}$ for Mine W-3 was calculated as 1098 ft from the available core log information. Using Equations (19), (23), and (24), the gob loads for the single panel, the active panel, and the previous panel were calculated and are presented in Table 4.12.

Table 4.12. Gob load percentages estimated using the new methodology for Mine W-3.

<table>
<thead>
<tr>
<th></th>
<th>Single Panel</th>
<th>Previous Panel</th>
<th>Active Panel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gob Load (%)</td>
<td>28%</td>
<td>76%</td>
<td>49%</td>
</tr>
</tbody>
</table>
Figure 4.23 shows how the estimated gob load percentages for Mine W-3 fit among the database cases. Different data points for Mine W-3 represent single panel, active panel, and previous panel gob load percentages.

![Figure 4.23. Comparison of estimated gob load percentages for the analyzed database including Mine W-3.](image)

**4.5 LaModel Implementation**

This new method of gob load estimation can be easily implemented into LaModel through the gob wizard option in LaMPRe 3.0 (Figure 4.24). After de-selecting the “Use the Suggested Value” tick box and inputting the estimated gob load percentage into the gob wizard, the user can easily calculate and implement the appropriate final gob modulus that will match the estimated gob load percentage. This allows the practical implementation of the effect of overburden geology into a design tool capable of modeling complex mine geometries. By selecting at least two “Number of Gob Materials to be Defined” the user can input the estimated gob load percentages for both the active and previous panels and calculate and use the appropriate final gob moduli.
Figure 4.24. Using gob wizard in LaModel to implement estimated gob load percentages

To check for its applicability, field studies from Australia were modeled using LaModel and the stress measurements on the pillars and the adjacent coal were compared with LaModel results.

4.5.1 Verification with Case Studies

An additional three cases that are not included in the original analyzed database were used for this verification. These case histories are obtained from personal communications with David Hill (formerly of Strata Engineering Australia, currently with Strata2 Pty Ltd). All three cases are from Australia with varying overburden depths between 1198 ft and 1683 ft. They utilize 2-entry chain pillar systems but instead of small yield pillars, they use large abutment pillars with similar widths ranging from 140 ft up to 150 ft. Table 4.13 shows the depths and the panel configurations for these cases.

Table 4.13. Depths and Panel configurations for the Australian case studies

<table>
<thead>
<tr>
<th>CASE</th>
<th>Depth of Cover (ft)</th>
<th>Panel Width (ft)</th>
<th>Entry Width (ft)</th>
<th>Pillar width (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mine AU-1</td>
<td>1198</td>
<td>820</td>
<td>16</td>
<td>140</td>
</tr>
<tr>
<td>Mine AU-2</td>
<td>1329</td>
<td>820</td>
<td>16</td>
<td>145</td>
</tr>
<tr>
<td>Mine AU-3</td>
<td>1683</td>
<td>745</td>
<td>16</td>
<td>150</td>
</tr>
</tbody>
</table>
Core logs from near the instrumentation sites were visualized and presented in Figure 4.25. Layers with more than one rock type represent interbedded or intermixed components, but the percentages may vary. Also, thick layers do not necessarily represent massive rock formations. Adjacent thin layers of the same rock types were combined for easier representation. Using the information from the core logs, the geological parameter $t_{str}$ for each case was calculated.

![Figure 4.25. Stratigraphic columns for the Australian case studies.](image)

Using Equations (19), (20), (21), and (22), the gob loads for the single panel, the active panel, and the previous panel were calculated and are presented in Table 4.14, together with the gob load percentages calculated by using default calibrated parameters in LaMPre 3.0.
Table 4.14. Gob load percentages estimated using the new methodology for the Australian cases

<table>
<thead>
<tr>
<th>Mine AU</th>
<th>Single Panel</th>
<th>Previous Panel</th>
<th>Active Panel</th>
<th>LaMPre 3.0 Default</th>
</tr>
</thead>
<tbody>
<tr>
<td>AU-1</td>
<td>26%</td>
<td>43%</td>
<td>32%</td>
<td>44%</td>
</tr>
<tr>
<td>AU-2</td>
<td>51%</td>
<td>69%</td>
<td>51%</td>
<td>40%</td>
</tr>
<tr>
<td>AU-3</td>
<td>11%</td>
<td>26%</td>
<td>19%</td>
<td>29%</td>
</tr>
</tbody>
</table>

LaModel grids for the Australian cases were constructed to simulate the development loading as well as both the maingate and tailgate loading conditions. Figure 4.26 shows the LaModel steps configured for the analysis. Active and previous gob moduli were calibrated according to the gob percentage estimations and two different gobs are defined.

Figure 4.26. LaModel gridding for the Australian case studies
The stress profiles obtained from LaModel were plotted and compared against the stress measurements. The calibration procedure followed by Colwell et al. (1999) was used to calibrate the HSC cell results. This calibration procedure employs a calibration factor $K=1$ for a stress increase up to 725 psi (5 MPa) and $K=1.3$ for that portion of the stress increase above 725 psi. As seen in Equation (25), the $K$ factor relates the monitored change in cell pressure ($\Delta P_c$) to the actual in-situ vertical pressure change ($\Delta P_i$) (Colwell et al., 1999).

$$\Delta P_i = \frac{\Delta P_c}{K \text{ Factor}}$$

(25)

Figure 4.27 through Figure 4.29 shows the comparison of the stress profiles obtained from LaModel with the calibrated field measurements.

Figure 4.27. Comparison of maingate and tailgate field stress measurements with LaModel results for Mine AU-1.

Figure 4.28. Comparison of maingate and tailgate field stress measurements with LaModel results for Mine AU-2.
Figure 4.29. Comparison of maingate and tailgate field stress measurements with LaModel results for Mine AU-3.

The comparison of stress measurements with the LaModel results was achieved by assessing the “area under the curve” for both stress profiles which gives the total load within that distance. The load increase on the pillars and the load increase on the solid coal were compared separately for both the maingate and tailgate loading conditions (Figure 4.30). The R² value was computed as 89.7% when we compare the estimated results with the measured values.

Figure 4.30. Comparison of LaModel results with the field measurements in terms of areas under stress profiles.

The next step was to compare the new method against the default ALPS method already implemented in LaModel. The models were re-run with the default gob percentages calculated by the LaMPre 3.0 and the areas under the stress profiles were calculated for the loads on the pillars.
and the solid coal. The $R^2$ was calculated as 82.8% and the percent deviations from the field measurements are plotted in Figure 4.31. No difference was observed when the coal is failed at the measurement points since both methods use the same coal properties with the same post-peak behavior.

![Graph](image.png)

**Figure 4.31. Comparison of LaModel results with the field measurements in terms of areas under stress profiles for both the default and the new method.**

The improvement with the new method can be seen, compared to the default method included in LaMPre 3.0. The higher loads observed for both methods can be accounted for the default abutment extent used in LaMPre 3.0 when calibrating the lamination thickness. For deeper mines, it was observed in the field that the extent of the mining-induced loads can be larger than what the empirical formula by Peng and Chiang (1984) calculates (Eq.(3)). A comprehensive study should be conducted to verify these observations.
CHAPTER 5 – CONCLUSIONS AND FUTURE STUDIES

5.1 Summary and Conclusions

The most popular pillar design software for underground coal mines determines the adequacy of the design by comparing the estimated loads to the load-bearing capacity of the pillars, making use of historical databases of case studies. Accurate estimation of the mining-induced loads plays an important role in successful pillar design but the effect of varying overburden geology on abutment loads has often been overlooked for underground coal mine pillar design practices. In this study, numerical models of different case study mines were used to investigate the effect of specific overburden geology distilled into one parameter on mining-induced loads.

Field measurements from 12 case studies conducted in 11 different longwall coal mines were back analyzed and used to create and verify FLAC3D models of these cases. Each verified numerical model was re-run with different panel dimensions for parametric analysis. Initially, abutment loading results obtained from a total of 36 different numerical models were used for statistical analysis, to determine a way to better estimate the percentage of load carried by the gob, by including simplified geology data. To include the effect of overburden geology, a new parameter called the total strong layer thickness ($t_{str}$) is derived that considers the critical span ($S_i$) of the overburden layers together with the panel width and overburden depth. It is calculated as the sum of all layers with $S_i/pw$ values larger than 0.1. The $t_{str}$ parameter can then be used to estimate the gob load percentage using Eq(19) for single panel configurations and Eq(20), Eq(21), and Eq(22) for the consecutive panel mining. The new methodology was compared against the empirical estimates for the field study mines, and the new methodology was found to give better results except for two of the cases. Special consideration was given for mines that utilize 2-entry yield pillar systems and the modified methodology for those mines is presented in Section 4.3.1.

Using the new estimation methodology, a field case study that was not included in the first database was analyzed. FLAC3D models verified against field measurement data were compared to the results that were estimated with the new method and the new methodology was found to be successful. Following the verification of the new methodology, the next step was the implementation of the new method of gob load estimation into a practical design tool. LaModel
software was selected for this purpose due to its ability to model complex geometries in addition to its practicality. To check the applicability of introducing the new method into LaModel, additional three field case studies were analyzed. Using the gob wizard in LaModel, the gob load percentages calculated by the new method were input to the program and the models were run. The loads on the pillars and the adjacent coal were calculated from the LaModel results and compared to the loads calculated using the case study model results and the new method was found to be successful. Finally, the same loads were calculated using the default LaModel parameters and it was observed the new methodology improved the results.

5.2 Suggestions for Future Studies

This study used case studies from underground coal mines to develop the new load estimation methodology. Different longwall mines were also used for the verification of this methodology. However, the findings of this study are also applicable for retreat room-and-pillar mines where similar overburden mechanisms are involved. ARMPS software has an extensive database of case studies from room and pillar coal mines and the cases with detailed geological information can be used to further verify the new methodology. ARMPS-LAM software can also help batch-run these cases after the information about the overburden geology is introduced.

One thing observed from the numerical models was that the load extents were larger, especially for the deeper cases compared to the empirical calculation using Eq.(3). A future study examining the load extents for deeper coal mines would be beneficial to further verify the new methodology combined with LaModel and the FLAC3D methodology. A larger extent with the same percentage of load transfer would result in less load on the pillar system (assuming the default stress distribution functions).

The scope of this study involved investigating the 2D cross-sections of longwall coal mines which restricted the analyses to either bleeder or isolated loading conditions as mentioned in Section 3.3.1. Further investigation of the new methodology should be carried out using 3D models to verify its use for headgate and tailgate T-junction loads. With the introduction of 3D mine maps, another issue to be considered is the changing overburden geology along the panel lengths. Special consideration should be given to strong and thick layers that might not be consistent along the panel length.
REFERENCES


