Integrated Large Discontinuity Factor, Lamodel and Stability Mapping Approach for Stone Mine Pillar Stability

Mustafa Baris Ates
ma00020@mix.wvu.edu

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

Part of the Mining Engineering Commons

Recommended Citation

This Thesis 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 Thesis 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 Thesis 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.
Integrated Large Discontinuity Factor, Lamodel and Stability Mapping Approach for Stone Mine Pillar Stability

Mustafa Baris ATES

Thesis 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

Master of Science
in
Mining Engineering

Ihsan Berk Tulu, Ph.D., Chair
Hassan Amini, Ph.D.
Ilkin Bilgesu, Ph.D.
Department of Mining Engineering
West Virginia University

Morgan M. Sears, Ph.D.
Pittsburgh Mining Research Division
National Institute for Occupational Safety and Health
Pittsburgh, PA
2022

Keywords: Limestone Pillars, Large Discontinuity Factor, Boundary Element Method Software, S-Pillar, LaModel, Stability Mapping.

Copyright 2022, Mustafa Baris ATES
ABSTRACT

Integrated Large Discontinuity Factor, LaModel and Stability Mapping Approach for Stone Mine Pillar Stability

Mustafa Baris Ates

The objective of this research is to develop a software tool that integrates the large discontinuity factor (LDF) and the Boundary Element Method software (BEM), LaModel, to allow stone mine operators to assess the impact of the large discontinuities on local pillar stability. National Institute for Occupational Safety and Health (NIOSH) published design guidelines for underground stone mines to guide the industry in designing pillar and roof support. These guidelines emphasize the impact of large, angular discontinuities on pillar strength. Esterhuizen et al. (2011) derived the large discontinuity factor (LDF) to account for the impact of discontinuities on pillar stability by adjusting the strength of the pillars. In this approach, the pillar load is calculated at the maximum depth over the pillar layout, and the tributary area loading calculation is valid if the mine layout consists of regular-sized pillars. Escobar (2021) extended the application of this approach to the BEM to allow stone mine operators to integrate overburden stress distribution under variable topography and pillar layouts with irregularly sized pillars into their designs.

The software tool developed in this thesis incorporates the large discontinuity impacts, overburden stress distribution under variable topography, and irregular pillar layouts by utilizing: LDF, AutoCAD ObjectARX add-in Integrated Stability Mapping Software (ISMS), and LaModel software. In this research, a new term, Local Large Discontinuity Factor (LLDF), is proposed to explicitly account for the impact of large discontinuities on local pillar stability. The ISMS step transformation function is used to identify the pillars intersected by the large discontinuities and to generate the LLDF grid of the intersected pillars. LaModel is used to compute the safety factor of the stone mine pillars by simulating the strength of complex pillar geometries with the empirical stone mine pillar equation (Esterhuizen et al., 2011; Escobar, 2021). The software tool uses the LLDF grid and LaModel output files to generate the final pillar stress safety factors, which can be visualized in AutoCAD. After the development of the software tool, a case study was performed to demonstrate the application and usefulness of this new engineering tool.
To My Lovely Family

and

To Everyone Family to Me
ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my advisor Dr. İhsan Berk Tulu, who gave me courage and inspiration during these two years. He gave me and my other colleagues the opportunity to work with him just by looking at our transcripts (which for me is nothing more than a piece of paper!). His trust in us changed our lives. He was there whenever I needed him and feeling his support made me achieve more. I am lucky to have his guidance and to have learned from him.

I would like to thank Alpha Foundation for financially funding this research within the framework of the Autonomous Robotic Early Warning System for the Underground Stone Mining Safety Project with the grant number AFC820-69.

I would like to express my gratitude to my committee members: Dr. Hassan Amini, Dr. Ilkin Bilgesu, and Dr. Morgan Seers for their contributions and advice throughout my thesis. Also, I would kindly memorize my deceased professors-committee members: Dr. Yi Luo and Dr. John Craynon.

I would like to thank Mrs. Genette Chapman and Mrs. Karen Centofanti from the Mining Engineering Department at West Virginia University. They always tried to be helpful and answer my questions, no matter how strange they were. Many thanks to my friends from WVU: Victor, Mustafa, the “Denizes” - Deniz Talan and Deniz Tuncay, Sena, Zeynep, Haochen, Samuel and Francisco and the other friends from Mining WVU.

I would like to thank my professors back home at Middle East Technical University, Dr. Onur Gölbaşı and Dr. Mustafa Erkayaoğlu. Without their help and guidance, I wouldn’t be a part of West Virginia University. Thank you to my friends back home: Mert Avci, Cem Noyak Konuk, Burak Pehlivan, Ertuğrul Yıldız, Berat Güner, Dilara Çelikcan, Ozan Berat Öztaş, Ferhat Alsan, Veli Can Ertürk, GUSTO, Umut Cem Yıldız, Alper Şen, and Erdem Arslan for calling me whenever they do something that I can be jealous of.

Special thanks to Gary Laruta, Nicolas Uribe, Tyler Straka, HOLOO crew, and to my friends who made my time in Morgantown easier for me. We have become a “family” and had incredible adventures and memories. I’m proudly glad to know each and every one of you.
Many thanks to Volkan Nalçakan and Pınar Nalçakan, their kids, Maya and Kaan, and other family members; teddy, daisy, and cooper for their unconditional love.

I would like to thank Çağdaş Demirkan and Cansu Perdeli Demirkan for giving me challenging steps to follow. First METU, then the USA, and now Denver... I hope you are aware that there is no life for you without me around.

I would like to express my deepest love to my family; my mother Nurcan Ateş, my father Şenol Ateş, my sister Gizem Ateş Yalçın, my brother-in-law Mehmet Can Yalçın, and my lovely niece Duru Yalçın for their limitless love. I miss the two smiling faces that greeted me at home. I cannot come this far in my life without your support. I am truly blessed to have such an awesome family.

Last but not least, as all of the successes that I’ve achieved, I would like to dedicate this thesis to my lifelong mentor Bülent Gökalp. I feel very lucky and blessed to have the chance to learn from him. Bülent Hoca taught me not only how to calculate the length of the hypotenuse, but also how to empathize, how to be a person of the world, how to enjoy life, and how to stand up for the weak and minorities even if it causes me trouble. There are no words to adequately express my gratitude to him. Rest in peace Bülent Hocam.
## Table of Contents

**ABSTRACT** ............................................................................................................................. ii  
**ACKNOWLEDGEMENT** ........................................................................................................... iv  
Table of Figures .......................................................................................................................... vii  
Table of Tables ............................................................................................................................ viii  
Chapter 1 Introduction .................................................................................................................. 1  
  1.1. Overview ................................................................................................................................. 1  
  1.2. Problem statement ..................................................................................................................... 1  
  1.3. Objective of thesis ..................................................................................................................... 2  
  1.4. Statement of work ..................................................................................................................... 2  
Chapter 2 Literature Review ......................................................................................................... 4  
  2.1 Underground stone mine pillar design ......................................................................................... 4  
    2.1.1 Pillar load ............................................................................................................................. 4  
    2.1.2 Pillar strength ....................................................................................................................... 6  
  2.2 Influence of geological structures on the strength of stone mine pillars .................................... 13  
    2.2.1 Adjustment for the presence of large discontinuities ............................................................... 15  
  2.3 LaModel: Stress and stability analysis ......................................................................................... 17  
  2.4 Integrated stability mapping software and its applications ......................................................... 20  
Chapter 3 Methodology ................................................................................................................. 24  
  3.1 Simulation of stone mine pillar response in LaModel ................................................................. 24  
  3.2 Implementing the Local Large Discontinuity Factor (LLDF) ....................................................... 25  
    3.2.1 Verification of LLDF ............................................................................................................. 27  
  3.3 Implementing LLDF to pillar stability analysis ........................................................................... 29  
    3.3.1 Structure of the LLDF application methodology ................................................................. 30  
    3.3.2 Data format and required data ............................................................................................ 31  
    3.3.3 Large discontinuity gridding and integrated stability mapping software application ....... 33  
    3.3.4 Software tool for LLDF implementation ............................................................................ 35  
Chapter 4 Case Study ..................................................................................................................... 38  
  4.1. Loyalhanna formation and case study mine layout ................................................................. 38  
    4.1.1. Loyalhanna formation ........................................................................................................ 38  
    4.1.2. Case study mine layout ..................................................................................................... 40  
  4.2. Implementing Local Large Discontinuity Factor (LLDF) to case study mine ....................... 41
4.3. LDF and S-Pillar comparison ........................................................................................................................................... 46
Chapter 5 Conclusion and Future Studies .................................................................................................................. 50
5.1 Summary ........................................................................................................................................................................... 50
5.2 Conclusion ........................................................................................................................................................................... 50
5.3 Suggestion for future studies ........................................................................................................................................... 51
REFERENCES ........................................................................................................................................................................... 52

Table of Figures

Figure 1: Tributary and pillar area of a room and pillar mine (Zipf, 2001). ................................................................. 5
Figure 2: Mohr's circle diagram regarding average pillar confinement $C_{pav}$. ................................................... 8
Figure 3: Confinement Method Elements (Roberts, 2007). ......................................................................................... 9
Figure 4: Pillar loading (Johnson, 2014) and LaModel material element representation ............................................ 10
Figure 5: Plan view of the square pillar divided into 8 pieces (Johnson, 2014). ....................................................... 11
Figure 6: Three pillar cell types (Johnson, 2014). ........................................................................................................... 11
Figure 7: The Sideling Hill road cut (Duff, 2014). ........................................................................................................... 13
Figure 8: Geomechanics Classification (Bieniawski, 1989). ....................................................................................... 14
Figure 9: Rock mass properties (Wylie, 1999). ................................................................................................................ 14
Figure 10: Examples of large discontinuities (Esterhuizen, 2011). ........................................................................... 15
Figure 11: LaModel Lamination Thickness Wizard. ..................................................................................................... 19
Figure 12: LaModel In-Seam Material Models – Gob Wizard .................................................................................... 19
Figure 13: Integrated stability mapping software user interface example (Wang, 2005). ......................................... 21
Figure 14: The changes of the influence of the structural features depending on the distance. ... 22
Figure 15: Seam grid generation (Wang, 2005). ............................................................................................................. 23
Figure 16: Mine plan and discontinuity AutoCAD drawing. ......................................................................................... 27
Figure 17: Illustration of the scenario and divided areas. ........................................................................................... 28
Figure 18: LDF and LLDF results. ................................................................................................................................. 29
Figure 19: Data flow chart of LLDF application. ........................................................................................................... 30
Figure 20: LaModel and AutoCAD gridding sequences. .............................................................................................. 32
Figure 21: Mine plan and discontinuity AutoCAD drawing. ......................................................................................... 33
Figure 22: The application of SMAP_SFACTORINAREA command for intersected pillars. ... 34
Figure 23: Pillar stress safety factor output after identification of intersected pillars. ........................................... 35
Figure 24: Details of the generating new safety factor file by using Python code. ................................................... 37
Figure 25: Structure contour map of the topographic features on Loyalhanna (Iannacchione & Coyle, 2002)............................................................................................................................................. 39
Figure 26: Massive roof failure (Iannacchione & Coyle, 2002)................................................................................................................................................. 40
Figure 27: Case study mine layout........................................................................................................................................................................... 41
Figure 28: Overburden stress distribution (psi) with topography contours................................................................. 42
Figure 29: Total vertical stress distribution (psi)................................................................................................................................. 42
Figure 30: Pillar stress safety factor distribution ............................................................................................................................... 43
Figure 31: Arbitrary created discontinuities and intersected pillars ...................................................................................... 44
Figure 32: Illustration of the mine layout to exemplify the LLDF factor............................................................................. 45
Figure 33: The safety factors of pillars before and after implementing LLDF ................................................................. 45
Figure 34: Selected areas in the Loyalhanna Limestone Mine layout .................................................................................. 46
Figure 35: The illustration of the comparison between LLDF and LDF..................................................................................... 49

Table of Tables

Table 1: Empirical pillar strength equations for coal pillars........................................................................................................ 6
Table 2: Empirical pillar strength equations for hard rock mine pillars.......................................................................................... 7
Table 3: Comparison of Escobar (2021) and the S-Pillar database results...................................................................................... 12
Table 4: Discontinuity dip factor coefficients................................................................................................................................. 16
Table 5: Frequency Factor coefficients............................................................................................................................................... 17
Table 6: The parameters of the pillars in the selected areas ............................................................................................................. 48
Table 7: The comparison between LDF calculations and LDF calculations.............................................................................. 48
Chapter 1 Introduction

1.1. Overview
In 2021, 72% of crushed stone was utilized for road construction and maintenance, 16% for cement manufacturing, and 8% for lime manufacturing. The rest was used in agriculture, chemical manufacturing, and other miscellaneous processes (USGS, 2022). In the U.S., the major crushed stone producing states are Texas, Missouri, Florida, Pennsylvania, and Ohio. Crushed stone production in the United States, which was about 1.5 billion tons in 2021 with a 10% increase in the last five years, cannot satisfy the country's domestic demand (USGS, 2022). With the increasing demand for limestone due to the increasing infrastructural developments in the public and private sectors, the cut-off grade of limestone decreases with increased prices, and the mining companies are extending their operations to deeper formations by developing underground stone mines.

There are approximately 109 active underground stone mines in the USA (NIOSH, 2022), and underground stone mining represents around 21% of the total underground mining operations in the U.S. (NIOSH, 2021). In 2019, more than 2000 people worked in the underground stone mining industry (NIOSH, 2021). In 2020, 43% of the fatal accidents reported in the underground mines were caused by fall of ground (NIOSH, 2022). Fall of ground accidents are responsible for 10% of nonfatal lost-time injuries in all underground mines (NIOSH, 2022).

In the U.S., "Pillar and Roof Span Design Guidelines for underground Stone Mines" and S-Pillar program have been used by mining engineers for designing pillar layouts and roof supports for over ten years (Esterhuizen et al., 2011). The S-Pillar program conservatively calculates the pillar load as the maximum depth over the pillar layout, and the tributary-area stress calculation is only truly valid if the mine uses regularly sized pillars (Esterhuizen et al., 2011). Escobar (2021) extended the application of the S-Pillar empirical strength equation to Boundary Element Method (BEM) software, LaModel, to allow the assessment of the influence of variable topographies and irregular seized pillars on stone mine pillar stability.

1.2. Problem statement
Five massive pillar collapses occurred between 2015 and 2021 (4 of them after October 2020) in the older workings of active limestone mines. These massive pillar collapses led to powerful air blasts and, in some cases, even surface subsidence. On January 7, 2022, a massive roof fall claimed
the life of a dozer operator in an underground mine operating in the Loyalhanna formation, and reports of extensive regionalized roof falls in other mines demonstrated the potentially severe risk to the safety of miners in underground stone mines. MSHA (2021) stated that ignored or unrecognized geological features (joints, weak bedding planes, etc.) might reduce pillar stability, induce roof/rib falls, and increase the likelihood of massive collapses.

NIOSH design guidelines also emphasize the effect of large, angular discontinuities on pillar strength. Esterhuizen et al. (2011) proposed to use large discontinuity adjustment based on dip angle and spacing of the large discontinuities to assess their impact on pillar strength in the S-Pillar program. However, this approach does not consider the relative location of geological structures with respect to pillars or the multiple joint sets that may intersect a pillar. Large discontinuities can be widely spaced and do not necessarily intersect each pillar in a layout (Esterhuizen et al., 2011). Overlaying the map of the geological structures with the factor of safety and stress plots generated by LaModel can further improve both the global and local stability of the stone mines and improve the safety of miners working in the underground stone mining sector.

1.3. Objective of thesis

This research aims to develop a software tool that can integrate the LDF approach with the LaModel stress and safety factor analysis and propose a Local Large Discontinuity Factor (LLDF) for assessment of the local pillar stability. This new design tool will allow stone mine operators to integrate geological structures, irregular pillar layouts, and variable topography into the global and local pillar stability analysis.

1.4. Statement of work

In this thesis, a local large discontinuity factor (LLDF) is proposed to evaluate the impact of large discontinuity on the local pillar stability by developing a software tool that integrates the large discontinuity factor proposed by Esterhuizen et al. (2011), integrated stability mapping system (Wang, 2005), the Boundary Element Method software (BEM) LaModel, and empirical S-Pillar strength equation. The computer code is developed to incorporate these tools and compute the safety factor of each pillar in a mine layout, including the strength adjustment due to the presence of large, angular discontinuities.

This study consisted of 3 specific tasks:
• Task 1: Development of a methodology that allows identification of the interaction between pillars and discontinuities on the mine layout.
  o Integrated stability mapping software features are used to identify the pillars that are intersected with the discontinuities and create the grid file.

• Task 2: Develop a computer code that incorporates the large discontinuity impacts, overburden stress distribution under variable topography, and irregular pillar layouts by utilizing: Large Discontinuity Factor (LDF), AutoCAD ObjectARX add-in Integrated Stability Mapping Software (ISMS), S-Pillar and LaModel software.
  o LaModel software with empirical S-Pillar strength equation (Escobar, 2021) is used to compute the safety factor of the stone mine pillars. This approach automatically accounts for the effect of topography and irregular pillar sizes for the pillar stability analysis.
  o The software tool is programmed to read the LaModel output and integrated stability mapping software grid files and output the results in the same format.
  o The tool computes the safety factors of the mine pillars, including the large discontinuity adjustment for intersected pillars, and generates LaModel and grid files with new safety factors.

• Task 3: Apply the LLDF calculations on a stone mine case study, illustrate them by using LaModel software, and compare them with the LDF calculations and S-Pillar outcomes.
Chapter 2 Literature Review

This chapter summarizes research studies related to the development of the software tool and Local Large Discontinuity Factor (LLDF) proposed in this thesis. First, principles of pillar design and the current state of the underground stone mine pillar design in the U.S. are discussed. Then, the influence of geological structures on rock mass and pillar strength and behavior are presented. Next, the confined core concept and the simulation of the pillars in BEM software are introduced. After the detailed summary of the LaModel software and its' applications, the integrated stability mapping software and its' functionalities are presented.

2.1 Underground stone mine pillar design

The room and pillar underground mining method is commonly used for mineral deposits that are roughly tabular and generally flat-lying such as coal, trona, salt, oil shales, borates, or limestone (Bullock, 2011). It is defined as an unsupported mining method where natural supports, which are ore remnants called "pillars", are left to carry the weight of the overburden strata. In this method, the "rooms" refer to entry and crosscut areas (Brady and Brown, 2004). The room and pillar method is a highly selective mining method since the mining plan can be adjusted by leaving low-grade ore as a pillar. Peng (2008) stated that in pillar design, there are three primary steps: determining the estimated load on the pillar during its service life, determining pillar strength, and determining the factor of safety.

2.1.1 Pillar load

A stone mine pillar during its service life is first subjected to a development load during entry/crosscut development and then mining induced loading during floor benching. Peng (2008) indicated the tributary loading concept can be used to calculate the development load on a pillar during the extraction of entries/crosscuts. Farmer (1992) stated that the tributary area method provides a first-order estimate of average pillar stress on a pillar. The tributary area method assumes that: (i) overburden weight is equally distributed among all the pillars, (ii) all pillars have the same dimensions, and (iii) the pillar stresses are uniformly distributed (Zipf, 2001). Peng (2008) explains that this approach assumes the overburden carried by the pillar is separated from the adjoining overburden with its weight resting on the pillar, and this assumption tends to overestimate the pillar load. Hill et al. (2008) indicated that the tributary loading assumptions aren't
valid in Australia's NSW Southern coalfield, otherwise the main headings should have failed under the overburden load estimated by the tributary area loading approach. Due to similar reasons, Mark (2010) developed the pressure arch loading concept for the deep cover retreat room and pillar coal mines in the USA. The tributary area, which is the total area each pillar supports, and the pillar area are shown in Figure 1.

![Figure 1: Tributary and pillar area of a room and pillar mine (Zipf, 2001).](image)

The vertical stress in the traditional room and pillar design method is estimated by Eq. 1:

\[ \sigma_s = \lambda z \quad (1) \]

where \( \lambda \) is the unit weight of overlying rock, \( z \) is the depth of cover. If the room and pillar system is in a square shape, the average pillar stress is computed by Eq. 2:

\[ \sigma_{pa} = \sigma_s \left( \frac{W_p + W_o}{W_p} \right)^2 \quad (2) \]

where \( W_p \) is the pillar width, and \( W_o \) is the opening width, as shown in Figure 1. If the room and pillar system has rectangular or irregular shaped pillars, the average pillar stress is calculated using Eq. 3:

\[ \sigma_{pa} = \sigma_s \frac{(W_p + W_e) \times (L_p + W_c)}{W_p \times L_p} \quad (3) \]

Where \( W_e, W_c, \) and \( L_p \) are the entry width, crosscut width, and pillar lengths.

Esterhuizen et al. (2011) recommended applying the tributary area loading approach to estimate an upper limit of the average pillar stress in the U.S. stone mines. They also stated that numerical models can be used to estimate average pillar stresses when the tributary area technique is not
viable, such as irregular pillars, limited mining extent, or changing depths of cover. The numerical modeling techniques such as finite element, boundary element, discrete element, and finite difference techniques are applicable for performing mechanical analysis of the geologic structure of mining operations and estimating the stresses on the pillars. The main purpose of a numerical simulation in mining geomechanics is to simulate the behavior of geomaterials due to mining using the solutions of a set of differential equations in a particular region of space and time, as well as pre-determined boundary conditions (LeVeque, 2007; Suner, 2021). To simulate geomaterials, one can use one of three material mechanics methods: 1) continuum, 2) distinct/discrete fracture (i.e., dis-continuum), or 3) a combination of the two (Suner, 2021). Finite Element Methods (FEM), Finite Difference Methods (FDM), and Boundary Element Methods (BEM) are the most prominent continuum methods utilized in geomechanics. Application of the FEM, FDM, and dis-continuum methods are not in the scope of this research, so they are not discussed in this thesis. LaModel software, a displacement discontinuity variation of BEM, is discussed in the upcoming section of this thesis.

2.1.2 Pillar strength

Esterhuizen (2008) defines pillar strength as the maximum resistance of a pillar to axial compression caused by the weight of the overlying rock mass. Empirical pillar strength equations, which are only applicable for similar mine conditions, show that pillar strength depends on pillar volume and shape (Peng, 2008). Table 1 shows some of the empirical coal pillar strength equations used in the USA.

<table>
<thead>
<tr>
<th>Source</th>
<th>a*</th>
<th>b*</th>
<th>α</th>
<th>β</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunting (1911)</td>
<td>0.7</td>
<td>0.3</td>
<td>-</td>
<td>-</td>
<td>Pennsylvania anthracite</td>
</tr>
<tr>
<td>Obert and Duvall (1967)</td>
<td>0.78</td>
<td>0.22</td>
<td>-</td>
<td>-</td>
<td>Laboratory rock and coal</td>
</tr>
<tr>
<td>Bieniawski (1968)</td>
<td>0.64</td>
<td>0.36</td>
<td>-</td>
<td>-</td>
<td>U.S. coal mines</td>
</tr>
<tr>
<td>Skelly et al. (1977)</td>
<td>0.78</td>
<td>0.22</td>
<td>-</td>
<td>-</td>
<td>West Virginia coal</td>
</tr>
<tr>
<td>Greenwald el al. (1939)</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>0.83</td>
<td>Pittsburgh seam mines</td>
</tr>
<tr>
<td>Holland (1964)</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>1</td>
<td>U.S. coal mines</td>
</tr>
</tbody>
</table>

Source: Zipf 2001
*a and b are dimensionless

$$\sigma_p = \sigma_s \left(a + b \frac{W}{H}\right)$$  
(4)
\[ \sigma_p = K \frac{W^{\alpha}}{H^{\beta}} \]  

(5)

where \( \sigma_s \) is the strength of a cubical pillar (W/H=1) at or above the critical size, K is the constant characteristic of the pillar rock, and a, b, \( \alpha \), and \( \beta \) are the constants that account for the shape factor. The recommended \( \sigma_s \) value is set to 6.2 MPa (900 psi) for the coal mines in the United States (Mark and Chase, 1997).

The same equations used in coal mine design (Eq. 4 and 5) with different coefficients are also used for estimating strength of hard rock mine pillars. One of the earliest hard-rock pillar strength equations accepted and implemented by the industry was published by Hedley and Grant (1972) when they were studying pillar and rib failures in uranium mines. Von Kimmelmann et al. (1984) used the displacement discontinuity variation of the boundary element method in underground nickel and copper mines. Krauland and Soder (1987) and Sjoberg (1992) derived the same constants for the limestone mines with different \( \sigma_s \) coefficients. The coefficients of empirical hard rock pillar equations are shown in Table 2.

Table 2: Empirical pillar strength equations for hard rock mine pillars.

<table>
<thead>
<tr>
<th>Source</th>
<th>a*</th>
<th>b*</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( \sigma_s )</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hedley and Grand (1972)</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
<td>0.75</td>
<td>133</td>
<td>Uranium mines</td>
</tr>
<tr>
<td>Von Kimmelmann et al. (1984)</td>
<td>-</td>
<td>-</td>
<td>0.46</td>
<td>0.66</td>
<td>65</td>
<td>Nickel and copper mines</td>
</tr>
<tr>
<td>Krauland and Soder (1987)</td>
<td>0.78</td>
<td>0.22</td>
<td>-</td>
<td>-</td>
<td>35</td>
<td>Limestone mines</td>
</tr>
<tr>
<td>Sjoberg (1992)</td>
<td>0.78</td>
<td>0.22</td>
<td>-</td>
<td>-</td>
<td>74</td>
<td>Limestone mines</td>
</tr>
</tbody>
</table>

*a and b are dimensionless

Lunder (1994), during his cooperative work with Westmin Resources Ltd. and The Canadian Centre for Mineral and Energy Technology (CANMET), proposed a confined core method for estimating pillar strength. His confinement formula is similar to the Mohr-Coulomb shear strength equation (Eq. 6). The average confinement term, \( C_{pav} \), which is the average \( \sigma_3 \) divided by the average \( \sigma_1 \), is analog to the approximate influence of the width/height ratio (Lunder, 1994). The author determined the term "kappa (\( \kappa \))", described as average pillar confinement and a friction term, using basic trigonometry on Mohr's circle diagrams shown in Figure 2.
Figure 2: Mohr’s circle diagram regarding average pillar confinement $C_{pav}$.

$$C_{pav} = \frac{\sigma_3}{\sigma_1}$$

(7)

$$\cos(\beta) = \frac{(\sigma_1 - \sigma_3)}{2} + \frac{\sigma_3}{2} = \frac{(\sigma_1 - \sigma_3)}{\sigma_1 + \sigma_3} = \frac{1 - C_{pav}}{1 + C_{pav}}$$

(8)

$$\kappa = \tan \left[ \cos^{-1} \left( \frac{1 - C_{pav}}{1 + C_{pav}} \right) \right]$$

(9)

where $\kappa$ is the mine pillar friction term, and $C_{pav}$ is the average pillar confinement. The confinement formula for the hard rock pillar mines is in the form of Equation 10.

$$P_s = (K * U.C.S.) * (C_1 + C_2 \kappa)$$

(10)

where

$P_s$ = Pillar strength

$K$ = Pillar strength size factor

$U.C.S.$ = Unconfined compressive strength

$C_1, C_2$ = Empirical rock mass constants

$\kappa$ = Pillar friction term

Esterhuizen et al. (2011) collected data on operational and pillar performance from 34 stone mines in the Eastern and Midwestern United States. They identified 18 instances of failing individual pillars and visually inspected each of the failed pillars. Later, they established a base pillar strength
equation (Eq. 11) governing stone mines in the United States by completing a comprehensive numerical modeling work to understand pillar behavior while taking into account brittle rock spalling, large and angular discontinuities, weak bedding bands, floor benching, and pillar length.

\[ \sigma_p = K \frac{W^{0.3}}{H^{0.59}} \]  \hspace{1cm} (11)

Esterhuizen et al. (2011) observed that when the average pillar stress exceeds 10% of its UCS value in stone mines, spalling starts to be observed. This spalling decreases the perimeter of a pillar, resulting in concave pillar ribs, and reduces the width factor of the pillar.

Roberts et al. (2007) made the same observation in Doe run’s underground room-and-pillar lead mines and proposed empirical pillar design guidelines from the back analyses of the observed pillar spalling and damage. They used displacement discontinuity models to predict pillar stability. The authors used three different element types in their study (Figure 3). They fit 2.4 m (7.9 ft) square blocks of the elements, which can properly represent the rib and core of the pillar, to back-calculate the strengths of these elements. To replicate the effect of confinement on pillar strength, they modeled the strength of hard-rock pillars with various rib and core cell parts (such as A and B in Figure 3). Method proposed by Roberts et al. is similar to the one used in LaModel to model coal pillar strength (Heasley et al., 2010).

![Figure 3: Confinement Method Elements (Roberts, 2007).](image)

Heasley (1998) established a boundary element method software, LaModel, to calculate the displacements and stresses in flat-lying seams such as coal, potash, trona, etc. by using a laminated overburden model. Heasley (2010) uses concentric rings of different materials and separates the properties of the material of the ribs and the openings to model the strength of materials in LaModel software. (Figure 4, right-hand side). The average peak stress values of the elements
change depending on their confinement and their location if it's at the side or corner of the pillar (Figure 4).

![Figure 4: Pillar loading (Johnson, 2014) and LaModel material element representation.](image)

Even though the real post-peak behavior cannot be foreseen entirely (Iannachione, 1999), Johnson et al. (2014) and Escobar (2021) derived a numerical approximation for the local pillar strength by using a distance from a pillar rib as a parameter of the stress distribution. The authors imply that the maximum vertical stress is not a constant value and can be explained by a function. The assumptions that the authors used are (i) pillars are square with elastic-plastic material, (ii) strength value varies depending on the distance from the closest rib, and (iii) the square pillar is divided into eight symmetric pieces to simplify the integral equations of the stress function (Figure 5). Heasley (2010) used concentric rings of different materials and separates the pillar into different types of cell elements to model the strength of materials in LaModel software. Two pillar cell equations are identified: (i) rib cell and (ii) corner cell (Figure 6). Because of their additional confinement, the defined core cells are stronger than the rib cells, which are stronger than the corner cells.
Variables are defined are follows:

- Pillar half-width = \( W \) (Figure 4)
- Pillar width = \( w = 2W \)
- Pillar height = \( h \)
- Total vertical force applied to pillar = \( F \)
- Pillar load capacity = \( R \)
- Strength coefficient = \( \sigma_0 \)
- Average pillar strength = \( \sigma_p \)
- Horizontal location within pillar = \( x \)
- Local strength = \( \sigma_\lambda(x) \)
- Pillar rib at \( x = 0 \)
- Pillar centerline at \( x = W \)

**Figure 5:** Plan view of the square pillar divided into 8 pieces (Johnson, 2014).

**Figure 6:** Three pillar cell types (Johnson, 2014).
Escobar (2021) derived the stress gradient equations (Eq. 12; Eq. 13) and cell pillar strength functions for a stone mine pillar, as a function of the pillar width-to-height ratio, from the empirical pillar strength equation (Eq. 11) proposed by Esterhuizen et al. (2011). Then he implemented them into LaModel and verified these equations by two different methods. First, he changed the pillar width-to-height ratio and kept the cell element size the same and compared the pillar strengths computed by cell strength functions and the empirical S-Pillar equation (Table 3). Then, he kept the width and height of pillars the same and changed the element size. In this case, he recognized that the difference between his results and the S-Pillar database results got closer when the element size was reduced (Table 3).

\[ \sigma_v(x) = 1.84\, \sigma_0 \frac{x^{0.3}}{h^{0.59}} \]  

(12)

\[ \sigma_{\text{corner}} = \left( \frac{1.23\, \sigma_0}{h^{0.59} W^2} \right) \left[ \left( \bar{x} + \frac{W}{2} \right)^2 - 2.3 \left( \bar{x} + \frac{W}{2} \right) \left( \bar{x} - \frac{W}{2} \right)^{1.3} + 1.3 \left( \bar{x} - \frac{W}{2} \right)^{2.3} \right] \]  

(13)

**Table 3: Comparison of Escobar (2021) and the S-Pillar database results.**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.500</td>
<td>40</td>
<td>80</td>
<td>5.00</td>
<td>4397</td>
<td>4393</td>
<td>0.0822%</td>
</tr>
<tr>
<td>1.000</td>
<td>40</td>
<td>40</td>
<td>5.00</td>
<td>6618</td>
<td>6613</td>
<td>0.0822%</td>
</tr>
<tr>
<td>1.500</td>
<td>40</td>
<td>27</td>
<td>5.00</td>
<td>8407</td>
<td>8400</td>
<td>0.0822%</td>
</tr>
<tr>
<td>2.000</td>
<td>40</td>
<td>20</td>
<td>5.00</td>
<td>9962</td>
<td>9954</td>
<td>0.0822%</td>
</tr>
<tr>
<td>1.000</td>
<td>50</td>
<td>50</td>
<td>2.00</td>
<td>6198</td>
<td>6196</td>
<td>0.026%</td>
</tr>
<tr>
<td>1.000</td>
<td>50</td>
<td>50</td>
<td>2.50</td>
<td>6198</td>
<td>6200</td>
<td>0.028%</td>
</tr>
<tr>
<td>1.000</td>
<td>50</td>
<td>50</td>
<td>5.00</td>
<td>6198</td>
<td>6200.4</td>
<td>0.035%</td>
</tr>
<tr>
<td>1.000</td>
<td>50</td>
<td>50</td>
<td>10.00</td>
<td>6198</td>
<td>6162</td>
<td>0.573%</td>
</tr>
</tbody>
</table>

Finally, Escobar (2021) validated his work with a case study from an underground stone mine. He applied his derived stone mine pillar equations to compute the stress and safety factors on the case study mine pillar layout using LaModel. He defined eight rib cell elements and eight corner cell elements for simulating development and bench pillars. He manually added the in-seam properties and the topography file into LamPre, the pre-processor for the LaModel software, and run LaModel for computing seam stresses and displacements. Then, he computed the safety factor of the pillars system with S-Pillar. Both software results were reasonable and within the expected
range. LaModel takes into account the mine topography, while S-Pillar uses the maximum depth of cover instead of topography. Both results satisfied the recommendations of the NIOSH design guidelines.

2.2 Influence of geological structures on the strength of stone mine pillars

The geological structures such as bedding planes, large-angular discontinuities, joint sets, or weak bands are the main causes of the weakening effect on pillar stability (Esterhuizen, 2006). Mapping the geological structures would improve the safety of the underground operations and provides site-specific information to be used in mine design. A discontinuity is defined as a formation that makes a change in physical or chemical properties in a rock mass. (Figure 7). Bieniawski (1989) implies that although there could be some exceptions, the discontinuities' features have more importance than the features of the intact rock material for estimating the rock mass stability. For geomechanics classification (Figure 8 and Figure 9), the features of discontinuities are divided into the following parameters: Spacing, orientation, roughness of the discontinuity surface, separation, weathering of the wall rock of the planes of weakness, and infilling material (Bieniawski, 1989). Iannacchione et al. (2002) states that mapping and quantifying the characteristics of a discontinuity is essential for reducing miners' exposure to hazards. Discontinuities cannot be accurately detected by basic sampling methods (Brady and Brown, 2005) because it is difficult to recognize them during the development. They are more likely to be detected when the pillar is completely loaded, or bench mining is done around the pillars (Esterhuizen, 2008).

*Figure 7: The Sideling Hill road cut (Duff, 2014).*
Figure 8: Geomechanics Classification (Bieniawski, 1989).

Figure 9: Rock mass properties (Wylie, 1999).
2.2.1. Adjustment for the presence of large discontinuities

Esterhuizen (2008) describes the large angular discontinuities as the discontinuities which can be observed throughout the whole pillar (Figure 10). They might have a significant impact on the strength of the pillars depending on the dip of the discontinuity plane. Esterhuizen et al. (2011) defined the large discontinuity factor (LDF) to quantify the effect of the larger angular discontinuities on the pillar strength.

Both the dip and spacing of the discontinuities impact the pillar strength. The adjustment of the pillars' safety factors is determined by taking them into account. The discontinuities with less than a 30-degree dip angle are assumed to have little or no cohesion. Esterhuizen (2008) introduces the discontinuity dip factor (DDF) as the reduction factor to calculate the strength of a pillar intersected with a single large discontinuity. Table 4 shows the effect of DDF and how it increases when the width-to-height ratio decreases.
The assumption to use only DDF throughout the mine could be fallacious because the large discontinuities would not intersect every pillar. After the results of numerical models and case study evaluations, Esterhuizen (2000) states that the frequency of the large discontinuity, which is called the frequency factor (FF), should also be considered in the large discontinuity effect calculations. It is demonstrated by Priest and Hudson (1976) that the spacing of the discontinuities in a rock mass can be represented with a negative exponential distribution. Eq. 14 shows the frequency, \( f(x) \), of a discontinuity spacing, \( x \), using the negative exponential distribution (Esterhuizen, 2000):

\[
\begin{equation}
    f(x) = \lambda e^{-\lambda x}
\end{equation}
\]

Where \( \lambda \approx \frac{1}{\bar{x}} \) is the mean discontinuity frequency of a large discontinuity population and \( \bar{x} \) is the mean spacing.

Esterhuizen et al. (2011) derived Eq. 15 based on Eq. 14 to calculate the frequency of large discontinuities per pillar, frequency factor (FF), using average discontinuity per pillar values determined from field surveys. The frequency factor coefficient (right side of Table 5) is calculated with Equation 15. The average frequency of large discontinuities per pillar is abbreviated as AFP in the formula which is dividing the pillar width by the average spacing of the discontinuity.

\[
\begin{equation}
    FF = 1 - e^{-AFP}
\end{equation}
\]

As a result, even though the discontinuity spacing per pillar is shown on the left side of Table 5, the coefficient on the right side, FF, represents the frequency of a large discontinuity population in a layout of many pillars. The frequency factor (FF) results are simplified and tabulated as shown in Table 5.
Table 5: Frequency Factor coefficients.

<table>
<thead>
<tr>
<th>Average frequency of large discontinuities per pillar</th>
<th>Frequency factor (FF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.00</td>
</tr>
<tr>
<td>0.1</td>
<td>0.10</td>
</tr>
<tr>
<td>0.2</td>
<td>0.18</td>
</tr>
<tr>
<td>0.3</td>
<td>0.26</td>
</tr>
<tr>
<td>0.5</td>
<td>0.39</td>
</tr>
<tr>
<td>1.0</td>
<td>0.63</td>
</tr>
<tr>
<td>2.0</td>
<td>0.86</td>
</tr>
<tr>
<td>3.0</td>
<td>0.95</td>
</tr>
<tr>
<td>&gt;3.0</td>
<td>1.00</td>
</tr>
</tbody>
</table>

With DDF and FF, the average impact of the discontinuity on the pillars' strength can be determined. The equation of the large discontinuity factor is shown in Eq. 16. This equation is also derived as Equation 17. If there isn't any interaction with the discontinuity, \(1 - e^{-0}\) will be zero, so FF can be taken as zero. Therefore, LDF becomes one.

\[
LDF = 1 - DDF \times FF
\]

\[
LDF = 1 - DDF \times (1 - e^{-AFP})
\]

LDF can be computed in several steps. To illustrate, if the mine pillar design is set as 60 ft wide pillars with 50 ft height (width-to-height ratio of 1.2) and we are trying to estimate the impact of large discontinuities with dipping at 40 degrees and spaced 60 ft apart, the following steps should be followed: (i) calculate the average frequency of large discontinuities per pillar by dividing pillar width by discontinuity spacing (60/60 = 1.0), (ii) find F.F. of the average frequency in Table 5 (FF=0.63) or calculate with the formula of \(1 - e^{-1} = 0.63\), (iii) find DDF in Table 4 (DDF = 0.23), (iv) Calculate the LDF by using Eq. 16, (LDF = 1- 0.23*0.63= 0.8551). Therefore, after determining the large discontinuity factor (LDF), the pillar strength can be calculated using Eq. 18:

\[
\sigma_p = LDF \times K \frac{W^\alpha}{H^\beta}
\]

2.3 LaModel: Stress and stability analysis

Heasley (1998) developed the software called LaModel, to model the stresses and displacements of tabular ore bodies. LaModel is the displacement discontinuity variation of the boundary element method, and the model’s flexibility for simulating stratified sedimentary geologies and multiple-seam mines makes it unique compared to any other boundary-element software (Zhang, 2014).
LaModel is applicable to the single and multiple seams where there are irregular pillars and variable topography. Convergence, vertical stress, overburden stress, pillar safety factors, intra-seam subsidence can be calculated by the LaModel software. The software is an applicable tool for estimating seam level displacements and stresses, and surface subsidence as well.

Its effectiveness, modeling feature, and applicability in determining stresses and displacements have been demonstrated in the coal mining industry. Even though generally used in coal mines, Heasley (1998) defines LaModel in overall as "a program nominally calculates the displacements and stresses for user-defined pillar geometries in flat-lying seams using a laminated overburden model."

LaModel aims to improve the quality of the mine design and provide documented and repeatable techniques for calculating stresses and loads as realistic and accurate as possible. It can work with a constant overburden or a variable topography and create a 2,000 x 2,000 grid with six different material models and 52 in-seam materials (Heasley, 2010). LaModel consists of three separate components. The first one is the pre-processor of LaModel, called LamPre. LamPre is used for preparing the input file for LaModel where the user sets the parameters, creates a mine grid (Figure 4, right side), and assigns the material elements (Figure 12). Whereas LaModel models the stresses and displacement according to the inputs prepared using LamPre. Finally, LamPlt visualizes the outputs calculated by LaModel.

Pre-processor of LaModel, LamPre, has two "Wizards" to calculate the lamination thickness and gob properties. The stiffness of the surrounding rock mass and geometry of the mine plan are the main factors of the local mine stiffness. Moreover, the stiffness of the rock mass depends on the lamination thickness and elastic modulus of the rock mass (Li, 2015). The lamination thickness wizard (Figure 11) determines the lamination thickness that matches the known or calculated abutment extent. Abutment extent can be imagined as the maximum distance the stress effects can be transferred from an active zone. The gob wizard (Figure 12) calculates the "Final Gob Modulus" meaning the modulus that provides site-specific or calculated overburden load on the gob.
Esterhuizen (2011) suggests using numerical models such as LaModel to calculate the average pillar stress when the tributary area method isn't applicable, like complex geometries, the limited extent of mining, or variable depth of cover. Escobar (2021) extended the application of the S-Pillar strength equation to the Boundary Element Method software (Heasley, 1998) to allow stone mine operators to integrate accurate overburden stress distribution under variable topography and for irregular pillar layouts.

Applications in the industry showed that end-users might need some improvements for faster, more complete, and more complex analysis. Some developments were done by integrating LaModel
with AutoCAD software in response to these requests (Wang, 2005). LaModel output files were arranged to be used in AutoCAD for advanced analysis and illustration (Heasley, 2008). For example, AutoCAD visual interface was implemented for complex irregular mine layouts and faster algorithms. Furthermore, LaModel can also develop appropriate seam and overburden grids using AutoCAD files.

2.4 Integrated stability mapping software and its applications.
Stability mapping practices is used in the mining industry for evaluating the stability features of the underground mine during the mine design and operations. However, since mining conditions are becoming more complex, deeper, and consider more than one seam deposit, computer-aided geology mapping is becoming necessary for getting a satisfying mining plan (Wang, 2005). The enhancement of the technology enables the storage of a huge amount of information as computer files. As a result of these advancements, different software is created to interpret and manipulate this information.

The Integrated Stability Mapping Software (ISMS) is a supportive tool for engineers to combine stability parameters with geo-mechanical information. It allows mining engineers to perform extensive, fast, and precise analyses to obtain safer mine and support designs. Decreasing the number of injuries and fatalities related to ground fall in underground mines is aimed by using ISMS. (Wang, 2005)

AutoCAD software is a popular drafting tool in the mining industry. ISMS executes AutoCAD as an automatic platform to unite the geologic characteristics. Then, the boundary element program, LaModel stress calculations combine the true topography consideration, the laminated overburden model, and pillar design. ISMS can develop appropriate seam and overburden grids from AutoCAD files (Figure 13). At the same time, ISMS can visualize LaModel output files in AutoCAD for advanced analysis and illustration (Heasley, 2008). Therefore, the collaboration between an Integrating Stability Mapping Software and the boundary element program LaModel allows the user to determine the stress influences.
Figure 13: Integrated stability mapping software user interface example (Wang, 2005).

With integrated stability mapping software, the user can define stability factors of a particular mine, such as the strength of a layer, the chemical composition of the layer, the presence of weak partings, the thickness of the layers, etc. The integrated stability mapping software was built into AutoCAD to satisfy the demand for functional and auxiliary modules. The critical influence factors are defined by using appropriate modules (Wang, 2005). The geology-oriented modules, stress-oriented modules, and index mapping modules are used in the integrated stability mapping software.

2.4.1 Geology oriented modules

The geology-oriented modules evaluate the mine stability according to the geologic properties collected from drill hole data such as seam thickness, overburden depth, seam composition, etc., and structural features like stream valleys, sandstone channels, faults, etc. The data of geologic properties are located in the mine map as the X and Y coordinates or contours. Then, the values
are defined as Z values. By using interpolation, the modules calculate the values for each grid element. The influence of the structural features generally depends on the distance (Figure 14). Therefore, according to their representations in the mine map, the feature can affect the stability in two ways: linearly proportional to distance or whether it is inside or outside the polygonal boundary.

![Image](image.png)

*Figure 14: The changes of the influence of the structural features depending on the distance.*

### 2.4.2 Stress oriented modules

The stress-oriented module is used to convert the LaModel results into the grid format. Three functional sub-modules are built-in to improve and simplify the process. The first one is automatic overburden/topography grid generation, and it creates the input file that LaModel uses for calculating the vertical stresses. The second one, which is automatic seam grid generation, assigns the material codes for specific properties to all grid elements (Figure 15). Considering the pillar boundaries, the element value is assigned to imply if it's an opening element or an element of the pillar. The overburden-horizontal stress modules are the last ones. The overburden stress module creates a horizontal datum plane by using normal stresses depending on the elevation differences in the topography. The horizontal stress module introduces the influence of horizontal stress orientation into integrated stability mapping software.
2.4.3 Index mapping modules

After the calculations on the geology-oriented and stress-oriented modules, the index mapping modules estimate the final index using the functions of stability factor transformation, final stability index, and final index mapping modules. The stability factor transformation normalizes all the individual critical factors into the 0-100 numeric range by linear, step, exponential, and user-defined functions. The final stability index module calculates an overall stability index by multiplying every stability factor with its weight and dividing the result by the summation of the weights (Eq. 19).

\[
\text{Ind}_{ij} = \frac{\sum_{k=1}^{n} (V_{ij}^k \times W_k)}{\sum_{k=1}^{n} W_k} \tag{19}
\]

Where \(\text{Ind}_{ij}\) is the stability index at element \((i,j)\), \(k\) is the \(k\)th influence factor, \(n\) is the total number of factors, \(V_{ij}^k\) is the individual stability index at element \((i,j)\) for influence factor \(k\), and \(W_k\) is the assigned weight for the influence factor, \(k\). Finally, the final index mapping module plots the stability index results over the mine map.
Chapter 3 Methodology

As presented in the literature review section, underground stone mines in the U.S. use the room-and-pillar method of mining for flat-lying bedded formations. Depending on the distribution of large discontinuities within the local formation, large angular discontinuities intersecting the pillars influence the global stability of the pillar layout marginally or dramatically. Esterhuizen et al. (2011) developed a Large Discontinuity Factor (LDF) that reduces the strength to account for the impact of large angular discontinuities on pillar strength and stability of the global layout of the pillars. In this thesis, the software tool that integrates the large discontinuity factor (LDF) and the Boundary Element Method software (BEM), LaModel, was developed. It was aimed to allow stone mine operators to assess the impact of the large discontinuities on local pillar stability. The methodology followed for this study is detailed in the following parts.

3.1 Simulation of stone mine pillar response in LaModel

Esterhuizen (2011) used the power equation (Eq. 5) to estimate a stone pillar strength. The pillar strength in this equation (Eq. 20) is determined by the pillar shape parameters, width, and height of a pillar.

\[
\sigma_p = K \frac{W^{0.3}}{H^{0.59}} \quad \text{or} \quad \sigma_p = \sigma_0 \frac{W^{0.3}}{H^{0.59}}
\]  

(20)

As discussed in the literature review section, by dividing the pillar into several forms of cell elements, LaModel (Heasley, 1998) simulates the strength of a pillar based on the empirical Mark-Bieniawski pillar strength equation (Mark et al., 1992). The formulation of variable pillar strength equations by Johnson et al. (2014) allowed the simulation of different empirical pillar strength equations in a boundary element program. Escobar (2021) derived the gradient stress equations, also known as pillar cell equations, for the empirical stone mine pillar strength equation (Eq. 20) by following similar approaches to those presented by Mark et al. (1992) and Johnson et al. (2014). Separate cell strength equations that represent the rib and corner elements of a pillar were derived, and the stress variation within the pillar is assumed to be a function of distance to the closest rib.

First, Escobar obtained the rib cell equation (Eq. 21) for estimating the strength at a distance x from the rib of the stone mine pillar:
\[ \sigma_v(x) = 1.84 \sigma_0 \frac{x^{0.3}}{h^{0.59}} \]  

where \( \sigma_v(x) \), \( \sigma_0 \), \( x \), and \( h \) are the strength at distance \( x \), the rock strength parameter, the distance from the rib, and the height of the pillar.

Then Escobar focused on the corner cell element. He used the same approach published by Mark et al. (1992) to compute the ultimate load-bearing capacity equation:

\[ F_{\text{corner}} = 2 \int_{x_1}^{x_2} \sigma_v(x)w(x)dx \]  

where \( w(x) \) is the width function for the pillar and "W" is the cell width:

\[ w(x) = (x_2 - x) \] (23)

When

- \( x = x_1 \), then \( w(x) = x_2 - x_1 = W \)
- \( x = x_2 \), then \( w(x) = x_2 - x_1 = 0 \)

The final equation for the corner cell element was derived as:

\[ \sigma_{\text{corner}} = \left( \frac{1.23 \sigma_0}{h^{0.59} W^2} \right) \left[ \left( \frac{\bar{x} + \frac{W}{2}}{\ell} \right)^2 - 2.3 \left( \frac{\bar{x} + \frac{W}{2}}{\ell} \right) \left( \frac{W}{2} \right)^{1.3} + 1.3 \left( \frac{\bar{x} - \frac{W}{2}}{\ell} \right)^{2.3} \right] \] (24)

Equations derived by Escobar assume that no large discontinuities are present and that discontinuities do not impact the strength calculation. This thesis uses the equations derived by Escobar (2021) and extends his approach by integrating the large discontinuity factor (LDF) to assess the impact of the large discontinuities on local pillar stability.

### 3.2 Implementing the Local Large Discontinuity Factor (LLDF)

In underground stone mines, natural characteristics of geological structural features in a geological formation, such as distribution, size, orientation, and spacing, influence the stability of an excavation span and a pillar, hence the design of a pillar layout. Geological structures can dominate the response of a rock mass at shallow depths in such a way that structurally controlled failures may be the major concern in design (Brady and Brown, 2004; Esterhuizen et al., 2011). Although at deeper mines, the stress state is always considered the major design factor, recognizing geological structural features is even more important for the safety of the operations. The geotechnical field data collection is an important source for defining the natural characteristics of
the geological structures like discontinuities and their potential impact on the ground control design. Esterhuizen (2008) recognized the importance of the large angular discontinuities on the strength of the stone mine pillars (Esterhuizen, 2008), and he developed the large discontinuity factor (LDF) to quantify their influence on pillar stability (Esterhuizen et al., 2011). The large discontinuity factor represents the average impact of large discontinuities on the strength of pillars in a layout of many pillars. Therefore, LDF implicitly accounts for the spatial distribution of the large discontinuities at a stone mine.

In this research, a new term, Local Large Discontinuity Factor (LLDF), is proposed to explicitly account for the impact of large discontinuities on local pillar stability. To better understand this concept, intersected pillars term is used to represent the pillars intersected with a discontinuity. Local large discontinuity factor of the pillar (LLDF\textsubscript{pillar}) specifically examines the safety factor of an individual pillar that intersects a discontinuity. Esterhuizen (2008) applies the LDF reduction to the whole mine layout. Instead of applying the effects of large discontinuities to the whole mine layout, LLDF allows quantifying the influence of large discontinuities on a selected local area within the mine. As shown in Figure 16, red lines represent the local discontinuities, yellow boxes show the intersected pillars, and black boxes are the pillars with no interaction with the discontinuity.
LLDF strength reduction calculations are done in two steps. First, the safety factor of each pillar in a defined local area is calculated, and if large discontinuities intersect any pillars, strength reduction is computed using Equation 25. Then the $LLDF_{mean}$ of the specified area or the whole mine is found by the summation of safety factors of intersected pillars and undisturbed pillars divided by the total number of pillars (Eq. 26).

$$LLDF_{pillar} = 1 - DDF$$

$$LLDF_{mean} = \frac{(LLDF_{pillar} \times \text{intersected pillar number}) + (1 \times \text{undisturbed pillar number})}{\text{Total number of pillars}}$$

### 3.2.1 Verification of LLDF

As mentioned in the literature review, field data collected and presented by Esterhuizen et al. (2011) demonstrated the necessity of accounting for the impact of large, angular discontinuities on pillar strength. Esterhuizen et al. stated that such an adjustment should include both the inclination and spacing of the large discontinuities. In the field, it was observed that large discontinuities are generally widely spaced and do not necessarily intersect each pillar in a layout. Esterhuizen et al.
derived the discontinuity dip factor (Table 4) that relates the undisturbed pillar strength to the strength of pillars intersected by a single, large discontinuity. He also indicated that applying the DDF to the stability of a layout of many pillars is conservative since the natural spatial distribution of large discontinuities observed on the field indicated that they are generally widely spaced.

In order to prove the LLDF concept, one scenario is created as follows and compared with LDF calculations. The mine layout of 100 pillars with 60° discontinuity dip angle and 0.6 pillar width-to-height ratio is set (DDF=0.86). 16 out of 100 pillars are intersected pillars (Figure 17). The layout is divided into four different districts.

![Diagram](Image)

Figure 17: Illustration of the scenario and divided areas.

LLDF reduction for an intersected pillar is:

\[ LLDF_{pillar} = 1 - 0.86 = 0.14 \]

There are 16 intersected pillars with LLDF reduction safety factors and 84 undisturbed pillars. The mean LLDF of the mine is calculated as:

\[ LLDF_{mean} = \frac{(0.14 \times 16) + (1 \times 84)}{100} = 0.8624 \]

As explained in Chapter 2, LDF calculations (Eq. 17) is as follows:
\[ LDF = 1 - 0.86 \times (1 - e^{-0.16}) = 0.8728 \]

Figure 18: LDF and LLDF results.

The LLDF calculations of both individual and combinations of the areas are done as shown in Figure 18, where blue points show the LLDF values of the specified areas, and the orange line represents calculated LDF value.

The points below the orange line show us that using LDF for the whole mine makes us overestimate the safety factors in some local parts. In this scenario, especially for Area 1, it can be seen how the LDF overestimates the safety factor of local layout by almost 10%. Therefore, LLDF approach allows mine operators to assess the influence of spatial distribution large discontinuity sets on pillar stability explicitly and to estimate potential hazards in localized areas across the whole mine map.

3.3 Implementing LLDF to pillar stability analysis

The logic behind LLDF is nothing more than precise field observation and basic mathematics. The challenging part of implementing the LLDF is to define intersected pillars, find their safety factors, and replace them correctly with new safety factors. For this purpose, the combination of LaModel output and AutoCAD Integrated Stability Mapping Software methods are used. To perform stress-strength calculations, it is essential to use LaModel software for the most accurate results. Also,
the data of intersected pillars generally is stored in a grid format. This section discusses a detailed structure of implementing LLDF to pillar stability analysis.

3.3.1 Structure of the LLDF application methodology

For LLDF application into the mine layout, it is necessary to obtain the geological features from field surveying and mapping, the operational parameters from mine observations, overburden topography and pillar layout inputs from the mine surveyor. The AutoCAD and LaModel software have been chosen for the illustration and calculation parts of the application. The LLDF application follows the procedure shown in Figure 19.

![Data flow chart of LLDF application](image)

*Figure 19: Data flow chart of LLDF application.*
### 3.3.2 Data format and required data

Implementing LLDF to the mine layout requires all inputs and outputs to be in the same format or convertible to each other. The structure of a typical LaModel output file (.f1) is shown below:

```
1, 640000, 5, 800, 800, 1300, 1100
6, Seam Convergence, Total Vertical Stress, Overburden Stress, Element Strain SF, Pillar Stress SF, Pillar Strain SF
6, ft, psi, psi, Strain Safety Factor, Stress Safety Factor, Strain Safety Factor
0.0012269, 382.57, 378.68, 0, 0, 0
0.0012289, 383.21, 380.6, 0, 0, 0
0.0012323, 384.28, 382.52, 0, 0, 0
```

The values in the first line represent; the total number of mining steps in the model, the total number of points in the off-seam grid, the distance between grid points, the number of points along the x-axis, the number of points along the y-axis, the x coordinate of the origin of the off-seam grid, and the coordinate of the origin of the off-seam grid, respectively (Heasley, 1998). The second line represents the names of the calculated parameters, and the other lines represent each element where the numbers are calculated values for the parameters given in the second line.

A grid file (.grd) stores the x and y coordinates of an element with an assigned z value. The Z value can be any parameter depending on the user's different applications. The grid origin and dimensions are specified in the first six lines of a grid file. An example of a grid file (.grd) is shown below:

```
1100.000000
1300.000000
5100.000000
5300.000000
800
800
0.000000
0.000000
0.000000
....
```
• The first and second lines represent the Y and X coordinates of the lower-left corner of the grid, whereas the third and the fourth lines represent the Y and X coordinates of the upper right corner of the grid.
• The fifth and sixth lines are for the number of elements in the X and Y directions, respectively.
• The remaining lines are the Z values of the grid elements.

Unfortunately, LaModel output format (.f1) and AutoCAD Integrated Stability Mapping Software gridding output format (.grd) are different. LaModel gridding sequence starts from the left bottom of the grid and goes to upper elements till that element column ends. After the first column, it starts at the second column from the bottom and goes up again. Although the stability mapping sequence also starts from the left bottom of the grid, it goes from left to right and covers the last row of the mining grid. After the last column, it goes to the upper rows, one by one (Figure 20). Also, the backend coding of AutoCAD Integrated Stability Mapping Software gridding puts one more element at the end of every grid line. As a result, if we have an element size of x, $E_X$, and an element size of y, $E_Y$, the total number of elements in the AutoCAD gridding file will be $(E_X + 1) \times (E_Y + 1)$. Therefore, necessary conversions must be done before running the model. The python script is used for this purpose.

![LaModel and AutoCAD gridding sequences](image)

*Figure 20: LaModel and AutoCAD gridding sequences.*
3.3.3 Large discontinuity gridding and integrated stability mapping software application

Integrated stability mapping software is used to identify pillars that are intersected by a large discontinuity. Esterhuizen (2011) states that at least 30% of the pillars must be intersected by large discontinuities to be considered as an intersected pillar. Small intersections between discontinuities and pillars, on the other hand, only induce spalling failure and decrease the perimeter of the pillar. Geology-oriented modules enable us to define geologic properties or specific values as Z values on the mining map. The mine plan and discontinuities inside the mining area have already been defined. The pillars intersecting the discontinuities are marked manually in the AutoCAD software (Figure 21) where red lines represent the local discontinuities, and yellow boxes show the intersected pillars. Then those pillars are assigned with a constant number via the SMAP_SFACTORINAREA command. The module automatically assigns the number "100" as its default value. However, a specific number, such as the LLDF factor value, can be given if the user wants to indicate it in the grid file (Figure 22).

Figure 21: Mine plan and discontinuity AutoCAD drawing.
Figure 22: The application of SMAP_SFACTORINAREA command for intersected pillars.

The mine plan is shown in Figure 21 and Figure 22, with the red lines representing the local discontinuity lines, yellow hatched areas showing the intersected pillars, and black boxes showing the undisturbed pillars. It's important to remind that discontinuity must intersect at least 30% of the pillar to be considered as an intersected pillar.

After marking the intersecting pillars with integrated stability mapping software modules, we need to run the model one more time with the identification of intersected pillars. Figure 23 illustrates the pillar stress safety factor changes after running the model one more time with the implementation of LLDF.
Figure 23: Pillar stress safety factor output after identification of intersected pillars.

3.3.4 Software tool for LLDF implementation

The parameters of Eq. 25 were inserted into the python code. It calculates a pillar width-to-height ratio, reads the discontinuity dip angle, and then gets the corresponding coefficients from Table 4.

The python code includes the following steps:

- Read LaModel output file (.f1).
- Convert .f1 file into AutoCAD Integrated Stability Mapping Software grid format.
- Read AutoCAD Integrated Stability Mapping Software mine plan and intersected pillars (.grd).
- Define Local Large Discontinuity Factor .
- Match the safety factors in .f1 file with intersected pillars in grd file.
- Multiply the safety factors of the intersected pillars by LLDF.
- Generate a new grid file with new safety factors.
- Convert new grid file into LaModel output format (.f1).
- Generate a new .f1 file with new safety factors.
Figure 24 shows the flow chart of how python code implements a large discontinuity factor and inserts it into the output files.
Figure 24: Details of the generating new safety factor file by using Python code.
Chapter 4 Case Study

The proposed Local Large Discontinuity Factor (LLDF) and its associated software tool have been developed as a Python script program. In order to demonstrate the application of this new approach and tool, a simple case study has been performed with overburden topography, pillar layout, and geomechanical data from a case study mine, and theoretically generated fracture network that is representative of a realistic large discontinuity distribution from the formation of the case study mine. The case study was conducted in a mine extracting the Loyalhanna Limestone formation. First, general information about the case study mine and the associated limestone formation are presented. Then the integrated LaModel stress analysis, grid generation with the Integrated Stability Mapping Software, and application of the LLDF are presented.

4.1. Loyalhanna formation and case study mine layout

The local large discontinuity factor (LLDF) approach developed in this thesis is tested in an underground limestone case study mine. For applying the LLDF approach to an underground stone mine, first, stress and safety factor analysis with LaModel, using the cell strength equations derived by Escobar (2021), is necessary. The mine plan, the topographic map, pillar sizes, and UCS of the Loyalhanna Limestone formation were obtained from Escobar (2021). LLDF approach requires the knowledge of the distribution of large discontinuities on the mine layout. This information can be gathered from geological surveys or by using advanced surveying like UAVs or a robotic system (Bendezu, 2021; Bishop, 2022). In this thesis, a theoretical distribution was generated for the mine layout to demonstrate the LLDF approach. This theoretical large discontinuity distribution was selected according to observations of Esterhuizen et al. (2011) and the characteristics of the formation.

4.1.1. Loyalhanna formation

The Loyalhanna Limestone spreads out 17,000 miles of West Virginia, Southern Pennsylvania, Maryland, and Ohio, and it is a lower member of the Mississippian-age Mauch Chunk Formation and is characterized by broad folding with dips ranging from 20 to less than 5 degrees (Edmunds et al., 1979). The maximum thickness of the formation is 103 feet, with an average thickness of 60 feet. Even though there are outcrops at different places in Northeastern West Virginia and
Southwestern Pennsylvania, the main part of Loyalhanna Limestone underlies deeper than a thousand feet (Iannacchione & Coyle, 2002).

Shaffner (1958, 1963) and Hickok and Moyer (1940) reported six major faults in the mining area as shown in Figure 25. Iannacchione et al. (2002) states that discontinuities have the potential to adversely affect ground control conditions on Loyalhanna formation. The discontinuities can cause ground control problems ranging from small rock falls to large roof collapses (Figure 26), or even pillar failures.

Figure 25: Structure contour map of the topographic features on Loyalhanna (Iannacchione & Coyle, 2002).
4.1.2. Case study mine layout

Escobar (2021) applied his cell strength equations for simulating the stone mine pillar strength and stress-strain response in the case study mine. The following parameters and assumptions were used in this study. The case study mine is regarded as a flat-lying mine with a dip angle of less than 5°. The case study mine pillar layout consists of square development and benched pillars with approximately 50 ft x 50 ft dimensions. In different areas, there are development and benched pillars with a width-to-height ratio of 1.85 and 1.0, where the width is approximately 50 ft and the height is either 27 ft or 50 ft (Escobar, 2021). 5 ft element size is used in the study and one linear elastic, and 16 elastic plastic in-seam materials are defined in LaModel for simulating development and benched pillars. The average Uniaxial Compressive Stress test results of the Limestone formation is 29,401 psi, which is in the range of expected values of 29,000 psi - 32,000 psi for the Loyalhanna formation (Esterhuizen et al., 2011). Also, the maximum overburden depth is estimated as 675 ft from the topographic and seam elevation contour maps. The pillar layout is shown in Figure 27.
4.2. Implementing Local Large Discontinuity Factor (LLDF) to case study mine

LaModel was used to compute the safety factor of the mine pillars by simulating the strength of complex pillar geometries with the empirical stone mine pillar equation (Esterhuizen et al., 2011; Escobar, 2021). All the mine parameters and the mine grid are input into LamPre and the input file for LaModel is created. After the input file is successfully read by LaModel, it calculates the stress and displacement on the seam elements (Heasley, 1998). The post-processing program, LamPlt, allows the visualization of the LaModel stress analysis outputs. Figure 28 illustrates the overburden stress distribution with topography contours of the case study mine Figure 29 illustrate the total vertical stress on the seam. The factor of safety of the pillars calculated by LaModel are shown in Figure 30. The green section in Figure 28 shows that the overburden stress is higher in the deepest sections of the mine. Related to this, it can also be seen that the increase in the total vertical stress and the decrease in the factor of safety are related to the depth of the mine.
Figure 28: Overburden stress distribution (psi) with topography contours.

Figure 29: Total vertical stress distribution (psi).
A theoretical large discontinuity distribution (red lines in Figure 31), generated by Discrete Fracture Network (DFN) option of FLAC3D software, and a grid file for intersected pillars (yellow pillars in Figure 31) are generated using the integrated stability mapping software to implement LLDF calculations in the case study mine. Large discontinuities are distributed using the negative exponential distribution on the area of mine grid to give average frequency factor of 0.1 large discontinuities per pillar (Esterhuizen et al, 2011). Dip of the large discontinuity set was set to 60° and strike of the large discontinuity set was defined as approximately N 45° E based on the observations of lannacchione and Coyle (2002). There are 55 intersected pillars over 525 total development pillars. Integrated stability mapping software identifies pillars that are intersected by the large discontinuities and generates the LLDF grid file by using the area-based step transformation method as described in Chapter 3 of this thesis.
The computer code developed in this study reads LLDF grid and LaModel output files and finds the intersected pillars in the LaModel output file by taking the grid file as a reference. The discontinuity dip factors (Table 4) are encoded on the code, and user is required to enter dip angle of the large discontinuity set and pillar width-to-height ratio to run the code. By entering the necessary input parameters and selecting the LLDF grid file, the code applies discontinuity dip factors to the intersected pillars and calculates new safety factors. After this calculation, the code updates the pillar safety factors in the LaModel output file to generate the final pillar stress safety factor output. This final output file is suitable for visualization in both AutoCAD and LaModel software. Final stage of the LLDF approach is to select the local area on the mine pillar layout to calculate the average safety factor of the pillars in the specified location.

To be able to better illustrate the LLDF approach, calculations are demonstrated on a local area in the case study mine pillar layout that consists of 21 pillars as shown in Figure 32. Figure 33 shows
the LaModel safety factor plots which illustrate the difference between the scenarios: on the left before LLDF is applied and on the right after LLDF is applied.

![Image](image1)

*Figure 32: Illustration of the mine layout to exemplify the LLDF factor*

As seen in Figure 33, the safety factor reduction is applied to the intersected pillars, and safety factor of the pillars are reduced approximately 40%. LLDF approach allows the mine engineers to identity potential hazards due to the large discontinuities by explicitly considering the spatial distribution of the large discontinuities in a mine layout, whereas S-Pillar software LDF factor averages the influence of large discontinuities along the whole mine layout.
4.3. LDF and S-Pillar comparison

In the previous section, the concept of LLDF is applied to a case study mine, and in this section, LLDF results are compared with S-Pillar’s LDF approach. For LDF comparison, five local areas within the mine are arbitrarily selected as shown in Figure 34.

Table 6 summarizes the parameters of the pillars in these areas. As stated in the previous section, frequency of large discontinuities per pillar is theoretically selected as 0.1, and discontinuity dip factor is assigned to 0.34 (pillar width-to-height ration of 1.0 and dip angle of 60°). We can calculate the LDF of the mine layout using Eq. 17 as:

\[
LDF = 1 - 0.34 \times (1 - e^{-0.1}) = 0.97
\]
Therefore, in S-pillar approach for the given parameters of this case study, safety factor of the pillars is reduced by 3% in average. The LLDF is computed for five local areas using Eq. 26. As observed in Table 7, even though the difference between LLDF and LDF are not high for this case study with maximum difference of -7%, results demonstrate the potential benefit of LLDF approach for identifying potentially hazardous locations on a mine plan.

Figure 35 illustrates the differences of the LDF and the LLDF where the orange line represents the LDF equal to LLDF values and blue points are the LLDF coefficients.
Table 6: The parameters of the pillars in the selected areas

<table>
<thead>
<tr>
<th># of intersected pillars</th>
<th>Total pillars in the area</th>
<th>Width to height ratio</th>
<th>DDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area 1</td>
<td>2</td>
<td>20</td>
<td>1</td>
</tr>
<tr>
<td>Area 2</td>
<td>4</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>Area 3</td>
<td>5</td>
<td>21</td>
<td>1</td>
</tr>
<tr>
<td>Area 4</td>
<td>4</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>Area 5</td>
<td>1</td>
<td>28</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7: The comparison between LDF calculations and LDF calculations

<table>
<thead>
<tr>
<th># of intersected pillars</th>
<th>Total pillars in the area</th>
<th>LLDF calculations</th>
<th>LDF calculations</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Eq 26 $LLDF_{mean}$</td>
<td>Eq 17 LDF</td>
<td></td>
</tr>
<tr>
<td>Area 1</td>
<td>2</td>
<td>$LLDF_{mean} = \frac{(0.66 \times 2) + (1 \times (20 - 2))}{20}$ = 0.97</td>
<td>$LDF = 1 - 0.34 \times (1 - e^{-0.1}) = 0.97$</td>
<td>0.00%</td>
</tr>
<tr>
<td>Area 2</td>
<td>4</td>
<td>$LLDF_{mean} = \frac{(0.66 \times 4) + (1 \times (15 - 4))}{15}$ = 0.90</td>
<td></td>
<td>-7.00%</td>
</tr>
<tr>
<td>Area 3</td>
<td>5</td>
<td>$LLDF_{mean} = \frac{(0.66 \times 5) + (1 \times (21 - 5))}{21}$ = 0.92</td>
<td></td>
<td>-5.00%</td>
</tr>
<tr>
<td>Area 4</td>
<td>4</td>
<td>$LLDF_{mean} = \frac{(0.66 \times 4) + (1 \times (16 - 4))}{16}$ = 0.91</td>
<td></td>
<td>-6.00%</td>
</tr>
<tr>
<td>Area 5</td>
<td>1</td>
<td>$LLDF_{mean} = \frac{(0.66 \times 1) + (1 \times (28 - 1))}{28}$ = 0.99</td>
<td></td>
<td>+2.00%</td>
</tr>
</tbody>
</table>
Figure 35: The illustration of the comparison between LLDF and LDF
Chapter 5 Conclusion and Future Studies

5.1 Summary
The underground stone mine design guidelines published by National Institute for Occupational Safety and Health (NIOSH) pointed out the importance of large, angular discontinuities on pillar strength. Esterhuizen et al. (2011) derived the Large Discontinuity Factor (LDF) to incorporate average influence of large discontinuity distribution throughout the whole mine on pillar layout design. They recommended using the maximum depth over the pillar layout to calculate pillar loads and indicated that S-Pillar approach is valid only for regularly sized pillars. Escobar (2021) improved this approach to integrate accurate overburden stress distribution under variable topography and irregular pillar layouts. His derived equations are implemented in the Boundary Element Method (BEM) software LaModel (1998) for the stress and stability analysis.

In this study, the new term Local Large Discontinuity Factor (LLDF) is proposed to explicitly account for the impact of large discontinuities on local intersected pillar stability. The LLDF enables the miners to incorporate impact of spatial distribution of large discontinuities on the pillar stability and to identify the hazards in local areas on the mine layout. The software tool developed in this thesis incorporates the large discontinuity impacts, overburden stress distribution under variable topography, and irregular pillar layouts by utilizing: LDF, AutoCAD ObjectARX add-in Integrated Stability Mapping Software (ISMS), and LaModel software. The ISMS step transformation function is used to identify the pillars intersected by the large discontinuities and to generate the LLDF grid of the intersected pillars. LaModel is used to compute the safety factor of the stone mine pillars by simulating the strength of complex pillar geometries with the empirical stone mine pillar equation (Esterhuizen et al., 2011; Escobar, 2021). The software tool uses the LLDF grid and LaModel output files to generate the final pillar stress safety factors, which can be visualized in AutoCAD. After the development of the software tool, a case study was performed to demonstrate the application and usefulness of this new engineering tool.

5.2 Conclusion
The software tool with LLDF integration is applied on both created scenarios and an underground stone mine. The generated scenarios prove the theoretical logic behind the Local Large Discontinuity Factor which enables the mine operators to apply the Large Discontinuity Factor in
specific areas in a more accurate way. Then, the case study demonstrates the feasibility of the software tool. The software tool finds the LLDF factor according to mine parameters, converts the input files (.f1 and .grd) into the same format and gives correct results in both of the formats. The results are compared with LDF calculations, although there isn’t such a large difference between the LLDF and LDF results for the case study mine, results demonstrated the potential impact of applying LLDF on stone mine pillar stability.

In this research, it is pointed out that a single factor, LDF, may lead to an overestimation of safety factors in some localized areas. The term LLDF and the software tool will be a good fit to avoid this problem. LaModel and AutoCAD plots obtained by outputs enable the miners to elaborate the mine design on the specific local areas. Implementation of the software tool will improve measures to address pillar failures and provide safer mine operations. LLDF makes it possible to know more about the effects of discontinuities, predict future scenarios and provide a safer environment for miners. Overall, this new engineering tool and the term LLDF is feasible, useful, reliable and will be a good fit for the industry.

5.3 Suggestion for future studies

The software tool gives the LaModel and AutoCAD outputs to display the implementation of LLDF. The miner has to check the input files and decide on the reliability of the output file by itself. The user is responsible for the consistency of data. Currently, the software tool doesn't have any user guide or interface that can warn the user of any unexpected condition. This software is coded as running with the correct inputs, without any problem, and when the input files perfectly match with each other. To avoid any undesirable circumstances, a user friendly interface can be developed, or the code can be inserted into LaModel software. In addition, in this thesis, only one joint set is simulated, code developed in this thesis can be improved to incorporate multiple joint sets.
REFERENCES


Li, K. (2016). Implementing the Local Mine Stiffness Calculation in LaModel (Order No. 10246805). Available from Dissertations & Theses @ West Virginia University; ProQuest Dissertations & Theses Global.


http://filebox.vt.edu/j/jjmartin/preventcollapse.pdf