DEVELOPMENT OF A STABILITY MAPPING PLATFORM FOR STONE MINES THAT WILL COMBINE NUMERICAL MODELING AND EMPIRICAL CRITERIA

Synopsis: Provide a one-page synopsis that includes: 1) Problem Statement, 2) Research Approach, and 3) Impact of the Research.

Problem Statement

Underground stone mining represents around 21% of the total underground mining operations in the United States (NIOSH, 2021). In 2019 more than 2000 people worked in underground stone mining (NIOSH, 2021). Approximately 40% of fatalities have been linked with falls of ground from roofs and pillars in underground stone mines since 2006, and the time lost related to ground control issues represents about 15% of the total lost working days in underground stone mining (MSHA, 2016). In the U.S., the S-Pillar program was developed by the National Institute for Occupational Safety and Health (NIOSH) to assist in designing stable pillars in underground stone mines (Esterhuizen et al., 2011). S-pillar considers the influence of a large joint set intersecting a pillar on the stability of the pillar. This approach does not consider the relative location of geological structures with respect to pillars or that multiple joint sets may intersect a pillar. Therefore, the S-Pillar program can be further improved by extending the stability analysis of pillar systems to variable topographies and geometries.

In addition, there has not been any roof support design tool accepted by stone mine operators. Geological structures play an important role in the stability of the roof strata and operators generally decide, based on their experience in the mine, to support a roof if they encounter a geological structure. NIOSH roof span design guidelines recommend stone mine operators should conduct detailed geotechnical characterization of the mine since the discontinuities play a major role in roof stability and should monitor changes in rock mass conditions. Therefore, successful roof support design depends on accurate identification of the geological structures and recognition of the adverse changes in rock mass conditions in the stone mines, and failure to recognize these hazards caused many massive roof fall accidents, the most recent fatal accident happened on January 2022 in the mine operating in Loyalhanna formation.

Research Approach

The ultimate goal of this project is to develop a stability mapping platform (software package) that is independent of the AutoCAD package which allows mine operators to assess both stone mine pillar and roof stability to identify potential hazard zones in the mine. This project team will pursue two main objectives. The first objective is related to the development of a stand-alone user-friendly software tool based on the Microsoft Windows platform that will comprise the stability mapping platform. The platform will allow for different inputs layers that would be combined to present an overall stability map of each project. The second objective relates to a research component that will target (i) extension of the stone mine pillar concentric zone capacities derived by Escobar and Tulu (2021) to semi benched pillars, (ii) development of laminated overburden model calibration method for stone mine stress analysis, and (iii) development of simplified stone mine roof hazard index that would be a function of horizontal stress, discontinuity condition, roof beam thickness, and pillar stability.

Impact of the Research

Mine operators and stakeholders will be able to visualize stability indices that pertain to pillars, the roof and other components of underground openings to make informed decisions on mine and structure stability. The new stability mapping platform (StabMap) will be a tool provided for free to the mining and geotechnical community. The tool will be made available through a website.Problem Statement and Background: Provide a concise and specific statement (not more than a few sentences) of the problem that is being addressed. Follow this with a discussion of the context of the problem and its relevance to existing mine health and safety issues. Link the focus to one of the Foundation's research topics and associated priorities as designated on the Foundation's website.

Problem Statement

Underground stone mining represents around 21% of the total underground mining operations in the United States (NIOSH, 2021). In 2019 more than 2000 people worked in underground stone mining (NIOSH, 2021). Approximately 40% of fatalities have been linked with falls of ground from roofs and pillars in underground stone mines since 2006, and the time lost related to ground control issues represents about 15% of the total lost working days in underground stone mining (MSHA, 2016). Five massive pillar collapses (Crab Orchard Mine – August 2021, Torrance mine - November 2020 and July 2021, Subtropolis Mine – October 2020 and Whitney Mine – May 2015) occurred between 2015 to 2021 in older workings of active limestone mines. 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.

In the U.S., the S-Pillar program was developed by the National Institute for Occupational Safety and Health (NIOSH) to assist in designing stable pillars in underground stone mines (Esterhuizen et al., 2011). S-pillar considers the influence of a large joint set intersecting a pillar on the stability of the pillar. This approach does not consider the relative location of geological structures with respect to pillars or that multiple joint sets may intersect a pillar. Moreover, 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). Currently, the S-Pillar program calculates the stability factor of underground stone mines by assuming that the full weight of the overburden is evenly distributed among the pillars and is only valid if large areas are mined using regularly-size pillars (Esterhuizen et al., 2011). In addition, there are not any roof support design guidelines available for stone mine operators. Geological structures play an important role in the stability of the roof strata and operators generally decide based on their experience in the mine to support a roof if they encounter a geological structure. Therefore, the S-Pillar program can be further improved by extending the stability analysis of pillar systems to variable topographies and geometries. Overlaying the map of the geological structures with the factor of safety and stress plots generated by LaModel can further improve both global and local roof stability of the stone mines and improve the safety of miners working in this sector.

Background

Pillar Design: The S-Pillar program was developed by the National Institute for Occupational Safety and Health (NIOSH) to assist in designing stable pillars in underground stone mines (Esterhuizen et al., 2011). The S-Pillar program is used to calculate the stability factor of limestone (stone) pillars and compare this stability factor with historical data to guide mine engineers to select suitable pillar sizes that will ensure the local and global stability of the mine.

Esterhuizen et al. (2011) collected operational information, such as excavation dimensions, pillar stability data, rock jointing data, and rock mass classification data from 34 underground limestone mines in the U.S. From the information collected, they determined that from the 91 pillar layouts surveyed, just 18 individual pillars were considered failures. The 18 failed cases were assessed visually, and the modes of pillar instability were categorized as either crushing or structure-controlled failure. Then, they developed an empirical equation that estimates the strength of pillars in underground stone mines and that accounts for strength reduction due to large discontinuities.

In 2015, the first major stone mine pillar collapse since the development of the NIOSH design guidelines, the Whitney mine collapse, occurred. Esterhuizen et al. (2018) performed a detailed analysis of the incident and concluded that without considering the large discontinuities observed in the mine, pillar strength equations would significantly over-estimate the strength of the collapsed pillars. Based on their conclusions, accurate identification and mapping of the geological structures will improve the safety of the miners. Since 2015, four more major pillar failures and a fatality due to a massive roof fall were reported in the stone mines.

In 2019, the Alpha Foundation funded a project at West Virginia University entitled "Autonomous Robotic Early Warning System for Underground Stone Mining Safety". In this project, which aimed to improve the safety of underground limestone mines by extending the application of the S-Pillar stone pillar strength equation to Boundary Element Method (BEM) software, the gradient stress equation for stone mine pillars and the function of pillar width-to-height ratio, were derived from the empirically-based S-Pillar strength equation (Escobar and Tulu, 2021). This is essentially the same approach used by Heasley (1998) to numerically simulate the empirical coal strength equation in LaModel. Heasley et al. (2010) indicated that the integration of empirical coal strength equation in LaModel allows empirical pillar stability analysis to be extended over complex mine geometries and variable topography.

The gradient stress equations for the stone mine pillars were derived by following similar approaches to those presented by Mark (1992) and Johnson et al. (2014). In these approaches, it is assumed that the variation of stresses within the pillar is a function of distance to the closest rib. The stress gradient function provides the stress distribution within the pillar and is used to derive concentric rings (zones) to simulate stone mine pillar yielding in the boundary element software. This stress gradient function assumes that there are no large discontinuities present and that discontinuities do not have an impact on the strength calculation. Escobar and Tulu (2021) demonstrated that together with the stability mapping software, this new approach can be used to simulate the effect of variable topography and irregular size pillars on the stability of stone mine pillar layouts (Figure 1).

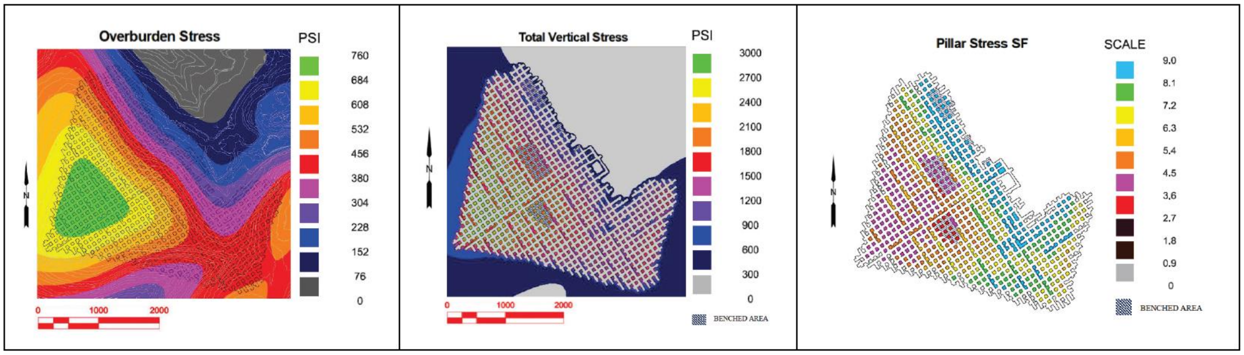
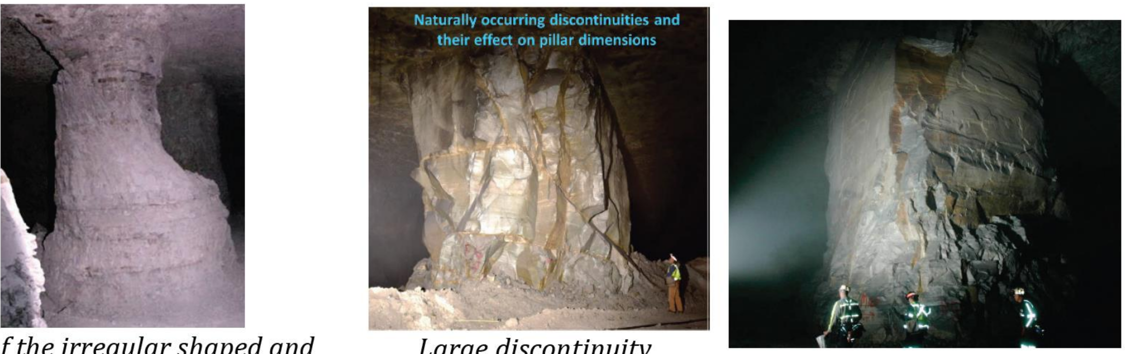


Figure 1. (a) Overburden stress distribution (b) vertical stress distribution (c) stone mine pillar safety factors.

The Mine Safety and Health Administration (MSHA, 2021) indicated that it is not possible to predict when, or even whether, a particular pillar or group of pillars would collapse, but it is possible to recognize hazards that might increase the likelihood of these massive collapses. MSHA (2021) listed the following hazards that might cause pillar collapses: (i) irregular undersized pillars due to surveying or blasting errors, (ii) ignored or unrecognized geological features (joints, weak bedding planes, etc.) on the pillars that might reduce pillar stability or induce rib falls and (iii) potential weaknesses of tributary area loading approach.



One of the irregular shaped and undersized pillars that failed during a recent mine collapse

Large discontinuity intersecting a pillar at the Whitney mine.

Rib failure due to a joint intersecting the pillar.

Figure 2. Hazards that might lead to injuries and fatalities (after MSHA, 2021)

In two of the five recent massive pillar collapses, operators were benching the sections nearby the collapsed area (Figure 3a). During the development of NIOSH design guidelines, one of the collapsed mines was visited by NIOSH, and pillars in the older workings were photographed (Figure 3b). It is clear from the figure that many of these pillars are irregularly shaped and hence not suitable for the tributary area assumption.

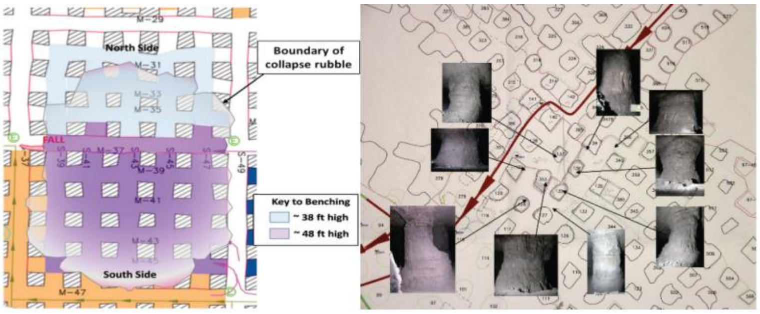


Figure 3. (a) Pillar layout of a collapsed area and (b) irregular pillars from another collapsed mine.

Roof Design: Esterhuizen et al. (2011) stated that in underground stone mines, rooms are on average 44-ft wide, and the desired roof span dimensions are generally predetermined by the operational requirements, the size of the mining equipment, etc. Roof design is generally focused on optimizing the stability of the roof under the usual rock mass conditions. Unsupported roof is common in underground stone mines due to the inherently strong rock mass of these mines. Operators generally support the roof based on their experience in the mine if they encounter a geological condition or geological structure.

Esterhuizen et al. (2011) proposed a combined empirical and analytical approach for stone mine roof span design that relies on information collected on past performance of 34 different stone mines in the Midwest and Eastern US where rock formation consists of bedded stone deposits. The collected rock mass conditions, discontinuities, roof span dimensions, support methods, and factors that contributed to instability were recorded during the field visits. Supplemental data on defects within the roof were collected using a borehole video camera at 13 different mines; roof monitoring data from 15 different mine operations were considered.

Esterhuizen et al. (2011) stated that large roof falls were observed at 19 mine operations visited and made up a small percentage of the exposed roof in the mines. They assessed that high horizontal stress contributed to 36%, failure of the weak band / parting plane within the roof beam contributed to 28%, large discontinuities contributed to 21% and failure of weak immediate roof strata contributed to 15% of all roof falls. They stated that pillar layout can have a significant impact on roof stability and recommended that pillar and roof design guidelines should be considered together to produce a stable overall mine layout. The following roof design guidelines were recommended by NIOSH:

- Since discontinuities play a major role in stability, a geotechnical characterization of the mine should be conducted.

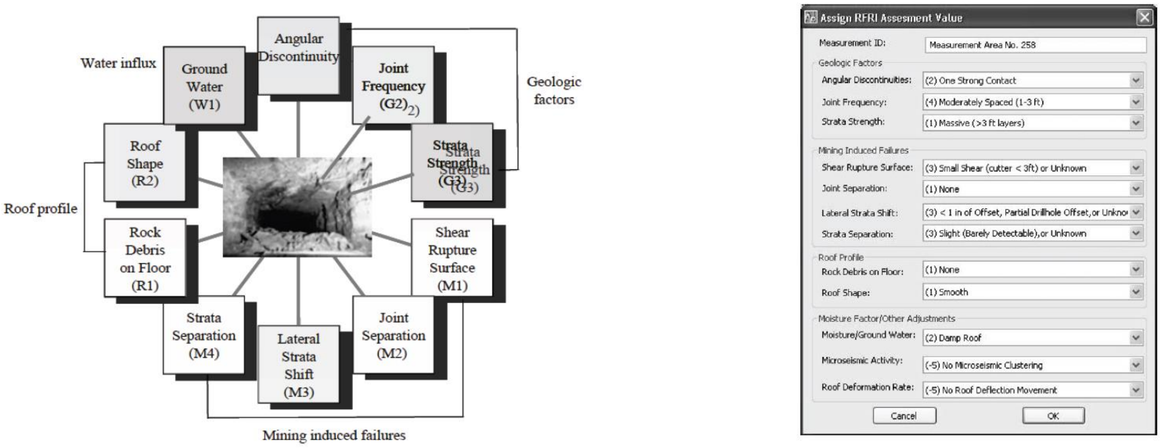
- The location of the roofline relative to pronounced bedding planes or lithology changes should be identified next. Experience has shown that if the immediate roof beam is less than 1.2 m (4 ft) thick, it is highly likely that it will be unstable.

- The direction of the headings in the production areas should be favorably oriented to any expected horizontal stress and the prevalent jointing.

- The NIOSH stone mine pillar design guidelines should be followed.

- The roof stability mapping method, Roof Fall Risk Index (RFRI), proposed by Iannacchione et al. (2007) should be used to monitor changes and verify rock mass conditions.

RFRI was developed by Iannacchione et al. (2007) for determining potential higher roof fall risk areas due to geologic factors, mining-induced failures, roof profile, and groundwater influx. Figure 4a. shows the factors used to calculate the RFRI value. In the field, mapped sections of the mine are divided into small measurement areas i.e., 50 x 50 ft, where RFRI is considered uniform (Bajpayee and Schilling, 2009). RFRI was programmed to the stability mapping program by Dr. Keith Heasley and for a specific polygon that represents the measurement area. A form-based application can be used to input RFRI survey data.



Measurement ID: Measurement Area No. 258

Geologic Factors
Angular Discontinuities: (2) One Strong Contact
Joint Frequency: (4) Moderately Spaced (1-3 ft)
Strata Strength: (1) Massive (>3 ft layers)

Mining Induced Failures
Shear Rupture Surface: (3) Small Shear (cutter < 3ft) or Unknown
Joint Separation: (1) None
Lateral Strata Shift: (3) < 1 in of Offset, Partial Drillhole Offset,or Unkno
Strata Separation: (3) Slight (Barely Detectable),or Unknown

Roof Profile
Rock Debris on Floor: (1) None
Roof Shape: (1) Smooth

Moisture Factor/Other Adjustments
Moisture/Ground Water: (2) Damp Roof
Microseismic Activity: (-5) No Microseismic Clustering
Roof Deformation Rate: (-5) No Roof Deflection Movement

Figure 4. (a) RFRI parameters and (b) stability mapping RFI input form.

Project Goals and Specific Aims: Provide a clear description of what is expected to be achieved with this project at its completion and what specific aims will be used to facilitate achievement of these goals. The overall goal of the project is to develop a stability mapping platform in the form of a software package that will be standalone and independent of the AutoCAD platform. The stability mapping package will be geared towards mapping the stability of pillars and roof for underground stone mines. Import and export routines from and to AutoCAD or CAD like platforms will be provided through the Drawing Interchange Format (DXF) which is an industry standard for exchanging information between cad platforms. The main objectives of the project are given below and also explained under “Research Execution Plan and Timeline” below. This project team will pursue two main objectives. The first objective is related to the development of a stand-alone user-friendly software tool based on the Microsoft Windows platform that will comprise the stability mapping platform. The platform will allow for different inputs layers that would be combined to present an overall stability map of each project. The second objective relates to a research component that will target (i) extension of the stone mine pillar concentric zone capacities derived by Escobar and Tulu (2021) to semi benched pillars, (ii) development of laminated overburden model calibration method for stone mine stress analysis, and (iii) development of simplified stone mine roof hazard index that would be a function of horizontal stress, discontinuity condition, roof beam thickness, and pillar stability.

Research Approach: The primary requirement is to explain in simple terms your research strategy for accomplishing the project specific aims. Essentially, summarize how you are going to address this problem. Within this context, a description of the research methodology, study design, modeling approach, and/or experimental plan relating to the generation and analysis of data and any underlying assumptions that are related to this process can be provided. If the proposed research will involve any human subjects, the proposal must describe the steps that will be taken to ensure human subject protection.

The research approach comprises of five objectives as listed below. Tasks per objective are detailed in the next section.

Objective 1: Perform Background Research and Application Design

Objective 2: Develop Appropriate Tools and Populate the Application with Data

Objective 3: To Perform research with respect to Extending the Laminated Overburden Model for Stone Mine Stress Analysis.

Objective 4: To Test the Stability Mapping Application

Objective 5: To manage the project and disseminate the results

Objectives 1 and 2 are related to application development. Objective 3 will be completed by WVU through a subaward. Objective 4 relates to internal and external testing of the application and Objective 5 includes all project management and dissemination activities.

The following section provides an overview of research objective 3 and its related tasks. This research objective consists of a post-processing task, a laminated overburden model development task, a geomechanical analysis task, and a statistical analysis task. More details for each task are given in the next section.

During the post-processing task: field data collected by WVU and VT autonomous systems data from stone mines will be post-processed to extract the necessary data for this project. In each mine visit, a 3D map of the pillar layout and high-resolution 3D point clouds maps of the pillars and roof will be generated. The research team will also map outcrops using the UAVs. 3D point clouds will be used in the post-processing phase to identify the geological structures on the rock mass. In addition to the point-cloud data, the research team will collect rock samples that will be used to characterize the intact rock properties by laboratory tests. This geological and laboratory test information will be used to characterize each pillar and the local rock mass of the case study mine formation using the rock mass rating systems.

During the laminated overburden model development task: the stone mine pillar stress gradient equation derived by Escobar (2021) will be extended to the semi-benched pillars. In this task, also the laminated overburden model and benched pillar stiffness calibration methods, and stone mine benched pillar griding logic that will be integrated into the stability mapping will be developed.

During the geomechanical analysis task: rock mass characterization, pillar layout, topography, and other related operation parameters will be used to perform stress, ground response, and geomechanical analysis of the pillar and roof system for each case study mine.

In the statistical analysis task: the data generated in this project will be processed with existing integrated stability mapping approaches to develop parameter grids over the mine layout, and these parameter grids will be used in statistical analysis to develop design guidelines for recognizing hazards that might increase the possibility of massive pillar and roof collapses.

Research Execution Plan and Timeline: This section is to provide a blueprint for how the research will be conducted. If appropriate, the research plan should be presented in phases which provide logical stages of research that serve as prerequisites for advancing to the subsequent phase. This blueprint must be in the form of a set of objectives related to the specific aims and associated research tasks necessary to achieve these.

- Objectives provide direction to the project and are precise statements that concisely describe what the research is trying to achieve in a particular segment of the work. They are usually headed by infinitive verbs such as: To identify, To establish, To describe, To determine, To estimate, To develop, To compare, To analyze, To collect, etc. These objective statements should be fairly self-explanatory but may be accompanied by a short paragraph if necessary, to fully convey their meaning.

- Research tasks are a group of logically connected activities or undertakings that must be done to achieve a specific objective. A full description of the effort associated with each research task must be provided so that a clear understanding is presented of what is being done and how it is being done.

Identify the desired start date and provide a monthly timeline depicting a planned schedule by Phase if appropriate and objective and research task in the form of a Gantt chart or similar graphical display.

Objective 1: To Perform Background Research and Application Design

Task 1.1: Background research. In this task, analysis of the features of the current (AutoCAD-based) stability mapper will be combined along with an exhaustive literature review on what is the best way to represent and manage the data needed for stability mapping. The current stability mapper imports data from LaModel output and generates entities in the AutoCAD environment. The process needs to be replicated every-time when there is a change in the parameters of the data. This task will establish suitable procedures for managing both input and output data and for querying the dataset for appropriate data, the identification and modeling of trends. The end of Task 1.1 coincides with Milestone 1 (M1).

Task 1.2: Design of the database-driven application to ensure optimum performance as well as reliable data storage and retrieval. The application will include a database-driven back end that will allow efficient data management. In addition, a project and scenario-based structure will be built into the platform. The platform will allow for different inputs layers that would be combined to present an overall stability map of each project. In this task, the main component of the application will be designed. Data management will be optimized for the particular application. Appropriate data indices will be developed to ensure fast and reliable system response. Grouping queries will be developed so that data can be quickly retrieved. LaModel output data which will serve as input data in this application will also be stored along with the parameters used to process such data.

The application will be packaged in a self-extracting installer. It will also feature a versioning system so that it can automatically update itself by connecting to a particular web page. The application will come bundled with a help subsystem, but in CHM and PDF formats. CHM files provide local context sensitive format while the PDF file will be easily printable.

Objective 2: To Develop Appropriate Tools and Populate the Application with Data

Task 2.1: Develop appropriate import routines. In this task, appropriate import routines will be developed to allow importing data from different environments. This will include importing of the F1 file generated by LaModel as well as other data that will be needed to create the background information for the stability mapping tool. The procedures will be automated in order to reduce operator error and ensure as much as possible a seamless integration with existing packages. Import routines will check for invalid or null data to minimize data management issues. For example, invalid data correspond to “out of range” data, alphanumeric characters in numeric fields, etc.

Task 2.2: Develop appropriate export routines. In this task, appropriate export routines will be developed to allow exporting data to AutoCAD and other environments. Appropriate windows-based components will be purchased that allow managing map-like data structures on a windows platform. These components provide export utilities. Routines will be written that take advantage of these export utilities to export data in universal formats such as DXF (drawing interchange format). DXF formatted files can be imported in any CAD package.

Task 2.3: Create database management tools and populate the database with data necessary to run the program. In this task, database management tools will be created that will allow project management, scenario management as well as management of general data in the database. Depending on the outcome of the research component of this project, data for different US regions may need to be created and be available to the user. Many mining applications include different datasets for different US regions. In addition, a tool will be created to allow updating of the user database when needed without affecting existing projects.

Task 2.3: Create database management tools. In this task, database management tools will be created that will allow project management, scenario management as well as management of general data in the database. In addition, a tool will be created to allow updating of the user database (if and when needed) without affecting existing projects.

Task 2.4: Populate the database with data developed with respect to pillar and roof stability. In this task, the database management tools and import/export tools created in previous tasks will be used to populate the database driven application with appropriate data. Depending on the outcome of the research component of this project, data for different US regions may need to be created and be available to the user. Many mining applications include different datasets for different US regions. The data will be developed by WVU through the subaward to this project. Frequent online and in-person meetings will ensure that data are developed in appropriate format(s).

Objective 3: To Perform Research with Respect to Extending the Laminated Overburden Model for Stone Mine Stress Analysis.

Task 3.1: Post-processing of the autonomous mapping and field survey data. In this task, field data collected by VT and WVU teams will be processed to extract the datasets of parameters that will be used to generate parameter grids in the statistical analysis and the development of the design guidelines. There are five companies openly supporting the autonomous UAV and robotic system inspections proposal by WVU and VT by providing mine access: Argos USA, Carmeuse Americas, Lhoist North America, Vulcan Materials, and Nyrstar. During the mine visits, the following data will be collected and will be available for this project:

3D point cloud data from LIDAR and/or photogrammetry scans: There will be two different point cloud data sets available for the autonomous robotic scans. The first set will be lower resolution LIDAR data that would be collected by the UGV or UAV during the autonomous navigation (Figure 5-left). This lower resolution data will be used to compute the dimensions of the surveyed rooms and pillars (Figure 5-middle), roof spans, and bolting patterns (Figure 5-right).

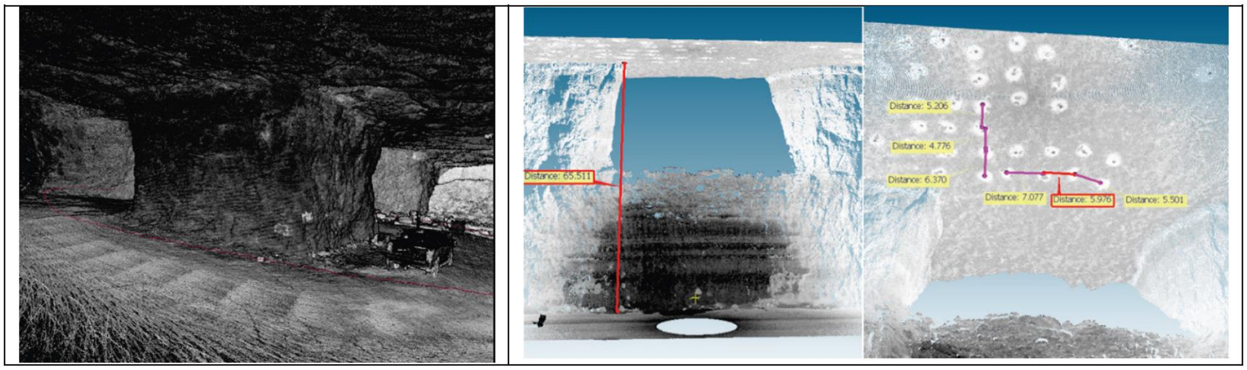


Figure 5. Low resolution LIDAR data.

The second set of point cloud data will be a high-resolution data sets as shown in Figures 6 and 7. This data will be used to evaluate the rock mass by extracting the discontinuity sets on the roof and pillar. The following information will be gathered from the field surveys: orientation, spacing, persistence, roughness, aperture or filling (if applicable) of the discontinuities, and number of discontinuity sets. During the field visits, if water flow or free moisture would be visible, this information will be noted separately. In this study, since the full three-dimensional view of the rooms and pillar will be available, 2D and/or 3D (number of fractures in an area or volume) discontinuity measures will be used to characterize the rock mass of the formation. In addition to the underground surveys, high resolution point cloud data of the outcrops will be available from the UAV surveys.

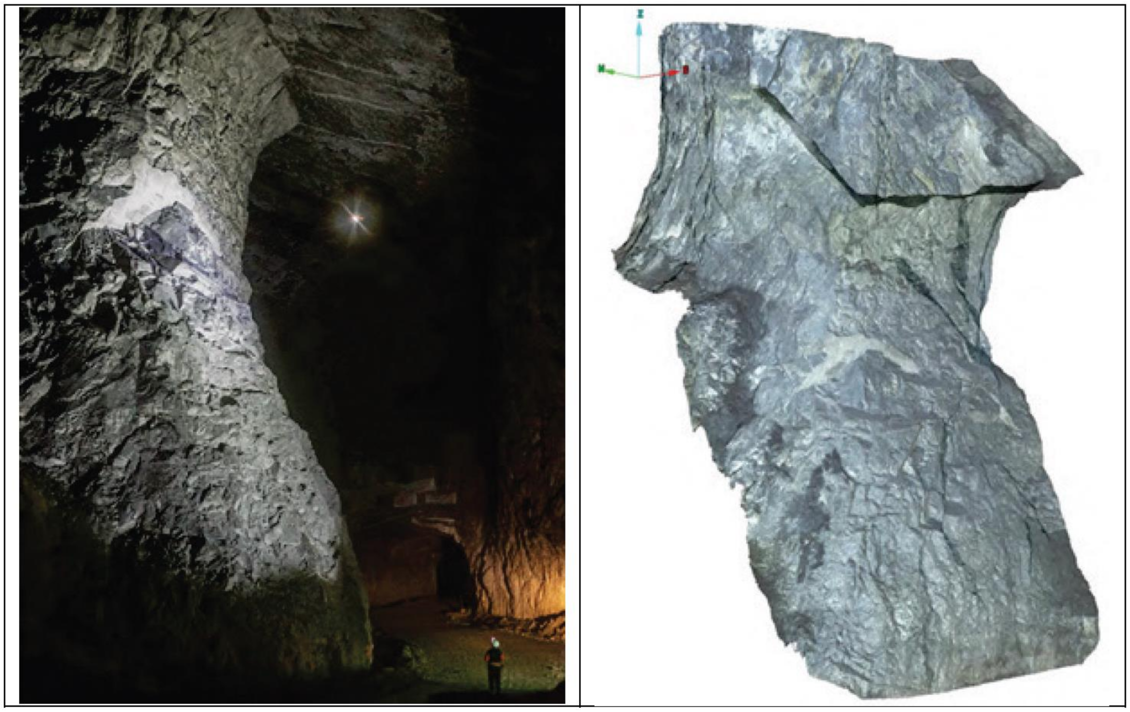


Figure 6. High resolution point cloud data of a pillar (after Bishop, 2022).

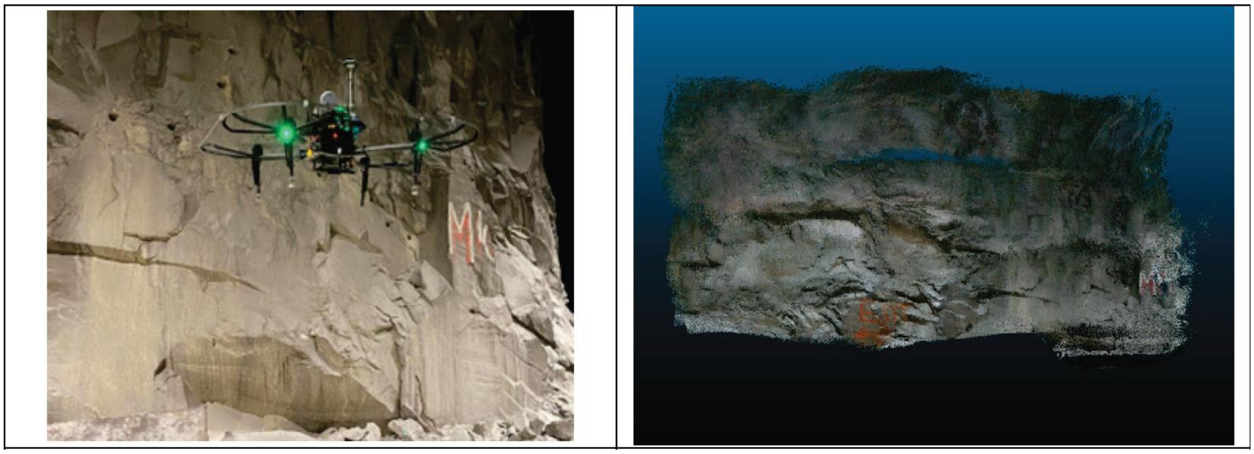


Figure 7. High resolution point cloud data of a pillar wall (after Bendezu, 2021).

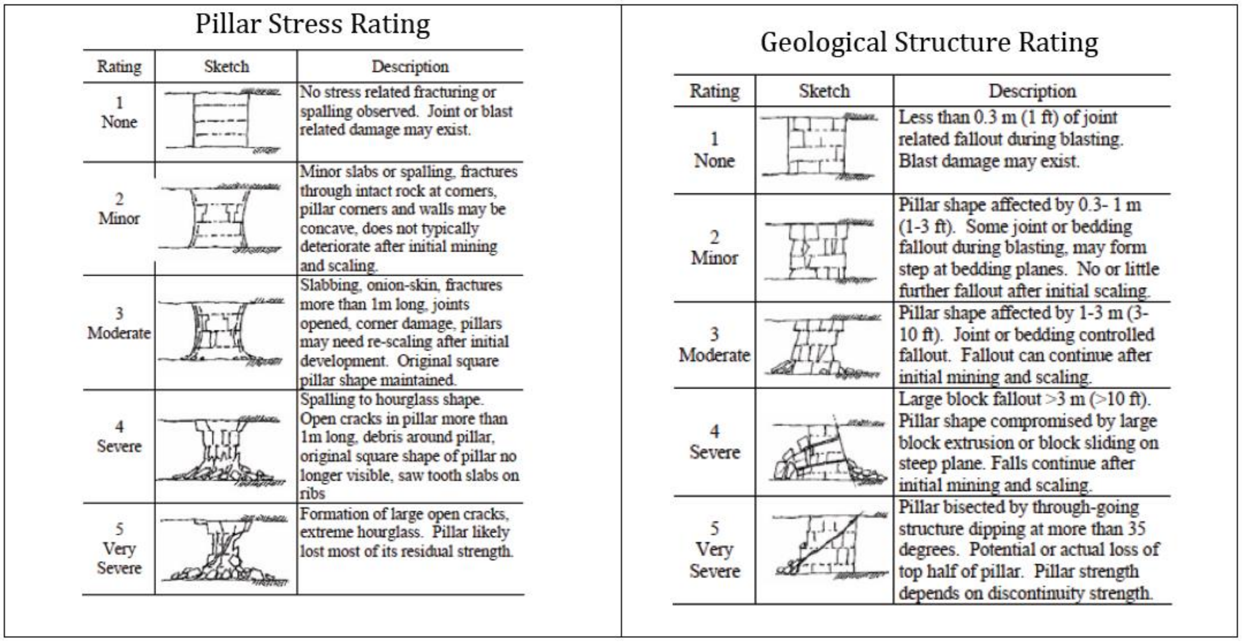
Intact rock mechanical properties: From each mine, in addition to the point-cloud data, rock samples will be collected and tested to characterize the intact rock properties. Therefore, the mechanical properties of the intact rock portion of the rock mass will be identified for each mine.

Roof profile, pillar and room condition: From low resolution 3D maps, the research team will qualitatively rate the conditions of the pillars, rooms, and entry roof. For pillar condition assessment, the rating system proposed by Esterhuizen et al. (2011) for stress and geological setting will be used (Figure 8). Roof profile will be rated as proposed by Iannacchione et al. (2007): smooth, intermediate, or rough. Any significant rock debris on the floor will be easily visible from the low-resolution 3D maps and will be rated as proposed by Iannacchione et al. (2007): none, slight, moderate, or significant.

Operational and design parameters: Mine pillar layout (CAD file), seam elevation, topographic elevation (CAD file), and other operational parameters will be available from each mine.

Support practices and thickness of the roof beam: MSHA Handbook Number PH20–V–2, Roof Control Plan and Ground Support Review Procedures, states that inspection personnel may use the guidelines and procedures in the PH20–V–2 handbook to evaluate the suitability of ground support materials and rock burst control plan, but unless a mine is burst-prone, there are no federal regulations stating that M/NM mines have to submit a ground support plan (MSHA, 2020). Pillar and roof span dimensions and roof bolt application in the M/NM mines are largely based on experience, developed through trial and error. Therefore, during the field visits, mine personnel will be interviewed for the application of the roof bolts. From the low resolution 3D maps (Figure 5-right), where roof bolts were applied within the mine will be easily seen. The research team will note the reason of roof bolt application (i.e., weak immediate roof, discontinuity, or low roof beam thickness) and thickness of the roof beam. Core hole data will also give this information, however, in these mines core holes are generally widely spaced and it is difficult to observe any changes in roof beam thickness between working faces.

Horizontal stress related data: Regional horizontal stress directions will be estimated from the publication of Mark and Gadde (2008). Direction of the horizontal stress can also be verified, if applicable, from the stress mapping. High resolution 3D maps will allow the mapping of the horizontal stress related damages (i.e., roof cutters) from the point cloud data. Direction of the horizontal stress with respect to mine plan will be gathered from the survey data.



Pillar Stress Rating

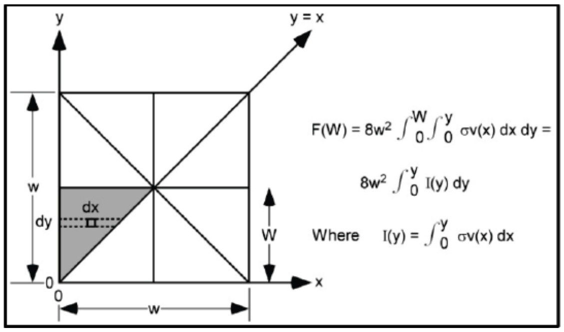
Rating	Sketch	Description
1 None		No stress related fracturing or spalling observed. Joint or blast related damage may exist.
2 Minor		Minor slabs or spalling, fractures through intact rock at corners, pillar corners and walls may be concave, does not typically deteriorate after initial mining and scaling.
3 Moderate		Slabbing, onion-skin, fractures more than 1m long, joints opened, corner damage, pillars may need re-scaling after initial development. Original square pillar shape maintained.
4 Severe		Spalling to hourglass shape. Open cracks in pillar more than 1m long, debris around pillar, original square shape of pillar no longer visible, saw tooth slabs on ribs
5 Very Severe		Formation of large open cracks, extreme hourglass. Pillar likely lost most of its residual strength.

Geological Structure Rating

Rating	Sketch	Description
1 None		Less than 0.3 m (1 ft) of joint related fallout during blasting. Blast damage may exist.
2 Minor		Pillar shape affected by 0.3- 1 m (1-3 ft). Some joint or bedding fallout during blasting, may form step at bedding planes. No or little further fallout after initial scaling.
3 Moderate		Pillar shape affected by 1-3 m (3-10 ft). Joint or bedding controlled fallout. Fallout can continue after initial mining and scaling.
4 Severe		Large block fallout >3 m (>10 ft). Pillar shape compromised by large block extrusion or block sliding on steep plane. Falls continue after initial mining and scaling.
5 Very Severe		Pillar bisected by through-going structure dipping at more than 35 degrees. Potential or actual loss of top half of pillar. Pillar strength depends on discontinuity strength.

Figure 8. Pillar stress and geological ratings (after Esterhuizen et al. 2011).

Task 3.2: The laminated overburden mode development task. Escobar and Tulu (2021) derived the gradient stress equation for stone mine pillars and the function of pillar width-to-height ratio from the empirically-based S-Pillar strength equation to extend the application of the S-Pillar stone pillar strength equation to Boundary Element Method (BEM), LaModel. The integration of the empirical stone pillar strength equation in LaModel allows the empirical pillar stability analysis to be extended over complex mine geometries and variable topography. Escobar (2021) used approaches proposed by Mark et al. (1992) and Johnson et al. (2014) to derive stress gradient equations for rib and corner elements. Initially, Johnson et al. (2014) used four general assumptions to obtain the gradient stress equations that make this methodology valid for deriving gradient stress equations from empirical strength formulas: (i) The derivation of gradient stress equations is performed on square pillars. (ii) When the overall pillar strength reaches its maximum, all the "portions" of the pillar are at maximum strength. (iii) The variation of stress is a function of the distance to the nearest rib and is not dependent on the width of the pillar (Mark et al., 1992). (iv) The square pillar is divided into 8 symmetric pieces to simplify the calculations that relate the stress function to the failure force that is a function of its width. Figure 9 visualizes and shows their approach.



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 = σ_0
Average pillar strength = σ_P
Horizontal location within pillar = x
Local strength = $\sigma_v(x)$
Pillar rib at x = 0
Pillar centerline at x = W

Figure 9. Pillar stress and geological ratings (after Johnson et al., 2014).

It is proposed to expand the application of the Johnson et al. method to derive the stress gradient equations of the semi-benched pillars (Figure 10). The last assumption of the work by Johnson et al. will be replaced with “the square pillar which will be divided into 8 pieces (not necessarily symmetric depending on benching stage) and failure force will be applied as a function of its width and height.” Therefore, the following general equation will be used in the calculations where vertices of each triangular piece will be used to linearly interpolate vertical height (z) within the pillar:

$$\frac{F(W,h)}{W^2} = \sum_{i=1}^{8} \int_0^h \int_0^w \int_0^y \sigma v(x)\, dxdydz \tag{Eq. 1}$$

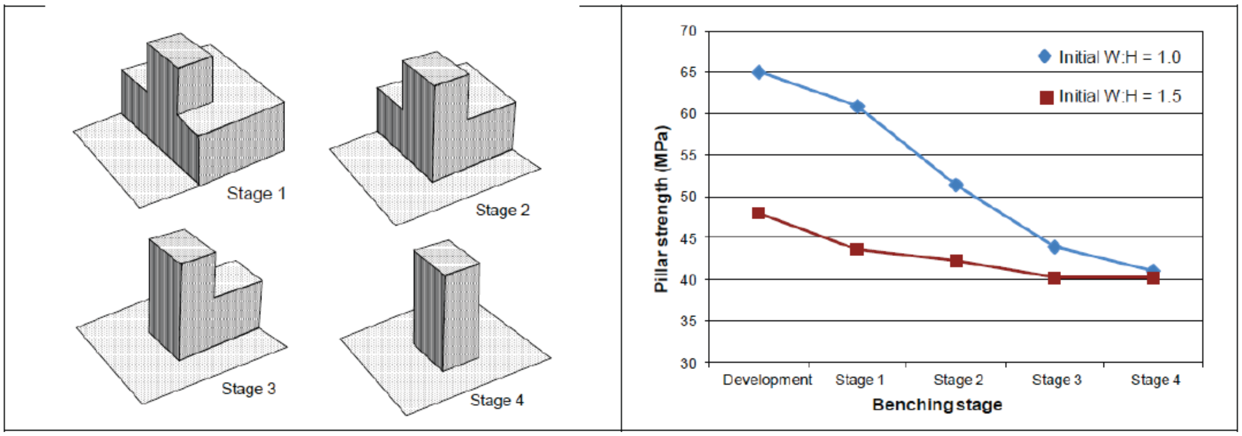


Figure 10. Benching stages and pillar strength (after Esterhuizen et al., 2011).

Since the response of the overburden strata in the LaModel is the function of the seam convergence, and seam elements are one-dimensional spring elements, Escobar (2021) simulated the benched pillars with a reduced stiffness to simulate the stress distribution between the benched and development pillars realistically such that benched pillars in the lower areas of the mine have higher stresses with reduced stiffness. This application also increased stresses on the parameter pillars as observed in the field (Figure 11). As shown in Figure 3a, some of the recent pillar failures occurred when benching was in progress nearby the collapsed area. Therefore, accurate calculations of the stresses in stone mines is critical. However, there isn’t any calibration method available to select the lamination thickness or the benched pillar stiffness reduction ratio. In addition, these two parameters are interrelated when LaModel calculates stress distribution. A guideline will be developed for calibration of these parameters based on field observations.

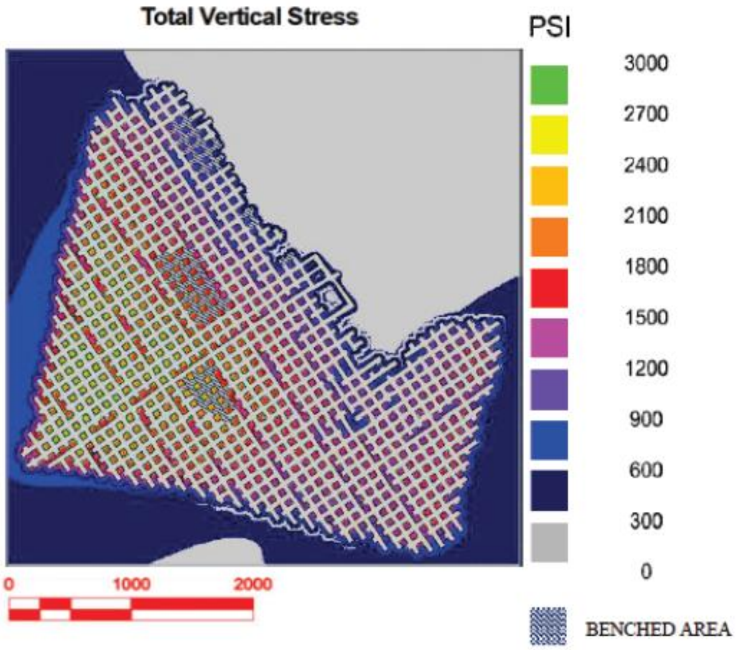


Figure 11. Total vertical stress with reduced stiffness in benched pillars (after, Escobar, 2021).

In this approach, it is proposed to use the stress mapping approach use by Heasley (1998) for calibrating the model inputs in multiple seam coal mining operations. Heasley maps the stress damage on the ribs and overlays the vertical stress grid on the rib condition rating grid to evaluate total stress distribution on the pillar system and if necessary, calibrate the lamination thickness parameter. For the stone mining operations, a similar approach is proposed. In stone mines however, pillar or rib conditions are greatly influenced by the discontinuities. Since the field data that will be used in this project will allow project team to characterize the geological structures on each surveyed pillar, it can be determined whether the damage on the pillar is attributed to stress or geology. Then a similar comparison and calibration can be performed as proposed by Heasley (1998).

Task 3.3: Geomechanical analysis task. Laboratory test and discontinuity data will be used to compute the rock mass rating of the formation. Suner (2021) demonstrated that stone mine rock masses, within the range of the S-Pillar database, can be represented as blocky (Figure 12). In Figure 12, the yellow area represents the range of GSI values of the stone mines in the S-Pillar database. For each case study mine, rock mass rating values will be computed for each surveyed pillar. GSI rating of each pillar will be used as an interpolation point and used to generate the GSI grid file. This approach is already included in the Integrated Stability Mapping software (Nandula et al., 2018) for Coal Mine Roof Rating (Figure 13). Similar to CMRR, a GSI grid will be developed in this project.

In addition to the GSI grid, large discontinuity sets that would affect the pillar and roof stability will be gridded to a discontinuity factor grid. Ates (2022) demonstrated the application of this approach to pillar stability by finding the intersection of the large discontinuity set with pillars on a mine layout and reducing the load bearing capacity of the pillar with a discontinuity factor (Figure 14). In this project, we are proposing to apply the same approach for the entry and intersection roof spans.

The stress and safety factor analysis will be performed using the mine plan, topography map, and operational parameters collected from the mine (Figure 1). LaModel and methods published by Escobar (2021) and Ates (2022) and the new methods that will be developed in Task 3.2 will be used during the analysis. A horizontal stress grid will be developed by generating a pseudo-depth grid as demonstrated by (Nandula et al., 2018) and using the equations proposed by Mark and Gadde (2008).

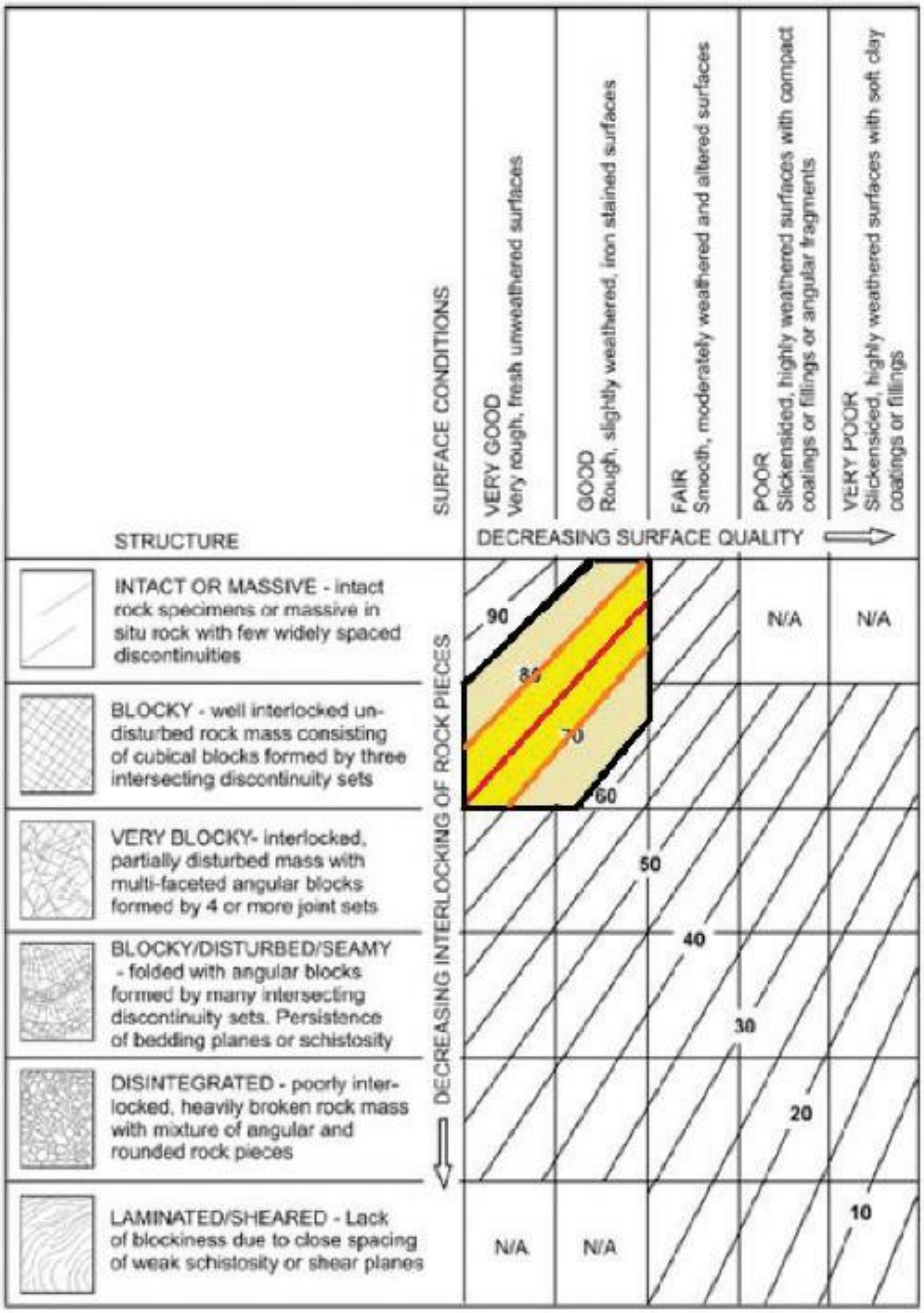


Figure 12. S-Pillar Database GSI Representation.

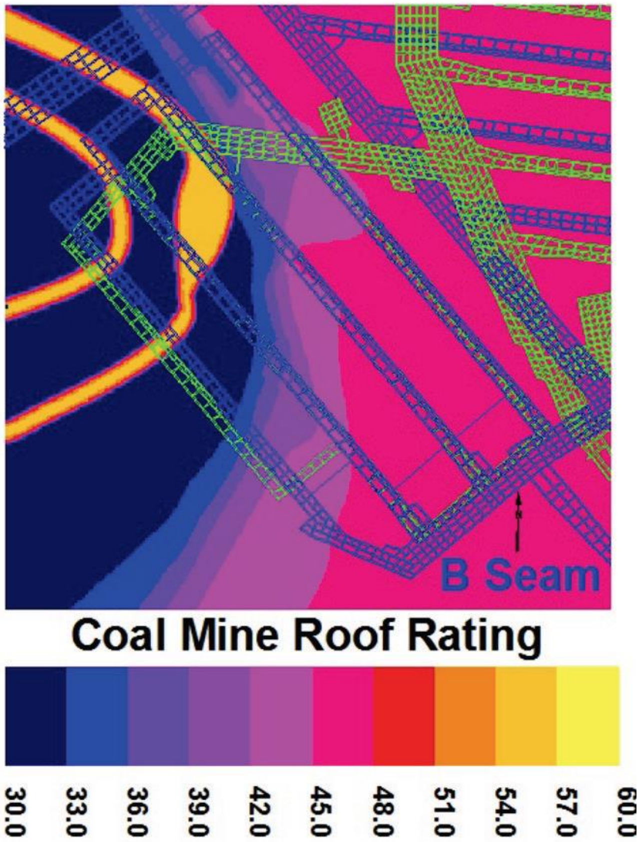


Figure 13. CMRR application with stability mapping software.

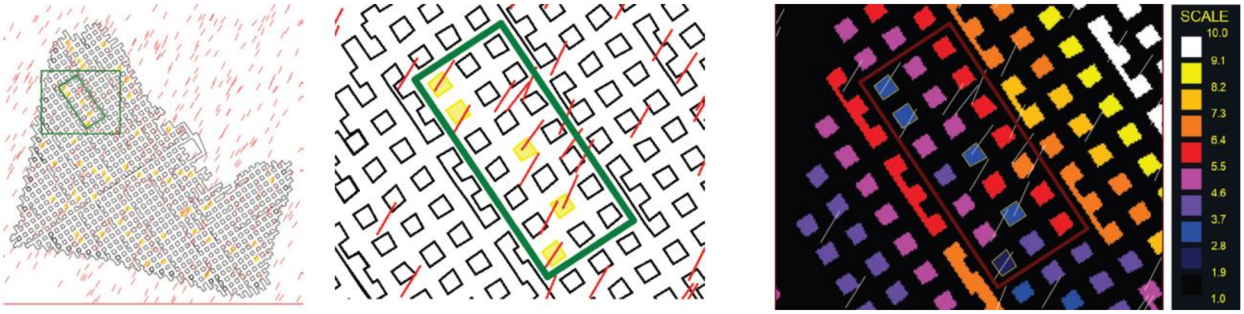


Figure 14. Application of the local large discontinuity factor.

Like the Analysis of Mine Roof Support (AMRS) approach (Mark et al., 2020), primary roof support rating (PSUP) for the bolted sections will be computed. This rating will be converted to the grid file using an approach like Ates (2022) applied for the pillars. In his approach, Ates assigned a discontinuity factor to the pillars by using the step function method of the stability mapping software. Similar approach will be used to assign a PSUP rating to the bolted entry and intersection spans.

Task 3.4:Statistical analysis and guideline development task. In this task, entry and intersection roof parameters (dimensions, GSI rating, roof beam thickness), stress parameters (overburden stress grid, horizontal stress grid, pillar safety factor grid), rock mass strength parameters (GSI grid), roof support parameters (PSUP grid), and large discontinuity distribution grid will be overlaid on the mine layout, and compared with the roof, rib, and pillar condition ratings. For each case study mine, mine layout will be divided into sub-sections (Figure 15). Relationships between the dependent parameters (condition ratings) and independent parameters will be derived using the logistic regression analysis by finding the separation between different condition-ratings to derive the hazard index.

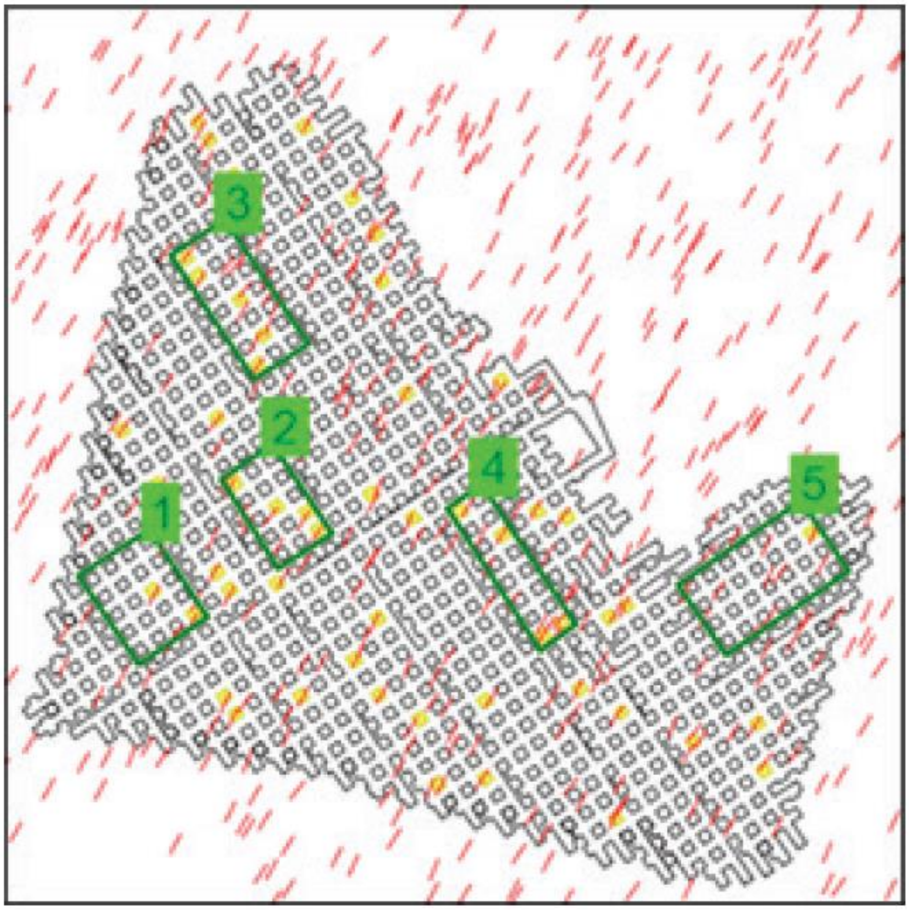


Figure 15. Mine layout is divided in sub-sections.

Objective 4: To Test the Stability Mapping Application

Task 4.1: Internal testing. The new stability mapping application will be continually tested during the development by sharing different builds with the research team both at UK and WVU. The PI of the project has a lot of experience in building applications, sharing, and troubleshooting applications in a variety of programming environments. One of the free bug-tracking web platforms (e.g., Trello at www.trello.com) may be employed to track development progress and bug resolution. The deliverable of this task will be an application running on a Windows-based desktop or laptop. An installer and a context sensitive help file will also be provided such as the files available for the ACPS (Mark and Agioutantis, 2019) and the AMRS (Mark et al, 2020) programs. The end of Task 4.1 coincides with Milestone 2 (M2). After Task 4.1 is completed, testing will be continued by colleagues external to the research team. Any programming and development issues that arise during this task will be promptly addressed.

Task 4.2: External testing. The new stability mapping application will also be shared with experts in the field, preferably mine operators, consultants and regulators, and their input will be solicited as to the ease of use, the stability of the application, output options, etc. As this will happen before the end of the project there will be time to correct any issues that may arise. Any programming and development issues that arise during this task will be promptly addressed. The end of Task 4.2 coincides with Milestone 3 (M3). After Task 4.2 is completed, the application will be made available to the public.

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