# Application of the Ground Response Curve for Understanding the Overburden Load Transfer Mechanism

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## ABSTRACT

Analysis of Longwall Pillar Stability (ALPS) and Analysis of Retreat Mine Pillar Stability (ARMPS) treat the pillar as a passive structure that is designed to carry overburden dead-weight. This dead-weight is calculated by simple rules based on the geometry of the mining, such as "tributary area theory," "pressure arch theory," and "abutment angle theory." Although the pressure arch loading approach indirectly accounts for the generally stiffer overburden response of narrow and deep panels, it does not include the effect of specific geology of the overburden in load calculations. The relationship between successful pillar layouts and overburden geology can be incorporated into the load calculation by using the Ground Response Curve (GRC) approach.

This paper introduces the GRC modeling methodology to investigate the effect of overburden geology and excavation geometry on load transfer mechanisms using seven field measurement case studies from four U.S. mines. It was also shown that the modeling methodology used to derive GRC in this study approximates mining-induced stresses and deformations within 5% of the values measured in the field.

## INTRODUCTION

Frith and Reed (2017) stated that current state-of-the-art pillar design methods ignore the overburden mechanics and use estimated dead-weight of overburden to compute pillar sizes. In the United States and around the world, overburden loading is typically estimated by simple geometric rules, generally with the tributary area theory (TAT). The specific overburden mechanics, structural competence of the overburden strata, geology, in situ stresses, and overburden/pillar interactions are typically ignored. However, these important mechanical responses affect the stability of the mine pillars and openings; therefore, they also affect the safety of the mine workers.

Research conducted by the National Institute for Occupational Safety and Health (NIOSH) after the Crandall Canyon mine disaster (Esterhuizen, Mark, and Murphy, 2010) showed that small panel width-to-depth ratios and stiff-strong overburden result in a reduction of the observed pillar loads, much smaller than the TAT estimate. In fact, as a response to the Crandall Canyon disaster, Mark (2010) implemented a pressure arch loading approach into the latest ARMPS program to recognize the inherently greater stability of narrow panels at depth. The pressure arch approach is a first logical step to introducing non-tributary area loading into the practical ARMPS program. Although the pressure arch loading indirectly accounts for the generally stiffer overburden response of narrow and deep panels, it does not include the effect of specific geology and mechanical response of overburden in the load calculations.

Zhang and Heasley (2013) developed the ARMPS-LAM program which uses the mechanistic overburden model of LaModel and the ARMPS database to improve the ARMPS pillar design guidelines. LaModel is a unique boundary element code as the overburden material includes laminations, giving the model a very realistic flexibility for stratified sedimentary geology (Heasley et al., 2010). Implementation of LaModel into ARMPS was a major step towards using a mechanistic overburden model in pillar design, but the accuracy of a LaModel analysis depends entirely on the accuracy of the input parameters. Therefore, the input parameters need to be calibrated with the best available information. Without any site-specific information, Heasley et al. (2010) recommended the use of the empirical information as implemented in ARMPS to calibrate the LaModel program. The ARMPS-LAM program also adapted this calibration procedure and produced design guidelines very similar to ARMPS.

Esterhuizen, Mark, and Murphy (2010) proposed the use of the Ground Response Curve (GRC) approach to assess the pillar stability. They stated that it is difficult to measure the GRC in the field, but calibrated numerical models can be used to estimate it. They used the finite difference software FLAC3D to develop GRC curves for coal mining excavations. The GRC was estimated by progressively reducing the internal pressure in a model excavation while monitoring the resulting convergence. The GRC approach as proposed by Esterhuizen, Mark, and Murphy allows for the investigation of the relationship between pillar strain, stress, and successful pillar layouts for a range of geologies and mining geometries. In this paper, an updated version of GRC modeling methodology that can explicitly include pillar/overburden interaction into GRC analysis is presented, as well as the verification of modelling methodology used to derive GRC.

## GROUND RESPONSE CURVE APPROACH

Barczak (2017) defines the ground reaction curve as "the support pressure plotted against the opening convergence." Esterhuizen, Mark, and Murphy (2010) adapted the GRC to assess the stability of the pillars. In Esterhuizen's approach, pillar support pressure and GRC are modeled separately. In this paper, the pillars and gob are kept inside the excavation during the gradual reduction of the internal pressure to determine the response of the overburden. Figure 1 compares the GRC approach used by Esterhuizen, Mark, and Murphy (2010) and the proposed method in this research. Arrows represent internal pressure initially applied to the boundary of the excavation. The method proposed in this paper will explicitly include pillar/overburden interactions and in-situ vertical stress on pillars into the GRC analysis.

The recently developed modeling approach (Tulu et al., 2018) is used to drive GRC for seven field measurement case studies from four U.S. mines. In this approach, a systematic procedure is used to estimate the model's mechanical inputs. Shearing along the bedding planes is modeled with ubiquitous joint elements and interface elements. Interfaces between the geological layers in the overburden were modeled with interface elements. Coulomb's criterion was used to define the limiting shear strength of the interfaces. As described by Su (1991, 2016), the coefficient of friction of interfaces was set to 0.25. A constitutive coal-mass model recently developed at NIOSH to simulate coal ribs (Mohamed, Tulu, and Murphy, 2016) was used. The coal-mass model can simulate the degradation of both strength and stiffness seen during brittle failure. It can also simulate transition from brittle to ductile failure with increasing width-to-height ratios. The model's post-peak stiffness degradation parameters are calculated from laboratory tests and scaled down to the in situ pillar level. It has been shown that this new coal model can be used to simulate the Bieniawski pillar strength formula (Tulu et al., 2018). Gob behavior is important to understanding the overall overburden behavior and mine stability. It is assumed that the gob was formed under an average bulking factor of 1.5, which represents a maximum strain of 33% and a caving height equal to three times the mining height measured from the floor. This value of the bulking factor also provides reasonable estimates of the subsidence when used in numerical models (Tulu et al., 2018). In the model, strain-hardening gob behavior is simulated by updating the elastic modulus of each zone with the expected tangent modulus. This task is performed by using the FISH option of the FLAC3D software (Itasca, 2016).

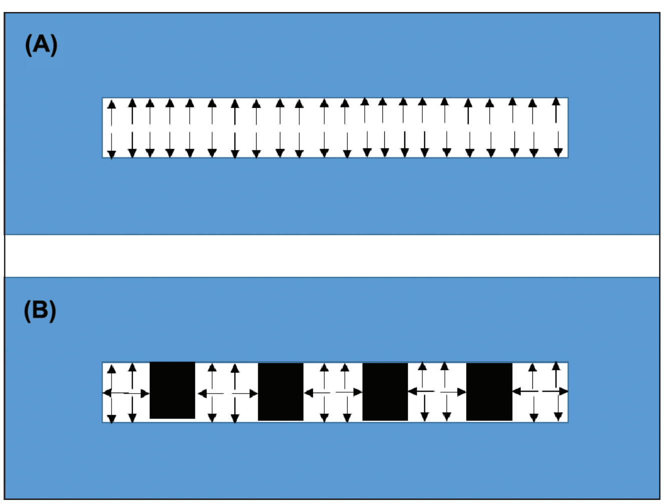


**Figure 1. (a) GRC approach used by Esterhuizen, Mark, and Murphy (2010), (b) GRC approach proposed in this research.**

## CASE HISTORY MINES

Overburden stiffness, stability, and overburden/pillar interactions are affected by many parameters, such as overburden geology, structural competence of the overburden, in situ stresses, and extraction geometry. The relative importance of each of these parameters needs to be understood to establish a true understanding of the overburden mechanics on pillar design. The critical parameters affecting overburden stiffness and stability are investigated by the analysis of field monitoring case studies with calibrated numerical models. It is necessary to have a calibrated model against actual field data to ensure that the model provides realistic results.

In this paper, each case study is characterized based on the local geology, structural competence of overburden, in situ stress, and panel width-depth ratio. The following methodologies are used to characterize each case study:

a. *Overburden geology* is characterized based on the seam and geologic formation.
b. *Overburden competence* is characterized by the percentage of hard-rock (%HR) amount on the overburden. The same approach used in the Surface Deformation Prediction System (SDPS) is used to compute percentage of hard-rock amount. Percentage of hard-rock is defined as the sum of the strong rocks (e.g., sandstone, limestone), having a minimum thickness of 5ft within the overburden (Agioutantis and Karmis, 2017). Available mechanical property tests, Ferm numbers and/or geologic definitions of the rock layers (detailed on the geologic log) are used to define hard-rock.
c. *In situ stresses* are characterized by the regional tectonic horizontal stress and overburden depth of the case study mine.
d. *Panel width-to-depth ratio (PW/H)* is calculated by the subsidence profile—subcritical, critical or supercritical—of the case study mine.

A summary of the four case study mines analyzed in this paper are shown in Table 1. Geological logs of the same four case study mines are shown in Figure 2.

## RESULTS OF MODEL VERIFICATION WITH FIELD MEASUREMENTS

Seven cases from four case history mines were back analyzed with the GRC modeling methodology. Geologic log data for the case history mines (Figure 2) were used to derive overburden model input parameters as described in Tulu et al. (2018).

**Table 1. Characteristics of four case study overburden geologies.**

| Mine Name | Seam Name and Height (ft) | Geologic Formation | Overburden Competence (% of HR) | In-situ Stress Region | Operational Panel Width-Depth Ratio (PW/H) |
|---|---|---|---|---|---|
| A | Hiawatha, 8 ft | Blackhawk Formation | 44% | Western U.S. | 0.42 |
| B | Pocahontas Number 3, 6.5 ft | Pocahontas Formation | 48% | Eastern U.S., Central Appalachia | Case B1: 0.35<br>Case B2: 0.56 |
| C | Middle Kittanning, 6.5 ft | Allegheny Formation | 28% | Eastern U.S., Northern Appalachia | 2.23 |
| D | Pittsburgh, 7 ft | Pittsburgh Formation | Case D1: 25%<br>Case D2: 37% | Eastern U.S., Northern Appalachia | Case D1: 1.1<br>Case D2: 2.1 |

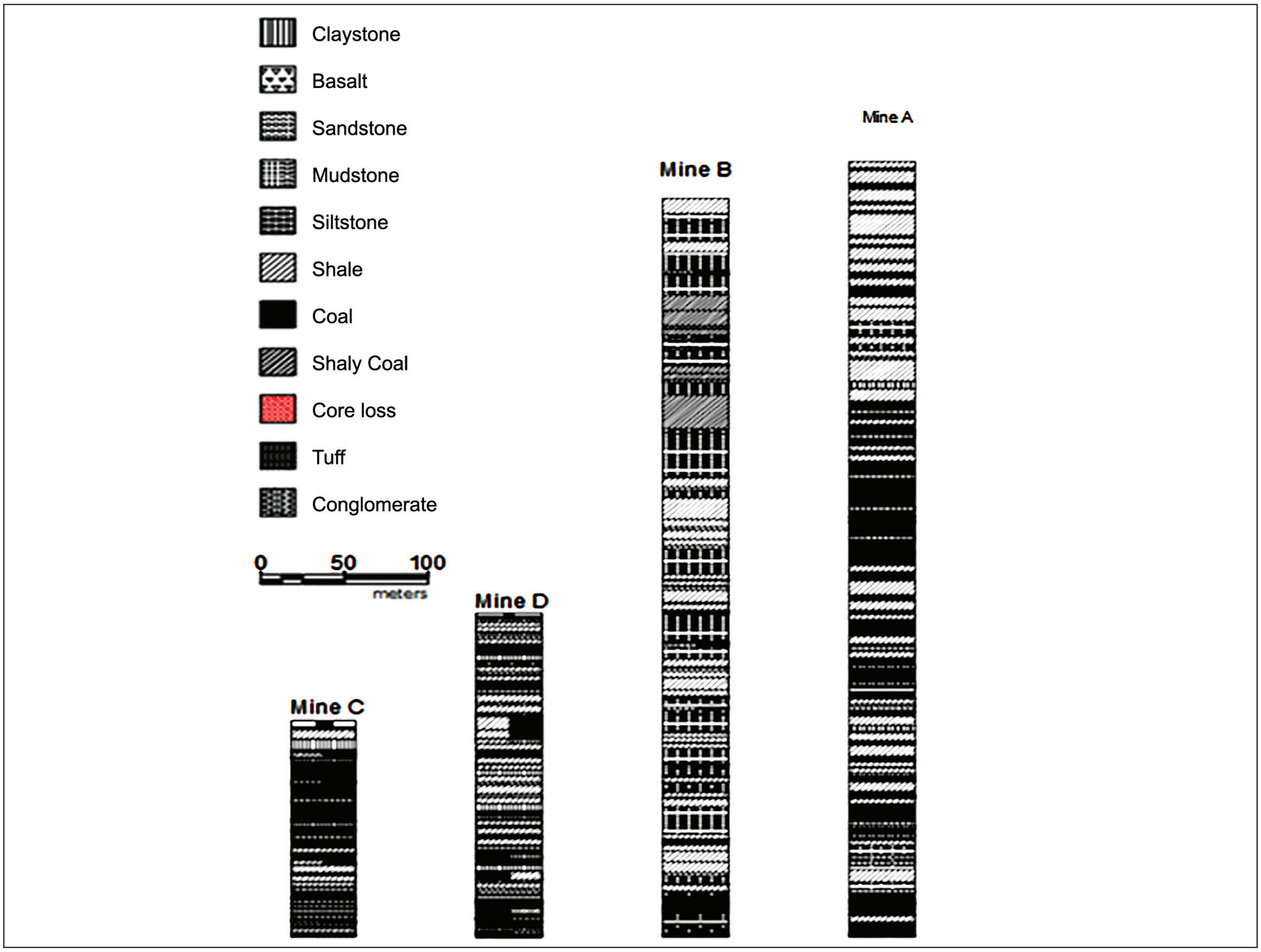


**Figure 2. Geological log of four case study mines.**

***Case #1 Mine A***

Mine A was an underground bituminous coal mine in northwestern Emery County, Utah. Overburden depth ranges from 1,200 to 2,200 ft. In 1999, a subsidence monitoring line was established on the north-to-south trending ridge of East Mountain. The survey line over a portion of Main West and Panels 13 to 17 was monitored from September 2000 to July 2004 using GPS survey technology. The width of longwall panels was 780 ft. The gateroad comprised a two-entry pillar system with 80-ft × 92-ft (center-to-center) pillars. Mining height was approximately 8 ft. Table 2 shows the

**Table 2. Comparison of measured and computed maximum subsidence.**

| Mine Name | Overburden Depth (ft) | Panel Width–Depth Ratio | Overburden Competence (% of HR) | Model Calculated Subsidence (ft) | Measured Subsidence (ft) | Error (%) |
|---|---|---|---|---|---|---|
| A | 1,880 | 0.42 | 44% | 4.77 (For 4 Panels) | 5.00 | 4.6% |
| B | 2,057 | 0.35 | 48% | 1.59 (For 1 Panel) | 1.55 | 2.5% |
| | 2,057 | 0.35 | | 2.35 (For 2 panels) | 2.40 | 2.1% |
| | 1,800 | 0.56 | | 3.72 | 3.4 | 9.4% |
| C | 518 | 2.23 | 28% | 1.14 | 1.17 | 2.6% |
| D | 715 | 1.10 | 25% | 1.05 | 1.07 | 1.9% |
| | 647 | 2.10 | 37% | 1.45 | 1.52 | 4.6% |

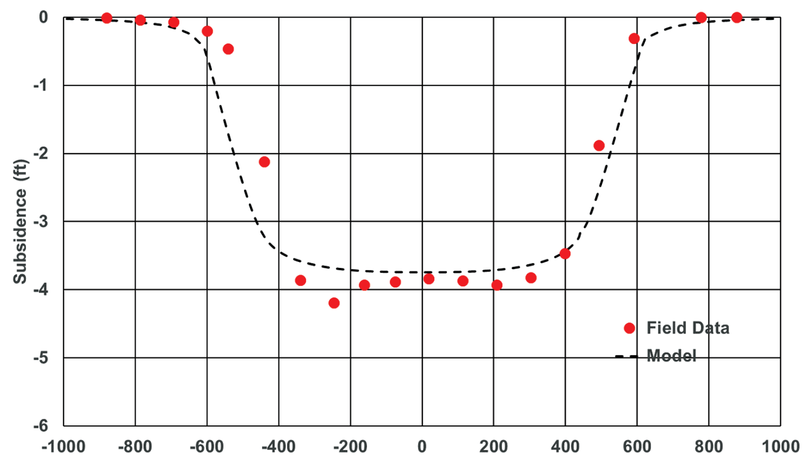


**Figure 3. Subsidence comparison for Mine C.**

comparison of the measured and computed (modeled) maximum subsidence.

***Case #2 Mine B***

The depth of cover throughout Mine B ranges from 1,600 to 2,200 ft. The longwall panels in the older districts are approximately 1,000 ft wide and in newer districts are 700 ft wide. The gateroad comprises a yield-abutment-yield system. Subsidence over one older district longwall (1,000 ft wide and 1,800 ft deep) and two consecutive newer district longwall panels (700 ft wide, 2,057 ft deep) were monitored. Mining height is approximately 6.5 ft. Table 2 shows the comparison of the measured and computed (modeled) maximum subsidence for three cases from Mine B.

***Case #3 Mine C***

The depth of cover throughout Mine C ranges from 400 ft to 600 ft. The longwall panels in the area are approximately 1,100 ft wide. The gateroad comprises a three-entry system. Subsidence over a longwall panel and vertical stress change up to 30 ft into the abutment pillar were monitored. Table 2 shows the comparison of the measured and computed (modeled) maximum subsidence. Figure 3 shows the comparison of the measured and computed subsidence profile. The comparison of the measured and computed stress is shown in Figure 4.

***Case #4 Mine D***

Mine D is located in Greene County, Waynesburg, Pennsylvania. The mining height is approximately 6.5 ft. In previous operations, the panel widths were around 800 ft. Currently, the mine operates with panel widths greater than 1,500 ft. Average overburden depth for the previous operations was 700 ft. The gateroad comprises a three-entry system. Subsidence over an older longwall panel (panel width 786 ft and depth 715 ft) and a newer longwall panel (panel width 1,391 ft and depth 647 ft) was monitored. Figure 5 shows the comparison of the measured and computed subsidence profile.

Table 2 shows the comparison of the measured and model-computed maximum subsidence values for seven measurement cases from four case study mines. The maximum error between measured and computed subsidence is calculated as 9.4%. The mean of error for seven cases is 4.6%, and standard deviation is 2.7%.

## ANALYSIS OF OVERBURDEN LOAD TRANSFER MECHANISMS

The GRC for three cases from two shallow mines (Mine C and Mine D) is shown in Figure 6. The vertical axis in the graph represents normalized internal pressure (internal stress/in situ stress), and the horizontal axis is the average convergence along the gob. The green line indicates the ground reaction curve for Mine C with Panel Width/Depth ratio (PW/H) of 2.23 and %HR of 28%. The red line represents the ground reaction curve for Mine D with PW/H ratio of 2.10 and %HR of 37%. The blue line is the ground reaction curve for Mine D with PW/H ratio of 1.10 and %HR of 25%. Initially, all three curves are steep and nearly linear. This behavior embodies the elastic response of the overburden (Barczak, 2017).

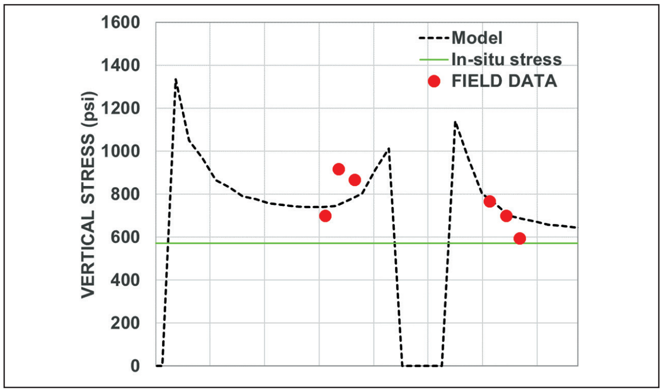


**Figure 4. Stress comparison for Mine C.**

As the internal pressure reduced, the ground reaction curve becomes nonlinear and begins to flatten, indicating that the overburden is failing (Barczak, 2017). The difference between the normalized internal pressure and normalized in situ pressure (100%) indicates the percentage of in situ load transferred to the abutments. Figure 6 shows that as PW/H ratio decreases, the elastic part of the ground response curve's slope increases. In addition, load transferred to the abutments also increases with decreasing PW/H ratio. When similar PW/H ratio cases (green and blue curves) with different HR percentages are compared, the elastic part of the GRC's slope is steeper and load transferred to abutments are larger for stronger overburden. Figure 7 shows the GRC for three cases from two deep mines (Mine A and Mine B). Similar to the shallow cases, the slope of initial elastic response of overburden steepens with decreasing PW/H ratio. For deeper mines with low PW/H

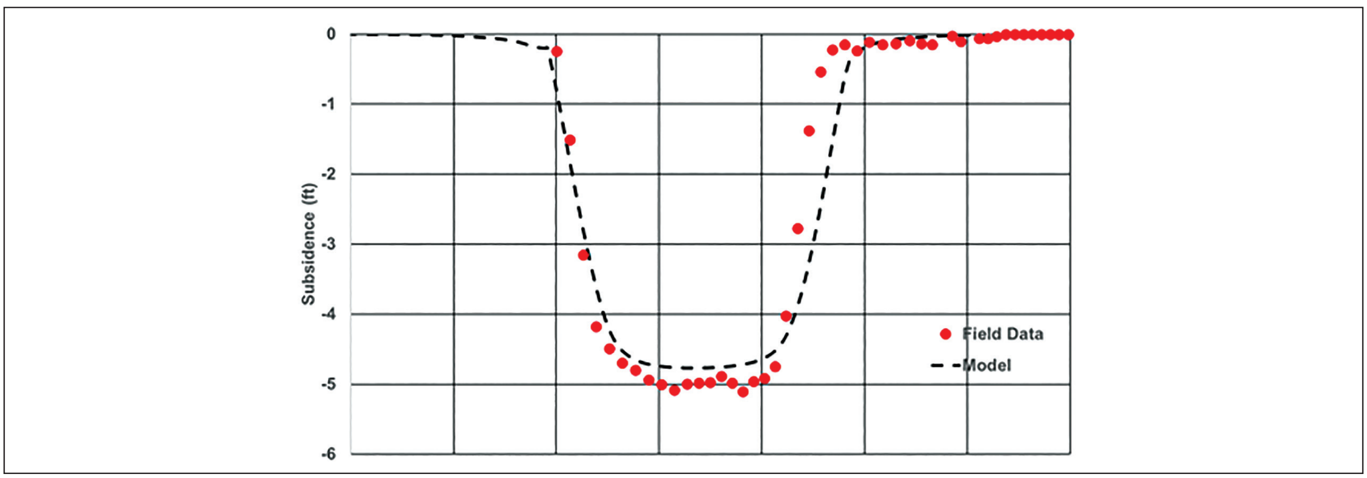


**Figure 5. Subsidence comparison for Mine D.**

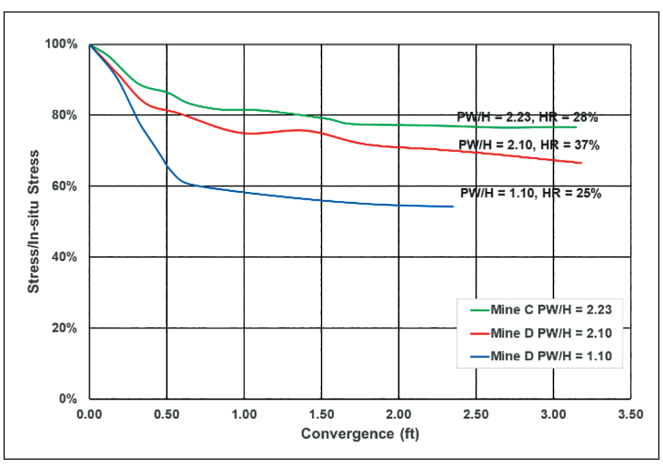


**Figure 6. GRC for three shallow mines.**

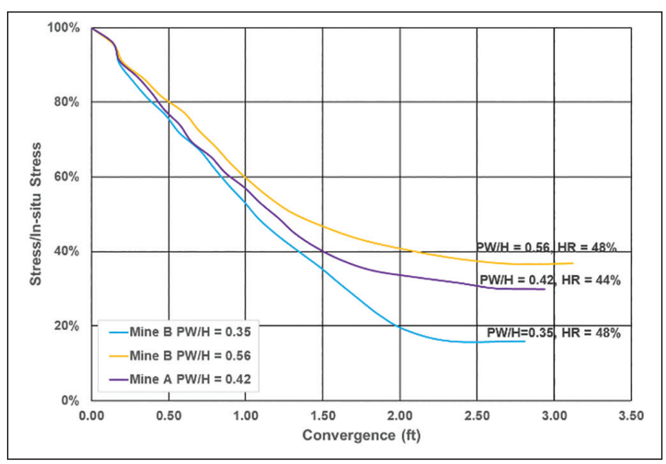


**Figure 7. GRC for three deep mines.**

ratios, load transferred to the abutments are much larger compared to shallow mines.

## SUMMARY AND FUTURE WORK

The results of this initial study showed that the modeling methodology used in this study approximates mining-induced stresses and deformations within 5% of values measured in the field. The influence of the panel width to depth ratio and overburden geology on GRC has been demonstrated. When panel width to depth ratio is small or the overburden consists of strong rock layers, the ground response is stiffer, and loads transferred to the abutments are larger. In the future, case studies from 8 more U.S. mines will be analyzed with the modelling methodology described in this paper, and GRC will be derived for each case study. The results of these analyses will be used to develop a practical approach to incorporate effect of geology and mechanical overburden in ARMPS and ALPS load calculations.

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The findings and conclusions in this report are those of the author(s) and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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