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A New Abutment Angle Equation for Deep Cover Coal Mines

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ABSTRACT: The National Institute for Occupational Safety and Health (NIOSH) first developed the Analysis of Retreat Mining Pillar Stability (ARMPS) program to help the U.S. coal mining industry to design retreat room and pillar panels. Similar to other pillar design methodologies, ARMPS determines the adequacy of the design by comparing the estimated in situ and mining induced loads to the load bearing capacity of the pillars. ARMPS calculates magnitude of the in situ and mining induced loads by using geometrical computations and empirical rules. The program uses the "abutment angle" concept in calculating the magnitude of the mining induced loads on pillars adjacent to a gob. The value of the abutment angle for coal mines in the United States was derived by back analysis of field measurements, and ARMPS2010 engineering design criterion was derived from the statistical analysis of the databases of more than 640 retreat mining case histories from various U.S. coal mines. In this study, stress measurements from U.S. and Australian coal mines were back analyzed using the square decay stress distribution method, and the abutment angles are investigated. The results of the analyses indicated that for shallow mines with overburden depths of less than 200 m, empirical derivation of 21° abutment angle used in ARMPS2010 was supported by the case histories. However, at depths greater than 200 m, the abutment angle was found to be significantly less than 21°. A new equation employing the overburden depth to panel width ratio was constructed for the calculation of abutment angle for deep cover cases. Finally, the new abutment angle equation was tested using 336 deep cover cases from the ARMPS2010 database. The new abutment angle equation was found to perform a good classification compared to using 21°. It was also apparent that, for deep cover cases (deeper than 200 m), the barrier pillar stability factors were the governing parameters in classification of failed cases and the results can be considered an indicator for the importance of barrier pillars in deep cover retreat mines.

1. INTRODUCTION

The abutment angle concept is used to calculate the magnitude of abutment loading adjacent to a gob area. It considers an angle between the vertical plane and the panel roof in order to calculate the transferred load to the abutments when the panel is mined (Fig. 1). If you consider the total area above the mined-out panel as the total load to be transferred, the hatched area constitutes the load that is transferred to the side and the remaining load is carried by the gob.

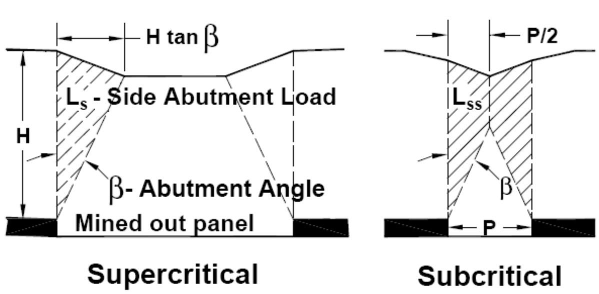

Fig. 1. Abutment angle concept. (Mark, 1992)

In 1990, Mark analyzed the abutment stress measurements collected from five different mines. All measurements were conducted using vibrating wire stressmeters (VWS). The U.S. Bureau of Mines (USBM) conducted three of the studies, all of which were in the Pittsburgh seam. Pennsylvania State University conducted the fourth study in the Lower Kittanning seam, and U.S. Steel Research conducted the fifth study at a mine operating in the Harlan seam. Mark (1987, 1992) back-calculated the measured side abutment load by multiplying the load-bearing area of the pillars by the average pillar stresses determined from the array of VWS inside each pillar.

Table 1 shows the summary of the panel widths and depths from the case histories that were analyzed by Mark (1992). A total of sixteen VWS arrays were installed in 5 different mines, but side abutment measurements were available only from six arrays due to the damage to some of the instruments during mining. This is why Table 1 only has data for six cases from four different mines. Mark concluded that an average abutment angle of 21° would yield a conservative estimate of the side abutment load, but there was a wide range (10.7° to 25.2°) in the measured values as seen in Table 1.

Table 1. Summary of the stress measurement sites used by Mark (1990).

Case	Panel Depth m (ft)	Panel Width m (ft)	Seam	Abutment Angle (deg.)
Mine A:2	159 (520)	143 (470)	Pittsburgh	21.8
Mine B:2	198 (650)	183 (600)	Pittsburgh	25.2
Mine B:3	183 (600)	183 (600)	Pittsburgh	10.7
Mine B:4	139 (455)	183 (600)	Pittsburgh	17.3
Mine D:1	232 (760)	305 (1000)	Lower Kittanning	18.5
Mine E:3	192 (630)	153 (500)	Harlan	20.3
			Average	18.97

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

$$D(m) = 5.13\sqrt{H} \quad (1)$$

From the stress measurements at the five mines (Table 1), Mark found that Eq. 2 (square decay function) fits the measured stress distributions best.

$$\sigma_a(x) = \frac{3L_s}{D^3}(D - x)^2 \quad (2)$$

where:

σ_a = the abutment stress level
x = the distance from the panel edge
L_s = the total side abutment load
D = the extent of the abutment stress from Eq. 1.

Currently, active mines have significantly different panel dimensions compared to the mines where the data were collected for the derivation of the abutment extent formula (Eq. 1) and the 21° average abutment angle. More recent in situ stress measurements of abutment loading conducted in Australia (Colwell *et al*., 1999) and in the United States (Vandergrift and Conover, 2010) showed that there can be significant deviations in the measured abutment magnitude and extent, compared to the predicted values from the empirical formulas used in ALPS and ARMPS2010. It seems reasonable that the site-specific overburden geology, seam thickness, and extraction panel width should have a significant effect on the extent and magnitude of the abutment load, but these parameters are not included in the present calculations.

2. RE-ANALYSIS OF ABUTMENT ANGLE

2.1. Stress Measurement Database

The cases used to derive the default 21° abutment angle have significantly narrower panel dimensions and relatively shallower overburden depths than most modern longwall panels. In this paper, this MSHA recommended abutment angle used in ALPS and ARMPS is re-examined using more recent in situ stress measurements.

Regarding the recommended abutment angle, it can be seen from Table 1 that there were not any stress measurements from a panel deeper than 232 m and that most panels were 183 m wide or less when the average 21° abutment angle was determined. To re-examine the abutment angle, a database was developed with the addition of more recent stress measurements. Six stress measurement case histories from Colwell et al. (1999) and another six case histories from Hill (2016) are added to the database. In addition to those cases and the ones studied by Mark in 1990 (Table 1), another 10 supplementary cases (Colwell et al., 1999) were added where only the total side abutment loads were known. Twenty of the 28 additional case histories are from Australian longwall mines and the remaining 8 cases are from U.S. longwall mines. Table 2 shows the statistical summary for the 28 case histories used in this study.

Table 2. Summary statistics of the present stress measurement database.

	Depth of Cover (m)	Panel Width (m)	Width / Depth
Average	289	191	0.83
Standard Deviation	158	44	0.43
Minimum	125	105	0.29
Maximum	625	305	2.2

2.2. Stress Measurements and Calibration of the Stress Cells

In analyzing the stress cell pressures, it is not necessarily important which stress cell calibration method is used if the method is consistent from site to site (Mark, 1992; Colwell *et al*., 1999). The stress measurement cases used in this paper include two types of stress cells; Hydraulic Stress Cells (HSC) used in Australia and Borehole Platened Flatjacks (BPFs, Fig. 2a) used in the U.S. Measurements from each type of cell were calibrated according to the most accepted calibration factor recommended for that device to try and calculate a true stress change in the coal pillar.

The HSCs were developed by Mincad Systems (Colwell *et al*., 1999) and the calibration procedure followed by Colwell *et al*. is used to calibrate the HSC cell results. This calibration procedure employs a calibration factor K=1 for a stress increase up to 5 MPa and K=1.3 for that portion of the stress increase above 5 MPa. The K factor relates the monitored change in cell pressure (ΔP_c) to the actual in situ vertical pressure change (ΔP_i), where;

$$\Delta P_i = \frac{\Delta P_C}{K\ Factor} \tag{3}$$

The BPFs used for the U.S. cases (US1a-b) were tested by Su and Hasenfus (1990) using a modified nonlinear finite element model. According to their analyses, they determined that the BPF K-factor increases with increasing pillar loading, changing between 2.0 and 2.5 (Fig. 2b). The calibration calculations for the U.S. cases in this study are made accordingly.

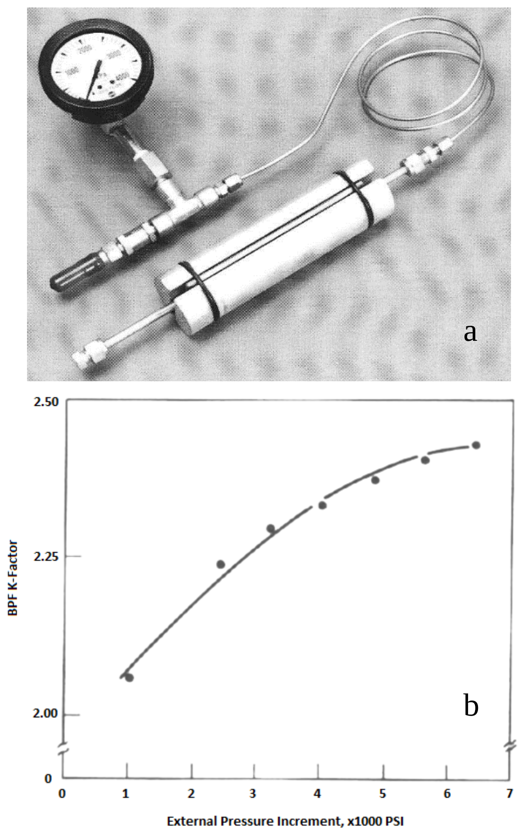

Fig. 2. (a) BPF with platens, tubing valves and gauge (Mincad Systems Pty. Ltd., 1997) (b) K-Factor of the USBM Borehole Platened Flatjack versus External Pressure in Coal (Su and Hasenfus, 1990)

3. ABUTMENT ANGLE CALCULATION

Using the calibration approach described above, in situ stress measurements are used to constitute the calibrated stress profiles. The square decay stress distribution is used to extrapolate the stress measurements to determine the measured abutment extent, since the case histories were unable to measure to the full extent of the abutment load.

A sample stress profile plotted using the measured values can be seen in Fig. 3. The figure represents the stress change profile of a two-entry system where the measurements are taken from the pillars and the adjacent solid coal. The area L_A represents the abutment load on the gateroad pillar and the area L_B represents the abutment load on the adjacent solid coal. After the calibration of the stress cells as explained in the previous section, the areas L_A and L_B were numerically calculated by integrating the load under the curve. Then the L_A / (L_A+L_B) ratio was calculated.

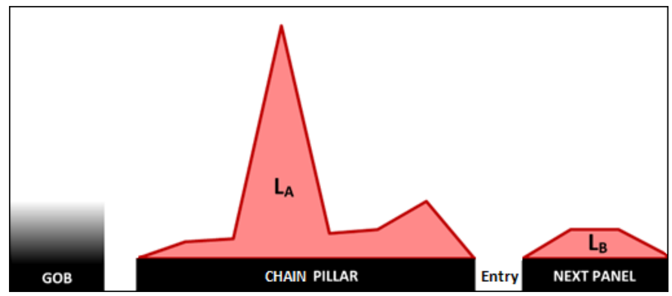

Fig. 3. Sample stress profile from a two-entry mine

The abutment angles are back calculated using the square decay stress distribution approach. Eq. (2), gives the abutment stress distribution (σ_a) as a function of the full abutment extent (D), total side abutment load (L_S), and the distance (x) from the panel rib. The calculated load on the abutment pillar for the two-entry gate road system can be determined by integrating Eq. 2 over the distance x_1 from the panel edge (Eq. 4).

$$L_A = \int_0^{x_1} \sigma_a(x)dx = \frac{3L_s}{D^3}\left(D^2x_1 - Dx_1^2 + \frac{x_1^3}{3}\right) \tag{4}$$

Likewise, Eq. 2 is integrated over the distance x_2 from the panel rib to calculate the total load on the abutment pillar and solid coal.

$$L_A + L_B = \int_0^{x_2} \sigma_a(x)dx = \frac{3L_s}{D^3}\left(D^2x_2 - Dx_2^2 + \frac{x_2^3}{3}\right) \tag{5}$$

Then, the percentage of the abutment load on the abutment pillar can be determined by dividing Eq. 4 by Eq. 5 as:

$$n = \frac{\frac{3L_s}{D^3}(D^2x_1 - Dx_1^2 + \frac{x_1^3}{3})}{\frac{3L_s}{D^3}(D^2x_2 - Dx_2^2 + \frac{x_2^3}{3})} \tag{6}$$

Finally, Eq. 7 is solved numerically for the full abutment extent (D).

$$0 = n - \frac{D^2x_1 - Dx_1^2 + \frac{x_1^3}{3}}{D^2x_2 - Dx_2^2 + \frac{x_2^3}{3}} \quad (7)$$

After the calculation of the inverse squared abutment extent, the total abutment load (L_S) can be calculated by using the measured abutment load for pillar A and solving Eq. 8 for the associated side abutment load.

$$L_s = \frac{L_A D^3}{3\left(D^2x_1 - Dx_1^2 + \frac{x_1^3}{3}\right)} \quad (8)$$

Finally, the abutment angle can be back-calculated from the values of "L_S" according to the appropriate subcritical or supercritical panel formulas (Mark and Bieniawski, 1986):

$$L_s = H^2(tan\beta)\gamma \qquad \text{supercritical} \quad (9)$$

$$L_{ss} = \left(\frac{H \times PW}{2} - \frac{PW^2}{8\,tan\beta}\right)\gamma \qquad \text{subcritical} \quad (10)$$

where H is the overburden depth, PW is the panel width and γ is the average unit weight of the overburden

4. RESULTS OF THE ANALYSIS

4.1. Re-analysis of the Abutment Angle

The abutment angles back calculated can be seen in Table 3. The results of these calculations for deeper mines do not match the average 21° abutment angle used in ALPS and ARMPS2010.

Table 3. Back calculated abutment angles

Case	Abutment Angle	Overburden Depth (m)	Panel Width (m)
AU-1	22.50	265	200
AU-2	18.74	125	275
AU-3	16.69	130	200
AU-4	15.18	180	130
AU-5	6.04	475	200
AU-6	9.23	240	145
AU-7	12.14	405	250
AU-8a	11.40	513	227
AU-8b	8.35	510	237
AU-9	9.82	365	250
US-1a	8.02	594	195
US-2b	7.73	625	183

Fig. 4 shows the results for the abutment angles back calculated using the square decay stress distribution approach together with supplementary cases (Colwell *et al*., 1999; Hill, 2016; Mark, 1990). For the mines, deeper than about 200 m, it can be seen that the abutment angle values are distributed between the maximum value of 23.4° and minimum value of 4.7°, with the mean of 12.2°. For the mines with overburden depth less than 200 m, the scatter is much larger, but the average abutment angle of 21° is appropriate to assume. A 21° abutment angle was proposed by Mark (1990) and has been successfully used for more than three decades and proven to be applicable for shallow cover mines.

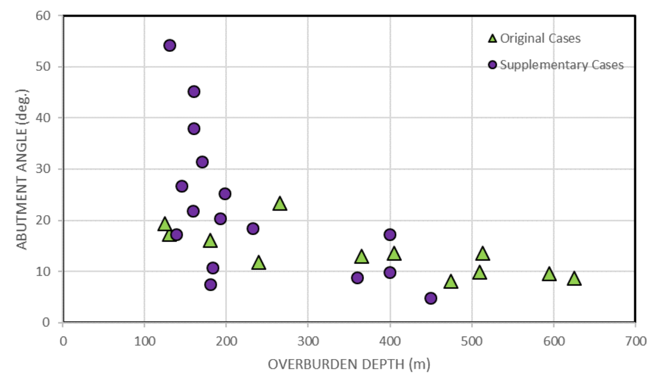

Fig. 4. Abutment angles with respect to overburden depth

As seen in Fig. 5, there is also an apparent trend of decreasing abutment angle with increasing ratio of overburden depth to panel width (H/PW). A regression analysis to determine the abutment angle for deep cover cases (>200 m) is conducted; 200 m is selected as the limit depth because it is proven that ARMPS2010 and previous versions, design recommendations with default 21° abutment angle historically been very successful for shallow mines (<200 m) (Mark, 2010).

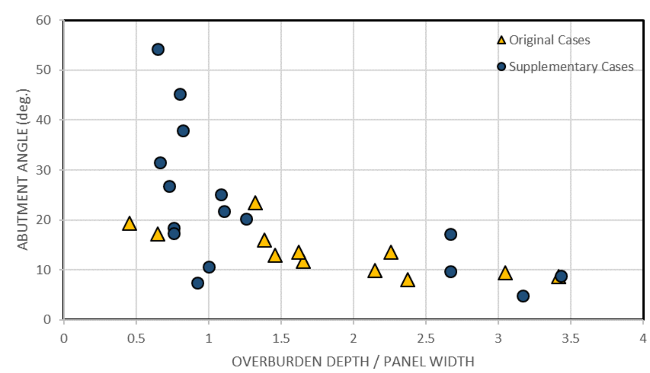

Fig. 5. Abutment angles with respect to panel width to overburden depth ratio

From the regression analysis, the overburden depth to panel width ratio (H/PW) was found to be the most significant parameter for determining the abutment angle, so the following equation is proposed with a constant b<1;

$$Abutment\ Angle = a \times b^{(H/PW)} \quad (11)$$

Based on the field data analyzed in this paper, the proposed abutment angle equation is shown as the red line in Fig. 6. When the overburden depth is less than 200 m, a constant abutment angle of 21° is still applicable. For an overburden depth from 200 m to 625 m, an abutment angle (β) that decreases with a continuous function of the H/PW ratio is proposed (Table 4). This equation was derived by performing a least-square error fit to the measured abutment angles above 200 m overburden depth. Almost all the cases deeper than 200 m also have an H/PW ratio more than 1. The new equation should be considered applicable inside the range of the case studies (0.7 < (H/PW) < 3.5).

Table 4. Proposed abutment angle equation for H/PW ratios from 0.7 to 3.5

Overburden Depth (H)	Abutment Angle
H ≤ 200 m	21°
200 m ≤ H ≤ 625 m	$\beta = 29.42 \times 0.68^{(H/PW)}$

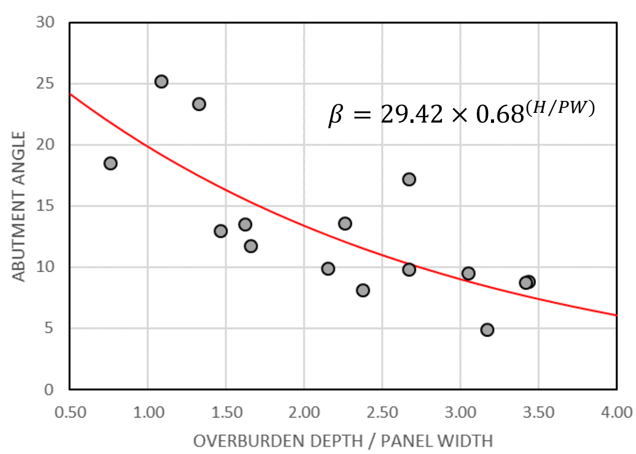

Fig. 6. New abutment angle equation for deep cover cases

4.2. *Logistic Regression for Modified Abutment Angle Equation*

In the early 1990s, the Analysis of Longwall Pillar Stability (ALPS) was introduced by Mark (1990) as a chain pillar design software and was generally accepted and used by the U.S. coal mining industry. Following the success of ALPS, the National Institute for Occupational Safety and Health (NIOSH) developed the Analysis of Retreat Mining Pillar Stability (ARMPS) program for designing retreat mining pillars (Mark and Chase, 1997). The Australian coal mining industry also recognized the success of ALPS, and Colwell et al. (1999) calibrated the program to Australian conditions. The ALPS and ARMPS programs draw their strengths from the large databases that are used to calibrate them (Mark, 2009). However, following the Crandall Canyon Mine collapse in 2007, NIOSH had to reconsider the pillar design criteria used in deep-cover retreat mining (Mark, 2010). ARMPS overburden load prediction algorithm was improved to more accurately predict the loading of narrow panels with high overburden depths by implementing the pressure arch concept and this new version is called ARMPS2010.

The case study database used to develop the ARMPS2010 design criteria is analyzed using the new abutment angle equation. The database includes 640 cases of which 520 of them are successful and 120 are failed case histories. The failed cases include; 14 collapses, 81 squeezes, 16 multi-pillar and 9 local bursts. The analyses considered the classification success of ARMPS2010 design criteria. The failure Classification accuracies of ARMPS2010 design criteria is matched and compared.

The first analysis is conducted using the deep cover cases, only considering the active mining zone (AMZ) stability factors since some of the cases are front abutment only and does not have a barrier pillar stability factor (BP SF). Also, the development cases are omitted since their stability factors are calculated using the tributary area or pressure arch theory and the abutment angle has no effect. There are 336 cases that fall into this category, of which 61 of them are failed cases. These cases were initially analyzed using 21° abutment angle and standard ARMPS2010 design criteria that use 1.5 for ARMPS2010 stability factor (ARMPS2010 SF). Corresponding classification accuracies are given in Table 5. ARMPS2010 design criteria correctly predicted 52 of 61 failures (85%), and 103 of 275 successful cases (37%).

Table 5. Classification accuracies for deep cover cases of ARMPS2010 SF of 1.5 using 21° abutment angle

	Success Observed	Failure Observed	Total
Success Predicted	103	9	112
Failure Predicted	172	52	224
Total	275	61	336
Accuracy	37%	85%	46%

The same case histories (deep cover with production) are re-analyzed using the ARMPS2010 program with the new abutment angle (Table 4) instead of the constant 21°. In order to provide with a failure classification accuracy of 85%, the limit ARMPS2010 SF is determined as 1.57. As shown in Table 6, classification of successful cases increased up to 39% (114 out of 275).

Table 6. Classification accuracies for deep cover cases using the new abutment angle equation using the ARMPS2010 program with ARMPS2010 SF: 1.57

	Success Observed	Failure Observed	Total
Success Predicted	108	9	117
Failure Predicted	167	52	219
Total	275	61	336
Accuracy	39%	85%	48%

The second set of analyses are conducted using the 215 deep cover case histories that utilize barrier pillars. Out of those 215 cases, 182 of them were successes and the remaining 33 were failures. These cases were initially analyzed using the 21° abutment angle and standard ARMPS2010 design criteria that require a SF of 1.5 for both active mining zone and barrier pillars. Corresponding classification accuracies are given in Table 7. ARMPS2010 design criteria correctly predicted 29 of 33 failures (88%) and 61 of 182 successful cases (34%). Out of the 4 falsely predicted cases, one of them was a local pillar burst, and the other three were pillar squeezes (Fig. 7).

Table 7. Classification accuracies for deep cover cases of ARMPS2010 SF and BP SF of 1.5 using 21° abutment angle

	Success Observed	Failure Observed	Total
Success Predicted	61	4	65
Failure Predicted	121	29	150
Total	182	33	215
Accuracy	34%	88%	42%

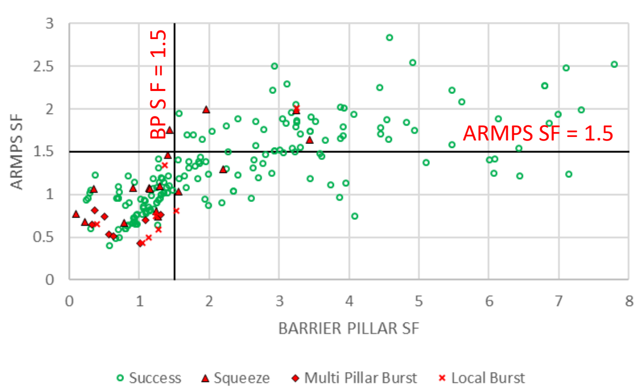

Fig. 7. ARMPS2010 SF values for deep cover cases that utilize barrier pillars

The same case histories (deep cover with barrier pillars) are re-analyzed using the ARMPS2010 program with the new abutment angle equation (Table 4) instead of the constant 21°. In order to provide with a failure classification accuracy of 88%, the ARMPS2010 SF and BP SF values are determined as 1.33 and 1.75, respectively. As seen in Table 8, classification of successful cases increased notably up to 47% (86 out of 182). Failure types of the falsely predicted failed cases remained unchanged (Fig. 8). Also, both Fig. 7 and Fig. 8 show that the barrier pillar stability factor alone makes a good separation and this can be considered as an indicator for the importance of barrier pillars in deep cover retreat mines.

Table 8. Classification accuracies for deep cover cases using the new abutment angle equation using the ARMPS2010 program with ARMPS2010 SF: 1.5 and BP SF: 2.15

	Success Observed	Failure Observed	Total
Success Predicted	86	4	90
Failure Predicted	96	29	125
Total	182	33	215
Accuracy	47%	88%	53%

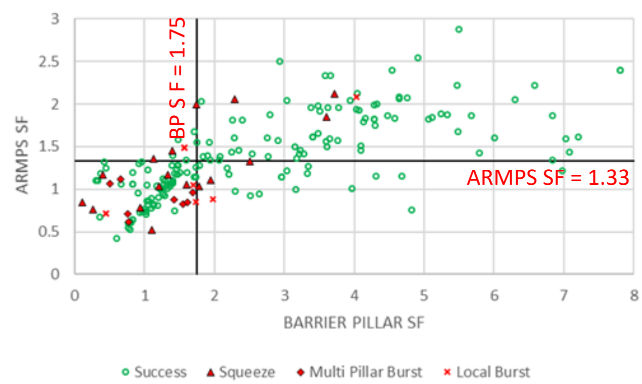

Fig. 8. ARMPS2010 classification capability for deep cover cases that utilize barrier pillars with the new abutment angle equation

5. SUMMARY AND CONCLUSIONS

The ARMPS2010 design software for retreat mining pillar design uses the empirically derived abutment angle of 21° that was derived from field studies conducted in the mid-1980s and 1990s (Mark, 1992; Peng and Chiang, 1984). Modern mine designs use significantly different panel depth and widths compared to these cases. In this paper, traditional calculations for abutment loading are re-examined using a current database of more recent in situ stress measurements from 12 case studies with an additional 18 supplementary case studies.

The re-analysis of the abutment angles presented in this paper show that for higher overburden depths, abutment angles appear to be much less than the traditionally used 21°. Based on the field data analyzed in this paper, a new abutment angle calculation with panel width-to-depth ratio is proposed (see Table 4). When the overburden depth is less than 200 m, the 21° abutment angle proposed by Mark (1992) should be used. It is known from the ARMPS2010 analysis that the 21° abutment angle has been successful for the shallow cover cases (Mark, 2010). However, between depths of 200 to 625 m, the abutment angle should be calculated with the function in Table 4.

Using the proposed new abutment angle equation, cases used to develop ARMPS2010 were re-analyzed. It was observed that for the deep cover cases with barrier pillars, the classification accuracy of ARMPS2010 is improved with the newly proposed abutment angle equation. Further, 88% of the failed cases and 47% of the successful cases were correctly predicted compared to using a constant 21° abutment angle (88% and 34% respectively). It can be concluded that, for deep cover cases, a better classification accuracy can be achieved by the new abutment angle equation.

DISCLAIMER

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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