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Simulation of Macro and Micro responses of yielding rock pillar

Salah Badr, PhD

King Abdulaziz University, College of Engineering, Mining Eng. Dept, Jeddah, KSA

Rock structures (e.g. rock pillars) at deep underground environment may fail in violent mode causing loss of life and property. The failure mode is reliant at both rock structure stiffness and the surrounding loading system. The available violent behavior "assessment predictors" relay on empirical relations and field experience. The numerical modeling seems suitable to relate rock structure macro-scale response and micro-scale yielding of its parts, thus a better "assessment predictor" could be developed.
A simulation exercise of coal pillar yielding phenomenon was conducted. The pillar yielding was numerically simulated using the FLAC3D program for pillars of width to height ratio range 1 to 9. The yielding was simulated based on Mohr-Coulomb failure criterion with a degraded strength parameters (cohesion and friction angle). Various parts of a pillar footprint show different yielding modes with the changes in pillar width to height ratio. The skin of the pillar is the first part to fail and causing footprint area reduction thus transferring loads to the pillar remnants. The model was able to seize quantitatively the energy transferred to pillar remnants from failed skin. The energy transferred was used as an assessment indicator of violent pillar failure. The simulation results indicate that coal pillar violent failure is initiated in pillars of width to height ratio exceeding four at depths exceeding 400m. The highlighted "assessment indicator" is suitable to replicate the phenomenon for various rock types at different pillar sizes with various loading environment.

Key words: Mining, Rock Pillars, FLAC3D, Violent failure and prediction

1. Introduction

Coal pillars are structure elements that are formed during the extraction of coal seams by leaving behind part of the seam to support the immediate roof. The pillar as it carries design loads may fail smoothly "yielding" or suffer instability due to unfavorable loading conditions. This instability "violent failure" is a major safety hazard that noticeably increases with the mining depth. Instability occurs unexpectedly, without warning in form of bump or bounce involving hundreds of tones of rock materials expelling violently to working zones. Significant fractions of the available progresses in this area are related to the global stability of pillar workings. These analyses are global in a sense that individual pillars are treated as single structure unit (macro behavior) without regard to the distribution of stress and strain in them (micro behavior). This assessment global predictor provides an explanation of catastrophic collapses involving many, sometimes even hundreds of pillars. However, this approach does not consider the mechanisms involved in localized failures, such as the rock bumping from the side of a pillar or roadway. Salamon "2003" stated that "If progress is to be made, it is necessary to evolve methods of analyzing the behavior of single pillar "micro-response", up to the moment of instability, taking into account the detailed distribution of stress and strain inside the pillar itself".

In this study numerical modeling exercises are conducted to examine both micro / macro response of single coal pillar due to depth related loading. A pillar FLAC3D " ItascaCG, MN, USA" model is examined at different pillar size and fixed rockmass loading rate (depth related). A Strain-softening Mohr-Coulomb constitutive is used to simulate the coal domains. An acquisition algorithm records the stress and deformation response across diagonal elements of the mid-height of the pillar elements to monitor micro scale behavior of pillar. While, the pillar macro response is developed by averaging behavior of the all pillar elements for both stress and strain. The stress-deformation response is interpreted based on post-peak behavior of elements. A violent failure occurs when an element shows a sudden loss of bearing capacity in terms of abrupt change in strain-strain relation after passing the pillar peak strength. Field experience of documented violent pillar failure cases confirmed the validity of this approach as an "assessment predictor" for iterative design of pillar size to mitigate violent failures.

2. Methods

2.1. FLAC3D® Pillar Model

The model simulates a single pillar in an assumed large room and pillar mine (Figure 1-a). Various symmetry planes are identified in a room and pillar mine layout; the symmetry planes are shown in Figure 1-b.

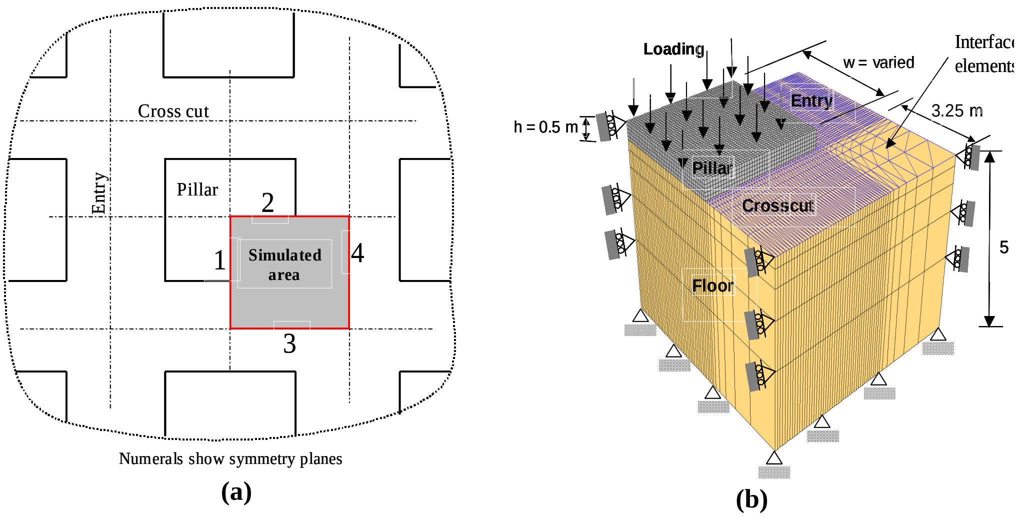

Figure 1: the symmetry lines across a room and pillar mining configuration

The Pillar model simulates the quarter of the lower half of the pillar setting on the elastic floor (Figure 1-b). Mohr-Coulomb interface as shown in Figure 2-b separates the pillar from the floor domain. To maintain the unity element aspect ratio, the number of elements keeps changing for each w/h ratio model while maintaining an absolute element-side length of 0.11 m. The pillar height is kept constant at 1 m while the pillar width changes to simulate the different width/height ratio pillars. A constant entry and crosscut width of 6.5 m is used. The boundary conditions are specified as frictionless for all model vertical planes except pillar ribs facing entries, which are free of any imposed stress or displacement. The vertical displacement at the bottom of the model is fixed. The model is loaded using the constant displacement rate of $2*10^{-7}$ m per FLAC3D step acting on the model's top nodes. The model strength parameters, floor and interface properties are shown in Table 1.

Table 1. Model domains properties

Property	**Value**
Pillar elastic modulus	$3e^9$ Pa
Rock strength	$7.6e^6$ Pa
Rock Poisson's ratio	0.25
Rock Density	1313 kg/m^3
Cohesion Table	[0.0,2.200e6 - 0.0005,2.200e6 - 0.02145, 1.050e5 – 0.100,1.050e5]
Friction Table	[0, 23 0.0005, 30 0.0370, 30]
Dilation Table	[0, 0 0.0005, 15 0.010, 15 0.030, 5]
Floor elastic modulus	$20e^9$ Pa
Floor Poisson's ratio	0.25
Floor density	2500 kg/m^3
Interface type	Mohr-Coulomb
Interface cohesion	0.5e6 Pa
Interface friction angle	20^o

2.2. Running the FLAC3D® Pillar Model

The pillar model simulates pillars of width to height ratio ranged from 1 to 9. The model is assumed to have zero virgin stresses before being loaded. The simulation procedure starts with an elastic run to develop the contact stresses on the interface elements. After reaching equilibrium, the pillar elements are assigned MCSS "Mohr-Coulomb Strain Softening" material model while the floor remains elastic. The entry and crosscuts are mined all at once and the constant displacement loading of $2*10^{-7}$ m per FLAC3D step is immediately applied on pillar top nodes. The run is stopped when most of pillar elements experience considerable yielding.

2.3. Pillar Responses Monitoring Protocol

The behavior of the model is monitored by means of recording histories of vertical stress and deformation at all the elements located at the top of the model (pillar mid-height). The FISH (FLAC3D built-in programming language) is used to develop an algorithm for real-time estimates of the average pillar stress-deformation curve at all pillar top elements histories "macro response". The history records of individual elements across the diagonal of the pillar represent the micro response of the pillar (Figure 2).

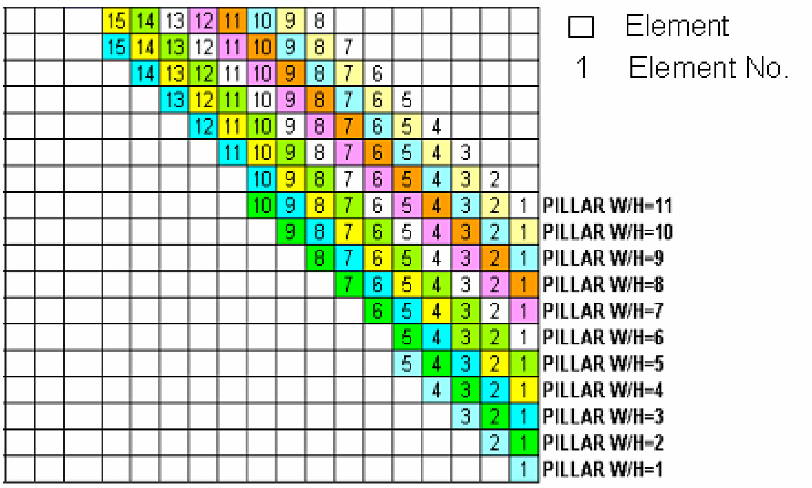

Figure 2: Stress- deformation recording locations across the model diagonal

3. Model Runs Outcomes

By closely examining the stress-deformation graphs of the pillar model elements at varied width to height ratio the elements failure modes can be summarized as follow:

1. For w/h = 1, 2 and 3 pillars, the elements stress-deformation graphs show smooth post peak behavior for all diagonal zones (Figure 3).

2. For w/h = 4 pillar, elements 17, 18, 19, and 20 show a tendency for steep strength loss (Figure 4).

3. In the range $5 \leq w/h \leq 9$, a band of the diagonal elements close to the pillar side show noticeable steep strength loss (Figure 5). The steep strength loss practiced by these band of elements is specific in the following:

    a) The elements involved have the same relative location from pillar side. Specifically speaking, elements involved are number 10, 11, 12, 13, 14 and 15. Accordingly, the highly stressed area that later practiced steep strength loss is located at 1:1.5 times the height of the pillar.

    b) When the steep strength loss occurred, the maximum stress experienced by the concerned elements and the average pillar displacement were almost constant. For example, zone 14 showed the following status at different w/h pillars:

W/h	Zone peak stress (MPa)	Zone compression (m)
5	64	0.0125
6	60	0.0123
7	59	0.0124
8	58	0.0125

4. W/h ratio 5 pillar has noticeably different mode of failure when compared to w/h ratio 4 pillar. The w/h ratio 4 pillar completely yielded while w/h ratio 5 pillar partially yielded and the pillar core "element beyond No 20" became highly stressed.

5. For w/h = 9 pillar; different mode of failure is detected. The highly stressed area that later practiced steep strength loss moved inward and now located at 1.4 to 2 times the pillar height (Figure 6). Zone 14, the first to practice steep strength loss, showed a 38 MPa peak strength that is noticeably lower than an average of 60 MPa for w/h 5 to 8 pillars range.

6. The steep strength loss at the specified band of zones induced similar response at the average pillar stress-deformation curves "Macro-Scale" (Figure 7). The impact is discrete since large numbers of zones (all top pillar zones) are included on the averaging process.

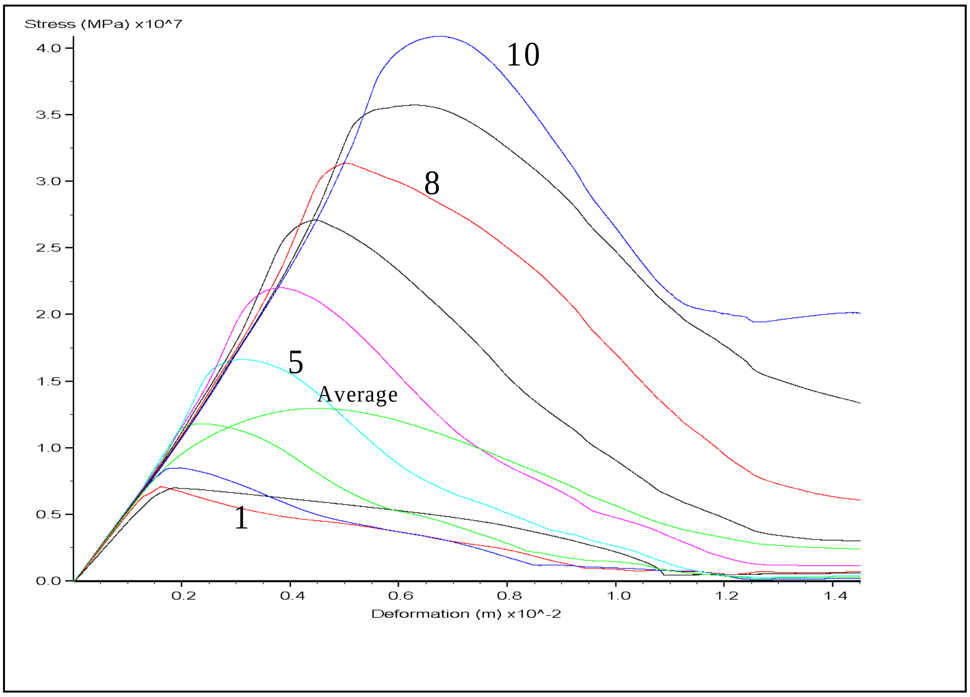

Figure 3**:** Benchmarked element stress versus average pillar deformation (w/h = 2)

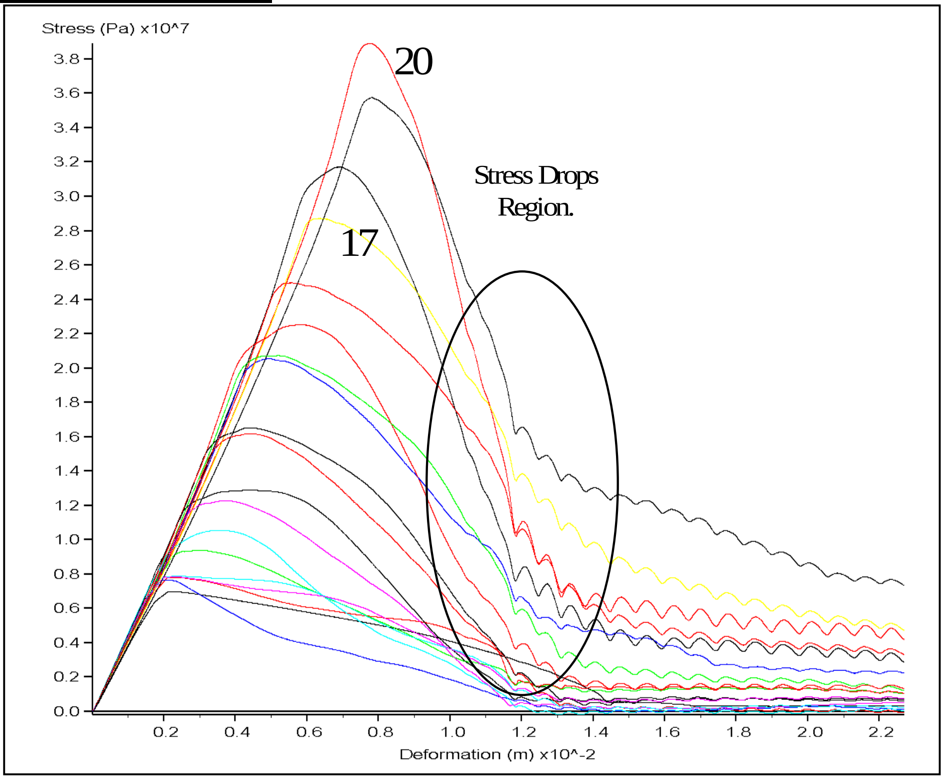

Figure 4**:** Benchmarked element stress versus average pillar deformation (w/h = 4)

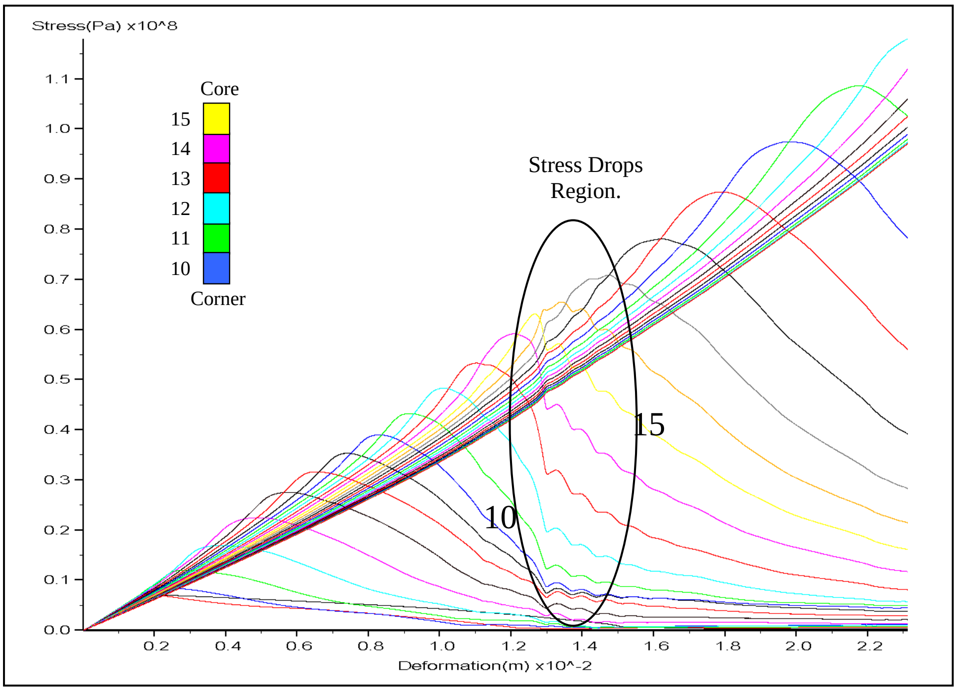

Figure 5**:** Benchmarked element stress versus average pillar deformation (w/h = 6)

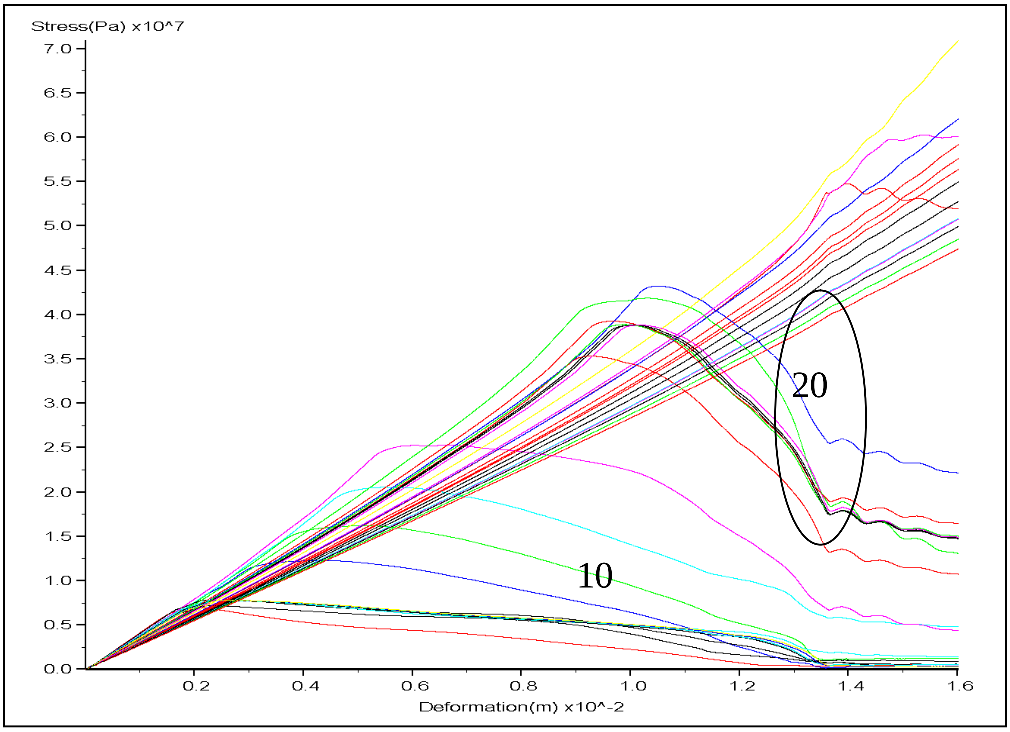

Figure 6**:** Benchmarked element stress versus average pillar deformation (w/h = 9)

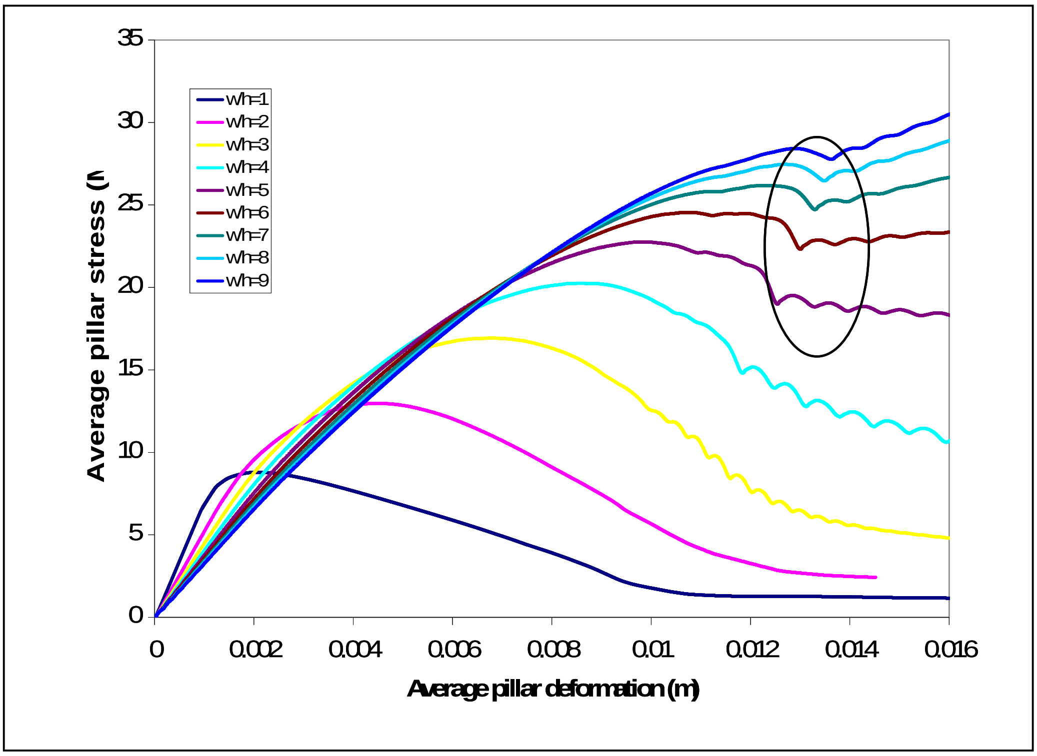

Figure 7: Average pillars vertical stress versus deformation for pillar model

4. Verification of Model Outcomes

Modeling outcomes showed consistent mode of failures at micro/macro scale, however back analysis must confirm the occurrence of physical stability to validate models' outcomes. DeMarco in 1996, after surveying coal pillar sizes of the US deep longwall mines, published a chart showing the pillar's practical sizes that maintain serviceability of its entries as long as mining activity is needed (Figure 8). According to DeMarco the successful cases caused no major 'instability' while unsuccessful cases did. The chart showed that the pillars are categorized into three groups: stable yielding (w/h ratio 3:5), unstable critical (w/h ratio 5:10) and stable abutment pillar (w/h ratio 10 and higher). Comparing the outcomes of the modeling studies with DeMarco pillar grouping significant similarities revealed (Figure 8).

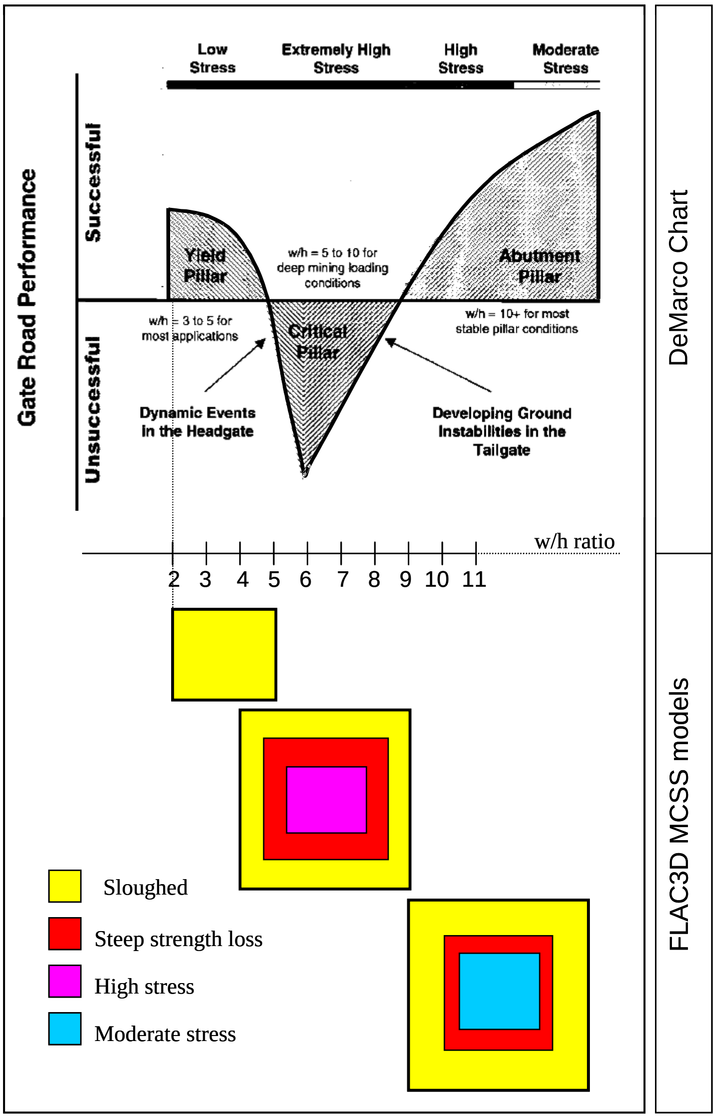

Figure 8: Verification of model results versus DeMarco's conceptional diagram of the instable pillar

5. Conclusions

The FLAC3D program utilizing MCSS failure criterion was able to capture particular pillar instable modes of failure that correlate well with the physical instability studies and observations.

Part of the importance having a " assessment predictor" to forecast pillar local instabilities is the fact that none of the current pillar design approaches have the ability to predict or account for instability. Future areas of research would include the validation of MCSS model mesh dependency and the implementation of the rockmass load lines to quantify severity of the instability events.

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