Calculating the Potential for Coal Pillar Bumps Using a Local Mine Stiffness Criterion

Kaifang Li, Heasley, K. A.
Dept. of Mining Engineering, West Virginia University, Morgantown, WV

ABSTRACT: Coal mine bumps are a serious safety problem in coal mines and they are very hard to predict due to the poor understanding of the exact mechanics of this dynamic failure phenomena. However, previous research has demonstrated that the local mine stiffness (LMS) criterion is a promising approach for analyzing the possibility of violent pillar failure. Typically, the local mine stiffness calculation quantifies the loading stiffness of the surrounding rock mass and compares that to the stiffness of the support pillars in the post-failure range in order to determine if a pillar failure in the mine will occur in a stable or unstable manner. If the loading stiffness is softer than the support stiffness, a dynamic failure can occur. With this knowledge ahead of time, mine engineers can modify the geometries and pillar sizes in the mine design to help eliminate violent pillar failure.

In this paper, the principles of the LMS criterion for evaluating stable versus unstable failure are reviewed. Then the mathematical techniques used to implement a LMS calculation into LaModel are presented. Next, a simple idealized model is used to demonstrate and quantify the effects of rock mass stiffness and mine geometry on the LMS calculated by LaModel. Then, an actual coal mine, pillar bump accident is back analyzed with the LaModel code with the recently implemented local mine stiffness calculation. The numerical model was initially calibrated to thoroughly match the observed mine failure, and then the local mine stiffness and post-failure pillar stiffness were calculated and compared. In this mine model, the mine stiffness steadily decreased to eventually match the pillar stiffness at the time of the observed violent failure. This case study demonstrated that the local mine stiffness criteria can be successfully calculated and applied, but the accuracy of the calculation is very dependent on accurate rock mass and pillar properties.

1. OVERVIEW

Pillar bumps are a longstanding ground control problem associated with coal mining. This kind of pillar failure has presented serious safety problems in the United States throughout the 20th century [1, 2]. In order to attack the problem of bumps, the local mine stiffness stability criterion has been recognized as a reasonable analysis approach and it provides a means to distinguish if the pillar will fail in a stable or unstable manner [3, 4].

Although this theoretical criterion has been well established for a long time, there are still significant gaps in our ability to accurately evaluate the stability of pillars with it due to the challenges of accurately determining the post-failure pillar stiffness and the local mine stiffness in a mining layout [2].

2. LOCAL MINE STABILITY CRITERION

In 1970, Salamon extended the laboratory system stability criterion to full-scale mine pillars using the concept of local mine stiffness (LMS). Equations 1 and 2 illustrate this well-known criterion mathematically and Figure 1 explains the criterion graphically. Stable, nonviolent failure occurs when the absolute value of the local mine stiffness (|K_{LMS}|) is greater than the absolute value of the post-failure pillar stiffness (|K_P|) (at any point along the post-failure load-convergence curve for a pillar):

\[ |K_{LMS}| > |K_P| \tag{1} \]

And unstable, violent failure occurs when the absolute value of the local mine stiffness (|K_{LMS}|) is less than the absolute value of the post-failure pillar stiffness (|K_P|)
According to the stability criterion, the hatched area in Figure 1b is the excess energy put into the pillar that is not consumed by the failure process of the pillar. The LMS approach essentially postulates that this excess energy is then available for the dynamic failure of the pillar.

\[ |K_{LMS}| < |K_P| \]  \( (2) \)

Figure 1. Stable, nonviolent failure (a) vs. unstable, violent failure (b) (after Salamon, 1970)

To evaluate the mine design using the LMS criterion, the in situ values of both the mine stiffness and the post-failure pillar stiffness must be determined. Unfortunately, neither of these values is very easy to obtain from field measurements. A jacking test in the entry might be used to develop a local roof stiffness value, but how well this entry value will correlate to the mine stiffness over the pillar is questionable. For the pillar, laboratory tests could be performed on specimens of various sizes and width-to-height ratios to determine the post-failure stiffness of the various specimens; but again, how well the laboratory values will extrapolate to the in situ values is questionable.

2.1 Local Mine Stiffness Determination

Without any reliable field tests for determining local mine stiffness, researchers have historically used analytical or numerical analysis for investigating the LMS. Specifically, in 1970, Salamon developed an analytical approach, and in 1968, Starfield and Wawersik [5] proposed a numerical approach. With the advent of computers and geo-mechanical models for mines which could quickly calculate stress and displacements values at the seam, the numerical approach for determining LMS gained the most popularity [2, 6, 7].

In these numerical models, a technique known as the “perturbation method” was used to determine the LMS from a converged stress and displacement solution for a given mine plan. With the perturbation method, the equilibrium stress on the area of interest (elements or pillar) is artificially changed, or perturbed. The model is allowed to again reach equilibrium with the new stress on the area, and the associated change in seam displacement over the area is noted. The perturbation method is essentially a numerical simulation of a using a hydraulic jack to pressurize (or depressurize) the mine roof. The ratio of the force increment over the resulting displacement increment is defined as the local mine stiffness for that particular area:

\[ K_{LMS} = \frac{\left( S_u - S_p \right) \times A}{D_u - D_p} \]  \( (3) \)

Where:
- \( K_{LMS} \) = local mine stiffness
- \( S_u \) = unperturbed stress
- \( S_p \) = perturbed stress
- \( D_u \) = unperturbed displacement
- \( D_p \) = perturbed displacement
- \( A \) = test area

In LaModel [8], the mine is typically perturbed by removing a pillar and changing the area to an opening with zero stress; therefore, Equation 3 can be simplified with a perturbed stress value of zero.

2.2 Post-Failure Pillar Stiffness Determination

As implied above, the most reliable approach to determine the post-failure pillar stiffness would be to load a pillar to failure directly in the field, and then obtaining the stiffness from the post-failure load-deformation curve of the pillar. However, such field measurements are not very practical; and therefore, the only post-failure measurements that are available come from laboratory specimens and very small pillars tested in the field [9, 10, 11]. As with the determination of the local mine stiffness, the pillar
post-failure stiffness has most commonly been done numerically.

In LaModel, pillars are composed of elements with individually specified stress strain behavior (typically strain-softening for LMS calculations). The behavior of the pillar is then determined by the composite behavior of the elements. Using the stress-strain behavior of each element and assuming a constant strain across the pillar, the composite stress-strain curve for the pillar can be calculated. With this pillar stress-strain curve, the post failure pillar stiffness can be numerically calculated at any post-failure strain value.

2.3 Simple Validation Model

In an actual mining situation and in LaModel, the local mine stiffness partly depends on the stiffness of the surrounding rock mass and partly on the geometry of the mine plan. When the local mine stiffness was first programmed into the LaModel program, a number of simple models were run to investigate the influence of the rock mass stiffness and mine geometry on the calculated LMS. In LaModel, the lamination thickness and elastic modulus of the rock mass primarily control the stiffness of the rock mass [12]. If the elastic modulus is kept constant, a lower value for lamination thickness implies softer strata and a higher value implies stiffer strata. The geometric impact in LaModel comes primarily from the amount of opening versus support material surrounding the LMS area, and secondarily from the stiffness of the surrounding support. When there is a lot of opening (or soft material such as gob or failed pillars) around the LMS area, the local mine is softer and when the LMS are surrounded with stable support (stiff, stable pillars) then the LMS is stiffer.

Figure 2 is a schematic of a number of simple models that were run in LaModel to validate, analyze and document the effects of the rock mass stiffness and mine geometry on the LMS.

In this simple mine layout, D is the open distance from the central pillar to the surrounding pillars; therefore, different values of D imply different amounts of opening around the central pillar. In this analysis, D was varied from 30 to 152 m (100 to 500 ft) and the rock mass lamination thickness (t) was varied from 15 to 152 m (50 to 500 ft).

![Figure 2. Lamination thickness and pillar geometry calibration](image)

The central pillar dimension was 30×30 m (100×100 ft) and the surrounding pillars were 24×24 m (80×80 ft). The seam was modeled as 1.8 m (6 ft) high with an elastic modulus of 300,000 psi and 183 m (600 ft) deep. In these models, the local mine stiffness was calculated for the area of the central pillar. The strain-softening properties of the elements in the pillars were determined using the approach recommended by Karabin and Evanto [13], which is specified by the following equations:

\[
S_p(i) = S_l \times (0.64 + 2.16 \times (x/h)) \\
\epsilon_p(i) = S_p(i)/E \\
S_R(i) = S_l \times A \times (x/h)^B \\
\epsilon_R(i) = 4 \times \epsilon_p(i)
\]

Where:

- \(S_l\) = in situ coal strength (psi)
- \(x\) = distance from element center to free face (ft)
- \(h\) = seam height (ft)
- \(E\) = coal seam modulus (psi)
- \(S_p(i)\) = peak stress of element (psi)
- \(\epsilon_p(i)\) = peak strain (in/in)
- \(S_R(i)\) = residual stress of element (psi)
- \(\epsilon_R(i)\) = residual strain (in/in)
- A&B = residual stress control parameters

Model results in Figures 3 and 4 clearly demonstrate the effect of rock mass stiffness and mine geometry on the LMS. In the Figures, it can clearly be seen that increasing the lamination thickness (t) for a given opening distance (D) increases the unloading stiffness of the mine in the central pillar area. Similarly, it can also be seen that increasing the opening distance (D) for a given lamination thickness decreases the unloading stiffness of the mine in the central pillar area. Finally, for this
simple validation model, it can be seen that the lamination thickness in LaModel has a relatively greater influence on the LMS than the opening distance.

All model input parameters were previously calibrated so that the pillar failure in the model of the South Barrier Section coincided with the timing and geometry of the actual failure [14]. Specifically, the major input parameters included: a lamination thickness of 152 m (500 ft), a final modulus of the southern gob of 1103 MPa (160,000 psi), a coal strength in the North and South Barrier sections of 8.96 MPa (1300 psi) and a slightly raised coal strength in the Main West of 9.38 MPa (1360 psi).

The strain-softening coal behavior was calculated using Equations 4 to 7 above and the residual stress was set with a 33% reduction from the peak stress. Using these coal properties, the complete stress-strain and pillar stiffness behavior of the 18×34×2.44 m (60×110×8 ft) pillars in the South Barrier section can be determined as shown in Figure 6. The stress-strain behavior shown in the figure is typical for a strain-softening coal pillar. Throughout the loading of the pillar, the pillar stiffness starts high and positive, and the fairly consistently decreases. At the point of pillar failure, the stiffness goes sharply negative and then slowly increases back to zero at the residual stress level. It is the magnitude of the peak, post-failure stiffness of a pillar that determines how likely it is to fail dynamically. In this model, please note that the peak, post-failure softening modulus of these pillars is approximately -700 psi/in.

3. BACK ANALYSIS OF CASE HISTORY

In order to further evaluate the utility of the local mine stability calculation in LaModel, the cascading pillar failure (CPF) which occurred at the Crandall Canyon mine on August 6th, 2007 [14] was back analyzed with the program. In this back analysis, the modeling concentrated on the mining in the South Barrier Section and 5 steps were used to simulate the extraction in that area (see Figure 5). The first step was the extraction of the initial 14 pillars and the slab cut at the end of the section. Then, steps 2 through 3 were successive slab cuts into the southern barrier pillar, and finally, two pillars were removed in steps 4 and 5 at the location of the mining when the collapse occurred (see Figure 5).

Figure 3. Local mine stiffness behavior as a function of lamination thickness

Figure 4. Local mine stiffness behavior as a function of mine geometry
This final calibrated model, as shown in Figure 7, does a fairly good job of simulating the observed results at the Crandall Canyon Mine [14]. In mining step 1, after 14 pillars had been retreat in the south barrier section, most of the remaining pillars in the South Barrier section exhibit a safety factor just above 1.0. Then, after removing the barrier coal and two pillars through mining step 5, the August 6th collapse is simulated. The removal of this minor amount of coal has caused the model to show an additional 94 pillars failing in the Main West and 59 pillars failing in the South Barrier section. And the failure runs from crosscut 125 to crosscut 147 in the South Barrier section (see Figure 7).

The local mine stiffness calculation in LaModel was then used with the calibrated model to analyze the local mine stiffness around pillars 1 and 2 (see Figure 5). As previously discussed, the local mine stiffness values at the locations of pillar 1 and pillar 2 for each mining step were derived by removing the pillar to perturbing the model, and then determining the change in displacement that resulted from the perturbed stress (see Equation 3).

The comparison of the calculated LMS around pillars 1 and 2 against the pillar stiffness is shown in Figure 8. As seen in the Figure, during steps 1 to 3, the mine stiffness at the location of Pillar 1 and 2 was relatively stiff. But as slab cut 3 was taken and then the pillar in step 4 was removed, the mine stiffness “decreased” (a decrease in the absolute value) dramatically, until the mine stiffness approached the pillar stiffness curve at mining step 4. At this mining step, the local mine stiffness is very close to the stiffness of the pillar and LMS theory would suggest that a dynamic failure could possible occur.

It needs to be noted here that LaModel will never actually converge to a solution where the LMS is less that the pillar stiffness. As shown in Figure 1b, if the LMS is less than the pillar stiffness, then the stress applied by the mine roof is typically more than the level that the pillar can support. In this situation, LaModel would keep iterating until the stresses (and displacements) balance. In other words, the pillar where the LMS criterion is violated will continue to fail/strain and the convergence will increase until the stresses and stiffness equalize between the mine and the pillar. So, when LaModel encounters a situation where the LMS is less than the pillar stiffness, the model shows a “excessive” amount of pillar yielding and failure for a relatively small mining step (as seen in Figure 7 between steps 1 and 5). Therefore, when using LaModel to determine the mine stability, the user should look for excessive pillar yielding/failure associated with a relatively small change in mine geometry and/or a value of the LMS close to the peak post-failure modulus of the pillar. It is suggested that either one of these situations is sufficient to indicate a potential unstable failure.

Also, in this analysis, the trigger for the pillar collapse was failure in the coal pillars around pillar 1&2. This strain-softening coal failure then progressed across the south barrier section. Other possible mechanisms that could have triggered the collapse include failure in the roof or floor, or failure of the coal in other nearby areas of the mine. (These other triggers may have also shown a low LMS.)
Some of these other collapse triggers are investigated in [14].

Further, it needs to be noted here that the change in mine stiffness at the point of the Crandall Canyon Mine collapse was not due to a change in the surrounding roof/floor stiffness or a large change on the mine geometry (as demonstrated with the validation model), but rather, the LMS was primarily reduced at the time of the collapse due to yielding of the surrounding entry and barrier pillars. Obviously, this massive area of pillar yielding caused an associated drop in the LMS. This observation also leads to the insight that the pillar collapse and associated drop in LMS are both very sensitive to an accurate pillar yield strength.

Figure 8. Pillar stiffness and local mine stiffness for pillar 1 and pillar 2

4. SUMMARY AND CONCLUSIONS

In this paper, the principles of the local mine stiffness criterion for evaluating stable versus unstable failure are reviewed. Then, the perturbation method is introduced and presented as a reasonable method to numerically calculate the LMS in LaModel. Also, a technique for determining the complete stiffness curve of a pillar by combining the stress-strain curves of the pillar elements is described. Next, a simple idealized model is used to demonstrate and help quantify the effects of rock mass stiffness and mine geometry on the LMS calculated by LaModel. Finally, a model of the Crandall Canyon Mine which was successfully calibrated to accurately show the observed pillar collapse is used to investigate the LMS calculation. Using this mine model, the local mine stiffness is seen to drop to the level of the post-failure pillar stiffness at the time of the mine collapse.

A number of conclusions can be drawn from this research. First, the Local Mine Stiffness calculation has been successfully implemented into LaModel and the validation model demonstrates that the calculation appropriately responds to deviations in rock mass stiffness and mine geometry. Also, when applied to an actual case history of a massive pillar collapse/bump, the LMS calculation correctly shows the mine stiffness dropping to the level of the post-failure pillar stiffness at the time/geometry of the collapse. However, this case history also highlighted the limitation of LaModel that it will not converge to a solution where the mine stiffness is less than the pillar stiffness due to its requirement to reach a stable equilibrium at each solution step. Therefore, it was also concluded that when using LaModel to determine the mine stability, the user should look for a value of the LMS “close” to the peak post-failure modulus of the pillar and/or excessive pillar yielding/failure associated with a relatively small change in mine geometry to indicate a potential unstable failure. In the future, with additional case histories of LMS calculations, a reasonable “safety factor” between the LMS and the post-peak pillar stiffness may be determined.

The research presented in this paper, also produced a couple of critical insights related to the numerical calculation of the mine stability using the LMS. First, while performing this research, it was clear that the calculated local mine stiffness values were highly dependent on the values of the critical input parameters. This dependency was demonstrated both by the results of the validation model as shown in Figures 3 and 4, and by the observed sensitivity of the case history results to the input pillar yield strength.

Now, it has always been known with numerical modeling that the accuracy of the model results are directly dependent on the accuracy of the model input values, hence the old adage, “garbage in, garbage out.” However, with the LMS calculation and criterion, the ability to obtain accurate values for all of the critical input parameters (mine geometry, rock mass stiffness, and pillar strength and stiffness) is very limited. The mine geometry is probably the one parameter with the least amount of problem in
getting good input data, since accurate mine maps are typically available. Determining an accurate rock mass stiffness is always a concern with a mine model [12], but there is much more leeway in the value of the input rock mass parameters to get a reasonable result when calculating pillar stresses and safety factors, than when precisely calculating a LMS. In regard to having the accurate input parameters needed to calculate an accurate pillar strength, it is probably about equally important for either pillar safety factor or LMS calculations, and considerable previous research has been done in this area. However, to fully evaluate the LMS criteria, the post-failure stiffness of the pillars needs to be accurately determined and there is extremely limited data or research on how to develop accurate input parameters for this determination.

While performing this research, in addition to the importance of accurate input parameters, it was also observed that the actual geo-mechanical approximation being modeled needs to be very realistic to calculate an accurate/realistic LMS. LaModel, like all numerical methods, uses a simplified geo-mechanical model of reality in order to perform calculations. Specifically, LaModel simulates the overburden as a stack of homogeneous (identical thickness, elastic modulus and Poisson’s ratio) laminations with frictionless interfaces, and simulates the in-seam material with input vertical stress-strain curves. For the Crandall Canyon case history, the LMS calculation in LaModel correctly indicated the observed unstable failure, which was easy to simulate with the model. However, it is easy to envision actual unstable mining situations which are more localized and may incorporate local anomalous behavior for which the simplified geo-mechanical model used in LaModel will not provide a realistic enough model to accurately simulate the observed instabilities.

REFERENCES
