Effect of lithological variations of mine roof on chock shield support using numerical modeling technique

A K Verma and D Deb

1Department of Mining Engineering, BESU Shibpur, Howrah 721 302
2Department of Mining Engineering, Indian Institute of Technology, Kharagpur 711 103

Received 30 August 2005; accepted 10 May 2006

Interaction between chock shield supports, the most popular powered supports in Indian longwall mines, and surrounding coal measure strata is analyzed using finite element models. Thickness and material properties of the main roof, the immediate roof and the coal seam are varied to simulate various geological conditions of Indian coal measure strata. Contact/gap elements are inserted in between the main roof and overburden layer to allow strata separation. Nonlinear material properties are applied with plastic corrections based on Drucker-Prager yield criterion. This paper illustrates effects of lithological variations on shield load, abutment stress, yield zone and longwall face convergence.

Keywords: Chock-shield, Drucker-Prager, Finite element method, Longwall, Regression

IPC Code: E21C41/28

Introduction

Longwall method is the most productive and efficient underground coal mining method especially for deep coal seams in USA, China, South Africa and European countries, whereas in India, it faced with both successes and failures. Several longwall faces in India had collapsed due to adverse geological conditions and/or inadequate capacity of powered supports. In some cases, entire panel and equipments had to be abandoned due to severity of damage occurred in the form of roof and face collapse. In most of the mines (250 m deep), 4x550 to 4x800 ton capacity chock shields are used to support the roofs.

Lithology of Indian Coal Measure Rocks

Rock lithologies above coal seam are significant factors in mine stability, particularly with respect to their strength properties. In Indian coal measure rocks, two particular roof rock sections viz. immediate roof and main roof, have been well accepted. Generally, composition of these roofs has great influence on pressure distribution at a longwall face. Excessive growth of main roof cantilever can cause severe periodic weighting while the weak immediate roof can create roof fall problems in between the canopy and the coal face. Indian coal measure strata accounts for more than 90% of sandstone and shale, whereas 50-85% of coal measure rocks comprise of sandstone. Immediate roof, consisting of weak and soft carbonaceous shale, sandy shale, laminations of shale in argillaceous sandstone, soft and fractured intercalation, etc., caves in shortly after the roof support advances, without forming any step or overhang.

Main objective of this study is to evaluate the loading behavior of powered support and conditions of longwall face for different geological variations of main roof, immediate roof and coal seam. Study provides a comprehensive understanding of loading pattern on powered support in terms of lithological variations of roof strata especially for identifying the cause of support yielding.

Materials and Methods

Coal measures strata in Jharia and Raniganj Coalfields of India were modeled to analyze loading behavior of chock shields. Typical dimensions of Indian longwall panel are: width, 120; length, 850-1000; depth, 50-300; and average height of extraction, 2.4 m. Behavior of coal measure strata were thoroughly studied and explained through a generalized borehole litholog (Fig. 1). A number of
layers of rock were either grouped into composite layers or simply taken as a unit rock layer, depending upon the nature, thickness and physico-mechanical properties of rock. For Finite Element Model (FEM), material properties and thickness of roof strata and coal seam are varied to generalize the region of coal measure strata.

In FEMs, 4x550 ton capacity Gullick-Dobson powered support is used for the analysis of interaction between support and surrounding rock strata. Hydraulic legs of powered support are assumed to be elastic-perfectly plastic material upon yielding. All rock and coal strata are modeled with nonlinear material based on Drucker-Prager yield criterion.

In this study, six lithological variations of the geological strata above the longwall panels of Jharia and Raniganj Coalfields are proposed. The thickness of immediate and main roofs are taken as the ratio of the height of extraction (Table 1, Fig. 2).

\[
\pi_1 = \frac{E_m}{E_C}, \quad \pi_2 = \frac{E_i}{E_C}, \quad \pi_3 = \frac{T_m}{T_C}, \quad \pi_4 = \frac{T_i}{T_C}, \quad \pi_5 = \frac{E_C}{MCM}
\]

where, \(E_m\) = Modulus of elasticity of main roof, \(E_C\) = Modulus of elasticity of coal seam, \(E_i\) = Modulus of elasticity of immediate roof, \(T_m\) = Thickness of main roof, \(T_C\) = Thickness of coal seam, \(T_i\) = Thickness of immediate roof, and \(MCM\) = Mean Coal Modulus.

Based on the three variations of thickness (4.8m, 12m and 19.2m) and modulus of elasticity of the main roof, the linguistic hedges such as "thin", "thick" and "thicker" roof strata are defined as below 8 m, between 8-15 m and above 15 m respectively. Similarly, "weak", "hard" and "massive" roof strata will be signified by a ratio of \(E_m/E_c\) as 1-3, 3-8 and more than 8, respectively.

Two-Dimensional FEM Analysis

The 2D FEM elasto-plastic analysis are performed using structural analysis software ANSYS. In this study, 2D plain strain condition is simulated. Mesh is developed by quadratic 6-noded triangular elements (Fig. 3a), which describe structural characteristics of longwall mine viz. longwall face, chock-shield support, main/immediate roof, overhang length of main roof, gob, contact planes, and various rock layers. Zoomed view of the longwall face (Fig. 3b) describes structural characteristics of chock-shield support such as canopy, base, hydraulic legs, lemniscate links, pins and gob shield. Domain for FEM is the vertical cross-section along center axis of the longwall panel. Boundary of the model is taken far away from region of interest (longwall face) so as to minimize the end effects around longwall face area. Total width of the model (200 m) consists of 100 m of intact coal in front of face and rest 100 m consists of working area, gob and the chain pillars at mine boundary. Total height of the model (82.4 m) consists 50 m above the coal seam and 30 m below the seam. Additional 50 m of overburden load is applied uniformly on top of the model as an external load to simulate a depth of 100 m from surface to the roof level. FEM model consists of 21,129 elements and 43,097 nodes. Separation of main roof with superincumbent strata is simulated by 2-noded point-to-point contact elements; total of 96 contact elements are used. Normal stiffness \((K_n)\), shear stiffness \((K_s)\)
Fig. 2—Geometrical (thickness) variations of roof at longwall face

Fig. 3—a) Finite element model of longwall panel along central axis; b) Close view of FEM model of longwall face
and coefficient of friction are taken as 10 MN/m, 2 MN/m and 0.3 respectively for each model.

Periodic weighting interval varies (21-22 m) from one seam to the other at Jhanjra longwall project in Raniganj coalfield. Hence, in this study, main roof overhang length (22 m) is modeled behind the face line to simulate non-periodic/periodic weighting condition depending on the lithological strata. However, overhang length depends upon thickness of the roof rock layer and physico-mechanical properties of rocks, thickness of the roof rock layer and others. Gravity load is applied by assigning the materials’ unit weights. For the boundary conditions, the horizontal displacements are constrained on two vertical sides and the vertical displacements are restrained at the bottom of the model.

Material Model and Parameters
Rock Layers

Drucker-Prager failure criterion is used for the material yields with a smooth failure surface. Every rock layer is assumed to be isotropic, homogeneous, and elasto-plastic material. The material properties used for each rock layer (Table 2) are determined from laboratory tests, field tests or by referring to relevant geological data. Rock mass properties, mainly compressive strength, cohesion and elastic modulus, are reduced by a factor of 1/5 of the values obtained from laboratory tests. Weak and strong coal is considered with elastic modulus of 1 GPa and 2 GPa respectively. Cohesion and friction angle of roof strata are varied to analyze the effect of loading on powered support.

Components of Hydraulic Powered Support

Except hydraulic legs, all other components are assigned hard steel properties. Legs are assigned non-linear elastic properties based on load-deformation characteristics of the chock shield support (Fig. 4). There are three different phases of loading conditions (oa, ab and bc) on shield legs. In initial phase (oa), shield leg has a near zero modulus of elasticity to simulate the first-stage deflection caused by gravitational load of overburden strata and pre-existing deformation of surrounding strata before shield is advanced and reset with the roof. From in situ FEM models, 6 mm of initial roof to floor convergence is obtained. In second phase (ab), operating phase, an equivalent elastic modulus or stiffness of the shield leg is assigned. In third phase (bc), perfectly plastic behavior is modeled once the load on shield exceeds its yielding capacity. Yield stress for 550-ton capacity powered support is found to be 35.4 MPa per leg. Elastic modulus of phase (ab) is calculated on the basis of yielding load and corresponding maximum leg convergence in the shield leg, as given in the following equation:

\[ K = \frac{\frac{P_m - P_0}{U_m - U_0}}{A} \]
where, \( K \) = Elastic modulus of hydraulic leg; \( A \) = Equivalent cross-sectional area of shield leg, 0.0381 m\(^2\); \( L \) = Length of shield leg, m; \( P_m \) = Yield load, 34.5 MPa; \( P_0 \) = Load at \( U_0 \), 1 MPa; \( U_m \) = Maximum leg convergence corresponding to \( P_m \), 0.026m; and \( U_0 \) = Leg-convergence corresponding to \( P_0 \), 6mm.

Based on above relation, elastic stiffness of hydraulic leg in phase ab is estimated to be 1475 MPa for the front leg and 1470 MPa for the rear leg for an extraction height of 2.4 m. Modulus of elasticity for both lemniscate links is 206.8GPa and the equivalent cross section area of the upper and lower lemniscate links are measured as 0.143m\(^2\) and 0.012m\(^2\) respectively.

**Goaf/Gob**

Caved rock mass that forms gob plays an important role in supporting the overburden strata. The degree of compaction of caved rock mass affects the capacity of gob to support overburden. Theoretically, if compaction occurs fully in the gob area, then vertical stress will reach to \textit{insitu} stress, which is usually achieved at a distance of \( 1/3 \) rd of the mining depth from faceline. In this study, for a depth of 100 m; \textit{insitu} stress would be achieved at a distance of about 33 m from faceline. To account for increasing compaction of gob, three zones are assigned based on three compacting conditions (loosely packed, packed and well packed gob regions). Stress-strain characteristic of gob material is taken to be linear (Table 3).

### Concepts of Longwall Support Load

Loading at longwall face is manifested by main roof as a cantilever beam behind the powered supports. Length of cantilever depends upon strength, thickness, and elasto-plastic properties. As cantilever length increases, load on the face and powered support increases. At a particular length, when cantilever load exceeds its strength, cantilever breaks.

Two concepts of loading on longwall support are given as:

**Detached Roof Rock Mass (Dead Weight)**

As the length of cantilever beam grows to a sufficient length, it may break ahead of the longwall face. Measurement of shield pressure data shows that main roof can break about 3-6 m ahead of the face. In case of weak and thick main roof strata, a dead weight is applied on top of the powered support once the roof breaks ahead on the face line (Fig. 5). Powered support capacity in this situation is estimated by the largest roof block liable to need support. In case of weak and thin roof, length of roof cantilever beam is short. For massive and thicker roof, the interval of cantilever beam is very high.

**Deflection of Roof Strata**

Roof cantilever can grow to a considerable length if the rock strata is hard-massive and thick-thicker. Then roof beams will deflect and may separate with each other (Fig. 6). The load carrying capacity of the roof strata does not diminish owing to the deflection. The roof strata are self-supportive meaning that it can support the overburden load. At this time, loading on the shield is low. However, when the roof strata breaks ahead of the face, it caused tremendous load on the shield and sometimes air blast also occurred. This phenomenon is sometime referred as uncontrollable periodic weighting.

### Results and Discussion

Load distribution among supporting elements (Powered support, Goaf and Coal face) must comply with conservation of energy requirements in such a way that the combined work of coal, powered supports, and goaf must equal the loading imposed by overlying rock mass. This means that if coal bed is very strong and part of the overburden load can be supported by goaf, the loading on powered supports will be considerably less. On the contrary, if coalbed is weak and deformable and goaf is newly formed then load on powered support will be higher. Results obtained from FEM analysis also support this concept.

**Abutment Pressure (AP) and Load on Canopy**

AP distributions in unmined coal are characterized by peak stresses near faceline, which decreases in magnitude with distance towards the solid coal (Fig. 7). AP results are defined in terms of unit less quantity abutment stress ratio (ASR), which is the
ratio of induced stresses to the *insitu* stress (2.05 MPa). Peak AP is 2-3 m inside the solid coal; this is because the face coal has yielded due to high stress and low confinement. AP increases with the increase of both strength and thickness of the main roof. But thickness of the strata is significant in determining the self-supporting capability of roof strata.

Among distinct four zones of stress variation (Fig. 7), in the elastic zone, stress uniformly and monotonically decreased inside the coal seam. Plastic
Yield Zones in the Face Area

For every model, the face and the immediate roof area have yielded the span of yield zone at longwall face that varied (2.00-2.54 m) depending upon main roof thickness and material properties (Fig. 8). Yield zone is calculated based on the stress state ratio defined as trial stress to stress on yield. If stress state ratio is greater than or equal to unity then yielding occurs after last iterative load cycle. If the ratio is less than one then stress state is in elastic regime. Higher stress state ratio signifies intensive yielding.

As a result, strain-energy accumulated in the rock layer. The situation become dangerous when geological anomalies are like fault or shear plane intersect with the layer. Then a big chunk of solid roof will detach and will sit over a number of powered supports causing them to solidify. Apart from angle of internal friction, all other material properties of main and immediate roof are same (Fig. 8b). Yield zone in roof is extended on top of the unsupported zone but confined due to stronger overlying main roof. This yielding behavior is conducive for periodic breaking of immediate roof behind the support, and also induce inherent micro-macro crack to propagate up to shear bedding plane and finally detached from roof layer.

The thicker main roof strata interact with coal seam and powered support (Fig. 8c). The roof is 19.2 m thick and weak. The vertical extent of yield zone is more than the previous cases but, it is not extended upto the next overlying strata. It is observed that as the modulus of main roof increases, the yield pattern remains the same with less intensity.

Loads on Hydraulic Leg

Load on hydraulic legs are the results of interaction between powered supports and surrounding strata. Variation of the load on the hydraulic legs is an important manifestation of strata behavior. Fig. 9 shows the vertical and horizontal displacements of the leg top as well as the change in inclination of legs after loading for thicker and weak main roof having no- (o-a), weak- (o-b) and hard-immediate (o-c) roofs. Horizontal displacement in case of no-immediate roof is more than others, but vertical displacement in case of weak-immediate roof is more. The more horizontal displacement suggests that more loads from goaf sides are performed due to horizontal forces generated by overhang main roof, whereas high vertical displacement is mainly due to dead weight. In this case, stiffer immediate roof is imparting minimum vertical and horizontal displacement to the hydraulic legs. It suggests that for this particular length of overhang main roof, deflection of main roof is less. So for massive and thicker strata, overhang length can grow longer behind the powered support and impart more horizontal load as compared to weak immediate roof. In most of the mine, setting pressure is set close to 80% of the total capacity. Under various lithological conditions, weak and thicker roof exerts more load on the legs than other cases (Table 4).

In general, load on shield increases with increasing thickness and stiffness of the main roof. This is expected since much of overburden load will be transferred to the coal seam rather than to the powered support. It is found that, as the main roof overhang length grows behind faceline, load on the coalface and on the powered support will increase. However, in case of no-immediate roof conditions, thick (over 10 m) and massive sandstone type of main roof would be self-supportive and may not exert high pressure on the coalface, during non-periodic time. However, when overhang length is sufficiently grown behind the shield; much load will be applied on the coalface and on the powered support.
Leg Pressure Monitored Data

In the study mine, leg pressures are measured several times daily for each leg. These data are collected over a period of twelve (12) days after the first periodic weighting; this is equivalent to face advancement of approx 18 m. Although a continuous data monitoring is more representative of strata behavior, but this data may provide some insight and validate FEM and analysis results. Chock shield (capacity, 4x550 ton) was installed in the mine at a cover depth of approx 100 m. Other parameters of longwall panel are as follows: $T_1$, 1.51 m; $T_m$, 17.48 m; $E_c$, 1.00 GPa; $E_i$, 1.77 GPa; and $E_m$, 4.89 GPa. Fig. 10 shows the measured front and rear leg pressure data of the longwall panel.

In this panel, the main roof rock can be classified as thicker and moderately hard whereas immediate roof as weak strata. FEM results suggest that this type of roof causes high load (31.0-35.4 MPa) on the shield in the front leg. Daily average rear leg pressure for the same period remains almost the same at 31MPa. It is also found that for these roof conditions the ratio of front leg pressure to the yield pressure may be 0.8-1.0, which is supportive to the field data.
obtained from that panel. Most of the FEM models also show lower pressure (5-10% lower) at the rear leg as compared to front leg.

**Statistical Analysis of FEM Results**

Data obtained from 54 FEMs are analyzed using multivariate regression analysis. From an engineering viewpoint, all third and higher-order interaction effects between input parameters can be considered insignificant or not interpretable. So the factorial design is constructed with 5 main effects ($\pi_1, \pi_2, \pi_3, \pi_4$ and $\pi_5$), and second-order interaction between these parameters. Dependent variables such as ratio of front leg pressure to yield pressure (FLP/YP), ratio of rear leg pressure to yield pressure (RLP/YP) and ASR are standardized into a scale of 0 and 1 for statistical analysis (Table 5). Similarly, all main effects are also standardized between scale of 0 to 1.

Leg pressure monitored data shows that RLP is less than FLP for the given geomining condition. Leg
Fig. 10—Field measured data of leg pressure from the study mine

Pressure is made dimensionless by dividing it with YP of the leg. Regression analysis is carried out using SPSS software package\(^3\). Backward regression model is used to obtain the best-fit model for FLP/YP, RLP/YP, and ASR based on the F test and t tests of each coefficient as follows.

\[
\frac{FLP}{YP} = 0.296 - 0.324\pi_1 + 0.849\pi_4 + 0.223\pi_4 - 0.504\pi_5 - 0.253\pi_3 - 0.170\pi_4 - 0.260\pi_4 - 0.260\pi_4
\]

\[
\frac{RLP}{YP} = 0.273 - 0.270\pi_1 + 0.876\pi_3 + 0.206\pi_4 - 0.492\pi_5 - 0.112\pi_2 - 0.306\pi_3 - 0.306\pi_3 - 0.306\pi_3
\]

\[
ASR = 0.186 + 0.436\pi_1 - 0.288\pi_3 + 0.720\pi_5 - 0.310\pi_1 + 0.285\pi_3 + 0.584\pi_5
\]

Above equations provide solutions in standardized scale ranging 0 to 1. In order to convert them in actual values, following mapping function is used:

\[
y_{\text{actual}} = y_{\text{model}} \times (\text{Max} - \text{Min}) + \text{Min}
\]

where, \(y_{\text{actual}}\) = Converted value of output parameters, and \(y_{\text{model}}\) = Output from the statistical model as given in the above equations.

From statistical analysis, coefficient and the magnitude of t-statistic of \(T_m/T_c\) are found higher than \(E_m/E_c\) suggesting that former is more significant than the later for determination of load on the shield. Strength of coal and stiffness of main roof are the most significant parameters for estimation of ASR. Based on above equations, leg pressures and ASR are estimated for the study mine as follows: estimated FLP, 30.97 MPa; estimated RLP, 30.53 MPa; estimated AP, 6.67 MPa; estimated ASR, 3.25; field data of FLP (av), 32.74 MPa; and field data of RLP (av), 31 MPa. It can be seen that both estimated front and rear leg pressures are comparable with the average pressures obtained from the field-monitored data.

**Conclusions**

In general, self-supporting nature of the roof rock is playing a pivotal role in determination of shield load. Load on hydraulic legs is high for thicker and weak main roof because thicker and weak main roof tends to exert load as dead weight on the shield. The magnitude of ASR is less for such roof condition. On the contrary, ASR will be high for thicker and massive roof. For an overhung length of 22 m, shield legs are yielded in the presence of a weak roof. However, shield leg does not yield for hard roof meaning that 22 m overhung length is not sufficient to cause fracturing in the roof. Hence, this roof acts as self-supportive and can carry overburden load. On the other hand, for weak main roof, the 22 m overhung length is sufficient to cause periodic weighting. In general, rear legs of a chock type powered support will carry lower load than the front legs due to lower stiffness of the rear hydraulic leg. In addition, convergence of canopy tip will directly affect the front leg pressure rather than rear leg. Multivariate regression analysis suggests that the thickness of main is the most significant parameter for the determination of load on the shield. On the other hand, strength of coal and stiffness of main roof are the significant parameters for determining peak abutment stress.

**References**


---

**Table 5**—Range of input and parameters in statistical analysis

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Range</th>
<th>Output parameters</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{E_m}{E_c})</td>
<td>(\pi_1)</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>(\frac{E_l}{E_c})</td>
<td>(\pi_2)</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>(\frac{T_m}{T_c})</td>
<td>(\pi_3)</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>(\frac{T_l}{T_c})</td>
<td>(\pi_4)</td>
<td>0</td>
<td>0.75</td>
</tr>
<tr>
<td>(\frac{E_c}{MCM})</td>
<td>(\pi_5)</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

---

**Table 5**—Range of input and parameters in statistical analysis

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Range</th>
<th>Output parameters</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\frac{E_m}{E_c})</td>
<td>(\pi_1)</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>(\frac{E_l}{E_c})</td>
<td>(\pi_2)</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>(\frac{T_m}{T_c})</td>
<td>(\pi_3)</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>(\frac{T_l}{T_c})</td>
<td>(\pi_4)</td>
<td>0</td>
<td>0.75</td>
</tr>
<tr>
<td>(\frac{E_c}{MCM})</td>
<td>(\pi_5)</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>


