ANALYSIS OF LONGWALL SHIELDS AND THEIR INTERACTION WITH SURROUNDING STRATA IN A DEEP COAL MINE

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ABSTRACT

A vast majority of the operating longwall sections use shield-type face supports to provide ground control in the United States. As a co-operative research program between the University of Alabama (UA) and Jim Walter Resources, Inc. (JWR), a joint research program is underway to study interaction of shields with surrounding rock masses. A series of analyses on the response of shields are performed using monitored data at a longwall face in a deep coal mine. In this paper, various effects of parameters, such as leg pressure, setting load, developing load, maximum loading rate, pressure in cap zone, and convergence between canopy and base, are discussed and recommended as stability indices. A microcomputer program is being developed for instantaneous interpretation of the shield monitored data and for giving warnings of potential problems. The preliminary results define the effects of the setting load, developing load, and rate of developing load on the closure rate. The objective of the study is to understand the shield characteristics and their interaction with surrounding strata in real time, then develop a reliable program for maintaining longwall stability.

INTRODUCTION

Longwall mining has become a popular coal mining method in the United States due to its higher productivity and safety, but the system is complicated and expensive, and requires extreme caution for reliable and efficient operations. In critical importance is understanding the behaviour of face supports and their interaction with surrounding rock masses in the roof and floor to enable operators to better predict hazardous conditions and improve support design.

In recent years, some researchers studied reaction of face supports to geologic variations and mining operation (Hanna and Hanratty, 1991, Hendon et al., 1990, and Zelandko, et. al., 1991). Face supports are monitored by means of recording leg pressures and convergences. It is now possible to obtain this information on shields in real time. Microcomputer technology is effectively utilized to monitor responses of supports and evaluate the monitored data. In this study, the data analysis and evaluation of shield performance were conducted according to the monitored data from a longwall face at JWR. Efforts have been made to interpret field monitored data, evaluate shield performances, and to provide a warning system of instability using a microcomputer program which is presently being developed.

The data were taken at Jim Walter No. 4 Mine located in west Alabama, where the Big-Creek seam is mined at a depth of 610 m (2,000 ft). The immediate roof consists of a sandy shale layer and the Mary Lee seam, with a total thickness of four feet. The main roof is approximately 9.2-m (30-ft) thick and consists of sandy shale. More than 80 consecutive monitored mining cycles were used for evaluating the roof behavior and shield performance in this paper.

SHIELD PERFORMANCE AND STABILITY AT A LONGWALL FACE

1. SHIELD RESISTANCE AND LEG CLOSURE

It is well known that shield resistance and leg closure are generally the results of interaction between the roof, support, and floor. Their variations are the important manifestations of strata behavior on a longwall face. Four distinct periods of a mining cycle are shown in Fig. 1. Once the support is advanced and reset, an initial setting load, \( P_w \), is achieved. As the roof rests on the shield canopy and the adjacent shields also advance, the support resistance increases rapidly in the period \( t_s \), between \( s \) and \( a \), until it reaches a relative equilibrium. This is called the Rapidly Increasing Period. Then comes the Relatively Stable Period \( s \), between \( a \) and \( b \). This period is longer,
and the shield resistance is relatively stable. When the cutting action of the shearer approaches the shield, the resistance increases rapidly. This is the Cutting-Influenced Period, between b and c. This period can be divided into two different periods, between b' and c' and b'c. b'c' indicates the period of rapid initial pressure increase and b'c is the period of stable period before the neighboring shields advance. Finally, as the neighboring supports are disengaged and advanced, the roof load is suddenly transferred to the adjacent support thereby rapidly increasing the support resistance in a short time period. This is the final rapidly increasing resistance period, called the Neighboring Shield Movement Period, between c and d. As the shield is released for advancing, its resistance drops almost instantaneously to zero (d-e).

Here, P is the setting load, P is the final load, and AP is load increment (dev euping load), which is equal to the difference between the final load and setting load.

2. LONGWALL STABILITY

Roof falls and failure of powered supports are major threats at a longwall face. Roof falls often occur in unsupported areas, between canopy tip and faceline, under a weak roof condition, resulting in a caving zone. In most cases, this is due to the existence of weak planes, such as fractures, joints, and cracks.

Setting load is a key factor that is related to roof and shield stabilities. An inadequately low setting load may cause an excessive face convergence, that also may result in roof falls in the unsupported areas. If the main roof contains a strong thick rock layer, such as sandstone, low setting load may cause a large impact, resulting in a rapid settlement of the roof strata that can produce a catastrophic effect on the support. Thus, minimum required setting loads should be determined for different roof conditions. The criterion to determine the minimum required setting load should be established to ensure the integrated roof condition in the working area and keep the roof fully controlled with a self-supporting ability.

The effects of shield overloads usually occur in legs, capsule, bases, and laminate links as follows:

(a) **Leg Overload**

Damage can be caused by the following conditions:

(a) The roof load is high and it is transmitted rapidly to the leg, the hydraulic fluid cannot be released fast enough through the yield valve, causing rapid and sudden increase of the leg pressure, and
(b) Roof load stays high, the yield valves open frequently, allowing rapid leg-closure and resulting in the shield going too solid.

(2) Capsule Failure

Even though it is not common, capsule failure can occur when 2-leg shields are utilized. The function of the capsule is balancing of the canopy and widening the working zone of the resultant force, but the design capacity of a capsule is low. Once there is a bad roof condition, and the resultant force cannot be adjusted to the working zone, causing a large load increase on the capsule. It causes the capsule to reach yield and results in failure if the stroke is exhausted.

(3) Overload in Lemniscate Links

The function of lemniscate-link system is to resist the horizontal force. The stresses applied in the upper and lower lemniscate links of the system is always opposite. This means that if there is a tension load in the lower link, then a compression load is applied in the upper link, and vice versa. The results of the analyses using the finite element method show that the load on the upper link, UL, or lower link, LL, are linearly related to the horizontal and vertical displacements, $\delta_1$ and $\delta_s$, at the link between the canopy and caving shield. That is:

$$\begin{align*}
UL &= K_1 \delta_1 + K_2 \delta_s \quad (1) \\
\text{or} \quad LL &= K_3 \delta_1 + K_4 \delta_s \quad (2)
\end{align*}$$

where $K_1$, $K_2$, $K_3$, and $K_4$ are horizontal and vertical stiffness of the lemniscate-link system, that can be obtained from laboratory tests or finite element analyses. In general, the horizontal stiffness is much higher than vertical stiffness, and a small horizontal displacement may cause a large load in the lemniscate links. Therefore, the roof movement, especially from the horizontal, produces high stresses in the lemniscate links.

3. SHIELD MONITORING

As discussed above, the objective of evaluating longwall shield performance is to understand and predict the shield performance, such as the maximum loading rate, shield yielding and yielding rate, pressure in capsule, and stresses in lemniscate links.

The leg pressure change is influenced by the horizontal as well as vertical displacements, except when the leg inclination is near vertical. Therefore, from the information of leg pressure and convergence between canopy and base, the horizontal movement can be estimated. As shown in Fig. 3, the horizontal displacement can be calculated from convergence between canopy and base, $\delta_s$, by the following equation:

$$\delta_h = a \left( 1 - (1 - b \Delta P + c \delta_s)^{1/2} \right) \quad (4)$$

where $a = l \cos \alpha$, \( b = \frac{2}{AE \cos^2 \alpha} \), \( c = \frac{2H}{l^2 \cos^2 \alpha} \), \( l \) is the length of the hydraulic leg, \( A \) is the area of the hydraulic leg, \( E \) is the Young's Modulus of the hydraulic leg, \( \alpha \) is the inclination of the legs from the horizontal, degrees, \( \Delta P \) is the leg pressure increment (pressure decrease is defined as minus), and \( H \) is original shield height.

Usually $\delta_s$ direction is waste-to-face, but a negative value of $\delta_s$ means the direction of the horizontal movement is waste-to-face. The load in the upper or lower links can be estimated by the following equation which is obtained by substituting Eq.(4) to Eqs. (1) and (2):

$$\begin{align*}
UL &= K_1 \delta_1 \left( 1 - (1 - b \Delta P + c \delta_s)^{1/2} \right) + K_2 \delta_s \\
\text{or} \quad LL &= K_3 \delta_1 \left( 1 - (1 - b \Delta P + c \delta_s)^{1/2} \right) + K_4 \delta_s
\end{align*} \quad (5)$$

If the leg closure or orientation can be monitored, the
horizontal displacement can be estimated by the following equation:

\[ \delta_x = \Delta l \cos \alpha_2 \cdot (\cos \alpha_2 - \cos \alpha_1) \]  
\[ \delta_y = \Delta l \sin \alpha_2 \cdot (\sin \alpha_2 - \sin \alpha_1) \]  

(7)  

(8)

All of the above discussions indicate that the evaluation of longwall characteristics and shield performance can be conducted by monitoring pressures in legs and capsule, and convergence between canopy and base.

DATA ANALYSIS AND SHIELD PERFORMANCE EVALUATION USING A MICROCOMPUTER PROGRAM

A microcomputer program has been developed, and some of the capabilities are presently being used for data analyses. The MAIN MENU of the program includes five major parts: Data Edit / Input Menu, Graphics Menu, Data Analysis Menu, Warning System, and Exit to DOS. When the program is completely developed, it will perform all the following tasks:

1. GRAPHIC PRESENTATION

The history of monitored data related to leg pressure and closure can be plotted using the program. Fig. 4 shows the monitored data from JWR No. 4 Mine involved in this research, representing the history of the leg pressure with time. Using the program, the mining cycle can be automatically identified, then the setting load, final load, load increment, loading rate, and leg closure are determined for each cycle of supports advance. Thus, the variations of developing load or leg closure of each mining cycle can be illustrated. Figs. 5(a) and (b) show the variations of leg closure, developing pressure, and the rates of pressure increase in the relatively stable period with the face advancing in the mine. Developing pressures and leg closures fluctuate periodically, possibly attributed by the periodic breakage of the main roof. It was found that the intervals of the periodic weighting is from 35 to 70 ft of face advance. Comparisons of developing pressure and the rates of pressure increase in the relatively stable period indicates that, obviously, there is a relationship between them (Fig. 5(b)). This effect is discussed later in this paper.

Fig. 5 (a) Leg Closure vs. Mining Cycle; and (b) Developing Pressure and Pressure Rate in the relatively Stable Period vs. Mining Cycle

2. ANALYSIS OF REAL-TIME DATA

After the mining cycles are identified by the computer program, several parameters, such as setting load, final load, developing load, and loading and closure rates are calculated and tabulated. Afterwards, statistical analyses are performed for setting load, final load, and developing load. Fig. 6 shows a typical illustration of statistical results for setting load, final load, and developing load. The maximum, average, and minimum loads are also sorted. After running a certain number of mining cycles, the relationships such as developing load versus setting load, weighting intensity factor versus intervals of periodic weighting, and initial loading and closure rates versus those for final periods can be established. Some of these relationships are discussed later in this paper. These analyses will be helpful to the longwall operators for evaluating ground conditions and shield performance.
helping them make decisions for the best performance. If some other parameters such as convergence between canopy baffle or leg orientation are monitored, the stresses in Lemniscate links can be estimated by Eqs. (5) and (6), and the effect of the horizontal force can be evaluated in real time. These results can also be useful in the computer prediction and warning system.

![Graph of Setting Pressure](image)

**Fig. 6 Statistical Analysis of Setting, Final, and Developing Loads**

3. PREDICTION OF SHIELD PERFORMANCE

(1) The Effects of Setting Load

The results of analysis of the monitored data from the study site indicate that the setting load plays an important role in the longwall mining. Fig. 7 shows the results representing the relationship between the developing load and setting load. The curves 1 and 2 show the relationships during non-periodic and periodic weighting times.

![Graph of Setting Load and Developing Load](image)

**Fig. 7 Relationship between the Setting Load and Developing Load During Periodic and Non-Periodic Weighting Times**

The results indicate that a low setting load may cause an excessively large load increment during periodic weighting times, but the effect was not so obvious during non-periodic weighting time. During the non-periodic weighting times, even a low setting load did not cause a large developing load (curve 1). This is because the main roof cantilever is rather short and still growing in this period, and the weight of the main roof is mostly supported by the solid coal in front of the shield and some by the shield.

On the other hand, a tremendous developing load was imposed on the shield at low setting loads during the periodic weighting times (curve 2). The reason is that, during periodic weighting time, the main roof cantilever beam is fully grown and fractures are initiated above the face and shields and causes high stress concentrations in the face area. Usually, the stresses rapidly drop as the fractures grow, the main roof beam fails and the end of the cantilever sags to rest on the gob spoils. However, if fractures develop above the solid coal ahead of the face line, excessive high stresses are imposed on the shields for a longer period. This particular case does not commonly occur, but if it does due to particular ground conditions, a disaster may result. If an insufficient setting load is applied in this period, an excessive deflection will occur, causing high developing load. This means the effects of setting load is especially important during the periodic weighting time. Fig. 7 indicates that...
when the setting load is smaller than a certain low value such as 200 tons, more than 400 tons of developing load is created during the periodic weighting time. Consequently, to ensure the stability of the longwall face is fully controlled, a minimum setting load and a rated yield load must be designed properly.

(2) Prediction of Developing Load, Maximum Loading, and Closure Rate

As discussed earlier, developing load and the maximum loading and closure rates are important factors in evaluating shield stability. For each mining cycle, it always experiences the periods of initial, relatively stable, cutting influence, and neighboring shield movement (Fig. 1). The load increases steadily, and leg closure rates are low in the Relatively Stable Period but high in cutting-influence and neighboring moving periods. From the analysis of monitored data from the mine, it has been found that the developing load and maximum loading and leg-closure rates in the final period of a mining cycle are related to the loading or leg-closure rates in the Relatively Stable Period.

The major characteristics found are described as follows.

(a) Loading and Leg-Closure Rates. The Curve of Fig. 8(a) represents the relationship between leg closure rate in the Relatively Stable Period versus the maximum load increase rate in the final period of the mining cycle. Fig. 8(b) shows the relationship between the maximum rates of pressure increase and the pressure increase rate in the Relatively Stable Period. These two curves indicate that the maximum loading and leg-closure rates in the final period are closely related to the rates in the Relatively Stable Period. The following two equations have been established from the monitored data:

\[ C_{max} = 0.0343 \times 10^{6.72 \times P_{max}} \]  
\[ P_{max} = 0.374 \times 10^{2.75 \times P_{max}} \]

where \( P_{max} \) and \( C_{max} \) are the maximum loading and leg closure rates in a mining cycle, and \( P_{min} \) and \( C_{min} \) are the loading and leg-closure rates in the Relatively Stable Period of a mining cycle. The units of loading and leg-closure rates are MPa/min and cm/min, respectively.

(b) Developing Load and Shield Yielding. Fig. 9 shows the monitored results representing the relationship between the total developing pressure in a mining cycle and the rate of pressure increase in the Relatively Stable Period. It indicates that the total developing pressure was increased with the increase of pressure rate in the Relatively Stable Period before shield yielding. The relationship can be expressed as:

\[ \Delta P = 7.27 + 87.8 \times P_{max} \]  

From the analysis of the results, it has been obtained that most of the mining cycles yielded when the loading rate was higher than 0.14 MPa/min (20 pdi/min) in the Relatively Stable Period. It has been found that the developing pressure is also related to time, setting load, and face advancing rate.

![Graph showing relationship between leg closure rate and maximum loading rate](image)

![Graph showing relationship between pressure increase rate and maximum pressure increase rate](image)
From the relationships shown in Figs. 8 and 9, it was found that the shield yielding and maximum values of load increase rate or leg-closure rate can be predicted based on those during the Relatively Stable Period before any damage occurs. If problems are predicted, remedial operations can be adopted, such as increasing the setting pressure, and increasing face advancing rates.

![Graph showing relationship between developing pressure and pressure increase rate](image)

**Fig. 9** Relationship between Total Developing Pressure in a Mining Cycle and Rate of Pressure Increase in Relatively Stable Period

4. **DEVELOP A REAL-TIME WARNING SYSTEM FOR FORTHCOMING STABILITY PROBLEMS AND RECOMMENDATION FOR CORRECTION**

One of the objectives of this study is to provide operators with a system of warning during the early stage if the shield is going to become unstable or any bad roof conditions are forthcoming. The above discussions indicate that it is possible to predict eminent danger forthcoming, such as excessive roof load and leg closures using the pressure increase rate in the Relatively Stable Period. The flow chart of a warning system, which is being developed, is shown in Fig. 10. The system may employ the information of leg pressure or leg closure, pressure in capsule, canopy-base convergence or leg orientation. There are three main steps to be included:

1. Analysis and evaluation of real-time data,
2. Prediction of longwall stability, and
3. Giving advice or warnings.

Once the following situations are predicted or started, the program will give messages about the problems such as: (a) setting load is too low, (b) possibility of shield yielding, (c) predicted maximum loading or closure rates exceed the critical value, (d) high yielding rate, (e) yielding at capsule, and (f) high stress in laminate links.

**CONCLUSIONS**

Microcomputer technology has now made it practical to monitor the responses of longwall faces in real time. It has become possible to predict ground-control problems at longwall faces, such as roof falls in unsupported areas and overloads on shields, and take preventive measures before a disaster. The major parameters that can be used for evaluating longwall stability are setting load, maximum loading rate, shield yielding and yielding rate in leg and capsule, maximum leg-closure rate of the shields, and the stresses in laminate links. These parameters can be obtained and estimated by a well-planned monitoring program. Some parameters can be predicted in the early stage of a mining cycle. Using the microcomputer technology, the real-time monitoring, data analysis, evaluations of longwall stability, and early warnings of instability can be conducted not only for understanding interactions of roof, support, and floor but also for preventing ground-control failures. The efforts will also contribute to future automation of coal mining.

**REFERENCES**


Fig. 10 The Flow Chart of Warning System