Simulation and Optimization of Filled Support Based on ANSYS & AMEsim

Kaige Song, Guorui Feng*, Tingye Qi, Yuxia Guo

Abstract
A crushing experiment was conducted on the main structure of ZC4800/16/25 paste-filled support under two conditions using ANSYS finite element analysis. Meanwhile, combined with AMEsim hydraulic system simulation software, the operating characteristics of the hydraulic system of support leg and valve group were analyzed. Simulation results show that the setting load of support increases with the increase of advance length. In such a geological condition as the rough roof and floor of working face leads to unstable immediate roof directly reflect the stability of overlying strata, then this support system is unstable.

Key words: Strip Filling; Hydraulic Support; Simulation Analysis; Dynamic Characteristic.

1. INTRODUCTION

In the process of coal mining under railway, water body and buildings, paste-filled hydraulic support, as a key device of filling mining technology, plays a key role in roof support and filling mining process. In the R&D process of support device, the advantages of computer simulation include testing system performance in the process of design at any time, promoting design, optimizing efficiency and improving the stability of whole structure and system. Relying on the above advantages, this research method is widely applied (Wang, 2014; Guo and Huang, 2011). For the simulation of common hydraulic supports for fully-mechanized mining, most domestic scholars (Zhang and Cao, 2015; Yang and Long, 2013) analyzed structural strength using ANSYS analysis. Studies on filled hydraulic support mainly focus on gangue-filled support (Zhang, Zhang and Tai, et al., 2014), while a finite element analysis of paste-filled support is absent. On the other hand, Zhang Zhongwei and Yang Guolai et al. (Zhang and Zhang, 2013; Wang and Pang, 2016) made simulation analysis of the entire gangue-filled support and partial hydraulic system based on AMEsim. However, studies on hydraulic system based on paste-filled hydraulic support are still inadequate.

Under geological conditions containing different working faces, whether paste-filled support can meet mining requirements is closely associated with its structural strength and the operating stability of hydraulic system. So combined with the geological background in Xinyang Coal Mine, this article attempts to make a simulation analysis of the main structure and hydraulic system of ZC4800/16/25 paste-filled support, evaluates the operating stability of filled support in an all-round way and provides a reference for further optimization of paste filling mining technology and equipment in coal mines.

2. THE MECHANICAL RELATIONSHIP BETWEEN FILLED HYDRAULIC SUPPORT AND SURROUNDING ROCK

2.1. The Establishment of a Mechanical Model
The stability of filling mining work face depends on the stability of “filled support- surrounding rock-filling body” system, as well as the movement of overlying strata. If in the late filling, the immediate roof is separated from the upper roof, then this support system is unstable.

During filling mining, under the limit condition that the immediate roof on the top of mined area broke (Xu and Qian, 2014; Qian and Miao, 1996), according to the macro breakdown law of immediate roof, a quadrilateral immediate roof breakage was taken as the research object to make a mechanical stress analysis. The stability of immediate roof directly reflected the stability of overlying strata structure, as shown in Figure 1 below:
Hence, we had the following relationship equation:

\[
\begin{align*}
\sum x = F - T_x - T_f &= 0 \\
\sum y = P + T_y - Q &= 0 \\
\sum M &= P \cdot x + T_y \cdot h + F \cdot \sum h - G \cdot y - Q \cdot y - T_f \cdot h_y = 0
\end{align*}
\]  

(1)

Where the symbols stood for:
- \( P, T_x, T_y \): The vertical and horizontal supporting force of filling body on the immediate roof, kN;
- \( Q, T_f \): The vertical and horizontal force of breakage on the immediate roof, kN;
- \( G \): The weight of immediate roof, kN;
- \( P \): The supporting force of filled support, kN;
- \( Q \): The given yield pressure of upper roof, kPa;
- \( F \): Friction, kN;

In actual filling mining, under the following circumstances, the setting load of filled support would change accordingly:

1) Under the limit condition that the filled-paste just filled the mined-out area and hadn’t produced strength yet, i.e., it applied no force on the immediate roof, we can simplify the above equation as:

\[
P \geq \frac{G(x_d - x_y) + Q(x_d - x_y) - F \cdot \sum h}{x_p - x_d}
\]  

(2)

2) If in the early filling, the filled-paste didn’t contact the roof when producing strength, the vertical and horizontal force of breakage on the immediate roof would become 0, i.e., \( Q_d = 0, T_d = 0 \). Likewise, we can simply the above equation as:

\[
P \geq \frac{G(x_d - x_y) + F \cdot \sum h}{x_p - x_d}
\]  

(3)

3) During the filling, it took some time for the filling body to produce enough strength for the roof. The roof would continue sinking. Meanwhile, due to inadequate filling body compressibility and limited capacity of hydraulic support, the working face would not contact the roof. Hence, from the above stress analysis, \( Q = 0, F = 0 \), and the equation can be simplified as:

\[
P \geq \frac{G x_d}{x_p}
\]  

(4)

From Eq. (2-4) above, in the early filling, before the filling body produced enough strength, to maintain the stability of support system, when the filled support satisfied the above three conditions, the system would be stable.

Through a parallelogram mechanical analysis, combined with the concrete structure of mined area, under the limit condition that the rock broke, we can get the maximum support strength of the support. Suppose that the right side of the rock broke, then the rock would move around the pivot, so the right boundary was set as a hinge structure. Adjacent rocks would exert an extrusion force on the left section of the rock. So the left...
boundary of the rock was set as a roller bearing. The supporting force beneath the rock was replaced with an equivalent spring. Meanwhile, equivalent uniform pressure was used as the overlying strata force on the rock, as shown in Figure 2:

![Figure 2. The Mechanical Model of Basic roof](image)

As shown in the above figure, the symbols stood for:
- Q: The overlying strata pressure on the rock, equal to \( \gamma h \);
- \( \gamma \): The average bulk density of overlying strata;
- h: The distance from basic roof to key stratum;
- \( M_x \): The left roller constraint of the rock;
- \( F_y \): Friction (extrusion force in the x direction);
- \( F_x, F_y \): The horizontal and vertical stress on the right hinge;
- \( \Delta \): The filling body compressibility;
- \( \Delta(x) \): The settlement of the whole beam;
- L: The span of basic roof;
- a, b: The dry shrinkage rate of filled paste;
- \( \sigma(x) = ae^{\frac{\Delta(x)}{L}} \) = \( \frac{ba}{\sigma} e^{\frac{\Delta(x)}{L}} \);

Therefore, the balance relationship of the support in this stress field was:

\[
\begin{align*}
\sum F_x &= F_{mx} - F_{Fy} = 0; \\
\sum Y &= F_{sy} + F_{sy} + \int_0^L q(x)dx - qL = 0; \\
\sum M_a &= F_{sy} \Delta_m + F_{sy} L + \int_0^L xq(x)dx - \frac{qL^2}{2} = 0; \\
\end{align*}
\]

Solving Eq. (7), we can get the stress on N:

\[
F_y = \frac{qL(0.15L - \Delta_m) - 0.3\int_0^L xq(x)dx + \Delta_m \int_0^L q(x)dx}{0.3L - \Delta_m}
\]

Taken together, a simultaneous equation of required supporting force \( F_z \) in paste filling mining can be obtained:
\[
F_Z = \frac{\gamma h L (0.15 L - \Delta_w)}{0.3 L - \Delta_m} + \frac{a e^{-\frac{L}{L_0}}}{0.3 L - \Delta_m} \left[ \Delta_w - 0.3 (L - L_0 - 1) \right] - \frac{b e^{-\frac{L}{L_0}}}{0.3 L - \Delta_m}
\] (9)

Combined with the above analysis, relevant parameters of Xinyang Coal Mine were substituted into the equation. As the setting load was affected by fixed parameters and variables, such as average bulk density of overlying strata, distance from basic roof to key stratum, filling body compressibility, dry shrinkage rate of filled paste, advance length of working face, etc., we set the value of variables as in Table 1 below and calculated by Eq.(9).

<table>
<thead>
<tr>
<th>Table 1. The Values of Parameters of Filled Support</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Bulk Density of Overlying Strata</td>
</tr>
<tr>
<td>r/kN/m³</td>
</tr>
<tr>
<td>24.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2. The Minimum Setting Load Required by the Support with Different Advance Lengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advance Length/m</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>6</td>
</tr>
</tbody>
</table>

According to the above choice of relevant parameters, substituting three sets of data about filling body compressibility and dry shrinkage rate into the equation, we can get the minimum setting load of the paste-filled support when the advance length ranged from 0m to 6m, as shown in Table 2. Under different compressibility, the relationship between minimum setting load (F) and advance length (L) was shown in the following figure.

Figure 3. The Variation of the Minimum Setting Load of Filled Support

According to Fig. 3, with the advance of working face, the setting load of filled support gradually increased. With the increase of mining distance in the filling cycle, the increase rate of setting load gradually reduced. When the advance length was up to 3.5 m, the increase rate of minimum setting load slowed down and tended to be stable. Besides, different filling body compressibility made the setting load differ. With the increase of compressibility, with the same advance length, the setting load increased. But the variation trend of setting load with advance length was not significantly related to different compressibility.

According to the above analysis of the variation trend of setting load, combined with existing literature(Huang, Zhang and Zhang,2012),with 0.2 compressibility as the research condition, we substituted the actual geological conditions in Xinyang Coal Mine into the equation and the maximum setting load of filled support was 4470KN. Meanwhile, the above parameters were substituted into the equation, to validate whether the calculation results met mining standards.
3. FINITE ELEMENT ANALYSIS OF FILLED SUPPORT

3.1. The Preprocessing of Model

The proposed ZC4800/16/25 filled support in this article was designed and analyzed according to the guidelines of MT312-2000 General Technical Conditions of Hydraulic Support. Using UG 3D modeling software, the support was simplified and adjusted to a reasonable crushing height. The established UG model was converted to igs format and imported into ANSYS. According to actual geological conditions under the shaft, blocks were loaded on the support to simulate conditions. The loading methods were: (1) to load on both ends and middle of the top beam, to load on the top beam secondly; (2) to load on both ends and middle of the floor or to reverse the floor. After meshing, the support structure model was as shown in Fig. 4.

The main force involved in the mining process of paste-filled hydraulic support included: (1) overlying strata pressure; (2) floor pressure; (3) leg support; (4) filling body support. The effect of surrounding rock on the immediate roof and floor in the yielding process greatly affected the distribution of top beam and floor in a reasonable contact area. In ANSYS analysis, the constraining force was the given load force in block area. Combined with basic requirements in General Technical Conditions of Hydraulic Support, the experimental force changed with different loading methods. The support height \( H \) and experimental force \( F \) were shown in Table 3 below. \( F_R \) was the rated working resistance of leg, whose value was 865KN.

<table>
<thead>
<tr>
<th>Loading Method</th>
<th>( H ) / mm</th>
<th>( F ) / kN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load on both ends of top beam.</td>
<td>2200</td>
<td>1.2 ( F_R )</td>
</tr>
<tr>
<td>Load on top beam secondly</td>
<td>1900</td>
<td>1.1 ( F_R )</td>
</tr>
<tr>
<td>Load on both ends of floor</td>
<td>2200</td>
<td>1.2 ( F_R )</td>
</tr>
<tr>
<td>Reverse the floor</td>
<td>2200</td>
<td>1.2 ( F_R )</td>
</tr>
</tbody>
</table>
3.2 ANSYS Simulation Analysis under Single Loading Conditions

By setting the loading boundary and loading force, a finite element analysis was conducted on single and complex loading on top beam and floor respectively and their equivalent stress and displacement cloud chart are obtained.

![Cloud Chart of Single Loading](image1)

**Figure 5.** The Stress and Displacement Cloud Chart of Single Loading on Top Beam and Base

Combining the above two conditions, when the top beam was loaded alone, under Condition 1, the stress was concentrated in the rear leg and joint between front and rear top beams on the second side. The maximum stress occurred at the pin shaft between the rear leg and top beam on the second side. The value was 139.97Mpa. Under Condition 2, the stress was concentrated in the rear leg. The maximum value was 91.105Mpa. Under both Condition 1 and Condition 2, large yields occurred at the tail of top beam. The maximum yields were 10.165 mm and 10.46 mm respectively. When the floor was loaded alone, under both Condition 1 and Condition 2, large stresses were distributed in the rear leg. The maximum stresses occurred at the rear leg and the pin shaft between top beam and leg. The maximum stresses were 112.92Mpa and 48.679Mpa respectively. Large yields occurred at the tail of floor. The maximum yields were 2.445mm and 1.0294mm respectively. To sum up, the stress can satisfy the allowable stress of ordinary steel.

3.3 ANSYS Simulation Analysis under Complex Loading Conditions

The crush degree of roof of paste-filled working face in Xinyang Coal Mine was high. On an unstable large working face with large local seam inclination and large variation in thickness, the top beam of hydraulic
support would have an asymmetric contact with the roof. The floor was rough. In the presence of floating gangue, Condition 1 would be used to crush the support. If the roof fall occurred during mining, there would a crack between top beam and roof. The crush degree of floor was high and there was floor heave. When there was a crack between floor and floor, Condition 1 would be used to crush the support. In the early filling, before the paste formed strength, the overlying strata pressure on the support would reach the maximum. Crushing treatment was conducted using the maximum supporting force. The resulting maximum stresses were 169.53Mpa and 133.2Mpa respectively, occurring at the joint between front and rear beams. The tail of top beam had a certain yield. The settlement values were 7.59mm and 8.1581mm respectively. According to the above data analysis, roof settlement in the early filling was effectively controlled.

Figure 6. The Stress and Displacement Cloud Chart of Complex Loading on Top Beam and Base

4. AMESIM SIMULATION ANALYSIS OF HYDRAULIC SYSTEM OF FILLED SUPPORT

4.1. The Establishment of Simulation Model

The leg, as a main component of hydraulic support, plays an important supporting role in the working face. So among all hydraulic control circuits of filled support, the leg control circuit is very crucial (Ma, Huang and Hao, 2006). The stability and safety of this system greatly affect the safety and reliability of support. The leg control circuit mainly includes the following components: leg, hydraulic pump, oil tank, high flow relief valve, hydraulic one-way valve, reversing valve and hydraulic pipe, etc. There are abundant hydraulic components in the AMESim hydraulic library. A simulation model was set up according to the actual dimension and structure of key components in the AMESim/HCD module. During the simulation and design of leg, the leg was mainly composed of hydraulic parts and mechanical structure. The basic control circuit, structural mix and stress distribution were shown in Fig.7.

Figure 7. Leg Hydraulic System

According to the above basic structure of leg, in the working process of leg, the effect of roof and floor on leg was noticeable. So in roof control, the following factors must be considered: leg elasticity and hydraulic oil compressibility, for in the working process of filled support, it bore the dynamic load produced by the movement and yield of basic roof and the static load produced by the weight of immediate roof. In modeling, the static load produced by the weight of immediate roof and the dead weight of top beam were replaced with a relatively static mass block. Meanwhile, linear signal source and spring damper were used instead of the dynamic load of basic roof. Since the roof load always changed in the process of filling mining, the spring stiffness and damper parameters can be changed. Moreover, in floor control, due to floor compression in the
process of leg shrinkage, when the support stiffness cannot meet the requirements, the roof settlement in the early filling may be too large and further weaken the filling effect. So in simulation, the floor was replaced with equivalent linear spring damper and zero velocity source. Through an equivalent replacement of roof and floor, a leg model was hereby accomplished. As shown in Fig. 8, its entire working state connected to the roof and floor and was closely related to their stress and yield.

![Figure 8. The Simulation Model of Leg Hydraulic System](image)

**4.2 An Analysis of AME-Sim Simulation Results of Leg**

In the setting stage, before contacting the roof, the load on the leg was the dead weight of top beam. After the leg was lifted, the pressure on the leg gradually increased. Before simulation, the command box was switched to the run mode. Meanwhile, the start time, stop time and interval of simulation were set. The simulation results were shown in Fig. 9 below.

![Figure 9. The Simulation Results of Leg in the Setting Stage](image)

From Fig. 9 (a), it can be seen that in the setting stage, the leg was completely lifted at 12.3s. The height rose to 2.1m. The slope of curve gradually decreased over time and finally approached zero. From Fig. 9 (b), in the process of lifting, the spool displacement of one-way valve increased over time. At 16s, the spool displacement of hydraulic one-way valve reached the maximum of 2.15mm. By analyzing the above phenomenon, in the lifting stage, with the rise of leg, due to the contact and pressure-bearing between top beam supported by the leg and roof, the lifting rate of leg gradually decreased and finally tended to be stable. In the actual working process, as the load on the leg increased, the pressure on one-way valve also gradually increased. The opening of valve port gradually increased until the leg was completely lifted and tended to be stable. Combined with the variation trend of leg and spool displacement of one-way valve, it can be seen that compared with spool, the displacement of leg fluctuated significantly. This was because the liquidity of oil and mechanical error of system led to nuances of setting load and set pressure, caused pressure loss and made graphs in actual working process different from those in the simulation process.
4.3 An Analysis of AME-Sim Simulation Results of Safety Valve

The working state of safety valve greatly affected the work state of the whole hydraulic system of filled support. In the early filling, before the filling body formed strength, the safety valve (overflow valve) came to an overflow-bearing stage. When the valve port was opened, the start-stop characteristic of pilot spool was shown in Fig. 10.

![Figure 10. The Start-stop Characteristic of Pilot Spool](image)

As shown in Fig. 10 above, at 0.2s, 2.8s, 5.7s and 8.6s respectively, the spool pressure jumped, indicating the relief and pressure-holding time of safety valve. Before the filling body formed strength, with constant weighting from the roof, the oil pressure on the valve port increased. When the pressure from roof exceeded the rated working resistance of safety valve, the pilot spool would be pressed. The port would be opened. At 2.8s, 5.7s and 8.6s after the support contacted the roof, the roof would produce an impact load on the top beam, making the leg cavity pressure greater than the set pressure of safety valve. The valve port was opened to relieve pressure. Therefore, the working state of safety valve provided a basis for the estimation of the impact time and strength of roof load on support.

![Figure 11. The Variation Curves of Spool Displacement and Moving speed](image)

As shown in Fig. 11 (a), with the passage of time, the spool displacement of safety valve jumped periodically. The variation was like a downward “parabola”. The spool displacement reached the maximum of 18.4 mm. In each jump, the maximum gradually decreased and tended to be stable at 47s. Fig. 11 (b) showed the variation law of moving speed over time. The moving speed reached the maximum of 1.8mm/s at 2.8s. With the passage of time, the change of moving speed gradually decreased and stopped moving at about 49s. So according to the curve law, with the increase of filling body strength, the spool displacement was gradually reduced to the minimum. In the working process of support, the periodic weighting of roof determined the periodic change of curve. With the increase of filling body strength, periodic weighting gradually weakened. Thus, during the formation of filling body strength, the overflow rate from the valve port gradually decreased with the increase of strength. The oil pressure of hydraulic system gradually dropped to a stable state.

5. CONCLUSIONS

(1) The present study establishes a paste-filled support- surrounding rock-filling body mechanical model, analyzes factors contributing to the balance of filling mining system and obtains a check formula for the minimum setting load in the early filling, as well as basis for the mechanical calculation of setting load.

(2) Based on the geological background in Xinyang Coal Mine, the setting load of support gradually
increases with the advance of working face. The greater filling body compressibility, the higher requirements for supporting force. The increase rate grows with the increase of advance length.

(3) A crushing experiment is conducted on the main structure of ZC4800/16/25 filled support in Xinyang Coal Mine. It is concluded that the stress is concentrated in the rear leg and pin shaft between top beam and leg and provides a reference for the optimization of support structure.

(4) A simulation analysis is performed on the leg hydraulic system of support. The actual work state of the support can be obtained directly from the lifting time, flow rate and pressure on the leg, the spool displacement, pressure and moving speed of safety valve and other physical properties, to provide a variety of standards and references for the further optimization design of support.

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