Research Article

Application of Pedrail Powered Support on Strata Control in Short-Wall Coal Mining

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In this study, the role of the pedrail powered (PP) support produced in China in the Wongawilli short-wall mining was explored, and the process from its import and introduction to its localization and use effect were detailed. The influences of the gob side and the solid-coal side on the pillar pressure were numerically simulated by exploring the working resistance of PP support at different locations and under different widths of pillar between mining caves (PMC) of the same branch lane during mining and investigating the pressure distribution and variations of each single pillar. The main influencing factors and their relationships with the working resistance were derived accordingly. Finally, key processing technologies to solve the problem of PP support crushing in the crushed zone were analyzed. The results suggest that the rated working resistance of PP support satisfies the requirement for use, and the roof of the branch lane behind the cutting roof line does not collapse, which ensures the safety of short-wall mining. The gob-side pressure is notably higher than the solid-coal-side pressure. When the PP support undergoes a support crushing accident, it can be pulled out by jointly adopting four key technologies, i.e., reinforced support to the roof, reinforcing rib support and ground bolt support for caving gangue piles, roof and loose body reinforcement by grouting, and traction by a prop-pulling winch.

1. Introduction

Pedrail powered (PP) support, which boasts convenience in movement, is a key device widely used in short-wall mining systems, especially room-column or Wongawilli mining systems. The original foreign prototype was a simple support invented in 1979. This support was modified on the basis of a drill carriage, and it merely relied on four jacks in the middle of it and on its arm to support the roof. It was first proposed by the American Mining Council after 1980 [1]. The Austrian mining and lane company Wurst-Albeni was the first to manufacture a prototype in 1987. The same year also witnessed its invention by Fletcher Company. This support consisted of a crawler chassis and a four-jack shield support, with a working resistance of 6000 kN, and employed in the USA and Australia [2]. In China, this kind of support was first developed by Shendong Coal Company and Taiyuan Branch of General Institute of Coal Science and Technology in 1999. In 2000, it started service in the mines of Shendong Coal Company, raising the resource recovery rate of working face by 15%-20%. This not only filled the void in China but also promoted the development of short-wall mining technology [3, 4]. Furthermore, after nearly 20-year application, the imported equipment has been completely replaced by domestic ones and successfully applied to marginal coal mining under moderately-stable or stable roofs.

However, study on the controlling role of PP support on rock strata in the working face containing marginal coal in China is rarely available. In the previous researches, Li and Zhou [5] determined the working resistance of PP support and revealed the main factors affecting working resistance based on the roof collapse characteristics and strata pressure behaviors in the working face. Wang et al. [6] summarized
the structural parameters of PP support and the application data in Daliuta Coal Mine to illustrate its supporting role on the mining site. Through numerical simulation on its mechanical behavior, Zhou et al. [7] proved the feasibility of reducing relevant coal pillars, which provided a theoretical basis for raising the recovery rate. In fact, the use of PP support in China often emphasizes the role of its pillar in protecting coal workers in front of the support, but the role of its support resistance in predicting and monitoring mine pressure in the stope is generally ignored. In this study, the technical characteristics and main functions of PP support produced in China were detailed. Besides, factors influencing the stress of PP support in the stope were derived through working resistance formula and numerical simulation analysis. Meanwhile, the distribution of working resistance was monitored during the recovery of marginal coal in Shengping Coal Mine. Moreover, key technical measures for pulling out the support in the case of a support crushing accident caused by geological abnormalities were explained in detail. This study is of important theoretical and practical value for comprehensively grasping the role of PP support in marginal coal mining.

In this study, we firstly summarize the development of the PP support in China and elaborate on its applications in Wongawilli coal mining systems. Afterward, the interaction between support and surrounding rock is analyzed. Then, the mechanical analysis of the PP support in surrounding rock control is verified, and some key techniques are illustrated. Finally, some conclusions are drawn.

2. Features and Necessity of PP Support

2.1. Features of Use. PP support, whose supporting principle resembles that of long-wall mining shield support, is suitable to be used in the case of roof cutting. However, different from long-wall mining shield support, it is equipped with a power system and travels on tracks. It adapts well to the geological conditions of coal seams. The supporting heights of the six models are 1.2 m, 1.7–3.0 m, 1.9–3.5 m, 2.1–4.0 m, 2.45–4.6 m, and 2.55–5.0 m, respectively. The rated working resistance is 7000 kN; the initial supporting force is 3959 kN; the weight of the machine body ranges from 25 t to 37.5 t; the climbing capacity is up to 10°. In addition, it can assist the continuous miner in escaping independently when the roof gets crushed; its top beam and shield beam are highly adaptable to the roof. It also boasts the following functions [8–11]:

1. It is equipped with an automatic cable reeling device to lower labor intensity and promote work efficiency. Besides, it generates little heat when reeling cable, which improves the reliability

2. It can be operated through wired remote control or wireless remote control. For remote control, the built-in antenna provides a good signal reception and excellent operability for workers

3. It improves the precontrol of strata movement in the stope. During mining, the law of roof weighting can be analyzed by the pressure variation of PP support pillar, thus realizing early warning and prediction for roof weighting in the gob

3. Theoretical Analysis on the Role of PP Support

The PP support is mainly applied in two types of short-wall mining processes, namely, Wongawilli full-wind-pressure short-wall mining (with 2 PP supports) and block type short-wall mining (with 4 PP supports) (Figure 1).

As shown in Figure 1, the branch lane of the mining working face where the continuous miner works is generally
During mining, due to the anchor belt mesh rope support in the branch lane, the compressive stress area formed by the bolt support protects the roof. As a result, the immediate roof behind the support can hardly cave during mining. As the empty roof area behind the support expands, before the immediate roof reaches the collapse limit, the PP support resists the force along the roof cutting line of the gob and jointly bears the roof pressure with the coal pillar. According to the auxiliary area theory [5], the coal pillar bears the weights of the overlying strata above it and the overlying strata within half of the widths of the lanes on both sides, that is, the coal pillar and the PP support bear half of the suspending roof area, respectively. The stress state is given in Figure 2. Hence, the supporting area for each PP support is calculated with reference to Figure 2.

The supporting area for each support is calculated by:

\[ S = \frac{1}{2} W_2 \left( L_1 + L_2 + \frac{d}{2 \sin \alpha} \right) + \frac{W_1}{4} \left( L_1 + 2L_2 + \frac{d}{\sin \alpha} - \frac{1}{2} W_1 \frac{1}{\tan \alpha} \right), \]  

(1)

where \( S \) is the supporting area for a single support, \( m^2 \); \( L_1 \) is the length of the empty roof behind the support, \( m \); \( L_2 \) is the length of the immediate roof, \( m \); \( W_1 \) is the span of the mining cave, \( m \); \( W_2 \) is the width of the branch lane, \( m \); \( d \) is the width of the mining cave, \( m \); \( \alpha \) is the angle between the mining cave and the branch lane.

The load from the immediate roof to the PP support is calculated with reference to previous study [12]:

\[ N_{\text{immediate}} = S \times \sum_{i=1}^{n} H_i \gamma, \]  

(2)

where \( N_{\text{immediate}} \) is the load from the immediate roof; \( H_i \) is the thickness of the \( i \)-th layer of immediate roof.

The load from the main roof is usually estimated by the measured dynamic load coefficient \( \eta \). The working resistance of the PP support is

\[ P = N_{\text{immediate}} \times \eta, \]  

(3)

where \( P \) is the working resistance, kN; \( \eta \) is dynamic loading coefficient whose value is 1.05 for type I: roof with unobvious stope weighting, 1.05~1.15 for type II: roof with obvious stope weighting and 1.15~1.3 for type III: roof with strong stope weighting. According to previous study, the support is in a pressure-free circle during mining [5], and the immediate roof behind the support does not collapse. Therefore, the dynamic loading coefficient is smaller than that of long-wall working face under the same conditions; \( \eta \) can be set in the range of 1.0~1.05; a better roof lithology corresponds to a smaller value, which is infinitely close to 1.

4. Numerical Simulation on Support Movement in the Stope

4.1. Numerical Simulation

4.1.1. Establishment of the Numerical Model. Based on the actual situation of short-wall mining in Shengping Coal Mine, Linfen, Shanxi Province, China [13], the branch lane recovery was divided into three stages, namely, initial section mining, middle section mining, and final section mining (Figure 3). Initial section mining referred to the stage from the start of recovery to the completion of 1/3 of the lane length, middle section mining from 1/3 to 2/3 of the lane length, and final section mining from 2/3 of the lane length.
length to the completion of recovery. The supports were, respectively, numbered as 1# (on the gob side) and 2# (on the solid coal side).

The numerical model (196 m × 144 m × 56.1 m) contained 159,868 units and 202,377 nodes. It was solidly supported at the bottom. The boundary restricted normal displacement. The stress boundary was applied at the top instead of the overlying rock weight, with gravity \( g = 9.81 \) m/s\(^2\). The PP support used the extrusion module, with 1 m row spacing for bolts, and fish language to control step-by-step excavation. Each cycle contained a pair of mining caves (left and right sides) and a calculation of 500 steps. The mining caves were marked in different colors for representing the sequence of recovery. The parameters of rock mechanical properties of numerical model are shown in Table 1 in detail.

4.1.2. Numerical Simulation Results. Four schemes whose PMC widths were 1.0 m, 1.25 m, 1.5 m, and 1.75 m, respectively, were established. And their stress states of top beam and pillar of the support were contrastively analyzed. To simulate the on-site process, the support was moved

![Schematic diagram of the PP support area.](image)

**Figure 2:** Schematic diagram of the PP support area.

![Numerical simulation model of PP supports in different stages.](image)

**Figure 3:** Numerical simulation model of PP supports in different stages (1-main transport chute; 2-auxiliary transport chute; 3-branch lane; 4-gob side; 5-solid coal side; 6-1# PP support; 7-2# PP support).
whenever the recovery of a group of mining caves was completed. The states of the support are exhibited in Figure 4.

The nephogram indicates the magnitude of the force, and the colored part of the support contour is the stress tensor (magnitude and direction). The data of the maximum values of the working resistance of each pillar of 1# and 2# supports in three mining stages (initial, middle, and final sections) were compiled to obtain the distribution pattern. Figure 5 presents the simulation of maximum working resistance distribution of two PP supports under different coal pillars between mining caves and in different mining stages. Correspondingly, Figure 6 shows the simulated relationship between coal pillar widths and pillar pressures in different mining stages.

Based on Figures 5 and 6, the following results can be drawn:

1. Under the same coal pillar width, the working resistance of PP support differs in different mining stages, specifically, $P_{\text{final}} > P_{\text{middle}} > P_{\text{initial}}$. In the same mining stage, $P_{1#} > P_{2#}$. With respect to pillar pressure, $P_{\text{side front}} > P_{\text{side rear}} > P_{\text{middle front}} > P_{\text{middle rear}}$. This indicates that the roof support of four pillars differs in different mining stages. The side pillars play a far more significant supporting role than the middle pillars, and the working resistance is positively correlated with the size of the mining area.

2. Different coal pillar widths influence the working resistance to different extents, and the overall trend is $P_{1.0 \text{ m}} > P_{1.25 \text{ m}} > P_{1.5 \text{ m}} > P_{1.75 \text{ m}}$

3. The whole mining process (including the initial, middle, and final sections of branch lane mining) indicates that $P_{\text{gob side}} > P_{\text{solid coal side}}$ for a single support. For the side front pillars, side rear pillars, middle front pillars, and middle rear pillars, the final section corresponds to the greatest pressure difference, followed by the middle section, and the initial section corresponds to the smallest pressure difference. For both the side pillars and the middle pillars, $\Delta P_{\text{final}} > \Delta P_{\text{middle}} > \Delta P_{\text{initial}}$. The pillar pressure on the gob side is 3 ~ 4 times higher than that on the solid coal side. And the pillar pressure decreases with the increase in the coal pillar width. The side pillars experience a greater pressure decrease than the middle pillars, which indicates that the variations of PMC width and pillar pressure can affect the pressure of the side pillars. Therefore, it can be tentatively concluded that in the on-site practice, the

<table>
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<tr>
<th>Lithology</th>
<th>Layer thickness/m</th>
<th>Volumetric modulus/GPa</th>
<th>Shear modulus/GPa</th>
<th>Tensile strength/MPa</th>
<th>Cohesion/MPa</th>
<th>Angle of internal friction/°</th>
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<tr>
<td>Siltstone</td>
<td>4.5</td>
<td>16.7</td>
<td>6.2</td>
<td>2.1</td>
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<td>17.5</td>
<td>6.4</td>
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<td>5.73</td>
<td>1.7</td>
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<td>25</td>
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<tr>
<td>Sandy mudstone</td>
<td>3.2</td>
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<td>2.3</td>
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<td>7.9</td>
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<td>0.3</td>
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<tr>
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<td>5.7</td>
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<td>27</td>
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<td>12.3</td>
<td>3.1</td>
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<td>3.3</td>
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<td>3.6</td>
<td>0.6</td>
<td>2.7</td>
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<td>2# coal</td>
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<tr>
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pressure variation of side pillars can help analyze and predict the variations of roof pressure and load on the gob side.

4.2. Factors That Influence Support Stress. According to equation (3) and numerical simulation, the main factors influencing the variation of working resistance of PP support in the stope include the length of the gob roadway behind the support \( L_1 \), the length of the support top beam \( L_2 \), the width of the branch lane \( W_2 \), the span of the mining cave \( W_1 \), the feeding angle \( \alpha \), the width of the mining cave \( d \), and the thickness of the immediate roof strata \( \sum H \), the dynamic loading coefficient \( \eta \) (roof lithology), support boundary, etc. The main relationships are analyzed as follows:

1. The width of the branch lane \( W_2 \), the length of the gob roadway behind the support \( L_1 \), the length of the support top beam \( L_2 \), the width of the mining cave \( d \), and the thickness of the immediate roof are linearly correlated with the working resistance.

2. The feeding angle of the continuous miner \( \alpha \) is positively correlated with the working resistance. The reason is that as the feeding angle rises, the width of the gob increases, which raises the support working resistance; \( \alpha \) is typically in the range of 35°-45°.

3. There is a positive exponential growth correlation between the span of the mining cave \( W_1 \) and the working resistance. An increase in \( W_1 \) significantly influences the working resistance of the support. This phenomenon is especially obvious under a large \( W_1 \) value. Generally, the value of \( W_1 \) is below 10 m.

4. The support boundary is an important factor that affects the pressure on pillars. The support undergoes "lowering-moving forward-rising" after
each support cycle, so the initial support force
should be reasonably adjusted according to the
actual action and the magnitude of the force.

5. Engineering Application

5.1. Geological Conditions of the Coal Sea. Shengping Coal
Mine adopts the short-wall mining method to recover the
marginal coal resources of 2# coal seam. Its 2208 working
face, which is located in the north of the mine field, has a
dip angle of $3 \sim 5^\circ$ and a relatively stable coal seam thickness
(3.1 m on average).

The coal seam, with a bulk density of 1.35 t/m$^3$, belongs
to a low gas seam. The buried depth of the coal seam is
210~300 m; the 2208 continuous mining working face boasts
a coal reserve of about 210,000 t. Both sides of the working
face have been mined out, with one side backed by a big
fault, making it a typical residual coal mining area. The roof
and floor parameters of the working face are listed in
Table 1. The immediate roof, with a thickness of 3.5 m, is
sandy shale and fine-grained sandstone, and the immediate
floor, with a thickness of 1.2 m, is mudstone and sandy mud-
stone. The short-wall working face is mainly equipped with
equipment produced in China, including a continuous coal
miner, a shuttle car, a no. 1 continuous transport car, and
two PP supports. In addition, the roadway is arranged using
the full-negative-pressure Wongawilli coal mining method;
the branch lanes are 62~82 m long, and the PMC is 1.0 m
wide (Figure 7).

Equation (3) can calculate the working resistance of the
support: $L_1 = 0$ (the roof behind the support is supported
by bolts, so there is no empty roof), $L_2 = 6$ m, $W_1 = 9$ m,
$W_2 = 5.5$ m, $d = 3.3$ m, $\alpha = 45^\circ$, $\eta = 1.05$, $h = 4.1$ m, $\gamma = 25$
kN/m$^2$, then $P = 3,777$ kN. Since the working resistance of
the single support is 3,777 kN, smaller than 7,000 kN, it is
considered to meet the requirements.

In engineering practice, in order to explore the working
resistance distribution of PP support, its data are monitored
in real time [14].

The converted working resistance distribution of a single
support is shown in Figure 8. The working resistance that is
below 3,800 kN accounts for 18.21% of the total monitored
amount. It is preliminary analyzed that the PP support has
a small initial supporting force; the working resistance rises
slowly, and the final working resistance fails to reach the ini-
tial support force. The working resistance that is in the range
of 3,800~4,800 kN accounts for 70.13% of the total moni-
tored amount (the theoretical calculation result, 3,777 kN,
is approximately in this range, which proves that the theo-
retical calculation result can guide on-site application).

The maximum value of pillar pressure that is in the
range of 1,000~1,200 kN accounts for 60.45% of the total
monitored amount, obviously below the theoretical value. The main reasons are that the branch lanes are just 62–82 m long, and that the roof and side bolts also play a supporting role. As a result of the two factors, roof weighting is insignificant during mining. The bolt support on both sides enhances the strength of PMC, so that the observed working resistance is smaller than the predicted value. The working resistance that is over 5,200 kN accounts for 1.32% and the single-pillar pressure that is over 1,400 kN accounts for only 0.5%, indicating that the actual supporting force of PP support is smaller than the simulated value. However, as the gob expands, the working resistance increases, which agrees with the numerical simulation results.

### 5.2. Key Processing Technology for Support Crushing

#### 5.2.1. Analysis on the Mechanism of Support Crushing

During mining of the 2208 working face, the hidden fault is exposed. Correspondingly, the roof is of a poor intensity, and the coal is of a low strength. The PMC becomes unstable and fails in advance, and the roof above it falls. As the PP support supports the roof, the continuous miner can withdraw in time. However, the roof suddenly falls in a large area when the support is lowered, resulting in support crushing.

#### 5.2.2. Key Technologies for Pulling Out the Support

1. Support of the roof around the PP support is reinforced [15]. Bolts and cables, together with W-shaped steel belt, are installed for the caving gangue piles on both sides of the support. In addition, a roof separation instrument is installed in the middle of the roof. Wooden point columns are installed for the rear roof, caving gangue piles against the coal wall side (Figure 9(a))

2. Reinforcing rib support and ground bolt support are adopted for caving gangue piles. After caving piles stabilize, bolt supports are immediately added from top to bottom to prevent collapse. Metal mesh circles a scope, along which a circle of ground bolts is installed, and thin wooden backboard is adopted to reinforce gangue piles (Figure 9(a))

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*Figure 8: Actual distribution of the working resistance of the PP support. (a) Distribution of the maximum working resistance. (b) Distribution of the maximum pressure of pillar.*

*Figure 9: Schematic diagram of the PP support. (a) Diagram for gangue pile reinforcement. (b) Grouting diagram.*
(3) Roof and loose bodies are reinforced by grouting. A strong pulling force will cause a wide range of roof disturbance, which leads to a larger area of secondary caving from the separated roof. To prevent such a phenomenon, grouting is used to reinforce roof and loose bodies, and the reinforcement agent is injected to form a regenerative roof. This ensures the stability of the roof and loose bodies during pulling (Figure 9(b)).

(4) The PP support is pulled out through its own escape ability and the pulling force of the prop-pulling winch.

The winch with reasonable traction force should be selected according to the analysis on the separated immediate roof height based on anchor cable situation [16]. The formula is

$$Q_z = N_1 (\sin \beta + f_1 \cos \beta) \times g + P_f \times L_t \times (\sin \beta + f_2 \cos \beta) \times g,$$

where $Q_z$ is the traction force; kN; $N_1$ is the separated roof load, kN/m; $\beta$ is the lane slope, $^\circ$; $f_1$ is the resistance coefficient of the PP support, 0.015; $f_2$ is the resistance coefficient of the steel wire, 0.15; $P_f$ is the unit weight of the wire, 2.16 kg/m; $L_t$ is the lifting distance, 30 m. According to calculation, $Q_z = 269.14$ kN, nearly 27 t. Therefore, the JH30 prop-pulling winch is selected. Its parameters are as follows: wire rope tension 300 kN, motor power 45 kW, rope capacity 200 m, deadweight 4.46 t, and wire rope diameter 31 mm. Thanks to the above four key technologies, the PP support is successfully pulled out.

6. Conclusions

The force variation of PP support in marginal coal is affected by multiple factors, including the length of the gob roadway behind the support, the length of the support top beam, the width of the branch lane, the span of the mining cave, the feeding angle, the width of the mining cave, the thickness of the immediate roof strata, the dynamic loading coefficient (roof lithology), and the support boundary.

The support can be pulled out through four key techniques: Support of the roof around the PP support is reinforced; reinforcing rib support and ground bolt support are adopted for caving gangue piles; roof and loose bodies are reinforced by grouting; the PP support is pulled out through its own escape ability and the pulling force of the prop-pulling winch.

Data Availability

All data required for this research is included in the paper.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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