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Floor heave characteristics and control technology of the roadway driven in deep inclined-strata

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ABSTRACT

Based on in-mine instrumentation and theoretical analysis of the unsymmetrical large-deformation that occurred in the roadway after excavation, Differential Floor Heave (DFH) was found to be the main reason for roadway failure. It needs to be pointed out that the specific roadway was driven in inclined rock strata. In addition, the factors that contribute to the occurrence of DFH are discussed in detail. It is believed that DFH is triggered by the unsymmetrical stress distribution in the floor and the different rock types encountered near the two floor corners. Hence, DFH control should be focused on the left floor corner where shearing failure occurs initially and the left floor surface where tensile failure is more severe. The proposed DFH control strategies include unsymmetrical grouting for the whole roadway, re-design of the roof and ribs support, reinforcement of the weak zones, and release of the concentrated stress in the earlier stage. Meanwhile, it is recommended that in the later stage, both bolts and cable bolts with higher strength and the backfilling technique using the coal measure rocks and concrete should be employed in the reversed-arch floor. The field instrumentation results, after using the proposed control strategies, indicate that large deformation in a DFH roadway has been successfully controlled.

1. Introduction

As the energy demand and mining intensity increases, many Chinese coal mines have begun to extract coal seams with deeper cover due to the depletion of shallow seams. The behavior of the coal measure rocks and the stress environment in deep seams are very complicated: for instance, the coal measure rocks tend to behave as a weak material and thus large non-linear deformation usually occurs [1–3]. In addition, the roof and ribs receive most attention during roadway development, while the floor is seldom supported since it is time and cost-consuming. Theoretically, the concentrated stress induced by mining activity has to be released; hence the floor usually has priority since most of the floor is unsupported. Meanwhile, the potential plastic flow in the roof and ribs may be triggered by massive floor heave and, under the worst conditions, complete roadway failure may occur. In this respect, floor heave becomes one of the key factors that restrict safe and efficient mining of deep coal resources [4,5].

Based on the differences in terms of geological conditions, surrounding rock behavior, and stress level, floor heave can be classified into four types: squeezing flow, flexural folding, shearing movement, and water swelling [6]. Much research into floor heave in deep cover roadways has contributed to the control of floor heave. Jiang et al. [7] indicated that the use of a U-shaped compressible-shield and floor bolting combined with grouting is necessary for floor heave control, while for roadways with a larger opening, cutting into the roof to release the high stresses is recommended for floors in severely concentrated stress conditions. Chang et al. [8] concluded that combined strategies including over-excavation into the floor strata, bolting with grouting, and backfilling are quite effective for floor heave control in deep cover roadways. Li et al. pointed out that complete grouting for the surrounding rocks and bolting in the floor corners can be used to control floor heave. Water sensitive floor strata were studied by Kan et al. [9,10]. The concept of a low-effective reinforcing zone was proposed and the recommended reinforcement depth and the corresponding strategies for floor heave control were reported. Cutting vertically into the floor strata for floor heave control was studied by Guo et al. [11]. Based on their conclusions, the appropriate depth for the floor cutting is half the roadway width. Yang et al. [12] developed a floor heave control technique by studying the effect of reinforcement in the middle and deep sections of the floor. The floor heave control technique includes cable bolting with

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grouting and concrete beam support in the floor. According to the staged dynamic reinforcement theory for the roadway driven in weak rock, An et al. [13] proposed a combined method for floor heave control: initial spraying onto the roadway boundaries, high support intensity in the roof and ribs, secondary cable bolting in the key zones, and complete grouting of the roadway. Zhang et al. [14] identified a "stiff-yielding-support" control method for swelling floor heave which occurred in complex geomechanics conditions. They proposed bolting with grouting, construction of a polyethylene buffer zone, and full support by building a steel and concrete reinforcing layer.

In the present study, the in-mine instrumentation results of the symmetric large-deformation in the roadway after excavation are analyzed. The main factor (i.e. the Differential Floor Heave (DFH)) that contributes to the symmetric large-deformation is then discussed. Additionally, the reason for the occurrence of the DFH and its failure behavior are demonstrated in detail, which greatly helps to identify floor heave control strategies. The proposed control strategies are validated by performing a case study.

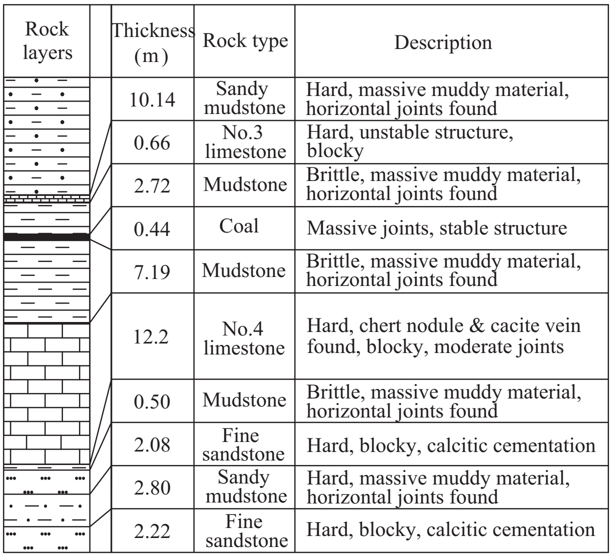
2. Geological conditions and roadway failure behavior

2.1. Geological conditions

The roadway selected for the case study is located at the No.2 mining district in the western part of the coal mining region. The inclined angle and the length of the roadway are 0.3% and 1310 m, respectively. The roadway is driven in rock and oriented in an east–west direction. Longwall panel 9418 is located at the south side of the roadway, while the north side is solid coal. Development of the roadway starts in the No.4 limestone in the Taiyuan Formation, as shown in Fig. 1. The inclined angle of the rock strata and the cover depth of the roadway are 16–20° and 1030 m, respectively. Limestone, fine sandstone, sandy mudstone, and mudstone were encountered during roadway development. The maximum water flow into the roadway during excavation was 15 m^3/h.

2.2. Previous support

The roof of the roadway is arch-shaped, while both the ribs are straight. The opening size is 4.6 m wide by 4.1 m high. The bolting-mesh-spraying support method was used for deformation control. The roof and rib bolts with 800 mm × 800 mm spacing were installed as the primary support in the roadway, while the roof was secondarily supported by using the cable bolts with 2.4 m spacing. All the bolts are 22 mm in diameter and 2.4 m in length and the cable bolts are 18.9 mm in diameter and 8.3 m in length. It should be pointed out that three cable bolts were installed in each row. Steel mesh (6 mm in diameter) was laid on the roof and ribs. Additionally, a steel channel (14 mm in diameter) was installed between the bolt bearing plates and mesh. Concrete was sprayed onto the roof, ribs (100 mm thick) and floor (200 mm thick) after finishing the installation of the primary and secondary supports.



Rock layers	Thickness (m)	Rock type	Description
	10.14	Sandy mudstone	Hard, massive muddy material, horizontal joints found
	0.66	No.3 limestone	Hard, unstable structure, blocky
	2.72	Mudstone	Brittle, massive muddy material, horizontal joints found
	0.44	Coal	Massive joints, stable structure
	7.19	Mudstone	Brittle, massive muddy material, horizontal joints found
	12.2	No.4 limestone	Hard, chert nodule & cacite vein found, blocky, moderate joints
	0.50	Mudstone	Brittle, massive muddy material, horizontal joints found
	2.08	Fine sandstone	Hard, blocky, calcitic cementation
	2.80	Sandy mudstone	Hard, massive muddy material, horizontal joints found
	2.22	Fine sandstone	Hard, blocky, calcitic cementation

Fig. 1. Stratigraphic column.

2.3. Failure behavior

As stated previously, the same support parameters were used in the roadway. Since the rock types exposed by the floor excavation changed along the roadway (see Fig. 2), difference in deformation or failure manner in the roadway were noted. The main features of the deformation or failure can be summarized as below:

(1) Severely damaged sections ($III_1 + III_2 + VI_1$ sections)

Massive cracks were initiated in the left side of the concrete floor; long-term plastic flow was then triggered, resulting in the higher left floor and the corresponding lower right floor. Note that the left side of the floor or left floor involves the south rib of the roadway. Thereafter, the floor strata near the right rib were moved towards the opening, resulting in overall subsidence in the right rib. A notable roadway-oriented crack was generated at the right-upper corner. The bearing plates of the bolts and cable bolts were broken at such stress-concentrated zones. Experience shows that severe floor heave occurred within 60 days after development, followed by a moderate plastic deformation process. The 300 mm floor heave and 100 mm roof sag were accumulated within 120 days after the development. The underground transportation system was terminated by the inclination of the rails. Therefore, re-support of the roof and continuous cutting of the heave floor strata are required for keeping the safety of the miners and transportation.

(1) Slightly damaged sections (the other sections)

The surrounding rocks of the roadway in these sections are relatively stable. No crack was noted on the sprayed concrete. A few cracks appeared in the concrete floor, however, but there was no continuous heave and the maximum amount of floor heave was only 100 mm. The transportation system was not affected by the roadway deformation.

Based on the analysis above and the current research results [12–15], the process of roadway deformation can be concluded as: (1) unsymmetrical plastic-flow of the floor strata was initially developed near the left rib; and (2) the floor strata near the right rib were moved toward the opening, resulting in the occurrence of the overall subsidence of the right rib. These procedures are believed to be the main reasons that contribute to the unsymmetrical large-deformation of the roadway. To distinguish the unsymmetrical deformation characteristics of the roadway from failure behavior in the floor, the concept of Differential Floor Heave (DFH) is proposed in this study. Since DFH is the main contributor to the large deformation of the roadway, the control strategies should be emphasized on the reduction of DFH.

3. Analysis of floor heave contributors and DFH features

Many researchers [7,14–18] indicate that the main factors that contribute floor heave include the rock type, water corrosion,