

Ground Response and Support Interaction in Coal Mine Longwall Gateroads Subject to Changing Stress

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ABSTRACT: Gateroad entries provide access to the operating face in longwall coal mines. These entries are subject to significant changes in the vertical and horizontal stress caused by stress redistribution around the approaching longwall panel. Estimating the required support for these extreme conditions is difficult because the rock is typically in a post-peak loading condition associated with large deformations. This paper presents a conceptual model of support loading and deformation caused by longwall-induced stress changes that is based on in-mine monitoring studies and numerical modeling results. The conceptual model is based on the principle that the volume of the detached roof that may collapse during a roof fall represents the load that must be controlled by the support system. The model also considers the fact that stress-driven roof deformations are essentially irresistible and support systems should ideally yield without shedding load. An example is provided in which the effect of roof dilation on roof reinforcement and standing supports is evaluated and the ability of the system to control the deadweight load of the detached roof strata is assessed. The conceptual model can be used to develop an understanding of likely support performance during the design of longwall gateroad support systems.

1. INTRODUCTION

Gateroad entries provide access to the operating face in longwall coal mines. These entries are subject to significant changes in the vertical and horizontal stress caused by stress redistribution around the approaching longwall panel. The stress changes can exceed the rock and coal mass strength, resulting in large deformations of the excavation walls. Consequently, extreme support methods are implemented that may combine both internal rock reinforcement and external standing supports to maintain safe working conditions. Figure 1 shows a deformed gateroad in a U.S. coal mine that has been supported and re-supported using various types of strata reinforcement and standing supports. The support system is required to accommodate the essentially irresistible deformation of the surrounding rock that is driven by the longwall-induced loads, while preventing the collapse of the yielding roof strata.

Methods of estimating the required support density for coal mine excavations include empirical methods, based on statistical analysis of case histories (Mark, 2000;

Stone, 2016), analytical models based on beam theory (Frith and Colwell, 2010; Canbulat, 2011), numerical-model-based analysis (Seedsman, 2013, Gale and Fabjanczyk, 1993), and ground response curve analysis (Barczak et al. 2003, Barczak et al., 2008, Esterhuizen and Barczak, 2006)..

Recent research at the National Institute for Occupational Safety and Health (NIOSH) has further investigated gateroad loading and support performance in longwall gateroads. This research included observations, measurements, and analysis of ground response at several longwall mines in the United States (Gearhart et al., 2017, Gearhart et al., 2018; Esterhuizen et al., 2018). As part of the research, a conceptual model was developed to help understand how longwall-induced stress changes and the associated ground deformation impact the support requirements and how well the supports will control the roof strata. Some of the key observations that led to the development of the conceptual model are presented in the sections below, followed by a detailed description of the conceptual model.



Fig. 1. Gateroad supported by various standing supports and roof reinforcement systems.

2. OBSERVATIONS REGARDING ROOF RESPONSE AND GATEROAD SUPPORT PERFORMANCE

The support system in gateroads is different from most other support systems because it is required to control yielding rock with associated large deformations for a relatively short period of time. For example, supports in a longwall headgate belt entry may only be subject to the peak loading conditions for a few hours as the longwall face approaches and mines up to the supports. In some cases, the supports are required to provide limited control of the roof in by the face (in the gob) for ventilation purposes. This paper only considers support performance out by the longwall face and right up to the longwall face location.

2.1. Height of Detached Roof

In principle, the support system is required to control the roof strata that would collapse in the absence of any support. The potentially collapsing strata is called the “detached roof” in this paper. The deadweight of the detached roof represents the load that must be controlled by the support system. If there is no detached roof, the support system only needs to provide surface control to prevent smaller fragments from falling.

Since the detached roof represents ground that can potentially collapse, a review of roof-fall reports can provide useful information about this topic. Figure 2 shows the cumulative distribution of reportable non-injury roof-fall heights in U.S. coal mines (Bajpayee et al. 2014). The maximum height of the falls is approximately equal to the typical 5 to 6-m width of entries found in U.S. coal mines. Observation of roof falls shows that they will propagate upwards until a stable arch is formed or a strong bed is encountered that arrests the further development of a fall. Numerical model analyses also showed a similar trend, with the height of roof yield stabilizing when an

arch configuration is achieved at a height that is approximately equal to the entry width shown in Figure 2 (Esterhuizen et al., 2020).

The roof-fall statistics presented in Figure 2 largely reflect fall heights over intersections. The height of detached roof is expected to be greater over intersections than over entries because of the greater excavation dimensions. The height of the detached roof over entries is, therefore, likely to be less than indicated in Figure 2.

2.2. Longwall-induced Roof Deformation

During development, the roof of gateroad entries is usually supported with fully grouted bolts and cable bolts, in preparation for the future elevated loading that will be induced by longwall mining. Consequently, the entries are well supported when considering the much lower development stress conditions. During the development stage, any gravity-driven bed separation or beam deflection should be adequately controlled, and the roof can be assumed to be stable. Therefore, the accelerating roof deformation observed as the longwall face approaches is assumed to be driven by yielding of the roof strata. This leads to the conclusion that as the height of yield increases the observed roof sag will also increase. The increasing yield will result in an increase in the volume of detached roof, which in turn increases the deadweight that must be supported. The height of the detached roof reaches a limit approximately equal to the excavation width as a stable arch is formed over the excavation.

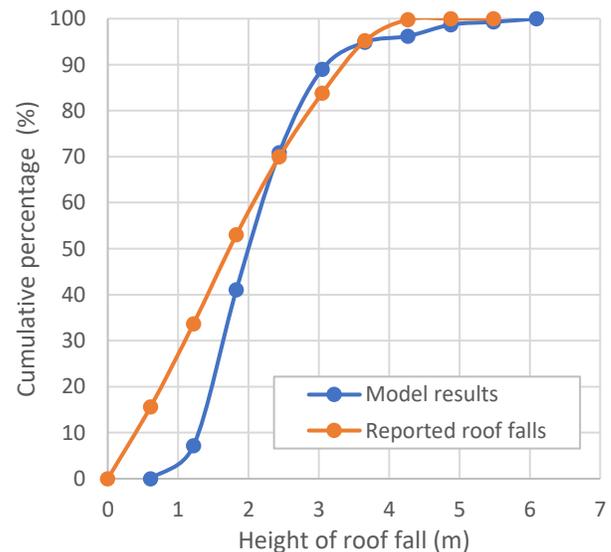


Fig. 2. Reported roof-fall heights and numerical-model-calculated height of potential roof falls.

2.3. Response of Roof Reinforcement

Roof reinforcement in the form of fully grouted roof bolts and partially grouted cable bolts is usually installed in gateroad entries during development. The fully grouted bolts are much stiffer than the longer cable bolts and,

therefore, respond to roof dilation sooner than the cable bolts. However, as the extent of roof yield develops upwards, the bolts may become encapsulated in the yielded rock and their reinforcement capability, as well as their load suspension capability, becomes reduced. Once the detached roof extends above the bolts, the bolts will start sagging with the yielding roof and become ineffective.

The deadweight of detached roof that the fully grouted bolts can carry is limited to the weight of the roof within the bolted height minus the length of bolt required to provide anchorage. The fully grouted bolts are, therefore, unlikely to be loaded to their full capacity by the deadweight of the yielded strata, given that bolt lengths are typically 1.8-m-long spaced on a grid pattern of 1.2 x 1.2 m. Bolt failures are more likely to be associated with shearing in the roof, driven by ground stress, rather than deadweight gravity loads.

The cable bolts on the other hand, with their greater length and typically wider spacing, need to suspend a greater deadweight of detached rock and can become overloaded.

Both fully grouted bolts and cable bolts may fail if the stress-driven roof dilation results in them being elongated beyond their tensile strain limit.

2.4. Response of Standing Supports

In coal mine gateroads the standing supports, which are designed to yield in a controlled manner, typically take over the roof support function when the reinforcement systems start to become ineffective. Figure 3 illustrates field monitoring data that shows how longwall-induced roof yielding causes cable bolts to achieve their peak load and start shedding load and load is transferred to the standing supports as the longwall face approaches and passes by the monitoring location (Esterhuizen et al., 2018).

The capacity of standing supports is not able to make a significant impact on the stress-driven roof deformation associated with longwall mining (Mirable and Westman, 2019). This is not unexpected because the equivalent pressure that standing supports exert on the entry roof is much less than the ground stress that is driving the deformations. However, the ability of most modern standing supports to yield allows them to provide adequate support in the most demanding situations.

3. CONCEPTUAL MODEL OF GROUND AND SUPPORT INTERACTION IN GATEROADS

The conceptual model for gateroad stability uses a simplified form of the ground reaction curve (Brown et al., 1983). Similar to the ground reaction curve, the change in support load is considered as the roof yields and deformation develops due to longwall-induced stress changes.

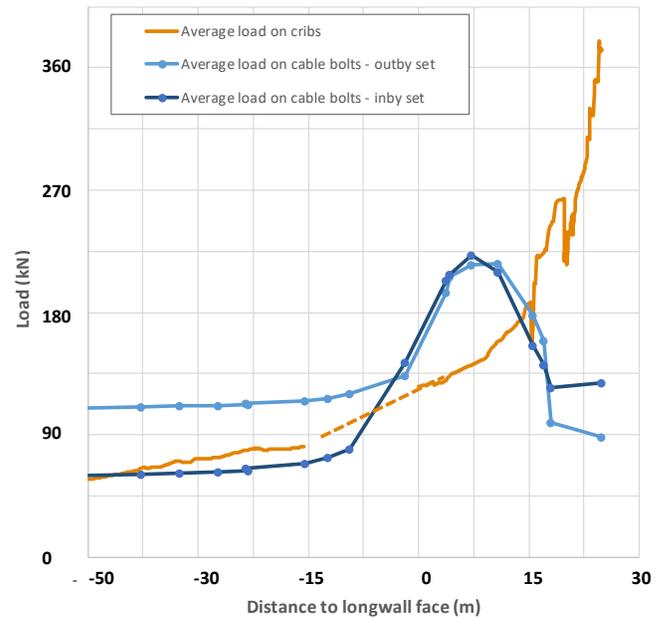


Fig. 3. Average response of crib standing supports and two sets of cable bolts against the distance to the advancing longwall face (after Esterhuizen et al., 2018).

In this model the entry roof is assumed to consist of two types of strata: self-supporting strata and detached strata that would collapse if it is not supported. The self-supporting rock may have yielded to a minor extent but has sufficient strength to prevent collapse under its own weight. The detached strata have yielded to such an extent that the residual strength is insufficient to prevent it from collapsing in the absence of support.

Figure 4 illustrates the ground response curves for the roof strata above a gateroad entry that is subject to increasing longwall-induced loads. Four loading stages are shown: 1) the initial development stage; 2) side abutment loading associated with the mining of the first panel adjacent to the entry; 3) loading caused by mining of the second panel; and 4) loading when the entry is isolated between two gobs. The figure also shows how the detached roof develops with the increasing loads. As the roof deformation increases, the detached roof curve flattens as an arch shape develops.

The support requirements are based on the premise that the support system should prevent the collapse of the detached strata above the roof line of the entry. Interaction between the ground, the roof reinforcement, and the standing supports is illustrated in Figure 5 and can be described as follows:

- a) The initial condition is a stable entry under development loading conditions that is reinforced by bolts and/or cable bolts. At the initial condition gravity-related beam deflection, beam building effects of the support system, initial yield of the roof strata, and associated roof deformation have already

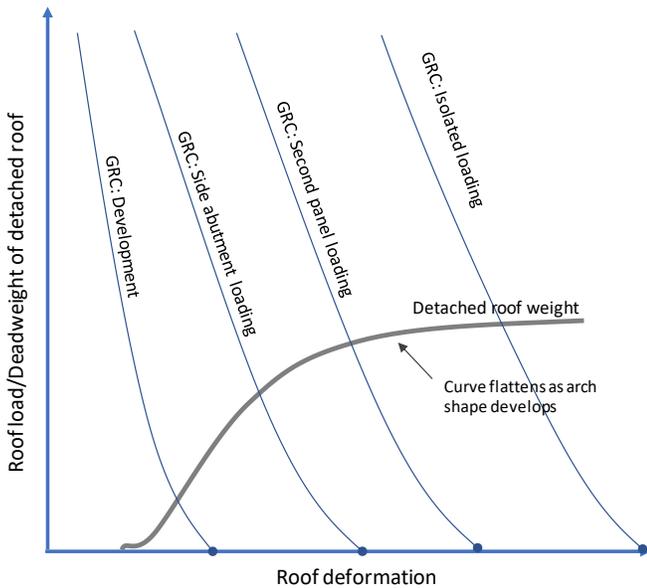


Fig. 4. Ground response curves (GRC's) for the roof of a gateroad entry for various longwall-induced loading stages, showing the development of detached roof as deformation increases.

taken place. The bolts are assumed to have been installed near the development face and have been subject to approximately 60% of the development related roof sag. At this stage, the roof sag is likely to have generated tension in the bolts and cable-bolts. In weaker ground, a limited depth of detached roof may have formed, that is suspended by the roof reinforcement. This condition is illustrated by point 'A' in Figure 5. At point 'A' the fully grouted bolts are carrying a greater proportion of the detached roof because they are stiffer than the cable bolts.

- b) The approaching longwall face induces horizontal and vertical stress changes in the surrounding rock, which causes an increase in the degree and height of roof yield. Dilation of the new fractures within the yielding roof drives the roof downwards. The dilation causes elongation of the reinforcement, which in turn generates further resisting forces in the supports. At point 'B' in Figure 5.
- c) Once the yielded roof extends up to and above the anchorage zone of the bolts/cable bolts, their effectiveness in preventing a roof collapse is diminished. This is illustrated in Figure 5 after point 'B' where the bolts are shedding loads while the remainder of the weight of the detached roof is taken up by the cable bolts. The dilating rock may also fail the bolts and cable bolts if they are elongated beyond their maximum yield strain.
- d) When standing supports are installed, they are essentially passive or may be pre-loaded during installation by a small amount relative to their ultimate strength. Once the approaching longwall

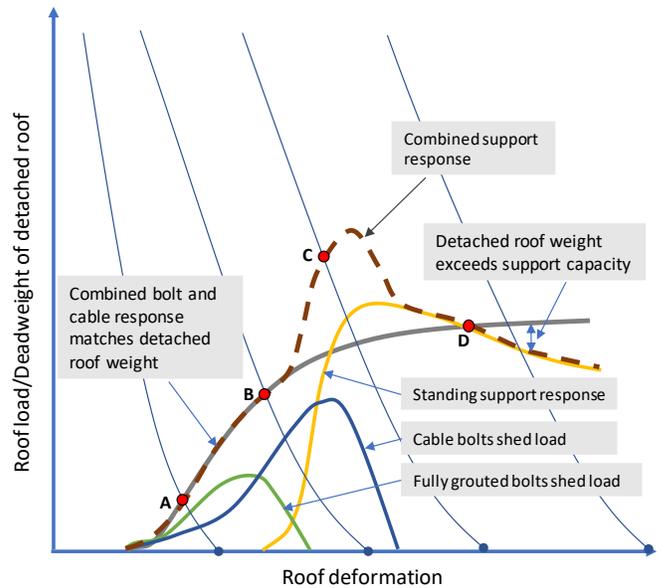


Fig. 5. Ground response to increasing longwall-induced loads, showing the weight of detached roof and support response.

causes the roof to yield and dilate, the standing supports will be compressed between the roof and floor and will generate a reaction. Floor heave can further compress the standing supports and generate additional reaction loads. In Figure 5, the standing supports are installed at the second loading stage and rapidly develop a reaction as the ground deforms in response to the third loading stage. The active response of the standing support and the load in the cable bolts exceeds the deadweight of the detached strata, shown at point 'C' in Figure 5. At this stage, the cable bolts are at their peak load and will start to shed load with further elongation.

- e) As the longwall-induced load continues to increase, the resulting roof deformation causes the cable bolts to yield, and the standing support must carry the full weight of the detached roof. Standing support will be effective in preventing a roof collapse provided their reaction load is greater than the weight of the yielded roof strata. At point D in Figure 5 the deadweight of the detached roof exceeds the capacity of the standing support, and the roof is likely to collapse.

A further consideration is that the yielded roof may lose its integrity and fall out in fragments around the support units at one of the early loading stages. This can occur if the roof has dilated and sagged beyond a critical value where interlocking between rock fragments is lost. Roof screen or other surface supports can assist in delaying the disintegration of the roof.

According to this model the success of a support system can be assessed if the height of detached roof and the amount of roof deformation are known. The height of detached roof determines the deadweight that must be supported, and the deformation determines the response

generated in standing supports as well as the survival of the bolts and cable bolts against elongation failure.

4. ASSESSING SUPPORT PERFORMANCE

Decisions about the appropriate support system for gateroads must be made during the planning stages of a longwall panel. At this stage, geologic data may be limited, and the ground control engineer is faced with numerous support options that can be used. The conceptual model for gateroad support loading can be used to assess the various support options if the expected roof sag and height of detached roof are known. At operating mines, observations of roof sag and roof-fall heights in current longwalls will help to make realistic estimates of these parameters.

For illustration, the results of a NIOSH monitoring study were used to compare the outcome of the above conceptual model against observed gateroad support performance. Details of the geology, mining system, and monitoring results are provided in Esterhuizen et al. 2018. Briefly, the monitoring was conducted in the tailgate entry of a longwall operating at a depth of cover of 180 m in a coal mine in northern West Virginia. The roof strata consisted of alternating shale and silty shale beds with uniaxial compressive strengths ranging from 44 MPa to 61 MPa. Support consisted of four 1.8-m-long fully grouted bolts in rows 1.2 m apart and two 3.6-m-long cable bolts in rows 2.4 m apart. Standing support was two rows of 9-point mixed timber wood cribs spaced at 2.4-m centers.

The instrumentation results provided accurate data on the roof deformation associated with longwall-induced loading. The average roof sag caused by the passing of the first longwall was measured to be 9 mm and was 40 mm at the tailgate corner. Measurements were made inby the longwall face, adjacent to the gob. The average roof sag was 90 mm at a point 20 m inby the face, when the outby dataloggers were removed.

The detached roof height was assessed from the results of multi-point borehole extensometers installed in the tailgate entry. Given the observed stable condition of the roof during development, it was assumed that no detached roof existed under development loading. At the tailgate corner, the detached roof height was estimated to be 2.2 m above the roof line, coinciding with a sudden increase in roof sag from about 6 mm to 21 mm. The inby detached roof height was estimated to be about 4 m above the roof line, based on the almost doubling of roof sag that was measured.

The support response to deformations and deadweight loading from the detached roof was calculated by accounting for the reduction in bolt effectiveness as the height of detached roof starts to encroach on the anchorage zone of the fully grouted bolts, which is

assumed to be the upper 60 cm of the bolts. The load-carrying capacity of the bolts is assumed to linearly decrease to zero when the height of roof yield reaches 60 cm above the top of the bolts. This assumption is partially justified by the fact that 69% of reported roof falls extend between 0 and 60 cm above the top of the bolted horizon (Bajpayee et al., 2014).

For cable bolts, the impact of roof yield height on their load-carrying capacity is determined in the same manner as for bolts, described above. Two additional checks are made for cable bolts: a) a check for the capacity of cable bolts to carry the weight of the detached roof strata and b) a check to determine if the roof sag exceeds the ultimate tensile strain limit of the cable bolts.

The contribution of standing supports was determined by comparing their support capacity to the deadweight load of the detached roof rocks minus any weight borne by the roof reinforcement system. The support capacity of standing supports depends on the amount of compression of the supports by roof sag and floor heave. For these calculations, floor heave was ignored because of the limited floor heave observed during the monitoring period.

The expected support performance was calculated to reflect the effect of the side abutment loading of the first longwall panel, with 9mm of roof deformation and about 30 cm of detached roof, followed by 40 mm of roof deformation and 2.2 m of detached roof at the longwall face corner, and finally 90 mm of roof sag with 4.0 m of detached roof inby the longwall face. The detached roof was assumed to take the shape of an elliptical arch over the 5-m-wide excavation for the deadweight calculation.

The results of the calculation are shown in Figure 6 where the support response is plotted relative to the approximate face location of the second longwall, allowing comparison to Figure 3. The load in the calculation is based on the loads associated with a 2.4 m length of the entry, which includes two standing supports, eight bolts and two cable bolts. The results show that very similar cable bolt and standing support performance is predicted by the calculations derived from the conceptual model. The bolts are shown to lose effectiveness as they become encapsulated by the detached roof, while the cable bolts achieve peak loading at the longwall face corner but shed load soon after. The standing supports are shown to rapidly add load as the longwall face passes outby the supports, similar to the measured response in Figure 3.

5. CONCLUSIONS

This paper presents an adaptation of the classic ground response curve to develop a conceptual model of the effects of longwall-induced stress changes on the performance of gateroad support systems. The conceptual

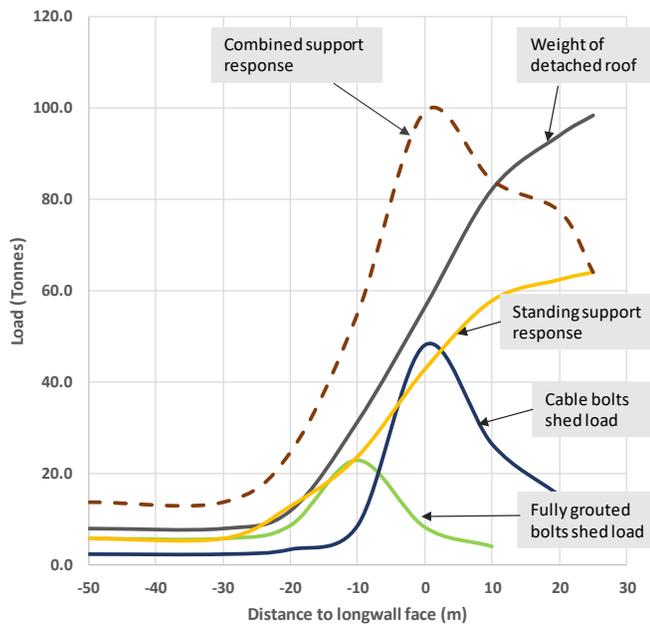


Fig. 6. Detached roof and support response calculated for a longwall mine in West Virginia based on the conceptual model presented in this paper.

model assumes that longwall-induced stress deformations in a gateroad entry are essentially irresistible and the support system needs to yield in a controlled manner to survive the imposed deformations. In addition, the large deformations result in a volume of detached roof strata that must be prevented from collapsing by the support system.

The principles of the conceptual model are applied using the monitoring results of a longwall mine in West Virginia to estimate the amount of roof deformation and height of detached roof. The resulting support response is similar to the monitored response observed in the mine. The simple approach in the conceptual model can be used to develop an understanding of likely support performance during the design of longwall gateroad support systems.

Disclaimer: The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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