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Investigation of fill distribution in post-injected longwall overburden with implications for grout take estimation

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ABSTRACT

In civil and mining engineering, grout injection technology, which involves the injection of grout into the bedding separation zone or other voids through surface boreholes, is used to stabilize the ground above underground excavations. The injected fill at the targeted void space mitigates the deformation of overlying strata, thus reducing surface subsidence. When applying this technology it is important to determine the distribution of the injected fill in the overburden, as it affects grout take estimation, evaluation of subsidence control effectiveness, etc. In this paper, we present theoretical and physical models of the distribution of the injected fill. According to previous borehole data, the location of the injected fill is assumed to be a single horizon. Based on the characteristic of the main injection horizon and geological features of the surrounding strata, an easy-to-use theoretical model of injected fill distribution is proposed, which quantifies the fill thickness at different locations along the main injection horizon. The proposed model is verified using a physical model of overburden grout injection. In addition to the injection parameters such as the horizon depth and ratio of injection, a site-specific geological parameter, namely the angle of full subsidence, as well as the underground opening width, play a vital role in governing the fill distribution. Using the proposed model, we develop a method for estimation of grout take, which may facilitate the injection design, thus improving the effectiveness of ground stabilization.

1. Introduction

In civil and mining engineering, ground stabilization is applied as a basis for surface engineering construction on unstable ground (e.g., fractured rock foundation, karst cavern zone, and around mine voids). This is particularly necessary in areas of large-scale mine voids (Holz and Batchelor, 2012); without stabilization, unexpected subsidence or sinkholes may occur at the ground surface, posing a risk to public safety (Helm et al., 2013; Ju and Xu, 2015; Turka and Gray, 2005). One such stabilization method is void filling using grout injection, which is applied to remediate sinkhole subsidence associated with voids in abandoned room-and-pillar mines (Greenwood and Hill, 2012; Holmquist et al., 2003; Karfakis and Topuz, 1991; Siriwardane et al., 2003), and surface settlement induced by other abandoned spaces such as drifts (Kipko and Kipko, 1990; Song et al., 2015). Grout injection into bedding separation (GIBS) is another effective method of ground stabilization; this method is used in existing or planned surface construction sites in conjunction with active longwall mining and utilizes the horizontal fractures at the rock layer interfaces associated with underground extraction (Xuan and Xu, 2014; Xu et al., 2015).

Traditionally, the GIBS technique involves the injection of grout into mining-induced strata separations through surface boreholes using a pump, thus limiting the deformation of the upper rock layers and reducing subsidence (Palarski, 1989; Xuan et al., 2013). The feasibility of grout injection technology – filling overburden separation voids– was assessed as a means of mining slope management (Shen et al., 1995). In recent years, an improved GIBS technique was developed, namely isolated overburden grout injection, which was successful in mitigating subsidence in populated areas (Xuan and Xu, 2014; Xuan et al., 2013) and in controlling geological hazards (Xuan et al., 2014). With advantages such as being a relatively simple technical process and the low cost of grout injection, this technology has been drawing increasing attention (Shen and Poulsen, 2014).

Estimating grout take, which is a major factor in the overall effectiveness of subsidence control, is an important component of injection design. Although one can easily measure the final grouting volume following injection, the prediction of grout take injection is very difficult because it requires an estimate of the actual injected fill distribution (i.e., thickness and horizons of fill). This is because the stabilization target of overburden grout injection is invisible, complex, and site-dependent, and strongly influenced by the underground extraction method. Thus, it can only be accessed using one or more surface boreholes, unlike in other ground stabilization methods (e.g., gob area backfilling). The lack of understanding of overburden injected fill

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distribution, even following injection, raises difficulties in estimating the grouting volume and the operational costs and may affect the effectiveness of the engineering operations. Thus, injected fill distribution and the associated grout take estimation are a major concern in this field.

Numerical modeling (Chen and Guo, 2008; Shen and Poulsen, 2014) and field measurement studies (Palchik, 2005, 2010; Xuan et al., 2014) of overburden bedding separation resulting from traditional longwall mining (i.e., without grouting) were conducted. The results of these studies were intended to be used to infer the distribution of the injected fill. Xuan and Xu (2014) put forward a hypothetical fill distribution model but did not verify it. Studies on the actual distribution of injected fill were carried out using numerical modeling (Saeidi et al., 2013) and in-situ tests (Chen et al., 2000; Xuan et al., 2015; Zhou et al., 2006). For example, Chen et al. (2000) developed a fluorescent approach to visualize grouting horizons; this method was successfully tested in cement grouting into jointed rock mass. Ackman et al. (1998) tried to locate injected fly ash grout using the non-intrusive geophysical technique of magnetometry following injection into mine voids of an abandoned mine site but could not show a definite correlation between the results and the fill distribution. Similarly, using the geophysical technique of ground penetrating radar and borehole image scanning, Zhou et al. (2006) and Guo et al. (2007) located some of the grout fill in a longwall overburden. Recently, Xuan et al. (2015) drilled two test boreholes to determine the fill distribution in a post-injected longwall mining area, and the characteristics of the main injection section were found, indicating that more than 90% of the total fill was concentrated in the studied section. Although these studies promote the understanding of injected fill distribution, they did not propose a general theoretical or empirical method to determine the overall fill distribution in longwall overburden. Generally, the understanding of this topic is still rudimentary.

Moreover, research on the estimation of grout take by mine voids is lacking, especially on grout take in bedding separations. For fractured rock grouting operations (e.g., a rock dam), empirical calculation methods, numerical modeling, and statistical analysis methods were developed to estimate the grouting take (Elledge et al., 2012). In contrast, in the field of mining void grouting, only a few methods for injection volume estimation have been published. Using case studies, Lloyd et al. (1995) developed a grout take estimation formula for injection into abandoned mined-out areas. This involved in-situ parameters such as borehole density, total thickness of the voids, and total thickness of the broken ground. However, unlike an abandoned mine space, whose volume is mostly unchanged, the aperture of overburden bedding separation changes considerably during longwall extraction, undergoing the processes of initiation, development, and closure. Thus, the equation proposed by Lloyd et al. (1995) would likely be unsuitable for overburden grout injection. In this case, in addition to the height of the extraction space, underground opening geometry, and overburden lithology, the injection pressure also plays a vital role in determining the bedding separation aperture by expanding it (Xuan et al., 2015). When injecting into such zones, the grout take varies considerably with the geological, mining, and injection parameters. However, currently there is no effective method for estimating the grout take and distribution.

In this paper, we develop an easy-to-use theoretical model of injected fill distribution for the engineering of longwall overburden grout injection and verify the model using a physical model. Finally, with a focus on surface subsidence control, the implication of the proposed model for grout take estimation is discussed in detail.

2. Theoretical model

2.1. Theoretical background

To determine the injected fill distribution, the stiffness of the grout in the overburden should be identified. When grouting is used for ground stabilization in coal mines, fly ash from coal combustion is typically used to form the slurry. The fly ash, rather than the water in the grout, acts to mitigate subsidence. Although the fly ash grout that contains water spreads in the overburden voids during injection, the water drains gradually, leaving the grout as compacted fill, which may sometimes be wet (Ilgner, 2000; Ward et al., 2006). This was demonstrated by a field borehole investigation conducted by Xuan et al. (2015). In view of this, the scope of this study was limited to the distribution of the final compacted fill rather than that of the initial flowing grout, and the grout take refers to the actual dry fly ash injected.

Another parameter that has to be determined is the horizon of the injected fill. In this regard, Xuan et al. (2015) found that the injected fill gathered mainly in a main injection section (with a height of 4.8–18.4 m) of the overburden, which included more than 90% of the total fill; vertically, the main injection section was found to be located between the bottom of the injection borehole and the strong rock layer (i.e., the key stratum, defined by Qian et al. (1996)) immediately above. Considering the characteristics of the main injection section, it is reasonable to assume that the fill occupies a single horizon—the main injection horizon. To build the unified model of injected fill distribution in this study, we take the depth of the bottom of the injection borehole as the estimated depth of the main injection horizon. Thus, the thickness of the injected fill can be determined as the difference between the vertical subsidence of the strata overlying and underlying the hole bottom (Fig. 1). However, it is generally very difficult to obtain the actual deflections of the two rock layers under grout injection using analytic calculation; therefore, here we develop a simplified model of injected fill distribution that is easy-to-use for engineering design. For this purpose, as well as determining the stiffness and fill horizon, two additional parameters should be determined: the boundaries of the fill and the fill thickness between the boundaries.

To determine the fill boundaries, the injectable region at the layer interface (the planned main injection horizon) needs to be first identified. A potential injection region is an area along the interface where separation will occur in response to traditional longwall mining (i.e., without grout injection), although the separation apertures will generally be small. Thus, the boundaries of the fill at the main injection horizon can be inferred from those of the general bedding separation at the layer interface. The criterion for separation at a bedding interface, by definition, is that the subsidence of the rock layer above the interface is less than that of the one below it; thus the boundaries of the bedding separation (or the injectable region) can be determined by examining ground movements, for example, using numerical modeling. Generally for a longwall, the mechanism for the movement of the overburden immediately above the extracted space is entirely different from the movement of the overburden above the un-extracted zones (i.e., a pillar zone). To illustrate this, vertical profiles of subsidence for overburden with different depths were obtained using numerical modeling for a longwall site; the modeling was done using Itasca's Universal Distinct Element Code

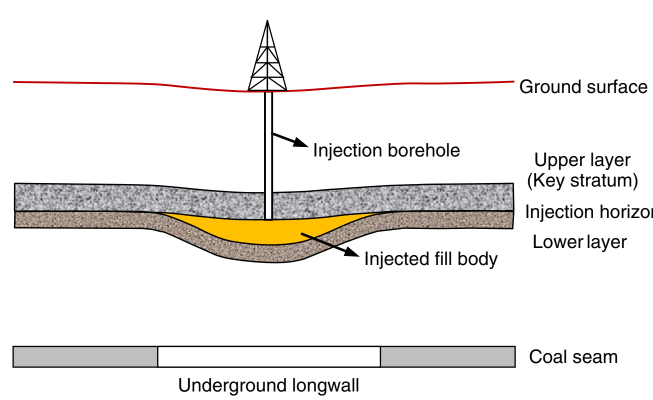

Fig. 1. Illustration of injected fill distribution in longwall overburden.