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Time function model of dynamic surface subsidence assessment of grout-injected overburden of a coal mine

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1. Introduction

Coal-mining-induced surface subsidence is a complex spatio-temporal phenomenon. With the progressive mining of the working face, the surfaces of the affected areas undergo three stages of subsidence, namely, initial subsidence, active subsidence, and residual subsidence.[1] Initial subsidence generally only accounts for 10–15% of the final subsidence and causes minor ground deformation. Active subsidence is the principal subsidence corresponding to about 75% of the final subsidence and causes major ground deformation. Residual subsidence may vary from 5% to 10% of the final subsidence and will result in further ground deformation.[2] The displacements and deformation that occur in each of these stages significantly affect and may damage buildings and other surface infrastructure such as railways, roads, and water facilities,[1,3] resulting in substantial economic losses.[4,5] Hence, to ensure the safety of surface structures, it is necessary to obtain a thorough understanding of the dynamic changes induced by surface subsidence.[6,7]

Time function models are important for predicting dynamic surface subsidence processes. Numerous time function models have been proposed in the literature, and they may be broadly classified into two categories. The first category comprises single-parameter time function models, a classic example of which is the Knothe time function model.[8] The second category comprises multi-parameter time function models such as the Sroka–Schober,[9] arc tangent,[10] logistic,[11] and normal distribution[7] models. The predictions of multi-parameter models are more accurate because they are based on more parameters. However, the difficulty associated with the determination of these parameters reduces the practicality of the models. The Knothe time function model is a particularly simple type of single-parameter time function model because it contains only one easily determined time parameter. Thus, it is often the first choice for use in the prediction of surface subsidence.[3,12] However, since the model was first put forward, a number of researchers have noted its lack of generalisability. To address this issue, the Knothe time function model has been augmented through various approaches to facilitate its application to different practical conditions. Examples of the modified versions are the segmented Knothe model,[13] exponential Knothe model,[14] and Kelvin–Voigt creep equation Knothe model,[15] which have enabled extended applications.

However, most of the abovementioned time function models were intended for conventional longwall working faces, and they also rarely consider the effects of the specific method used to control mining-induced subsidence. One of the methods used to control mining-induced subsidence is the isolated overburden grout injection technique. The technique involves the drilling of boreholes from the surface down to the bedding separation cavities located at certain heights above the ceiling of a longwall panel for the injection of fly-ash slurry. The injection compresses the underlying bedding; then, a grouting pillar with a certain width can be generated at the centre of the longwall panel. The grouting pillar works the same way as a coal pillar in partial mining (e.g. room and pillar mining); therefore, with the support of the grouting pillar, surface subsidence can be better controlled (refer to Fig. 1).[16–22] The technique has been successfully applied in numerous coal mines.[17,18] However, previous studies mainly focused on the final subsidence when the technique was used,[22] with very few studies considering the dynamic processes of subsidence, especially their quantitative relationships with the grout injection parameters. Owing to the limited research and knowledge in this area, subsidence analyses

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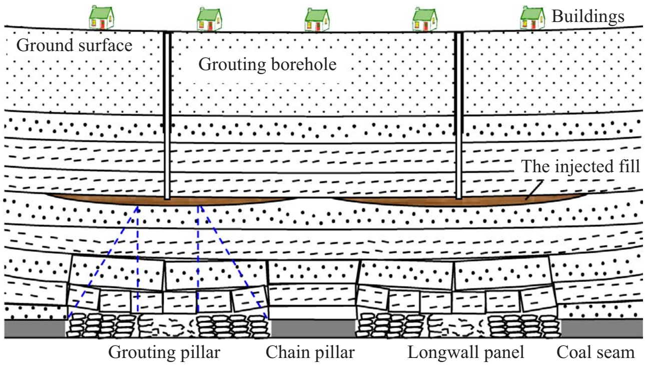

Fig. 1. Schematic cross section of the isolated overburden grout injection technique (after[22]).

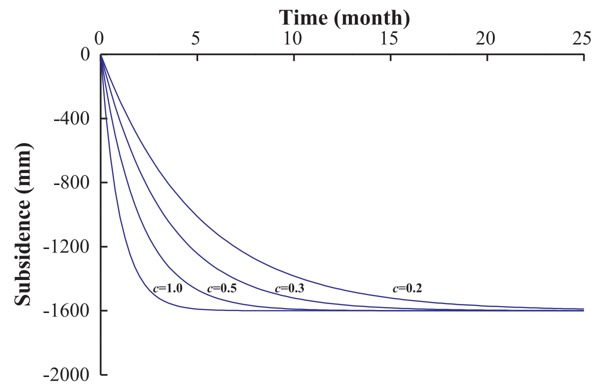

Fig. 2. Knothe time function curves for various values of the time parameter *c*.

during practical grout injection works heavily rely on high-density surface subsidence measurements. This makes advance predictions difficult and hampers on-the-fly control of the grout injection parameters, strongly undermining the protection of surface facilities. Thus, the development of a time function model of the dynamic processes of the subsidence that occurs during overburden grout injection mining is of utmost importance.

On the basis of the Knothe time function, we analysed how the parameters of the isolated overburden grout injection technique affected the time parameter, which represents the difference between conventional longwall mining and mining using the isolated overburden grout injection technique. On the basis of the findings, we introduced a time parameter c_g into the Knothe time function model. The new developed time function model enabled the modelling of the surface subsidence during mining with overburden grout injection. Case studies of different coal mine working faces where the injection technique was employed were used to determine the parameters of the developed model, the reliability of which was further verified by field measurement data.

2. Theoretical background

2.1. Knothe time function model

To describe the displacement and deformation of the surface with time, Knothe, a Polish mining engineer, proposed the Knothe time function model, which assumes that the rate of subsidence $\frac{dW(t)}{dt}$ is proportional to the difference between the maximum subsidence W_0 and the dynamic subsidence at some time t, $W(t)$, which may be expressed as

$$\frac{dW(t)}{dt} = c(W_0 - W(t)) \tag{1}$$

where c is the time parameter (1/year). Given the initial boundary condition $W(t) = 0$ at $t = 0$ (i.e. $W(0) = 0$), the time function model may be derived by solving the following first-order linear differential equation:[3,8,14]

$$W(t) = W_0[1 - \exp(-ct)] \tag{2}$$

2.2. Time parameter c and its determining factors

The time parameter c is an important parameter for characterising the duration of the subsidence process in the Knothe time function model. The duration of the subsidence is inversely proportional to the time parameter c; that is, a larger value of c means that the duration of the subsidence is shorter. Different Knothe time parameter curves may be obtained by varying the value of c, as shown in Fig. 2, which considers the case where the final subsidence $W_0 = -1600$ mm. The duration of the subsidence is 9 months when $c = 0.5$ and increases to 23 months when $c = 0.2$.

Thus, accurate determination of the time parameter c is important for the accurate prediction of dynamic subsidence. Numerous studies have investigated the factors that determine c for conventional longwall mining,[23–25] and c has been determined to be a location-dependent constant generally related to the rate of progression of the working face, the lithology of the overburden, and the burial depth. For some working faces, when these conditions are fixed, the value of c can be determined and remains constant with time. However, because the conditions of coal mining are highly complex and variable, c substantially differs with the location. To address this issue, numerous equations for estimating c have been proposed.[3,23,25]

2.3. Applicability of the Knothe time function to overburden grout injection mining

To examine the applicability of the Knothe time function model (Eq. (2)) when overburden grout injection is used during mining operations, we measured the subsidence at the points of maximum subsidence for four different working faces with grout injection in the Huaibei coalfield and fitted them to the curves predicted by the Knothe time function model (Fig. 3). Although the correlation coefficients of the fits were as high as 0.81–0.88, the shapes of the fitted curves substantially differed from those of the measured data. For example, the subsidence of Longwall 8103 indicated by the fitted curves were significantly larger than the actual measurements up to 5 months, whereas they were significantly lower thereafter (Fig. 3(d)). This shows that the Knothe function model does not accurately describe the dynamic processes of the subsidence that occurs when overburden grout injection is employed in coal mining.

3. Time function model for mining with overburden grout injection

The main cause of the failure of the Knothe time function to correctly predict the dynamic subsidence during mining with overburden grout injection is that the time parameter of the function for this mining technique, c_g, distinctly differs from the conventional longwall mining time parameter c. Ideally, the subsidence is caused by the propagation of the fracture cavities in the overburden resulting from the continuous progression of the mining space.[26,27] Compared to conventional longwall mining, mining with the injection of grout into the overburden eliminates some of the fracture cavities, thereby terminating their propagation to the surface and significantly decreasing the duration of the surface subsidence. This causes c_g to be larger than c.

The determination of c_g is thus key to the development of a time function model for a longwall working face with overburden grout injection. In this section, we first analyse the determining factors of c_g and