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Geomechanics of subsidence above single and multi-seam coal mining

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ABSTRACT

Accurate prediction of surface subsidence due to the extraction of underground coal seams is a significant challenge in geotechnical engineering. This task is further compounded by the growing trend for coal to be extracted from seams either above or below previously extracted coal seams, a practice known as multi-seam mining. In order to accurately predict the subsidence above single and multi-seam longwall panels using numerical methods, constitutive laws need to appropriately represent the mechanical behaviour of coal measure strata. The choice of the most appropriate model is not always straightforward. This paper compares predictions of surface subsidence obtained using the finite element method, considering a range of well-known constitutive models. The results show that more sophisticated and numerically taxing constitutive laws do not necessarily lead to more accurate predictions of subsidence when compared to field measurements. The advantages and limitations of using each particular constitutive law are discussed. A comparison of the numerical predictions and field measurements of surface subsidence is also provided.

1. Introduction

Empirical methods are mainly used in Australia and elsewhere for predicting ground subsidence induced by mining. However, the primary limitation of empirical prediction methods is that generally they cannot be used with great confidence when predicting subsidence in new mining environments, at least until the methods have been calibrated locally. A large database of recorded field measurements of subsidence applicable to those new environments is usually required for such calibrations. In this context, new mining environments include mining in different geological conditions or the use of a new mining method or approach, e.g. multi-seam mining.

Numerical modelling, when used as an alternative or indeed an adjunct to empirical techniques, can predict subsidence in any environment, at least in principle, if a sound knowledge of the geology, particularly the stratigraphy, and the material behaviour of the subsurface strata are available. However, currently, the prediction of subsidence using numerical modelling is renowned for poor accuracy (Coulthard and Dutton, 1988; Kay et al., 1991; Mohammad et al., 1998; Esterhuizen et al., 2010), and this stems in large part from a lack of understanding of the constitutive laws of the coal measure strata.

There have been several subsidence studies conducted previously for a range of constitutive laws describing the material behaviour of coal measure strata (e.g. Kay et al., 1991; Lloyd et al., 1997; Coulthard and Holt, 2008), but there has been no single study conducted to date that provides a comprehensive assessment of the effectiveness with which commonly used constitutive laws can predict surface subsidence and subsurface displacements. The present study compares predictions obtained by modelling the coal measure strata with constitutive laws of varying complexity in the displacement finite element method (DFEM). Two different mining scenarios are considered, i.e. a single seam super-critical longwall panel and multi-seam mining involving first the extraction of super-critical longwall panels and then the extraction of longwall panels in an underlying seam. Only predictions of the surface subsidence are presented. The material above the coal seam, or so-called overburden, is represented by three mechanically different ideal materials: a purely isotropic linear elastic material; an elastoplastic material; and a horizontally bedded material, which is represented as a series of horizontal layers of isotropic linear elastic material separated by closely spaced frictionless interfaces (i.e. bedding planes). The effects of modelling the caved goaf as a strain-stiffening material, as suggested originally by Terzaghi (Pappas and Mark, 1993), are also included in the study.

Subsidence profiles observed in a multi-seam coal mine located in New South Wales, Australia are used to assess the accuracy of the predictions and to assess which one of the ideal constitutive laws

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considered here best represents the overburden material when predicting the displacements of the coal measure rocks.

2. Longwall panel width

The longwall mining technique is now used widely around the world for the extraction of coal from underground coal seams. Based on the cover depth and the panel extraction width, a longwall panel may be classified as being sub-critical, critical or super-critical in width. For a given height or thickness of coal extracted, the critical panel width is defined as the width of an extracted panel for which the maximum possible subsidence is developed (Mills et al., 2009). The critical width represents the cross-over point from a “wide” or relatively “shallow” longwall panel to a “narrow” or relatively “deep” longwall panel. The critical width depends upon the geological characteristics of the overburden. Extracted panels narrower than the critical width are deemed to be sub-critical longwall panels. Those wider than the critical width are known as super-critical longwall panels. The latter are characterised by a surface subsidence profile that is relatively flat over the middle portion of the longwall panel. In single seam coal mining operations in New South Wales, Australia, the critical width of a longwall panel is typically 1–1.6 times the depth of the overburden (McNally et al., 1996; MSEC, 2007a,b; Mills et al., 2009).

3. Numerical predictions of subsidence

A realistic numerical simulation of the longwall mining process is likely to require a three-dimensional (3D) model with progressive coal extraction and accurate determination of the location and properties of any significant discontinuities present in the coal measure strata. However, 3D models can be prohibitively difficult to be constructed, and 3D analyses require substantially longer computer run times compared to two-dimensional (2D) models. Furthermore, the accuracy of the predictions obtained from such an explicit 3D model is highly dependent on realistic constitutive laws being used to represent the mechanics of the coal measure strata.

Subsidence profiles can also be predicted approximately assuming plane-strain (2D) conditions in the numerical model. Models of this kind have been considered for both the transverse cross-section (i.e. parallel to the advancing face) and the longitudinal cross-section (i.e. a slice through the centre of the longwall). In order to capture the subsidence profile with the largest change in tilt, transverse cross-sections are considered here.

4. Single seam mining

4.1. Geometry

One of the problems considered in this study is the extraction of a single longwall panel that is super-critical in geometry. Of interest are predictions of the maximum surface subsidence S_{max}, which usually occurs over the middle region of the single panel, and the subsidence over the edge of the panel, S_{edge} (Fig. 1).

The numerical model adopted to examine this problem consists of a cross-section parallel to the longwall face and assumes plane-strain conditions. The initial pre-mining geometry of the model has an overburden depth (H) of 150 m, a width of the longwall panel (W) of 300 m, and a height (thickness) of extraction (T) of 3 m (Figs. 1 and 2a). These dimensions are typical of some mines in New South Wales, Australia.

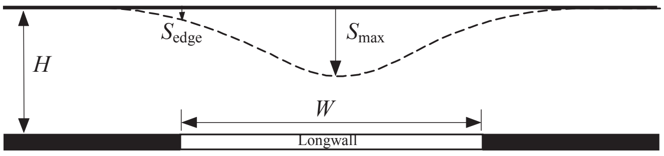
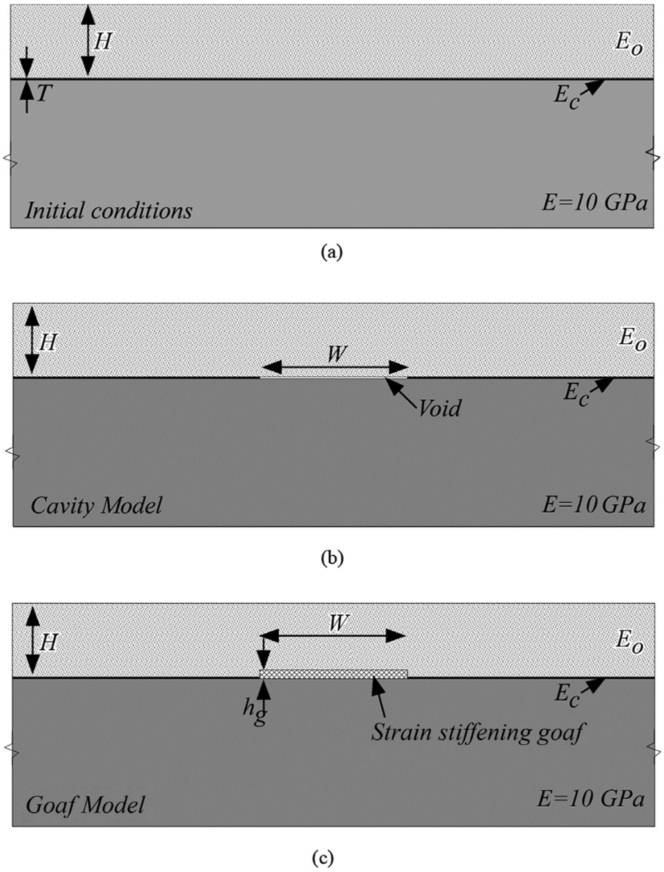


Fig. 1. Schematic diagram of a single seam extraction.

Two different options were considered to represent the post mining strata, designated here as (a) the Cavity Model and (b) the Goaf Model. In the Cavity Model, it is assumed that a void remains after extraction of the coal seam, as shown in Fig. 2b, and that subsidence is induced as the void deforms under geostatic stresses, assuming that the roof and floor of the void can converge but not overlap. This was implemented using a “self-contact” function in ABAQUS assuming frictionless contact. Although leaving a void may not be realistic, this model provides a benchmark for understanding deformation of the overburden.

For the Goaf Model, it is assumed that a strain-stiffening material can be used to represent the behaviour of the caved goaf. This model attempts to represent the situation where, during and after coal extraction, the material from the roof of the longwall panel collapses onto the longwall floor and bulks in volume so as to fill the void left by the extracted coal. The geometry of the Goaf Model is shown in Fig. 2c. The interface between the caved goaf and the surrounding strata in the Goaf Model was prescribed assuming frictionless contact, with no overlapping permitted. The height of the caving above the longwall floor (h_g) in bulking-controlled caving is calculated as follows (Salamon, 1990):

$$h_g = T\left(\frac{1}{b-1}+1\right) \tag{1}$$



(a)

(b)

(c)

Fig. 2. Scale drawing of geometry and material properties of (a) initial conditions, (b) final conditions for Cavity Model, and (c) final conditions for Goaf Model.