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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.
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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.

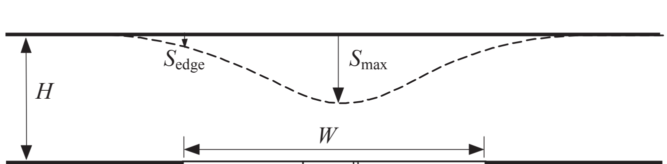


Fig. 1. Schematic diagram of a single seam extraction.

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):

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

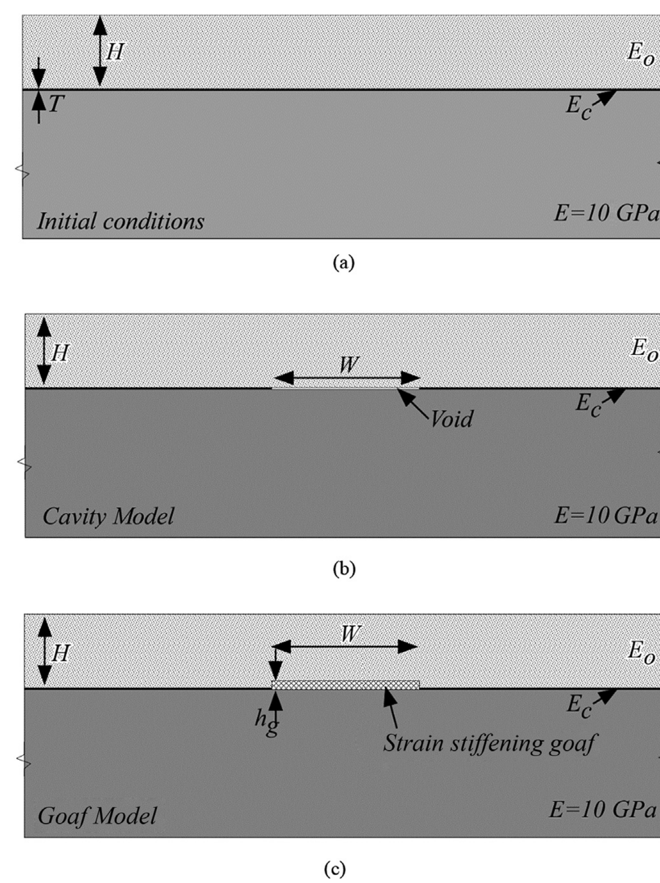


Fig. 2. Scale drawing of geometry and material properties of (a) initial conditions, (b) final conditions for Cavity Model, and (c) final conditions for Goaf Model.

where b is known as the bulking factor. This equation assumes that the convergence of the longwall roof and floor is much smaller than the extracted seam height (T). For the cases examined here, it was assumed that the value of b is 1.2, such that the caved goaf extended to a height of $h_g = 6T$ above the floor of the longwall panel.

4.2. Material behaviour

Three different constitutive laws were used to represent the mechanical response of the overburden strata: (i) an isotropic linear elastic continuum, (ii) a conventional linear elastic-perfectly plastic (Mohr-Coulomb) continuum, and (iii) a horizontally bedded material represented as a series of horizontal layers of isotropic linear elastic materials separated by closely spaced frictionless bedding planes simulated by defining frictionless contact interfaces at vertical intervals of depth D within the material. Details about these constitutive laws are presented in Suchowerska (2014). In the analyses presented here, the Young's modulus of the coal (E_c) was assumed to be equal to that of the overburden strata (E_o), and both the Young's modulus and the Poisson's ratio (ν) are taken to be constant with depth. Numerical values of the material properties assumed in the finite element analyses are presented in Table 1.

Although there have been many previous articles that presented predictions of subsidence assuming an isotropic linear elastic overburden, this case is included here for completeness. The predictions obtained assuming a linear elastic response of the overburden are useful as a reference when compared to the results obtained using more sophisticated and complex constitutive laws.

It has been hypothesised by several authors that the caved goaf responds to loading in a hardening manner (Wardle and Enever, 1983; Smart and Haley, 1987; Trueman, 1990). The caved goaf, which initially is a pile of caved rock, compacted as the overlying strata deflect and apply load to it. Currently there are no preferred and generally agreed equations that should be used for the constitutive law for the caved goaf material. For simplicity, the Terzaghi (Pappas and Mark, 1993) elastic strain-stiffening material model was used in this study, where the tangent Young's modulus (E_t) of the goaf material is specified as

$$E_t = E_i + a\sigma \tag{2}$$

where E_i is the initial tangent modulus, σ is the applied uniaxial stress acting on the goaf material, and a is a dimensionless constant. This equation assumes one-dimensional (1D) compaction conditions in the goaf. The corresponding stress–strain relationship and the secant modulus (E_s) for the caved goaf are detailed in Morsy and Peng (2002).

The ranges of magnitude suggested for the parameters a and E_i vary significantly in the literature. For example, values of E_i obtained by Pappas and Mark (1993) from laboratory testing of caved goaf consisting of shales and sandstones were 10–15 MPa and 5–6 MPa, respectively. The magnitudes of the parameters a and E_i, obtained by Morsy and Peng (2002) from back analysis using a numerical model, were 355 and 31 MPa, respectively. Since it is not possible to independently assess the most appropriate values for parameters a and E_i, the complete range of values from previous studies has been considered, as indicated in Table 2.

Table 1
Values of overburden properties used in parametric study.

Young's modulus, E_o (GPa)	Poisson's ratio, ν	Cohesion, c (kPa)	Friction angle, φ (°)	Dilation angle, ψ (°)	Unit weight, γ (kN/m^3)	Spacing of horizontal bedding planes (m)
1, 5, 10	0.25	2000	30	30	25	No bedding, 30, 15, 7.5

4.3. Subsidence predictions

In all cases considered here, predictions were made of the subsidence induced by the extraction of a single longwall using the commercial finite element package ABAQUS. The predicted results for the surface subsidence are presented here according to the three forms of constitutive laws used to represent the overburden, with results for the Cavity Model and Goaf Model presented separately. The analyses were conducted for an initial ratio of horizontal in situ stress to vertical in situ stress (K) of 1.5.

Tables 3 and 4 provide a summary of the maximum subsidence above the centre of the longwall (S_{max}) and the ratio of the subsidence above the edge of the longwall panel to the maximum subsidence (S_{edge}/S_{max}) for all types of overburden materials used in the Cavity Model and the Goaf Model, respectively. More detailed information about the results from an extended form of this study can be found in Suchowerska (2014).

In the sections that follow, subsidence predictions are compared with typical values for Australian coalfields, ascertained from field measurements. The measured maximum subsidence above a single seam super-critical longwall panel (S_{max}) is typically 55%–65% of the seam's extracted thickness (T). The maximum subsidence above the edge of the longwall panel (S_{edge}) has been recorded to be within the range of 5%–15% of S_{max} (Holla, 1985, 1987, 1991; Coulthard and Dutton, 1988). These values should be considered indicative only, as surface topography and unusual geological fea-

Table 2
Parameters used for the Terzaghi strain-stiffening goaf material.

Goaf material	E_i (MPa)	a	Reference
Stiff	30	350	Morsy and Peng (2002)
Average	20	50	–
Soft	5	15	Pappas and Mark (1993)
Multi-seam	5	38	–

Table 3
Normalised maximum subsidence and edge subsidence – Cavity Model.

Overburden	Variable	Magnitude	S_{max}/T	S_{edge}/S_{max}
Elastic	E_o	10 GPa	9%	47%
		5 GPa	17%	47%
		1 GPa	75%	48%
Elastic-perfectly plastic ($c = 2000$ kPa, $\varphi = 30°$)	E_o	10 GPa	96%	5%
		1 GPa	82%	45%
Bedded material	D	30 m	54%	20%
		15 m	100%	11%
		7.5 m	100%	0.5%

Table 4
Normalised maximum subsidence and edge subsidence – Goaf Model.

Overburden	Variable	Magnitude	Goaf	S_{max}/T	S_{edge}/S_{max}
Elastic	E_o	10 GPa	Stiff	4%	50%
		1 GPa	Stiff	5%	53%
		10 GPa	Soft	9%	48%
		1 GPa	Soft	48%	40%
Elastic-perfectly plastic ($c = 2000$ kPa, $\varphi = 30°$)	E_o	10 GPa	Stiff	4%	50%
		10 GPa	Ave.	10%	34%
		10 GPa	Soft	32%	12%
Bedded material	D	7.5 m	Stiff	6%	28%
		7.5 m	Ave.	27%	11%
		7.5 m	Soft	97%	7%

tures can lead to anomalies in subsidence profiles (Kay and Carter, 1992; McNally et al., 1996; Holla and Barclay, 2000).

4.3.1. Isotropic linear elastic overburden

Fig. 3 shows the predictions of the normalised subsidence caused by the extraction of the single super-critical longwall panel, assuming the Cavity Model, for the case of an isotropic elastic overburden with varying magnitudes of Young's modulus (E_o). The maximum subsidence (S_{max}) for the elastic overburden when $E_o = 10$ GPa is approximately 9% of the extracted seam thickness (T). The maximum subsidence (S_{max}) increases for smaller magnitudes of Young's modulus for the overburden (E_o), such that $S_{max} = 75\%$ of T for $E_o = 1$ GPa. The ratio S_{edge}/S_{max} remains constant at approximately 47% for all magnitudes of E_o considered. Therefore, a softer elastic overburden increases the maximum predicted subsidence but, as expected for a linear material, it does not change the overall shape of the subsidence profile. These results also support previous observations that an isotropic linear elastic overburden predicts a subsidence profile that is generally shallower and wider than what is normally observed in the coalfields of New South Wales, Australia (e.g. Fitzpatrick et al., 1986; Coulthard and Dutton, 1988).

Fig. 4 shows the subsidence profiles predicted for the Goaf Model with either a stiff or soft goaf material (Table 2), and with overburden stiffness of either 1 GPa or 10 GPa. The similar magnitude of the predicted maximum subsidence of approximately 5% of T for both cases with the stiff goaf suggests that the subsidence profile is governed more by the stiffness of the caved goaf material than the overburden stiffness. Indeed, predictions of the subsurface vertical displacements in the caved goaf and overburden show that the stiff goaf was compressed to a maximum of approximately 0.1 m. Correspondingly, the secant modulus of the goaf material rose from its initial value of 30 MPa to a maximum of 287 MPa and 239 MPa for an overburden stiffness of 1 GPa and 10 GPa, respectively.

For the cases with the soft goaf, the subsidence profiles shown in Fig. 4 are quite different for the two magnitudes of E_o. The maximum subsidence is predicted to be approximately 9% and 48% of T for $E_o = 10$ GPa and $E_o = 1$ GPa, respectively. Both profiles indicate that generally the subsidence is significantly larger in magnitude than that predicted for the stiff goaf. A soft overburden with a relatively soft caved goaf material allows the maximum subsidence to be achieved, while the sagging limit of a stiff

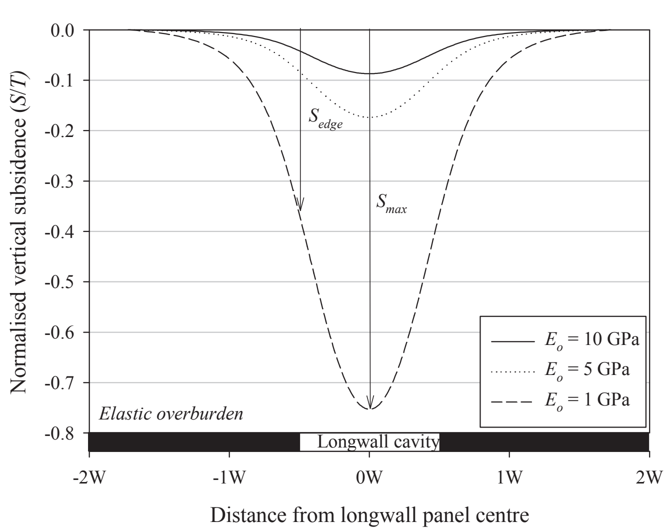


Fig. 3. Subsidence normalised by extracted seam height for an elastic overburden material with varying Young's modulus of the strata (E_o) – Cavity Model.

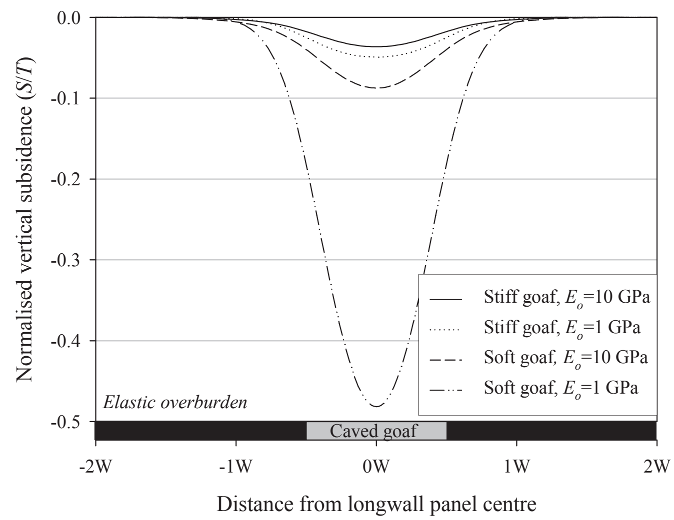


Fig. 4. Subsidence normalised by extracted seam height for an elastic overburden material with varying Young's modulus of the strata (E_o) and goaf material – Goaf Model.

overburden governs the compression of the caved goaf and the overall surface subsidence. The secant modulus in the goaf was predicted to rise from an initial value of 5 MPa to the maximum values of 12 MPa and 6 MPa for an overburden stiffness of 1 GPa and 10 GPa, respectively. The ratio S_{edge}/S_{max} for all four Goaf Model cases is presented in Table 4, and they all fall in the range of approximately 40%–55%. This result confirms the trend observed in all predictions with an elastic overburden compared to measurements made in the field: use of an isotropic elastic overburden overestimates the relative subsidence above the edge of the longwall panel relative to the maximum subsidence (Coulthard and Dutton, 1988; Kay et al., 1991).

4.3.2. Elastoplastic overburden

Fig. 5 presents the predicted subsidence for the Cavity Model for two magnitudes of E_o, when the overburden material is assumed to be an elastic-perfectly plastic material. Shear failure in the overburden is defined by the Mohr-Coulomb criterion with cohesion $c = 2000$ kPa and friction angle $\varphi = 30°$. These strength parameters were selected based on the findings presented by Suchowerska (2014), who assumed associated plastic flow ($\psi = \varphi$) and concluded that a friction angle of $\varphi = 30°$ best predicted the pattern of roof collapse as compared to field observations. The normalised maximum vertical subsidence is 96% and 82% of T for $E_o = 10$ GPa and $E_o = 1$ GPa, respectively. The ratio S_{edge}/S_{max} is 5% and 45% for $E_o = 10$ GPa and $E_o = 1$ GPa, respectively. The decrease in the maximum vertical subsidence with a decrease in Young's modulus is somewhat counterintuitive but explained by the effect of plastic deformation. When the Young's modulus is relatively large, the overburden deforms primarily by concentrated plastic shearing (i.e. roof collapse) above the longwall panel, whereas a low Young's modulus enables the overburden to sag elastically prior to the onset of failure. The differing behaviour can be better appreciated when comparing the subsidence for the elastic-perfectly plastic overburden to the isotropic linear elastic overburden results, which are also shown in Fig. 5. The softer overburden undergoes much less plastic strain than the stiffer overburden before the longwall roof touches the longwall floor, at which point further vertical displacement effectively ceases.

Predicted distributions of the vertical displacement for the elastic-perfectly plastic overburden show that there is effectively a

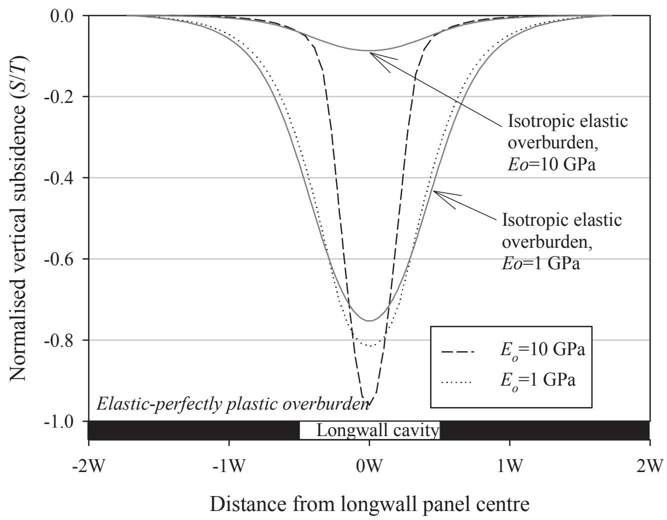


Fig. 5. Normalised surface subsidence for an elastic-perfectly plastic overburden with varying Young's modulus – Cavity Model. Isotropic linear elastic overburden results have been included for comparison.

mass downward movement of a trapezium-shaped block of the overburden directly above the extracted longwall panel. This failure mechanism has previously been described as Terzaghi's trap door problem. The overall shape of the subsidence curves (Fig. 5) appears to be primarily governed by the elastic properties of the overburden outside the area of failure, and by the plastic flow rule in the thin failure zone defining the trapezium-shaped block of overburden. For this reason, the subsidence bowl is still relatively wide for the case where $E_o = 1$ GPa.

Fig. 6 shows the subsidence profiles for the Goaf Model for the elastic-perfectly plastic overburden with c = 2000 kPa and $E_o = 10$ GPa for three values of caved goaf stiffness (Table 2). For the stiff goaf case, the maximum subsidence corresponds to that predicted assuming an isotropic elastic overburden because the goaf does not permit the overburden to yield. On the other hand, the overburden above the average goaf and soft goaf yields in both cases in the manner described above. The maximum vertical subsidence is 10% and 32% of T for the average goaf and soft goaf, respectively. The ratio S_{edge}/S_{max} decreases as the stiffness of the goaf is reduced, such that S_{edge}/S_{max} is 12% for the soft goaf.

Additional cases that allow softening of the elastoplastic overburden have been considered by Suchowerska (2014) but are not discussed in detail here due to space limitations. Preliminary simulations suggest that strain-softening of the overburden may reduce the ratio of the subsidence over the edge of the longwall panel to the subsidence over the centre (S_{edge}/S_{max}). However, robust implementation of the strain-softening constitutive laws in DFEM is required.

4.3.3. Bedded overburden

Fig. 7 shows that the inclusion of smooth interfaces in an elastic overburden ($E_o = 10$ GPa) increases the maximum subsidence and also changes the shape of the subsidence profile in the Cavity Model. Smooth interfaces vertically spaced at intervals (denoted by the parameter D) of 15 m or less allow the cavity roof to touch the floor of the longwall panel and the subsidence to reach 100% of T. The relative subsidence at the panel edge (S_{edge}/S_{max}) reduces from 47% for the elastic overburden down to 1% for the elastic overburden with smooth interfaces spaced at 7.5 m intervals (Table 3).

The results presented in Fig. 8 are for the Goaf Model with an elastic overburden ($E_o = 10$ GPa) and smooth horizontal interfaces spaced every 7.5 m vertically. Three degrees of stiffness were considered for the strain-stiffening goaf material, with the relevant parameters provided in Table 2. It is evident from Fig. 8 that the stiffness of the strain-stiffening goaf material again governs the maximum subsidence. The soft goaf model predicts that the maximum subsidence reaches almost the full extracted seam height. The average goaf and stiff goaf models predict a maximum subsidence of 27% and 6% of T, respectively. The selection of appropriate values for the strain-stiffening goaf parameters would need to be further investigated, possibly through back calculation, in order to achieve a prediction of maximum subsidence equal to the magnitudes typically recorded in the field. This is conducted in the multi-seam case study presented below.

4.4. Discussion

The results of the simulations of single seam, super-critical longwall mining presented above indicate that modelling the

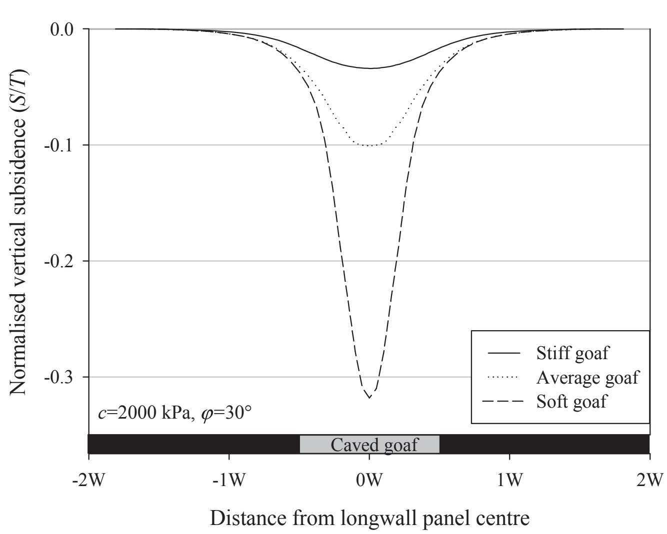


Fig. 6. Normalised surface subsidence for an elastic-perfectly plastic overburden with varying Young's modulus – Goaf Model.

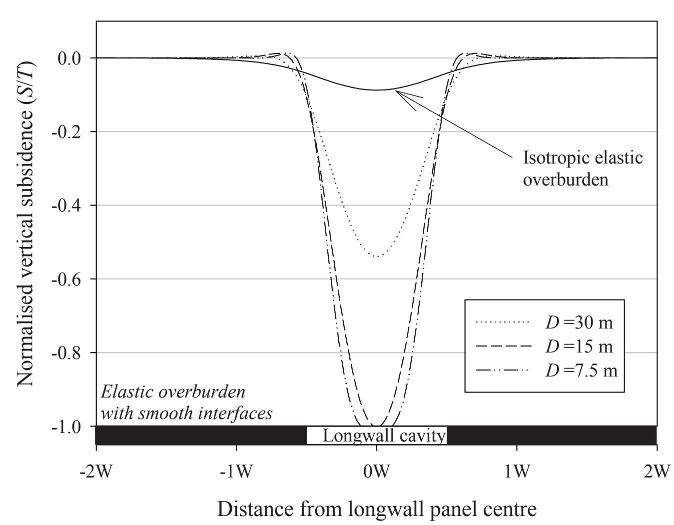


Fig. 7. Normalised surface subsidence for an elastic overburden material containing smooth horizontal interfaces separated by spacing D – Cavity Model.

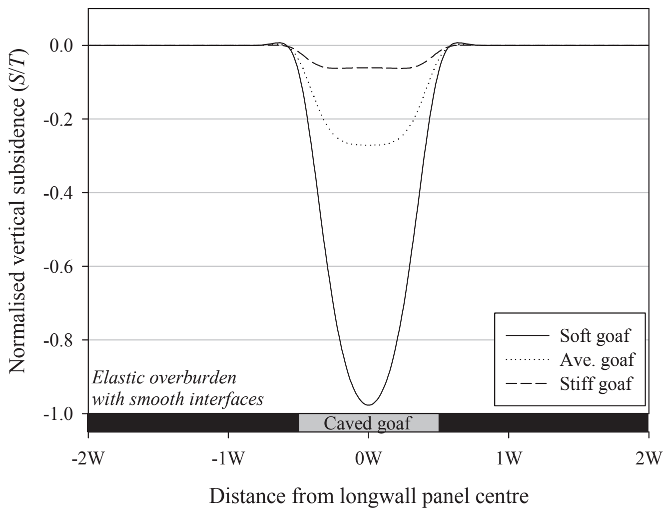


Fig. 8. Normalised surface subsidence for an elastic overburden material containing smooth horizontal interfaces spaced every 7.5 m – Goaf Model.

overburden rock mass as an isotropic linear elastic medium results in subsidence profiles that extend over a large region. Such a simple model is known to have numerous shortcomings when used to predict the profile of surface subsidence above super-critical longwalls in Australia, and possibly elsewhere. Field measurements indicate that the actual profile is more likely to be deeper and narrower than the wide, shallow profile predicted by the linear elastic model.

Although not explored in this paper, it is well known that the predicted subsidence profile is more like what is observed in the field, if a transversely isotropic elastic model is adopted for the overburden in place of the isotropic counterpart. If subsidence prediction for single seam mining is the only concern, then the selection of transverse isotropy may be adequate for numerical modelling. However, it is noted that even then, predictions of other aspects of the rock mass behaviour may be unsatisfactory. For example, Suchowerska (2014) has shown that selection of the transversely isotropic elastic overburden may result in inappropriate predictions of the post-mining stresses around a longwall. Obviously, such predictions will be important when considering the stability of mine pillars, and they may even become critical when attempting to predict the subsidence for multi-seam mining. Namely, when predicting the incremental subsidence due to mining of a second underlying coal seam, it will be important to have accurate knowledge of the stresses induced in that underlying seam due to the earlier mining of the overlying seam. That particular stress state will form the starting point for modelling the effects of the second seam extraction.

As pointed out by Suchowerska (2014), if the primary goal of a numerical model is to predict accurately the subsidence due to multi-seam mining, then the constitutive models used for the overburden would need to ensure prediction of an appropriate shape for the subsidence profile, as well as allow for the weight of the overburden to be transferred through the goaf formed above the first seam onto the material between the coal seams, or so-called interburden. The results presented thus far indicate that an appropriate subsidence profile is likely to be predicted assuming a model with a strain-stiffening goaf material, in conjunction with an overburden composed of layers of linear elastic material separated by horizontal planes with limited ability to transmit horizontal shear stress. Furthermore, Suchowerska (2014) demonstrated quite clearly that such a model also has the potential to predict accurately the transfer of the overburden load through the goaf to the underlying strata.

5. Multi-seam mining layouts

It is possible to conceive a variety of feasible layouts of longwall panels for a multi-seam mining operation. The two particular layouts illustrated schematically in Fig. 9b and c, referred to as the "stacked" and "staggered" respectively, are considered here.

For the predictions presented, the initial geometry consists of an overburden thickness above the first seam (H) of 150 m and an interburden thickness between the first and second seams (B) of 40 m. For both models the width of each longwall panel (W) is assumed to be 300 m and the height of extraction in the first seam (T_1) and the second seam (T_2) is 3 m. In the stacked arrangement, the longwall panel extracted in the second seam lies directly beneath the longwall panel extracted in the first seam (Fig. 9b). In the staggered arrangement, two longwall panels are extracted in the first seam and one longwall panel is subsequently extracted in the second seam. The centreline of the longwall in the second seam aligns with the centre of the chain pillar in the overlying seam (Fig. 9c).

Due to space limitations, predictions of subsidence will be presented here only for the staggered arrangement of multi-seam panels and for a limited set of material properties. For these predictions, Young's modulus for all coal measure strata was kept constant at $E = E_o = E_c = 10$ GPa. Each goaf was modelled as a strain-stiffening material with the properties defined for the multi-seam case identified in Table 2. For consistency with the general findings of the study of surface subsidence due to single seam

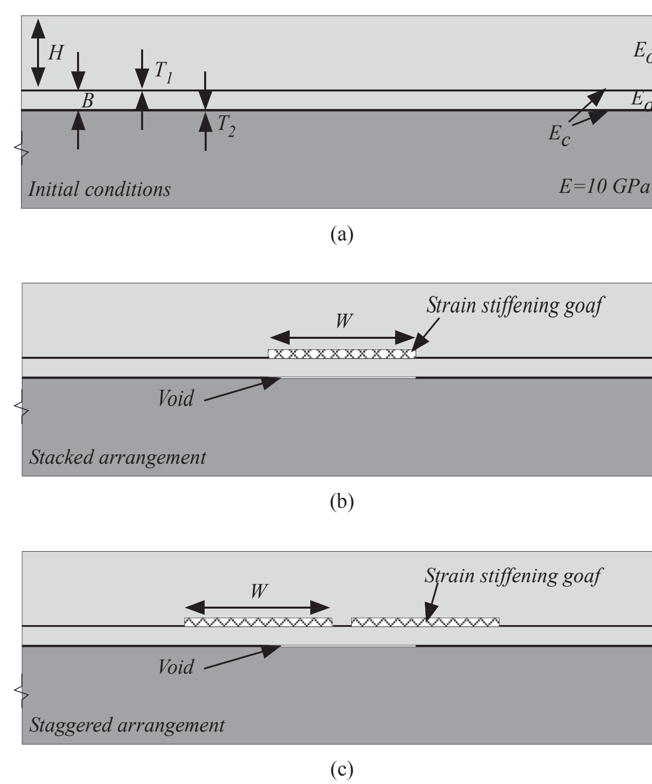


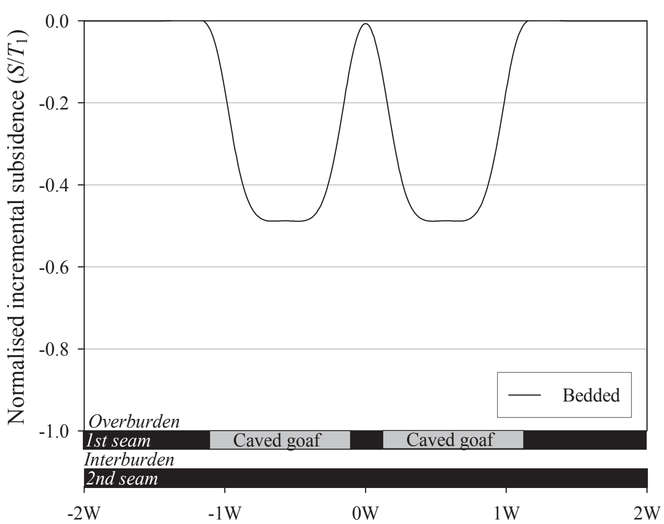
Fig. 9. Schematic drawing of geometry and material properties of (a) initial conditions of both stacked and staggered arrangements, (b) final conditions for the stacked arrangement, and (c) final conditions for the staggered arrangement. As a scale drawing, the void in the second seam is placed as marked but cannot be seen in the figure.

mining, both the overburden and interburden were modelled in this case as a "bedded" material consisting of horizontal layers of isotropic linear elastic rock separated by frictionless horizontal interfaces at 5 m vertical spacing.

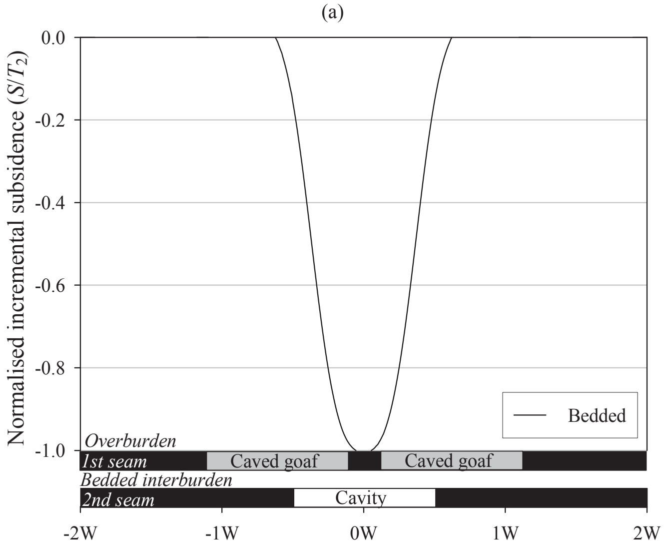
5.1. Subsidence predictions

Fig. 10a shows the predicted incremental subsidence after the extraction of the two longwall panels in the first seam of the staggered arrangement. The maximum subsidence above the centre of each longwall panel in the first seam is 48% of T_1. The superposition of the subsidence above each longwall panel for the bedded overburden does not cause the ground surface above the chain pillar to subside and this is because the sagging of the bedded overburden strata is limited primarily to the width of each individual longwall panel.

The curve plotted in Fig. 10b shows the predicted incremental subsidence after extraction of the longwall panel in the second seam for the staggered arrangement. The maximum incremental subsidence above the longwall panels in the second seam was approximately 100% of T_2 for the bedded overburden and interburden considered here.



(a)



(b)

Fig. 10. Plots of incremental subsidence profiles from the staggered arrangement after extraction of the longwall in (a) the first seam and (b) the second seam.

5.2. Discussion

The load distribution at the depth of the first seam in the staggered arrangement can effectively be simplified to a point load being applied to the mid-span of the interburden beam at the location of the chain pillar dividing the two longwall panels. This load distribution gives rise to additional deflection of the interburden and the subsequent increased incremental subsidence upon extraction of the longwall panel in the second seam.

It has been hypothesised that the additional subsidence typically recorded above multi-seam longwall panels may be caused by additional compaction of the caved goaf material above the first seam due to extraction of the second seam. Such a mechanism has not been observed in the modelling described in this paper. The results obtained in the sensitivity study conducted by Suchowerska (2014), and illustrated here, confirm that it would only be possible to replicate this additional displacement in the first seam goaf in a continuum approach, such as the finite element method (FEM), if there are additional stresses applied to the caved goaf material. However, additional compaction is deemed to be unlikely if the magnitude of the vertical stress in the centre of the first seam longwall panel has already returned to the magnitude of the original overburden stress after extracting the first seam. It is understood that the FEM would not be able to simulate well, if at all, the displacements that might occur due to rock fragments in the first seam reconfiguring into a more compact arrangement. Further investigation is required to see if other numerical methods, such as the discrete element method (DEM), would be able to represent the reconfiguration of the first seam caved goaf as a result of extracting a second seam longwall, and if this would lead to the appropriate shape of the subsidence profile recorded above multi-seam longwall panels.

6. Multi-seam subsidence case study

In this section, subsidence predictions from numerical simulations are compared to field observations of the surface subsidence above a multi-seam mining operation at Blakefield South in the Hunter Valley of New South Wales, Australia. The Blakefield South underground coal mine is part of the Bulga Complex, which is located approximately 5 km north of the town Broke in the Upper Hunter Valley. Current mining operations by GlencoreXstrata Pty Ltd. involve extraction of longwall panels from the Blakefield coal seam, which undermine the previously extracted longwall workings in the Lower Whybrow coal seam. The Bulga Complex is part of the Hunter coalfields which together with the Newcastle coalfield, Western coalfields, and Southern coalfields are part of the Sydney Basin. The Sydney Basin contains sediments from the early Permian to Triassic. The Lower Whybrow and Blakefield seams lie within the Jerry Plains Subgroup of the Wittigham Coal Measures (Stevenson et al., 1998) and mainly comprise bedded sandstones and siltstones.

Within the case study mine site, the surface topography is generally flat to undulating. Both the Lower Whybrow and Blakefield seams generally dip from the north down to the south. The depth to the Whybrow seam varies from 40 m at the northern end of the site to 350 m at the southern end of the site. The overburden consists of moderate strength strata near the surface (uniaxial compressive strength (UCS) = 30–40 MPa) and at greater depth consists of interbedded sandstones with an increased strength

(UCS = 50–80 MPa). The thickness of the interburden varies between 70 m and 100 m. The interburden strata comprise interbedded weak to moderate strength units (UCS = ~20–50 MPa). More detailed information about the geology of the site can be found in the reports by MSEC (2008, 2011) and SCT (2008).

A plan showing the layout of the various longwall panels at the Blakefield South mine is presented in Fig. 11. The panel of interest here is designated as BSLW2. It is noted that panels in the Lower Blakefield seam are oblique to the panels in the overlying Lower Whybrow seam. Fig. 11 also indicates the DL survey line along which measurements of surface subsidence were made and used in this case study.

A modified version of the multi-seam numerical model described previously has been adopted in this case study. Scale drawings of the initial and final conditions of the multi-seam case-study models used are shown in Fig. 12a and b, respectively. The dimensions of the models reflect the geometry of the excavations of BSLW2 and the overlying LW2 and LW3: An overburden height (H) of 155 m, an interburden thickness (B) of 80 m, a width of longwall BSLW2 (W) of 410 m, and a coal seam thickness of the Blakefield seam (T_2) of 2.8 m were used. The original width of the panels in the overlying Lower Whybrow seam was 210 m. However, because the DL survey line crosses LW2 and LW3 on a diagonal, the width of LW2 and LW3 was assumed to be 242 m in the cross-section used in the numerical model. The extracted height in the overlying Lower Whybrow seam (T_1) was 2.5 m. The overburden and interburden were modelled as a bedded material, which consisted of an elastic material with horizontal frictionless interfaces that were equally spaced at a vertical distance (D) of 5 m. The relevant constitutive properties are listed in Table 5.

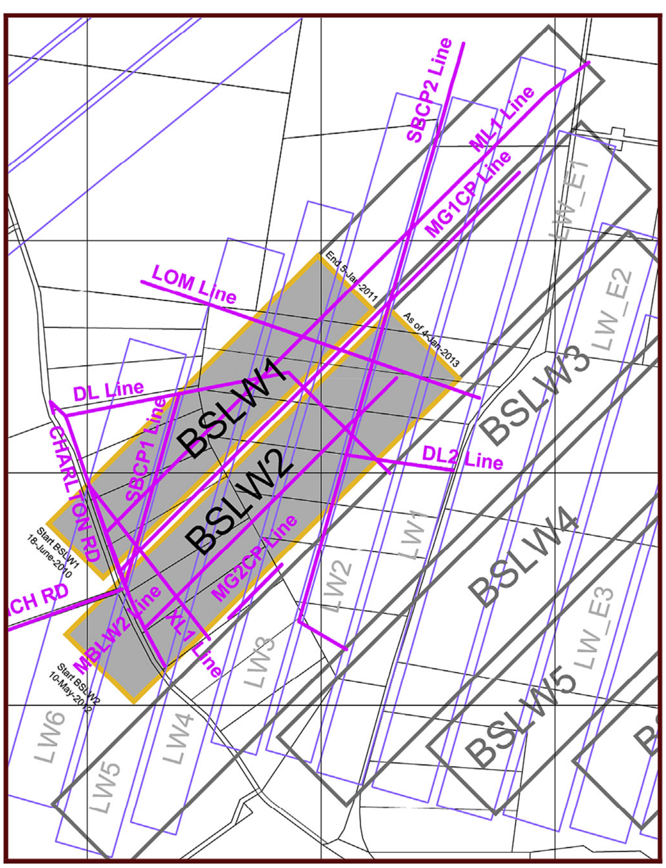


Fig. 11. Map showing the survey lines used to monitor the subsidence when extracting longwall BSLW2 (MSEC, 2013).

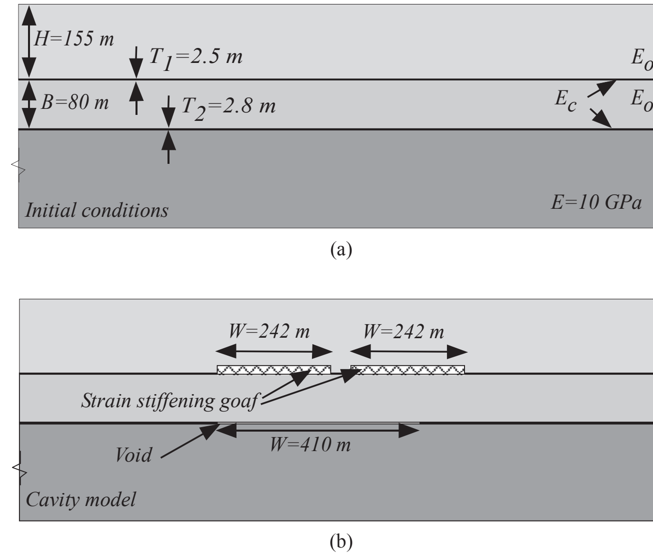


Fig. 12. Scale drawings of the geometry and material properties used in the numerical models to predict subsidence above BSLW2 in the Blakefield seam, with (a) initial conditions and (b) final conditions.

A strain-stiffening goaf was included in the first seam as well at the second seam longwall panels. The parameters assumed for the first seam strain-stiffening goaf were $b = 1.2$, $E_i = 5$ MPa and $a = 38$, as these magnitudes yielded appropriate subsidence profiles upon extraction of the first seam longwall panels that matched field measurement (Suchowerska, 2014). For the second seam, a bulking ratio of $b = 1.2$ was assumed, such that the caved goaf height (h_g) would correspond to 16.8 m. In order to achieve a subsidence profile similar in magnitude to the field measurements, the assumed values for the strain-stiffening parameters of the caved goaf in the second seam were adjusted to $E_i = 4$ MPa and $a = 40.6$ to achieve a better match between the predicted and measured subsidence profiles. All other specifications of the multi-seam case-study model were as per the description provided previously.

6.1. Subsidence predictions

Fig. 13 shows the predicted incremental subsidence for the extraction of BSLW2 using the multi-seam case-study model with a bedded overburden and interburden. The maximum predicted subsidence is 91% of T_2, and the subsidence above the edges of longwall BSLW2 is predicted to be approximately 5% of T_2. The subsidence predicted above areas of caved longwall goaf present in both seams is approximately 79% of T_2, which matches the measured subsidence quite well. The predicted subsidence located above the chain pillar and the edges of the caved goaf present in the first seam workings does not match the recorded subsidence measurements. The maximum predicted subsidence occurs above the chain pillar present in the first seam workings. The finite element model is able to match approximately the general subsidence profile, but not the local variation close to the chain pillar.

6.2. Discussion

One explanation for the inability of the finite element model to capture local variations in the subsidence profile is the possible existence of several separate subsurface deformation mechanisms: (i) sagging of the interburden and overburden, (ii) additional compaction of the caved goaf material at the depth of the first extracted seam, or (iii) a complex combination of deformation that

Table 5
Case study parameters.

Young's modulus, E_o (GPa)	Poisson's ratio, ν	Unit weight, γ (kN/m^3)	Spacing of horizontal bedding planes, D (m)
10	0.25	25	5

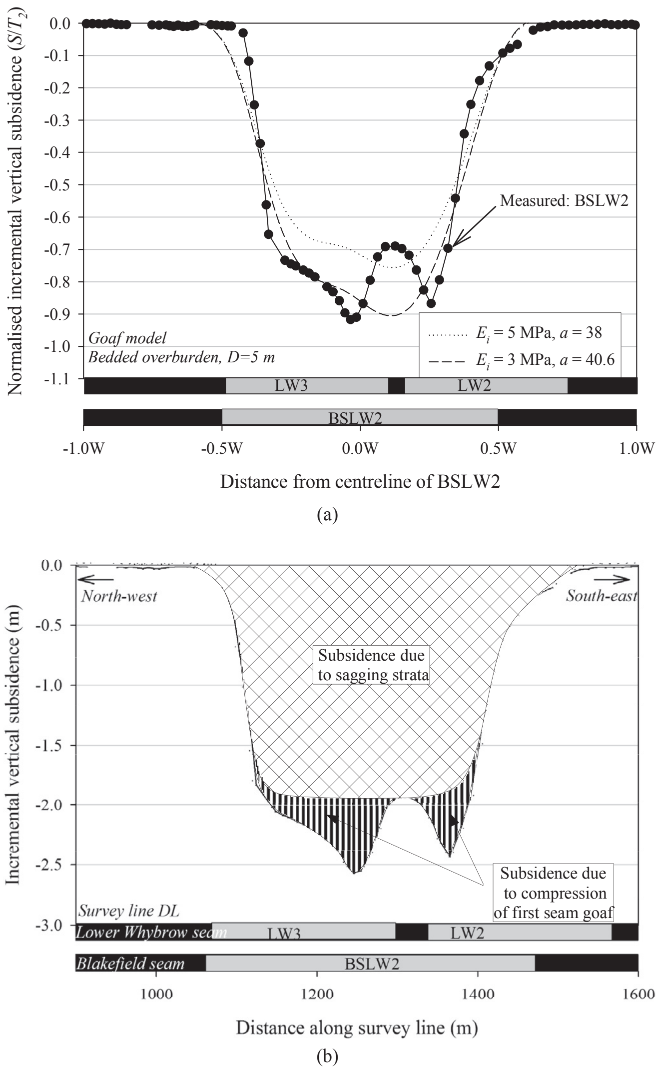


Fig. 13. (a) Normalised incremental subsidence for BSLW2 predicted using the Goaf Model with a bedded overburden and the normalised measured subsidence for BSLW2 along DL survey line (values of E_i and a identified in the legend correspond to the second seam); (b) Inferred subsurface deformations contributing to the subsidence recorded at the ground surface.

is highly dependent on the local geology. It could be postulated that all the subsidence larger than that recorded above the first seam chain pillar is due to compaction of the first seam goaf. The relative contribution of the first two forms of subsurface deformation to the overall subsidence profile is schematically shown for the case-study DL survey line in Fig. 13b. The comparison between the predictions and measurements (Fig. 13a) suggests that the finite element model is not able to replicate displacements associated with remobilisation and compaction of the first seam goaf. For the predictions shown in this comparison, the subsidence profile assumed to be generated by sagging of the interburden and overburden (as shown in Fig. 13b) was achieved by using the same properties for the second seam goaf as adopted for the first seam goaf (b = 1.2, E_i = 5 MPa, and a = 38). The predicted subsidence curve is a reasonable shape for a super-critical longwall panel, except for the fact that the maximum subsidence occurs directly above the Lower Whybrow chain pillar. This occurs because the chain pillar in the first seam attracts more vertical stress than the adjacent strain-stiffening goaf, as a consequence of the isotropic elastic overburden layers redistributing stress to surrounding strata.

In summary, it is noted that the FEM was able to predict reasonably well the basic subsidence profile created above the multi-seam longwall panels due to sagging of the interburden and the overburden. However, it was not successful in predicting the local variations of subsidence above the chain pillars in the first seam, which is hypothesised to be generated by compaction of the goaf in the first seam.

7. Conclusions

A theoretical study to investigate the subsidence profiles predicted above single and multi-seam longwall panels has been described. Three forms of constitutive laws were used to represent the coal measure strata in finite element modelling of the problem. When the overburden and interburden were represented by a bedded material, consisting of horizontal layers of isotropic linear elastic material separated by smooth horizontal interfaces, the predicted subsidence profiles best matched typical field measurements. This was the case for both single and multi-seam extraction, with the latter involving a staggered arrangement of longwall panels.

The subsidence measured in a field case above a multi-seam extraction using the longwall method was compared to predictions of subsidence using the DFEM. The multi-seam model with a strain-stiffening caved goaf in both seams and a bedded overburden and interburden was able to match the general shape of the subsidence profile that formed above the longwall panel extracted in the second seam. However, the DFEM was not able to predict the variation in the surface subsidence profile immediately adjacent to the chain pillar in the first seam, presumably because it was not able to replicate the remobilisation and compaction of the first seam goaf.

The significance of the research presented here for multi-seam mine designers is that the general shape of the subsidence profile above a multi-seam longwall panel can be achieved with finite element modelling. However, further investigations are required to be able to match more closely the locations of the maximum and minimum subsidences measured above multi-seam longwall panels.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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