The Numerical Modelling of International Trends in Subsidence Models

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Abstract: This paper initially outlines a numerical modelling approach designed and validated for subsidence simulation within UK Coal Measures. The methodology utilised was modified for application to a number of distinctly different International Coalfields. The basis of this approach is the development of representative in-situ rock mass properties for stiffness and strength parameters for use within a complex non-linear Numerical Model using a Finite Difference Method, Fast Lagrangian Analysis of Continua (FLAC). Specific features of the methodology include the simulation of the development and propagation of the caving process with unique modification of the post failure properties within the zone of influence, as well as rock mass property changes with depth. This numerical modelling technique has been adapted and modified taking account of lithological stiffness and strength differences to simulate subsidence within Australian, USA, South African and Indian coal measure strata conditions.

Key Words: FLAC, longwall mining, numerical modelling, rock mass classification rating (RMR), subsidence

Introduction

The development of subsidence over longwall panels is an international problem effecting many types of surface structure in many parts of the world. Subsidence is one of the few areas where the mining process has a direct impact on the public and as such its accurate prediction and control is an important priority. Comprehensive monitoring strategies are difficult and expensive and hence much work has been undertaken modelling the process both empirically and, in more recent times, numerically. Numerical models have the additional advantage of demonstrating the whole caving to subsidence process and thus have importance to many aspects of longwall design in addition to simple subsidence prediction. The problems and additional costs associated with the inflow of water and gas, face weightings, and interaction effects are all closely linked to the subsidence caving process. The available observed subsidence data clearly indicates that although the basic process and features of subsidence development are common, each geological environment has its own unique features, which require universal models to be substantially adjusted. The development of a unifying approach to the modelling of these differing subsidence profiles is an important objective for subsidence engineers and a number of authors have attempted this with some success, Figure 1 (Whittaker and Reddish 1989). However, there are significant contradictions in some of the observed data that cannot be dismissed as monitoring error or spurious geological anomalies. Linking trends simply to average rock strength has proven to have limitations. The ratio between stiffness and strength for rock masses can vary and has a significant influence on numerical models. The actual immediate caving process of the longwall is a dramatic process influenced by rock strength, stiffness and more importantly the rocks
structure, (Peng and Chaing, 1984). This paper demonstrates the modification of a subsidence numerical modelling approach developed to simulate average UK conditions, to a series of international observed case histories. It provides a useful set of monitored and published international case histories with their geological details as a test base for the modelling approach. The paper answers a significant number of unknowns concerning modelling this process however some systematic empirical control has had to be retained in determining the vertical extent of the caving zone to avoid excessive failure in the models.

Modelling Methodology

Input Parameters

A thorough literature review was undertaken seeking measured laboratory and modelled numerical rock properties as applied to common case history. The review concentrated on relating strength and stiffness values for laboratory scale testing to modelled insitu properties. The other objective of the review was to assess and evaluate different property reduction techniques, used by different modellers, to accurately represent rockmass conditions (Mohammad et al., 1997b). The difference in strength and stiffness reduction factors was analysed in light of the review case data and plotted on the summary graph (Figure 2). Ignoring the bulk of modellers who applied no reduction to properties to take into account rock mass, the Rock Mass Classification System, (RMR) was found to be the most widely used system to systematically derive values for strength and stiffness parameters for numerical modelling input (Mohammad et al., 1997b)

Subsidence Numerical Model for UK Coalfields, SEH-NUM
Figure 2: Young's Modulus from case histories for laboratory tests and numerical modelling input (Mohammad et al., 1997b)

\[ E_m = 2RMR - 100 \]

\[ E_m = 10 \cdot \frac{RMR}{40} \]

\[ RF = \frac{E_m}{E_{ia}} = 0.0028RMR^3 + 0.9 \exp\left(\frac{RMR}{22.82}\right) \]

\[ Y - 0.4092X \]
\[ R^2 = 0.899 \]

Figure 3: UK subsidence numerical model (SEH-NUM), relationship between depth and RMR (Mohammad et al., 1997a)

\[ RMR = 27.213 \ln(D) - 121.65 \]

where \( D = \text{depth (m)} \)
A UK modelling methodology effective in subsidence prediction for a wide range of panel geometries and for a depth range from 100m to 800m has been established. The input values of the pre- and post-failure strength and stiffness parameters being derived using the RMR system as their main reference. The actual numerical code utilised was a strain softening version of a commercial finite difference package, Fast Lagrangian Analysis of Continua \textit{(FLAC, Itasca, 1995)}. This code was used to simulate surface subsidence above idealised longwall panels within the UK Coalfields. The model was constructed with roller boundaries at the sides and bottom of the model and with gravitational loading to generate the initial stress condition. The key features of the modelling methodology were as follows:

1) Empirical simulation of the extent of propagation of the caving process. This proved necessary as available failure criteria proved unable to control the extent of caving automatically. The extent of the failure zone was used as a control parameter and was determined using equations 2 and 3 below for the respective extraction thickness and panel width. Equations 2 and 3 were derived by a mixture of systematic back analysis and engineering judgement.

2) A unique modification of the post failure properties within the zone of caving was used with bulk and shear moduli as $1/10$ of the original rockmass moduli.

3) Adjustment of the rock mass properties as a function of depth. Basically the RMR was increased with depth to simulate consolidation effects to the rock mass. The expression derived between depth and RMR (Equation 1) was used to determine RMR for the rockmass at their corresponding depth (Figure 3). \textit{(Lloyd et al., (1997), Mohammad et al., (1997a)).}

The methodology developed was given the name \textit{SEH-NUM}. The results of the model were validated against an extensive set of simulations using Subsidence Engineers Handbook (SEH) method rather than against individual case histories, (NCB, 1975). This was to ensure the methodology had the ability to effectively simulate a wide range of panel depths, widths and extraction thicknesses in a single average UK geological setting.

\[ RMR = 27.213 \ln(D) - 121.65 \]  
\[ \frac{Y}{X} = 37.435 e^{0.415Y} \]  
\[ \frac{Y}{X} = 89.596 \ln(PW) - 394.59 \]

where $D =$ Depth of seam below surface (m)

where $Y =$ Extent of yield and failure zone (m)

where $X =$ Seam Extraction Thickness (m)

where $PW =$ Panel Width (m)
<table>
<thead>
<tr>
<th>Location</th>
<th>Depth (m)</th>
<th>PW (m)</th>
<th>Ext. Th. (m)</th>
<th>SEH-EMP (m)</th>
<th>$S_{\text{max}}$ Actual (m)</th>
<th>RMR (Eq. 1)</th>
<th>Failure Zone (m)</th>
<th>SEH-NUM (m)</th>
<th>Adjusted RMR</th>
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<td>Angus Place Colliery</td>
<td>270</td>
<td>211</td>
<td>2.47</td>
<td>1.777</td>
<td>0.612</td>
<td>32</td>
<td>190</td>
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<td>490</td>
<td>140</td>
<td>2.6</td>
<td>0.553</td>
<td>0.2</td>
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<td>35</td>
<td>120</td>
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<td>1.8</td>
<td>1.131</td>
<td>0.22</td>
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<td>215</td>
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Simulation of Subsidence from International Coalfields

The original SEH-NUM model has been adapted and modified taking account of the lithological stiffness and strength differences of various International Coalfields. The resulting surface subsidence was plotted against SEH empirical data enumerated as SEH-EMP.

In the second stage RMR was adjusted to derive pre- and post-failure bulk and shear moduli representative of the respective rockmass condition to fine-tune the maximum subsidence, $S_{max}$ and vertical displacement distribution compatible with the actual monitored data from all cases. The adjusted RMR was related to the lithological structure over the longwall panel. Modifications to the existing methodology for the corresponding International Coalfields has then been suggested.

International Coalfields

Fourteen different longwall panels from Australian, Appalachian, South African and Indian Coalfields, with their respective longwall configurations presented in (Table 1), were simulated. The geological details for the following cases were obtained from different publications, indicated for each and reproduced in Figure 4. Australian Cases: Appin Colliery (Kapp, 1982), Gross Valley Colliery (Shu, 1990) and Angus Place Colliery (Kay, 1990), Kay et al., (1991), and Shu, (1990). South African Case: New Denmark Colliery (Schumann, 1993). Indian Case: Moonidih Colliery (Prasad and Kumar, 1989) and Appalachian Cases: Shoemaker I and Shoemaker II (Adamek and Jern, 1981). However, the geological description of the overlying strata for the remaining cases is mentioned below:

Bulli Mine, Australia

The coal seam of the Southern Coalfields lie within the Illawara Coal Measures. The Bulli seam is mined extensively throughout the Southern Coalfields. The overburden varies from less than 100m at Wongawilli Colliery in the south to 500m at Appin Colliery to the north-west. The strata overlying the Bulli seam is mainly composed of massive sandstones as well as some clay and shale bands (Shu, 1990), Kapp, (1982)).

The top of the Bulli seam is taken to be the marker horizon between the Premier Coal Measures and the overlying Triassic strata. The Coal Measure sequence is up to 270m in the area of mining. These strata consist of intervening coal seams, sandstones and shales with most of the sequence being lithic sandstones. The strata dip on a regional scale of $2^\circ$ in a general northerly direction. (Kapp, 1982).

Durban Navigation Colliery, South Africa

Two Longwall panels (longwall 420 and longwall 491) at Durban Navigation Colliery were simulated in the following study. Two coal seams, 1.1m top and 1.2m bottom with an unmined 1m wide shale parting in between, were extracted from longwall 420 situated at a depth of 211m. An equivalent coal seam of 2.37m thickness was extracted from longwall 491, leaving the shale band in between unmined. (Schumann and Hamerstadt, 1989). A sequence of shale and sandstone vary in thickness from
Figure 5: Gross Valley Colliery: Monitored subsidence and numerical models predictions

Figure 6: Moorsidh Colliery: Monitored subsidence and numerical models predictions
Figure 7: Durban Navigation Colliery: Monitored subsidence and numerical models predictions

Figure 8: Shoemaker I Colliery: Monitored subsidence and numerical models predictions
100m to 135m overlying the coal seams. The strata are covered by massive dolerite sills of about 70m thickness. Various observations of strata behavior have shown that where the roof of the coal seams comprises sandstone and shale layouts, it caves readily. At a mining span up to 200m the 70m thick dolerite sills which covers the whole property, deflects elastically without failing. A gap of 0.6m at the base of the dolerite sills was observed and this whole process has been described as discontinuous subsidence.

Appalachian Case Studies

A longwall panel situated in the Pittsburgh seam of the northern Appalachian coal region located in southwestern Pennsylvania was simulated (Jeran and Barton, 1985). According to boreholes drilled in the vicinity of the panel, the overburden averaged about 30% resistant strata (i.e. sandstone and limestone). Typical of Pennsylvanian age sediments, there is lateral variation and the range of resistant rock content is from 10 to 40% of the total thickness. The monitored surface subsidence data indicated that the profile is not uniform due to variation in overburden thickness, variation in extracted thickness, or variation in lithologic composition of the overburden (Jeran and Barton, 1985).

The surface subsidence profiles and other pertinent information regarding longwall panels from Ireland Mine (Adamck and Jeran, 1981), North Appalachian Case (Kohli et al, 1980) and North Appalachian Case 1 (Karmis et al, 1981) was obtained from their respective sources. However, the detail of lithological structures above the seams was not discussed in detail. The authors carried out their study based on the average lithological structures of the Northern Appalachian coal basin.

Modelling Results

The SEH-NUM was applied to fourteen different longwall configurations from International Coalfields. A reasonable fit, both in $S_{max}$ and surface subsidence profile, was observed when the results obtained were plotted against SEH-EMP data. The actual monitored data for each case was also plotted on the same graph. Out of fourteen different plots, only four representative plots from Gross Valley Colliery, Australia, Moonidih Colliery, India, Durban Navigation Colliery, South Africa and Shoemaker I Colliery, North America are presented as figure 5 to figure 8 respectively. Simulation of propagation of failure zone was used as a control parameter when the extent of failure zone was calculated through expressions 2 and 3. RMR was adjusted to derive modified bulk and shear moduli to represent stronger rock masses, where needed. The modelling results with adjusted RMR are shown on the corresponding plots. The analysis of the results indicated that manipulation of RMR can be used successfully to converge $S_{max}$ and surface subsidence profile to actual monitored data. The subsidence data, adjusted RMR and other modelling results are presented in (Table 1).

The Angus Place and Durban Navigation Case Studies were isolated from other Australian and South African Cases because of their peculiar narrow surface subsidence profiles and geological conditions. In order to accurately model the actual profile, the sensitivity of the model towards different parameters was assessed and a
significant variation in the surface subsidence profile was observed due to changes to the Poisson’s Ratio \( \nu \). A \( \nu \) value of 0.3, instead of 0.2, gave a much closer modelled profile when compared with actual data for the following reasons.

1) different values for bulk and shear modulli as \( \nu \) is used in the derivation of these parameters.

2) simple gravitational loading was considered throughout the analyses and a higher value of Poisson’s ratio \( \nu \) provided more confinement in the horizontal direction. Horizontal stresses calculated from \( \nu=0.3 \) were 1/2 of the vertical stress, whereas, \( \nu=0.2 \) give horizontal stress as 1/4 that of vertical stress.

The results obtained for Appalachian cases were found compatible with SEH-NUM however slight adjustment in the RMR was needed to simulate the actual \( S_{\text{max}} \) in the case of Ireland Mine (Table 1).

Conclusions

The UK based modelling methodology based on RMR has proven to be reasonably adaptable to other International Coalfields as long as the basic RMR is adjusted to reflect the local geological conditions. A few cases however require consideration of the horizontal stress field before profiles narrow enough could be generated. This was achieved by adjustment of Poisson’s ratio rather than directly adjusting the stress regime. Because most of the data reviewed and modelled was extracted from published sources it has been difficult to consider factors such as changes in horizontal displacement patterns and the international validation has been almost exclusively based on the published surface subsidence. The original UK model upon which these models are based was validated against surface subsidence, horizontal displacements and even stress distributions to a limited degree and these characteristics should carry forward into the new international approach.

References


