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Numerical modelling of the effects of weak immediate roof lithology on coal mine roadway stability

John Coggan [a,*], Fuqiang Gao [b], Doug Stead [b], Davide Elmo [c]

[a] Camborne School of Mines, University of Exeter, United Kingdom
[b] Simon Fraser University, Burnaby, British Columbia, Canada
[c] Golder Associates, Vancouver, Canada

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ABSTRACT

The stability and associated design of roof reinforcement requirements of tunnels driven in United Kingdom Coal Measures strata is directly related to the engineering characteristics of the immediate roof lithology and the effects of redistribution of the in-situ stress. Numerical modelling carried out by the authors has been used to simulate the widely observed detrimental effects of both high horizontal stress and weak immediate roof lithology on tunnel roof stability. Different numerical modelling techniques, such as continuum, discontinuum and hybrid finite element-discrete element codes, have been used to model the deformational behaviour of Coal Measures strata and are discussed in the context of specific case examples to highlight their application and suitability for modelling of weak rock. The modelled results demonstrate that the thickness of the relatively weak mudstone in the roof of the tunnel has a significant influence on the extent of failure and, ultimately, the need for additional reinforcement.

1. Introduction

Until recently 5 mines worked the Barnsley seam in the Selby Complex (Wistow, Stillingfleet, Riccall, Whitemoor and North Selby). The seam dips at approximately 7° to the North-East, ranging in depth from 250 m West of the Wistow Mine to in excess of 1200 m East of the North Selby Mine. Typical seam thickness varies from 3.5 m in the West to 1.8 m in the East of the Selby Coalfield. The roof strata typically consist of an immediate, relatively weak mudstone (up to 1 m thick) overlain by more competent silty mudstones, siltstones and sandstones. The mudstone thickness varies across the Coalfield, ranging from non-existent due to high energy depositional river channels where the sandstone lies directly above the seam to an extensive thickness of greater than 4 m. Typical tunnel or roadway dimensions are 3.5 m high by 5.0 m wide.

The successful implementation and subsequent use of roofbolting in United Kingdom coal mine tunnels have provided a large database of tunnel deformation monitoring information, including in-situ measurement of strata behaviour, tunnel deformation and reinforcement performance. Kent et al. (1999) provided a summary of the analysis and interpretation of deformation monitoring data from across the Selby Complex during the period 1988 to 1994. The database provided an ideal opportunity to investigate how geological and stress variations affect the stability and deformational behaviour of tunnels driven through Coal Measures strata. The data were established for tunnels on drivage, prior to face retreat and any additional deformation associated with longwall extraction. Detailed analysis of the database confirmed that the stability and associated design of roof reinforcement requirements of tunnels driven in United Kingdom Coal Measures strata is directly related to the lithology of the immediate roof of the excavation and the redistribution of the in-situ stress caused by creation of the excavation (Hurt (1992), Kent (1996), Kent et al. (1999) and Siddall and Gale (1992)). For example, significant increase in tunnel roof deformation is observed when excavations are driven perpendicular to the maximum horizontal principal stress direction. Tunnels driven at an angle to the in-situ stress field suffer asymmetrical deformation, with pronounced observed stress effects that require additional reinforcement for stability. These observed effects include the formation of "guttering" or excessive bulging/bulking of the immediate roof. The thickness of the relatively weak mudstone in the roof of the tunnel has a significant influence on the extent of failure and, ultimately, the need for additional reinforcement.

Recent numerical modelling carried out by, or undertaken as part of research supervised by the authors over the last fifteen years has provided a wide range of case examples and different applications of use of numerical methods to model weak rock behaviour. This has involved the use of a combination of continuum, discontinuum and hybrid methods, where the choice of the numerical method adopted took into consideration the capabilities and limitations of the software. The factors considered included: choice of appropriate

* Corresponding author at: Camborne School of Mines, University of Exeter, Cornwall campus, Penryn, Cornwall, TR10 9EZ, United Kingdom. Tel.: +44 1326371824; fax: +44 1326371859.
E-mail address: J.Coggan@ex.ac.uk (J. Coggan).

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input parameters such as material constitutive criteria, whether there is a need to model discontinuity behaviour, what failure mechanism is being simulated and whether or not there is a need for two or three-dimensional analysis. The modelling has been used to simulate the widely observed detrimental effects of both high horizontal stress and weak immediate roof lithology on tunnel roof stability, using specific case examples taken from the Selby Coalfield. The detrimental effects of weak roof lithology on tunnel roof behaviour are demonstrated using both 2 and 3-dimensional numerical modelling. The examples concentrate on the modelling of tunnel roof behaviour, including fracture initiation and subsequent propagation of the fracture zone in the immediate roof of the excavation.

2. Numerical modelling: available methods—their advantages and disadvantages

Table 1 provides a summary of the advantages and limitations of the most commonly used numerical methods for modelling of tunnel roof behaviour, which are continuum methods, discontinuum or discrete methods and hybrid continuum/discrete methods. Examples of the application of these different numerical methods to modelling the effects of rock failure around underground excavations include Alvarez-Fernandez et al. (2009), Barton and Pandey (2011), Coggan et al. (2003, 2006), Curran et al. (2003), Eberhardt (2001), Gale et al. (2004), Islam et al. (2009), Islam and Shinjo (2009), Martin and Maybee (2000), Pine et al. (2006) Unver and Yasitli (2006) and Zipf (2006).

2.1. Choice of available methods

Successful application of the various methods available for modelling of coal mine roof behaviour requires a sound knowledge of the capabilities, advantages and limitations of the various methods used. Alvarez-Fernandez et al. (2009), Islam et al. (2009), Islam and Shinjo (2009) and Unver and Yasitli (2006) have shown how numerical modelling techniques can be used to simulate coal strata deformation. Cassie et al. (1999), Clifford (2004), Garrett (1997), Meyer (2002), Sharpe (1999) and Sharpe et al. (1998) have all demonstrated how numerical modelling can be used to provide guidance for reinforcement design in coal mine roadways in the United Kingdom. It is important to match the capabilities of the software to the engineering situation being modelled. For example, relatively simplistic boundary element modelling can provide useful simulation of stress redistribution and coal strata deformation around coal mine roadways (Islam and Shinjo, 2009), but more sophisticated models are required to model the detrimental effects of progressive rock failure and fracture behaviour (Unver and Yasitli, 2006).

Research summarised by Clifford (2004) highlights the use of a boundary element approach to initially model the three-dimensional stress redistribution around a coal longwall panel before undertaking more detailed two-dimensional finite difference modelling of roadway behaviour. The stress output from the boundary element model is used as input for the subsequent two-dimensional continuum modelling. This highlights that results from a combination of modelling methods may provide useful insight for a particular problem being modelled. It is often beneficial to adopt a modelling philosophy

Table 1
Numerical methods for analysis of rock failure around excavations.

Analysis method	Input assumptions	Advantages	Limitations
Continuum: Boundary element	Representative tunnel geometry, usually adopt simple constitutive criteria	Elastic analysis, capability of three-dimensional modelling, rapid assessment of designs and stress concentrations	Normally elastic analysis only, (non-linear and time dependent options are available.)
Continuum: Finite-element and finite-difference	Representative tunnel geometry, wide range of constitutive criteria, including weakness plane, groundwater, shear strength/stiffness of discrete interfaces, in-situ stress, support properties	Allow for material deformation and failure, can model complex behaviour, capability of three-dimensional modelling, able to assess simulate both saturated and unsaturated (multiphase) flow/water pressures, recent advances in hardware mean that complicated models can now be PC-based and run in reasonable time periods, can incorporate coupled dynamic/groundwater analysis, suitable for soil, rock or mixed soil rock analysis, time dependent deformation readily simulated	Must be aware of model/software limitations including effects of mesh size, boundaries, symmetry and hardware restrictions (i.e. memory and time constraints) and data input limitations (such as effects of variation of critical input parameters etc.); simple structures can be simulated with interfaces, but not suitable for highly jointed-blocky media; well trained and experience users and familiarity with numerical analysis methods essential; validation through surface/subsurface instrumentation important
Discontinuum: Discrete element	Representative tunnel and discontinuity geometry, rock mass constitutive criteria, discontinuity shear strength and stiffness, groundwater, in-situ stress, support properties	Able to model complex behaviour; including both block deformation and relative movement of blocks (translation/rotation); three-dimensional models possible; effect of parameter variations on instability can be investigated easily; dynamic loading, creep and groundwater simulated; can incorporate synthetic rock masses to represent the fracture network; use of Voronoi polygonal blocks allows simulation of rock fracture between blocks	As above. Scale effects: simulate representative discontinuity geometry (spacing, persistence); limited data on joint stiffness available; predominantly used for jointed rock; validation through surface/subsurface instrumentation important
Hybrid codes incorporating intact rock fracture capability (finite–discrete element)	As above. Use fracture mechanics criteria or particle flow code (parallel/shear bonds) to simulate intact rock fracture	Able to allow for extension of existing fractures and creation of new fractures through intact rock, capable of three-dimensional modelling (although limited application to-date), can incorporate dynamic effects	Limited use and validation, state-of-the art codes requiring in-depth knowledge/experience of modelling methods/mechanics, must incorporate realistic rock fracture network, little data available for contact properties and fracture mechanics properties, limited capability to simulate effects of groundwater, extremely long run times will require use of parallel processing for large models