CHAPTER 4
DEVELOPMENT OF A NUMERICAL MODELLING APPROACH

4.1 INTRODUCTION

The numerical modelling of a geotechnical engineering problem can often be fraught with uncertainties not only about the choice of the model but also the choice of the values of input parameters and quite often assumptions are made without proper justification. In order to avoid falling into this trap, the proposed numerical modelling in this thesis will be developed in accordance to the principles outlined in Hudson, Stephansson and Andersson (2005). A literature review (in chronological order) of numerical modelling in mining subsidence related problems is also undertaken to determine what numerical modelling code is most suitable for the modelling of single isolated longwall panels and river valleys. The audits for the numerical modelling in this thesis can be found in Appendix A.

4.2 MODELLING PRINCIPLES

The development of a numerical modelling approach for isolated single longwall panels and the block movement model is based on the principles outlined in Hudson, Stephansson and Andersson (2005). The principles stipulate that the numerical modelling itself is not the most important aspect, but the conceptualisation of the problem, material properties and parameters should be paramount in any investigation. It is also stressed that the engineering problem at hand should be subjected to ‘soft’ and ‘hard’ audits.

The soft audit establishes an overview of the modelling work and determines whether well known issues of importance and difficulty in characterising and modelling rock masses have been addressed at the outset. The hard audit is similar to the soft audit but requires justifications to the answers given. The audits are designed to ensure that the numerical modelling is transparent and traceable through the audit trail.

Several references that deal with numerical modelling of mining subsidence or mining related activities with UDEC, FLAC or similar software are reviewed. The aim of this chapter is to make a decision on which numerical code is better suited to modelling mining induced subsidence for isolated single longwall panels and block movements based on the examples given.

4.3 LITERATURE REVIEW

4.3.1 Coulthard and Dutton (1988)

In this paper, the numerical modelling programs FLAC and UDEC are used to calculate the subsidence over a longwall panel for a range of longwall panel widths. The results from the numerical modelling were compared to the empirical predictions for the NSW Southern Coalfield.

Holla's empirical work on subsidence prediction in the Southern Coalfield indicated there was a large increase in the maximum developed subsidence as longwall panel widths increase from subcritical to critical.

At the moment, there are no critical width longwall panels in the Southern Coalfield, but the authors argue that subsidence prediction will only become feasible if it can capture the subsidence characteristics for a range or different mining geometries and geological conditions.

From the results of their numerical modelling, the authors reproduced the results of earlier workers that dismissed elastic analyses because of the shallow subsidence profile produced, and the unrealistic calibration of material properties required to fit the elastic analyses to observed subsidence profiles.

On the other hand, it was found that modelling a non-linear material with FLAC, containing horizontal ubiquitous joints, produced a large increase in the maximum developed subsidence, as characterised by Holla's work. It was also found that UDEC produced this large increase as well.

In conclusion, the authors felt that both the FLAC and UDEC models have the potential of predicting subsidence in new geological environments, but UDEC was favoured because of its ability to model roof behaviour. The authors found that the key factors governing the UDEC predictions were highly dependant on the material properties (joint friction angle and elastic modulus of the rock mass) and jointing pattern selected (finer upper strata increased subsidence magnitude).

4.3.2 Johansson, Riekkola and Lorig (1988)

In this paper, the authors discuss their experience in the design of multiple parallel caverns using explicit finite difference methods. The two programs that were used were FLAC and UDEC.

After the site characterisation was complete, preliminary modelling was performed on several major cross sections using FLAC. The purpose of this preliminary modelling was to identify potential areas where stability problems may arise. Once critical areas were identified, more detailed analyses were performed. Where joint spacing was relatively wide, UDEC was employed. Where rock was highly fractured, FLAC was used.

The purpose of this paper was to demonstrate how valuable numerical modelling can be in the design process.

4.3.3 Alehossein and Carter (1990)

In this paper, the authors discuss the difference between implicit and explicit modelling of joints (horizontal and vertical) in a rock mass. The numerical model used is a simple trench style excavation, with one-half of the problem discretised because of symmetry. The rock material was assumed to be an isotropic, linear elastic material, and the joints were assumed to conform to the elasto-plastic Mohr-Coulomb failure criteria. Joints were modelled implicitly as part of the constitutive model, i.e. ubiquitous, and explicitly. Joint spacing was varied in each model.

From the modelling of horizontal joints, it was found that jointing had little effect on overall horizontal movements, and the predictions from both the implicit and explicit modelling were quite close. On the other hand, it was found that vertical movement was sensitive to explicit joint spacing, compared to implicit joint spacing. From the modelling of vertical joints, it was found that both implicit and explicit joints produced similar results.

In conclusion, the authors suggested that the computationally more efficient method of implicit joint modelling was adequate for many practical problems. It was also noted that the accuracy of the implicit method depended of the spacing of the joints relative to a typical dimension of the excavation.

4.3.4 Brady et al. (1990)

In this paper, the authors used UDEC to model static and dynamic behaviour of jointed rock. The results from the modelling were then compared with the analytical solutions.

Four problems have been used for the study. These included:

- Jointed block subject to cyclical loading (static),
- Circular excavation intersected non-diametrically by a joint (static),
- Plane shear wave normally incident on a joint in an elastic solid (dynamic), and
- Explosive source located near a slip-prone joint (dynamic).

The joint deformation model used in the analysis was the Coulomb strength model. In all cases, the numerical simulation matched well with the analytical solutions.

From the results of the modelling, it was concluded that UDEC can simulate the mechanics of jointed rock, but the study did not confirm that UDEC is a valid simulation of the engineering behaviour of jointed rock.

4.3.5 Choi and Coulthard (1990)

In this paper, the authors examined the results of distinct element modelling applied to a simple trap door problem, and compared the results with Cosserat continuum limit load calculations. Distinct element studies of mining-induced subsidence were also discussed.

The authors reviewed the three different methods of modelling a jointed rock mass: explicit modelling, equivalent continuum modelling, and generalised continuum modelling. The general conclusion drawn was that explicit modelling of joints is the best method where block separation, rotation and slip, and large relative motions may occur. Equivalent continuum models were regarded as unreliable unless the joint spacings were very small compared with other system lengths. The generalised continuum method was viewed as a somewhat promising approach, as it was able to represent internal structure without being limited by the assumption that the structure is very small relative to system lengths.

From the results of their numerical modelling with UDEC, the DE analysis matched the Cosserat continuum method for the active case (simple mechanism), but not for the passive case (complex mechanism). It was concluded that for the passive case, the material in the upper part of the model should be treated as a continuum.

It was concluded that a discontinuum can be modelled as a generalised continuum where the structure is reasonable simple and the assumed mechanism is correct. If the structure is more complex and the mechanism not easily predicted, distinct element methods or finite element methods (incorporating the Cosserat theory) should be used.

The authors then discussed the applicability of distinct element modelling to subsidence, with reference to the Angus Place Case Study. Again, elastic models were discounted as reliable means of subsidence prediction due to their inability to model roof strata behaviour. The credibility of distinct element models was demonstrated by the comparison of DE modelling results and physical models in Australian rock conditions.

It was found that the major factors affecting the results of the UDEC modelling were the suitable spacing of bedding planes and sub-vertical jointing. Even so, the UDEC modelling matched the trends in surface subsidence better than continuum models. It was also noted that the method of excavation may produce different behaviour.

4.3.6 O'Conner and Dowding (1990)

In this paper, the authors described their findings from numerical modelling which complemented a field study that carried out extensive deformation measurements during the excavation of a longwall panel. The purpose of the numerical modelling was to try and simulate mining induced subsidence and to demonstrate the influence of discontinuities on the rock mass.

The authors used a hybrid code that combined the Northwestern University Rigid Block Model with the rigid block model developed by Peter Cundall. The main feature of this hybrid code is the edge-to-edge contacts between blocks. When all the edge-edge contacts of a block have satisfied one of three failure criteria (pure tensile failure, shear failure and rotation-tension failure) the block can undergo large displacements and rotations and develop corner-edge contact with any other block.

The subsidence model was based on a transverse cross section of the longwall panel. The bedding planes were approximated from borehole geophysics and mapping data. The joint sets were obtained from mapping of rock exposures. Six different scenarios were carried out, and these varied the number of strata types, joint and bedding plane stiffness, joint density, and shear resistance.

In conclusion, the authors found that the rigid block model was capable of simulating the general trend of vertical displacements within the overburden, but could not simulate fracturing and shearing above the zone of block caving. It was also found that the rigid block model behaved more stiffly than the actual rock mass, and consequently, the models which contained relatively low stiffness values produced the best agreement between measured and calculated displacements. Lastly, it was found that increasing the density of vertical joints or reducing the rigid block contact roughness did not improve the agreement between measured and simulated displacements.

4.3.7 Coulthard (1995)

In this paper, Coulthard reported on his work from the Angus Place Case Study. In this study, several scientists and engineers were invited to predict the developed subsidence over two longwall panels mined in virgin coal. The author chose UDEC to develop numerical models and subsidence predictions.

The author justified his choice of program by discussing the fact that distinct element methods such as UDEC can model the discontinuum behaviour that forms a key part of the mechanical response of a rock mass to longwall mining. The purpose of this study was to evaluate the potential of this numerical method for predicting subsidence in environments where no empirical data are available.

Parameters that were changed in the model (to fine tune) included DE sizes and shapes in the lower roof strata to produce bulking, joint constitutive model for sub-vertical jointing, and the finite difference zoning within the blocks. It was noted that little information was available on jointing in the rock mass apart from the sub-horizontal bedding planes, therefore the model did not attempt to represent the detailed geology of the rock strata. Average rock properties were used in all regions.

The blocks were governed by the Mohr-Coulomb elasto-plastic constitutive model. The bedding planes were modelled as standard UDEC joints, with initial elastic behaviour and with slip and separation determined by a Mohr-Coulomb shear strength criterion with tensile cut-off. The sub-vertical joints were modelled with UDEC’s ‘intact rock’ constitutive model.

In conclusion, it was found that the UDEC analyses yielded good qualitative agreement with the main aspects of the field measurements, including:

- Magnitude and asymmetry of subsidence,
- The narrowness of the subsidence peaks, and
- Collapse of immediate roof strata and trends in deformations in the central borehole.

The model was not calibrated after field results became available. It was also noted that the model was able to produce asymmetry in the subsidence profile, something that was not possible in an elastic continuum analysis.

The main limitations of the UDEC models were found to be:

- Failure to reproduce bulking of the collapsed goaf,
- Failure to match borehole displacements in the upper strata, and
- Considerable underestimates of subsidence over the chain pillar.

It was proposed to increase the orientation of potential crack planes by defining multiple sets of intersecting joints in the lower roof. It was suggested that this can allow some block rotation to develop and increase the bulking of the goaf.

4.3.8 Bhasin and Høeg (1998)

In this paper, the authors performed a parametric study on the joint constitutive model for a large cavern in the Himalayas using UDEC. The joint constitutive models that were compared were the Mohr-Coulomb and the Barton-Bandis models. The results of the parametric study indicated that deformations around an opening were dependant on the size or the number of blocks adjacent to the excavation. It was also found that in a model where the block size is small compared to the excavation dimensions, the failure mechanism in jointed rock masses was strongly influenced by volume changes when approaching failure, and these volume changes were generally determined by the dilation along pre-existing discontinuities. This dilation along the joints caused a build-up of high normal stresses which in underground openings can cause interlocking of the blocks and inhibit further deformation. This situation may be relieved by using the Mohr-Coulomb joint constitutive model instead of the Barton-Bandis model, as the Barton-Bandis model allows for the build-up of stress caused by dilatant behaviour. This may be particularly useful when modelling underground longwall excavations.

4.3.9 Alejano et al. (1999)

In this paper, the authors used FLAC to develop subsidence models for flat coal seam longwall mining in British basins. These FLAC models were validated from empirical methods (SEH). The authors also developed models for slightly inclined coal seams and for steeply inclined coal seams. The slightly inclined coal seam models were also validated by empirical observations, but the steeply inclined models were not. The numerical models were based on longwall mines from the Midlands coalfields in central England. There was a large amount of material properties data and empirical predictions available.

The authors chose an elasto-plastic material model with the following features:

- Transversely isotropic elastic pre-failure behaviour,
- Anisotropic yield surface, yield may occur by joints or material itself, and
- Isotropic elastic post-failure behaviour.

To assess the quality of the rock mass, the GSI rating was used. The strength parameters of the Coal Measures rock mass were determined by the Hoek-Brown criterion, and equivalent Mohr-Coulomb parameters calculated. Joint strength was determined by scaling the results of laboratory testing.

The calculation of pre-failure (E_x, E_y, υ_{xy}, υ_{yx} and G) and post-failure deformability parameters (E) relied on formulas suggested by several authors. It was stated that these formulas simulated rock mass behaviour quite well. It was noted that the material model described is not available in FLAC and must be implemented via subroutines written in an in-built language (FISH).

The implementation of the material model followed a two stage process. First, an isotropic elastic model was assigned to the rock mass, compatible with the ubiquitous joint model. The FLAC model was then run in order to estimate the height of the fractured zone. Any material lying above the fractured zone was then assigned a transversely isotropic elastic model.

It was stated that forty two models were created for coal seams located at 150 m, 200 m, 300 m, 400 m, 500 m and 700 m depth with W/H ratios of 0.4, 0.6, 0.8, 1, 1.25, 1.5 and 2 for each depth. This covered the range of subcritical, critical and supercritical values defined by the SEH.

From the results of the numerical modelling, it was found that the subsidence troughs produced by FLAC fit the empirical observations quite well, with the maximum differences always smaller than 10 % of the seam thickness. On the other hand, horizontal displacements did not match well at all. It was found that the maximum horizontal displacement for the supercritical case was overestimated, whilst for the subcritical case the opposite took place. The authors suggested that the occurrence of surface tension cracks may account for these differences, in effect turning a continuous material into a discontinuous material.

Other parameters that were compared to SEH results were fractured zone height, subsidence factor, rib-side subsidence, limit angle, and maximum horizontal displacement in trough. It was stated by the authors that the FLAC results agree or follow general trends given by the SEH results, with the exception of limit angle and maximum horizontal displacement. The limit angle predicted by FLAC was within the range of 30° – 45°, whereas the SEH assumed the limit angle to be constant at 35°. The reasons for the difference in horizontal displacement had been covered previously.

In conclusion, the authors stated that subsidence due to longwall coal mining can be adequately modelled by the described methodology, but there were still some issues to be overcome. These included:

- The problem of modelling a discontinuum with a continuum code. The authors argued that given the large scale of the models involved, continuum modelling can be representative of the actual rock mass behaviour. Also, it was pointed out that discontinuum models had not been used successfully, most probably due to the lack of knowledge about joint distribution,
- The use of a custom constitutive model, whilst still effective, did not behave exactly as required, and

- Using rock characterisation techniques with accuracy with published data on different Coal Measures rock masses.

4.3.10 Sitharam and Latha (2002)

In this paper, an equivalent continuum model had been incorporated into FLAC via the FISH utility. The equivalent continuum model was verified with three case studies.

It was pointed out by the authors that the requirements for an equivalent continuum model were Hoek & Brown parameters ‘s’ and ‘m’, JRC, JCS, and SRF (Barton and Bandis model). Such parameters may not be readily available rendering the analysis of such problems impossible. A new equivalent continuum approach was proposed, and this approach required the estimation of only two joint parameters, namely the number of joints in the rock per meter depth and the inclination of the most critical joint set. These two parameters were used in conjunction with the joint roughness or strength parameter to calculate the Joint Factor. The authors stated that the Joint Factor (J_f) can take care of the effects of frequency, orientation and strength of joint. The Joint Factor had been derived from extensive laboratory testing of intact and jointed specimens (plaster of Paris, sandstone and granite).

In the model, the rock mass properties were determined by a set of empirical relations, which expressed the elastic modulus of a jointed rock mass as a function of joint factor and the elastic modulus of intact rock. The authors stated that this model had been validated against experimental results and also with results from explicit modelling. It was also stated that the model worked well for jointed rock masses with different joint fabric and joint orientation.

The implementation of the model involved writing a FISH function that calculated the elastic modulus of the jointed rock in the changing stress field. The function also calculated the modulus ratio, the compressive strength ratio, and the confining pressure of the rock mass. The constitutive model used was the Mohr-Coulomb model with a confining stress dependant hyperbolic relation.

The model had been used in three case studies: two powerhouse excavations and one mine excavation. The values of the joint factor ranged from 13 to 111. It was found that the numerical analysis estimated the field behaviour very well. The authors concluded that the joint factor model can be confidently applied for solving excavation problems in jointed rock masses.

4.3.11 CSIRO Petroleum (2002)

Numerical modelling of undermined river valleys with UDEC and FLOMEC (three dimensional continuum code) was performed by CSIRO Petroleum in order to replicate observed behaviour in the Cataract and Nepean Gorges. Only the UDEC models will be discussed as three dimensional modelling is beyond the scope of this thesis. The modelling was carried out in two stages, the first being a geomechanical run, and the second being a geomechanical fluid flow run.

Parametric variations to the UDEC geomechanical models included:

- Gorge wall slope,
- Joint strength,
- Presence of ubiquitous joints,
- Magnitude of horizontal in-situ stress,
- Mining sequence, and
- Bedding plane and vertical joint geometry.

Parametric variations to the UDEC geomechanical fluid flow models included:

- Gorge wall slope,
- Shallow river valley geometry,
- Flat horizontal ground surface,
- Additional parallel joint set in gorge wall, dipping 10 to 30 degrees,
- Strength of 30 degree joints,
- Ubiquitous joints in gorge wall dipping 30 degrees towards gorge,
- Magnitude of horizontal in-situ stress,
- Depth of water table,

- Permeability of Bald Hill Claystone, and
- Poro-elastic and steady state responses to mining.

In both cases, the parameters that were found to have the greatest effect on model response were the magnitude of horizontal in-situ stress, the presence of ubiquitous joints, joint strength and permeability. The authors concluded that the numerical modelling provided greater understanding of general strata mechanisms that occurred during the undermining of surface topographical features. It was also concluded from the modelling that horizontal movements from valley closure induced by undermining were predominately associated with bedding plane shear at shallow depth, and these sheared bedding planes acted as conduits for ground water, and may impact on local hydrology.

It was noted that the numerical models were not verified in any way, and although the purpose of the exercise was to investigate valley closure outside longwall panels, no explanation was given for why this occurred.

4.4 SUMMARY

From the reviewed references, the following points are deduced regarding numerical modelling of mining induced subsidence:

- Elastic models are considered unsuitable for subsidence prediction due to the unrealistic calibration of material properties required in order to fit predicted subsidence profiles to observed profiles,
- Continuum codes like FLAC have been used to predict surface subsidence successfully, but subsurface behaviour or horizontal movement cannot be evaluated because of the continuum nature of the code,
- It has also been shown that FLAC is unable to reproduce the large increase in subsidence that occurs in the transition between subcritical and critical extraction widths in the Southern Coalfield,
- An equivalent continuum model has been produced, and it is claimed that it is suitable for modelling jointed rock. This method seems to be limited to simple excavations where large block movements are not expected,

- It has also been demonstrated that the computationally more efficient method of implicit joint modelling is adequate for many practical problems. It is also noted that the accuracy of the implicit method depends of the spacing of the joints relative to a typical dimension of the excavation. Again, this method is restricted to simple problems where large block movements are not expected,
- Distinct Element codes like UDEC were found to be generally more accurate than FLAC because of their ability to model discontinuous rock masses, therefore allowing evaluation of subsurface movements and roof behaviour,
- Key factors governing UDEC predictions were highly dependant on the material properties (joint friction angle and elastic modulus of the rock mass) and jointing pattern selected (finer upper strata increased subsidence magnitude),
- UDEC was able to produce asymmetry in the subsidence profile, something which is not possible in an elastic continuum analysis (Angus Place Case Study),
- UDEC modelling matched the trends in surface subsidence better than continuum models. It was also noted that the method of excavation may produce different behaviour (Angus Place Case Study), and
- From UDEC verification studies, it is concluded that UDEC can simulate the mechanics of jointed rock, but the study does not confirm that UDEC is a valid simulation of the engineering behaviour of jointed rock.

From the above summary, it can be concluded that UDEC is the most suitable code to develop a subsidence model in flat terrain and in areas of high topographical relief, provided verification can be undertaken. Even though FLAC has the capability of predicting surface subsidence quite well with equivalent continuum routines, the incorporation of such a routine introduces a range of additional parameters that have to be estimated, which in turn introduces a higher degree of uncertainty. Poor correlation with horizontal movements restricts the use of FLAC in modelling undermined river valleys due to resultant valley closure and horizontal movement of rock blocks.

Furthermore, UDEC has the advantage of being able to incorporate field properties directly into the model without calibration, eg. in-situ stress field, bedding plane spacing, joint spacing, sub vertical joint orientation, material and joint properties.