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A modelling technique for top coal fall ahead of face support in mechanised longwall using Discrete Element Method

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ABSTRACT

Top coal fall ahead of face support in mechanised longwall occurs from time to time that severely impacts the safety and productivity at face. This paper presents a new technique for studying this geotechnical problem by using a Discrete Element Method (DEM) code combined with plastic rock material. A field - scale Longwall Top Coal Caving (LTCC) extraction, mining cycle and support operation are incorporated in an LTCC model using the geological conditions from Seam 11, Ha Lam coal mine, Vietnam. The model is calibrated against the face advance where top coal starts caving observed at the site. During the simulation, the model has successfully represented the failure mechanisms and falling mode of top coal ahead of face support. The modelling technique is helpful to in - depth investigation of top coal or roof fall mechanisms ahead of face support in various geotechnical conditions.

1. Introduction

Longwall mining is one of the most productive methods for underground extraction of coal seam in the world. In this method, a long wall coal is manually or mechanically extracted in a longwall panel, which is typically 1.5 - 4.0 km long and 150 - 400 m wide, as illustrated in Figure 1 (Galvin, 2016). In Australia, Germany, UK, China and Vietnam, coal production from longwall mining significantly dominates the production from other methods due to its high productivity and a low rate of coal loss. A mechanised longwall operation is, however, commonly associated with near - seam strata stability problems such as top coal fall (in Longwall Top Coal Caving—LTCC) or roof fall (in Single Pass Longwall—SPL) ahead of face support that severely impact the safety and productivity at face (Le et al., 2018a). Study on mechanisms of the problems is therefore of importance to achieve better sustainable longwall extraction.

Empirical (including field measurement), analytical and modelling (both physical and numerical) methods are widely applied in investigation of top coal/roof fall at mechanised longwall. Empirical methods, as used in Frith et al. (1992), Prusek et al. (2017) and Le et al. (2019), are commonly based on field experience as well as trial and error procedures. The methods may only

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benefit studies of longwall mechanisms at new mine sites having similar conditions compared to those where the mechanisms were investigated. In contrast, if field measurement is to be applied, it should be carefully designed due to cost and practicality. Analytical methods use mathematical solutions based on principles of physics and mechanics to calculate stress and displacement behaviours (Galvin, 2016). The methods can be quick and low cost, producing accurate results in simplified rock mass conditions, as seen in Langosch et al. (2003). However, for realistic representation of rock mass, the methods can be too complex to solve manually. Physical modelling has been used in a few studies (Song et al., 2019; Yang et al., 2019); however, it should not be solely applied owing to drawbacks of the cost, difficulty and time consumed to design models.

For a mine site without any available similar experience of longwall operation, numerical methods provide a predictive and effective tool for studying longwall mechanisms since complex geological conditions and multiple possibilities of the conditions can be modelled. For detailed fundamentals of numerical methods, readers are referred to past studies (Jing, 2003; Brady and Brown, 2004). Regarding longwall problems, continuum methods provide a technique that can analyse complex mining - induced mechanisms, as found in Vervoort (1988) and Bai et al. (2014). Compared to discontinuum methods, continuum methods are limited in their ability to represent the large - scale opening, sliding and complete detachment of elements that typically occur in longwall. Discontinuum methods (e.g., Discrete Element Method - DEM) typically represent a problem domain as an assemblage of discrete and interacting bodies. The methods can capture important top coal fall characteristics because it (1) allows finite displacements and rotations of discrete bodies, including complete detachment and (2) recognises new contacts automatically as the calculation progresses (Cundall and Hart, 1992). The discontinuum methods have been mostly used in studying coal wall rather than top coal/roof stability (Wang et al., 2016; Yao et al., 2017). At present, hybrid methods find limited application in longwall mining.

This paper presents a DEM code combined with plastic rock material for modelling top coal fall ahead of face support. The geometrical configuration, material constitutive model, mining cycle and model calibration are performed based on geotechnical conditions of the mechanised longwall at Seam 11, Ha Lam coal mine, Vietnam. The proposed modelling technique is helpful to in - depth investigation of

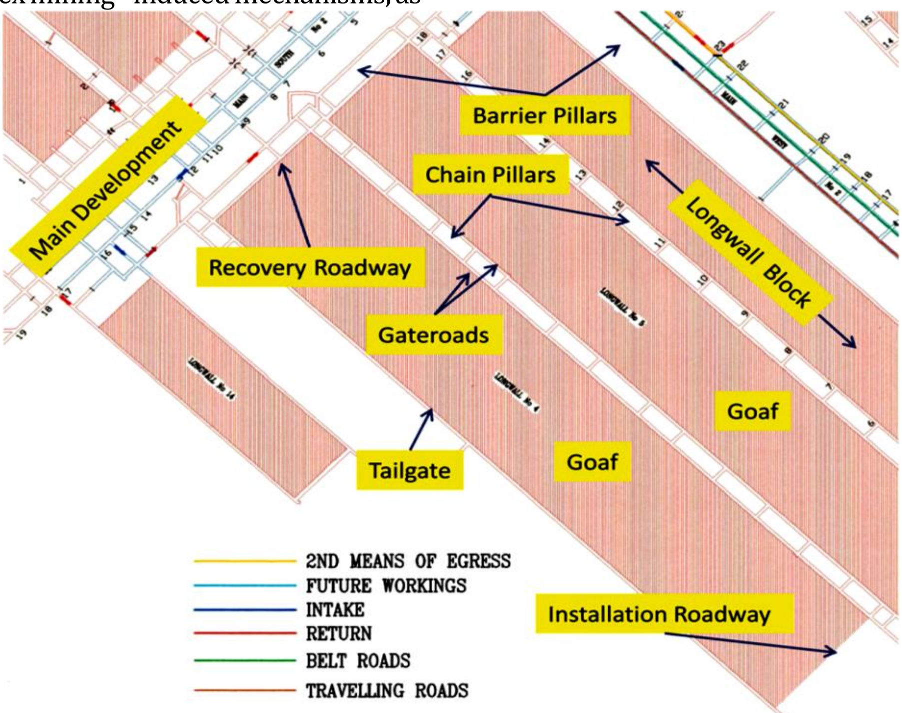

Figure 1. Longwall panels at a mine (Galvin, 2016).

top coal/roof fall mechanisms and other geotechnical problems involved in longwall extraction.

2. Geotechnical conditions and site observation at Seam 11

Ha Lam coal mine belongs to Ha Tu - Ha Lam coal basin, approximately 7 km east - northeast of Ha Long city, Quang Ninh province, Vietnam. According to Decision 2497/GP - BTNMT issued on 28 November 2008 by Vietnam Ministry of Natural Resources and Environment (MONRE), the mine extracts seams namely 14(10), 11(8), 10(7), 7(4), 6(3) and 5(2) in level from - 50 to - 300 m by underground method. The sedimentary thickness of the mine ranges from 500 to 700 m, mainly consisting of siltstone, sandstone and coal seams plus minor claystone and gritstone. At Seam 11, immediate and main roofs are moderate to strong, and fractured by vertical joints. Coal seam is highly jointed with an average spacing of 0.15 m and average strength of 25.8 MPa. Properties of typical rocks at the mine and Seam 11 are shown in Table 1 (Pham, 2012; Ha Lam Coal Company, 2015; Ha Lam Coal Company, 2018a). Stratigraphic sequences at Face 11 - 1.14, Seam 11 are displayed in Figure 2.

Legend for value: $\frac{min - max}{average(number\ of\ sample)}$

Ha Lam coal mine currently operates two mechanised longwall lines applied at Seam 11 and Seam 7 (Ha Lam Coal Company, 2018b). For the first line at Seam 11: the designed production is 600,000 tonnes/year, average seam thickness is 10.99 m, seam dip angle is 5 - 10 degrees, cutting height is 2.6 m and caving height is 8.39 m. For the mechanised longwall at Seam 7, the production is 1,200,000 tonnes/year, seam thickness is 18.9 m, dip angle is 15 degrees, cutting height is 3 m and the rest is allowed to cave. During the operation of mechanised longwalls, top coal fall and coal face spall have occurred from time to time in front of face support. The longwall faces had to stop for remedial cutting without recovering top coal that resulted in significant coal loss and low safety at work. The site observation indicates that top coal fall can occur less than 1.4 or more than 2.0 m in strike direction while it can spread over 3÷4 shields in dip direction. The depth of fall is about 0.2÷0.3 m, in arch shape and friable.

3 Description of DEM modelling technique

Universal Discrete Element Method (UDEC) (Itasca, 2014), which is a two dimensional program based on DEM, has been used to develop an LTCC model in this paper. The program is capable of modelling typical features of longwall mining such as high density of discontinuities, large - scale movement of rock strata, and fall of top coal/roof rock ahead of face support. Because in a longwall panel, the extraction along panel length is much greater than the extraction along panel width, the LTCC model represents a cross - section at mid - panel width and advances along panel length.

Table 1. Properties of typical rocks at Ha Lam coal mine.

Order	Material/ Rock unit	Uniaxial Compressive Strength (kG/cm²)	Density (g/cm³)	Cohesion (kG/cm²)	Internal friction (Degree)	Tensile strength (kG/cm²)
1	Siltstone	110 - 2104 613(1188)	2.02 - 3.25 2.65(1107)	34.5 - 800 189(856)	16 - 38 32.35(852)	1.22 - 179 61(850)
2	Sandstone	113 - 3132 1188(842)	2.16 - 3.07 2.628(781)	39 - 950 366(616)	18.30 - 38 33.56(615)	26.9 - 500 105(614)
3	Gritstone	148 - 3733 1413(300)	2.28 - 2.91 2.58(292)	118 - 1000 375(266)	22.30 - 38 33.51(266)	34 - 199 110(267)
4	Claystone	87 - 1043 350(90)	1.79 - 2.86 2.60(89)	11.6 - 315 92(72)	21 - 35.30 29.57(73)	17 - 103 32(72)
5	Seam 11 roof	166 - 3255 788(147)	2.35 - 2.74 2.62(118)	53 - 590 253(65)	26 - 34.12 32.56(67)	24 - 185 85(65)
6	Seam 11 floor	115 - 2811 572(118)	2.02 - 2.86 2.62(102)	36 - 900 261(58)	27.3 - 37.3 32.31(58)	20 - 238 84(58)

3.1. Geometrical configuration and pre - mining stress

The geometrical configuration is referred to the location of model boundaries and detailed level of geological structure in the model. Itasca Consulting Group (2004) suggested that for a single underground excavation, boundaries should be set around five excavation diameters from the excavation periphery so that the model response is not adversely impacted. Note that for a longwall simulation the region of study is not wholly extracted at one time but progressively mined accompanied by rock consolidation in goaf area. Hence, in the current model, the model width is 350 m which is five times the area of interest. The model height is 186 m, including 50 m thickness of siltstone in floor strata, 11 m thickness of Seam 11, 8.5 m thickness of siltstone in immediate roof, 16.5 m thickness of sandstone in main roof and 100 m thickness of siltstone in overburden strata.

Apart from top coal/roof fall caused by faults, important discontinuities to be modelled include bedding planes and vertical joints while face/butt cleats are ignored to reduce computation time. Discontinuities are most dense in the area of focus with a minimum spacing of 0.5 m while they are less dense in other areas. Since there is no available information on the pre - mining stress regime at Quang Ninh coalfield, the horizontal stress is assumed to be equal to the vertical stress, based on the regime at the neighbouring China. The vertical and bottom boundaries are fixed in horizontal and vertical direction, respectively. The top boundary is assigned a stress caused by 114 m thickness of surface strata. The model is comprised of 4687 blocks and completes the simulation in ten days. The geometrical configuration is shown in Figure 3.

3.2. Material constitutive model and properties

The top coal/roof fall ahead of face support can occur in various loading stages associated with complex failure mechanisms and gradual disintegration of rock mass. A proper constitutive

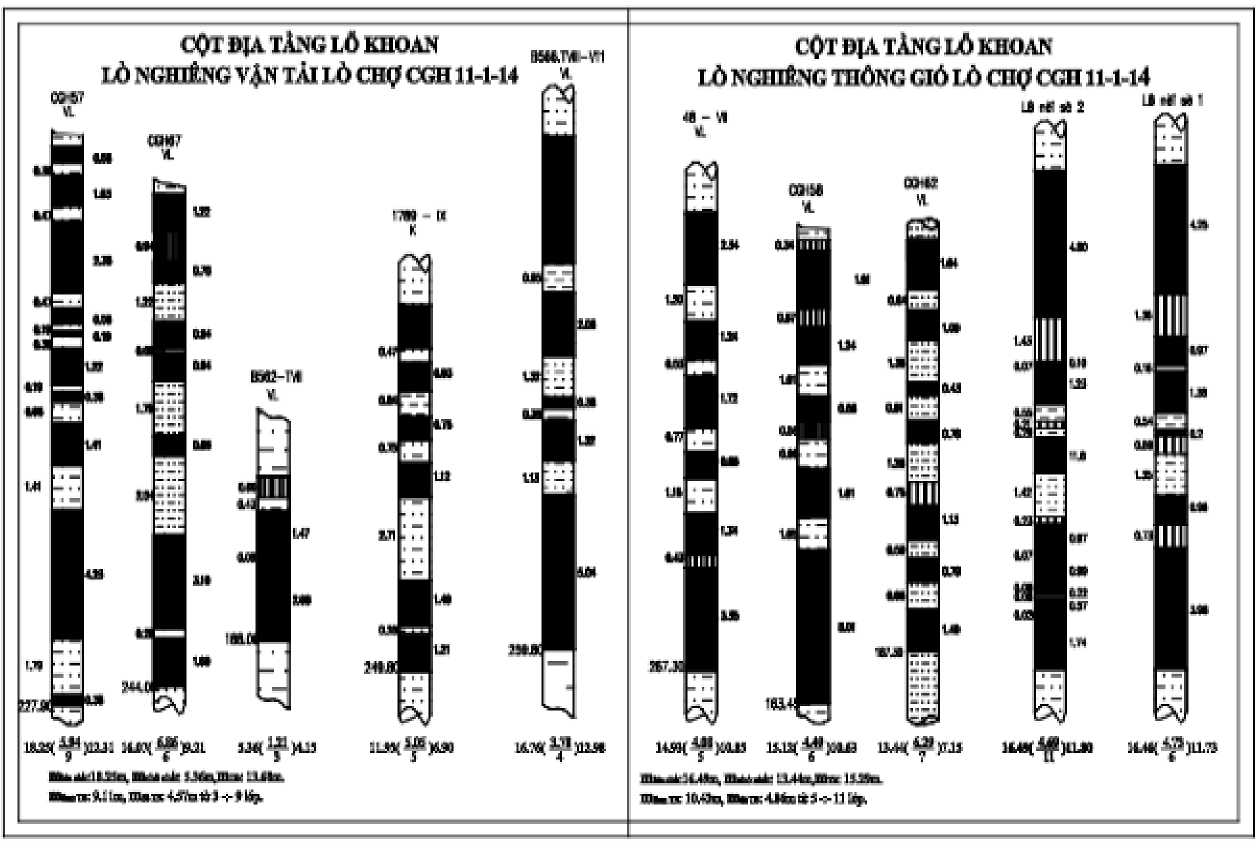

Figure 2. Stratigraphy sequences at Face 11.1 - 14, Seam 11, Ha Lam coal mine.

model should be able to represent key failure mechanisms and strength reduction in material. The strain - softening model available in UDEC can simulate the rock strength reduction during falling through the reduction of Mohr - Coulomb parameters according to change of softening/hardening parameter. For the current model, strain - softening behaviour is assigned to intact block in coal seam and roof strata. It is important to note that due to limited understanding of strain - softening response in jointed rock mass, a number of assumptions, back - analysis, user's experience and judgement are required to derive input parameters for modelling. At the same time, the Coulomb slip model is assigned to the discontinuities.

The properties of intact coal/rock and discontinuities are given in Tables 2, 3. From the available information on Uniaxial Compressive Strength (UCS), cohesion strength (C), internal friction angle (ϕ) and tensile strength (σ^t) of rock samples, the corresponding values for intact coal/rock at field scale are calculated using empirical equations from Kelly et al. (1996), Mohammad et al. (1997) and Vakili et al. (2012). Young modulus (E), Poisson ratio (ν) and residual strengths (σ^t_r, C_r) are similarly derived. The plastic strain rate required for reduction of strength from peak to residual value (ε^p) is adopted from Le et al. (2018b). For discontinuities, Itasca Consulting Group (2004)proposed a range of 10 MPa/m - 100 GPa/m for stiffness.

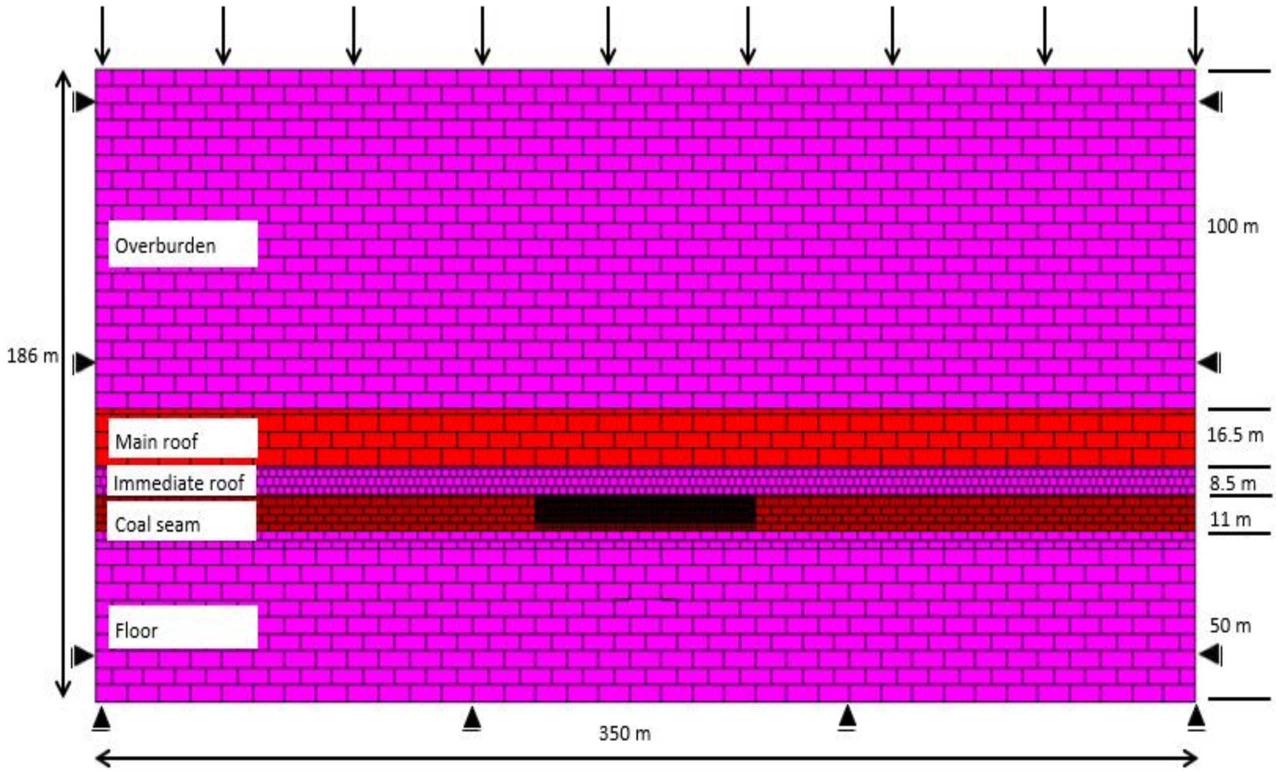

Figure 3. Geometrical configuration of LTCC model.

Table 2. Properties of intact coal/rock in LTCC model.

Material	Density (kg/m^3)	UCS (Mpa)	E (Gpa)	ν	ϕ (degree)	C (Mpa)	σ^t (Mpa)	C_r (Mpa)	σ^t_r (Mpa)	ε^p (%)
Coal	1500	5.176	1.821	0.25	32	1.52	1.55	0.304	0.155	0.5
Siltstone	2600	15.325	5.749	0.25	32	4.73	3.05	0.945	0.305	0.1
Sandstone	2600	29.7	11.143	0.25	34	9.15	5.25	1.83	0.525	0.1

A number of values were tested to find the optimal stiffness taking into consideration fall behaviour and computation time. The tensile strength and cohesion of discontinuities are assumed to be zero. Joints' friction angle increases from coal to siltstone and then sandstone.

3.3. Mining cycle and face support

One cycle of mining is modelled as follows. The face support in a previous cycle is deleted and one metre of coal face is removed in the cutting section, representing one cut of shearer. The face support is now set closely to the new face line after a number of numerical timesteps. The model then runs to reach equilibrium state, which is defined by a maximum unbalanced force - to - representative internal force ratio (R). During the run, top coal blocks caving into a designed area are deleted to simulate top coal recovery. One mining cycle is finally completed.

In this paper the face support is modelled by a set of parallel support members available in UDEC (Figure 4).

Table 3. Properties of discontinuities in LTCC model.

Strata	Normal stiffness (GPa/m)	Shear stiffness (GPa/m)	Cohesion (Mpa)	Friction angle (degree)	Tensile strength (Mpa)
Main roof	10	1	0	25	0
Immediate roof	10	1	0	20	0
Coal seam	10	1	0	15	0
Floor, overburden	10	1	0	20	0

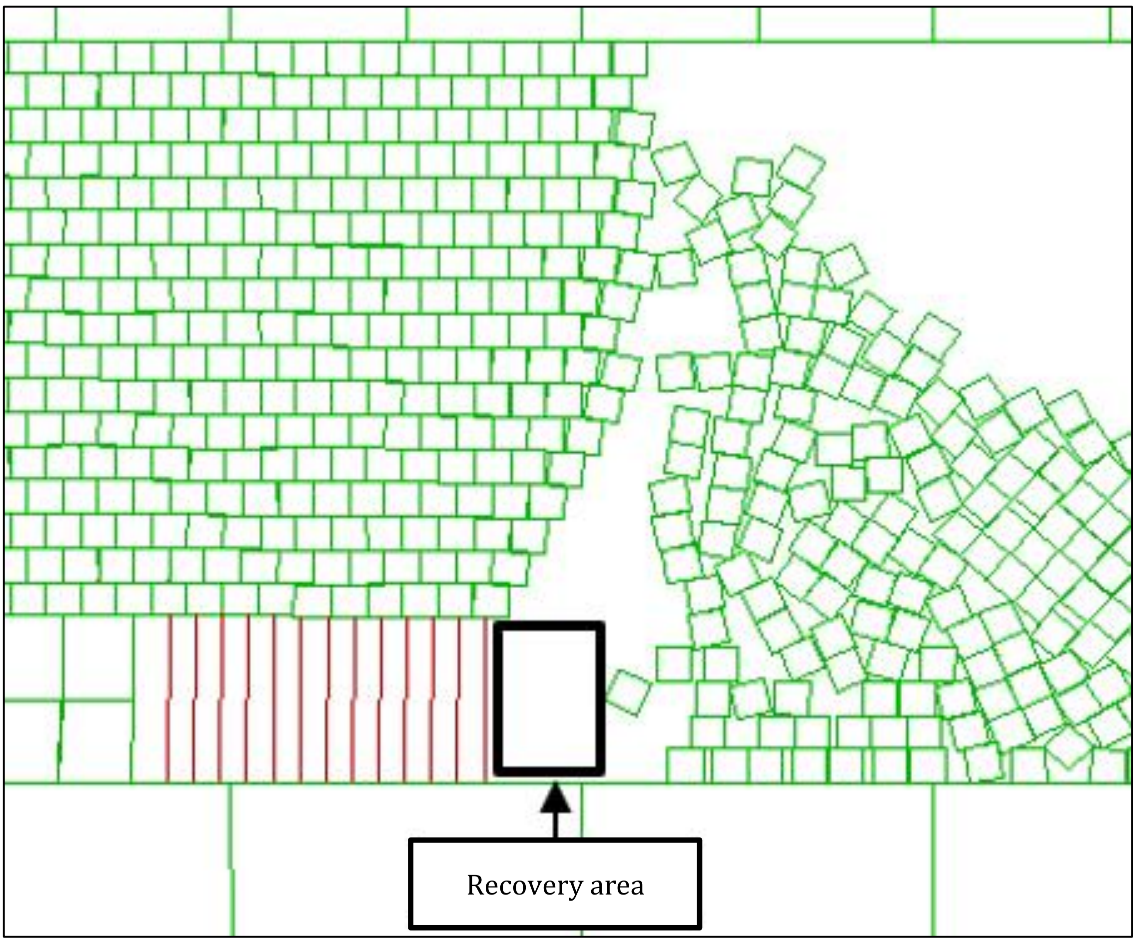

Figure 4. Modelling of face support in the LTCC model.

The members vertically connect top coal blocks with floor blocks, covering a width of 4.5 m to represent roof canopy. The support has a yield force of 4400 kN, setting force of 3520 kN and stiffness of 130 MN/m, which are in accordance with the on - site support.

3.4. Damping scheme and model calibration

Mechanical damping is introduced in UDEC for a static (or quasi - static) solution to quickly reach a force equilibrium state (Itasca Consulting Group, 2004). This is implemented by damping the equations of motion in the problem. For problems involving sudden load changes or progressive failure such as falling/caving of many blocks, local damping is recommended. For the current LTCC model, R ratio was adjusted to match the face advance where top coal starts caving observed at the site. This face advance (in strike direction) was reported at 6 - 8 m at site (Do, 2019).

4 Discussion and conclusions

A typical mining state with associated failure mechanisms when top coal caves cyclically is shown in Figure 5. The discontinuities that have opened (tensile failure) are in red and that have slipped (shear failure) are in blue. It is seen that

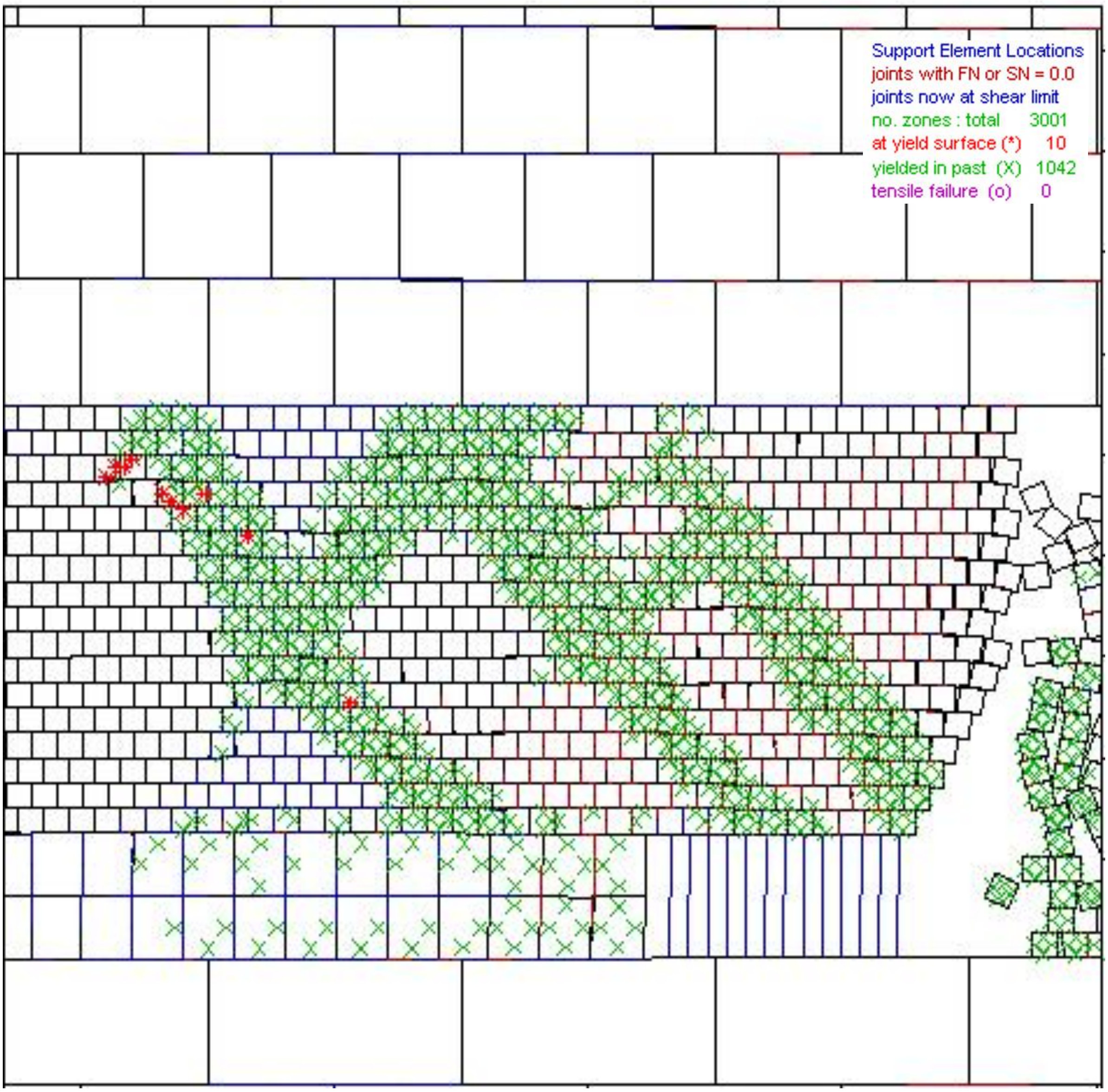

Figure 5. Failure state in a normal mining cycle.

above the support, the discontinuities mostly failed in tension due to significant relaxation of horizontal stress caused by previous mining.

Further into the unmined seam, the discontinuities mainly failed in shear because the horizontal stress gradually recovers its pre - mining value. Alternatively, the blocks at yield surface, yielded in past and failed in tension are in red *, green X and purple *o*, respectively. As shown, the blocks above and in front of the support have mostly failed in shear. This is due to the concentration of vertical stress while the horizontal stress is partly released in front of face line. The block failure causes new fractures that, along with the failed discontinuities, greatly facilitate top coal fall ahead of support in LTCC. If the broken top coal is small enough in size or if the support is not timely set at new face line, top coal will fall (Figure 6). The failure/fall mechanisms obtained from the modelling are consistent with site observations and empirical work (Le et al., 2019), confirming the validity of the modelling technique.

This paper presents a new modelling technique for studying top coal fall ahead of face support in mechanised longwall. The modelling is

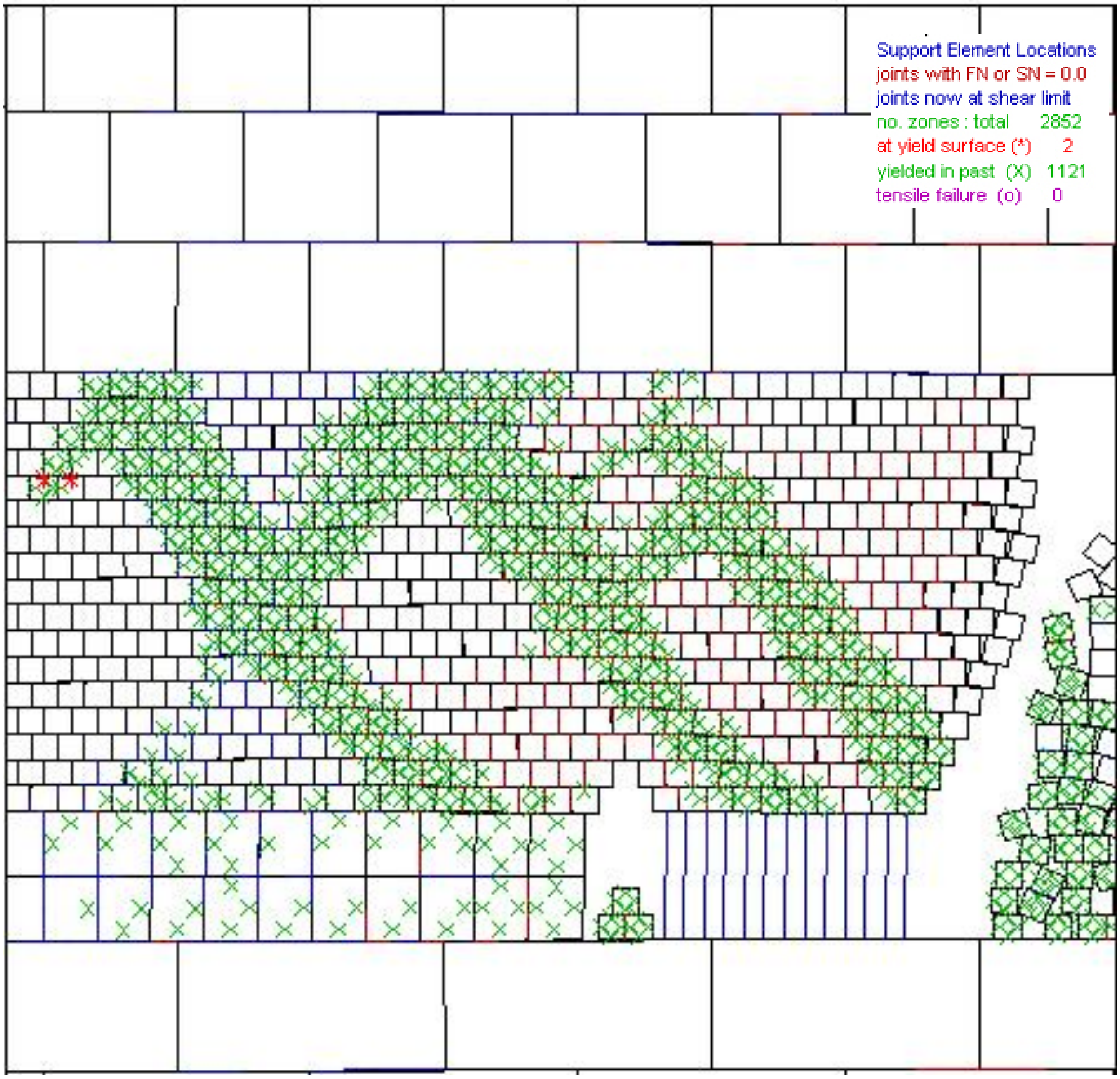

Figure 6. Top coal fall ahead of face support.

based on a Discrete Element Method code and uses plastic behaviours for coal/rock material. Using this technique, an LTCC model has been developed for the mechanised longwall at Seam 11, Ha Lam coal mine. The model has successfully represented the failure mechanisms and falling mode of top coal head of face support at the site. It should be noted that since intact blocks in UDEC cannot explicitly fail, the top coal fall may not be as realistic as in reality; further improvement for the technique is thus needed. The current modelling technique is helpful in studying top coal fall mechanisms in various geotechnical conditions.

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References

Bai, Q. - S., Tu, S. - H., Zhang, X. - G., Zhang, C. & Yuan, Y., 2014. Numerical modeling on brittle failure of coal wall in longwall face a case study. *Arabian Journal of Geosciences 7*. 5067 - 5080.

Brady, B. H. G. & Brown, E. T., 2004. Rock mechanics for underground mining, London. *Kluwer Academic Publishers*.

Ha Lam Coal Company, 2015. Quang Ninh: Ha Lam Coal Company. Mining passport for Face 11-1.14

Ha Lam Coal Company 2018a. Mining passport for Face 7-3.1. Quang Ninh: Ha Lam Coal Company.

Ha Lam Coal Company 2018b. Report on mechanisation of underground coal mining. Quang Ninh: Ha Lam Coal Company.

Cundall, P. A. & Hart, R. D., 1992. Numerical modelling of discontinua. *Engineering Computations 9.* 101 - 113.

Frith, R. C., Stewart, A. M. & Price, D., 1992. Australian longwall geomechanics - a recent study. *11th International Conference on Ground Control in Mining*. The University of Wollongong. AuSIMM, 131 - 139.

Galvin, J. M., 2016. Ground engineering Principles and practices for underground coal mining, Cham. *Springer International Publishing*.

Itasca 2014. UDEC Universal Distinct Element Code v6.00 users' manual. *Minneapolis*.

Itasca Consulting Group. 2004. UDEC Universal Distinct Element Code v4.0 users' manual.

Jing, L., 2003. A review of techniques, advances and outstanding issues in numerical modelling for rock mechanics and rock engineering. *International Journal of Rock Mechanics and Mining Sciences 40.* 283 - 353.

Kelly, M., Gale, W., Hatherly, P., Balusu, R. & Luo, X., 1996. New understanding of longwall caving processes: results of microseismic monitoring and initial computational modelling at Gordonstone mine. In: MCNALLY, G. H. & WARD, C. R., eds. *Symposium on Geology in Longwall Mining, 1996 Sydney. The University of New South Wales.* 153 - 161.

Langosch, U., Ruppel, U. & Witthaus, H., 2003. Longwall roof fall prediction and shield support recommendations. In: PENG, S., ed. *22nd International Conference on Ground Control in Mining*, Morgantown, WV. 27 - 32.

Le, T. D., Mitra, R., Oh, J., Hebblewhite, B. & Zhang, C. A review of roof instabilities associated with longwall top coal caving. 52nd U.S. Rock Mechanics/Geomechanics Symposium, 2018/8/21/ 2018a Seattle, Washington. *ARMA: Curran Associates, Inc.* 3370 - 3375.

Le, T. D., Oh, J., Hebblewhite, B., Zhang, C. & Mitra, R., 2018b. A discontinuum modelling approach for investigation of Longwall Top Coal Caving mechanisms. *International Journal of Rock Mechanics and Mining Sciences 106.* 84 - 95.

Le, T. D., Vu, T. T. & Dao, V. C., 2019. Mechanism and solution to top coal fall at Ha Lam mechanised longwall face, Vietnam. In: TRUONG, Q. H., TRAN, T. H. & PHAN, V. T., eds. *Conference on Advanced Researches in the Earth and Environmental Sciences (CAREES2019)*. Vietnam. Submitted.

Mohammad, N., Reddish, D. J. & Stace, L. R., 1997.

The relation between in situ and laboratory rock properties used in numerical modelling. *International Journal of Rock Mechanics and Mining Sciences 34.* 289 - 297.

Pham, D. H., 2012. Development of geomechanical database for mechanisation of coal industry in Vietnam. Hanoi: *Institute of Mining Science and Technology*.

Prusek, S., Rajwa, S., Wrana, A. & Krzemień, A., 2017. Assessment of roof fall risk in longwall coal mines. *International Journal of Mining, Reclamation and Environment 31.* 558 - 574.

Song, G., Ding, K. & Kong, D., 2019. Assessing longwall shield - strata interaction using a physical model. *Quarterly Journal of Engineering Geology and Hydrogeology.* qjegh2018 - 174.

Vakili, A., Sandy, M. & Albrecht, J., 2012. Interpretation of non - linear numerical models in geomechanics - a case study in the application of numerical modelling for raise bored shaft design in a highly stressed and foliated rock mass. *6th International Conference on Mass Mining*. 2012 Sudbury, Canada.

Vervoort, A., 1988. Influence of longwall support on the occurrence of roof cavities. *International Journal of Mining and Geological Engineering 6.* 313 - 326.

Wang, J., Yang, S. & Kong, D., 2016. Failure mechanism and control technology of longwall coalface in large - cutting - height mining method. *International Journal of Mining Science and Technology 26.* 111 - 118.

Yang, S., Song, G. & Kong, D., 2019. An evaluation of longwall face stability in thick coal seams through a basic understanding of shield - strata interaction. *Journal of Geophysics and Engineering 16.* 125 - 135.

Yao, Q., Li, X., Sun, B., Ju, M., Chen, T., Zhou, J., Liang, S. & Qu, Q., 2017. Numerical investigation of the effects of coal seam dip angle on coal wall stability. *International Journal of Rock Mechanics and Mining Sciences 100.* 298 - 309.