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An innovative methodology for improved simulation of goaf compaction in longwall workings using *FLAC3D*

S.K. Prajapati, A. Yadav, B. Behera, S.K. Sahoo, G.S.P. Singh & S.K. Sharma
Department of Mining Engineering, Indian Institute of Technology (Banaras Hindu University) Varanasi- 221005, India

1 INTRODUCTION

Longwall mining with caving is considered as the most productive and the safest method of underground coal mining. In this method, the compacted goaf acts like regional support and hence, plays a critical role in the distribution of stresses around the goaf area. Hence, a field representative simulation of the behavior of the goaf material is extremely important for stability evaluation and design of longwall structures using numerical modelling, which is widely used these days.

Measurement of vertical stress recovery within goaf material is difficult because of the inaccessibility of the goaf area and challenges in maintaining measuring instruments and lead wires to data loggers. Carr & Wilson (1982) proposed that goaf pressure increases linearly from the goaf edge and attains cover pressure at a distance of 0.2 to 0.3 times cover depth. Smart & Haley (1987) reported a fourth-order stress-strain characteristic for defining the constitutive behavior of goaf material. Later, Trueman (1990) modified the stress-strain relation proposed by Smart & Haley (1987) into a hyperbolic stress-strain relation to make it more representative of the goaf material. Salamon (1990) proposed the following stress-strain relationship to describe the compaction behavior of goaf material.

$$\sigma = \frac{E_0\,\varepsilon}{1-\frac{\varepsilon}{\varepsilon_m}} \qquad (1)$$

where σ is the recovered goaf pressure, E_0 is the initial tangent modulus, ε is the strain corresponding to the goaf pressure and ε_m is the maximum strain, the bulked goaf material can be subjected to.

Pappas & Mark (1993) conducted a confined uniaxial compaction test on the graded-down goaf material to determine its stiffness properties. They observed that Salamon's goaf model fit the laboratory data more closely and hence can be used with reasonable accuracy for defining the goaf compaction behavior. Using the laboratory data of Pappas & Mark (1993), Yavuz (2004) performed a three-dimensional regression analysis to establish a relationship between initial tangent modulus (E_0), the compressive strength of rock fragments (σ_c) and bulking factor of the caved material (b) (Eq. 2).

$$E_0 = \frac{10.39{\sigma_c}^{1.042}}{b^{7.7}} \qquad (2)$$

Equation 3 can be used for determining the bulking factor of the caved material. Maximum possible strain (ε_m) mainly depends on the bulking factor of the goaf material and can be determined by using Equation 4.

$$H_c = \frac{h}{b-1} \qquad (3)$$

$$\varepsilon_m = \frac{b-1}{b} \qquad (4)$$

This paper is focused on developing an innovative approach for three-dimensional simulation of longwall goaf by delineating the irregular geometry of the caved zone and its cyclic filling with progressive face advance. The hypotheses adopted for this purpose considers that the goaf material does not offer any mechanical reaction to the overlying fractured strata till the occurrence of main fall when the heap of caved rock establishes physical contact with the overlying roof strata. It also considers that in case of a sub-critical length of the face, the fractured zone which lies immediately above the caved zone does not contribute significantly in the loading of the goaf material because of constrained deformation of the upper strata. Hence, simulation of the fractured zone in this stage of modelling can be neglected at this stage.

2 BRIEF DESCRIPTION OF THE STUDY SITE AND MODELLING OF LONGWALL PANEL

A longwall panel belonging to Godavari Valley coalfield has been considered for the three-dimensional numerical simulation of goaf compaction process. The 6.3m thick coal seam at average depth of 254m is considered in this study. The mechanical properties used in the model are given in Table 1. The seam was developed along the floor, leaving 3.3 thick coal in the roof.

Table 1. Mechanical properties of geotechnical domains used in the numerical model.

Domain	Thickness (m)	Density (kg/m^3)	Elastic modulus (GPa)	Compressive strength (MPa)	Tensile strength (MPa)	Cohesion (MPa)
Overburden	210.1	2192	8.80	14.13	1.05	3.30
Main roof 2	4.30	2231	13.60	20.61	1.51	4.81
Main roof 1	20.10	2107	7.44	12.23	1.01	2.86
Immediate roof	21.00	2105	5.47	13.18	1.02	3.08
Coal seam	6.28	1440	2.00	3.61	0.36	1.15
Floor	100	2300	13.60	20.61	1.51	4.81

The model of longwall panel considered face length of 111m, panel length of 184m, gate road of 5m width and chain pillars of 31.5m width. The floor stratum of 100m thickness below the mining zone was considered in this study. The zone dimension within the mining zone ware$2 \times 1.5 \times 0.75\ m^3$; which ware increased gradually by 15% laterally and 10% vertically while moving away from the mining zone. The input vertical-stress in the model corresponds to a stress gradient of 0.025 MPa/m. In the absence of field measurement data, the average horizontal-stresses were initialized following the theoretical relation proposed by Sheorey (1994).

3 SIMULATION OF MINING SEQUENCE

The model was run to the state of mechanical equilibrium in elastic constitutive-model to avoid unrealistic yielding because of high inertial loading and transient stress conditions. The Mohr-Coulomb material model was activated at the next stage once the inertial loading phase passed off and the model was further solved to the state of the equilibrium. The panel was then developed and solved the model to a state of equilibrium. Shield supports were installed in the setup entries following the concept of Ground Response Curve (GRC) (Singh & Singh 2009). The modelling cycle followed at each stage of mining till the occurrence of main fall and two subsequent periodic caving are as follows: (1) extraction of 2m thick coal strip to advance the face by 2m; (2) numerical iteration to allow elastic convergence before advancing the support based on the concepts of GRC; (3) advancing of the supports; and (4) solving the model to the equilibrium. While going through numerical steps of iteration, the *FISH* routines developed for strain-softening behavior of superincumbent strata and monitoring of shear strain and vertical displacement to simulate the caving process were executed at every 100 steps. The readers are referred to Singh and Singh (2009) for a detailed explanation of the procedure adopted for this purpose in the paper.

4 DELINEATION AND FILLING OF THE CAVED ZONE

Since the geometry of the caved zone is highly irregular in shape. Hence, for delineating the geometry of caved zone, a *FISH* function was executed to find the centre of the caved zone. The centre was used to define the vertical centre line of goaf. Now trapezoidal shape planes, passing through centre line and extended to the caved area, of a finite thickness ware generated in such a way that no caved zone is left outside the generated plane. Each plane was assigned as the group 'goaf'. Then, each grid point within the group 'goaf' was repositioned to its initial condition to avoid computational error because of the badly deformed zones. The elastic model was assigned to the group 'goaf' to fill the caved zone (see Fig. 1). The subsequent goaf fillings were executed at an average periodic caving interval in the given working.

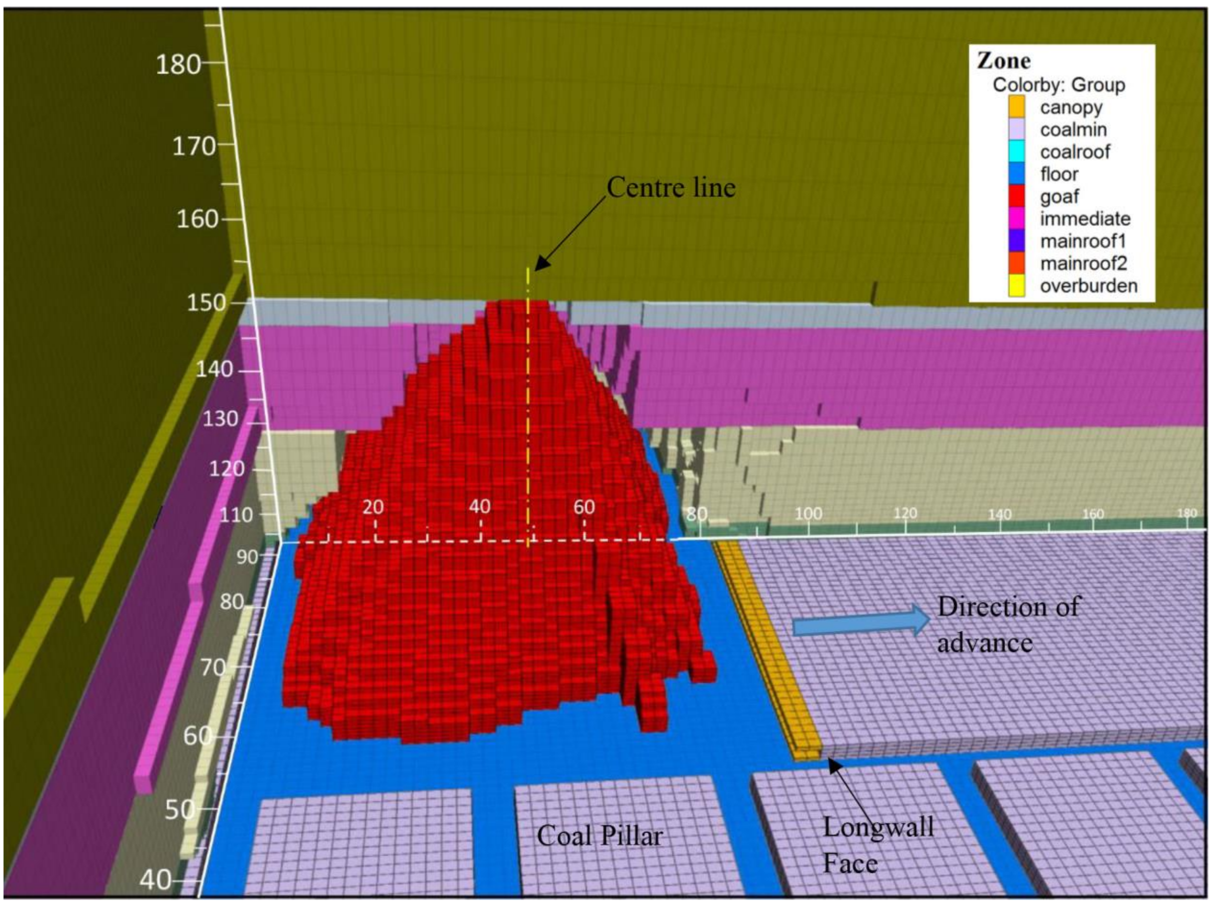

Figure 1. Filled-in Goaf material after Main fall.

5 SIMULATION OF STRESS RECOVERY IN GOAF MATERIAL

For simulating the goaf compaction behavior, the maximum strain (Eq. 4) and the initial modulus (Eq. 2) of goaf material were calculated. Compressive strength (Eq.2) was taken as a weighted average of the rocks up to caving height. The density and the Poisson's ratio of goaf were taken as 2000 kg/m^3 and 0.2 respectively. A *FISH* function was developed to obtain the volumetric strain and calculate the modulus and stress of each zone of the goaf material as shown in figure (Fig. 2)

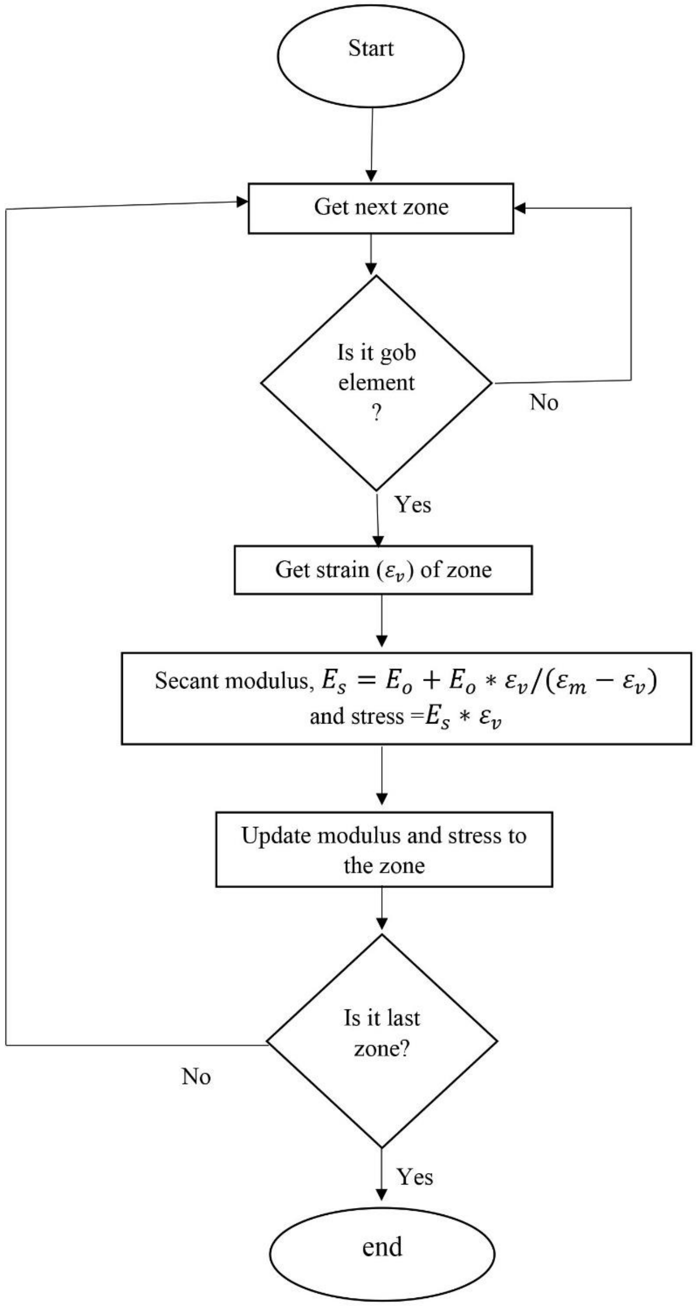

Figure 2. Flowsheet diagram illustrating the simulation process of goaf.

6 RESULTS AND DISCUSSION

The modelling of stress recovery with progressive longwall mining showed that the maximum stress in goaf is 0.8MPa just before the occurrence of first periodic caving although the maximum of average stress at the seam level is 0.517MPa. The maximum stress recovery in goaf material increased to 1.3MPa while the maximum average stress at the seam level was 0.62MPa just before the second periodic caving. In all such conditions, the concentration of recovered vertical stress is observed at the centre of the goaf due to confinement from the sides. As the working is of sub-critical nature, the maximum stress recovery is less than the in-situ vertical stress. However, the values are still underestimated.

7 CONCLUSION

This paper aimed to develop a numerical modelling procedure for delineation and filling of three-dimensional goaf and simulating its compaction behavior with progressive face advance in a longwall working using *FLAC3D* (Itasca 2017) software. The delineation and filling process works well with any shape of the caved region. For such geo-mining condition, recorded stress recoveries at the centre of goaf at the seam level ware about 10% and 12% before first periodic caving and after second periodic caving respectively. The study showed that Salamon's goaf model provides an improved and rational approach for simulating goaf behavior and abutment loading at the longwall face. It was also observed that the behavior of the roof changed when the caved area was filled with goaf material.

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