

Abstract

In India, the bord and pillar method of working is the most popular underground method for the extraction of coal. It can be done either by partial or complete extraction (de-pillaring). If important surface structures/futures are present, then it is preferable to adopt either partial extraction or de-pillaring with the stowing method to minimise the effect of subsidence. So that the surface structures/futures will be stable. Bord and pillar with caving method is being preferred where important structures/futures are not present at the surface. It is to be noted that in any method of working, the underground structures should be stable to create a safe working environment. Thus, it is important to assess the stability of underground structures (i.e. pillars and the roof) in a mine. The stability of underground structures (pillars) depends on the strength and stress acting on them. The numerical simulation technique is one of the best tools to assess the strength and stress acting on the pillar. The numerical simulation models require appropriate constitutive models for strata (coal-mass and other strata) and a goaf/ caving simulation approach specifically for caving panels. The most appropriate constitutive models representing the coal-mass are strain-softening considering either Mohr-Coulomb or Hoek-Brown failure criterion. This model is assigned to the coal pillar for stability assessment. These constitutive models do not consider the effect of time. However, it has been observed that the strength of the pillar decreases with time. Caving simulation is another very important issue/challenge for numerical analysts for assessment of the stress in a de-pillaring panel. There are various approaches for the simulation of caving behaviour, such as removing and replacing the extracted portion or roof up to caving height with goaf material with a logical process. However, these approaches are implicit in nature and require continuous monitoring of the strata behaviour to decide the goaf filling sequence, goaf compaction

behaviour, etc. Keeping these two issues, a comprehensive study has been carried out to develop the time-dependent constitutive model and simplified caving simulation approach.

A time-dependent Hoek-brown strain-softening constitutive model was developed for coal-mass. The basic strain-softening model requires strength parameters (m and s) as a function of plastic strain. In this process, the strength parameters reduce exponentially from the peak to the residual parameters. It requires peak strength, residual strength and softening parameters. It is to be noted that the material shows yielding before it reaches peak strength at the crack/yield initiation point. The yielded elements show time-dependent (creep) behaviour. In this process, the strength parameters are reduced with time. Keeping this, a mathematical exponential expression has been developed to estimate the peak strength parameter with time considering an additional peak reduction parameter. The peak strength parameter at zero time is referred to as the ultimate peak strength parameter. The constitutive model has three sets of strength parameters, i.e. crack initiation strength properties (m_c and s_c), ultimate peak strength parameters (m_p and s_p), residual parameters (m_r and s_r), the peak reduction parameter (β) and softening parameter (α). Deducing these parameters is practically not possible in the laboratory for large-scale coal-mass. Therefore, failed and stable field cases are used to deduce the strength parameters using a back analysis technique. One of the objectives is to deduce the strength parameters of Indian cases. However, because of the non-availability of documented/reported cases, South African coalfields were considered for assessing these parameters in that coalfield. Further, the strength parameters for Indian cases have been extrapolated using Logical Iterative Analysis. Twelve failed cases of bord and pillar mines from the Witbank Coalfield were utilised to estimate the strength properties of the time-dependent constitutive model using back-analysis techniques. Numerical models of

coal pillars for all the cases have developed. The material properties, in-situ stress and boundary conditions have been applied. The model has been divided into a number of elements having a size of 0.4 m X 0.4 m X 0.4 m. A simulation process has also been developed to incorporate the time-dependent strain-softening constitutive model. Based on the back analysis techniques are considered to deduced strength properties for South African coalfields. The deduced strength properties are crack initiation strength properties $m_c = 1.47$ and $s_c = 0.01$, peak strength parameters $m_p = 1.55$ and $s_p = 0.073$, and residual parameters $m_r = 0.125$ and $s_r = 0.00001$. The simulation results were obtained in terms of the average axial strain with time and life. It has been observed from the simulation results that the average strain of the pillar increased exponentially during the simulation stage of age before failure. Twenty-two stable cases from the Witbank coal fields were also chosen and simulated with age to validate the deduced strength parameters. The model of stable cases showed a negligible increment in axial strain, confirming the pillar's stability. The stress profile on the pillar with time has also been observed. The simulation results show that the crushing zone expands as the pillar ages, initially forming an M-shaped stress curve with peak stress at the start of the elastic zone. Over time, the stress curve transitions into an inverted V-shape just before failure. The simulation results showed that the pillar's deterioration begins at the surface and progresses deeper into the core, ultimately forming an hourglass shape. The pillar strength formula with respect to the age of the pillar has also been proposed based on the statistical analysis of the 36 cases of different geometrical parameters (including the failed cases). The calibrated material properties of the South African coal cases were considered for extrapolation to Indian cases using logical analysis. A statistical long-term pillar strength formula for India cases has been developed based on the field and stable pillar cases of the Indian coal field with a similar nature to the South African pillar strength formula (i.e. Salamon-Munro formula). Coal-mass

strength equivalence for both the Indian and South African coal fields has been considered for arriving at the strength parameters for Indian coalfields. The deduced strength parameters are peak strength properties (m_p and s_p) 1.39 and 0.059, crack initiation strength properties (m_c and s_c) 1.32 and 0.008 and the residual strength properties (m_r and s_r) 0.11 and 0.000008, and the softening parameters considered are β as 0.000195, and α as 200. The time-dependent strength parameters for Indian coal mass were used for the numerical simulation of failed and stable Indian coal pillar cases for validation. A time-dependent pillar strength formula was also proposed based on statistical analysis of the numerical simulation results.

Another objective is to develop a simplified caving simulation approach. The proposed simulation approach resembles the natural caving mechanism. Where the immediate layer settles on the floor after failure with uncontrolled deformation, other delaminated layers with uncontrolled deformation also settle on the lower settled layers during the progressive advancement of goaf. A mine case has been chosen for the implementation of the proposed models. The mine was initially developed by conventional mining through drilling and blasting. The depillaring activities started after ten years of development stage. The panel comprises two sub-panels: the dip side with larger pillars and the rise side with smaller ones. Strata issues i.e. side spalling were noticed, particularly, on the rise side after extracting pillar number 54, where smaller pillars were present, leading to some pillars being left out. A three-dimensional model of the depillaring panel has been created in FLAC^{3D}. The model was simulated sequentially pillar-by-pillar extraction by considering an explicit caving simulation approach to estimate the vertical stress acting on the pillars. The proposed time-dependent pillar strength formula was used to estimate the strength of the pillar and factor of safety (FOS) on the working pillars. During depillaring on the dip side, the FOS of the working pillars

was estimated by the time-dependent strength formula, and it was observed to be more than 1.7. However, on the rise side, some of the goaf edge pillars, including barrier pillars, had a FOS in the range of 1.14 to 1.3, leading to excessive side spalling of pillars. Based on this analysis, it was suggested that the minimum FOS of the working pillars should be more than 1.3, preferably 1.5, as a design criterion for the panel. Using this criterion, the next panel layout was proposed and numerically simulated to ensure it met the design requirements. The proposed panel was then investigated during the depillaring operations, where no major strata-related issues were observed. Simulation results have been obtained and found to reasonably match the physical observations from the field in terms of the first major fall, subsidence, and status of the goaf edge working pillars. Results during the depillaring stages just before and after the major fall have been presented. These stages are considered critical. Average vertical stress on the goaf edge working pillar was calculated for each depillaring stage. It has been observed that the vertical-induced stress increases with the advancement of the goaf. The maximum ultimate induced stress was observed just before the major fall, and after that, it was reduced due to *en-mass* caving. The first indication of subsidence was also observed at this stage. Field observations during depillaring further confirmed the accuracy of the simulation results, with no significant strata-related issues encountered in the redesigned panel. Observations such as the area of goaf exposure of the first major roof fall, the subsidence profile, and the status of the goaf-edge pillars closely aligned with the predictions made by the numerical model. This validation demonstrated the reliability of the scheme in real-world applications and its potential to improve operational safety.

The developed time-dependent pillar strength formula is used to estimate the life of the pillar. Estimating the life of the pillar is highly beneficial for predicting post-failure disasters, such as subsidence at partially extracted mines. Meanwhile, the proposed

explicit scheme resembles natural caving behaviour. It is easier to implement in the simulation process than the other implicit approaches. The integration of both caving and time-dependent deterioration models provides a comprehensive framework for managing the complex interactions between roof stability and pillar behaviour in underground coal mining.

