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A study on roof convergence monitoring in underground coal mining using embedded system

The prediction of roof convergence in mining area plays an important role in effectively preventing roof accidents and ensuring the safety of mine production. Because the roof pressure in the mine is affected by various natural and human factors, and there is a dynamic and fuzzy nonlinear relationship between the factors. At present, the lack of systematic management will seriously limit the analysis and judgment of the mine safety situation and lead to the occurrence of mine accidents. Strata control instrumentation and monitoring aim at the evaluation and monitoring of the trends of changing rock mechanical parameters such as dilation, load, convergence, stress and axial loading during mining. The objective of this paper is to provide an insight about the monitoring and analysis of convergence in underground coal mines. Also, it provides a comprehensive view of occupational accidents happened in mines along with the roof convergence and risk factors. Finally, the performance analysis of roof convergence rates is analysed.

Keywords: *Roof convergence; strata; dilation; load; stress, axial loading*

1.0 Introduction

The demand for energy is growing at a much higher rate than the growth rate of the economy in India. It will continue rising in India due to the increasing pressure of population, continuing urbanization, significant expansion of better living standards of the middle-class people, electrification in more and more villages, expansion of electrification of Indian railways, more demand of electric vehicles, and modernization of agriculture, infrastructure and manufacturing sectors [1]. In India, coal is a major fossil fuel and it is used for electricity generation, steel production and various other purposes. In India, coal will remain the most important source of energy till 2031–32 and possibly even further. Majority of coal reserves in India are amenable to underground mining. The Government of India (GoI) has an ambitious plan to increase underground coal production from 35 Mt/year (current) to 100 Mt/year (by 2019). CSIR-Central Institute of Mining and Fuel Research (CSIR-CIMFR), the only premier research institute of its kind in India has kept ‘‘development and adoption of coal production technology (especially related to mass production) in underground mining” as an important thrust area of research [2]. World coal production is depicted in Fig.1.

Underground coal mining is a complex organization of many work disciplines that requires serious experience and knowledge as well as continuous control. Due to the natural negative conditions of underground coal mines, a significant number of occupational accidents occur and often cause fatalities. Underground coal mines are dangerous working environments that have the highest rate of fatal accidents and injuries compared to other workplaces [3], [4]. The highest incidence rate occurs in unaffiliated companies. The types of mine accidents include poisonous gas leakage such as falling stone, blasting, run over, electrocuted and trapped by machinery, hydrogen sulphide or explosive natural gases such as fire damp or methane, toxic gases arising from mine fires, dust explosions, collapsing of mine stopes, mining-induced seismicity, roof fall, flooding, or general mechanical errors from improperly used or malfunctioning mining equipment [5][6].

Coal mine roadway junctions in mining are more vulnerable to roof fall due to the excavation induced stresses as well as general stress loading pattern inherent to the typical cross-section achieved in practice [7], [8]. Roof fall incidences are generally more in the junctions of development galleries and a cause of concern as they provide access to faces in different directions [9]. Roof fall in underground coal mines is always a matter of concern and subject of research for mining engineers while designing the support system. The fatality due to ground movement still contributes a very high percentage (41%) during the process of excavation. When the extraction is made in underground workings, particularly in the layered strata such as in coal measure rocks, re-distribution of stresses takes place which disturbs the state

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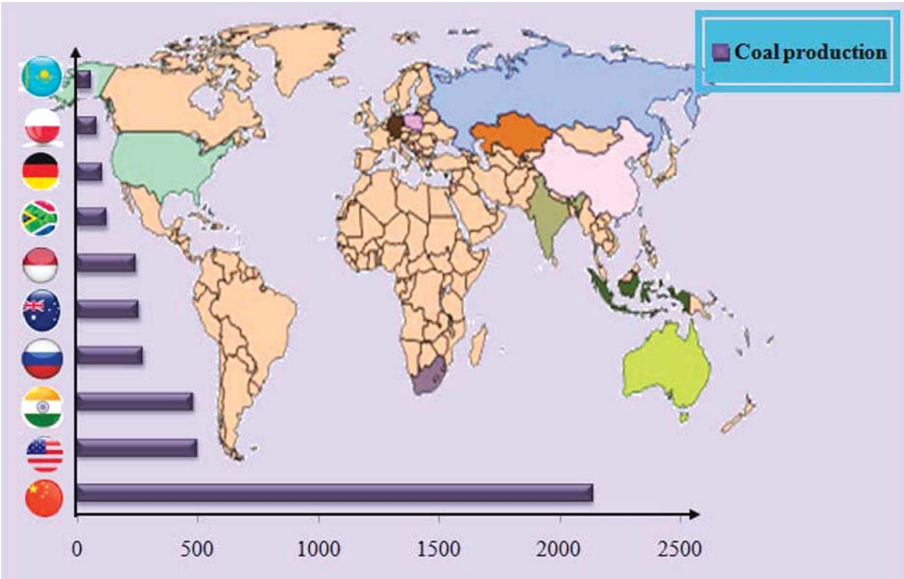

Fig.1: Coal production in the world

of equilibrium of stresses [10]. Thus, soon after the excavation is made, the coal mine roof should immediately be supported by installing an appropriate system of support [11]. Any time lag may cause the roof to deform and fail, resulting in serious fatalities [12], [13]. The purpose of monitoring the roof pressure of the mine is collecting and analysing the factors that affect mine safety [14]. Therefore, it is important to determine the information collected for monitoring roof pressure to process the collected information [15]. At the same time, the continuous collection of information, related to mine safety is important to the continuous improvement of the theoretical system of the mine [16].

A systematic process evolved within the Australian coal mining industry to ensure that no person is exposed to an unacceptable level of risk from an uncontrolled strata failure [17]. This approach is based on a standard Plan-Do-Check-Act (PDCA) methodology otherwise known as the Deming Wheel originally developed as a tool to control and continuously improve processes in monitoring [18]. The following principles form the PDCA model in an iterative manner:

- Plan: Planning and documentation of objectives, expected outcomes, systems, processes and activities
- Do: Acceptance and implementation of the plan
- Check: Measurement and analysis that is understood and accepted
- Act: Review and management follow-up, enact a response to changing conditions and implementation of improvement initiatives that are sustainable

Various roof fall hazard management techniques have been implemented by the tunnelling and the mining industries. Scaling and roof bolting are the two conventional roof fall hazard management techniques [19]. In addition to these, many operations adopt more advanced technologies. Recent advances in the field of artificial intelligence (AI) with embedded systems have created a promising alternative for developing fast and accurate hazard management tools [20]. Tunnelling and mining industries have started to use AI for various purposes in the last few years. Still, there is a lack among the state of art researches that clearly speaks about the roof convergence monitoring in underground coal mining. Hence, this study clearly presents an idea of various roof fall convergence procedures used till date.

The organizational structure of the paper is as follows: Section 2 presents the literature review of various case studies for underground coal mining techniques with its effects and roof convergence techniques. Section 3 provides performance analysis from the study. Finally, section 4 concludes the paper.

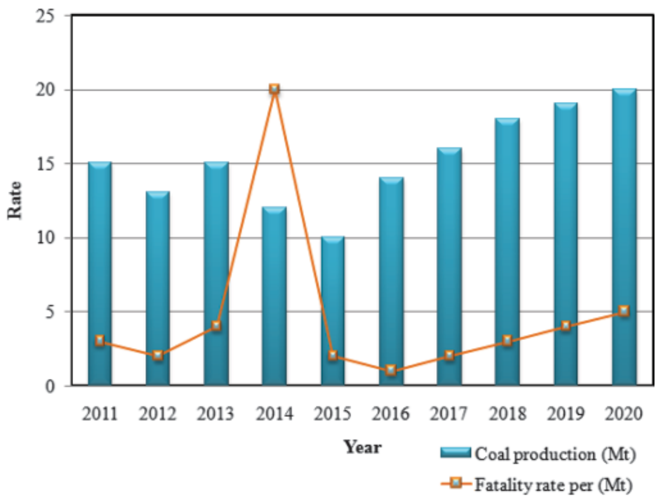

Fig.2: Coal production and fatality rate in India till 2020

2.0 Literature survey

This section explains the state-of-art methods of underground coal mining techniques, occupational accidents and risk control, Roof fall convergence prediction, and artificial intelligence-based roof fall convergence prediction along with the factors contributing roof fall and challenges in underground mines.

2.1 Underground coal mining techniques

Wanguan Qiao et.al [21] determined the factors that influence unsafe behaviour in Chinese underground coal mines. They analysed 35,364 unsafe behavioural data from 2220 people during the period from 2013 to 2015 using two methods (association-rule and decision tree) of data mining. The results indicated that the training, attendance, experience and age are the main four factors that affect the frequency of unsafe behaviours, in which the training factor has the greatest impact on unsafe behaviour. Moreover, people who have unqualified training, ineffective attendance and less work experience are more likely to conduct unsafe behaviour. In addition, six strong association rules about the moderate level of unsafe behaviour were excavated using the *A priori* algorithm in data mining and the efficiency of unsafe behaviour inspection can be improved by using those strong associations.

Heather E.Lawson et.al [22] studied the effects of overburden characteristics on dynamic failure in underground coal mining. Numerical modelling provided the setting and the effects of variability in a stiff discrete member in a hypothetical longwall mining scenario. A modelling experiment examined changes in rupture potential in stiff roof units for each stratigraphic type as discrete unit thickness and location that are manipulated through a range of values. Results suggested that the stiff-to-compliant ratio of the host rock had an impact on the relative stress-inducing effects of discrete stiff members. In other words, it is necessary to consider both the thickness and the distance to the seam, within the context of the host rock, to accurately anticipate areas of elevated rupture-induced hazard; acknowledging the presence of a discrete unit within the overburden is an insufficient indicator of risk. Those findings help to refine the understanding of the role of individual stiff, strong roof members in bumping phenomena and suggested that a holistic view of overburden lithology and site-specific numerical modelling were necessary to improve mine's safety.

A dynamic information platform was established for underground coal mine based on IoT technology by Yaqin Wu et.al [23]. The platform aimed to satisfy various objectives of potential users through combining four subsystems, including data acquisition, transmission, and analyzation, application systems. The platform monitors and records the working conditions data of the coal mine production systems as well as the location information of underground equipment and miners. Based on cloud computing techniques, big data related to underground coal mining can be analysed quickly, and critical data associated with user requirements can be extracted precisely. The platform provided a 3D virtual mine system, safety diagnosis system, safety inspection system and emergency rescue system for coal mines. With the established platform, the danger-spotting and subsequent decision-making capabilities of users can be greatly enhanced to ensure underground mining safety.

Qun Zhouet.al [24] developed and tested dust prevention technology of surfactant-magnetized water that utilizes the synergy between magnetization and surfactants to markedly improve the wettability of water, resulting in better dust suppression than water sprays alone in underground coal mines. A compound surfactant was developed as part of the new technology and was effective at low dosage. The new surfactant exhibited excellent synergetic effects with magnetization, with reduced surface tension. A new type of magnetic apparatus was designed and formed the core of the novel dust suppression technology. The magnetic device produces a powerful and consistent magnetic field to achieve effective magnetization of water flow. And the new technology effectively improves the atmosphere in mechanized underground coal mines, contributing to a safer and healthier working environment

An underground real-time micro-seismic monitoring technique was implemented by Ghosh, G. K., and C. Sivakumar [25] in the working panel-P2 in the Rajendra longwall underground coal mine at South Eastern Coalfields Limited (SECL), India. The target coal seams appear at the panel P2 within a depth of 70 m to 76 m. On that process, 10 to 15 uniaxial geophones were placed inside a borehole at a depth range of 40m to 60m located over the working panel-P2 with high rock quality designation value for better seismic signal. Various micro-seismic events were recorded with magnitude ranging from 5 to 2 in the Richter scale. The time-series processing was carried out to get various seismic parameters like activity rate, potential energy, viscosity rate, seismic moment, energy index, apparent volume and potential energy with respect to time. The use of those parameters helped to trace the events, understanding crack and fractures propagation and locating both high and low-stress distribution zones prior to roof fall occurrence. The results of the study reveal that underground micro-seismic monitoring provides sufficient prior information about underground weighting events.

Ján Kaèur et.al [26] researched the possibility of utilization support vector machines (SVMs) for underground coal gasification (UCG) data prediction. Support vector machines analyse data used for classification and regression analysis. They were tested the prediction difficult to measure underground temperature based on measured syngas composition and prediction of syngas calorific value from measured operating variables. The analysis was performed on data from the experimental laboratory gasifier.

Fa-qiang Su et.al [27] discussed the application of acoustic emission (AE) analysis for the evaluation of distinctly designed UCG models and operational parameters and described the gasification process. They studied the cavity growth, fracturing mechanism and the effects of various design and operational variables such as linking-hole type, gas feed rate and gasification agent. They found that the AE activity was closely related to the temperature change occurring inside the coal with AE generation apparently resulting from crack initiation and extension around the coal gasification area that occurs as a result of thermal stress. In addition, the quantitative information on the located AE sources can be obtained. Together, those processes have the potential to significantly reduce field risk in UCG by enabling the timely adjustment of operational parameters.

Jixiong Zhang et.al [28] proposed an integrated, closed-cycle mining-dressing-gas draining-backfilling-mining (MDGBM) technique. The approach involved the mining of protective coal seam, underground dressing of coal and gangue (UDCG), pressure relief and gas drainage before extraction and backfilling and mining of the protected coal seam. A system for draining gas and mining the protective seam in the rock stratum was designed based on the geological conditions. The system helped in realizing pressure relief and gas drainage from the protective seam before extraction. The mixed mining workface was designed to accommodate solid backfill and conventional fully mechanized coal mining, thereby facilitating coal mining, UDCG, and backfilling. The results showed that the process of simultaneously exploiting coal and draining gas was found to be safe, efficient and green.

Mohammad Javadi et.al [29] developed a new probabilistic approach to evaluate the most important hazard of coal mining. For that, a fuzzy TOPSIS model was applied at first to rank the risks of the mining. Application of that procedure showed that the roof fall was the most important hazard in the Tabas coal mine in Iran. Afterwards, they tried to quantify the roof fall risk as the most important hazard in underground coal mining. They found that the development of that model for the evaluation of roof fall risk under uncertainty condition had a key role in the safety of underground coal mines. For that, the major factors influencing the stability of the roof were utilized in a Bayesian network-based model. The method was illustrated with an application in Tabas coal mine. The results showed that BN-based model was a capable method for adjusting to uncertainties in the roof fall risk evaluation

Yuntao. Liang et.al [30] reviewed the mechanism and practical knowledge to forecast spontaneous combustion of coal in underground coal mines. To give more insights on the emerging order of fire gas, the study critically reviewed the detailed production sequences of those key gaseous products. It was indicated that production of carbon oxide, hydrogen, methylene and some other hydrocarbon gases can be used to forecast early heating of coal. They also summarised and discussed the interpretation of the index gases through the absolute concentration of key gas indicators and composite ratios. Six common gas monitoring techniques were discussed in terms of their advantages and limitations. Lastly, a practically demonstrated spontaneous combustion hazard management plan (i.e. TARP) was introduced. TARP uses different gas ratios in various locations to indicate escalating levels of severity of a heating event.

2.2 Occupational accidents and risk control in underground coal mines

A risk pre-control management system for safety in underground coal mines was built by Liu et.al [31]. Specifically, the risk pre-control management system for safety in underground coal mines uses hazard identification and risk assessment as its basis, risk pre-control as its core, and unsafe behaviour control as its focus. The system was composed of four main parts: scope, normative reference documents, terms and definitions and management elements and requirements. Thus, the management elements and requirements were the core of the system that consists of 8 first-level basics and 46 s-level basics. Moreover, an illustration was provided to show the process of building a risk pre-control management system for safety in underground coal mines. In addition, the application software Risk Pre-control Management System for Safety was developed and applied by the Shen Hua Ningxia Coal Industry Group in China.

Pramod Kumar et. al [32] proposed a methodology for the estimation of human error rate from a retrospective analysis of accident reports using fuzzy mathematical concepts. The work emphasises only two aspects such as activity and human error of system safety. System operation comprises a set of human interactions called activities, and the accident statistics vary with the type of activity. The approach uses accident reports of underground coal mines for assessing the human error rates of essential mining activities, identifying the critical activities and error types. It also suggests some error reduction strategies for devising an intervention to accidents.

Safa Eslambolchi S. et.al [33] emphasised to understand the changes in the safety measures of U.S. underground coal mines across different mine-size categories during the period 2005–2014. Empirical data were collected from the MSHA address/employment and accident/injury files, for the period 2005–2014. The differences in the means of two normalized safety measures, non-fatal days lost incident rate (NFDLIR) and severity measure/100(SM/100) as well as the changes in their trends, were examined across five mine-size categories, Very large, large, medium, small and very small, over the periods 2005–2009 and 2010–2014, before and after the institution of Mine Safety and Health Administration's (MSHA's) Impact Inspection programme. Both NFDLIRs and SM/100s of the very large, large, medium, and small mines were found to be significantly lower in the second period compared to the first period that can be attributed to MSHA's Impact Inspection programme in 2010. No significant differences were found in the NDLFIRs and SMs of very small mines from the first period to the second period. A drastic decrease of more than 50% in the SM/100 mean of small mines in the second period was observed and can be attributed to the closure of several small mines during that period.

Methane explosion accidents that occurred in Turkey's underground coal mines between the years of 2010 and 2017 were statistically analysed by Arif Emre Dursun et.al [34]. It showed that the number of deaths in Turkey's underground coal mines between 2010 and 2017 was 578 and the mortality rate was found to be 92.63%. The rate of the death toll caused by methane explosions and other gas-related accidents was 68.34%. For this, some counter measures were suggested and both prevent and control gas-related accidents. Furthermore, some recommendations for a decrease in the number of errors made in Turkey's underground coal mines were also presented

To improve the safety management model in underground coal mines from passive management to active management, the risk pre-control continuum and risk gradient control in underground coal mining were proposed by Quanlong Liu et.al [35]. There were three risk state correspond to three management models. The stable safety state corresponds to the hazard management model; the unstable safety state corresponds to the defect management model; the emergency accidents state corresponds to the emergency management model. Those three management models exist simultaneously, and each management model plays a role in pre-control to eliminate or reduce certain risks. The management level of those three management models determines the risk pre-control level and risk level of a coal mining enterprise. Finally, the idea of risk gradient control was proposed based on the risk pre-control continuum that includes three gradients from high to low, namely, hazard control, hidden danger control, and emergency control.

Rafa³ Czarny et.al [36] used passive seismic interferometry to monitor temporal variations of seismic wave velocities at the area of underground coal mining named Jas-Mos in Poland. Ambient noise data were recorded continuously for 42 days by two three-component broadband seismometers deployed at the ground surface. The sensors were about 2.8 km apart and measured the temporal velocity changes between them using cross-correlation techniques. Using causal and acausal parts of nine-component cross-correlation functions (CCFs) with a stretching technique, they obtained seismic velocity changes in the frequency band between 0.6 and 1.2 Hz. Correlation between average velocity changes and seismic events induced by mining was discovered. Especially, after an event occurred between the stations, the velocity decreased by 0.4%. Finally, they concluded that it monitors the changes of seismic velocities that are related to stiffness, effective stress and other mechanical properties at subsurface caused by mining activities even with a few stations.

Petr Konicek et.al [37] commented on the main causes of rock bursts and summarised the strategic measures taken against them of the recent opinion on rock burst issues in the Ostrava–Karvina coalfield. They highlighted the main mistakes in mine design of rockmass that lead to a rock burst risk and supports those arguments with illustrative examples from Czech hard coal mining. Long-term analyses of the causes of rock bursts provided recommendations on proper mining techniques for excavation of a rockmass with rock burst risk.

MelihIphar and Ali KivancCukurluoz [38] identified the safety hazards present in Indian underground coal mines and to build a preliminary database of the identified hazards. Accident data were collected from the Directorate General of Mines Safety in India and a public sector coal mining company was studied to identify safety hazards that may probably lead to accidents. The database could help mine management to improve decision making after analysing and evaluating the safety risks of identified hazards.

Erdogan H. H. et.al [39] proposed a quantitative methodology for the analysis and assessment of hazards associated with occupational accidents. The application of the proposed approach is performed on the mines of Turkish Hard Coal Enterprises (TTK). The accidents in TTK between 2000 and 2014 were first statistically analysed with respect to the number, type and location of accidents, age, experience, education level and main duty of the casualties and also injuries resulting from such accidents. The hazards were classified as individual, operational and locational hazards and quantified using contingency tables, conditional and total probability theorems. Lower and upper boundaries of hazards were determined and event trees for each hazard class were prepared. Total hazard evaluation results showed that Armutcuk, Karadon and Uzulmez mines have relatively high hazard levels while Amasra and Kozlu mines have relatively lower hazard values

2.3 Roof fall convergence prediction by Wireless Sensor Network and IoT based techniques

Prabhat Kumar Mandal et.al [40] assessed the roof convergence during the development of the coal seams by the continuous miner. Variations of the convergence with the major influencing parameters such as rockmass rating and the width of the gallery were obtained by the parametric study through elasto-plastic numerical modelling. A nonlinear multivariate model was framed by putting the constant and exponents in the input parameters. Those constant and exponents were determined through regression analysis to develop a predictive model. The coefficient of determination of the model was around 0.98. The model was validated with the monitoring data of different mines. The model can be applied for the assessment of the convergence of the roof in underground coal mines for safe driving of the roadways by a continuous miner.

Back-analyses were carried out by Trueman R., and I. Hutchinson [41] at Australian longwall mine sites to determine threshold values of critical leg pressure and convergence load cycle features capable of determining roof

TABLE 1: VARIOUS CASE STUDIES ONOCCUPATIONAL ACCIDENTS IN UNDERGROUND COAL MINING

Author	Type of investigation	Evaluation technique used	Findings and recommendations
Liu et.al [31]	Risk pre-control management	Scope, normative reference documents, terms, definitions, managementelements and requirements	The risk pre-control management system was built based on the study of risk pre-control continuums, hazards polarized management, the development and evolution of safety management,accident causes. It takes hazards identification and risk assessment as its basis, risk pre-control as its core, and unsafe behaviourcontrol as its focus
Pramod Kumar et.al [32]	The human error rate in underground coal mines	Fuzzy based mathematical rules	Shows a human error criticality-based approach formanaging and control of accidents, then the analysis servesas a guiding tool for the safety improvement in the Indian mining industry.
Safa Eslambolchi S et.al [33]	Policy changes in safety enforcement	Non-fatal Days Lost Incident Rate (NFDLIR) and Severity Measure/ 100(SM/100)	Recommended to create a separate modelfor each mine-size category, as mines of like size have similar characteristics and fewer variations are to be observed. Moreover, to consider a random effect regression model for mine IDand the interaction between the mine size and year is also recommended
Rafa³Czarny et.al [36]	Monitoring Velocity changes in coal mines	Passive seismic interferometry	The seismic velocities decrease with a large eventoccurred close to the direct wave path between tworeceivers used and the sensitivity relates to thereceiver location, noise environment and local geology
Petr Konicek et.al [37]	Long-Term Czech Experiences with Rockbursts	Software Phaseusing FEM	Theknowledge level is high in the USCB, both in the Czech Republic and in Poland and it should still be improved even ifonly a single ton of coal will be mined. On addition, theCzech experiences are based on Carboniferous sedimentarycoal deposits, many of them may be useful in undergroundmining
Erdogan H. H et.al [39]	Quantitative hazard assessment for Zonguldak Coal Basin	Probability theorem	Being one of the high rates of accident occurrence rate, analysesand implementation on Turkish data give important informationon reducing and mitigating the underground mine accidents inTurkey. These results are expected to guide decision-makers,regulators and managers to re-structure the system

control problems that were likely to occur in advance. Those threshold values were concluded to correctly predict roof cavities before they occurred approximately 80% of the time. That compared well to other rock mechanic empirical techniques. Threshold values were exceeded typically one-third shears in advance of cavities occurrence. That meant that a pre-warning was possible in time for operational controls to be enacted that were aimed at preventing the roof control problems deteriorating to an extent that the longwall stops production in the majority of cases.

Andrzej Walentek et.al [42] presented mine ventilation network-based framework to ensure the air composition at a certain humidity and temperature level that was comfortable for underground mine workers, especially in deep deposits. The results of numerical simulations of the influence of gate road convergence on the ventilation process of a selected part of the mine ventilation network. The gate road convergence was modelled with the finite element software phase 2. The influence of changes in the cross-sectional area of the gate road on the ventilation process was carried out using the computational fluid dynamics software Ansys-Fluent.

The architecture of ground control in intelligent mining with IoT was studied by Yang Hao et.al [43]. An on-going dynamic platform on ground control was explained based on non-destructive testing (NDT) on rock bolt anchorage quality assessment. The research progress was introduced with equipment introduction, principles and an onsite experiment. Future developments on the combination of NDT and IoT of ground control were discussed. The ideas and frameworks made efforts on safety control and spark new ideas in the much-anticipated intelligent mining

Zhang X et.al [44] presented a conceptual framework for the implementation of IoT to make this underground support system smarter. The taxonomy of security challenges in underground mine communication in IoT combination described in order to identify clear security goals. The block-chain based was used as a promising technology for the mining industry as it may help in curbing the penetration and disruption of cyber-attacks due to heterogeneous devices and distributed network. Vulnerabilities like information disclosure and Denial-of-Service attack (DoS attack) were discovered during the threat and risk analysis on the SAGES data logger. The SAGES falls into information generation block of the IoT ecosystem. Therefore, it is advisable to incorporate the security by design approach from the initial phase of the development to make the data transmission and storage secure

2.4 Artificial Intelligence-based roof fall convergence prediction

Xiliang Zhang et.al [45] suggested a technique for predicting roadways stability in tunnelling and underground space on a combination of particle swarm optimization (PSO) algorithm and artificial neural network (ANN), called ANN-PSO model. Accordingly, the stability of roadways in tunnelling and underground space was evaluated based on the geo-mechanical parameters. The uniaxial compressive strength, internal friction angle, rockmass rating, tensile strength, cohesion, density, Young's modulus, shear strength and slake durability were used as the influence parameters for evaluating and predicting roadway stability. Three model assessment indices, such as MAE, RMSE and R2 were used to simulate the accuracy of the roadway stability predictive models. Besides, ranking and color intensity techniques were also applied for assessment. The results showed that the stability of the roadway could be accurately assessed by the proposed ANN-PSO model with an RMSE of 9.708, R2 of 0.972, and MAE of 7.161. The sensitivity analysis indicates that the uniaxial compressive strength, shear strength, quench durability index, density and rockmass rating were the most important parameters for predicting roadway stability.

Directional roof pre-splitting (DRP) was introduced and examined by Debi Prasad Tripathy and Charan Kumar Ala [46] through a field experiment. The DRP method utilizes the mine pressure effect and broken expansion nature of rock to achieve the active pressure relief of retained roadways. Directional tensile blasting pre-splits the trial roadway roof by forming a smooth fracture surface in the roof. After mining, the gob roof within the pre-splitting height caves under the mine pressure and subsequently expands to fill the gob to counter the mine pressure. A field test was conducted, and a comprehensive monitoring scheme was designed to study the DRP effect. The results indicated that the trial roadway roof can be directionally cut apart under the guidance of the charge test and with the help of the established theoretical model for whole distance; after blasting, the roof could maintain its reliability, even though the working face approached. After mining, the retained roadway with DRP exhibited good pressure relief. Roof integrity was guaranteed; furthermore, roadway convergence significantly decreased, and sidewall stability on the pillar side was improved because the high pressure transferred to a farther position.

A new merging model, multiple regression-BP neural network (MR-BPNN) model, was proposed by Song Dai et.al [47] combining the multiple regression and BP neural network model. The prediction accuracy and generalization ability of the three models were verified by the recorded testing samples. Results of comparison suggested that three models had better applicability for predicting the height of WFFZ in the coalmine, compared to the existing empirical prediction methods. More importantly, the MR-BPNN merging model combined the nonlinear mapping ability of neural network and empiric of multiple regression models that could provide high-accurate, strong-generalized and practical application for predicting the height of WFFZ of coalfield. In addition, the reason for the inapplicability of traditional empirical formula and the practicability of the neural network-based prediction models were discussed

Large diameter blasthole-stoping method was selected to mine a copper orebody from underground below an open pit mine by Sumant Mohanto and Debasis Deb [48]. The damage induced in the rib pillars as a result of large-scale production was one of the major challenging issues. Three-dimensional numerical modelling techniques with the parametric variation of the material of ore and waste, stoping sequence and crown pillar thickness were applied to analyse the stability of stopes at various levels. A total of 138 finite element models were analysed. The concept of plastic damage index defined as the ratio of effective plastic strain to effective total strain was introduced along with strength reduction ratio. The parameter was determined during the post-yielding phase of rocks tested under uniaxial compression. An analytical equation was derived to relate those two parameters and five damage classes were also developed for predicting the rib pillar stability. Results of the numerical analysis were assessed in terms of the proposed plastic damage index and predictive models were developed using multivariate regression and artificial neural network. Those models suggested that stoping sequence was the most crucial parameter for rib pillar stability followed by the depth of working, rock material type and crown pillar thickness

Bayesian neural network (BNN) model was developed by Abhiram Kumar Verma et.al [49] for estimation of leg pressure and associated uncertainty. The 396 data sets from seven longwall panels are collected that includes depth of working, height of extraction, main roof thickness, face retreat distance, overhung length behind powered support and leg pressure of hydraulic-powered support. The leg pressure developed in hydraulic powered support was a manifestation of the various geo-mining parameters and therefore functional relationship exists between them. The results from BNN were compared to the Levenberg–Marquardt neural network and linear regression and found that BNN applied for prediction of leg pressure perform better than the other two approaches. The developed model was used to predict the leg pressure and hence powered support capacity for longwall projects

Satar Mahdevari et.al [50] predicted roadways stability equipped with a reliable support system in order to ensure their serviceability during mining life. Artificial neural networks (ANNs) were employed to predict the stability conditions of longwall roadways based on roof displacements. The data sets of the roof displacements monitored in different sections of 1.2 km long roadway in Tabas coal mine, Iran, were set up to develop an ANN model.

On the other hand, geo-mechanical parameters obtained through site investigations and laboratory tests were introduced to the ANN model as independent variables. In order to predict the roadway stability, those data were introduced to a multilayer perceptron (MLP) network to estimate the unknown nonlinear relationship between the rock parameters and roof displacements in the gate roadways. A four-layer feed-forward back propagation neural network was found to be optimum. As a result, high conformity was observed between predicted and measured roof displacement values and the predicted values are close enough to the measured ones with an acceptable range of correlation.

Artificial neural network (ANN) and spotted hyena optimized ANN (SHO-ANN) was used by Abiodun Ismail Lawal et.al [51] to develop reliable models in predicting coal spontaneous combustion liability. The coefficient of determination, mean error and root-mean-squared error were used to assess the performances of the models based on sixty-eight datasets. The data sets were used for training, testing and validation. The models provide excellent predicting ability with the coefficient value close to 1, errors close to zero while most of the data points fall within ±3% error bands. Sensitivity analysis was conducted using the cosine amplitude method and the result showed volatile matter (VM) and oxygen (O) as having the highest influence on the Wits-Ehac and FCC (Feng, Chakravorty, Cochrane) liability indices. In addition, it also provided a graphic user interface for the practical implementation in the coal mines.

2.5 Factors contributing the roof fall and installation challenges in Underground Mines

Christopher Mark and Michael Gauna[52] described the process of preventing roof fall fatalities during pillar recovery. They found that safe pillar recovery requires both global and local stability. Global stability was addressed primarily through proper pillar design and became a major focus after the Crandall Canyon mine disaster. But the most significant improvements resulted from detailed studies showed that local stability, defined as roof control in the immediate work area, could be achieved with three interventions: (1) leaving an engineered final stump, rather than extracting the entire pillar, (2) enhancing roof bolt support, particularly in intersections, and (3) increasing the use of mobile roof supports (MRS). A final component was an emphasis on better management of pillar recovery operations. That included a focus on worker positioning, as well as on the pillar and lift sequences, MRS operations, and hazard identification. As retreat mines have incorporated those elements into their roof control plans, and that becomes clear that pillar recovery was not ‘‘inherently unsafe”.

A practical method for assessing the risk of roof falls was presented by Prusek S et.al [53] influencing the stability of the roof in retreat longwall panels. It was a combination of empirical methods and expert techniques that enabled investigators to determine the probability and potential consequences of roof falls. The method applied was a practical decision tool to support mining management when planning the roof fall preventive measures. The extensive experience resulting from those underground observations and calculations allowed researchers to isolate seven significant factors influencing the stability of roof rocks in longwalls. The selected factors belong to the following groups: geological factors, mining factors and technical factors.

Satyabadi Kumar Jena et.al [54] aimed to develop a conceptual model that mainly focused to predict a critical strata movement value for safety of the bord and pillar method of mining, particularly depillaring. On that, roof fall warning index based on critical strata movement during underground coal extractions. The number of mining aspects such as analysis of instruments reading, geo-mining parameters, physico-mechanical properties roof formations and induced stress, were taken into considerations for the development of the model. Instrumentation and monitoring were undertaken aiming at the evaluation of changing values of rock mechanic parameters namely, dilation, load, convergence, and stress, during mining for a safe strata control. It enabled the mining practitioners to anticipate roof fall-related dangers in advance and took subsequent preventive measures while depillaring. The coal measure formations consist of relatively weaker stratified rockmasses. Bed separation occurred in the overlying strata due to induced mining stresses that cause the rockmass in its surrounding to displace. Also, the installed instruments can help in the prediction of any apprehensive condition during depillaring. The preventive measures can be taken if the strata movement was monitored and roof fall was predicted in advance.

Sarvesh Kumar Singh et.al [55] presented an automated method of roof bolt identification from 3D point cloud data, to assist in spatio-temporal monitoring efforts at mine sites. An artificial neural network was used to classify roof bolts and extract them from the 3D point cloud using local point descriptors such as the proportion of variance (POV) over multiple scales, radial surface descriptor (RSD) over multiple scales and fast point feature histogram (FPFH). Accuracy was evaluated in terms of precision, recall and quality metric generally used in classification studies. The generated results were compared against other machine learning algorithms such as weighted k-nearest neighbours (k-NN), ensemble subspace k-NN, support vector machine (SVM) and random forest (RF) and were found to be superior by up to 8% in terms of the achieved quality metric

Ju Y et.al [56] reported a novel in situ unmanned automatic mining method. That included a flexible, earthworm like unmanned automatic mining machine (UAMM) and a coal mine layout for in situ fluidized coal mining suitable for the UAMM. The technological and economic advantages and the carbon emission reduction of the UAMM based in situ fluidized mining in contrast to traditional mining technologies were evaluated. The development trends and possible challenges to the design were also discussed. It was estimated that the method costs approximately 49% of traditional coal mining costs. The UAMM-based in situ fluidized mining and transformation method reduces CO_2 emissions by at least 94.9% compared to traditional coal mining and utilisation methods. The approach was expected to achieve safe and environmentally friendly coal mining as well as low carbon and clean utilization of coal.

Mirzaei Aliabadi M et.al [57] aimed to analyse human and organizational factors involved in mining accidents and determine the relationships among those factors. Human factors analysis and classification system (HFACS) with Bayesian network (BN) were combined in order to analyse contributing factors in mining accidents. BN was constructed based on a hierarchal structure of HFACS. The required data were collected from a total of 295 cases of Iranian mining accidents. Afterwards, the prior probability of contributing factors was computed using the expectation-maximization (EM) algorithm. Sensitivity analysis was applied to determine the higher influence of contributing factor on unsafe acts to select the best intervention strategy. The analyses showed that skill-based errors, routine violations, environmental factors and the planned inappropriate operation had higher relative importance in the accidents. Moreover, sensitivity analysis revealed that environmental factors, failed to correct the known problem, and personnel factors had a higher influence on unsafe acts.

3.0 Performance analysis of roof convergence in mines

In order to understand the strata behaviour with respect to goaf edge distance, a number of observations were made by various researchers discussed in [58], [59], [60] were analysed. Convergence behaviour in different stations is critically observed and their deformation pattern characteristics are mathematically interpreted below.

Fig.3 compared the roof convergence techniques analysed by different reviewers in terms of goaf edge distance. With the panel advancing, dynamic convergence of gob roof changed with any of its characteristics. It is shown to increase slowly at first, then increases at the same rate then slows to zero. If more space is occupied by the backfill body, then there is a chance that replaces by nearby coal and undertakes more load of overburden. That caused the bending deformation of overburden to increase which resulted in a rapid increase in convergence but overall the change was relatively uniform indicating that the integrity of overburden was still well tolerated. Based on Meng Li et.al [58], the maximum convergence value measured by the roof dynamic displacement meter installed in the gob is 391 mm, which is extremely in close agreement with the predicted value. Drilling on the gob roof behind the panel resulted in

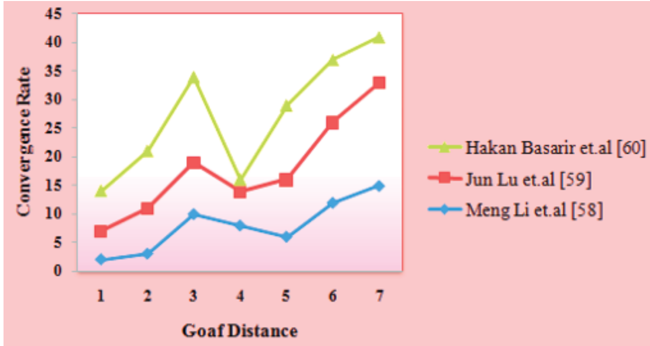

Fig.3: Performance analysis of different convergence rates

the development of a crack state being observed. The observation showed that roof integrity is good with the strata behaviours of the panel appears relatively smooth with no obvious phenomenon of first or periodic weighting.

4.0 Conclusions

Future of Indian coal mining industry is mostly dependent on all way success of underground mining. Whereas, roof and side management play a pivotal role in any underground technology for its success and sustainability. So, scientific and innovative reformations in roof management, the strata control monitoring have become bare necessity to come out of age-old presumptive practices, for survival and growth of the coal mining industry. Measuring roof deflection is the most common method of detecting roof instabilities. These measurements aid in monitoring mine roof performance and in determining where and often when, a roof fall may occur. The experience demonstrates that risk assessment techniques can be utilized to forecast roof rock instabilities in underground coal mines. Risk assessment techniques, suitably supplemented by strata monitoring technology can provide a means to warn of hazardous roof fall conditions. In this paper, a systematic review is carried out for the roof convergence in underground coal mining. Then the review on various cases of risk behaviours and factors that affect the underground panel installations were also summarised. In the performance analysis section, various convergence rates obtained from different reviewers are presented.

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