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Review Article

Numerical Modelling Approaches in Analysis and Design of Underground Coal Mines: A Review

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ABSTRACT

Underground coal mining has remained a prolific technique in advancement of human civilization by catering to the exponentially increasing energy demands. From time and on, underground mines have undergone different disasters leading to huge loss of life and assets. Subsidence or roof collapse in mines is one of the prime destructive hazards faced in the mines. Repetitive blasting and seismic induced vibration endure to be the main causes of subsidence in mines. This paper reviews the development made in the numerical methods and their reliability with respect to experimental techniques in addressing hazards encountered by underground coal mines. Preliminary focus of study has been laid upon seismicity induced subsidence in mines. Analysis based on finite element method, finite difference method and discrete element method has been appraised during the study. Furthermore, potential of coupled numerical model involving meshfree analysis technique and disturbed state concept has been highlighted in analysis of crack propagation and material heterogeneity analysis in underground coal mines that ultimately leads to subsidence in mines.

Keywords*:* Disturbed State Concept, Meshfree Analysis, Coal Mines, Numerical Modelling, Seismic Loading, Crack Propagation,

Introduction

Coal mining in India dates back to its inception in 1774, with the second-highest production in world mining, 716 million tonnes in 2018 alone, and about 8000 metric tonnesexploited worldwide annually. Coal mining sectors in India are for meeting energy requirements in India, and coal in India accounts for nearly 60% of the energy requirement in electricity generation. Coal mining in India is predominantly conducted through (i) (i) open-cast mines and (ii) underground mining regulated by the Mines and Minerals (Development and Regulation) Act of 1952 in India. In India, bituminous coal is predominant, constituting up to 80% of the country's coal deposits. Various global studies have addressed the essentiality of coal by analysing its constitutive behaviour and proposing design procedures to enhance safety in coal mines. Despite guidelines and codes issued both in India and worldwide for underground coal mining, the frequency of disasters remains high. Over the years, substantial loss of life and property has been attributed to the partial or complete collapse of ground mines, with impact loading and seismicity identified as primary factors in these incidents. Due to seismic loads or blasting shock waves, the rock or soil mass of mines undergoes the stress and strain changes at different rates, thus leading to deformation or, at times, the failure of the mine that in turn leads to huge loss of life and property. Underground mining is reliant on numerous characteristics that include the variety of ore body geometries, mining systems and size of mining operations. This diversity, joined with the significant level of vulnerability that exists in the condition of information on the rock and soil mass conditions, has been perceived as a significant challenge. Stress has been laid on having an unmistakable acknowledgement that there are various principal uncertainties in our comprehension regarding the coal mass that basically incorporate heterogeneity, anisotropy and non-linear behaviour. The coal mass is not a continuum and includes an enormous number of potential intermittences, the size, shape, orientation, location and number of which are to a great extent ambiguous. The forces or stresses acting in huge volumes of the rock and coal mass are commonly unclear and present variation with time (potentially because of block interactions or structural anisotropy); however, "point" estimations of the stress field are conceivable. Blast damage and seismic response in the coal mass framework, stemming from a wide range of impact and seismic activities, are often underestimated. Despite meticulous design, underground mines regularly face unexpected and unprecedented situations, challenging the notion of universal guidelines. Mining impacts, influenced by geological structure, rock stress, strength, groundwater, blast damage, and opening characteristics, can create potentially unstable conditions. Ground conditions may include low-strength, jointed, sheared, or plastic rock in a low-stress environment (soft rock conditions) [1]. Subsidence or collapse of mines is associated with different processes like seismic activities, adjacent mining activities, groundwater release, oil and gas pocket explosion, etc. The Mines Occupational Safety and Health Advisory Board in Western Australia has released guidelines for mining activities, focusing on geotechnical considerations, mining methods, hazard assessment, and safety plans. The guidelines encompass various methods, including geometrical and experience-based approaches, to predict subsidence risks in mines. Practical techniques, such as water pressure release, are recommended to control subsidence effectively [2-5]. Tectonic activities highly affect the underground mining operations, although the immediate effects may depict a lesser extent of damage. The impact on underground constructions relies upon geomechanical properties of the encompassing rock mass, the overburden pressure that adjusts the impact of the free surface from which estimations are typically acquired and the azimuth of the seismic activity, stress descent, rupture direction and seismic magnitude. On account of massive earthquakes, the rupture velocity and major aftershocks within the time span of dynamic loading should be considered as well, as was the case for the Sumatra earthquake in 2004 [6-10]. The intensity of ground mass shaking is numerically given by the integral of the square of the ground acceleration over time as given in **Eq. (1).**

$$I_A = \frac{\pi}{2g}\int_0^{T_d} a(t)^2\, dt \qquad \textbf{(1)}$$

Where, I_A is the intensity of ground acceleration, g is acceleration due to gravity (approx. 9.81 m/s² at a geographical latitude of 47.5°), Td is the duration of the signal above the threshold, a denotes the acceleration of transient seismic waves, and t denotes the duration of the transient wave.

The impact of tectonic earthquakes on underground mines can be described as the effect of observed dynamic strain, the velocity of the wave, the acceleration produced in the transient seismic wave and the time period of occurrence. Relations for the calculation of dynamic strain based on loading produced during a dynamic event are given in Eqs. (2) and (3).

$$\varepsilon_{l\max} = [\frac{v_{\max}}{2v_s}] + [\frac{0.7ra_{\max}}{(v_s^2)}] \qquad \textbf{(2)}$$

$$\varepsilon_{l\min} = [\frac{v_{\max}}{(2v_s)}] - [\frac{0.7ra_{\max}}{(v_s^2)}] \qquad \textbf{(3)}$$

where Ɛl max and Ɛl min represent maximum and minimum dynamic strain observed during the dynamic loading event, vmax denotes underground peak particle velocity in (m/s), amax represents underground peak acceleration in (m/s²), vs depicts shear wave velocity (m/s), and r represents the radius of underground excavation. The coordinated geotechnical information base and related tools permitted investigation of rock mass property variation in space and in relation to geological and geomechanical parameters. Seismic hazard parameters in link with the evolution of mining operations and seismic activity were additionally found to rely on time-dependent risk parameters that are activity rate, Gutenberg–Richter b-value, mean return period and exceedance probability of a prescribed magnitude for selected time windows related to the advance of the mining activity. A statistical damage-based method that incorporates characteristics of strain softening and hardening under the influence of voids and volume changes was inspected. It was supposed that a coal mass under stress conditions consists of three parts: voids, a damaged part, and an undamaged part. The effects of voids and volume changes on coal behaviour were evaluated to analyse the porosity and damage effect. A rating framework and strategies to introduce hazard maps and to coordinate with different stakeholders in the mine, for example, mine managers and the workforce, were generated. A comprehensive strategy for making a judgement about the kind of rock mass failure that happens during rock burst evolution in tunnels based on the magnitude of surface wave data recorded in instances to shape the fundamental models that can give a solid gauge of the rock mass failure during rock burst evolution. Some of the misconceptions that are primarily encountered while addressing the seismic hazard assessment in mines. This error in assessment may lead to overestimating or underestimating different hazards, like stress release, which may occur in the bedding plane due to mining activity, and we may still consider it as a potential failure site. Conducting rigorous tests on rock bursts or mine subsidence involves methods like direct and indirect blasting tests, as well as drop weight tests. It is recommended to validate rock burst support systems by subjecting them to intense loading, as in the case of direct blasting conditions. Numerous disasters may happen in mines that can occur individually or may initiate other disasters. Some of the common hazards faced in mines and their prediction techniques are enlisted in Table 1. Different parameters have to be taken into consideration pertinent to a particular hazard [11-13].

Table 1 Methods for disaster prediction in underground coal mines

Category of Disaster	**Parameters under consideration**	**Prediction Technique**
Rock fall or Subsidence	Movement of coal strata	Low frequency acoustic sensor, Accelerometer, Strain Gauge
Cave in	Seismic Shaking	Seismicity monitors
Gas pocket explosion	Methane(CH4) Leakage	Methane Sensor
Toxic gas release	Carbon monoxide (CO)	Carbon monoxide Sensor
Mine fire due to self-heating of coal	Temperature of coal strata	Thermal sensor
Inundation	Demarcation of water logged area, and maintaining safe distance between working area and water logged or old working area	Survey data by Ground Penetrating Radar system

The introduction highlights India's historical significance in global coal production, emphasising open-cast and underground mining methods and the classification of coal by carbon content. It stresses the need to understand coal's constitutive behaviour to address hazards and disasters. Seismic activities and blast damage are noted as contributors to mine collapses, acknowledging the challenges posed by uncertainties in coal mass conditions. The impact of tectonic earthquakes on underground mines is explored, and the lack of universal mine stability guidelines is recognised. The introduction concludes by underscoring the complexities of predicting and mitigating subsidence, paving the way for advanced numerical modelling approaches. These models, including finite element analysis and computational fluid dynamics, offer valuable insights for enhancing understanding and formulating robust design strategies in underground coal mining.

Numerical Modelling

Numerical models, employing mathematical time-stepping techniques, analyse the behaviour of prototypes or phenomena under various conditions. These models use mathematical equations and numerical techniques, like iterations, to describe geological conditions. Methods such as Finite Difference, Finite Element, or Meshfree are applied in geological investigations to approximate phenomena behaviour. Results, presented graphically or in tables, offer qualitative and quantitative insights into geological processes. Numerical modelling aids the study of rock mechanics, thermal history, impact loadings, ground deformations, and fluid flow.

Finite Difference Method

The finite difference method (FDM) is an estimation of the governing partial differential equations (PDE) by superseding partial derivatives with variations at regular or irregular grids enacted over problem domains, thus reassigning the existing PDEs into a scheme of numerical equations in terms of unknowns at grid points. Analysis of the stresses, displacements, and lateral strains in the ground subsidence due to underground excavation in rocks can be estimated by using the hybridised higher-order indirect boundary element/finite difference (BE/FD) technique. Research was conducted where the semi-infinite displacement discontinuity field was numerically discretised using cubic displacement discontinuity elements. This was followed by a hybridisation of the traditional finite difference formulation, including the backward, central, and forward finite difference formulations, using the boundary element formulation. This approach enabled the acquisition of the nodal tangential stresses and horizontal strains along the elements. A subsidence estimation methodology based on the finite difference method was developed, and it was reported that two dissimilar trends of subsidence were produced, presenting the maximum relative subsidence and extension along the surface area. Thus, it was dubious to predict and measure these troughs for prediction of subsidence (Alejano, Ramõâ and Taboada, 1999). The superficial subsidence due to inclined shallow coal seam mining of two underground mines in the Parvadeh (Tabas) coalfield was observed, and the same was simulated through the FLAC3D code that is established on the finite difference method. FDM results were matched with the observed profile and results obtained by using the profile function method. It was observed that FDM undervalued maximum subsidence by up to thirty per cent in comparison with surveying and profile function. It was observed that the FDM results obtained were in dissimilarity with the measured profiles acquired by surveying and the profile function method. A comparative description of stress vs. deformation prediction in coal mines is presented in Fig. 1. It can be inferred from the results that with an increase in stress the variable deformation profile is predicted by different methods of analysis. Thus, it may lead to overestimating or underestimating the stress-deformation condition that in turn may lead to a potential hazard.

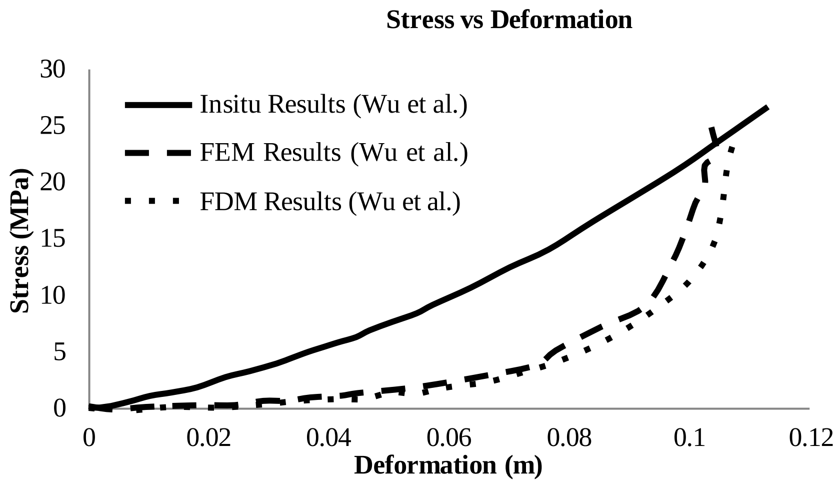

Fig. 1. Comparison of Stress vs Deformation Plot by Different Methods of Analysis (Wu *et al.*, 2019)

Prediction of surface subsidence in mines with two continuous coal seams is carried out. Primarily the subsidence for both the seams is examined; further, considering the subsidence data as indicators, the prime mechanical parameters of superimposing strata are acquired by orthogonal experimental design and inverse analysis of numerical simulation; thus, the subsidence prompted by two-seam mining is evaluated and predicted. Parameter inversion can predict the subsidence of neighbouring mines with analogous stratigraphic conditions. By applying the proposed optimal parameters, this approach can be utilised to evaluate the subsidence triggered by mining of more than two seams. When the excavation is carried out in one seam, it interrupts the stress regime of the existing mine and its adjacent excavated-out areas and changes the stress regime of the superimposing and underlying formations. The safety of the separating distance is evaluated by the analytical models, the numerical simulations using FDM and field exploration using geotechnical parameters like geo-mining conditions, thickness of seam, Young's modulus, triaxial compressive and tensile strength and uniaxial compressive strength. Several experimental and numerical studies have been carried out in the past to estimate and compare the subsidence in mines. Observations of subsidence along with the material parameters, a description of the error percentage recorded on comparison of experimental and numerical results, the calculation of maximum subsidence and the location of maximum subsidence and their comparison from different studies are presented in Table 2.

Table 1 Comparison of Subsidence Data from Different studies

Location of Mine and Extraction Component	**Material Parameters**						**Distance of trough from the point of observation**	**Maximum Subsidence observed**	**Maximum Subsidence predicted by numerical method**		**Error Percentage**
	Young's Modulus(GPa)	**Cohesion (MPa)**	**Poisson's Ratio**	**Tensile Strength (MPa)**	**UCS (MPa)**	**Friction angle (degree)**			**Method Used**	**Predicted Value (m)**	
Southern Coalfield, New	4.2	2.8	0.2	0.5	27.4	40	600-800	835.6 mm	UDEC	898.3 mm	6.97

South Wales, Australia (LW12)											
Southern Coalfield, New South Wales, Australia (LW13)	4.2	2.8	0.2	0.5	27.4	40	950-1150	770.3mm	UDEC	832.3 mm	7.44
Utah coal mine, United States of America (First Panel)	3.0	N.A	0.25	N.A	20	25	300-430	80 mm	FDM	60 mm	33.3
Utah coal mine, United States of America (Second Panel)	3.0	N.A	0.25	N.A	20	25	330-530	1050 mm	FDM	1180 mm	11.01
Madanjou coal mine, Tabas, Iran (Panel no. 28)	0.7	0.4	0.26	N.A	N.A	22	20-80	430mm	FDM	470 mm	8.5
Bulli Seam, New South wales, Australia	2.80	6.37	0.3	0.84	20.00	25	400-500	500 mm	UDEC	560 mm	10.7
Wongawilli Seam,	2.0	2.87	0.30	0.70	9.00	25	400-450	440 mm	UDEC	520 mm	15.3

New South wales, Australi a											

Finite Element Method

The Finite Element Method (FEM) is a robust and extensively researched technique widely employed for solving problems related to static and dynamic loading, linear and nonlinear stress, and fluid flow analysis in solids and structural formations. Commercially available FEM packages, known for their efficiency, are extensively utilised to address practical engineering challenges in solids and structures. FEM plays a crucial role in designing underground structures such as mines, tunnels, and thermal power plants. It is instrumental in evaluating the constitutive behaviour of intact rocks and segregated rock masses using models based on elastic, elasto-plastic, and strain-softening theories. A detailed study where calibrated mine-scale non-linear numerical modelling has been used to estimate the displacement and damage at three deep mines. Correlation has been developed between the dissipated plastic energy (DPE) and seismic event probability using the calibrated model. A strong correlation and non-linear relation between DPE and event probability was established that designates the deformation in rock pertinent to the development of peaks and declines in seismic stress. The relation between the DPE release rate and the event probability of a mine tremor of certain magnitude X, arising in a test block, is depicted by Eq. (4).

$$p(X) = x \approx \frac{n_{DPEi}}{e_{DPEi\ j}} \quad (4)$$

where the aggregate number of test blocks having values within any range of DPE release rate is denoted by eDPEi, with i being the fixed interval of DPE being evaluated, and the sum of blocks containing events within that magnitude range as nDPEj, with j being the event magnitude range. Different numerical methods used for analysis of rock mechanics and rock engineering-related problems highlight the importance of modelling for observing and estimating the fundamental processes occurring in rock, evaluating the predicted and actual behaviour of structures that are constructed over and inside the rock mass and assisting rock engineering design. Finite element methods lay emphasis on the depiction of fractures in the rock mass and behavioural couplings occurring amongst the thermal, hydraulic and mechanical processes. Finite element methods explore various issues in underground mining, such as subsidence from longwall coal mining, stress in adjacent slopes, and the interaction of tunnels. This approach, demonstrated in research and consultancy applications, provides insights into the evaluation of complex nonlinear systems, guiding geotechnical design and construction in underground mining. Different finite element techniques have been employed to predict and characterise the ground subsidence potential due to underground mining, with emphasis being laid on incorporating accuracy of geometrical and material parameters like non-linear behaviour of geological strata, shape of subsidence profile and development of plasticity zone. UDEC, a distinct element-based code, is employed for understanding mine subsidence-related problems, which accounted for joints that lead to reduction in rock mass strength. proposed a numerical model for wave propagation and subsidence assessment on fundamental rock mass behaviour. The resulting numerical model is able to capture rock mass strength, deformation modulus, anisotropy scale effects, and the effect of large-scale discontinuities on wave propagation behaviour. A case study on mining subsidence related to longwall excavations beneath significant natural features such as rivers and streams in the southern coalfield of New South Wales, Australia, and two-dimensional UDEC modelling for mining-prompted subsidence around river valleys were carried out. The study of the fracture systems helped in improving the understanding of the damage development associated with mining subsidence in a realistic manner. A numerical analysis of the hanging wall at the Kiirunavaara mine revealed induced failure, leading to caving and subsidence due to stress relaxation and gravitational effects. Results from continuous numerical methods indicated the formation of preliminary tension cracks on the ground surface due to extension strain, followed by shear failure along a nearly planar surface between the mining level and the tension crack. The break angle estimated from the model showed good agreement with calculated results using field data. Using FEM-based software ABAQUS/Explicit, a non-linear three-dimensional analysis was conducted on tunnels with a curved alignment along the longitudinal direction. The tunnels were subjected to internal blast loading simulated through coupled Eulerian–Lagrangian (CEL) analysis. Examination of deformation, stress, and damage responses in both the tunnel lining and surrounding soils, along with the attenuation of blast-induced stress waves in soil, revealed that the intensity of deformation and damage depends on the explosive position inside the tunnel and the tunnel's radius of curvature. Tunnels with a smaller radius of curvature exhibited more significant deformation and damage, with notable ground heave observed in all analyses. Various numerical methods, including FDM, FEM, and meshfree analysis, are proposed for mine design, aiding in insightful predictions of mine behaviour under static and dynamic loads. However, the application of FEM is limited by challenges in efficiently simulating fracture growth, necessitating different element sizes, continuous re-meshing, comfortable fracture paths, and addressing element edges. On comparison of subsidence measurements taken under different studies as presented in Fig. 2, FDM struggles with fractures, complex boundaries, and material heterogeneity, making it unsuitable for practical rock mechanics modelling. FEM, though flexible with non-linearity and complex conditions, is hindered by continuum assumptions in studies involving large-scale openings and sliding, as complete element detachment is not allowed.

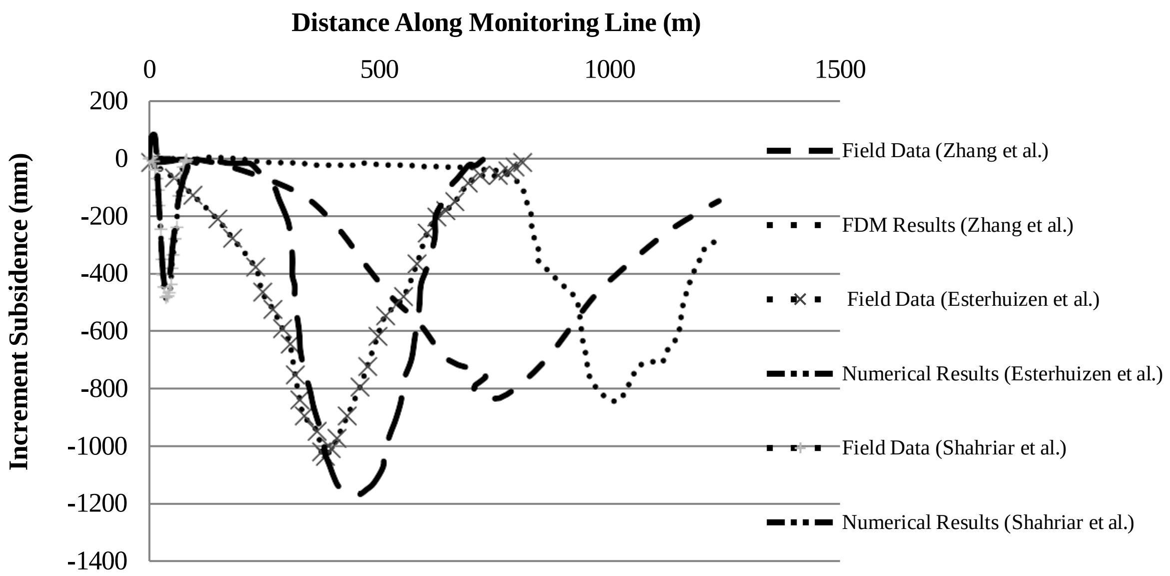

Fig.2. Comparison of Subsidence Results by Different Methods of Analysis

Disturbed State Concept

The disturbed state concept (DSC) is constructed on an idea that the behaviour of a material depends on its constituents and their interaction with each other. Based on DSC, the behaviour of soils or rocks can be expressed in terms of the response of their interacting constituents, encompassing physical properties like shape, size, discontinuity and orientation of the block and chemical properties like composition percentage of elemental constituents and micro-structure interaction of constituent compounds or elements. A unified constitutive model incorporating elastic, plastic and creep deformation, microcracking, fracture and cyclic fatigue under thermo-mechanical loading is formulated using DSC that in turn aids in analysing a wide range of constitutive characteristics, starting from the linear elasticity model to the complete damage model, which also includes elasto-plasticity conditions, fracture models and crack propagation along with the stress paths. The disturbed state concept evaluates the behaviour of the material in three categories that include when a material is in its original state without any impending stress, and it is termed as the Relatively Intact state (RI), As the application of stress takes place, the material undergoes different stress and strain accumulation or release, thus termed as the 'disturbed state' (D), and when the material loses ideally all its strength and has been transformed completely in comparison to its original state, it is termed as the 'fully adjusted state' (FA). Fig. 3 labels the complete analogy of disturbed state concept-based analysis.

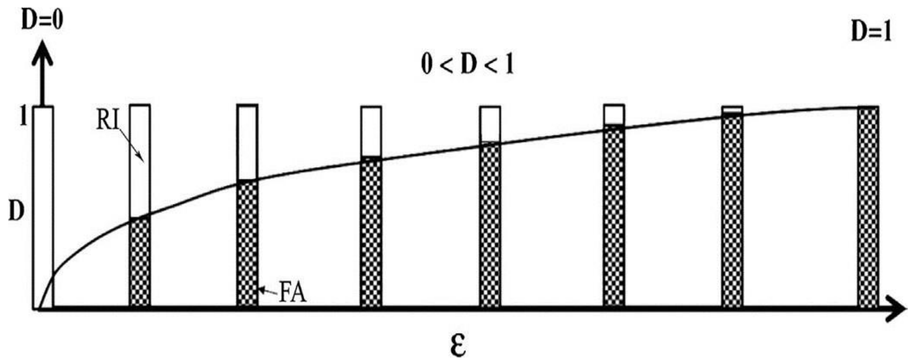

Fig.3. Disturbed State Concept description

It can be inferred from Fig. 3 that disturbance characteristics vary from 0 to 1, indicating the RI state at D = 0 and the FA state at D = 1, and the in-between range represents practically all the materials experiencing the stress state changes. Based on the disturbance characteristics of material models of analysis are accordingly devised, e.g., continuum-based models like elasticity, plasticity, and visco-plasticity models are used when D = 0. When D ranges between 0 and 1, that preliminarily indicates that the material is undergoing microcracking and fracturing, and numerous models like damage with microcrack interaction are used for the analysis. A description of the disturbed state concept is given in the Eqs. (5-9). Eq. (5) indicates the disturbance characteristics obtained from the stress-based change in material. Practically, the observed behaviour of a stress state in a material is depicted by σa. This empirical relation gives the idea about the disturbance state of a material that in turn aids in predicting the ultimate strength and complete failure stress point.

Measured Disturbance,

$$D_\sigma = \frac{(\sigma^i - \sigma^a)}{(\sigma^i - \sigma^c)} \quad \textbf{(5)}$$

Where D represents Disturbance, σ denotes the stress and a, i, and c superscripts denote observed (averaged), Relative Intact and Fully Adjusted states, respectively

$$D = D_u[1 - \exp(-A\xi_D^z) \quad \textbf{(6)}$$

where Du represents ultimate disturbance, A and Z are the disturbance parameters, and is the deviatoric part of the plastic strain trajectory given by the Weibull function presented in Eq. (6).

The deviatoric plastic strain trajectory is given by the square root multiplication of the incremental plastic strain given in Eq. (7), where Du represents ultimate disturbance, A and Z are the disturbance parameters, and is the deviatoric part of the plastic strain trajectory given by the Weibull function presented in Eq. (6).

The deviatoric plastic strain trajectory is given by the square root multiplication of the incremental plastic strain given in Eq. (7).

$$\xi_D = \int (d\varepsilon^{ip} d\varepsilon^{ip})^{\frac{1}{2}} \quad \textbf{(7)}$$

Thus incremental change in stress condition is given by the **Eq. (8)** and **(9).**

$$d\sigma_{ij}^{a} = (1-D)\sigma_{ij}^{i} + Dd\sigma_{ij}^{c} + dD(\sigma_{ij}^{c} - \sigma_{ij}^{i}) \qquad \textbf{(1)}$$

or

$$d\sigma_{ij}^{a} = (1-D)C_{ijkl}^{i} d\varepsilon_{kl}^{i} + DC_{ijkl}^{c} d\varepsilon_{kl}^{c} + dD(\sigma_{ij}^{c} - \sigma_{ij}^{i}) \qquad \textbf{(2)}$$

where Cijkl and denote fourth-order constitutive tensors and dD represents the incremental change in stress.

DSC has significantly aided in the robustness and consistency of computation for analysing intrinsic regularisation, localisation failure, implicit microcrack interaction and instability of microstructure without the use of external enrichment microcrack kinematics, Cosserat and strain gradient theories and pathological mesh dependence. Cosserat or micropolar elasticity is a continuum mechanics-based theory that incorporates local rotation and translation of points presumed in classical elasticity, couple stress and force stress conditions. The strain gradient theory of plasticity is formulated based on the concept of statistical and geometrical displacements. It incorporates couple stress on a single material for developing deformation and flow theory. On investigation of the behaviour of rocks, numerous multifarious factors were enlisted to have a significant effect on the behaviour of rocks, like the formation of rock, fissures in rocks, joints formed, in-situ stress conditions in seams, etc. DSC has proven to be very efficient in characterising the behaviour of rock mass despite complexities faced in the study of behaviour. Predominantly two methods, viz., the single-point method and the finite element method, had been used for predicting the stress-strain and strain-volume change behaviour of the rocks. After the inception of the Hierarchical Single Surface (HiSS) constitutive model developed based on DSC, it has been found to satisfactorily predict the behaviour of the modelled rockfill materials and looks suitable for characterising the behaviour of rockfill materials (Varadarajan et al., 2006). The DSC-based HiSS plasticity model characterises the "intact state"; it is proficient in comprehending the effects of confining pressure and initial density on the constitutive behaviour in drained and undrained conditions. Non-linearity in the rock mass, one of the major concerns in the analysis, is satisfactorily characterised by using a DSC-based HiSS-δ0 model that commendably takes effect on dynamic soil-structure interaction due to non-linearity into account as well. The HiSS model has been effectively used to analyse radiation damping in elastic half-space problems under dynamic loads using the incremental nonlinear HHT-α method with Newton-Raphson iteration. Apart from rock mass behaviour, DSC has greatly helped in bringing insights into the analysis of clays under variable water content conditions. DSC has satisfactorily predicted elastic and inelastic responses during loading and unloading in clays, stress path propagation, stress-deformation profiles, reduced triaxial extensions and pore water pressure effects in cyclic and non-cyclic loading conditions. DSC has established an explicit relationship between stress-strain and load-deformation behaviour of geomaterials that have an experimentally complex dependence on numerous critical factors like pressure, time, fracture accompanied by volume change, etc. Parameters requisite for evaluation of material properties based on DSC are comparatively lucid. DSC primarily uses both volumetric plastic strains and deviatoric plastic strains in comparison with conventional models for defining plastic hardening and stress paths in geomaterials, thus aiding higher accuracy in predicting the behaviour of geomaterials despite using lesser or equal numbers of constants. A comparative study between the DSC-based HiSS model and the critical state model based on the ease of use has been described in Table 3.

Table 3 Comparison of DSC with Critical State Model

Parameter	HiSS	Critical State
Number of functions for the yield surface	1	2
Number of Constants	5+2 (Linear Elastic Constants)	7+2 (Linear Elastic)

		+2 (Nonlinear Elastic)
Hardening	Total Plastic Strains	Volumetric Plastic Strains
Shear Dilation	Before Peak Stress	At The Peak Stress Only
Different Strength in Different Stress Paths	Yes	No
Modification for Added Features	Systematic Hierarchical Additions	No Method Available

Meshfree Analysis

Modelling and simulation techniques economically address advanced engineering challenges. Numerical methods, particularly meshfree techniques, efficiently handle complex problems such as material heterogeneity, anisotropy, and crack propagation without predefined meshes. Meshfree techniques enhance precision in studying stress paths, crack growth, and discontinuities, overcoming limitations in finite element methods. The Element Free Galerkin Method (EFGM) is a versatile meshfree technique applicable to elasticity, heat conduction, and crack growth problems. Utilising the Moving Least-Squares (MLS) system, EFGM constructs trial functions for the weak form solution based solely on nodal data. EFGM proves highly efficient for both static and dynamic fracture analysis, eliminating the need for element connectivity. Its appeal lies in handling studies involving damage, fracture, stress path, pore water pressure dissipation, and fatigue crack growth without requiring re-meshing or element deletion post-damage or fracture. Numerous studies have described the implementation of meshfree methods in linear elastostatic methods, elastoplastic methods, thermoelastic methods, etc., satisfactorily. A detailed description of EFGM is given in Fig. 4, which depicts the domain of influence or support domain with the moving least square method used in the Element Free Galerkin Method.

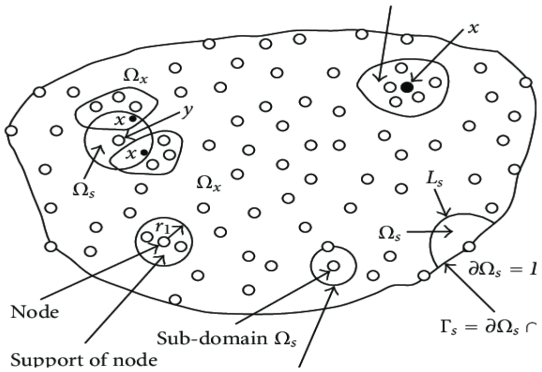

Fig.4. Meshfree Mapping Description

Apart from EFGM, meshfree methods include numerous other methods like the meshfree collocation method. It is a suitable method for solving elastic crack problems with the use of intrinsic enrichments and a diffuse derivative approximation. Elastic fracture problems are solved with robustness and pretty good accuracy on the application of this method. The meshless local Petrov-Galerkin (MLPG) method is an important technique that uses the strong form collocation scheme of solution. This method has proven efficient in the analysis of groundwater problems in comparison to FEM studies. Results obtained from using MLPG revive the fact that meshfree methods can be better used for the analysis of stress path prediction and crack growth patterns in geomaterials like rocks and soils. MLPG, along with the incorporation of the local symmetric weak form (LSWF), has proven to solve the problems of fracture and discontinuity in the material with high accuracy. Another meshfree technique, the local boundary integral equation (LBIE) method, has been developed that uses a meshless discretisation approach for obtaining the solution of boundary value problems. MLPG uses the idea of a companion solution, which uses the modified integral kernel, thus avoiding the use of a gradient or derivative over the local boundary. This technique aids in the accurate analysis of all nodes whose local boundary falls within the global boundary of the problem. Meshfree analysis technique and the disturbed state concept have been used as a coupled model in a study for the evaluation of the response of piles, softening behaviour under axial uplift loading, stress produced and deformation patterns. Results obtained from the model had been validated with large-scale in situ investigations and were found in good agreement with very high precision. Based on certain requisite parameters in the studies pertinent to mining, a comparison has been presented in Table 4; furthermore, it highlights the efficiency of EFGM in comparison to FEM and FDM.

Table 2 Comparison of EFGM, FDM and FEM

Parameter	EFGM	FEM	FDM
Mesh Requirement	No	Yes	Yes
Computational Time Required	Less	High	High
Large Deformation Estimation	Yes	No	No
Crack Propagation Evaluation	Yes	No	No
Adaptivity	Yes	No	Yes

Summary

- Efforts have been made in the past for understanding the behaviour of subsidence in mines; the majority of the problems encountered during the mining process are due to dynamic loading effects that are generally either overestimated or underestimated in terms of stress, strain and deformation consideration. Generally, that involves the release of stress or accumulation of strain due to impact loads.
- Different experimental methods have been suggested from time to time to predict the behaviour of mines under dynamic loads. These tests primarily include the vertical drop impact test, blast loading test, shake table test and column resonance test.
- Different analytical relations like rock mass rating (RMR), Q-system and geological strength index (GSI) have also been suggested from time to time to model the behaviour of rock-soil mass. These methods involve different parameters like uniaxial compressive strength of rock material, rock quality designation (RQD), spacing of discontinuities, condition of discontinuities, groundwater conditions and orientation of discontinuities to predict the behaviour of mines. Although the accuracy rate in the approximation of behaviour is quite low in the case of mines, they are used with higher safety factors to predict the behaviour of mines.
- FDM faces inflexibility in dealing with fractures, complex boundary conditions and material heterogeneity. FEM is more flexible in dealing with non-linearity, deformability and complex boundary conditions than FDM. However, FEM models are formulated on the continuum assumption that hampers the studies dealing in large-scale openings, as sliding as complete detachment of elements is not permitted.
- Challenges are faced practically while dealing with problems like heterogeneity, fracture, fluid flow, deformation, interface effects and nonlinearity in a mine. To deal with such problems, coupled model approaches are visualised. These models incorporate merit points from different models and try to address the concerning issue. The extended finite element method (XFEM) is an example of the coupled model. It has helped to get the insights of dealing with the fracture growth and fracture propagation in homogenous media problems.
- DSC is visualised to predict the constitutive parameters in mines, like stress, strain, and deformation, by considering the effect of the interface, material heterogeneity, and nonlinearity.

- Usually, experimental results obtained are compared with numerical results, and henceforth simulations are carried out, but so far, quite a few studies have been undertaken using meshfree methods for the analysis of mines that otherwise have an enormous potential of predicting and analysing large deformations, crack propagation and stress path prediction.

Conclusion

An approach may be visualised for constitutive modelling of mines by incorporating the disturbed state concept (DSC) and meshfree analysis. DSC is a relatively new concept that is a unified approach for constitutive modelling of engineering materials. DSC has proven to be robust and efficient in predicting numerous complex behavioural properties of geomaterials like strain, microcracking, damage, etc. DSC possesses a hierarchical framework that constitutes previously available models, such as elastic, plastic, thermo-viscoplastic, damage and softening, as special cases. DSC aids in the avoidance of spurious mesh dependence and provides implicit solutions for micro-crack interaction. Meshfree methods hold the principal attraction in the possibility of making simpler mesh adaptivity, moving boundaries and discontinuities associated problems. Meshfree methods hold a better reputation for solving phase change, discontinuous and crack-related problems and thus can be employed in the analysis of mines to analyse crack growth and complete or partial collapse with desired accuracy.

Credit authorship contribution statement

All authors have contributed to the manuscript and approved the final submission. Ilyas Bhat: Conceptualisation, methodology, validation, formal analysis, investigation, writing – original draft. Ankush Kumar Dogra: Conceptualisation, methodology, validation, formal analysis, investigation, writing – original draft, writing – review & editing. S Rupali: Conceptualisation, Supervision, Writing - review & editing. Arvind Kumar: Conceptualisation, supervision, writing – review & editing.

References

1. Cao WG, Zhao H, Li X, Zhang YJ. Statistical damage model with strain softening and hardening for rocks under the influence of voids and volume changes. Canadian Geotechnical Journal. 2010 Aug;47(8):857-71.
2. Alejano LR, Ramírez-Oyanguren P, Taboada J. FDM predictive methodology for subsidence due to flat and inclined coal seam mining. International Journal of Rock Mechanics and Mining Sciences. 1999 Jun 1;36(4):475-91.
3. Atluri SN, Zhu T. A new meshless local Petrov-Galerkin (MLPG) approach in computational mechanics. Computational mechanics. 1998 Aug;22(2):117-27.
4. Beck D, Reusch F, Arndt S. Estimating the probabaility of mining-induced seismic events using mine-scale, inelastic numerical models. InDeep Mining 2007: Proceedings of the Fourth International Seminar on Deep and High Stress Mining 2007 Nov 7 (pp. 31-41). Australian Centre for Geomechanics.
5. Belytschko T, Lu YY, Gu L, Tabbara M. Element-free Galerkin methods for static and dynamic fracture. International Journal of Solids and Structures. 1995 Sep 1;32(17-18):2547-70.
6. Carter JP, Desai CS, Potts DM, Schweiger HF, Sloan SW. Computing and computer modelling in geotechnical engineering. InISRM International Symposium 2000 Nov 19 (pp. ISRM-IS). ISRM.
7. Chaulya SK, Bandyopadhyay LK, Mishra PK. Modernization of Indian coal mining industry: Vision 2025. Journal of Scientific and Industrial Research. 2008 Jan 1;67(1):28.
8. Coulthard MA. Applications of numerical modelling in underground mining and construction. Geotechnical & Geological Engineering. 1999 Sep;17(3):373-85.
9. Das AJ, Mandal PK, Prakash A, Roy LB, Tewari S. Underground extraction methodology of contiguous coal seams ensuring the safety of the parting and the surface structures. Safety science. 2020 Jan 1;121:215-30.
10. Desai CS. Mechanics of materials and interfaces: The disturbed state concept. CRC press; 2000 Dec 20.

11. Desai CS, Drumm EC, Zaman MM. Cyclic testing and modeling of interfaces. Journal of Geotechnical Engineering. 1985 Jun;111(6):793-815.

12. Desai CS, Samtani NC, Vulliet L. Constitutive modeling and analysis of creeping slopes. Journal of geotechnical engineering. 1995 Jan;121(1):43-56.

13. Bodner SR. Unified plasticity for engineering applications. Springer Science & Business Media; 2001 Dec 31.