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Hazard Assessment of Coal Mines under Impact Loads using Holmquist Johnson-Cook Constitutive Model

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Abstract. Coal mines have been susceptible to hazards since the inception of mining activities. A Finite Element Based technique in ABAQUS has been visualized to address the estimation of Hazardous effect of low-velocity impact loads in coal mines. Based on Holmquist Johnson-Cook (HJC) constitutive model Parameters, the numerical simulation of mines has been performed using ABAQUS software. An appreciable agreement has been observed between experimental and simulation results of stress wave distribution and fracture patterns of the coal sample. Impact damage estimation has been carried out using validated parameters of Holmquist–Johnson-Cook constitutive model over shallow coal seam in ABAQUS. Holmquist–Johnson-Cook constitutive model has prominently helped in bringing insights of dealing with non-linearity and heterogeneity of coal seams. The achieved results indicated that the Holmquist Johnson-Cook constitutive model can be used to predict the chances of roof collapse in coal mines.

Keywords: HJC Model, Impact Loads, Fracture Morphology, Coal Mining, ABAQUS.

1 Introduction

Underground mining refers to various techniques used to excavate minerals, mainly those containing metals such as ores containing gold, silver, iron, copper, nickel, tin, lead and zinc. Mining is carried out under the mining (Act 1952) of Indian constitution in India[1]. It has been reported since ages that there has been a huge loss of life and property due to partial or complete collapse of ground mines. Numerous reasons have been reported so far that have an influence on the mining activity. Impact loading and seismicity are proven to be the main reasons involved in the collapse of mines[2]. Due to seismic loads or blasting, shock waves the rock and soil mass of mines undergo the stress and strain changes at different rates thus leading to deformation or at times the collapse of the mine that leads to huge loss of life and property. This diversity combined with a high level of uncertainty that exists in the state of knowledge of the rock and soil mass conditions has been recognized as a major challenge[3]. There needs to be clear recognition as there are a number of fundamental uncertainties in our knowledge of the rock and soil mass geotechnical conditions. The rock soil mass is not a continuum but comprised of a large number of potential discontinuity bound blocks of variable size, shape, orientation, location. The forces or stresses acting in large volumes of the rock and soil mass are generally unknown and are subjected to variation (possibly as a result of block interactions or rock anisotropy), however, "point" measurements of stress field are possible[4–6]. The strength of the rock and soil mass is not well known and is difficult to measure in large volume. The time-dependent behaviour of the rock mass is not well known. Blast damage and seismic response of the soil and rock mass system particularly from large scale blasting operations and seismic events is an important factor that has generally not been well quantified. In view of the above uncertainties, it is not surprising that even the most carefully planned and designed underground mines have to deal with the unexpected and unprecedented situations. Numerous reports of causalities have been reported from time to time that have happened due to the collapse of mines. Consequently, it would be wrong to suggest that there are rules of thumb or specific guidelines that are universally applicable in every situation, at any mine in perpetuity[4–9]. The range of ground conditions that may be encountered includes Low strength, jointed or sheared, plastic rock in a low-stress environment (soft rock conditions). High strength, well jointed, elastic rock in a low-stress environment (hard rock conditions) and High strength, brittle, sparsely jointed, elastic rock in a moderate to high rock stress environment that is prone to mining-induced seismicity (seismic rock conditions).Mines Occupational Safety and Health Advisory Board Western Australia [10] issued a set of guidelines for carrying out the mining activity. It includes different geotechnical considerations and guidelines to be followed during the mining operation. It primarily emphasizes on methods adopted for mining, hazard assessment and safety plan [11]. Different geometrical and experience-based methods have been enlisted to predict the chances of subsidence in mines. Some practical and viable techniques like the release of water pressure are also described to control the subsidence in mines. Seismic hazard parameters were evaluated in connection with the evolution of mining operations and seismic activity. The time-dependent hazard parameters estimated are activity rate, Gutenberg–Richter b-value and mean return period. Exceedance probability of a prescribed magnitude for selected time windows related to the advance of the mining front[9]. Development and assessment of an integrated geotechnical database for a hard rock, seismically active, underground mine located in the Abitibi-Témiscamingue mining district in Quebec, Canada. The integrated geotechnical database incorporates a geo-mechanical database with mining planning and seismic analysis [5]. The statistical damage-based approach was proposed in which the characteristics of strain softening and hardening under the influence of voids and volume changes were investigated. It supposed that a rock consists of three parts: voids, a damaged part, and an undamaged part. [12] . Emphasized on suggestions of design, installation, and operation of seismic systems in underground, hard rock mines[13]. a comprehensive method was proposed for judging the type of rock mass failure occurring during rockburst evolution in tunnels based on MS information recorded in real-time. The new method, which uses decomposed parts of the moment tensor and the P-wave development factor of the MS event to form the main judgment criteria (and energy ratio as an adjunct measure), can provide a reliable estimate of the rock mass failure type occurring during rock burst evolution. highlighted some of the misconceptions that are primarily encountered while addressing the seismic hazard assessment in mines [14]. Formulation of basis for carrying out severe testing about rock bursts or subsidence of mines with similitude. Testing methods have included direct and indirect blasting tests, and drop weight tests. It was advised to prove rock burst support systems by subjecting them to severe loading, as in case of direct blasting [15].

Numerical models are mathematical tools that use a numerical time-stepping procedure to obtain the model's behaviour over time. Finite Element methods are used to approximate the behaviour of a geological phenomenon. Numerical experiments are performed in these models, yielding the results that can be interpreted in the context of geological process. Both qualitative and quantitative understanding of a variety of geological processes can be developed via these experiments. Numerical modeling has been used to assist in the study of rock mechanics, thermal history of rocks, impact loadings, Deformations of ground and flow of fluids. Finite Element Method (FEM) is robust and has been thoroughly developed for static and dynamic, linear or nonlinear stress analysis of solids, structures, as well as fluid flows. Numerical methods especially finite element methods are important in designing the underground structures like mines, tunnels, thermal power plants etc. [16]. Constitutive models based on elastic, elasto-plastic and strain softening theories were used to characterize the behaviour of the intact rock and rock mass. A strong, non-linear relation between DPE and event probability was observed that describes the development, peak, and decline in seismicity as a rock is deformed carried out a review study of different numerical methods used for the analysis of rock mechanics and rock engineering. It highlights the importance of modeling for studying the fundamental processes occurring in rock, for assessing the anticipated and actual performance of structures built on and in rock masses, and hence for supporting rock engineering design. with focus on representations of fractures in the rock mass, the couplings between the thermal, hydraulic and mechanical processes performed numerical modeling to investigate a variety of problems in underground mining and tunnelling like subsidence induced by longwall coal mining, stresses generated during subsequent mining of adjacent stopes, the interaction of two tunnels and effects of under-mining a pre-existing tunnel and shaft. [17–20]. A three-dimensional nonlinear finite element (FE) analysis of tunnels with curved alignment in the longitudinal direction and it was subjected to internal blast loading. Blast load was simulated using the coupled Eulerian-Lagrangian (CEL) analysis tool available in FE software ABAQUS/Explicit. The deformation, stress and damage response of the tunnel lining and the surrounding soil were investigated. Higher deformation and damage was observed in a tunnel with a lesser radius of curvature. A significant amount of ground heave was also observed in all analysis [21].

Different experimental methods have been suggested from time to time to predict the behavior of mines under dynamic loads. These tests primarily include 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 and on to model the behaviour of rock-soil mass. Numerous numerical methods like Finite difference method (FDM), Finite element method (FEM), Meshfree analysis have been proposed for designing of mines. So, far these methods have greatly helped in bringing the insights in predicting the behaviour of mines under static and dynamic loads. Holmquist Johnson-Cook constitutive model has aided significantly in providing a reliable solution of impact-related problems. In the numerical simulation of coal, basic parameters can be directly obtained, and the remaining parameters are generally considered to be the same as concrete model parameters, which decreases the accuracy of numerical simulation results. Therefore, it is essential to understand the mechanism of coal/rock dynamic disasters by studying the dynamic mechanical parameters of coal to propose a systematic The validated HJC constitutive model parameters were applied to the numerical simulation of the impact damage of tunnel face, and the failure process of the coal seam in the roadway was visually displayed [22]. Abaqus/CAE is a complete Abaqus environment that provides a simple, consistent interface for creating, submitting, monitoring, and evaluating results from Abaqus/Standard and Abaqus/Explicit simulations using numerical tools [23].

Properties of Material

Bituminous coal has been procured from Khas Mahal Mines, Jharia, Jharkhand, India. it has been recorded that coal procured was Black in colour, layered in appearance and hard on striking. On experimental verification of properties of coal, it was observed that procured coal has a bulk density of 1.41g/cm^3 and Porosity of 12.6%. Detailed experimental analysis results of Coal are given in Table 1.

Table 1. Properties of Coal

Parameter Studied	Code of Guidance	Value Obtained
Bulk Density	IS 1122 : 1974 (Rev-2003)	1.41 g/cc
Dry Density	IS 1122 : 1974 (Rev-2003)	1.347 g/cc
Porosity	IS 1124 : 1974 (Rev 2006)	12.6%
Specific Gravity	IS 2386 (Part 3) : 1963 (Rev 1997)	1.39
Water Absorption	*IS 1124 : 1974 (Rev 2006)*	4.6%
Split Tensile Strength	*IS 1121(part -3) : 2012*	2.1 MPa
Uni-Axial Compressive Strength	*IS 1121 (Part 1) :1974 (Rev 2008)*	9.3 MPa

Analysis of properties of coal involved various testing techniques and some of them are given in Figure.[1-4]. Where Figure.1 represents the coal sample used during the analysis. Figure.2 is the representation of core drilling setup that is used to draw the cylindrical specimen for uni-axial and tri-axial strength determination. Figure.3 represents the Large Direct Shear Apparatus that is used for the determination of shear strength parameters of the coal sample. Figure 4. represents the sample coal sample after going through the Split Tensile test.

Fig. 1. Coal Sample

Fig. 2. Core Drilling Specimen

Fig. 3. Direct Shear Testing Equipment

Fig. 4. Split Tensile Disc

2 FEM Modeling

The FE model in this work was developed in 3-Dimensional Solid Elements of actual Size. FE model was meshed, and the impact, incident and transmission rods were divided into 20 parts along the radial direction. The impactor was divided into 50 parts along the axial direction, and incident and transmission rods were divided into 400 parts along the axial direction. Mesh Convergence study was performed to obtain accurate results. During the numerical simulation, the friction between contact surfaces was ignored. Figure.5 represents the Finite Element Mesh Model of mine and Figure.6 represents the wireframe view of shotcrete injected coal mine. The representative model has dimensions of 20 x 20 x10 m with the base of mine located at 2m from the crest and the dimensions of mine are as uniform radius of .5m extending up to 10m i.e. half of the depth in the model along the progressive excavation dimension. Shotcrete lining is injected to enhance the stability of coal mine and provide strength against caving in. Typical properties of shotcrete have been incorporated in the study for analysis.

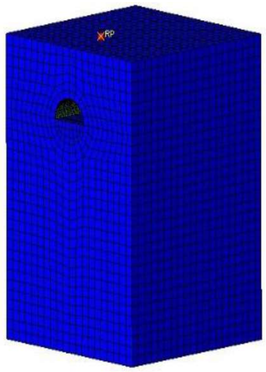

Fig. 5. Mesh Model of Coal Mine With Impactor

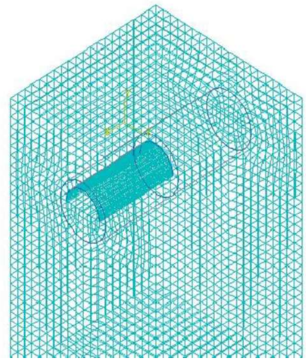

Fig. 6. Wireframe Model of Coal Mine With Shotcrete Lining

Holmquist Johnson-Cook Model holds a better reputation in solving the problems pertinent to fracture and damage mechanics. Some of the enlisted properties of HJC that makes it user friendly are as no subroutine and programming based are required to obtain the results, HJC model is incorporated as an inbuilt model of analysis in commercially available software packages and it provides reliability at par with user-defined models.

3 Results and Discussions

Numerical Model of Impact Damage on coal mine In impact testing on underground coal mines revealed the generation and propagation of shockwaves under the impact. loading. The resulted shockwaves possess a potential to deform, cause a cracking or complete collapse in coal mines based on the magnitude of impact load. The numerical simulation of the shockwave propagation on the mine can be observed in Figure 7. the resulted shockwaves are assumed to be caused by a mass of 104 kg dropped from a height of 3 meters and causing an impact force of 63kN of impact force. Furthermore, it can be observed from Figure 8 that the maximum damaged pronounced in the model takes place at the point of impact. it clearly shows the destruction process of the coal seam in the test. The spreading stress wave contacted the coal seam and triggered its failure. When t = 0.731 s, the coal seam was cracked by the action of the compressive stress wave, which continued to propagate deep into the coal seam. At t = .78 s, the crack progressively stretched and the coal seam was serrated. When t =.795 s. A large cavity was formed deep in the coal seam as the gap was increased. As can be seen, first the coal seam was cracked and destroyed by the propagation of the stress wave. In the impact damage model developed for the mine, the length and height of the roof and coal layers were considered to be 15 and 2 m, respectively. Figure 9. represents a damaged part of the coal mine model.at face. As it can be inferred there has been an extension in elements of coal which physically is not possible in case of coal and can be treated as detachment of coal block from the seam. The destructed coal mine model involved numerous failure patterns including tensile failure caused by compression expansion, and crack expansion phenomenon.

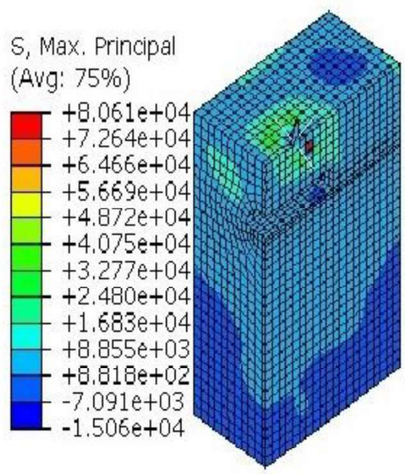

Fig. 7. Shockwave Propagation in Underground Mine Model.

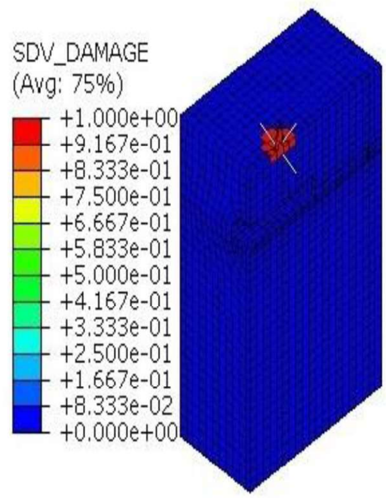

Fig. 8. Damaged Model During Impact Testing

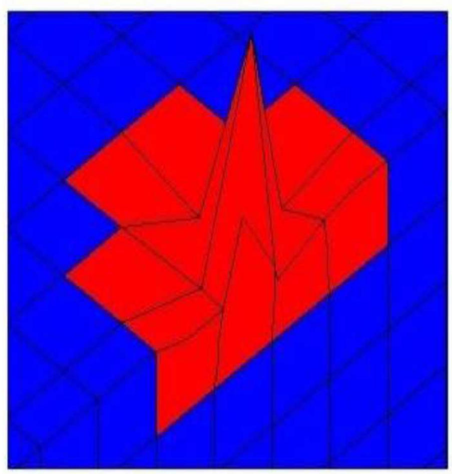

Fig. 9. Damaged Part at The Point of Impact

4 Conclusions

Numerical Analysis can play an important role in predicting the failure in coal mines susceptible to various impact loads that otherwise involves cumbersome experimental investigation and often leads to huge loss of life and assets.
1). The failure of coal mines started with the creation of axial cracks in the middle of the coal body starting from the point of impact. The destructed coal mine model involved numerous failure patterns including tensile failure caused by compression expansion, and crack expansion phenomenon.
2). The severity of coal body damage with an increase in impact velocity. At lower drop height of impact, the coal block was intact although producing local damage in a model of the coal mine.
3). The validated parameter values of the Holmquist Johnson-Cook constitutive model were incorporated in the study of impact damage model of the coal mine that visually depicted the extension and progression of damage in the coal mine. It was further concluded that the HJC Model works better for coal mines under impact loads.

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