Strata control problems of underground coal mining vis-a-vis geotechnical instrumentation and numerical model studies

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Abstract

This paper presents overview of problems of underground coal mining in India and the need of strata control investigations for improved safety, conservation and economy of the coal mining operations. Instrumentation required for better understanding of strata behaviour around underground opening is presented besides approaches for design of strata control techniques. In view of the significant level of accidents due to roof and side falls in Indian coal mines, emphasis is made on the recent trends in geotechnical investigations, application of numerical models with a case study for better understanding of strata behaviour in coal mines. The numerical model results on stress concentration over pillar, stook and the rib showed variation of 3.6%, 8.33% and 6.12%, respectively as compared to the field observations for 7 m thick coal seam. Purpose of geotechnical instrumentation for strata behaviour monitoring in coal mines and mining options in Indian coalfields is also discussed with reference to strata control problems.

1. Introduction:

The progress of the technology in many branches of engineering is quite rapid in recent years. However, in case of underground coal mining, the progress is not as expected. It remained a lot with traditional systems, and only a few attempts were made to adopt/absorb recent trends. Although it could be attributed partly to availability and adoptability of the modern mining machinery, but also mainly due to limitations of available strata control technology, be in underground (suitable designs of workings and support systems) or opencast mines (suitable design of pit slopes, stabilization of high walls/spoil dumps, etc.).

Prospects of coal mining depends upon the quantity and quality wise demand, heat energy, ash content, caking index, economics of mining, market pricing structure for the available produce and scope of value addition by way of washing or processing of ROM (Singh, 2007).The factors are influenced by geographical distribution with quality wise abundance, depth wise availability, geomorphology of coal complexity of the deposits and amenability to economic mining options. More than 98% of our coal resources occur in 7 eastern states, with Jharkhand accounting for 29.1%, Orissa 24.3 %, Chhattisgarh 17.1%, and West Bengal 11.1 %. Madhya Pradesh 7.8%, Andhra Pradesh 6.9% and Maharashtra 3.6%. Depth wise coal resource estimate as on 1st January, 2007 is presented in Table 1 (GSI, 2007).

The distribution of the coal resources is geographically imbalanced with just 2% of the global resource available in 8 eastern and central states of the country. A large part of the country has to transport coal from these remote areas or import from the favorable world market. The Australian and Chinese coal market is bubbling with activities and prepared to feed Indian market.

In olden days, due to lack of proper instruments, qualitative observations with limited possibility of quantification lead to some empirical relations/thumb rules. However, now-a-days, with improved technology of mining/instrumentation, numerical models - computer applications for analysis of data; investigators gained enhanced satisfaction through observational approaches. Acceptability of such studies by the field personnel may be improved by proper interpretation of the data so generated by experts in the strata monitoring. There is a need to be more innovative in application of the existing instrumentation with proper planning by experienced strata control engineers, which may lead to possibility of modification in existing practices for better safety and economy of mining venture.

In every coal mining company, Strata Control Cell shall be established at corporate and area levels within one year as per recommendations of the 10th National Conference of Safety in Mines held at New Delhi 26-27th Nov, 2007. However, till now strata control cell not establish in all the coal mining areas as required. This may be attributed partially due to lack of proper responsiveness among the officials of some coal mining Industries. Strata control cell in coal mines can assist mine managers, for formulation of Systematic Support Rules, monitoring strata control measures in a scientific way to ensure efficacy of support system and, for procurement/supply of quality supporting materials. This issue can be addressed by proper monitoring of strata and taking adequate control measures in time. Geotechnical instrumentation although has been extensively used in the coal mines, still there is no standard procedures for undertaking the investigation as well as type of instrumentation for monitoring of the strata behaviour. Keeping this in view, two short term courses were held at NIT-Rourkela on “Trends in strata control techniques and instrumentation for enhancing safety in coal mines” during July 28-31, 2008 and Nov 19-22, 2009. The Mining Engineering department of NIT-Rourkela also conducted Workshop/ Training programs in coalfield areas of M/s SCCL, SECL, WCL, MCL, etc. under the TEQIP sponsored by the World Bank through National Project Implementation Unit during October-December’08. Strata control technologies have undergone considerable change and it is pertinent that the field engineers must be trained in the state-of-the-art instrumentation for effective implementation of the strata control measures in coal mines.

2. Underground Coal Mining:

Nearly 61% of the total reserves of coal are estimated within 300m depth cover, distributed in all coalfields from Godavari Valley to Upper Assam. The prime quality coking coal of Jharia is available mainly in upper coal horizons while the superior quality non-coking coal of Raniganj is available in lower coal horizons. The quality coal of central India to Maharashtra is also available mainly in seams within this depth range. As a result all the mines worked such seams extensively, primarily developing on pillars and depillaring with sand stowing. With the unfavorable economics of sand stowing and non availability of virgin patches for further development, most of the mines have been working- splitting or slicing the pillars, winning roof or floor coals manually or with SDL, conveyor combination.

Table1
Depth wise coal resource estimate in various states of India
as on 1st January, 2007

State	Resource estimate as on 1.1.07 under depth			Total Reserve (Mt)
	0-300m	300-600m	600-1200m	
A P	7922	6514	3024	17461
Chhattisgarh	32167	8614	669	41450
Jharkhand	36998	14601	3285	54884**
**Jharia	-------14213---------------		5217	19430
Maharashtra	6789	2698	183	9670
M.P	12902	6727	148	19777
Orissa	44636	16139	1224	61999
W Bengal	12361	10975	4999	28335
Grand Total	155785	80636	18749	255170
% share	61.24	31.66	7.35	100

The resource position of coal shows nearly 37% within 300-700m depth cover and a small portion (7 %) below 600m depth cover. Quality coal below 300m depth cover in Raniganj, Jharia, East and West Bokaro, North and South Karanpura, Sohagpur, etc should be the main targets for underground mining. The coals of Godavari and Wardha Valleys may also be included in this category because of preferential pricing structure. The options world over for such deposits are pillar mining- pillar mining using continuous miner, longwall mining and sublevel or integral caving with special support system in case of complex thick seams.

Best performance of pillar mining is reported from that of Churcha mine, the only unit to cross 1 Mt annual production in the country. Flat 3m thick seam was worked with shuttle car and scraper loaders imported in 1960, used without design modification and even spare back up support. The valuable experience was not repeated in any other mine even though the identical equipments were introduced in a few other mines.

The next generation pillar mining equipment – continuous miner loader and bolting assembly has entered in the mines after nearly 4 decades with very encouraging performance at Chirimiri and Tandsi mines. The system has given 12-15t productivity and average production of 40000 t per month. Identical mines under suitable geo-mining condition should be identified and detailed geological exploration should be done for the deployment of such machines. From coal reserve and quality analysis and seam thickness and gradient, such sites appear to be in Rangundam, Sohagpur, E and W Bokaro, N and S Karanpura, Jharia and Raniganj coalfields where a large share of quality coal seams are still virgin. Isolated patches with quality coal seams in near flat seams beyond limiting stripping ratio in, Madhya Pradesh and Chhattisgarh may also be explored for the introduction of continuous miners.

Longwall technology should be adopted with due consideration of coal seam parameters, panel geometry and coal quality in seams below 300m depth cover in Jharia, Raniganj, Godavari Valley, Sohagpur, E Bokaro and S Karanpura where bulk of coking and superior grade non coking coals within 300-600m and below 600m depth are estimated. The faces should be equipped with high capacity support with rapid yielding valves to sustain ground movement shocks frequently felt due to massive roof. High supports suitable for 3-5m seam thickness should be used in areas where 12–15 km long panels could be formed, each of 2 to 3 km length and face length of 250 to 300 m. Gate road drivage technology using continuous miner, bolter and loader assembly should be perfected to maintain advance preparation of the panels so that the faces could get unhindered operation for its life.

Mining of complex deposits often worked with sand stowing has failed to meet the production target, productivity and economics. The method of slicing with mass caving in vertical section like horizontal slicing inclined slicing or sublevel and integral caving, used successfully in complex deposits of Yugoslavia, Romania, Soviet Union, Poland or France, may have to be perfected for underground mining of thick seams. Power support for working over sand stowed floor while mining thick seams in slices is available in the world market, particularly in Hungary may prove to be suitable for working of thick seams under riverbeds in different coalfields. Methane drainage from the seams under mining should be done to ensure better working environment, safety of the workers and the workings. The operating mines, with small patches declared to be virgin till date should not be selected for the deployment of longwall mining or continuous miners as invariably they lack vertical and horizontal transport facility and adequate number of panels for life time of equipment.

Geological exploration to locate suitable panels for each set of equipment with seam thickness variation within the permissible limit, coal of quality and roof rock formation should be done in depth before introducing any such cost intensive technology with continuous miners in 300-400m depth cover and longwall technology below 400m depth cover. Necessary steps to ensure their success is summarized as follows

- Shaft sinking technology should be perfected to develop access to deeper seams
- Back up facility – vertical and horizontal transport, processing and dispatch system should be compatible to the mass production technology.
- Equipment supply and spare availability should be ensured for efficient full life performance
- Man power preparation including training and on face operational skill should be developed on priority
- Work culture should be improved in respect of devotion, commitment and adaptation of modern technology with efficiency
- Program should have support of the nation for continuity and financial back up
- So far as possible, the equipment should be imported lock stock and barrel to start with, followed by manufacture within the country.

The nation has to gear up for large underground production within next three to four decades; for 300 to 400 Mt annual production. The involvement of industrial houses and those of leading global players should be encouraged for state-of-the-art resource input and managerial support.

3. Strata Control:

With the advent of modern coal mining techniques, it has become imperative to adopt roof bolting as a primary means of support in place of the traditional supports. About 2500 million tons of coal has been locked in pillars of which only about 1000 million tons is amenable to opencast mining, about 1500 million tons is to be extracted by underground mining. Strata control management is one of the major reasons for losing of pillars. Although technology has improved now-a-days with the introduction of Blasting Gallery method, Integrated Caving method and Hydraulic Mining, some of them are unsuccessful with the loss of trials at Churcha, Kottadih, etc., and many more due to lack of suitable strata control techniques. Salient features that lead to typical problems in underground coal mining include;

- ❖ Steeply dipping, faulted, folded, highly gassy beds under aquifers and protected land have remained virgin.
- ❖ Developed pillars under fires, surface features sterilized because of acute shortage of sand.
- ❖ Development has been in multi sections.
- ❖ Highly stressed zones have been created due to barriers/stooks causing difficulty of undermining of the seams.

Hazardous roof conditions identified in some mines of other countries were positively correlated with mining activities beneath stream valleys (Mucho and Mark, 1994). Evidence of valley stress relief was found beneath several valleys in the form of bedding plane faults and low-angle thrust faults. At many places the ratio of horizontal to vertical stress was in the range of 2 to 3. This type of failure, previously believed to be only a shallow phenomenon, was also found at increased mining depths.

Horizontal stresses affect a number of United States coal mines (Mucho, et al., 1995). To address the effects of the stress field and to control its potentially damaging effects, a number of control strategies have been developed, such as reorientation of the retreat direction, stress shadowing of the key openings, and altering the mining cut sequence. However, many of these techniques are direction dependent, and to be effective, they require precise determination of the major (maximum) principal horizontal stress direction. For these types of typical geo-mining condition associated with high horizontal stress, a system of **roof truss** was used successfully. Cable bolts were effectively utilized for strata control in thick seams and adverse roof conditions in Indian coal mines (Jayanthu and Gupta, 2001). Roof slotting is one tactic to stress shadow the adjacent workings (Frank et al., 1999).

The studies by the National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration (MSHA) at Sargent Hollow Mine, in Wise County, VA, indicated that the weak floor strata was being subjected to, and damaged by, high horizontal stresses. After the 'advance and relieve mining method' was implemented, the overall mining conditions at the mine improved, and the roof control plan was approved for further use. Various approaches such as empirical, observational, analytical required for design of strata control system is presented in Figure1.

Roof falls have been usually attributed to bad roof strata and high vertical stresses related to the overburden depth. However, for shallow depth conditions, roof falls in recent studies have been attributed to high horizontal stresses (Yajie and John, 1998). About 73 roof falls analysed in USA, 37 occurred in the entries with 52^o angle with the major horizontal stress. Unfortunately majority of the locked up pillars in thick seams have strata control problems possibly due to high horizontal stresses, and need careful review of history of falls. Through the horizontal stress recognition features, some of the following control techniques can be effectively implemented;

- reorienting the drivage direction of the mine openings
- panel orientation and retreat direction
- stress shadowing through key openings
- altering mining cut sequences

In absence of the in-situ stress measurements in majority of coal fields, the following symptoms of a horizontal stress concentration exceeding strength of the surrounding rock were identified in different case studies.

- ➢ The roof problems occur under lighter than average depth cover, so vertical stress is evidently not a factor.
- ➢ The roof in the other gate of a longwall face may be in excellent shape, implying it is stress relieved.
- ➢ There may be a stress valley above the problem area.
- ➢ The problems show a recurring pattern with each crosscut becoming unstable when the face approaches an intersection.
- ➢ The roof is week, particularly laminated shale.
- ➢ The panel may be the first in a set or lengthening of a panel has created a "stress shadow".

In the light of experience of past few years, the norm for designing of Systematic Support Rules in development roadways needs reexamination and modification. Life of the roadway should also be considered while designing the system. The galleries of a Bord and Pillar system may be self-supporting under a very strong roof or the immediate roof may be supported by props, roof bolts or roof stitching depending on the local conditions (Mathur, 1999). The weight of the main strata is borne by coal pillars. During pillar extraction, props, cogs, roof bolts have been conventionally used in splits, slices etc., with skin-to-skin chocks near goaf edges (Mobile Roof Supports in USA).Performance of the support systems have been extensively studied worldwide for understanding the strata mechanics. Higher bond strengths and anchorage capacities with reduced annulus were indicated (Tadolini, 1998). Developments in support systems are related to material for bolts (cuttable bolts, tendon, resin, acconex, etc., for grouting, swellex, truss bolts), mobility of supports (mobile roof support), capacity of supports (high capacity shields, props) (Gupta and Prajapati, 1997; Khan and Hassani, 1993).

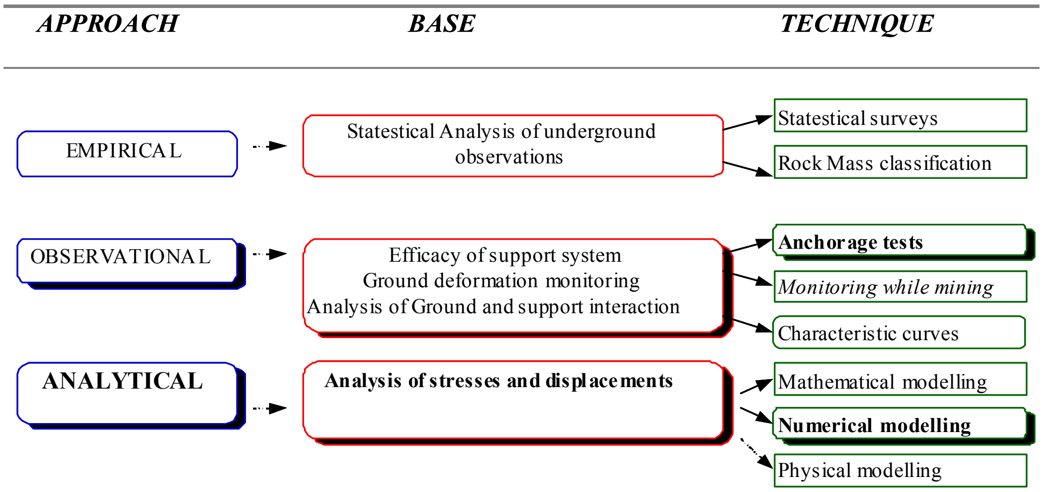


Figure1 Various approaches for development of strata control techniques

Mobile supports have been successfully deployed for depillaring (Larry, 1998). Support capacities up to 800 tons are available and need introduction in Indian coalfields. It provides an upward active force on the immediate roof strata and results in normal cave line pushed back into goaf. This allows a wide stook to be mined while depillaring, thereby costly and relatively unproductive cycle of splitting of pillars and associated support can be minimised. In near future, the concept of man-less mining needs to be adapted to the maximum possible extent for improved safety, production, and productivity.

Continuous monitoring of strata behaviour in terms of convergence of openings in advance on either side of the extraction line, and stress levels over pillars, stooks in advance of the extraction and ribs in the goaf was required through remote monitoring instruments for understanding the strata mechanics at critical conditions of roof falls. Continuous monitoring of support pressures was attempted to investigate the rock mass response to mechanised pillar extraction (Follington and Huchinson, 1993). Integrated Seismic System (ISS) was introduced for an experimental trial at Rajendra mine, SECL, for prediction of strata movement during coal extraction by longwall mining. The system developed by South Africa works on the principle of monitoring micro seismic activities through geophones. The concept of remote-monitoring or online monitoring is yet to be established to improve the safety aspects in underground coal mining. The use of Borehole TV Camera for cavability studies is the need of the hour for detailed analysis of strata behaviour during mining.

4. Purpose of Geotechnical Instrumentation:

Geotechnical instrumentation, although, has been extensively used in the coal mines, still there are no standard procedures for undertaking the investigations as well as type of instrumentation for monitoring the strata behavior. Over the years, geotechnical instrumentation and strata control technologies have undergone considerable change and it is pertinent that the field engineers must be trained in the state-of-the-art instrumentation for effective implementation of the strata control measures in coal mines. Purpose of the instrumentation should be clear for the planners before commissioning any instruments for understanding strata behaviour. Inadequate number or improper selection of instruments may lead to unsafe decisions by mine planners, while more than required number/type of instruments, not only lead to confusion but are also uneconomical. Therefore, experienced strata control engineers with proper understanding of the field problem, and sufficient knowledge on interpretation of the data so generated are primary requirements for a successful instrumentation program. Some of the common requirements for use of the strata monitoring instruments in underground coal mines are as follows:

4.1 Comparison of effectiveness of different strata control practices:

Qualitative as well as quantitative nature of strata behaviour was monitored in the development galleries. Details of the strata monitoring instruments, namely, convergence stations, extensometers and Tensmeg strain gauged cables along with other type of strata monitoring instrumentation are presented elsewhere (Jayanthu et al., 1998, CMRI, 1997, NIRM, 1997, 1998, 1999). These monitoring stations installed at about 10 m interval along the galleries and in junctions of the development workings with different type of supports could be used successfully for understanding the effectiveness of the support system with cable bolts and roof bolts.

4.2 Prediction/warning of roof falls:

Prediction of strata behaviour by theoretical analysis becomes unreliable due to almost impossibility of simulation of the real field conditions in mathematical, physical or numerical models. Thus, empirical formulation, based on in-situ measurements of strata behaviour parameters, is an accepted way to estimate the strata behaviour.

Critical conditions of strata behaviour invariably occurred in Indian geo-mining conditions after extraction of two rows of pillars with 50–60 m span, and at an area of extraction of 4,000-6,000 m^2 including the ribs in the goaf. Therefore, strata pressure and its manifestation in terms of convergence need intensive monitoring at these conditions. Attempts made for warning of such condition include measurement of convergence of galleries around the extraction line on daily basis, but indices formulated in terms of rate of convergence per day appeared to be useful for 60% of the cases.

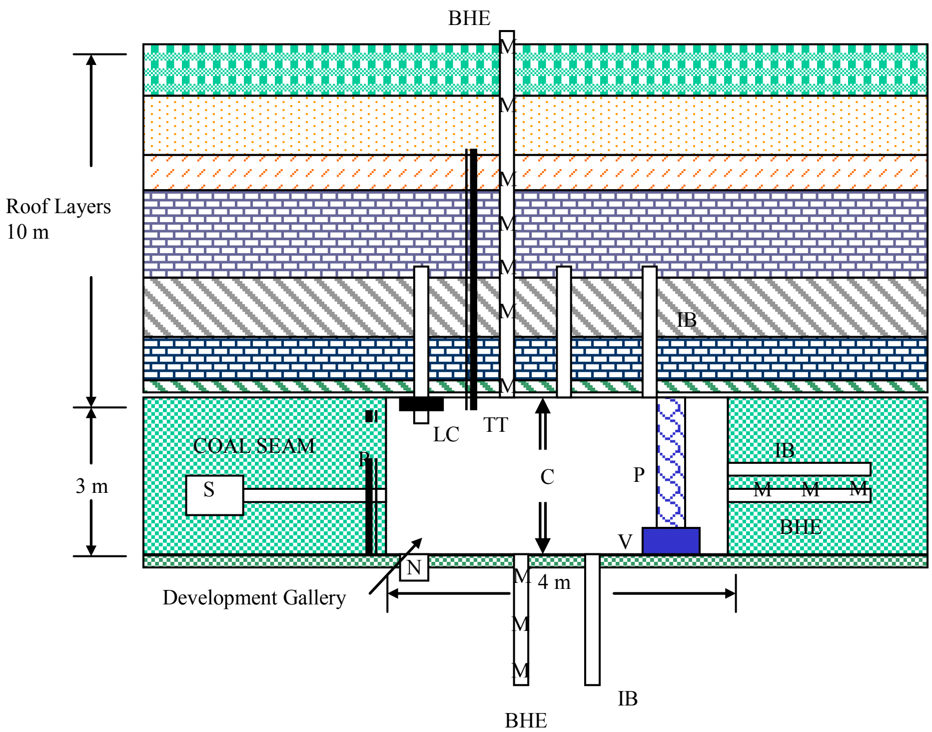
Continuous monitoring of strata behaviour in terms of convergence of openings in advance on either side of the extraction line, and stress levels over pillars, stooks in advance of the extraction and ribs in the goaf was required through remote monitoring instruments for understanding the strata mechanics at critical conditions of roof falls. Continuous monitoring of support pressures was attempted to investigate the rock mass response to mechanised pillar extraction by many investigators (Follington and Huchinson, 1993). Convergence of advance workings in depillaring panels has been widely believed to be a reliable indicator for warning of goaf falls. However, misconception on the limitations of the warning limits, interpretation of the convergence data caused confusion in taking the decisions on safety of the workings and the face workers in many situations of depillaring. Thus, the design and successful implementation of the warning system as part of the mine production cycle pose a stern challenge to mine managements. It is a challenge that will require adoption of a multi-disciplinary approach.

Many accidents in depillaring panels in recent times are self revealing and emphasize the need of proper education to the concerned on the limitations and applicability of the existing guidelines and further studies required for the purpose. Many a times, the rate of convergence in advance galleries/workings exceeding 2 mm/ day has been adopted for prediction (probable warning) of goaf falls in depillaring panels in Indian coal mines (Anon, 2001). The term, "prediction" may not suite well to the situations with uncertainty of input data such as; geo-mechanical properties, variation of different parameters from site to site, etc. (Peng et al., 1998). Therefore, use of only the term "probable warning" of goaf falls is emphasized in this paper. Prediction (probable warning) of goaf falls based on convergence data was discussed by many investigators (CMRI, 1987; Maity et al., 1994; NIRM 1997). However, its applicability in varying geo-mining conditions was not widely evaluated. As a result, applicability of such guidelines to the situations of some of the accidents, resulted in conclusion of the strata mechanics analysis as "a gods act", in view of the "art" of mining still taking over the available "Science" of mining. In all, strata movement has been accounted for about 30% of the total underground accidents due to fall of roof (Jayanthu et al., 1998). Nearly 50% of the accidents are in depillaring areas, and about 15% are due to abutment pressure. On the whole, $1/6^{th}$ of the accidents are attributable to lack of prior knowledge of unsafe conditions and unavoidable. This indicates the need for detailed technical examination of methods of extraction, formulation of reliable guidelines for warning of roof falls, and strategies to be adopted for improved safety, productivity and conservation.

4.3 Generation of data base/ formulation of guidelines/ evaluation of applicability of existing guidelines:

Technically, observational approaches for strata control have been widely thought over but limited attempts were made due to need of additional instruments for the purpose of monitoring of the roof behaviour. Various instruments visually showing bed separation, etc., are used in UK, USA etc., to evaluate the effectiveness of the support/ stability of roof. Modifications in the support systems were made based on the data from these instruments. A typical instrumentation at par with the international standards has been suggested for recent trials at some of the Indian mines, where the pillaring is critical due to difficult strata conditions (Figure 2).

Probable issues inhibiting formulation of reliable guidelines may be due to widely varying site conditions from one panel to another, limitations of the existing instrumentation, practical problems of commissioning and maintaining the instruments, collection of the monitoring data, lack of proper experience/ exposure of the investigators/ frontline supervisors to understand and infer the data, which may misguide the miners and probably create confusion on taking proper decisions based on such guidelines. Consequently, a permanent loss of the property or life is imminent in view of improper understanding of the limitations of the instruments, reliability of the data and the probably misleading inferences. Keeping these issues in view, an attempt is made to study the applicability of the existing guidelines for warning of roof falls based on convergence data with respect to the experimental studies in a bord and pillar panel at New Chirimiri Ponri Hill (NCPH) mine, Chirimiri area of South Eastern Coalfields Limited (SECL) (Jayanthu, 1999). Based on the available convergence data of four experimental panels, attempt was made in the beginning to derive warning limits based on application of the existing guidelines for warning of major roof falls.



Index:

IB Instrumented bolt
BHE Bore Hole extensometer
M Magnetic ring anchor
C Convergence indicator
N Notch along the floor for remote wire through conduit pipe
S Stress capsule
LC Anchor load cell
P Prop support
V Mechanical/Vibrating wire type load cells
R Remote convergence indicator in a grove at the proposed rib position
TT Tell Tale instrument

Figure 2 Typical instrumentation for strata monitoring around underground workings.

About 250 records of convergence were available for different monitoring stations before local/ major falls in the four depillaring panels. The distance between the monitoring station and the goaf edge was in the range of 5 to 50 m, and about 30 records were also available for the convergence inside the goaf. Maximum convergence recorded in panel

#15, #16 , #17 and #18 in advance workings/split/galleries was 26 mm, 20 mm, 28 mm, and 37 mm respectively (Jayanthu et al., 2004). Statistical analysis was conducted on the data eliminating the readings of some of the disturbed stations. Maximum rate of convergence before the major roof fall increased up to 4 mm/day within 10 m from the line of extraction, while it was within 1 mm/day beyond 50 m in advance of the line of extraction. It also indicated poor probability of warning of roof falls on the basis of cumulative convergence or the rate of convergence on daily basis. However, based on this data, it can be said in general terms that cumulative convergence exceeding 20 mm has a probability of 80% for warning of fall, while the rate of convergence exceeding 1.5 mm/day has 60% probability of warning the major roof fall in case of the instruments located within 60 m in advance of line of extraction. The present practices and purpose of some of the strata/ support monitoring instrumentation is as follows.

Extensometric Monitoring: Multi-point magnetic-ring extensometers will be used to monitor the bed separation up to 8-10 m in the roof at a few selected locations. A few Tell Tale instruments will also be installed for estimation of bed separation in the roof. Extensometers may also be installed in the floor, to determine the extent of floor heave. Similarly, the sides also will be monitored to assess the movements within the pillars. Based on the data recorded, the horizon of the weak planes along which bed separation or fracture is taking place, will be identified.

Strain in the Bolts: Instrumented bolts will be installed in the roof. These instruments will provide information about the strain or load developed along the length of the grouted bolt at different portions. These instruments will also be used in the sides of the pillars/ floor to estimate the thrust.

Load on Bolts: Anchor load cells will be installed along with the freshly installed bolts. These load cells will indicate the total load exerted by the strata along the bolt length.

Stress Changes: The change in stress with the extraction process will be monitored using stress gauges installed in the pillars. They will be installed at suitable depths inside the pillars, and they will be monitored as the drivage progress.

Roof-to-Floor Convergence: Convergence points would be installed at suitable locations for recording roof to floor movements at different stages of depillaring. The telescopic rod convergence meter measures the distance between two pegs, one in the roof and the other on the floor vertically below it. Remote convergence stations function on the principle of change of resistance due to convergence.

5. Mining Options:

In the light of limited coal reserves in Indian territory, limited quality coal reserves, quality coal reserves within 300m depth cover extensively disturbed by pillar mining and poor recovery with pillar mining, it is recommended to go for extensive surface mining in all the major coal basins up to the stripping ratio of 1:10. Similarly in case of newly explored power grade coal bearing basins - Singrauli, Rajmahal, Korba, Mand Raigarh, Talcher, etc. it is recommended to go far surface mining up to 1:8 stripping ratio. The coal seams below in selected basins of quality coals – Sohagpur, E & W Bokaro, N & S Karanpura, Jharia, Raniganj, Wardha and Godavari valleys are recommended to go for underground–longwall, pillar mining with continuous miner and mining with vertical production concentration technology in case of thick coalescing seams.

No pillar mining is techno-economically viable below 400m depth cover and therefore in deeper coal basins, longwall is the only technology but with state-of-the-art equipment and annual production guarantee above 2Mt. In view of more than half the share of total coal in seams over 5m thickness, longwall slicing in one or other form is suggested.

The future of the mining industry demands more emphasis on meticulous application of rock engineering techniques, support design, modification to the existing guidelines through observational approaches, for cost effective and safe mining operations. Many research and academic institutions initiated many studies to help coal industry for better, efficient and safe extraction of coal through i) analytical analysis and mathematical models, ii) empirical analysis and models, and iii) numerical modeling with computerization. Some of the rock mechanics analyses were aimed at i) support design in complex mining conditions, ii) partial extraction under water bodies/ townships through wide stall methods, and iii) mechanized depillaring with cable bolting as major support. The methods were site specific and were designed for intermediate level of mechanization and techno-economically viable in terms of production and productivity. Still there is a scope for rock mechanics application in the following areas.

- Development of scientific methods for maximum recovery under surface structures
- Exploitation of thick and multiple seams for shallow depth covers
- Utilization of crushed overburden material for stowing
- Support designs for deep mining of thick seams

Surface mining up to 1:10 stripping ratio in case of quality coal seams and at least 1:8 in case of power grade coal should be accepted before some of the coal fields are subjected to slaughter mining vis-à-vis selective mining of upper seams of quality coal with dumping of burden over the lower seams. This will block the future of surface mining in coalfields of Damodar Valley, MP and Chhattisgarh. Concurrent reclamation and rehabilitation of the mining area to the level better than the pre mining status should be done and the lease are returned to the oustees for agriculture, forestry or other gainful usage.

6. Application of Numerical Model - A Case Study:

Extensive application of numerical models was demonstrated by Jayanthu (1999) for understanding the stability of workings for extraction of pillars in thick coal seams. Depillaring process in the field experiments include different stages of division of pillars into stooks and extraction of stooks up to full seam thickness leaving some ribs in the goaf. For two dimensional representation of full seam extraction in a 7 m thick seam, vertical section with four galleries in an idealized panel was selected. A few parameters were kept constant for the models, e. g. width of pillar, development gallery, split gallery and rib as 20 m, 4.8 m, 5 m and 2.5 m, respectively. Pillar size was kept constant at 24.8 m center to center in accordance with the average size in the field experimental trials. In the first stage of extraction, splits of 5 m width are provided. Second, third and fourth stages of extraction include high openings up to full seam thickness in the goaf. In the fifth stage of extraction, other rib was removed to represent the increased span with only one rib in the goaf. Stress distribution in these conditions was studied in numerical models.

Finite difference code - FLAC (Fast Lagrangian Analysis of Continua) was used for understanding the influence of depth and thickness of coal seams on stress distribution over pillars, stooks, and ribs at different stages of depillaring through parametric studies. About 90 numerical models with different configuration of openings representing the range of parameters in the field experimental trials are used. Variables of the parametric studies for stress analysis are; seam thickness in the range of 3 to 11 m at an interval of 2 m, and depth cover of 60 m, 120 m, and 240 m. The following sequence of pillar extraction was simulated for all the above parameters.

- Development of pillars
- Splitting of two rows of pillars
- Extraction of a row of pillars with a single rib inside the goaf
- Extraction of two rows of pillars with two ribs inside the goaf
- Extraction of two and half rows of pillars with a single rib inside the goaf
- Extraction of two and half rows of pillars with two ribs inside the goaf

The coal elements in the panel are small, 0.5 m in the ribs and 1 m in the pillar. Each represents 2 m^2 area of the seam as maximum size. To reduce solution time, the dimensions of the mesh elements increase geometrically from the center of the model to its outer edges. The model has plate elements with nodes. The problem domain consists of appropriate boundary conditions and grid pattern for 60 m depth cover with development into three pillars of 24.8 m center to center and 4.8 m wide galleries. These models simulate pillar extraction in plain strain conditions with Mohr Coulomb material. Young's modulus and Poisson's ratio of the coal elements was 2 GPa and 0.25, respectively, while the corresponding properties for the sandstone elements was 5 GPa and 0.3, respectively. Cohesion, Density, tensile strength and angle of internal friction for the coal are assumed as 2.5 MPa, 1.4 g/cm^3, 1.8 MPa and 30, respectively. The model has its outer boundary located 150 m away from the mine panel i.e., three times the width of the final excavation. The top is free to move in any direction, and the bottom edge of the model is restricted from moving vertically. Roller type boundary conditions for all the models are placed along two edges of the models. In the absence of the in situ stress measurements in the coal field, the following norms were adopted for estimation of in situ stress field prior to the excavation of the area.

Vertical stress = $\gamma.H$ (1)

Horizontal stress= $3.75 + 0.015H$ (2)

Where,

γ = specific weight of the overlying rock mass, and

H = Depth cover

The model has a graduated internal stress that simulates gravity loading. To generate pre-mining conditions prior to adding the mine openings to the input, the model goes through an initial analysis to generate in situ stresses. Gravitational and horizontal loading are imposed on the other two surfaces in order to account for in situ stresses. The displacements are then reset to zero and mine openings are added. The model is then reanalyzed to obtain the final stress distribution. Stress over rib, stook and pillar for different seam thickness and depth cover in a typical numerical model is presented in Table 2. This parametric analysis helped in better understanding and design of suitable strata control techniques besides safe workings in an innovative experimental trial of a thick seam mining in India.

Table 2
Maximum vertical stress over rib, stook and pillar for different seam thicknesses and depth cover in the numerical models

Particulars	Depth (m)	Stress (MPa) for different height (h_e) of the workings				
		$h_e = 3$ m	$h_e = 5$ m	$h_e = 7$ m	$h_e = 9$ m	$h_e = 11$ m
Pillar	60	2.22	2.39	2.41	2.37	2.37
	120	4.14	4.39	4.39	4.65	4.45
	240	8.26	8.52	8.76	8.71	8.77
Stook	60	5.42	4.92	4.94	5.06	5.24
	120	11.2	10.36	9.92	9.76	9.76
	240	22.3	18.31	16.55	16.4	16.5
Rib	60	10.94	9.17	7.85	7.01	6.28
	120	12.4	11.6	9.85	9.89	9.79
	240	21.6	11.26	9.98	9.2	9.11

More stress levels noticed in the numerical models as compared to the filed observation of variation of stress for the ribs could be due to partial crushing/yielding of pillars, stooks, and ribs in the field with reduced width of the structures in the middle section. Stress distribution through the models showed the trend of asymmetrical loading around the galleries with high stress concentration towards the goaf side and comparatively low stress levels on the other side. Thus the asymmetrical support system comprising of chocks on the goaf side and props on the other side of the galleries in almost all the depillaring panels in India are in accordance with the requirements as anticipated through the models (Jayanthu, 1999b).

7. Conclusions:

In today's Indian coal mining scenario, meticulous evaluation and suitable application of the above mining options may lead to productive and safe mining of coal deposits with due regard to eco-friendliness and conservation. The expertise developed in some of the trials especially in central India has been allowed to be frittered away instead of their consolidation and extension. Development of thick seams without ascertaining the method of final extraction shall be discouraged in the interest of conservation of coal. The numerical model results in a typical depillaring panel are comparable to the field observations (Jayanthu, 1999a). Comparatively low stress levels in the models as compared to the field observations may be attributed to idealization of depillaring to two dimensional domains. The numerical model results on stress concentration over pillar, stook and the rib showed variation of 3.6%, 8.33% and 6.12%, respectively as compared to the field observations for 7 m thick coal seam. India's future coal mining will depend on how efficiently and economically we can exploit deep coal deposits by underground mining practices with safety and accepted level of productivity. Further studies are required for introduction of some innovative strata monitoring techniques including extensive use of ISS, Borehole TV Camera, etc. through application of suitable rock engineering techniques.

In every coal mining company, STRATA CONTROL CELL shall be established at corporate and area levels within one year as per recommendations of the 10th National Conference of Safety in Mines held at New Delhi 26-27th Nov, 2007. However, till now strata control cell has not been establish in all the coal mining areas as required. This may be attributed partially due to lack of proper responsiveness among the officials of some coal mining Industries. Strata control cell in coal mines can assist mine managers, for formulation of Systematic Support Rules, monitoring strata control measures in a scientific way to ensure efficacy of support system and, for procurement/supply of quality supporting materials. This issue can be addressed by proper monitoring of strata and taking adequate control measures in time. Although geotechnical instrumentation has been extensively used in the coal mines, still there are no standard procedures for undertaking the investigation as well as type of instrumentation for monitoring of the strata behaviour.

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