Extraction of Coal from Deep-seated Coal Seams in India Problems and Issues

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Abstract

In the last few decades, coal mining industry has played a significant role to cater the growing demand of energy almost throughout the world. Coal is the prime source of energy in India. As per facts and figures of energy scenario in India; it will remain so in the foreseeable future and at least in the next two decades, coal is likely to overtake the leading role of oil and gas due to its proven geological reserve. However, coal mining in India is mostly limited to shallow depth of cover range and extraction methodology is either opencast or underground bord and pillar method. To meet the growing demand of coal, after exhaustion of the reserve at shallow depth of cover range, Indian coal mining industry is bound to extract the coal at deeper cover very soon. But, underground coal mining at deeper cover encounters difficult rock mass, complex stress conditions, difficult underground environment due to increase in gas content and rise in temperature. Once the mining activity moves from shallow to deeper cover zone, the excavation starts encountering stress control regime rather than structural control behavior of the rock mass. In addition to the strata control problems, a deep seated coal seam finds increased amount of gas in the seam along with heating and ventilation problems, which make the underground coal mining quite challenging. This paper briefly discusses some important problems and issues related with mining of deep-seated coal seams in India.

Introduction

Geologically proven coal reserve is one of the best natural resources to meet the energy security of the country not only in India but also most of the nations in the world (Table 1). As per the statistics of World Coal Association, Coal provides 27% of global primary energy needs and generates 41% of the world's electricity. Considering current world coal production levels (around 5990Mt of hard coal in 2009), proven world coal reserves are estimated to last 119 years whereas proven oil and gas reserves are equivalent to around 46 and 63 years respectively considering current production levels (Coal facts, 2009). All these facts and figures reveal the dependency on coal in near future. Worldwide coal production data reveals that in between the two coal mining methods, presently, underground mining accounts for a bigger share of coal production than opencast mining. But, coal production from the opencast mining is more in some important coal producing countries like Australia, India and USA. Opencast mining accounts for around 80% of production in Australia; while in the USA it is around 67% (World coal, 2010).

Table 1: List of some countries heavily dependent on coal for electricity (World coal, 2010)

South Africa	93%	Kazakhstan	70%	Morocco	55%
Poland	92%	India	69%	Greece	52%
PR China	79%	Israel	63%	USA	49%
Australia	77%	Czech Rep	60%	Germany	46%

In India, more than 80% production is coming from opencast mines. The choice of 'underground' or 'opencast' is mainly depend upon the depth of cover besides a number of other factors related to the geology of the coal deposit and availability of suitable equipment. Coal production in India is mainly coming from the coal seams lying under

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shallow depth of cover range either opencast mining or underground mining by bord and pillar method. In India, for underground mining, the process of pillar formation received favourable situation due to presence of the competent coal seam and surrounding rock mass. This strategy of coal production found suitable for the Indian coal mining industry because of low capital investment and involvement of trivial technical expertise. However, after exhaustion of the reserve at shallow depth of cover and also to meet the increasing demand of coal, Indian coal mining industry is going to extract the coal at deeper cover very soon obviously by underground mining method. Depth wise coal resources of India as per Geological Survey of India (GSI) as on April, 2010 are shown in Table 2. Generally, coal seams situated at greater depth have better quality. There is no doubt that the extraction of coal from deep-seated deposits has great social and economic significance for development of a country like India.

Table 2: Depth-wise Coal Resources of India as on April, 2010.

(in billion tons)

Type of Coal	Proved	Indicated	Inferred	Total	Share %
0-300	86.14	66.98	12.89	166.01	60%
300-600	8.27	50.59	17.40	76.26	28%
0-600 (for Jharia)	13.71	0.50	0.00	14.21	5%
Total 0-600	108.12	118.07	30.35	256.48	93%
600-1200	1.68	12.57	6.06	20.31	7%
Total 0-1200	109.80	130.65	36.36	276.81	100%
% Share	40 %	47 %	13 %	100 %	

Most of the developed countries have studied their rock mass well and developed approaches to counter the menace of deep coal mining. The opening up of the economic policy makes it easier to import and implement the approaches, especially, mechanisation and automation for deep coal mining in India. These open policies will, in fact, provide strength to our coal mining industry to meet energy security challenge and to counter the global productivity competition. However, it is not straight-forward to apply imported technology for our coal production due to uniqueness of Indian coalfields. Coal mass and the surrounding rock mass of Indian coalfields are different than those of the developed countries. On the basis of our long association with considerably large number of underground coal mining faces, it is realised (Sinha, 2008) that the experience of rock mass behaviour is an important input for a successful adoption of the modern approaches of coal mining in our coalfields.

Basics of the Depth Variation

Depth cover is of great interest for the design of underground structures as it influences stress regime and nature of the rock mass. The variation of in situ stress field with depth cover was well experienced by the mining engineers even before advent of the modern in situ stress concept. This is the reason of age-old concept of increase in pillar size with depth cover (Table 3), which is a well familiar example of practical understanding of the phenomena. The rock mass at shallow cover is, generally, highly fractured and carries low value of elastic modulus. Dependence of horizontal stress on elastic modulus of the rock keeps very shallow cover regime almost free from high stress problem, while the deeper cover rock often encounters problem related with high stress field. Pillar bumps, excessive roof falls, spalling/crushing of natural support and floor heaving (Mark et al., 2002) are the most likely problems of deeper cover mining.

Table 3: Pillar size variation as per Indian Coal Mines Regulations, 1957.

Depth cover, m	Pillar size (centre to centre) for different roadway widths (B), m			
	B=3.0	B=3.6	B=4.2	B=4.8
Below 60	12	15	18	19.5
60 to 90	13.5	16.5	19.5	21
90 to 150	16.5	19.5	22.5	24.5
150 to 240	22.5	25.5	30.5	34.5
240 to 360	28.5	34.5	39.5	45
Above 360	39.5	42	45	48

Although, it is very difficult to have a clear demarcation line for deep cover but Deshmukh (1987) defines it to be 200m. This demarcation line is based on experience of coal mining in India. During recent field studies by Central Institute of Mining and Fuel Research (CIMFR), it is observed that if the cover of a depillaring panel exceeds 200m, natural supports around the face, generally experiences side spalling. This practical experience of Indian depillaring panels also supports 200m as demarcation line for deeper mine. This works well for estimation of nature of mining induced stress development (Singh *et al.,* 2006). However, American experiences for the continuous miner faces are bit different and, as per Chase *et al.* (2002), if the overburden exceeds 750ft (228.6m) then the property is called to be located at deeper cover. To develop appropriate design guidelines for depillaring at deeper cover in USA (Chase *et al.,* 2002), geo-technical data from 97 panels of 29 mines in 7 states were collected. The analyses of these data indicated that squeezing of pillar were the most likely failure mode where the depth was less than 1,250 ft (381m), but bumps predominated in the deeper cover cases (Fig. 1). Here, failed panel design case histories attributed to roof falls for different depth cover, which were documented under, both, weak and competent immediate roof strata. On the basis of this experience, it was observed that it is not feasible to mine the coal by bord and pillar technique under weak roof conditions in a deep cover of high stress regime.

Formulation of design norms

In last fifty years, CIMFR conducted extensive investigations in field and laboratory to formulate different indigenous design norms. A number of such successful developments are being widely practiced by our coal mining industry. However, for the changed situation of deeper cover, necessary adoption in these norms is also in progress as per the observed nature of rock mass. For example, CIMFR developed a pillar strength formula (Sheorey et al., 1987) on the basis of correlation of different parameters during a long term study of failed and stable cases of our coalfields. However, this formula encountered some problems when compared with the actual field observations. To remove these anomalies, the in situ stress conditions of these sites were considered (Sheorey, 1992) through depth cover incorporation and the resulted pillar strength (S) formula is:

$S = 0.27 \times \sigma_c \times h^{-0.36} + (H/250 + 1)(W_e/h - 1)$ MPa .... (1)

Where σ_c = Uniaxial Compressive strengthh of coal in MPa,

h = Working height in m,

H = Depth of cover in m,

W_e = Effective pillar width = $4A / P_c$

A = Area of pillar = $L_1 \times L_2$ and

P_c = Perimeter of the pillar (corner to corner) = 2 x (L1 + L2)

L_1 = Length of the pillar (corner to corner) and

L_2 = Width of the pillar (corner to corner).

Most other pillar strength formulae failed to consider the observed change in compactness characteristic of rock/coal mass with depth cover, which is well considered and addressed in this formula to explain the actual condition of the site.

Problems of Deep Underground Mines

Underground mining of coal from deep-seated deposits needs suitable techniques, support systems, equipment and instruments to counter a number of safety challenges of the difficult geo-mining conditions arising due to high cover pressure. A comprehensive and advance rock mechanics investigation is needed to understand the behaviour of rock mass to identify the problems and its control in India. Besides strata control problems like rock bursts, bumps, pillar squeezing,

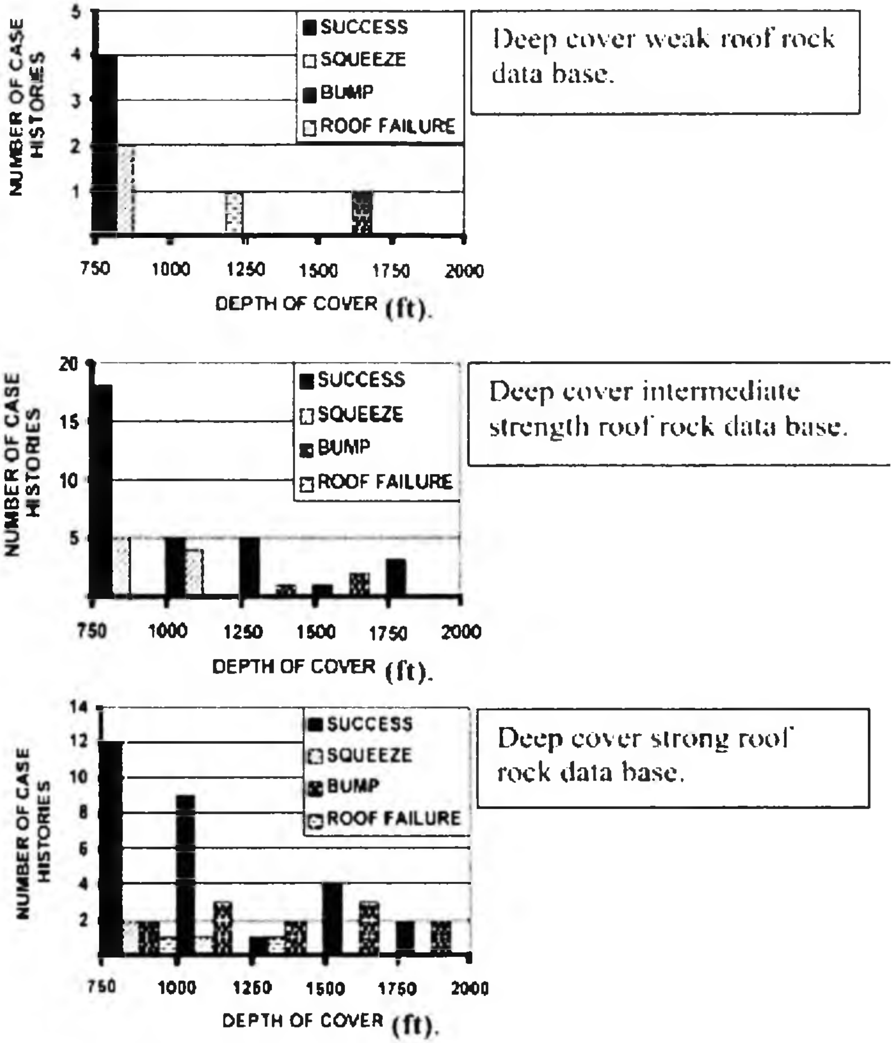

Fig. 1: Analysis of depillaring performance at deeper cover for different roof types (Chase et al., 2002).

collapse, etc., underground coal mining at deeper cover also involves a higher safety risk due to problems associated with mine ventilation, heat and gas.

In Situ Stress

The transition from structurally controlled excavation regime at shallow depth of cover to stress controlled regime at deeper cover involves information about *in situ* stress but measurement of in situ stress in coal measure formation is a difficult task and, therefore, only few measurements of this important parameter are available for this purpose. However, a theoretical model (Sheorey, 1994) of CIMFR received good acceptance for this purpose. Here it is assumed that the horizontal in situ stress is dependent upon the elastic modulus, Poisson's ratio and co-efficient of linear thermal expansion of the rock mass. Based on this concept, the equation for mean horizontal stress (σ_h) provided by the model is:

$$_{h} \quad \frac{\quad}{1} \; H \quad \frac{EG}{1}(H \quad 1000)MPa \text{ ....(2)}$$

where, ? is Poisson's ratio, ? generic unit weight, ? is co-efficient of linear thermal expansion, E is elastic modulus and G is geothermal gradient.

However, it is felt that for more realistic estimation and predictions of ground stability, in situ assessment of stress field is often essential. High value of stresses at deeper cover destabilises roof and pillars in and around an underground openings. Spalling of pillars and failure of roof strata (Fig. 2) are two commonly observed phenomena under high stress conditions of the underground. Here two types of stabilities are to be considered during pillar extraction, which are:

Global Stability: This stability considers prevention of section-wise pillar failure.

Local Stability: This stability considers prevention of roof falls in the working area.

The parameters involved with local stability are quite important for working at shallow cover and below weak and fragile strata. But, for workings at deeper cover and under massive roof strata of Indian coalfield, the global stability plays significant role, which depends on a number of factors and responsible for the strata control problems at deeper cover like pillar squeezing, massive collapse, rock burst, bumps, etc.

Rock Bursts and Bumps

Sudden outbursts of coal and rock occur due to high stresses in a coal pillar. Here, the coal/rock mass ruptures without warning and throws coal and rock flying with explosive force. A study in USA (Chase et al., 2002) shows that nearly 95% of the bumps occurred at depths greater than 1,000 ft (Fig. 1). Out of different rock mechanics problems of underground coal mining of deep-seated deposits, coal bump/rock burst is identified (CMRI, 1994) as a major hazard during underground coal mining at greater depth. Coal bump/rock burst engage violent and rapid failure of coal/rock in and around an underground excavation. Sudden release of accumulated elastic stain energy from a rock mass in the free face, created due to

Fig. 2: Roof instability during development of galleries at deeper cover.

excavation, is the origin of this phenomenon and is, mainly, related with the geo-mining conditions of the site, characteristics of the coal/rock mass and stress regime of the area.

It has been reported (Crouch and Fairhurst, 1974) that the following five factors (Sheorey and Singh, 1988) are important to cause bump/bursts.

1) Considerable large thickness of overburden, generally, more than 300m,
2) Structurally strong coal,
3) Massive, strong and stiff roof strata,
4) Competent floor not easily subjected to heaving and
5) The mining method causing development of high value of stresses.

Application of the conventional drilling-yield technique (Brauner, 1989) could give some idea about the burst/bump area but its control remained difficult. However, a modified version of this technique is working successfully for longwall faces of the Czech Republic. In Ostrava-Karvina Coalfield of the Czech Republic (Konicek et al., 2010), stress releasing is done by drilling parallel boreholes of around 20-30m length in the both gate roads of longwall, keeping the hole position in the middle horizon of the gallery and perpendicular to the gate roads from both sides at an interval of, generally, 5m. This approach is adopted for a coal seam of compressive strength of around 20MPa and the compressive strength of overlying sandstone strata of around 80-120MPa. The diameter of these boreholes are around 200mm and these boreholes are known as testing and destressing holes. To destress and fracture the massive roof, long boreholes of around 100m length are drilled from both sides of the gate roads at an angle of 30° (maximum) with horizontal. The diameter of the borehole is around 95mm. The 70% of each bore hole is charged with explosives and 30% is charged with stemming material like sand. Generally, 400 kg of explosives (rock blasting explosives) are charged in each borehole. Three to five boreholes are charged and blasted at a time without using delay. The purpose of this blasting to fracture the overlying rock mass is to avoid rock burst or violent failure of rock mass and to facilitate roof fall. Blasting is done 70-100m ahead of face. Generally, two gate roads are driven leaving 5m thick coal block (barrier) along both gate road-sides of a longwall panel. This 5m thick coal block, left between gate road and old workings, yields with overlying strata movement. This prevents violent failure of roof and avoids air blast.

CIMFR undertook an investigation related to this issue (CMRI, 1994) but this investigation remained limited, mainly, to identify different coal seams of the country likely to pose coal bump/rock burst problems and their causative factors. Some approaches to control the problems of coal bump/rock bursts were also investigated but their field application achieved partial success. However, this study could project characteristics of some the coal seams and found that the Dishergarh coal seam of Chinakuri Mine in Raniganj Coalfield is one of the most bump/burst susceptible seam in the country (Table 4).

Table 4: Characterisation of burst/bump proneness of Indian coal seams (CMRI, 1994).

Sl. No.	Seam/Mine	σ_c (MPa)	σ_t (MPa)	σ_c/σ_t	WET*
1.	Dishergarh/Chinakuri	35.8	1.51	23.7	4.02
2.	Hatnal/Seetalpur	39.2	1.73	22.7	3.46
3.	Koithee/Bhanora	32.8	1.43	22.9	3.17
4.	Savcotria/Parbelia	30.0	1.20	25.0	2.96
5.	XI seam/Jamadoba	20.1	1.02	19.7	1.90
6.	Poniati/Bhanora	35.6	1.07	33.3	1.44

*WET is strain energy storage index after (Kidybinski, 1981) and if WET is greater than 2, then the seam is considered bump-prone.

Study at Chinakuri Mine

Chinakuri Colliery 1 & 2 Pits of Eastern Coalfields Ltd. is situated in the heart of the Raniganj Coalfield on the bank of river Damodar near Asansol city of West Bengal. This is the deepest coal mine in the country, where underground mining is taking place at nearly 700 m depth of cover. Before nationalisation, this mine was owned by M/ S. Andrew Yule & Co. and has experienced mining of a number of coal seams by different techniques. However, mining of the Dishergarh coal seam at this mine by bord and pillar and longwall methods of this colliery has always been a problem, mainly due to occurrence of coal bumps.

Geology of the mine: Developed coal horizons in the leasehold area of this mine belong to Ranigunj Measure of Lower Gondwana Group. The exposure of the overlying barren Panchet Formation is met in the centre of the property. On the whole, coal measure formation in the leasehold area of the mine appeared to be inconsistent (Fig. 3). The take is crossed by two major faults, Deoli fault of 150m throw trending north to south and Patmohna fault trending north-south of 30m throw in the southern portion. There are a series of cross faults with minor displacement and are observed to be sympathetic to the boundary fault.

There are a number of coal seams in the area but the most valuable is the Dishergarh Seam (R-IV) developed to a thickness of 3.3 m in the southern portion and up to 4.5m in the northern part. This seam has extensively been developed and widely extracted in neighbouring mines due to its superior blendable quality. The upper most Bharatchak seam is extensively developed on bord and pillar up to 255m depth of cover and the working height is 2.5 to 2.6m. Dishergarh seam has been worked from 560 to 670m depth within Chinakuri Pit 1 & 2 by bord and pillar development/depillaring and by longwall in lifts.

Problems encountered: The Dishergarh seam at Chinakuri Colliery 1 & 2 Pits is seized with the following problems.

(i) Both longwall and bord & pillar workings have suffered from coal bumps,

(ii) The seam is gassy with rate of gas emission varying from 23 to 25m3/tonne of coal and

(iii) Higher depth of the seam (500-700m) is overlain by strong and massive sandstone, which do not cave and cause excessive mining induced stress development.

It is observed that drilling of destressing holes and fracturing of competent overlying strata could successfully control the coal bump/rock bursts, a study of roof strata of the Chinakuri Mine was conducted (Konicek *et al.*, 2010; CMRI, 1985). A set of three boreholes, drilled in 32 East dip (1 Rise), 47 East Dip (11½ Level) and 47 East Dip (9 Level), indicated (CMRI, 1985) presence of competent overlying strata (Fig. 3). In BH 32 Dip (1 Rise) the seam is overlain by 0.20 m thick shale band followed by 4.8m thick sandstone. The thickness of shale band in 47 dip (111/2 Level) and 47 Dip (9 level) was 2.2 and 2.8m respectively. Presence of geological disturbance was anticipated due occurrence of vertical cracks in BH 47 Dip (9 Level). Lithology of the formation along with different physico-mechanical properties of the overlying strata encountered in BH 1(0), drilled vertically upward from the working horizon, is shown in Fig. 4.

An analysis of cores of this borehole found that the intercalation along 13.79m to 13.98m horizon from roof is the only probable weakness for parting. An analysis of another borehole (Fig. 5), drilled upward from the working horizon, indicated that 5.3 m thick intercalation/shale band and 3.6m thick sandstone would act as an immediate roof and the thickness of main roof may vary up to 23 m in thickness. In order to identify a probable weak horizon, an inclined borehole at 20o was drilled from the working horizon and the interfaces were studied for cohesion and likely trend of bed separation (Fig. 6). In spite of change in lithology, the formation is massive and is of high compressive and tensile strengths. Applying empirically derived norms for Indian coal measure formations, the limiting span for first and recurring falls of different strata have been presented in Fig. 7.

of the goaf, chances of massive collapse are there and involves large areas. Study conducted in different mines suggests that massive collapses occur when the pillar width-to-height (w/h) ratio is 3.0 or less and the safety factor (SF) is less than 1.5.

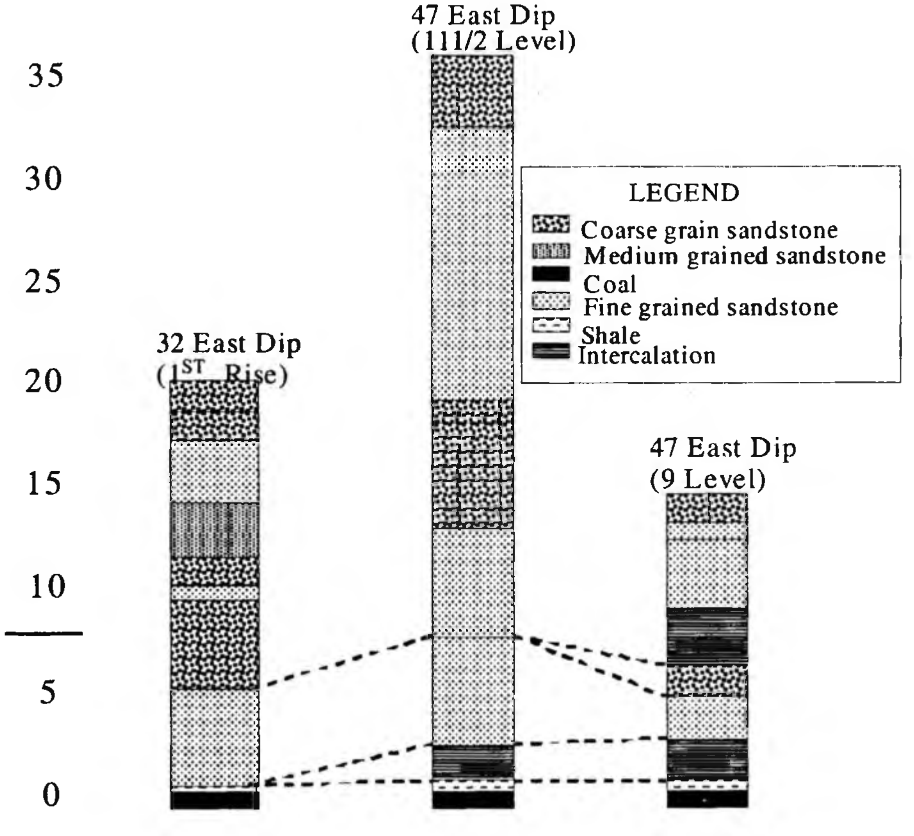

Fig. 3: Assessment of the nature of formation through different boreholes.

Pillar Squeeze

During depillaring, when the pillars are too small to carry the loads applied to them, squeezing of pillar occur. The small pillar starts squeezing and failing and the load is gradually transferred to the adjacent pillars.

Massive Collapse

When the roof strata hangs over a large area

Ventilation Challenges and Remedies

It is an established fact that effective management of ventilation plays an important role in production, productivity and safety in mines. The problem of ventilation in Indian coal mines is increasing with increase in depth cover and adoption of mechanisation to meet targeted production. Increase in depth cover aggravates the ventilation problem due to addition of geothermal heat

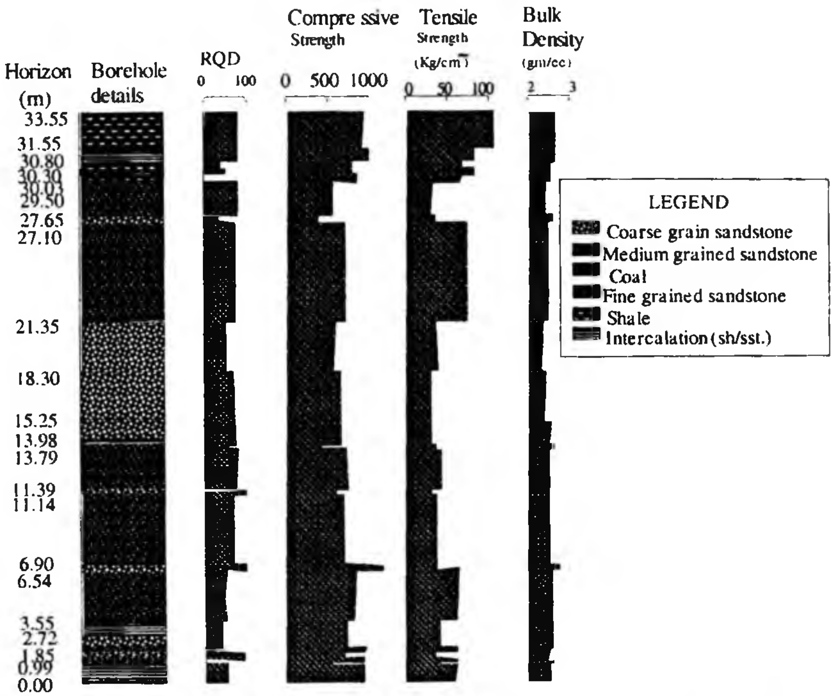

Fig. 4: Histogram of physico-mechanical properties and litholog of BH 1(0) of Chinakuri Mine.

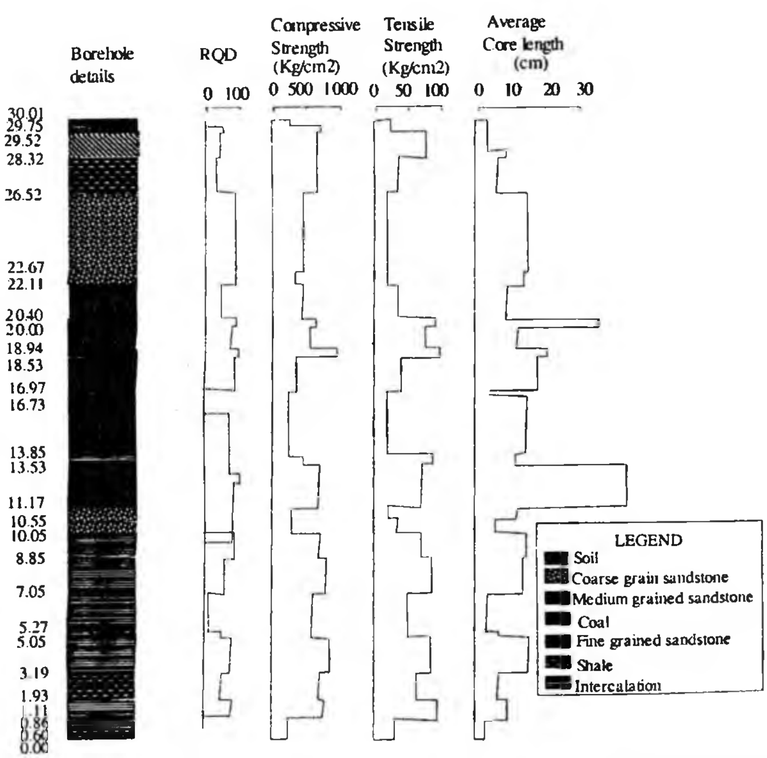

Fig. 5: Histogram of physico-mechanical properties and litholog of BH 1(V) of Chinakuri Mine.

and moisture. As per Pearce (1995), there is an established relation between productivity, i.e. OMS (%), and Wet bulb temperature as shown in Fig. 8. Productivity reduces to even less than 20% in case of wet bulb temperature more than 32°C.

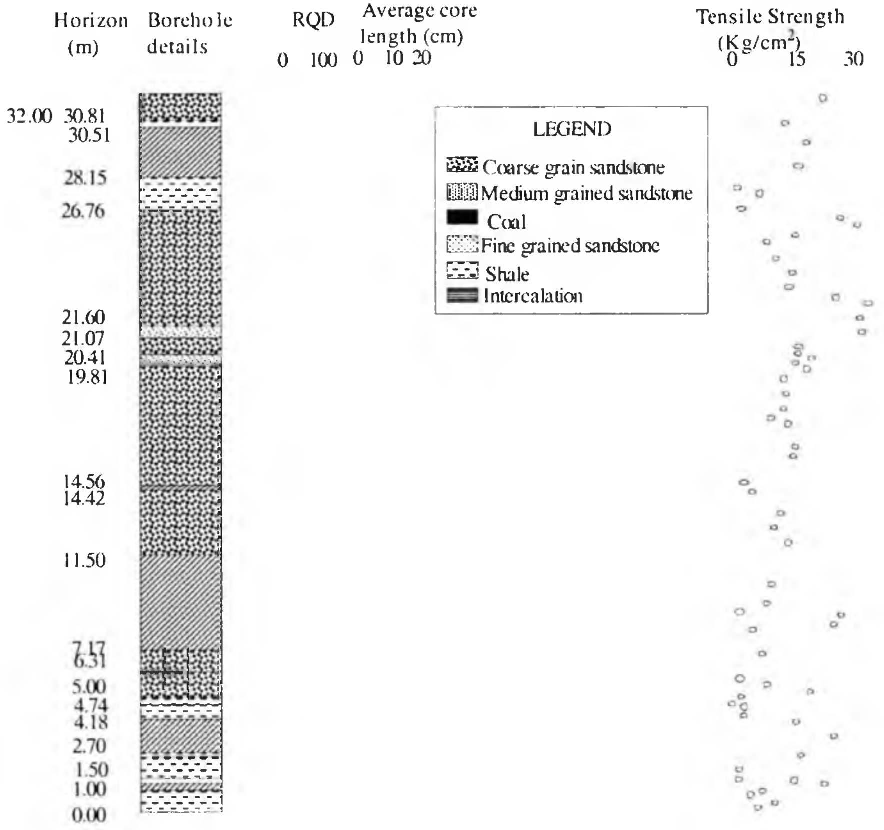

Fig. 6: Histogram of physico-mechanical properties and litholog of BH 1(I) of Chinakuri Mine.

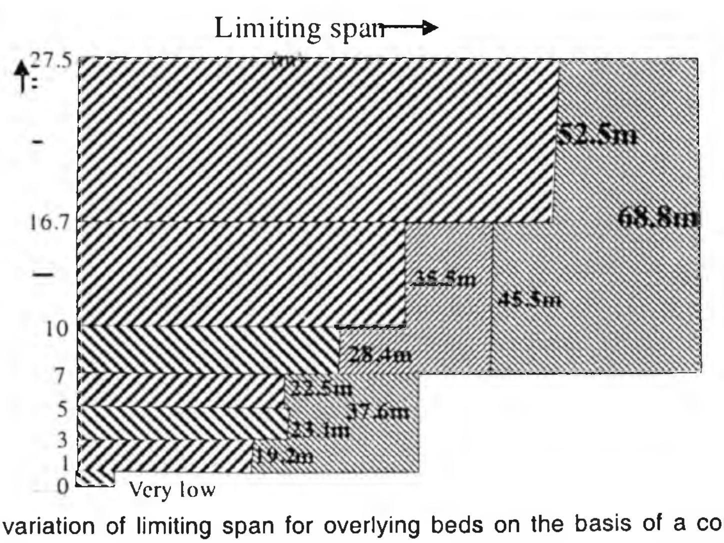

Fig. 7. Projected variation of limiting span for overlying beds on the basis of a compromise log of different boreholes.

Working at deeper cover requires powerful ventilation system but many mines are unable to digest the dose of power (pressure) because of risk of spontaneous heating due to complex geo-mining conditions like multi seam working, presence of sealed off areas near the pits, inter connected goaves, existence of fire, small dimension of pillars, etc. Thus, the situations demand a fresh look into this subject so that effective ventilation can be provided to deep and fire affected coal mines. The Institute, in recent past, has carried out extensive investigations for establishment of design parameters of a ventilation system of Indian coalmines. These studies include:

- Determination of resistance and coefficient of friction of different types of mine airway.
- Design of auxiliary ventilation system with particular reference to ventilation of long headings.
- Study of ventilation system for deeper cover and studies on heat and humidity in coal mines.
- Design of ventilation system of fire affected mines.

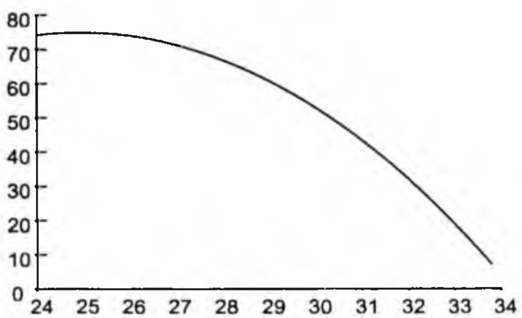

Fig. 8: Relationship between productivity and wet bulb temperature (Pearce, 1995).

Following techniques have been developed by the Institute to cater the ventilation needs of difficult coal mines.

Multi-zonal Ventilation system

The concept of Multi-zonal Ventilation system (Bhowmick and Dhar, 1993) was developed for effective ventilation of deep and extensive mines as well as an alternative for artificial cooling of mine air. The conceptual diagram of the system is shown in Fig. 9. This system can work effectively without overstretching the existing ventilation system of the mine.

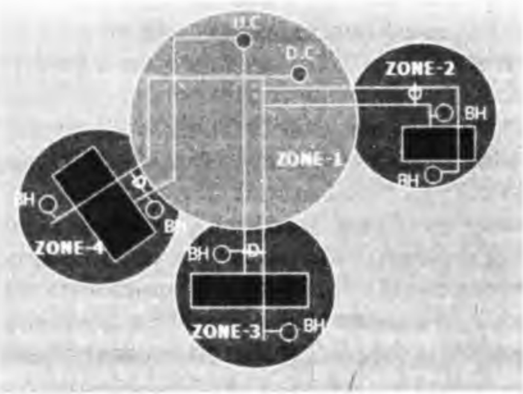

Fig. 9: Conceptual layout of multi-zonal ventilation system.

Design of ventilation of fire affected mines

A number of mines in Jharia and Raniganj coalfields are suffering from acute problem of ventilation and fires. Conventional solution of ventilation problems of these mines, i.e. simply by increasing fan capacity is a risky proposition. To overcome this problem, CIMFR has developed a technique for designing of ventilation of such mines by incorporating dynamic balancing of pressure around sealed off area as an integral part of main ventilation system (Sahay *et al.*, 2003).

Chamber method of ventilation

At some of the places, leakage of air from surface through cracks or underground mines from other goaf to working goaf becomes serious problem. To overcome this problem, fan pressure has to be reduced resulting in reduction of air quantity in the mine. To address this problem "Chamber Method of Ventilation" has been developed. It is a ventilation arrangement (Sahay *et al.*, 2002) which is superimposed on the main ventilation system to reduce the cumulative pressure drop in a desired area, responsible for leakage of air either from surface or from other goaves, without affecting the main fan pressure and ventilation in other part of the mine.

Gases in coal

Underground coal mines have an historical record of methane charged atmosphere posing safety hazard to mines and the miners. Release of toxic gases like carbon-monoxide, hydrogen sulphide and oxides of nitrogen in the underground environment further exaggerate the safety problem. Large amounts of natural gas are produced by chemical and biological process of coalification. This gas mostly contains methane (80-95%) and is referred to as coalbed methane. The quantity of methane present in the coal, known as the gas content of coal. The gas content depends on the degree of coalification and other geological parameters like depth of the coal seam, permeability, porosity, degree of fracturing of coal and adjacent rocks and chemical parameters like nature, rank and composition of coal. Depth of the coal seam is an important parameter controlling the gas content of coal. Study by CIMFR suggests that the gas content of coal seams generally increase with depth. The relation between *in situ* gas content and depth of coal seams studied from Raniganj Coalfield is shown in Fig. 10.

Mining Method

The problems of working deep deposits are also related to the search for fundamentally new mining methods of fracturing or cutting of rocks and coal seams and development of specific mining equipment. Solutions have to be found to the problems of controlling the surrounding strata, ventilation, and protection of personnel from high temperatures, differential pressures, and other specific factors which appear at deep underground mine workings. Increase of productivity, lowering of production costs, and creation of comfortable and safe working conditions are the key issues for exploitation of deep deposits.

With conventional methods of underground coal mining like - bord and pillar, there is a limitation of mechanisation and consequently limitation of production. At greater depth, it is very difficult to maintain the stability of roof in the vicinity of the workings, even after leaving large size remnant pillars. The geotechnical problems due to ground control aspects will become insurmountable in case of bord and pillar pattern (or room and pillar pattern) of mining in higher depth of cover. The percentage of extraction of coal goes on decreasing with increase in depth as well as heating.

Longwall method of mining has occupied a dominant position as far as mechanised underground mining technology is concerned worldwide and has been contributing about

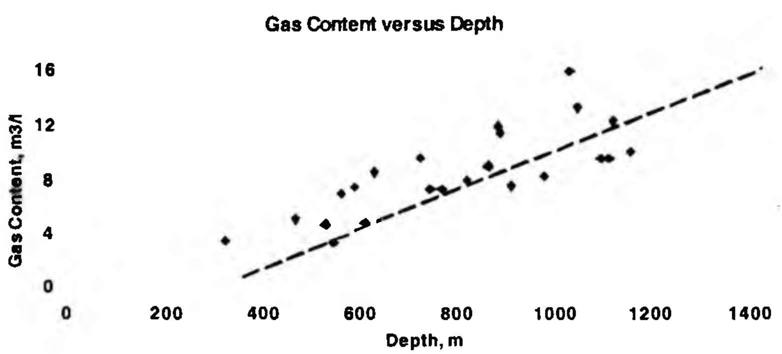

Fig. 10: Relationship between gas content and depth of coal seams.

67% of total world coal production. Longwall may be considered the most suitable underground mining technology (Boyd, 1998) for the virgin coal seams of deeper cover from productivity, safety, and conservation point of view. However, longwall mining could not get much momentum in India (Table 5) mainly due to the poor performance of the selected support system. Low capacity support system, suitable for easily caveable roof strata, may be the main reason for the poor performance under massive roof formation. There is no doubt, that an adequately supported longwall face is suitable for coal extraction. In case of longwall mining, the percentage of extraction will be almost 100% except the panel barrier pillars. The mechanized longwall mining with powered supports will be effective in safe and stable immediate roof in the working areas. The cavability of overlying strata will also be enhanced as the mining induced stress increases with increase in depth.

Continuous miner based methodologies, if designed for high extraction rate continuous with mobile breaker line support, can also be applied for coal extraction from deeper depth. Experience gained by CIMFR in a few underground mines presently being worked with continuous miners have given sufficient insight to work towards development of suitable methodology for extraction of coal seams under different geo-mining conditions with least deterioration in quality of coal due to mixing of waste material with the produced coal.

For higher depth of cover, the failure of rock mass is changed from structure control to stress controlled failure. Post-failure behaviour of coal seam and overlying and underlying formations are required to be assessed before designing of the method of mining for higher depth of cover. Another inherited geotechnical problem of Indian coalfields is the nature of roof which is generally massive. Management of hard roof is one of the major problems for success of any underground mining method. In most of the longwall workings in India, the production and safety suffered badly due to strata control problems created by the hard roof (Sinha, 2007). Therefore, adoption of a proper hard roof management technique is necessary for final extraction of coal under a massive roof condition for deep-seated deposits. In recent past, final extraction of few depillaring panels has successfully been completed with the help of hard roof management techniques.

Above mentioned discussions and examples are mainly limited to some of the R&D works carried out at CIMFR and available literature to tackle the rock mechanics problems of underground coal mining at deeper cover. CIMFR is undertaking extensive R&D investigations for extraction of coal from deep-seated deposits in India. In recent past, a collaborative programme had been undertaken with the Institute of Geonics, Ostrava, the Czech Republic for rock mechanics investigations to meet challenges of strata control of deep underground coal mining. In this programme, CIMFR scientists have gained experience in controlling coal bumps/rock bursts at Lazy Mine of Ostrava-Karvina Coalfield (OKC) in the Czech Republic. A detailed programme is being

Table 5: Coal production by the longwall method relative to total deep mine production (Boyd, 1998)

Country	Total underground production (Mt)	Tons per employee year	Longwall production (Mt)	Longwall % of total UG production
PR China	1240	180	-	>70%
USA	378	7710	146	39%
Australia	64.6	5680	46.5	72%
S. Africa	117	4640	12.2	10%
India	72	220	6.5	9%

framed to study their suitability for application of underground extraction of Dishergarh coal seam of Chinakuri Mine, ECL.

Conclusions

Future coal mining in India would encounter relatively deeper excavations in difficult rock mass and hostile underground environmental conditions. Presence of different unknown geotechnical parameters at deeper cover may lead to strata control problems while the increase in geothermal heat and gassiness of the coal seams is a potential threat for underground mines. These problems of deep seated coal seams make it challenging for mining. Mechanisation and automation of the mining process is of great importance to improve safety along with production and productivity. A quantum jump in coal production strategy of Indian coal mining industry is, mainly, dependent upon the success level of mechanisation and automation of the underground coal mining. However, the modernisation approach is likely to encounter difficult conditions due to increasing depth of coal seams in the country. The experience of rock mass behaviour and studies for improvement in underground working environment may prove to be important inputs for a successful adoption of a mechanised mining operation for extraction of deep seated coal seams. CIMFR has devoted last fifty years to gain strategic advantage of experience of geo-mining conditions and behaviour of rock masses of Indian coalfields and made significant contributions in the various fields of mining. During these studies, considerable efforts have been made to address the problem of increasing depth cover on different design parameters of an underground mine. A number of investigations have also been planned to provide effective solutions to the problems arising due to increasing of depth cover. In case of a method of mining for extraction of coal from deep-seated deposits, a comprehensive investigation is required to be taken up for understanding the rock mass behaviour and identification of the geotechnical problems to be encountered and its control. Longwall mining can play a vital role to exploit deep-seated coal deposits. A number of longwall faces have also been opened in India but, in a nutshell, longwall mining is still not so successful in India due to various reasons and further detailed studies are required. Continuous miner with fast extraction system for virgin seams can also be applied in limited scale under suitable ground conditions. Proper hard roof management techniques are also to be developed for effective control of massive Indian coal roofs.

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