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Role of geological discontinuities during application of continuous miner technology in underground coal mines

A major portion of ground control problems encountered in underground coal mines can be attributed to geological discontinuities in the coal seam and the strata surrounding the seam. The role of geological discontinuities becomes more vital during application of mass production technology like continuous miner in maintaining safety, production and efficiency. Careful and detailed geological mapping to pick up the trend of joints, faults/slips, cleat etc., and documentation of roof instability problems encountered during development is essential in anticipating and controlling instability in the mine roof before planning of pillar extraction. Mapping helps in planning the orientation of extraction line to induce caving during depillaring and improving stability at the face significantly. Loss or damage of machines including decrease in production and productivity due to trapping of continuous miner may also be avoided. This technique estimates the orientation of major principal stress and avoids heavy expenditure on conducting in-situ stress measurements. It enhances in understanding the influence of drivage direction on roadway conditions and re-orientation of the roadways to attain stability in the roof. In the present paper, authors have dealt two cases, VK-7 Incline and GDK-11 Incline mines of Singareni Collieries Company Limited (SCCL), where geological discontinuities played a crucial role during application of continuous miner technology in underground coal mines.

1.0 Introduction

Underground production has remained stagnant over the decade in Indian coal mining industry although the overall coal production has considerably increased due to opencast mines. To meet the growing demand of energy, it is important to focus on underground mining as well, particularly in the context of the reserves position in deeper horizons. Since inception of mining industry till now, bord and pillar (B&P) method of mining is still the predominant method of mining in India. Application of continuous miner (CM) technology for B&P mining may be instrumental in radical improvement in underground production. India has large resources of coal in existing underground coal mines with ideal conditions for extraction with mechanised continuous miner technology. In this direction, continuous miners have already been introduced in India in some mines of Coal India Limited (CIL) and Singareni Collieries Company Limited (SCCL) with an average production of around 1500 tonnes/day. Although productivity is generally high with CM technology, there are cases in India of ground control problems like pillar spalling, roof falls, strata control difficulties, problems associated with slicing in unsupported roof during liquidation of pillars causing injuries, trapping of CM and coal being left out with loss of production.

The role of geological discontinuities becomes more crucial in CM panels due to increased gallery, split and slice widths, unsupported slices, straight line of extraction, high depth of cover and presence of overlying goaved out workings and barrier pillars. Detailed geological mapping with careful identification of trends of joints, faults/slips, cleat etc., and documentation of roof instability problems encountered during development is a necessary requirement in foreseeing and controlling instability in the mine roof before planning of final liquidation of pillars. Extraction can also be planned advantageously for smooth caving considering the orientation of geological discontinuities. Mapping helps in understanding the stress conditions prevailing on developed workings and re-orientation of roadways accordingly for improving mine safety and achieving higher production. In this paper, authors have outlined the important geological discontinuities and its effect on underground mining and how geological discontinuities affected mine safety in CM panels at VK-7 Incline and GDK-11 Incline mines of SCCL. The paper also describes how geological mapping helped in addressing the ground control problems which resulted in successful development and depillaring of the CM panels.

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2.0 Geological discontinuities and its effect on mining

Integrity of a mine structure is greatly affected by the natural weaknesses or discontinuities that disrupt the continuity of the roof and pillar. Increased frequency of geological discontinuities reduces the overall grading of rock mass quality like rock mass rating (RMR) of the roof. Geological discontinuities can originate while the material is being deposited by sedimentary or intrusive processes, or later when it is being subjected to tectonic forces. Some of the most important discontinuities that affect mine safety are described below [1, 2 and 3]:

Slips and slickensides

Slips are small or longer thin visible breaks or cracks with slight rock displacement in the roof and are most often cited as a main cause in underground coal mine fatality reports. When slips are long and are steeply dipping, they form a ready-made failure surface. Two slips that intersect form an unsupported wedge. Undetected slips that do not fail during development have a tendency to pop out when subjected to abutment pressures during pillar recovery operations. Sometimes surfaces of slips are slickensided i.e., smooth, highly polished and striated (Fig. 1a-1d). Slickensides are irregular slips of smaller dimensions and unlike slips they are restricted to a particular bed only. They are characterised by smooth and curved surfaces with direction of movement indicated by the slickenlines. They lack cohesive strength causing separation of the beds into smaller blocks. Slickensides occur in both coal and shale rock types [2 and 3].

Clastic dykes

A clastic dyke is a tabular body of clastic material that has intruded into a fracture, joint or other zone of weakness in a coal seam, mine roof or floor. The clastic material may consist of sandstone, siltstone, clay or carbonate. The presence of clay veins in the roof of a coal mine creates hazardous condition. Sandstone dyke passing through a coal pillar causing pillar spalling is shown in Fig. 2 [3].

Fig.1a Slip plane associated with slicken sides

Fig.1b Displacement of different sandstone bands along slip plane

Fig.1c Two sub-parallel slips exposed in coal pillar

Fig.1d Seepage of water through slip plane

Fig.2 Sandstone dyke in the coal pillar, causing side spalling

FRACTURES, JOINTS AND CLEATS

Fractures, joints and cleats are structural discontinuities in rock strata that result from brittle deformation. Fractures form as cracks along which cohesion is lost. The fracture faces can be re-cemented after fracture formation either by precipitation of secondary minerals from solutions flowing through the fracture or by re-crystallization of original minerals in the host rock. Fractures can remain open with varying amounts of space between fracture planes (Fig.3) [2 and 3].

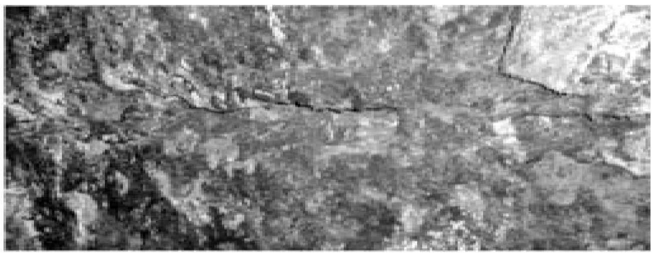

Fig.3 Fractures in roof

Joints are planes of fractures or divisional planes, which run through rocks and enable them to be split up into blocks of geometrical form. Joints occur as families of fracture in rock strata and occur in sets with similar orientation, spacing and extent. Often several sets of joints occur at angles to each other, creating unstable blocks that must be supported by roof bolts. In sedimentary rocks, the joints other than the bedding planes, usually run in two directions at right-angles, one set of joints, known as master-joints, being more prominent and more persistent than the other.

Cleats are weakness planes occurring perpendicular to bedding and they are specific to coal. Generally, two types of cleats; namely, face and butt cleats occur at right angles to each other: (i) face cleats are more prominent cleats which are continuous over some length and even cut across bedding planes in coal and (ii) butt cleats are short, discontinuous planes which terminate against the face cleats. Face cleats are believed to be extension fractures formed during erosion and uplift (Fig. 4a-b) [3].

Fig.4a Face cleat and butt cleat

Fig.4b Side spalling in the dip galleries

FOSSIL REMAINS

Fossil remains are the remnants of plants (Fig.5) [3] and animals that lived during the time when the sediments that later become rocks were being deposited. For example, kettlebottoms are fossil trees that grew in ancient peat swamps. Fossil remains can fall without warning and should always be carefully supported. Roof bolt holes should never be drilled directly in fossil remains because the vibrations could cause them to be dislodged.

BEDDING PLANES

Bedding planes are horizontal separations in sedimentary rocks and they indicate the termination of one deposit and the beginning of another. They are formed due to a break in continuity of the sedimentary regime and so can be distinguished by a discrete vertical change in lithology or grain fabric in the sedimentary units. Sedimentary rocks break

Fig.5 Leaf impressions in the exposed roof

easily along bedding planes that have low cohesion values and roof falls are associated most commonly with failure of the rock along these planes. De-lamination (separation of roof layers along the bedding planes) is the common type of roof failure associated with weak bedding planes and thin layering [1]. Associated structures are crossbeddings which are internal bedding structures ranging in thickness from 0.05 to 2.0m and oriented at an angle to horizontal bedding. They are planes of weakness within lithologic units and causes roof strata instability leading to roof falls in the area.

Fault

A fault is a dislocation of the strata whereby beds which were once continuous are displaced relatively to one another by tectonic forces acting regionally. Displacements may be either vertically upwards or downwards or horizontally in mining (Fig.6) [3]. In mining, the smaller faults are also often referred to as slips. Faults are divided into three main classes namely, (a) normal (b) reversed and (c) transcurrent. The first two cause vertical displacement. Normal faults are most common in coal-measure strata. The third variety causes only horizontal movement and is relatively rare in the coal-measures. Faults often contain weak gouge material, often cited as contributing to large roof falls in underground.

Washout

Washout is a channel that has partly or totally cut into or through a coal seam at some time during or after the formation of the seam and generally filled with sandstone. It generally forms unstable zone or roof conditions and often contributes to roof failures.

3.0 Continuous miner technology in VK-7 incline mine, SCCL

Continuous miner technology was introduced at VK-7 Incline mine [4] in the year 2006 at the dip side property to extract standing pillars in 6m thick king seam below 300 to 380m depth of cover (Fig. 7). The seam is dipping at 1 in 7.5 and is overlain by caved goaf of top seam with a parting of around 40m. There was setback initially with caving method of extraction which has lead to employing the yield pillar non-caving (YPNC) method for four numbers of panels as a confidence building measure. As many strata control problems have been faced with YPNC method, caving method of extraction was re-adopted with the support of CSIR-CIMFR scientific study. Till now, eight sub panels were extracted by caving method of mining with recovery of around 70%. Presently, extraction in the ninth sub panel with caving is in progress.

3.1 Geological study in king seam at VK-7 incline

One of the most pressing problems at VK-7 mine was found to be initiation of caving of the roof rock strata of king seam, when pillars were under extraction. The first 4 to 6m of strata formation was considered to be the most critical zone of strata from the caving and prevention of air blast point of view. Based on the analysis of tested data of 26m upper roof rock strata RQD, cavability index and strength of roof rock strata were plotted and which is shown in Fig.8. The strata up to 26m from the seam consisted mainly of very coarse-grained to coarse-grained sandstone with occasional inter-bedded medium-grained sandstone and shale. The compressive strength of the sandstone strata above king seam varies between 10.83 and 17.27 MPa and the average uniaxial compressive strength of the king seam coal was found to be 30 MPa. RQD of immediate roof rock varied from 0 to 87%. Low strength of the upper strata was responsible to give the low cavability index of the overlying rock strata. This characteristic of the upper strata would help in caving. But, the core samples recovered from hole was found to be severely fractured during

Fig.6 Faults in a coal mine

Fig.7 Plan showing the dip side property of king seam where CM is introduced

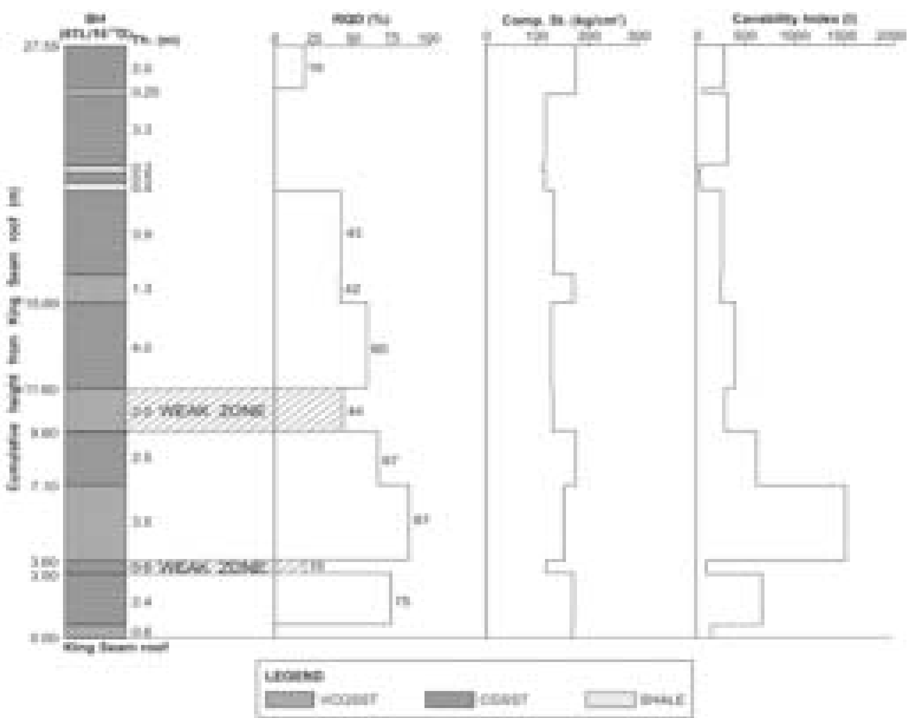

Fig.8 Compressive strength, RQD, cavability index of immediate roof rock strata above king seam of BH located at 67L/16½D

drilling and recovery. Fractures were inducted into the core during upward drilling causing vibration despite much of the rock consisting of good quality sandstones. RQD is a very good index to account for fracture spacing and depends on joint volume, bedding frequency and strength of rock. However, it is rarely possible to obtain cores maintaining the strict requirements like NX diamond drilling with double tube core barrels and without much vibration. This might be the reason for low RQD as obtained and strength of king seam roof. Therefore, it would be prudent to consider the roof difficult to cave as experienced in BG panels in king seam.

During extraction of CMP 6A(1), 6A(2) and 6B sub-panels at VK-7 Incline numerous faults, slips and fractures were encountered as shown in plan (Fig. 9). The RMR of the roof rock strata in the continuous miner district varies from 41 to 53. Interaction effects of top seam barriers have been observed in underlying king seam. Salient observations in underground workings were as follows:

(i) The geological anomalies observed were mostly normal faults and slips with minor displacement. Faulting was prominent throughout the CMP-6 panel. The majority of the faults were minor with a displacement of less than 0.5m trending between N40°E and N70°E. Few major faults of throw ranging from 0.5 to 3.3m were also existed. A fault of 87m throw existed at the dip-most side in the area. In most cases, faults were oriented sub-parallel to the dip direction of the seam.

(ii) The prominent joints sets were observed in these panels trending between N45°E and N75°E. The orientations of these joint sets were almost parallel to the corresponding faults and slip planes. Most of the joint surfaces were rough.

(iii) Other frequently occurring features include thickly filled calcite joints, which are 0.03-0.04m thick and traversed both in the seam and roof causing weakening of roof in the panel. Trend of face cleat was in N 85ºE direction while butt cleat was N5ºW.

(iv) Closed and open fractures were found throughout the panel. The fractures were oriented both along the dip-rise and level galleries. Fractures were more prominent below the left-out barrier pillars of overlying goaved out seam.

(v) Some localised roof falls were observed and majority of which were associated with litho-logical anomalies (Fig.9). Localized spalling in the pillar sides and pillar corners were also observed at few places in the panels. Heaving of coal floor was observed in the roadways below the top seam barrier pillars.

3.2 Role of geological discontinuities in CM panels at VK-7 incline

Geological discontinuities greatly influenced in deciding the line of extraction and required support system for fast and safe extraction of the panel with the help of CM. It is worth to mention here that where the caving method is practiced, the roof should be controlled in such a way that it should break as early as possible in the goaf with maximum possible height and extent of fall of the hanging roof. Wherever practicable, suitable measures should be taken to bring down the goaf at regular intervals. In VK-7 Incline, it was found that the strata immediately overlying the King seam was difficult to cave and inducement by blasting might be necessary. However, due to the frequency and orientation of small faults and joints in the sub-panels; an extraction sequence has been designed which maximized the likelihood of early caving and allowed the caving without air blast.

3.3 Suitable line of extraction for regular caving

It was decided to extract all the sub-panels in dip-rise direction based on its locations adjacent to the fault. It was planned to leave the pillars lying along fault plane and start extraction keeping a safe distance away from fault. There were numerous minor faults/slips present in CMP-6 panel and the orientations of those faults were sub-parallel to the dip-rise (Fig.9). Due to this orientation, the extraction line was planned to move in strike direction instead of dip to rise direction which would help in caving. Although, faults/slips present in the panel would help in caving but the chances of roof fall encroachment could not be ruled out in the working area during depillaring with "split and slices" method of mining. So, to prevent stress build-up and occurrence of air blast, induced blasting was introduced as and when required.

3.4 Support system for the immediate roof rock

The observed and estimated geological discontinuities indicated a large number of cleats/joints and faults were present in the panel, which required adequate support system

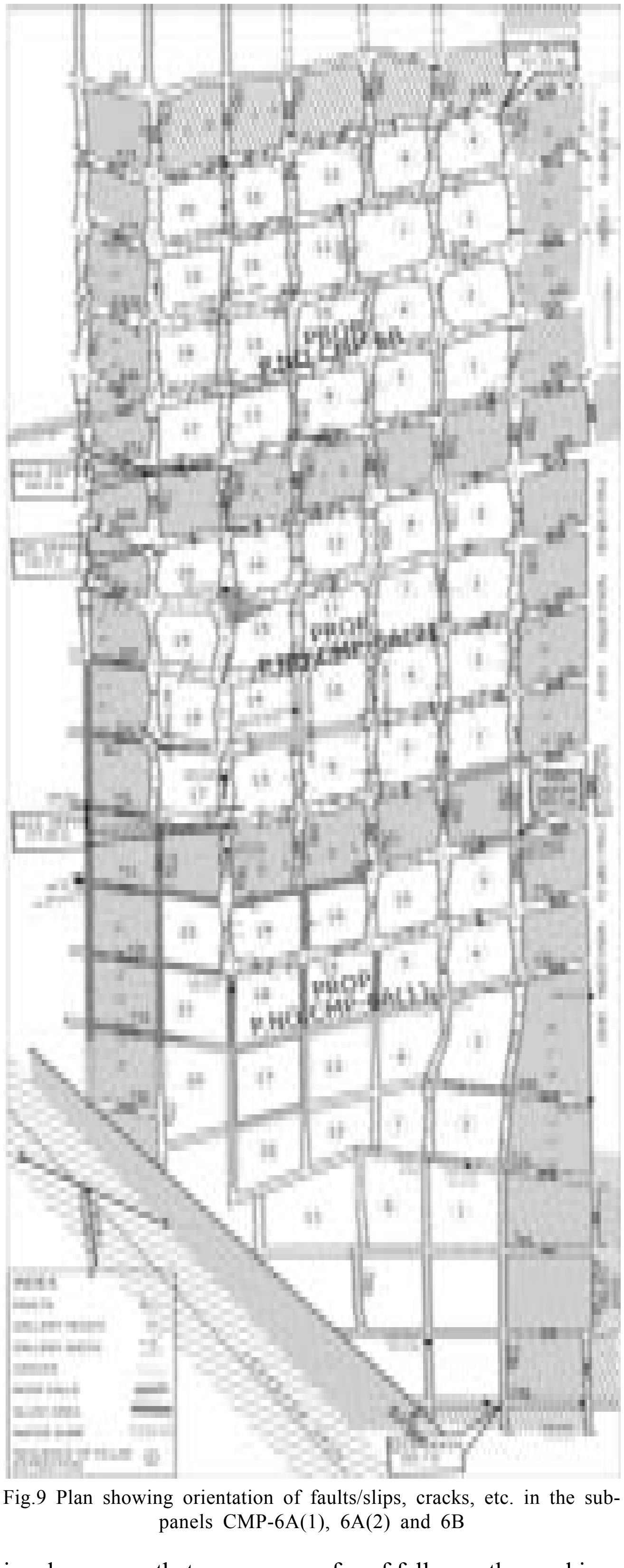

Fig.9 Plan showing orientation of faults/slips, cracks, etc. in the sub-panels CMP-6A(1), 6A(2) and 6B

in advance, so that occurrence of roof fall over the workings faces could be restricted. Three dimensional numerical modelling was used for estimating the support density for widened galleries and junctions, level splits and goaf edges below top seam caved goaf and its barriers. Estimated properties of immediate roof rock of king seam workings such as unadjusted RMR, presence of geological discontinuities were taken in the numerical models. Support design applied for widened galleries and junctions, level splits and goaf edges below top seam caved goaf and its barriers are given in Figs.10-13.

Fig.10 Roof fall at 24R/55L in VK-7 Incline

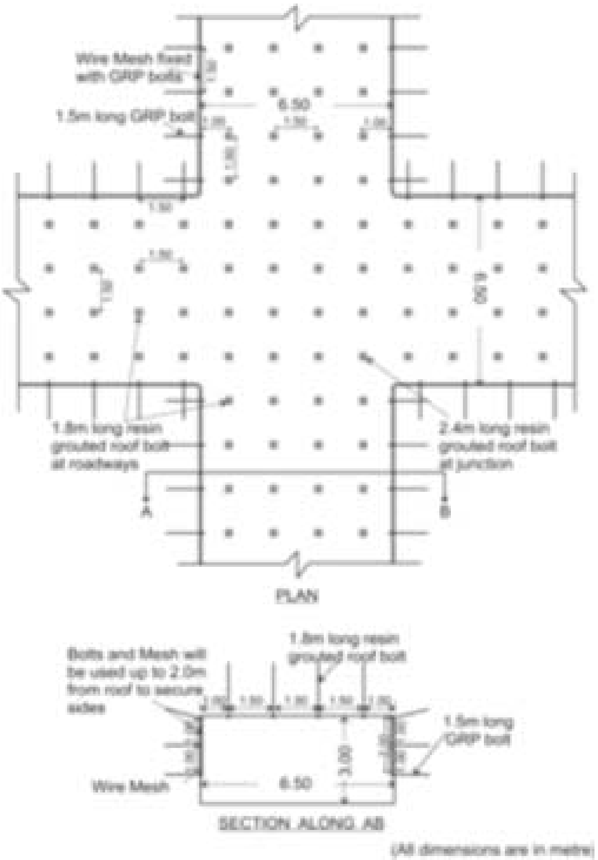

Fig.11a Support system for 6.5m wide gallery and junction below top seam goaf

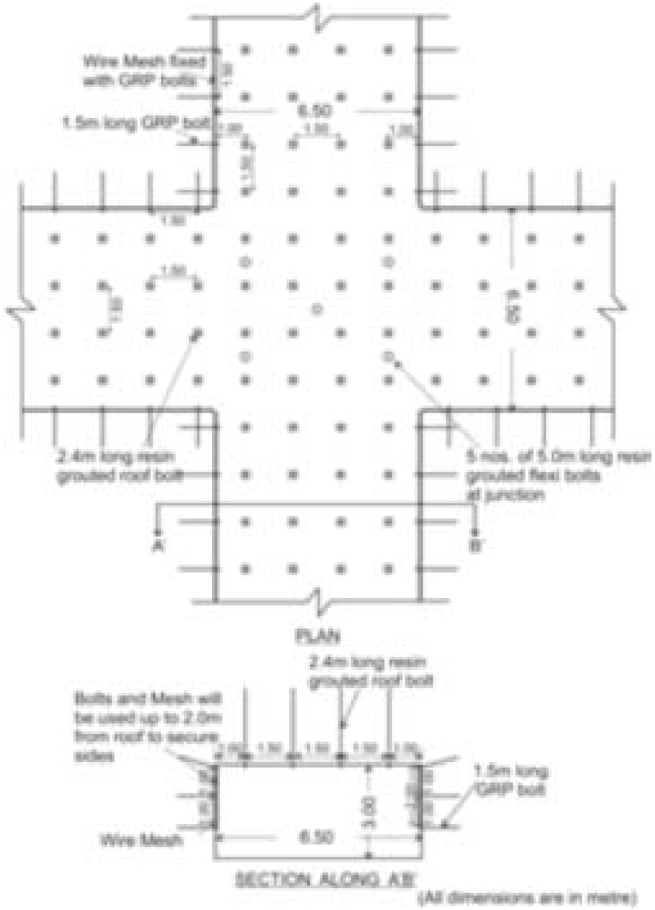

Fig.11b Support system for 6.5m wide gallery and junction below top seam barrier

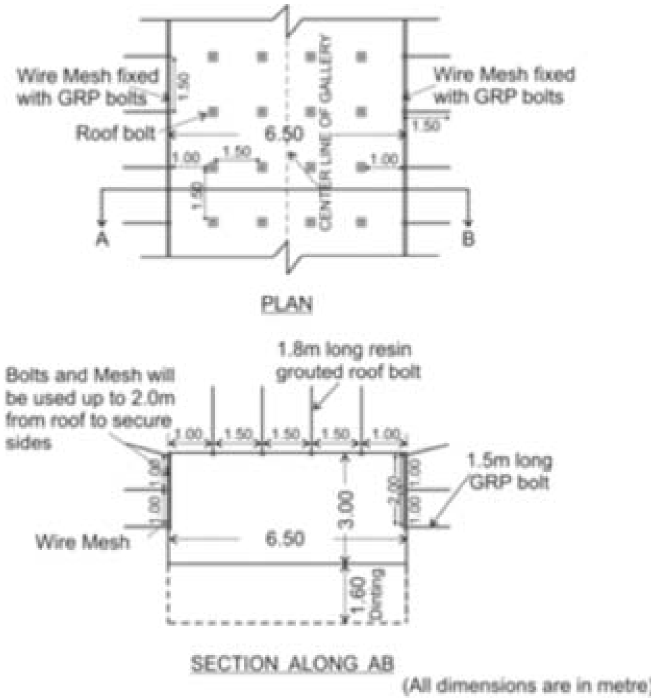

Fig.12 Support design for level splits and sides

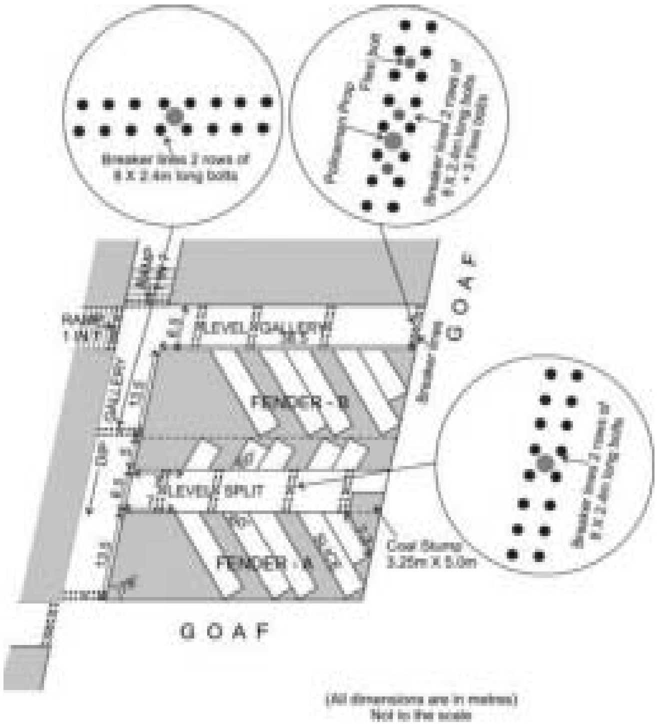

Fig.13 Goaf edge breaker line support for original galleries and level splits

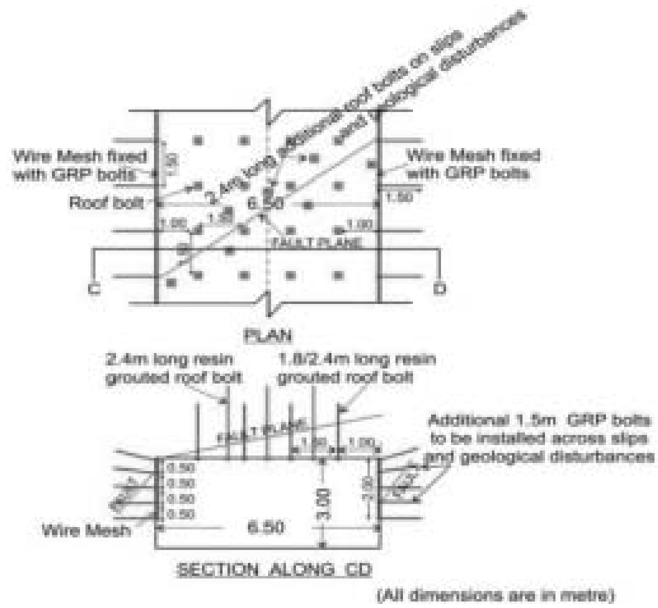

Fig.14 Support system for the area intersected with slips and faults

For split, instead of additional flexi bolts at goaf edge, it was suggested to keep coal stumps of 3.25m × 5.0m in the dip side at the end of the split (Fig.13). Only half width of split was remained open at the end of the split. This left out stook along with normal breaker line support system provided in the split goaf edge prevented any possible goaf encroachment. To arrest the side spalling due to presence of numerous cleats, all the pillar sides were supported with plastic mesh fixed with 1.5m long GRP bolts in three rows at 1.5m interval within the row and 1.0m between the rows (Figs.10-12).

In case of slips and faults intersecting the galleries, supports of 2.4m long resin bolts were provided as shown in Fig.14 in addition to regular bolting in galleries and splits. Additional supports were also provided as per requirement in form of wire netting, roof bolts with W-straps, cogs or other supports in old and newly formed cracks, fractured roof, deteriorating roof, excessive wide roadways and junctions etc. During depillaring of CM sub-panels at VK-7 Incline, it was observed that falls were regular in goaf with extraction of pillars and occurred subsequently after fender extraction within a shift time. Stress build-up and side spallings were observed in the pillar under extraction and up to one pillar ahead only leaving all other pillars without any disturbances.

3.5 Trapping of CM in CMP-6B sub-panel

During the extraction of fourth pillar in CMP-6B subpanel, CM was trapped (Fig.15). It was found that this pillar was existed below top seam longwall barrier pillar. At the point of trapping of CM, this pillar was encountered with several minor faults/slips and cracks. Slices were extracted normally. While extracting the last snook, auto warning tell-tale at the junction started flashing. Two slips that intersected formed an unsupported wedge was un-noticed. Therefore, while sweeping the junction, fall took place in the junction covering 80% area of the CM. Some damage had taken place in the CM and further extraction was stopped. Extraction was resumed after full filling the following measure steps:

(i) 5 numbers of 5m long flexi bolts were installed in all the junctions in addition to the 5 numbers of 10m long cable bolts. All the goaf edges were supported with 3 numbers of 5m long flexi bolts in addition to 2.4m bolts at 0.75m × 0.75m grid pattern.

(ii) All minor slips/intrusions/impressions and other geological disturbances were mapped and suitable support plan was prepared for securing the junctions. All sides were secured with plastic mesh.

(iii) Faster rate of extraction was attempted to achieve for the better strata conditions and special strategy was

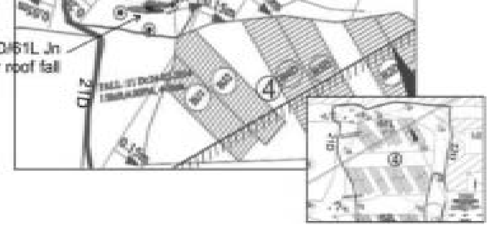

Fig.15 Extraction of pillar No.4 with several minor faults/slips and cracks in 21D/61L junction

drawn for the extraction of snooks under top seam barrier.

(iv) Before extracting the last snook, careful marking of geological discontinuities in the roof rock strata was done and supported well with bolting.

(v) No bottom sweeping of coal was recommended after extraction of snook and CM was withdrawn from the junction.

After the incident of CM trapping, pillar wise extraction strategy was planned by incorporating all the geological discontinuities mapped in and around the pillar. A pillar-wise extraction hand plan was prepared on a scale of 1:500 depicting all details like traversing geological disturbances etc. On completion of a pillar extraction, a fresh plan for the extraction of the next pillar was prepared and was made available to all mining personnel.

4.0 Continuous miner technology in GDK-11 Incline, SCCL

In GDK-11 Incline, CM technology was introduced in the year 2009 in No.1 seam with a depth of cover of around 325m (Fig.16) [5]. Due to the presence of adverse mining conditions in the dip-rise gallery, geological mapping technique was used to measure in-situ horizontal stress orientation. Based on horizontal stress orientation, pillars were re-oriented from proposed square geometry to rhombic-shaped geometry, resulting into reduced frequency of roof falls in dip-rise galleries and considerable improvement in roof stability. Panels were extracted by caving method safely without much strata control problems.

4.1 Orientation of the major horizontal in-situ stress from geological mapping

The geological mapping technique is widely used internationally to avoid heavy expenses on conducting in-situ stress measurements. Procedures have been developed to estimate the orientation of major principal stress (σ_1) [6]. Features such as roof guttering (Fig.17) [6] or roof pots are mapped along with structural discontinuities (i.e., fault, slip, joint, cleat) in underground working and the stress direction is inferred from their orientation and severity (Fig.18).

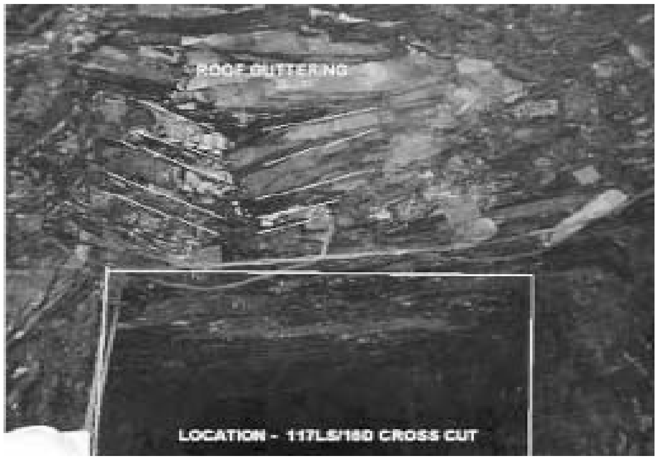

Fig.17 Roof guttering along level gallery

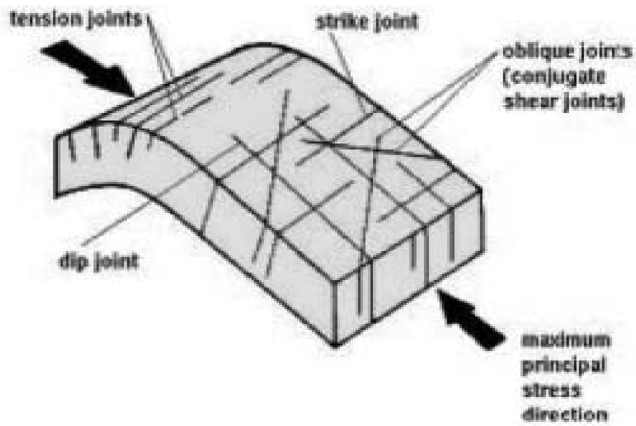

Fig.18 Stress orientation and joints

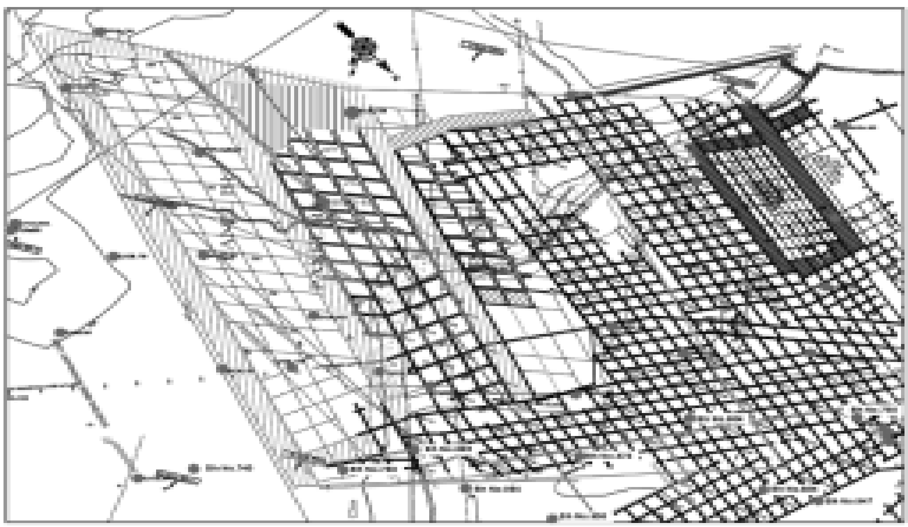

Fig.16 GDK-11 Incline mine plan showing panels B1, B2 and B3 in No.1 seam

4.2 Estimation of cut out distance for GDK-11 incline

Cut out distance is the maximum unsupported span of the gallery which can be cut with cutting machine safely without any failure of immediate roof, which may be supported later. It plays vital role in the selection of continuous miner technology for particular geo-mining conditions. Success of continuous miner depends on safe cut-out distance. Horizontal stress (aligned N35°W) caused failure in the dip galleries where the stress direction is aligned unfavorably to the roadway orientation. Therefore, dip galleries were drive with 60º instead of 90º which increased cut out distance from 6m to 12m. After re-orientation of pillar from square geometry to rhomboid geometry, frequency of roof falls in dip-rise galleries were reduced considerably [6-7]. Fig.19 indicates the original dip, oriented dip, level and horizontal stress directions.

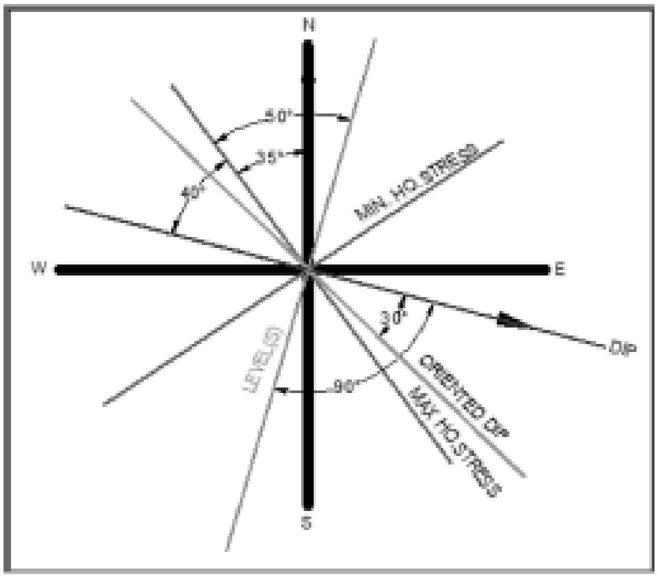

Fig.19 Oriented of dip galleries at GDK-11 Incline, SCCL

When roadways [7] are driven in line with major horizontal stress (σ_1) the stress concentrations at the face of the roadway are minimized and roadway stability would be highest. When roadways are driven perpendicular to σ_1, stress concentrations at the face are maximized and distributed across the full heading width. Under these conditions roadway stability is lowest. The observation of shear fracture orientations provides a good indicator of the stress direction. The technique described, correlates well with similar stress mapping technique used in GDK-11 Incline by conducting underground mapping to determine the reasons for roof instability in dip galleries. These studies, together with mechanical properties and rock mass rating as input data; three dimensional numerical modelling was done using FLAC3D to estimate the optimum orientation of the development roadways vis-à-vis in-situ stresses [6 and 7]. A detailed underground geological mapping was carried out in a nearby LHD panel to pick up the trends of geological discontinuities. From stress estimation through mapping carried out in 1 seam of GDK-11 Incline at 260m depth, backed by numerical modelling, the results are shown in Table 1.

Thirty two (32) numbers of roof falls in B2 CM panel of GDK-11 Incline of SCCL took place in dip galleries. Features like thinly laminated roof, cross stratification, washout, localized geological fractures present in the immediate roof might be responsible for the roof falls during development of the panel. During development of the pillar in square geometry, orientation of the dip-rise gallery was aligned unfavourably to the principal horizontal stress direction which was also responsible for the roof fall. So, the cut out distance in dip gallery was reduced to 4 to 6m causing frequent shifting of continuous miner affecting the production.

5.0 Conclusions

The influence of geological discontinuities on coal measures is manifested in the form of roof and side falls. Faults with an increased frequency of joints, cleats, slips and slickenside's and thinly bedded strata in the immediate roof area play a major role in coal-mine-roof instability. Joints and cleats running parallel to roadways also contribute to strata-instability and side spalling problems. Careful geological mapping to pick up the trend of joints, faults/slips, cleat etc., and documentation of roof instability problems encountered during development is a essential requirement in anticipating and controlling instability in the mine roof before planning of pillar extraction. Increased occurrence of geological discontinuities reduces quality indices of the roof. Significant control of such instabilities is possible by orienting roadways across the geological discontinuities and by increasing the quality and density of the supports. If the extraction line is oriented along the geological discontinuities, it can improve the caving characteristics of the roof. In geologically disturbed zones, stability of coal mine roadways is found to be a major problem in presence of horizontal stress anisotropy. On most of the occasions, geological discontinuities become more prominent in a particular direction. Based on geological mapping and underground observations of development roadways, orientation of major and minor horizontal stresses can be established. Maximum stability can be achieved in those roadways which are parallel to the major in-situ horizontal stress direction while roadways oriented at right angles to the major in-situ horizontal stresses suppose to face severe strata control problems. It is, therefore, proposed to re-orient roadways facing strata control problem closer to the mapped major horizontal stress direction. Geological mapping was introduced as part of the planning process before development and depillaring of CM panels at VK-7 Incline and GDK-11 Incline. Successful working of CM technology in SCCL led to higher confidence levels which paved the way for consideration of CM technology in other mines.

TABLE 1: ESTIMATION OF STRESSES THROUGH MAPPING AND NUMERICAL MODELLING IN 1 SEAM OF GDK-11 INCLINE

Mine	Seam	Depth (m)	Direction		Magnitude (MPa)	
			(σ_1 or σ_H)*	(σ_3 or σ_h)**	(σ_1 or σ_H)*	(σ_3 or σ_h)**
GDK-11 Incline	1 Seam	260	N35ºW	N65ºE	4.6	2.6

* major horizontal stress, ** minor horizontal stress

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