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Stress Orientation in the Godavari Gondwana Graben, India

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ABSTRACT

Roadway stability in underground coal mines directly affects production and productivity, and can be strongly influenced by the direction of the drivage. Stress studies provide a framework for understanding the influence of drivage direction on roadway conditions, and illustrate how mapping techniques can enhance this understanding. Mining can concentrate and re-orient the original stresses. Singareni Collieries Company Ltd. (SCCL) conducts coal mining operations in the Godavari valley coalfield, India. This paper presents a study to understand the stress conditions prevailing on the mine blocks in the Godavari valley coalfield, with a goal to improve mine safety and achieve higher production.

Keywords: Godavari valley coalfield; Satellite imagery; Cleat; Lineament; Joints; Stress mapping

1. GEOLOGY, STRUCTURE AND TECTONICS OF GODAVARI VALLEY COALFIELD

The Pranahita-Godavari Valley Coalfield defines a north-northwest to south-southeast trending basin on the Precambrian platform. It largely follows the course of Pranahita and Godavari rivers for approximately 350 km in the state of Andhra Pradesh, India. Based on the geological and structural conditions at the site, and the nature of the lithic fill, the Godavari Gondwana Graben is divided broadly into four sub-basins, the Godavari, Kothagudem, Chintalapudi, and Krishna-Godavari coastal sub-basin. Further, sub-basins are divided into eleven coalbelts (Fig.1).

In the Godavari sub-basin, the Archaean and the Proterozoic sediments located on either side of the Gondwana sediments exhibit a prominent NW–SE structural trend. Minor swerves are seen at places due to tight folding, with a NW–SE trending axis of Proterozoic sediments. In the "Mailaram High" area, the Proterozoic sediments show an open folding along a NE–SW axis. In the Chintalapudi basin, the Archaeans trend lines show a NE–SW direction. They swerve from N–S to E–NE/W–SW, and again to NE as a consequence of broad warping about NW axis. The faulting in the Godavari valley was, by and large, post-depositional and took place long after these beds were deposited (Ahmad, 1977). Ramanamurty and Parathasarathy (1988) presented a five stage tectonic evolution of the Godavari basin. The absence of volcanic activity and the narrow rift zones places this Graben in the category of "crevice" type platform rift zone (Milanovsky, 1972). It was inferred that movement along the NE–SW direction is responsible for the generation of the step faults modifying the morphology of Godavari Graben (Varadarajan and Ganju, 1989).

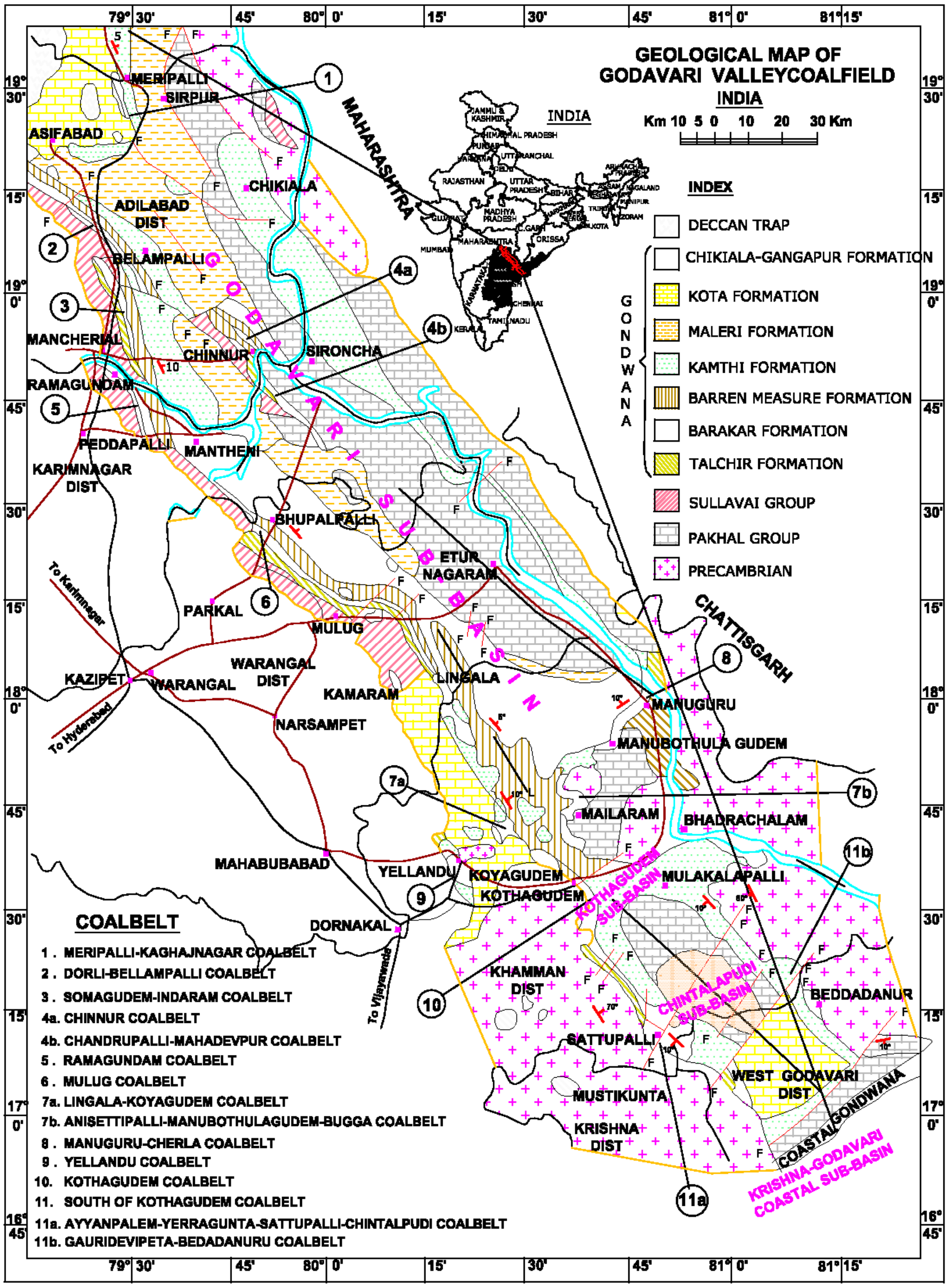

Fig. 1 - Geological map of Godavari valley coalfield showing sub-basins, coalbelts and geological formations

2. SATELLITE IMAGERY STUDIES

Ramanamurty and Parathasarathy (1988) conducted detailed studies using LANDSAT imagery and reported a total of 110 lineaments (Figs. 2 and 3). They found that the lineaments range in extent from 10 km to over 200 km. From the rose diagram, they inferred two preferred directions, that is NW–SE and NE–SW. The majority of the lineaments are believed to be of Achaeans age. Also it is opined that certain lineaments delimit the basin of deposition of the major geological units.

Further, major lineaments not only extend for long distances, but also show en echelon continuity. The lineaments also transgress geological formations of different ages.

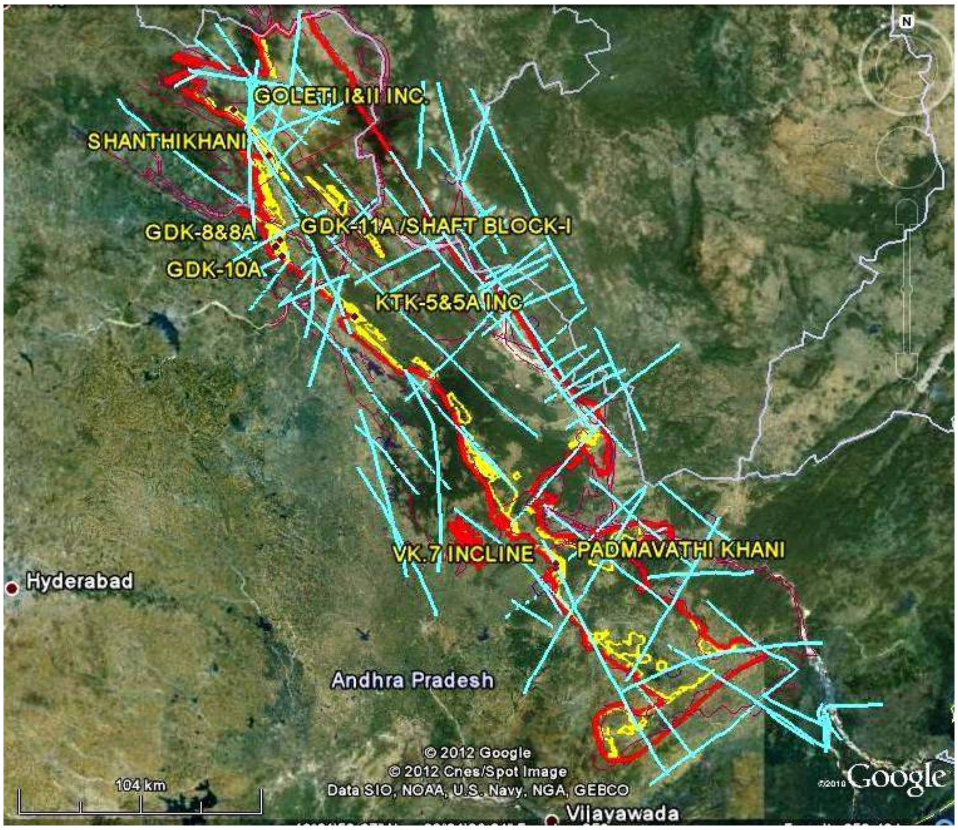

Fig. 2 - Geographical map of Godavari valley coalfield showing the major lineaments and mine locations

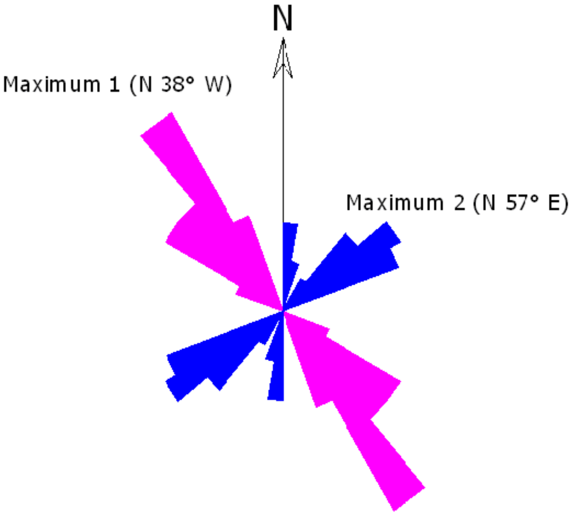

Fig. 3 - Rose diagram for major lineaments drawn at 10 degrees intervals
[Total number of readings = 110 (after Ramanamurty and Parathasarathy, 1988)]

The coal bearing Barakar formation in the Godavari valley coalfield exhibits predominant lineaments in the NE-SW direction, as seen from satellite imagery (Bhagavan et al., 2002). Trends of the majority of the lineaments vary between N15°E–S15°W. In the Barakar formation, the faults also trend more or less in the NE–SW and NW–SE directions. The NE–SW trending faults are more frequent compared to the NW–SE trending faults; the majority of them are in the N35°E–S35°W direction.

3. CLEAT PATTERN

Sharma (1996) examined the cleat pattern measured in one opencast and 16 underground mines, pertaining to five coalbelts: Dorli-Belampalli, Somagudem-Indaram, Ramagundam, Yellandu outlier and the Cherla-Manugur coalbelt of Godavari valley coalfield (Fig. 4). It was inferred that the general trend of the face cleat is NE–SW and the butt cleat is trending in the NW–SE direction. Further, he reported that the trends of cleats in equivalent seams of the five coalbelts do not suggest any major variation and the cleat pattern of overlying seams tally with that of underlying seams, suggesting that cleat pattern in a virgin seam can be predicted, if the data of an overlying or underlying working seams are available.

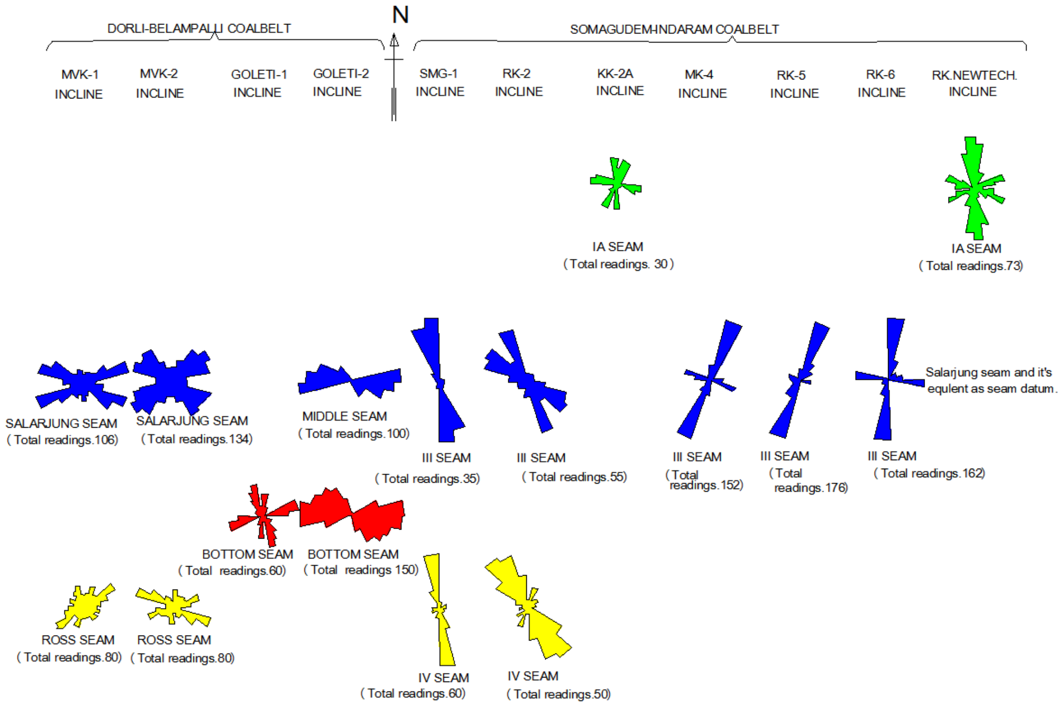

Fig. 4 - Rose diagrams of coal cleat pattern and correlation with equivalent seams (after Sharma,1996)

4. STRESS MEASUREMENT IN GODAVARI VALLEY COALFIELD

In July 2001, in-situ stress measurements were taken through hydro fracturing tests in underground workings of the III seam of KTK-5 Incline of SCCL by the National Institute of Rock Mechanics (NIRM, 2008) (Table 1). In 2004, in-situ stress measurement was conducted by Central Mining Research Institute (CMRI, 2007a) in the Shanthi Khani mine in underground workings in association with MeSy India Ltd. (2008, 2010). SCCL is the first coal company in India to conduct in-situ stress measurement at several horizons through a surface borehole in the GDK-8A incline by CMRI (2007b). Subsequently, hydro fracturing tests were conducted in the Adriyala shaft block (Fig. 5), KTK LW block and BHPL shaft block of SCCL. The test results of these blocks/mines are summarized in Table1.

Table 1 - Results of stress measurement tests carried out in Godavari Valley coalfield

Mine/block	Coal seam	Depth (m)	Direction		Magnitude (MPa)	
			Major principal stress (σ_1 or σ_H)	Intermediate principal stress (σ_2 or σ_h)	Major principal stress (σ_1 or σ_H)	Intermediate principal stress (σ_2 or σ_h)
Shanthi-Khani	Salarjung	395	N18E	N72W	4.08	2.04
Shanthi-Khani	Salarjung II(bottom)	476	N-S	E-W	10	5.8
GDK-8A	I	140	N15E	N75W	5.30	3.298
ADRIYALA	I,II.III and IV	522	N24 ± 14E	N66±14W	3.13	2.05
KTK LW	I,II,III and IV	328	N7±14E	N83±14W	1.7	1.4
			N (153 ± 20)	N(243±20)	5.9	3.4
KTK-5	III	223	N50E	N40W	8.62	4.31
		246	N50E	N40W	9.52	3.81
BHPL SB	I,II,III and IV	428	N11±10E	N79±14W	3.2	2.0

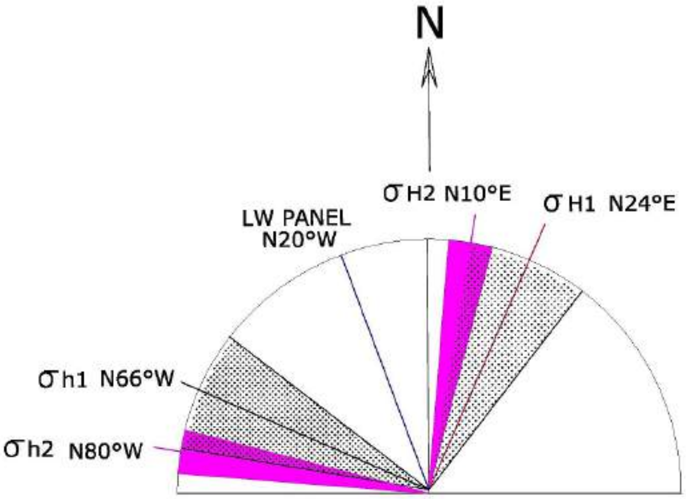

Fig. 5 - Stress direction of Adriyala shaft block by underground geotechnical mapping (σ_{H2} and σ_{h2} = σ_2 or σ_h) and hydro fracturing tests (σ_{H1} and σ_{h1} = σ_1 or σ_H)

5. STRESS MAPPING TECHNIQUE

The stress mapping technique is extensively used in many countries to avoid heavy expenditure on conducting in-situ stress measurements. Procedures have been developed to estimate the orientation of the maximum principal stress (σ_1). Features such as roof "guttering" or roof "pots" are mapped along with structural discontinuities (i.e., fault, slip, joint, cleat) in underground workings and the stress direction is inferred from their orientation and severity (Fig. 6).

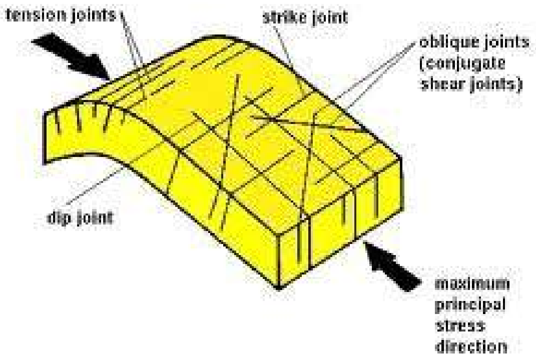

Fig. 6 - Relationship between stress orientation and joints

Sharma and Chandra (1988) investigated the orientation of the joints of the roof rocks and its bearing on the roof falls in the level galleries of Queen seam in VK-7 shaft. They found that the most prominent tensional joints J1 aligned to the greatest σ_1 are normal to the level galleries. At the same time, compressive forces also act perpendicular to the level galleries and hence the roof instability prevails only in level galleries. Conversely, the dip galleries are very stable.
Further, the above findings were considered to be valid in the practical field operations by Subba et al. (1993). They found that the performance of the strike face is better than the dip rise face. They described that "strata behavior in strike face was more favorable, as the periodic weighting interval was 12–15 m, unlike 16–20m in dip rise faces and breaker line during weighting is formed near to the face is stronger (Cleats are perpendicular to the face) unlike the dip rise face where the breaker line is formed away from the face as cleats are almost parallel to the face".

Mucho and Mark (1994) have explained stress mapping features like cutter, guttering or kink roof, tensile fractures, roof potting, roof bolt hole offsets, shear planes and rock flour and striations on roof rock. To facilitate the recognition of horizontal stress effects and to easily determine the principal stress direction without resorting to cumbersome, expensive and time consuming field measurements; the bureau has developed a stress mapping methodology. This approach has been used in other major coal producing countries, most notably Australia and UK and has greatly enhanced the safety of their mines.

Fabjanczyk (1996), invented that when roadways are driven in line with major horizontal stress (σ_1) the stress concentrations at the face of the roadway are minimized and roadway stability will be highest. (Further, the buckling of thin roof layers is reduced by the minor principal horizontal in-situ stress. Moreover, the coal pillar strength is also increased due to prestressing by the major principal horizontal in-situ stress). Also he added that when the 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. Further he described that 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-11A by conducting underground mapping to determine the reasons for roof instability in dip galleries (SCCL, 2000). These studies, together with mechanical properties and Rock Mass Rating as input data; three dimensional numerical modeling was done using FLAC3D to estimate the optimum orientation of the development roadways vis-à-vis in-situ stresses by Kushwaha et al. (2003).

Sharma (1999) in his studies inferred that changing the method of mining from bord and pillar to longwall has not much improved the working conditions. However, reorientation of longwall panels with reference to major stress direction has given a better working conditions and thereby improvement in the coal production.

Based on the stress mapping conducted by Sharma et al. (2006) in Padmavathi Khani in Kothagudem, the causative factor of unstable roof conditions in level galleries was found to be the most prominent Joint set J1 aligned to the greatest σ_1. Conversely, J3 joint set is parallel to the least stressed axis σ_3, and contributes to stable roof conditions in dip galleries. Roof strata consist of thinly layered beds and lead to failure that is confined to level galleries with an indication of "gutter roof". The trend of the "gutter roof" largely helped further to confirm the orientation of σ_1 in the study area. The findings of the present investigations agree with the stress orientation established in the adjacent block (i.e., VK-7 shaft).

Similar stress mapping was carried out in the middle seam of Goleti-1 incline and the probable $\sigma_1$was derived by the Exploration Division, Kothagudem (SCCL, 2006). It was inferred that the orientation of level galleries with reference to the σ1 was not favorable and hence roof instability is prevailing. Accordingly, it was suggested to reorient the galleries. Making use of this data, Shanker and Srinivas (2005) also recommended reorienting the galleries. Details of σ_1 derived from underground geotechnical mapping in the mines are furnished in Table 2.

Chary et al., (2006) suggested for more investigations by way of conducting hydrofrac tests and underground geotechnical mapping in different mines of Godavari valley coalfield. Based on the available data, they inferred that the general trend of σ_1 and σ_2 derived from the underground geotechnical mapping was in agreement with that of hydrofrac test results. Further, they added that, in general, trend of σ_1 is in NE and σ_2 is in NW in the Godavari valley coalfield

Table 2 - Stress measurements through mapping carried out in Godavari valley coalfield

Mine	Seam	Depth (m)	Direction		Magnitude (MPa)	
			Major principal stress (σ_1 or σ_H)	Intermediate principal stress (σ_2 or σ_h)	Major principal stress (σ_1 or σ_H)	Intermediate principal stress (σ_2 or σ_h)
VK-7	Queen Seam	250	N55°E	N35°W		
Padmavathi Khani	Queen Seam	340	N45°E	N45°W		
	King Seam	380	N45°E	N45°W	7.15	3.68
Goleti-1	Middle Seam	230	N5°E	N85°W		
GDK-11A	I Seam	260	N35°W	N65°E	4.6	2.6
GDK-10A	I Seam	300	N5–15°E	N75°–85°W		

Sharma and Jaidev (2011) carried out underground geotechnical mapping in GDK-10A mine and inferred that the most prominent joints J1 are in the direction of N5E and coincide with the pronounced set of normal slips. The next prominent joint set J2 trends in N75W and are closely spaced (Fig. 7). The face cleat trends in N5E and the butt cleat is in the direction of N80W. Based on mapping, it was presumed that σ_1 was between N5E and N15E. Subsequently, hydro fracturing tests conducted in the dip side block (Adriyala shaft block) indicated that σ_1 varies between N10E and N38E.

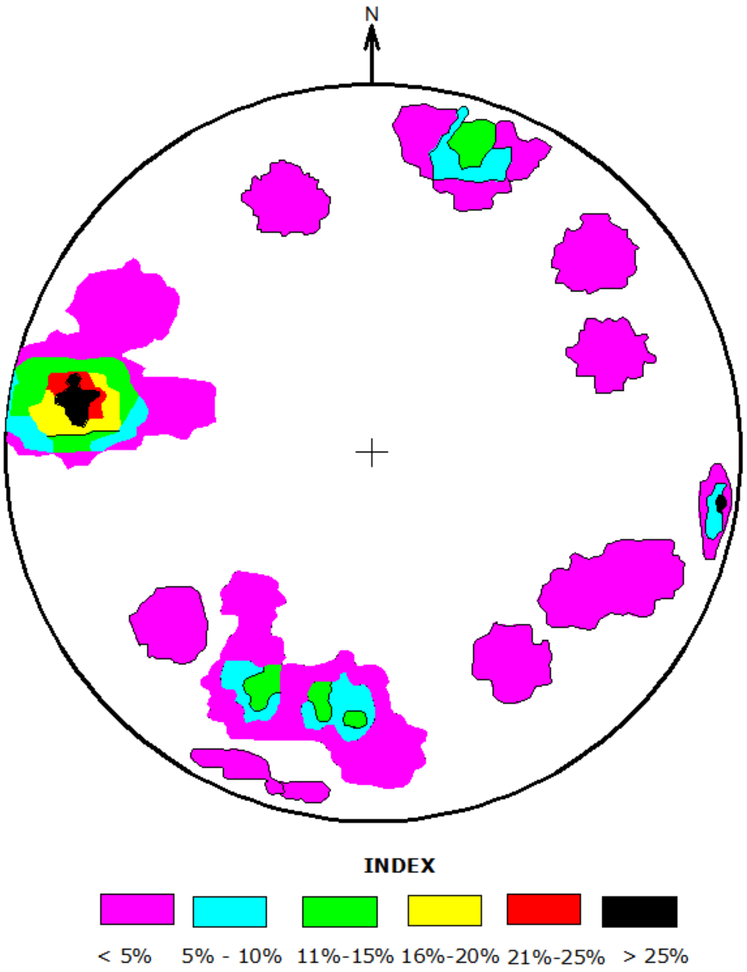

Fig. 7 - Contour diagram of joints plotted on equal area projection lower hemisphere of GDK-10A incline

Rao and Sharma (2014) reported that after reorientation of dip galleries closer to the mapped minimum horizontal in-stress direction, no bed dilation was observed in the roof strata of the dip galleries and maintained a cut out distance of 9m. No roof falls were observed after reorientation of the dip galleries and working conditions improved to achieve the set targets of production.

Kushwaha et al. (2012) carried out mapping in the underlying King seam in the Padmavathi Khani mine. Based on detailed field investigations, geo-technical mapping and underground observations of development roadways, orientation of the major and minor horizontal stresses were established. A numerical model was used to estimate the magnitude of major and minor in-situ horizontal stresses (Fig. 8). The magnitude of major and minor in-situ horizontal stresses in King seam of Padmavathi Khani mine in the proposed area are found to be 7.15 and 3.68 MPa, respectively and the direction of the major in-situ horizontal stress is found to be along N45E for King seam of the mine, which is almost perpendicular to the level galleries.

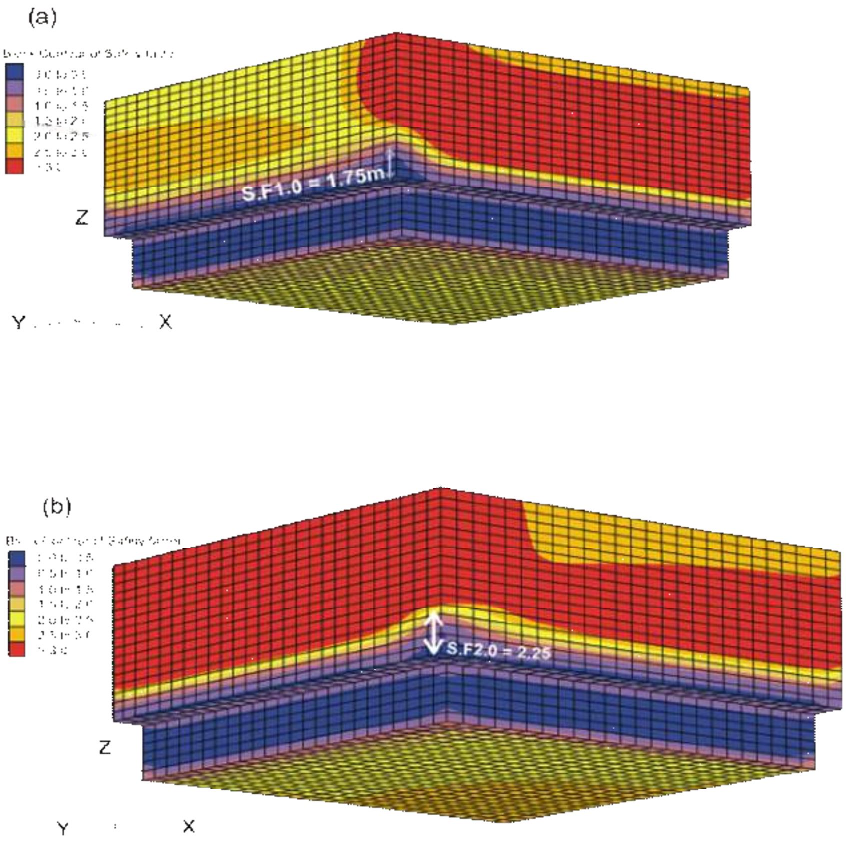

Fig. 8 - Contour of factor of safety around junction and galleries with (a) σ_H (or σ_1)at 28º with X-axis and (b) σ_H (or σ_1)at 130º with X-axis (after Kushwaha et al., 2012).

6. CONCLUSIONS

Horizontal stress factor serves as an input parameter for most of the studies needed for the design of support system and support selection of underground mining. The perusal of data generated by various studies conducted in Godavari valley coalfield helped to a large extent to establish the orientation of σ_1 (or σ_H)and are summarized below.

- Based on satellite imagery, the majority of the lineaments are trending in the NW–SE direction and least prominent set of lineaments are trending NE–SW.
- Lineaments in the Barakar formation are trending in N15°E–S15°W and faults trend in NE–SW direction.
- The face cleat trends in NE–SW and butt cleat trends NW–SE.
- Based on the hydro fracture tests conducted both from surface and underground boreholes, the major horizontal in-stress (σ_H or σ_1) trends NE–SW and minor horizontal stress (σ_h or σ_2) trends NW–SE. The magnitude of σ_H (or σ_1) ranges from 1.70-10MPa, whereas σ_h (or σ_2) ranges from 1.40-5.38MPa.
- Based on underground geotechnical mapping, σ_H trends N5°E–N55°E and σ_h trends N35°W to N85°W.

Based on the findings from the above available data, it is inferred that:

- Major trend of lineaments, faults and cleat are also NE–SW and tally with the trend of σ_H.
- In general, the trend of σ_H (or σ_1) is in NE and σ_h (or σ_2) is in NW in the Godavari valley coalfield.

- The general trend of σ_H and σ_h derived from the underground geotechnical mapping is in agreement with that of hydro fracture test results.

Nomenclature

σ_H or σ_1 = Major principal or horizontal stress direction; σ_h or σ_2 = Minor principal or horizontal Stress direction; σ_3 or σ_v = Vertical stress; MPa=Mega Pascal; J1 = Primary joints; J2 = Secondary joints; J3=Tertiary joints.

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