P. RAGHUPATHI
G. BUDI
R. M. BATTACHARJEE
and
A. K. SINHA

Study of strata behaviour in longwall workings

Coal has been one of the energy resources of the country and it is extracted from earth crust by different methods. Longwall mining is the most popular and productive method of coal mining in the world. Majority of the longwall mines in India have not become as successful as they were envisaged. The main reasons for the underperformance of the longwalls in India, among others, have been strata control problems due to inadequate geological and geotechnical assessment, poor understanding of strata behaviour and selection of under rated supports. Complex strata mechanics issues like excessive stress concentrations, strata dilation or convergence of roof strata in longwall workings are potential hazard of strata failure. Therefore, proper understanding of geo-mechanics of strata and continuous strata monitoring in longwall workings is prerequisite for its effective control and ensuring safe workings. This paper discusses the strata control problems in Indian longwall mines and presents the instrumentation for strata monitoring. It also suggests a general scheme of strata monitoring in a longwall workings and explains a case study.

Keywords: *Longwall mining, strata behaviour, strata monitoring, instrumentation.*

1. Introduction

Longwall mining is a popular and predominant underground coal mining method worldwide. Production, productivity, and resource recovery of the longwall method are unmatched by any other underground mining methods. Historically, longwall mining in India dates back to 1874 [2]. But the development of longwall technology in Indian coal industry has been slow and halting. Until 1960, longwall method was practised in conjunction with sand stowing and thereafter longwall with caving was started. During 80's of the last century, about 35-40 longwall faces were in operation in combination with hydraulic and friction props. The first fully mechanised longwall face was introduced in India in 1978 in Moonidih Colliery, BCCL [2]. Subsequently, about 32 fully mechanized longwall units were deployed in different Indian collieries, of which, presently, only 3 are in operation.

Mr. P. Raghupathi, Dy. Director of Mines Safety, DGMS, Dhanbad, raghupathi.ddms@gmail.com, Dr. G. Budi, Asst. Professor, anandbudi@gmail.com, Dr. R. M. Battacharjee, Professor, Department of Mining Engineering, IIT (ISM) Dhanbad, rmbhattacharjee@yahoo.com and Dr. A. K. Sinha, Dy. Director General of Mines Safety (Retd.), SEZ, DGMS, Ranchi, India, ashimkrsinha@gmail.com

Though the longwall technology is successful in many countries, majority of the longwall mines in India have not become as successful as they were envisaged. Longwall introduced in a few mines, like GDK10A, Jhanjra, Moonidih, worked satisfactorily. However, many other longwall faces in the mines like Dhemomain, GDK11A, Sitalpur, etc., faced severe strata control problems, and some of the longwall faces collapsed prematurely in the mines like Churcha, Kottadih. At Churcha mine of SECL, the very first longwall face collapsed after an advance of 190m due to dynamic weighting. Whereas, in Khottadih mine of ECL, first two longwall panels were extracted with considerable strata control problems while the third face met severe collapse after an advance of 791m due to a dynamic weighting. Moreover, excessive spalling, crushing of the barrier pillar was also reported during extraction of the third panel due to excessive stresses [2]. Longwall faces in RVII seam of Jhanjra mine of ECL in Raniganj coalfield were extracted at shallow depth of 40-60m without major strata control issues. However, longwall workings at a shallow depth of 50-80 m in Balrampur and New Kumda mines of Bishrampur coalfield and in Rajendra mine of SECL in Sohagpur coalfield faced sever strata control problems. In Balarampur colliery, P1 longwall panel experienced severe weighting after advance of 80m and again severe loading after advance of 160m resulting in damage of many powered supports in overcoming the weighting. Similar problems were experienced in P16 panel of Rajendra colliery. The severe load at the face during weighting periods was subsequently managed in these mines by regular blasting of the overhung strata in goaf from surface at every 15m of face advance [3]. The main reasons for the failure of the many longwalls in India were, – inadequacy of geological and geotechnical assessment of longwall locales, poor understanding of strata behaviour under different geo-mining conditions of the mines, along with flawed equipment selection with inadequate rating of supports and other equipment [4].

Collapse of the strata in longwall workings is one of the primary safety hazards, which not only hinders the production and productivity of the mine but also endangers the safety of the persons working therein. Accidents due to movement of strata in underground coal mines had been a major concern for the mining industry and it is still one of the major hazards in Indian coal mines. Roof and side falls accounted for about 22% of the total fatal accidents in the coal mines during the year 2016 [10].

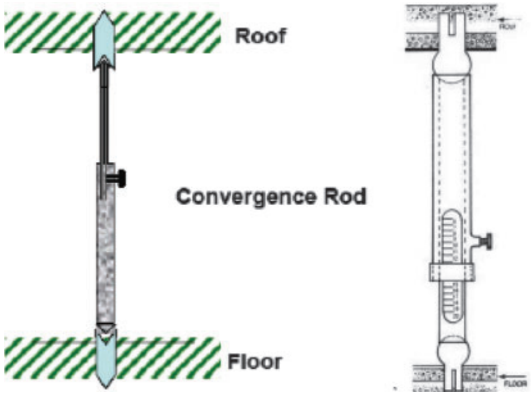


Fig.1a Telescopic convergence indicator

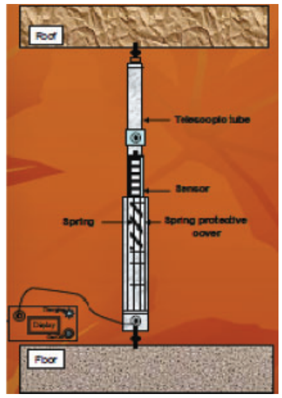


Fig.1b Remote convergence indicator

Depth of the mines in India is increasing steadily, some of the mines like Adriyala and Moonidih, are already working at a depth of 450m to 550m. In future, various coalfields may have to go for greater depths of about 600 m and more. Vertical and horizontal stresses and associated strata control problems will be more at such great depths. Complex strata mechanics issues like excessive stress concentrations, strata dilation, convergence of roof strata at any working place is a potential hazard of strata failure. The prediction of caving behaviour of roof strata and the support capacity requirement for safe working in longwall is a complex issue and requires utmost care while conducting strata behavioural studies [12].

The strata characteristics in longwall workings depend on caving nature of the strata above coal seam, which is a function of properties of roof strata, height of extraction, panel geometry, dipping of seam, etc. If the roof behind longwall face does not cave in the goaf regularly, excessive load is transferred on to the longwall face, face supports and side barriers which may result in failure of coal face, barrier pillars and closure (solid) of the face supports [1]. Accurate prediction of strata behaviour in general and the caving behaviour (weightings), stress concentrations that may occur during mining operations in particular are required for design of a safe and economical longwall panel. Thus, monitoring of strata behaviour during different phases of extraction of longwall panel is not only required for ensuring safety and stability at longwall workings but also provide essential inputs for proper planning and design of longwall panels, assessing support requirements and its verification, etc. [6]. Therefore, assessment of strata conditions of working places in longwall panels by scientific methods is essential.

2. Instrumentation for strata monitoring

2.1 Convergence indicators

Convergence indicators are used for measurement of roof to floor convergence of gate roadways, shown in Figs.1a and 1b.

2.2 Extensometers/tell tales

These instruments are used to measure bed separation or strata dilation in the roof strata of roadways and also to know the progressive failure (softening) of roof strata. Different types of extensometers/tell tales available are shown in Figs. 2a, 2b and 2c.

2.3 Load cell

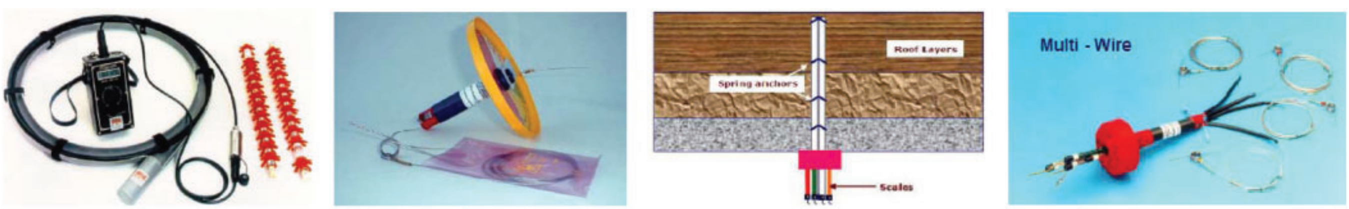
Load cells are used to measure the load exerting on the supports. These are many kinds based on the principle of operation like hydraulic, mechanical, strain gauged, vibrating wire type and some of them are shown in Fig.3.

2.4 Instrumented bolt

Instrumented bolts are used for determining distribution of load along the roof bolt (Fig.4). The bolt is used for obtaining data for design purpose. It is a valuable tool for monitoring support system performance against design specifications.

2.5 Stress cells

The stress cells are used for measuring stress changes in the in situ pillars, ribs or barrier/chain pillars (Fig.5).



(a) (b) (c)

Fig.2(a) Sonic probe extensometer (b) Rotary tell-tale (c) Multi anchor tell-tale

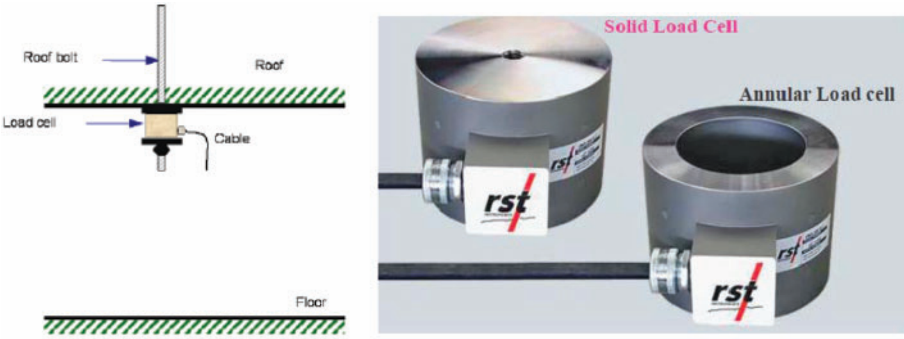


Fig.3 Load cells

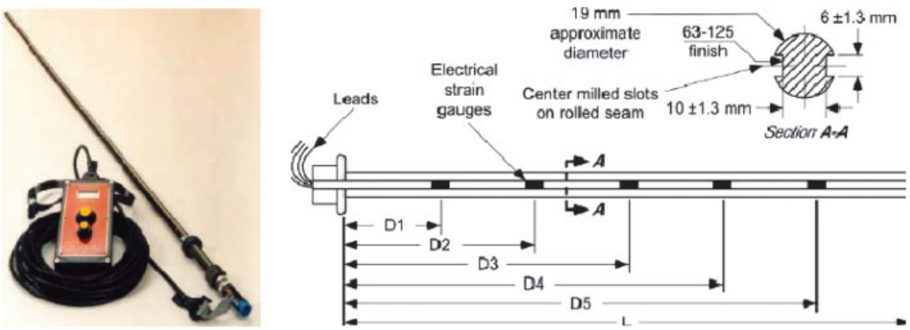


Fig.4 Instrumented bolt

3. Scheme of monitoring of strata during longwall extraction

Development of a suitable scheme for monitoring of strata behaviour in longwall panels is an important part of strata management plan. Strata behaviour is monitored in a longwall panel broadly at three areas, i.e. in gate roadways, at face area and on the surface over the longwall panel. The generalised scheme of monitoring of strata in a longwall panel and instruments used are given in Table 1.

4. Latest trends in strata monitoring systems

The conventional system of monitoring of strata in longwall panels by manually is intermittent, laborious and time taking. However, the strata behaviour in a longwall workings is dynamic and prone to change rapidly, which warrants continuous monitoring of the hazards to facilitate real time indication or warning to concerned stakeholder in the event of

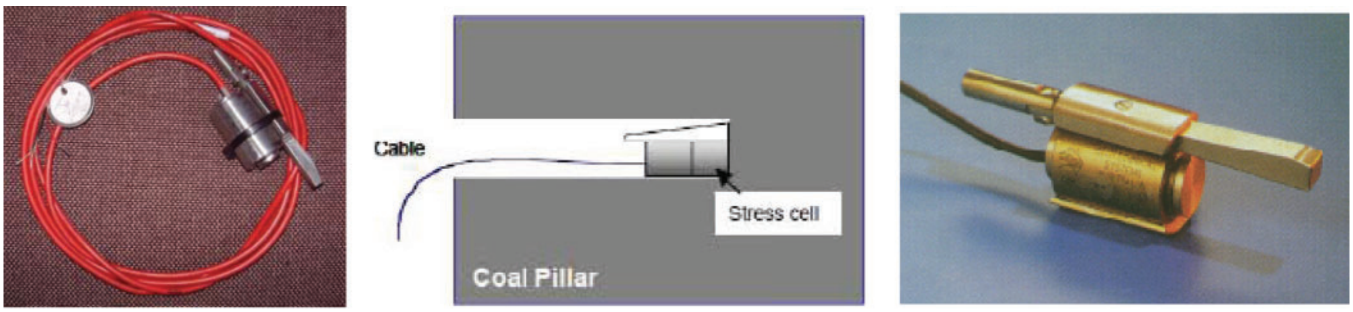


Fig.5 Stress cell

TABLE 1: PARAMETERS OF THE STRATA TO BE MONITORED IN A LONGWALL PANEL

	Place of monitoring	Parameter to be monitored	Instruments used
I	In gate roadways	Roof to floor convergence	Convergence indicators
		Strata dilation/separation in roof strata	Extensometers/tell-tales
		Load on supports installed in gate roadways	Load cells, instrumented roof bolts
		Abutment stresses on chain pillar/barrier pillar	Stress cells
		Abutment stresses on longwall pillar ahead of the face	Stress cells
II	At face area	Load on powered supports installed at face supports	Pressure gauges fitted in hydraulic legs of supports
		Convergence of powered supports installed at face	Leg closure indicators
		Physical observation of face spalling, cracks/ cavities in roof, water seepage from roof , etc.	Visual inspections
III	On the surface over the longwall panel	Monitoring of subsidence	Total station, theodolite
		Progressive caving of the roof strata in the goaf on retreat of longwall panel	Multi point borehole extensometers, borehole camera

risk level exceeding beyond threshold value. In the past, many incident evaluations have shown the existence of predictive data but a lack of integration and interpretation has inhibited the delivery of vital information to mine site personnel [11]. Therefore, continuous monitoring of the strata behaviour and giving timely warning of impending dangerous occurrence/strata movements, will definitely help in avoiding such events and aid in creating safer working conditions in mines. It is evident that monitoring and controlling, predicting and warning are the essential preconditions and key to prevent dangerous occurrences/accidents [15].

In view of the above, many mineral producing countries are focussing on real-time monitoring systems and efforts are being made to develop such systems. In Australia, integrated real time roof fall monitoring and warning system was developed for underground coal mines by CSIRO and the Japan Coal Energy Center (JCOAL) [5]. Development of real time strata monitoring systems for Indian mines is need of the day. With the advancements in information technology, development of an effective real time monitoring systems may be better feasible [15]. The real time monitoring systems will further augment the mine safety and enable the mine management to make information based decisions in safety-related areas and enable them to be ready for timely response to emergency situations.

5. Field investigations

The field investigations were carried out in the workings of a fully mechanized longwall panel of a coal mine in India. There were four coal seams in the mine having nomenclature as seam Nos. 1, 2, 3 and 4 in descending order. The longwall panel (panel A) was in the top most seam (i.e. Seam No.1) and all other seams below the panel were virgin. Thickness and gradient of the seam No.1 were about 6.50 m and 1 in 6 respectively. Gate roadways of the panel were developed along floor of the seam with a height of 3.0m. About 3.3m thick coal seam was being extracted along floor of the seam in the longwall panel by leaving 3.20m coal and clay along roof. The location of the panel with respect to previously extracted panels and borehole section are shown in Fig. 6 and its geo-mining parameters are given in Table 2. The longwall face was supported with chock shield supports of 4 × 800 T capacity with a support resistance of 98.3 T/m^2 and a tip load of 182.12 T. Yield pressure and setting pressure of the supports were 40 MPa and 30 MPa respectively. The gate roadways up to a distance of 30m from the face (in abutment zone) were supported by two rows of 40-tonne capacity hydraulic props at an interval of 1.5m between props in the same row. In addition to this, the gate roads were supported by full column grouted roof bolts set at 1.2m intervals with wire mesh and w-straps during development of gate roads.

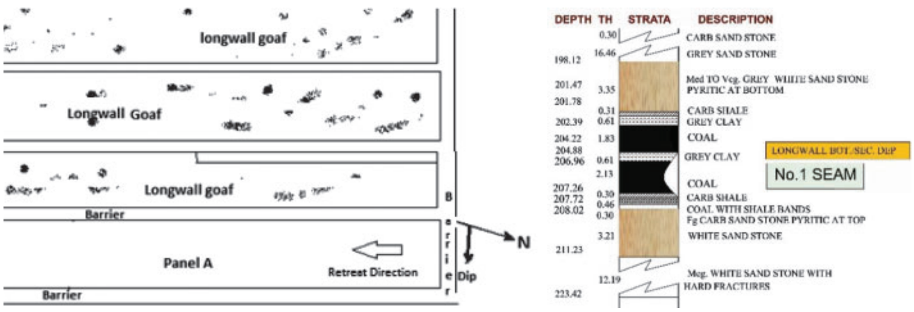


Fig.6 Location of the panel with respective to previously extracted panels and borehole section

Table 2: Geo-mining parameters of the panel

Name of the seam	Seam - I
Length of the face	165m
Length of the panel	1020m
Maximum cover depth	359m
Minimum cover depth	287m
Average cover depth	323m
Panel width/depth ratio	0.5
Seam thickness	6.5m
Height of extraction	3.3m along floor of the seam
Gradient of the seam	1 in 6
Degree of gassiness	Degree - I
Nature of the immediate roof	Coal with a clay band of 30 cm
Nature of immediate floor	Grey sand stone
No. of supports at face	108 nos.of 4×800Te chock shields

5.1 Strata monitoring

Different parameters of strata of the longwall panel were monitored with various instruments during extraction of the panel A. Details of the instrumentation in the panel are shown in Fig.7. The parameters of the strata monitored in the panel were,- convergence of the gate roads, load on individual hydraulic prop supports installed at the gate roads, front abutment stress on the longwall pillar, dilation (height of softening) in the roof strata of gate road ways, strain of the coal pillar in abutment zone, load on supports at the face during normal and weighting periods, convergence during normal and weighting periods at the face, physical observations in the panel to identify roof flaking, face spalling and cavity formation if any at the face during normal and weighting periods and goaf behaviour with respect to overhangs, caving nature, etc., and subsidence monitoring on the surface over the panel.

5.1.1 Convergence of the gate roadways

Convergence of tail gate and main gate roadways were monitored with telescopic convergence indicators as the face retreats. Convergence stations were fixed at an interval of 5m in both the gate roadways to measure the convergence of the gallery at that point. The cumulative convergence observed

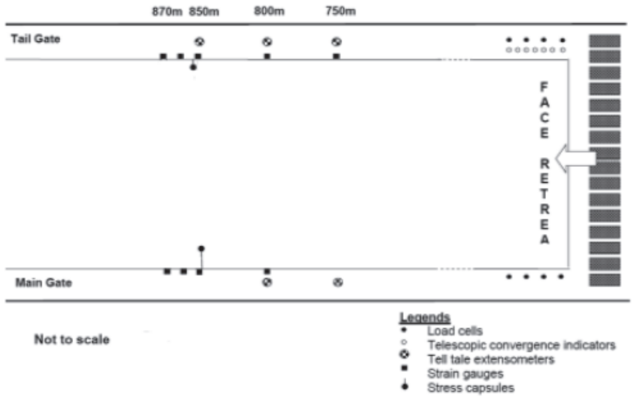


Fig.7 Instrumentation plan for strata monitoring in the panel

at 670m in MG and 720m in TG with retreat of the face are given in Figs.8a and 8b. The maximum cumulative convergence 140mm was found at 720m in TG, when face approached it. At all the stations, rapid increase of convergence was observed within 5m of the face and maximum convergence was at T-junctions.

5.1.2 Load on the hydraulic props in the gate roadways

Variation of load on individual prop supports was measured by installing load cell on the prop. In each gate road way, 3 load cells were installed at 10m interval. The load variation in the load cells was measured once in every day as face progresses. Only marginal increment of load on the OC props was observed with retreat of the face.

5.1.3 Strata dilation in the roof of gate roadways

Tell tales with three anchors were installed in the tail gate (TG) and the main gate (MG) of the panel to identify the location and magnitude of strata dilation in the roof strata of the gate roads. Tell tales were installed at 750m, 800m, 850m in TG and 753m, 801m in MG. Anchors of the tell-tales were fixed at 1m, 2.5m and 4.0m in the roof strata above the gallery. First two anchors were fixed in immediate coal roof and third anchor was in sand stone over the coal seam. The observations of the tell tales at 800m in TG and 801m in MG with retreat of the face are shown in Figs.9a and 9b respectively. The observations indicated that separation of roof strata took place at two parting planes between 1m and 2.5m anchors and 2.5m and 4m anchors in the gate roadways. Maximum separation of strata took place at parting plane lying between 2.5m and 4m above the roof (i.e. between coal and sandstone beds) in both gate roadways. Maximum strata dilation of about 80mm was observed at that parting plane between 2.5m and 4.0m at T-Junctions. The bed separation was started at the parting planes when the tell-tale was about 30 to 40m outbye of the face and dilation increased as face approaches it. Maximum dilation of the parting plane was observed within the 10m from the face and more than 50% of dilation of the strata was found within the 5m from the face.

5.1.4 Strain of the pillar

Strain bars were installed in coal pillar ahead of face in both main and tail gates to estimate the compressional strain

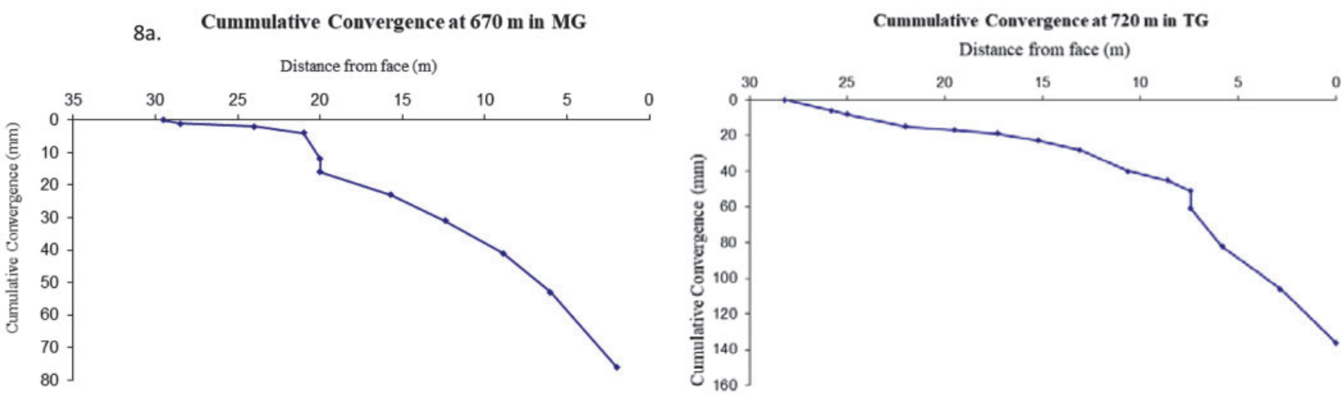


Fig.8a and 8b Convergence of gate roadways with retreat of longwall face

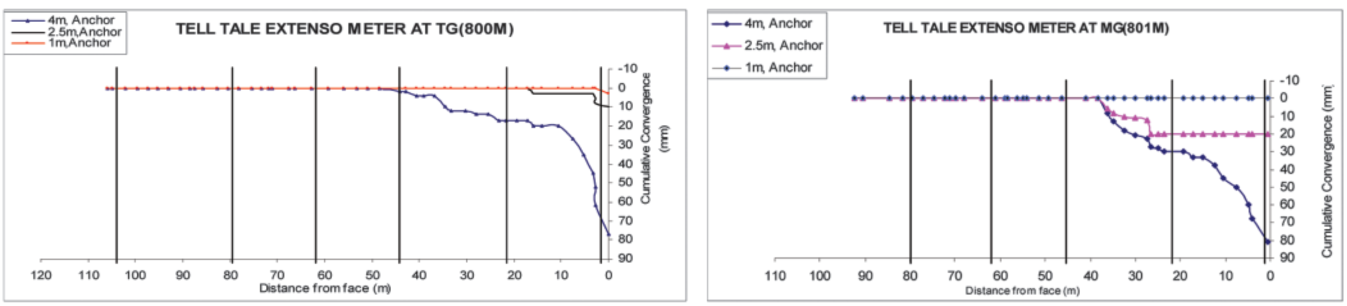


Fig. 9a and b Strata dilation in TG and MG with retreat of face

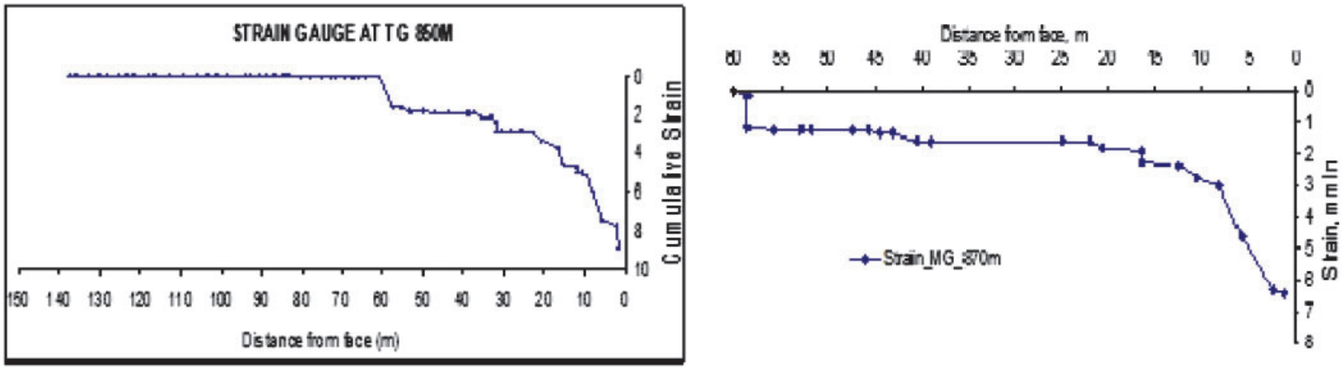


Fig.10a and 10b Cumulative strain in coal pillar with face retreat

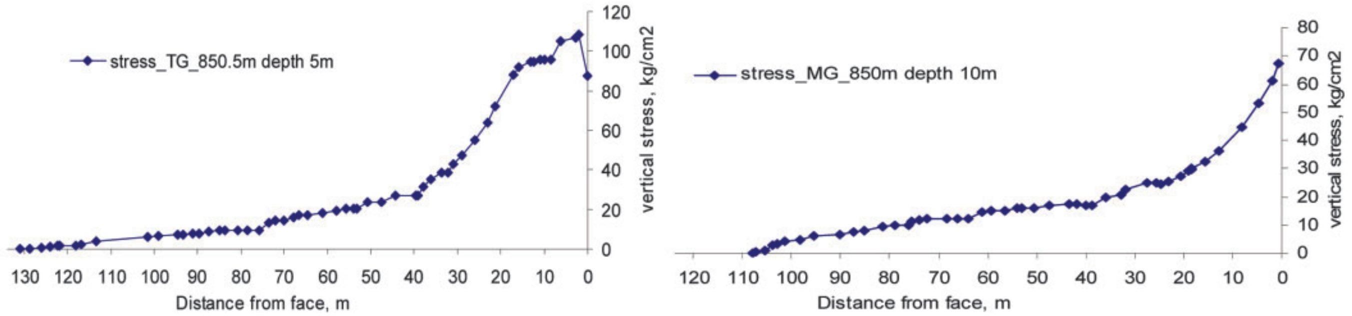


Fig.11a and 11b Variation of cumulative stress on coal pillar with retreat of face in TG & MG [8]

of the coal pillar due to front abutment loading. Strain bars were fixed between two rods, which were grouted in the coal pillar at an interval (l) of 1.5m vertically one above other. The reduction in the vertical distance (Δl) between the two rods in the coal pillar due to abutment loading of coal pillar was measured by strain bars. The strain Δl/l (mm/m) observed in the strain bars installed at 850m in TG and 870m MG with retreat of face was shown in Figs.10a and 10b. The rapid cumulative strain of the pillar was observed within 5m from the face. The maximum cumulative strain 8.84mm/m was recorded in strain bar fixed at 850m in TG when the face was approaching it. The observations revealed that the coal pillar up to a depth of 1.5m from the face got fractured and the strain bars got disturbed due to abutment loading as the face approached it.

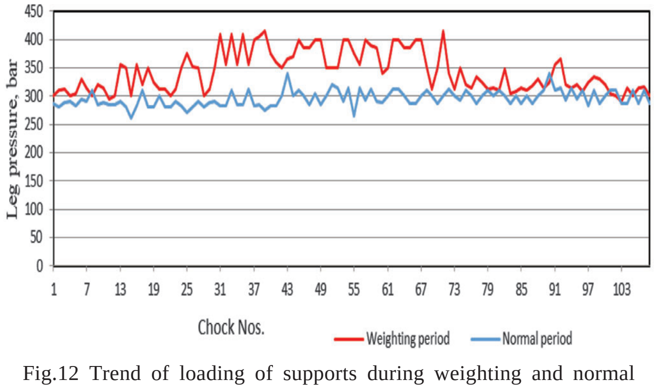


Fig.12 Trend of loading of supports during weighting and normal periods

5.1.5 Abutment stress on coal pillar ahead of face

Vibrating wire stress cells were installed in coal pillar from tail gate and main gate to monitor the front abutment stress induced on the coal pillar, ahead of the face. Abutment stress recorded in the stress cells at 850.5m in TG and 850m in MG with retreat of the face are shown in Figs.11a and 11b. The front abutment stress was first felt in the instruments at about 100m to 110m ahead of the face and the stress steadily increased in zone of 100m to 40m from the face. Rapid increase of the stress was started in the zone 20m to 40m ahead of the face. The peak front abutment stress 108.42 kg/cm^2 (1.4 times the burden stress) was recorded at about 2m ahead of the face in the stress cell installed at 850.5m from TG side. In other cases, the peak front abutment was less than the burden stresses. Therefore, it may be concluded that abnormal load was not transferred on to the face/ pillar, since the caving of the overlying strata was regular in the goaf. It was also observed that, the front abutment stress was more towards TG side (108.42 kg/cm^2) than MG side(68 kg/cm^2), which might be due to presence of previously goaved out panels on the TG side.

5.1.6 Load on the chock shield supports at face:

Variation of the load on the supports at the face was monitored with pressure gauges fitted to leg circuits of the supports. One gauge each was fitted in the circuit of front legs and the rear legs of a support. The pressure gauge readings were taken once in every day. Trend of variation of

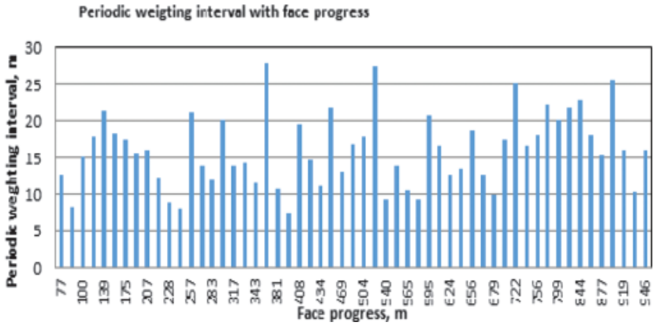


Fig.13 Periodic weighting interval in the panel

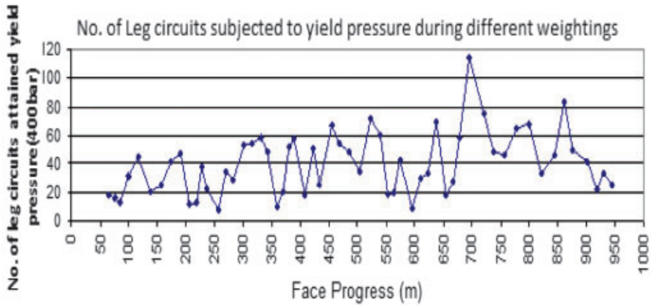


Fig.14 No. of leg circuits bleeding during weightings

the average pressure in the leg circuits during a minor weighting and normal period were as shown in Fig. 12. During most of the weighting periods, the supports at the mid zone (from C30 to C80) experienced weighting and few chocks subjected to yielding/bleeding. During major weighting periods, supports from C15 to C96 were subjected to loading.

5.1.7 Caving behaviour of roof strata (main and periodic weightings)

First local fall occurred in the goaf after a face retreat of about 17m and subsequently, two major local falls were observed in the goaf after face retreat of 41.7 m and 56.1 m respectively. Main fall/weighting took place after face retreat of 62.7m. Thereafter, periodical weightings were occurred regularly at an interval of 7.5m to 27.3m with an average interval of 16m. Details of periodic weighting interval is shown in Fig.13. It was also observed that, every 3rd or 4th weighting was more severe in terms of no. of chocks bleeding and duration of weighting. It was assumed that the major periodic weightings were occurred when the upper main roof caves in and minor weightings were due to caving of lower main roof. Severity of the weightings in terms of number of leg circuit bleeding during weighting is shown in Fig. 14.

5.1.8 Subsidence over the panel

Surface subsidence over the panel was monitored with total station. Fixing of the levelling stations and subsidence survey was conducted as per the DGMS technical circular No.4 of 1988. Maximum subsidence of 1.1m (33% of extraction height) was observed over the panel.

6.0 Discussions and conclusions

Many of the longwall mines in India, in the past, faced strata control problems due to selection of the unsuitable locales/ mines without proper understanding of its caving behaviour and deploying of under rated supports. For planning of successful longwall panels, understanding of strata characteristics, selection of suitable supports and devising proper strata control methods are essential. Strata monitoring by field instrumentation is vital tool in the prediction of ground behaviour in longwall workings and to obtain a detailed information of strata characteristics like stress concentrations and deformations, etc. Monitoring of strata behaviour during extraction of longwall panel is not only required for ensuring safety and stability at longwall workings but also provide essential inputs for proper planning and design of safe longwall panel layouts, assessing support requirements and its verification, etc.

This field study involved extensive field instrumentation to understand the behaviour of strata at different locations within the longwall panel. Results of the study revealed that the retreating longwall panel was having an influence of front abutment stresses up to a distance of about 100m ahead of the face. There was fractured zone in the coal pillar up to a depth 1.5m to 2.0m from the face, beyond which peak abutment stress of about 1.4 times initial burden stress was found towards tail gate. In other cases, the peak front abutment was less than the burden stresses. From the study, it may be concluded that abnormal load was not transferred on to the face or pillar, since the caving of the overlying strata was regular in the goaf. Stresses towards tailgate side were more than main gate side, may be due to presence of previously goaved out panels. It was also observed that increase in compressional strain of the coal pillar, convergence of gate roadways and dilation of roof strata in the gate roadways were more within the 5m of the face. However, the study indicated that convergence in gate roadways, strata dilation and stress concentration in the panel workings were not abnormal during longwall extraction. Thus, monitoring of strata characteristics in longwall panels by field instrumentation essential in assessing the behaviour of longwall panels during extraction and ensuring safety of the workings.

Readings of the instruments were recorded manually once in a day, which was a laborious and time taking process. Moreover, strata behaviour in a longwall panel is dynamic and prone to change more rapidly, which demands continuous monitoring, and interpretation to give timely warnings of impending failures. Therefore, development and implementation of systems like real time monitoring and integrated with a well-defined trigger action response plan(s) and emergency initiated protocol(s) are need of the day for Indian longwall mines.

Acknowledgement

The authors are obliged to Director General, DGMS for his permission to present this paper. The views expressed in this paper are those of the authors and not that of Directorate General of Mines Safety and also express their sincere gratitude to all those who helped directly or indirectly in preparing this manuscript. The analysis and work reported in this paper forms the part of PhD work of the first author.

References

1. Peng, S. S. (2006): Longwall mining, 2nd edn. Society for Mining, Metallurgy, and Exploration, Inc. (SME), Englewood.
2. Sarkar, S. K. (1998): "Mechanised Longwall mining, the Indian experience," Oxford & IBP.
3. Mozumdar, T. K. and Pan, B. (2015): Longwall mining at shallow depth of cover in India, Partridge India.
4. Ghose, A. K.: "Why Longwall in India has not Succeeded as in other Developing Country Like China," *Journal of Mines, Metals and Fuels*.
5. Shen, B., et al. (2006): An Integrated Real-Time Roof Monitoring System for Underground Coal Mines, University of Wollongong, Research Online.
6. Sastry, V. R. and Nair, R. (2009): "Study of behaviour of workings in longwall panel based on field instrumentation," *Int. J. Mining and Mineral Engineering*, Vol.
7. The Nexsys, Real-time Risk Management and Decision support System: Redefining the Future of Mines Safety by Kerstin Haustein, Eleonora Widzyk-Capehart, Peter Wang, Dean Kirkwood and Ricky Prout, Research Online, University of Wollongong, 2011.
8. CIMFR, NIRM & ISM (2010): Report on "Investigation of cavability of overlying strata and development of guidelines for estimation of support capacity for longwall faces."
9. Whittaker, B. N. (1974): "An appraisal of strata control practice." *The Mining Engineer* 134(2): 9-24.
10. Standard Note, 01.01.2017: Government of India, Ministry of Labour & Employment, Directorate General of Mines Safety.
11. Real time risk analysis and hazard management by G Einicke and G Rowan; Coal 2005: Coal Operators' Conference, University of Wollongong & the Australasian Institute of Mining and Metallurgy, 2005, pp. 299-306.
12. Singh, G. S. P. (2014): "Conventional approaches for assessment of caving behaviour and support requirement with regard to strata control experiences in longwall workings." *Journal of Rock Mechanics and Geotechnical Engineering*.
13. Walke, Deepak V. and Yerpude, Dr. R. R. (2015): "Significance of Strata Monitoring Instruments in Roof Fall Risk Assessment of an Underground Coal Mine," *International Journal of Scientific and Research Publications*, Volume 5, Issue 6, June 2015.
14. Raghupathi, P., et al., (2000): "New dimension in hard roof management," *Journal of Mines, Metals and Fuels*, January- February-2001.
15. Raghupathi, P., Sinha, Dr. A. K. and Bhattacharjee, Dr. R. M. (2016): "Innovative OSH Management in Indian Mines," APOSHO 31 Conference held on 5th -6th April, 2016 at Vigyan Bhawan, New Delhi.
16. Dattatreyulu, J. V., et al.: "Geotechnical studies for introducing high capacity longwalls and longwall top coal caving Mining in SCCL."

RESEARCH ON RISK ASSESSMENT OF DEBRIS FLOW IN A MINING AREA IN WESTERN CHINA BASED ON THE GAME THEORY EMPOWERING NORMAL CLOUD THEORY

(Continued from page 850)

8. Kuang, Lehong, Xu, Linrong and Liu, Baochen (2006): "Debris Flow Hazard Assessment Based on Extension Method [J]." *China Railway Science*, 2006, 27(5):1-6.
9. Wang, Yingchao, Jing, Hongwen and Zhang, Qiang, et al. (2015): "A Normal Cloud Model-based Study of Grading Prediction of Rock Burst Intensity in Deep Underground Engineering [J]." *Rock and Soil Mechanics*, 2015, 36(4):1189-1194.
10. Zhang, Gui (1999): "Prevention and Control Measures of Soil and Water Loss in the First Stage Development of Zhungeer Coalfield [J]." *Chinese Journal of Soil and Water Conservation*, 1999, 19(6):33-34.
11. Shang, Junlong, Hu, Jianhua and Mo, Rongshi, et al. (2013): "Predication Model of Game Theory-matter-element Extension for Blastability Classification and Its Application [J]." *Journal of Mining & Safety Engineering*, 2013, 30(1):86-92.
12. Liu, Jinpeng, Lan, Yongchao and Gao, Shiming, et al. (2015): "Application of Entropy Weight and Improved Extension Method to Debris Flow Risk Assessment [J]." *Mountain Research*, 2015, 33(4):496-502.
13. Gu, Fuguang, Wang, Qing and Zhang, Chen (2010): "Debris Flow Risk Assessment by PPC and Extenics [J]." *Journal of Jilin University (Earth Science Edition)*, 2010, 40(2):373-377.
14. Wang, Wei, Tian, Jie and Ma, Donghui. et al. (2011): "Evaluation of Dangerous Degree of Debris Flow Based on Fractal Dimension Weight [J]." *Journal of Mountain Science*, 2011, 29(6):747-752.
15. Wang, Minwu, Li, Li and Jin, Juliang (2009): "An Improved Set Pair Analysis Model for Evaluation of Dangerous Degree of Debris Flow [J]." *Journal of Natural Disasters*, 2009, 18(6):124-128.
16. Cao, Chen, Wang, Yihong and Chen, Jianping, et al. (2015): "Debris Flow Risk Assessment Based on Cloud in Miyun Beijing [J]." *Journal of Engineering Geology*, 2015, 23(s1): 624-630.