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Techno-economic analysis for development of a drive in view of geo-mining conditions – a case study

This paper presents all the rock mechanics studies carried out at an underground metal mine in Kadapa, Andhra Pradesh. The rock mechanics investigations in this mine include optimization of pillar dimensions by numerical modelling, the feasibility of hangwall lode mining at shallow depth, support design for deeper levels, instrumentation to monitor the strata for an experimental hangwall stope. The main aim is to improve extraction ratio and the mine safety levels from these rock mechanics studies to develop a mine. The effect on the linear advance in both footwall lode and hangwall lode is studied, monitored and found that there is almost 25% increase in total cost per round of blast due to difficult geo-mining conditions and affecting total cost per tonne of ore extracted from hangwall in contrast to footwall lode development and safety aspects. A critical case study with techno-economic cost analysis in view of their geo-mining conditions has been discussed.

Keywords: *Metal mine; rock mechanics; development; supports; linear progress; blasting.*

1.0 Introduction

In the erstwhile development era of the 20th century, the world has seen an innumerable number of products flourishing the market. The consumption power of people has increased which in turn has led to higher demand for products. This demand has led to a greater burden on the core sectors. Mining as core sector is considered as the corner stone for any industry as the raw material required for almost all the needs are derived from mining. Most of the metals, in India, come from underground metal mines and thus the development of underground metal mines is the base for ore production from a mine. Considering the increasing demands on base metals, there is a need to develop new underground metal mines or deepen the existing ones. During this process, there are many factors that influence the decision of selecting an opening for an underground mine. Some of these factors include the depth of the deposit, geotechnical aspects, production rate, dimensions, availability of capital, and operating costs [1]. A critical study was conducted in metal mine with the techno-economic analysis in view of its geo-mining conditions.

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2.0 Mine details

The study was conducted in an underground metal mine near YSR district, Andhra Pradesh, to mine the ore of mineral/Pitchblende hosted by the dolomitic limestone. Geologically the area falls in the SW part of the "Cuddapah" basin. The mine (14°18'36.6"N 14°20'20"N: 78°15'16.57"E 78°18'3.33" E) situated in the Cuddapah district of Andhra Pradesh. The mineralization occurring in underground metal mine of Kadapa is of two lodes i.e. hangwall lode (average width 3.2 m) and footwall lode (average width 2.5 m), separated by 1.5 to 3 m thick lean zone. The orebody is uniform in its thickness and trend, with an average dip of 15° due N22°E. The extent of the orebody is 5.6 km along the strike and 1 km along dip, with overburden depth ranging from 15 m to 275 m. The depth of present mine workings are below 100m. The weathering zone (weathering grade W2) extends for 40 to 50 m below the surface. Three declines, 5 m in width and 3 m in height, along with an apparent dip of 9° due NE, are being driven 15 m apart to work the two lodes at different levels. Various rock mechanics investigations are carried out at this mine to come out with the optimum solution for better safety and extraction ratio.

2.1 Geology and geo-mining conditions

The mineralization of mine in Kadapa area is hosted by Vempalle Dolomites of Papaghni group of Cuddapah super group. Mineralization is of strata bound type, confined between two lithological units' viz., red shale and massive limestone. The different lithologies observed from the vertical borehole section are overburden (~14.4 m), cherty limestone (~55.34 m), shale (~17.94 m), dolostone (~17.3 m), intraformational conglomerate (impersistent) and massive limestone. The rock formations in the area are mostly bedded dolomitic limestone. The strata have an average dip of 15°-

17° due N22°E. The extent of the orebody is 5.6 km along the strike and 1 km along dip, with overburden depth ranging from 15 m to 275 m. The orebody consists of two bands: Hang-wall lode (average width 3.2 m) and footwall lode (average width 2.5 m), separated by 1.5 to 3 m thick lean zone. The stratigraphy of the mine and borehole section is furnished in Table 1.

TABLE 1: STRATIGRAPHY AND BOREHOLE SECTION OF THE MINE

Pulivendula quartzite	
Disconformity	
Vempalle formation (1900 mtr)	Cherty limestone
	Purple shale (20 mtr)
	Dolostone (uraniferous)
	Intra-formational conglomerate
	Massive limestone
	Shale
Gulcheru quartzite	Quartzite/conglomerate
Eparchean unconformity	
Archean and dharwars	

2.2 METHOD OF MINING

The mine is a highly mechanized underground mine, which is developed with three sets of declines (5m × 3m) at a 15m interval, driven at 9° gradient in apparent dip direction in the orebody. The advanced strike drives (ASDs) of size 4.5m (W) × 3m (H) are driven in strike direction from both service declines at vertical intervals of 10m. Levels are connected with the ramps developed at 9° apparent dip with an interval of 120m.

Ore extraction (stoping) is carried by room and pillar method of mining. Stope blocks of dimension (120m length × 39m width) has been developed by driving ramps at every 120m interval between the rib pillars of 7mtr wide, which are left at 120m interval for supporting the roof. After developing the ramps, stope drives developed on either side of the ramp up to the limit of the rib pillars. These stope drives are interconnected by forming room and pillar of dimension of 4.5m × 4.5m as shown in Fig .1

3.0 Geo-technical parameters and geo-mining issues of the mine

3.1 GEOTECHNICAL PARAMETERS

The rock mass classification parameters such as rock quality designation (RQD), joint set number (Jn), joint roughness number (Jr), joint alteration number (Ja), joint water, reduction factor (Jw), stress reduction factor, UCS, average spacing of discontinuities, joints conditions, orientation of discontinuities and hydro-geological conditions were estimated from direct field observation in the geological mapping. Based on these parameters, rock masses have been characterized using Q-system [2], and RMR system [3]. (a) The joint properties observed in the field, (b) RMR values, and (c) Q values estimated for the different locations mapped.

3.2 HANGWALL (HW) LODE MINING AT SHALLOW DEPTH

Host rock for ore mineralization at this mine is Dolostone. Carbonate content of dolostone, when exposed to water, gets washed away and forming the cavities. Intensity and occurrence of cavities progressively decrease with depth. It has been observed that up to a depth of 100m from the surface, roof protection requires additional support. Series of solution cavities due to weathering of host rock (dolostone) and roof rock (shale) impeded the underground

Fig.1 Schematic diagram of underground mine development

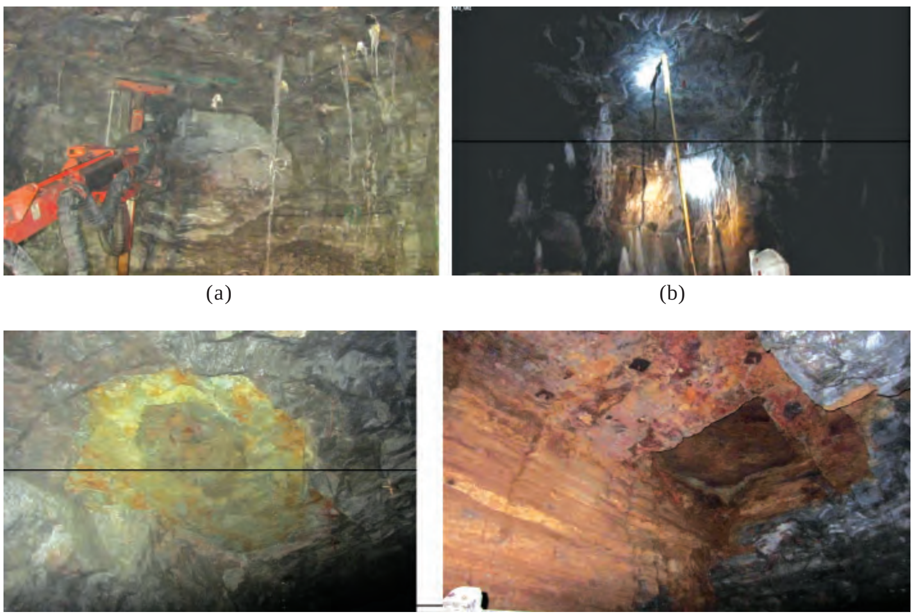
development. Solution cavities of shale and dolostone are shown in Fig. 2.

3.3 Shale roof problem

Lithologically, red shale (ferruginous) is an argillaceous rock formed due to compaction of clay minerals (mud). The major part of the reserves in the mine is confined to hangwall lode which is capped by red shale with adverse physical properties on stability considerations. However, efforts are being made to assess the properties at different depth with an aim to recover ore from hangwall lode. Experimental hangwall drives and trial hangwall stope have been opened randomly at vertical depths of 70m, 90m, 100m, and 120m to ascertain the ground conditions. The support design which is followed for supporting the dolostone has been practiced for shale rock, which is the roof for hangwall lode. Fig 3 (a,b,c,d) shows the following problems were encountered in the hangwall lode drive developments while supporting the roof.

- Continuous heavy water seepage from the roof i.e. from red shale (Fig.3a).
- Wash out of full column cement grout, due to the pressure of seepage water (Fig.3b).
- Collapsing of drilled holes constraining installation of Rock bolts (Fig.3c).
- Collapsing of layers (50cm transition zone) from the roof (Fig.3d).

Fig.2 Solution cavities of shale and dolostone of the HW lode



(a) (b)

(c) (d)

Fig.3 (a,b,c,d) Showing the shale roof problems

4.0 2D numerical modelling

With a view to ascertaining the stability of the hangwall lode workings at the shallow depth between 2nd and 6th levels, a 2-dimensional numerical modelling is performed. This modelling is also aimed at confirming the empirical design results. For these purpose models were created to ascertain the stability of the workings. The model geometry for this is shown in Fig.4 which indicates that the actual lithology up to the surface is considered in the model. The maximum depth of mining (100m) was also considered for the simulation.

4.1 Discussions and observation of numerical modelling

The model results yielded in the form of the mining induced stress and the strength factor (FOS) values over the pillars and over the roof of the gallery due to the footwall (FW) and hangwall (HW) mining. The effect of back filling on the stability of the pillars is also simulated in this analysis. All the material properties for the analysis is obtained from the laboratory testing of the relevant rock samples collected from the mine. For the purpose of in situ stress conditions, vertical loading was calculated for vertical stresses and the horizontal stresses were taken as twice the vertical stresses. The model was simulated under various mining options such as FW mining alone, both FW and HW mining, and also the backfilling of FW stopes. Results of the analysis were obtained in the form of stresses and strength factor (FoS) around the excavations. The mining induced stresses and the strength factor around excavations after FW lode and HW lode mining is shown in Figs.5 and 6 respectively.

The results in terms of mining induced stresses as shown in Fig.5, indicates that the tension failure occurs over the roof of the rooms due to the HW lode mining and leading to the collapse of the rooms. Even the pillars are experiencing this phenomenon which will eventually lead to weaker and unstable pillars. It can be observed from the Fig.5 that the ASD's are also experiencing the failure

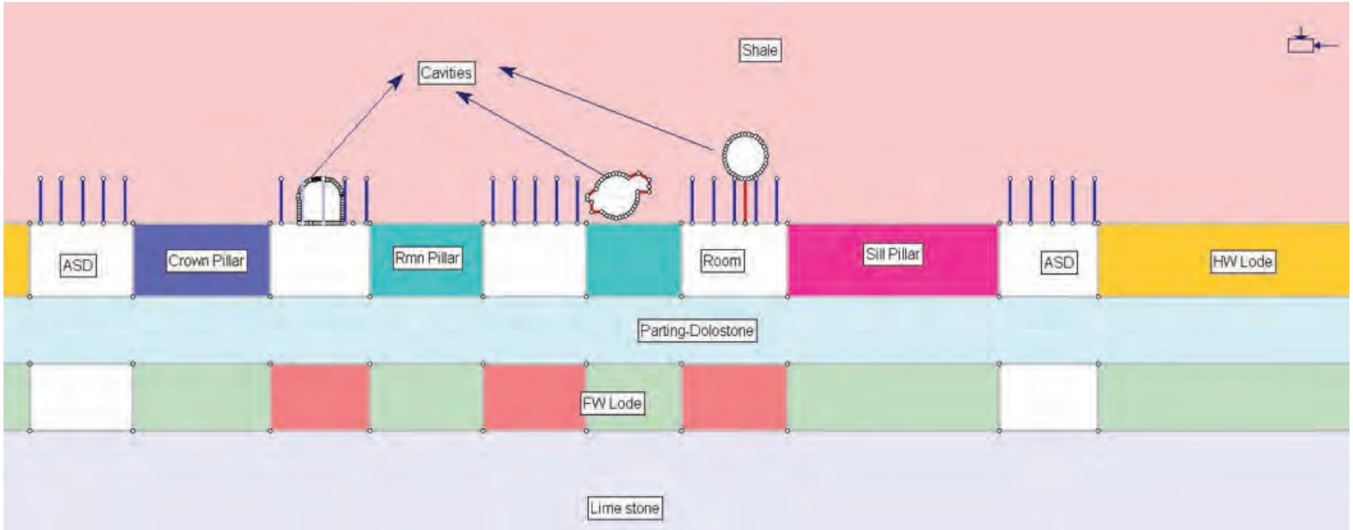


Fig.4 Model geometry of HW lode mining [4]

which cannot be maintained during the mining operation. The results in the form of strength factor (FoS values) as shown in Fig.6, indicates the low FoS values (less than 1.0) in and around the rooms due to HW lode mining. It can also be observed that the roof over ASD's also shows the low FoS values, which will lead to the collapse of the excavations. In both the cases, it can be observed that the failure of the shale roof is extended to a few meters leading to highly unsafe conditions.

The support system in the form of rock bolts was installed in the HW lode mining rooms and was simulated for their efficiency and behaviour. The results in the form of yielded bolts after the HW lode mining is obtained and shown in Fig.7. It can be observed from the Fig.7, that almost all the bolts yielded except a couple of bolts in the ASD. This clearly indicates the failure of the rock mass around the openings. The negligible axial force on the rock bolts can also be observed in this case.

4.2 Extraction ratio vis-à-vis safety factor

The present remnant pillar size is 4.5 × 4.5m square pillar. The rib pillar is 7m wide and the crown and sill pillars of 5m thick. The factor of safety and the extraction ratio of the present pillar sizes are estimated and detailed in Table 2.

Relevant data required for the classification of rock mass of deeper levels (beyond 10th level) was collected from the mine during the field visits by NIRM. Representative rock blocks were also collected from the underground mine, for determining physico-mechanical properties of these rocks in the laboratory at National Institute of Rock Mechanics [4]. Based on all these studies, the rock mass characterization is made and the rock mass are classified to establish its quality for the stability of the workings during and after mining in these levels and to design the appropriate support system. The average 'Q' and 'RMR' values estimated for the deeper levels is presented in Table 3.

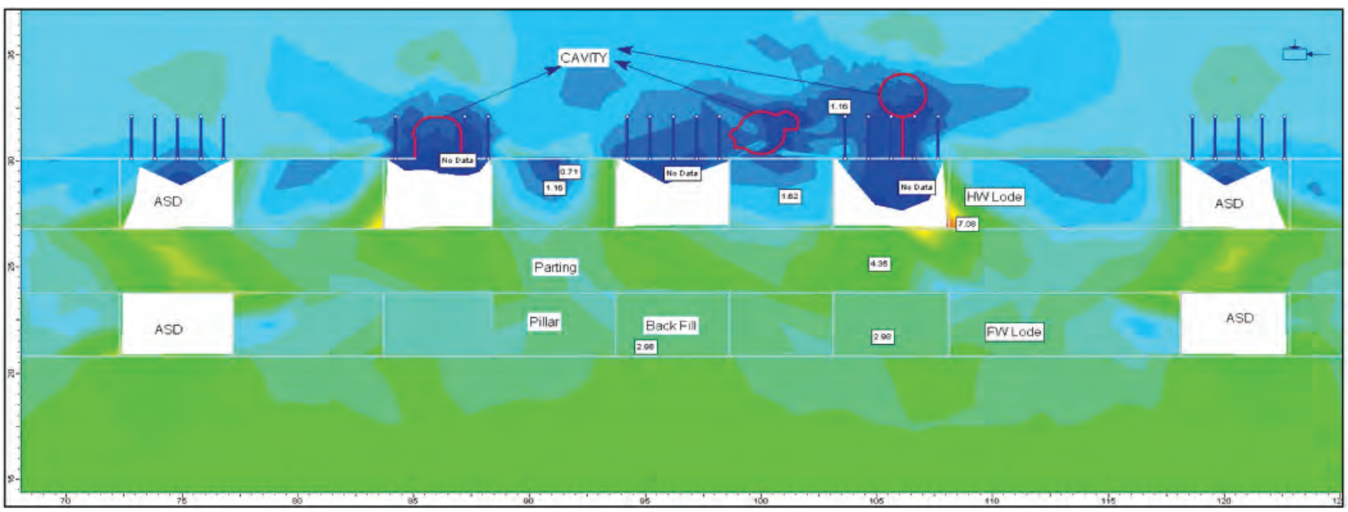


Fig.5 Mining induced stresses around excavations [4]

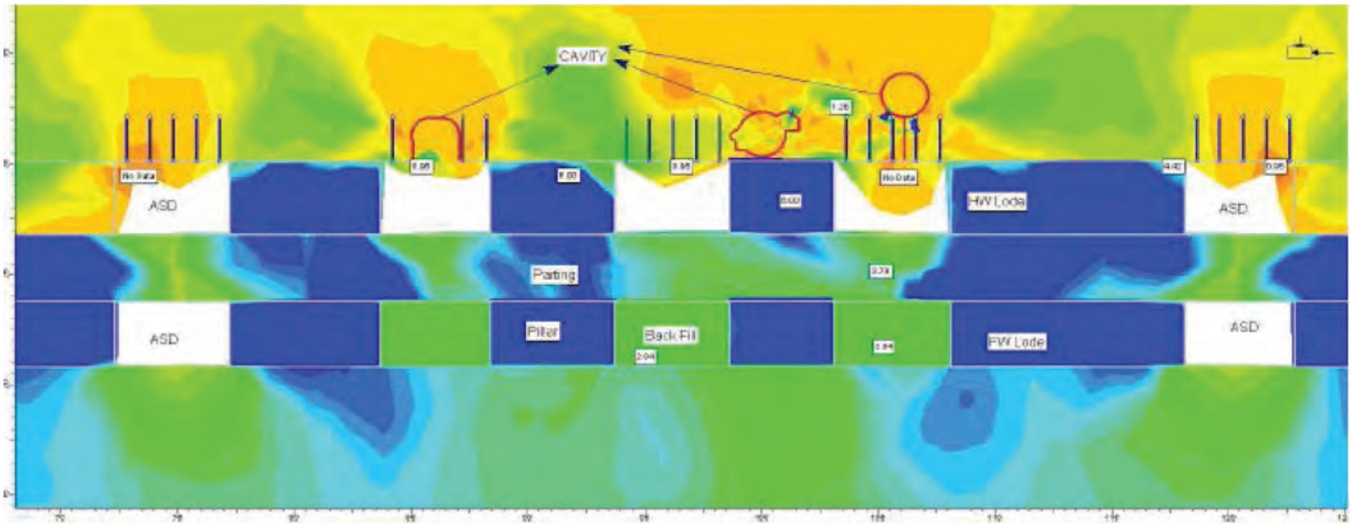


Fig.6 Factor of strength values around excavations [4]

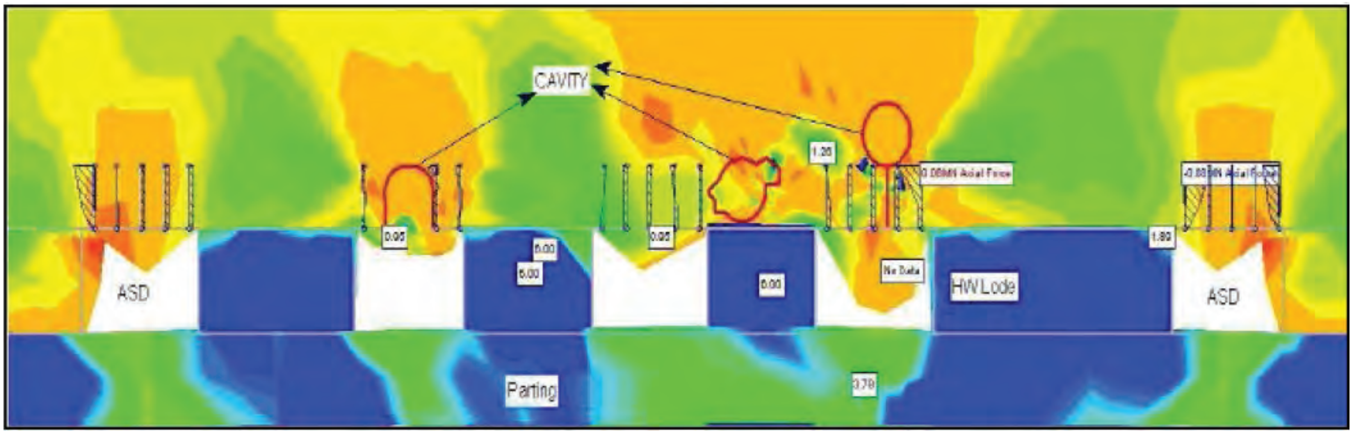


Fig.7 Yielded bolts in the rooms of HW lode [4]

4.3 Instrumentation

Stopping is being carried out at 5E HW lode panel, on an experimental basis. To understand the strata behaviour during and after stopping operations, the above panel is instrumented using the variety of instruments such as stress cells, load cells, extensometers to monitor the stress in the remnant and barrier pillars, load on the rock bolt support system and deformation in the roof and walls. The location and the type of instruments installed in the above panel are shown in Fig.8.

Legend:

S1 to S4 Stress cell

L1 to L4 Load cell

Ex1 to Ex4 Telltale extensometers

4.4 Feasibility of HW lode mining

The feasibility study of mining of the HW lode between 2nd and 6th levels was carried out. As part of this study, classification of the rock-mass was also carried out between 2nd and 6th levels to study its quality and evaluation of the mineability of HW load under shallow depth up to 100m. Numerical modeling for the feasibility of HW load mining using the rock mass properties was determined.

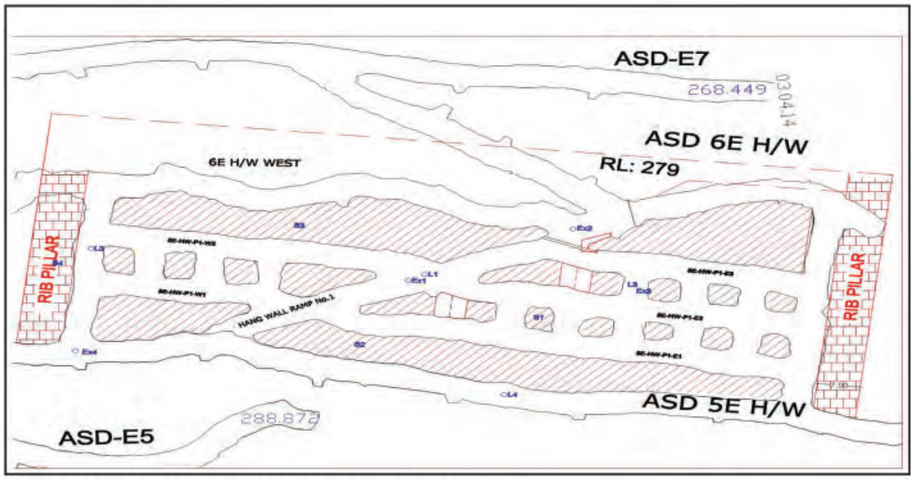
All the instruments are being monitored regularly and the

Table 2: Details of existing and recommended pillar dimensions

Pillar	Existing dimensions (m)	FoS	Recommended dimensions (m)	FoS (empirical)	FoS (numerical)
Remnant pillar	4.5 × 4.5	4.97	4.0 × 4.0	4.08	4.0-6.0
Rib/barrier pillar	7.0	14.51	4.0	10.80	4.0-6.0
Sill/crown pillar	5.0	13.46	4.0	11.85	3.0-5.5

TABLE 3: AVERAGE Q AND RMR VALUES

	Location	Average RMR	Average Q
1	ASD-5E HW R/Dn (40m in bye)	44.20 (fair)	2.86 (poor)
2	ASD-5E-P1-E2 (60m in bye)	45.85 (fair)	2.77 (poor)
3	ASD-5E-P1-E3 (30m in bye)	44.50 (fair)	3.35 (poor)
4	ASD-5E-P1-W2 (13m in bye)	41.60 (fair)	2.26 (poor)
5	ASD-6E HW drive west (70m in bye)	55.5 (fair)	5.67 (fair)
6	ASD-1E (130m in bye)	34.50 (poor)	2.94 (poor)
7	ASD-2E (150m in bye)	33.50 (poor)	2.50 (poor)
8	1E to 3E (120m in decline)	41.62 (pair)	3.56 (poor)



Legend:
S1 to S4 Stress Cell
L1 to L4 Load Cell
Ex1 to Ex4 Telltale Extensometers

Fig.8. Plan showing Instruments installed at 5E HW lode panel

data is being analyzed to understand the strata behaviour during and after de-pillaring which will enable to plan for effective strata control programme in the future panels.

4.5 Conclusion on feasibility study on mineability of HW lode

Feasibility study on mineability of HW lode of underground metal mine, Kadapa is conducted. Geological and geotechnical investigations were carried out in the mine between the 2nd and 6th levels with a view to studying the mineability of HW lode by both empirical and numerical methods. It was observed that most of the crown/roof area of the hangwall portion (transition zone) is weak due to the contact between shale and dolostone and the intersection of the joints. A number of cavities were observed in the HW drives. Most of the cavities were formed due to the dissolution of calcium carbonate rocks with water interaction, the intersection of the subhorizontal and verticals joints. The width of the cavities ranges from 0.5 m to 3.5 m. Water seepage is recorded along the vertical joints at some channels of the ASD 1E and ASD 2E. The rock mass was characterized using the Q and RMR systems. It was found that in both the systems the rock mass was classified as poor to fair category. The present rock mass of HW lode requires fair amount of support system. The maximum stable span estimated was less than 4.0 m for Q value of 2.26. It is also found that at the lower and average RMR values of 33 and 40, the HW lode workings are within "immediate collapse" zone and hence not offer any stand-up time. The results of 2D numerical modelling to study the feasibility of HW lode mining also confirms the failure and impending collapse of the workings, which makes mining operations in HW lode between 2nd and 6th levels not safe due to the strata control point of view.

5.0 Mining in FW and HW lode and its effect on linear progress and cost of operation

5.1 Mining in footwall lode

In the footwall lode, advance strike drive (ASD) of size 4.5m × 3m, was taken for full one month in 4th level of the mine (Fig. 9). The cycle time per round of blast is 3 shifts in footwall lode. The calculation is done for production cycle for each component. With a much-planned allocation of all types of resources available in the mine. Following are the achievements:

- The total number of days worked – 25 days.
- The total number of shifts worked – 75 shifts.
- Total linear progress achieved per month – 75 m.
- Total successful blasts have taken in a month – 25 nos.
- The average pull per blast – 3m.

5.1.1 Brief of total cost of operation per round of blast in footwall lode (F/W)

- The drilling cost per meter = Rs.56.40/ m
- Total meterage of drilling per blast with 33+3 reamers
  = 3.2m × 33 + 3 × 3.4m holes = 115.80 m
- Total cost of drilling = Rs 56.40 × 115.80 m = Rs.6531/-
- The total cost of charging and blasting = Rs.9616/-
- Total cost of mucking = Rs.4763/-
- Total cost of preparation of face and supporting with rock bolt = Rs.18083/-

  Total cost of operation per round of blast = Rs.38993/- (FW lode)

Fig.9 Drilling by extra low profile drill jumbo in development face of FW lode

5.2 Mining in hangwall lode

In spite of the weak hang wall lode, an advance strike drive (ASD) of size 4.5m × 3m was taken for full one month in 6th level of the mine. The cycle time per round of blast is found to be 4.5 shifts in hangwall. Due to above-mentioned geo-mining constraints, the use of welded mesh and hydra-bolts from South Africa were tried and tested. With a much-planned allocation of all types of resources available such as hydra bolt, wire mesh etc. in the mine (Fig.10). Following are the achievements:

- The total number of days worked – 25 days.
- The total number of shifts worked – 75 shifts.
- Total linear progress achieved per month – 51 m.
- Total successful blasts have taken in a month – 17 nos.
- The average pull per blast – 3m.

5.2.2 Brief of total cost of operation per round of blast in hangwall lode

- The drilling cost per meter = Rs.56.40/m
- Total meterage of drilling per blast with 33+3 reamers = 3.2m × 33 + 3 × 3.4m holes= 115.80 m.
- Total cost of drilling = Rs.56.40 × 115.80 = Rs.6531/-
- The total cost of charge and blasting = Rs.9616/-
- Total cost of mucking = Rs.4763/-
- Total cost of preparation of face and supporting with wielded mesh and friction bolt = Rs.27, 791/-

  Total cost of operation per round of blast = Rs.48, 701/- (HW lode).

The brief details of the above-calculated cost for development of drive in footwall and hangwall drive are given in Table 4 and plotted in Fig.11.

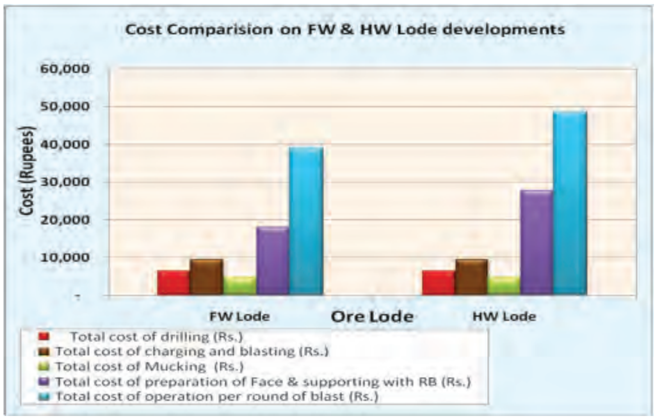


Fig.11 Cost comparison of all mining components for both HW and FW lodes

Fig.10 Fixation of welded support firmly to the immediate roof near the development face

Table 4: Comparison of cost components for operation of single round of blast in both FW and HW lodes

Lode	Total cost of drilling (Rs.)	Total cost of charging and blasting (Rs.)	Total cost of mucking (Rs.)	Total cost of preparation of face and supporting with bolt (Rs.)	Total cost of operation per round of blast (Rs.)
FW lode	6,531	9,616	4,763	18,083	38,993
HW lode	6,531	9,616	4,763	27,791	48,701

6.0. Conclusions

Extensive problem centric rock mechanics investigations have been carried out at mine such as optimization of pillar sizes, the feasibility of HW lode mining, support design for deeper levels, instrumentation for strata behaviour monitoring. New supporting items like friction bolts and welded mesh from South Africa are being used as additional supports in the weathered zones of the mine, which has proven beneficial in safe mining practices. In-spite of a technical recommendation of leaving hangwall lode ore due to difficult geo-mining conditions, an experimental stope was developed and stopped out to monitor with instruments. Due to the difficult geo-mining condition, it affected the cost of mining and on linear advance/progress. The cost analysis shows that the increase in mining cost due to the contribution of extra expenditure on manpower for preparation of face and supporting with a combination of hydra bolt and wielded mesh i.e. 53.30% than expended on footwall lode while other cost components nearly remain same. The installation of supports are found successful and had led to consumption of additional 1.5 shifts than practiced in footwall that resulted in 24.90% increase in total cost per round of blast, thereby significantly, affecting total cost per tonne of ore extracted from hangwall in contrast to footwall.

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