Final Report: CONS/6055/2021-22

3D Subsidence modelling for prediction of surface subsidence, strain and subsidence slope due to stoping (mining) at Surda Mine, HCL

Sponsored by

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October 2021

DISCLAIMER

It is appropriate to mention here that the relevant data required for the 3D Numerical Simulation of Subsidence due to stoping (mining) at Surda Mine, HCL, were supplied by the Management of Mine. The authors of this report would in no way be held responsible for any untoward incident, which might occur due to the implementation of the recommendations of this report. This report merely contains the results of 3D simulation of Subsidence and Surface Subsidence impact assessment due to stoping (mining) at Surda mine. This report is highly confidential and no part of the same may be reproduced and circulated to any outside agency without obtaining prior permission from authors except to the concerned Government Departments. The authors reserve the right to publish the results of the study for the benefit of Industry.

Executive Summary

Subsidence impacts occur at every underground mining operation bringing about changes to surface landforms, ground water and surface water. Although the same impacts to mining operations, man-made surface structures and other features are relatively well known and studied, the environmental impacts related to subsidence at underground mines are not well known and have not been extensively described. A scientific study of 3D Subsidence modelling for prediction of surface subsidence, strain and subsidence slope due to stoping (mining) at Surda Mine, HCL was awarded to Indian Institute of Technology (Indian School of Mines) Dhanbad vide the PO no. 16031 dated 13.07.21.

This report presents a brief description of mine, geology, mining methods, results of 3D subsidence modelling of stopping (mining) at Surda Mines, HCL.

The relevant rock parameters and stope geometry required for the 3D Numerical Simulation of Subsidence due to stoping (mining) at Surda Mines, HCL were supplied by the mine management.

The nonlinear solution with three-dimensional finite element simulation is used to investigate the actual behaviour of the surface subsidence due to stoping (mining) under three stages at Jaduguda Mine. Three dimensional numerical models were developed for stoping under three stages of stoping. The footwall and hangwall stopes were assembled to form 3D FEM model. The gravity load and in-situ stresses were applied to the model.

The results of 3D Finite Element Modelling (predicted subsidence) after different stages of stoping (mining) are presented in terms of surface strain contour maps on surface (along strike and dip directions) and vertical displacements.

The predicted strain values at the surface after stages I, II, III and IV of stoping and back-filling is less than 1 mm/m. The predicted maximum vertical displacement at the surface is also negligible. No visible cracks have been observed in any of the walls of surface structures located just above and nearby the mine workings. This observation corroborates with the findings of 3D numerical modelling for subsidence prediction due to stoping at Surda Mine.

The present location of mine workings is away from forest area and mining will further continue beyond the forest area. With such a negligible strain on the surface in the vicinity of stoping zone, no damage to forest area is anticipated during present stage of mining.

The amount of subsidence has been observed as a direct function of time. Even in cases where vein deposit mining methods are employed in competent rock at great depths with low extraction ratios, the surface expression of subsidence is not eliminated, but may not appear for some time. Based on the result of subsidence prediction by IIT (ISM), it is understood that negligible subsidence is occurring at present.

1. INTRODUCTION

Subsidence impacts occur at every underground mining operation bringing about changes to surface landforms, ground water and surface water. Although the same impacts to mining operations, man-made surface structures and other features are relatively well known and studied, the environmental impacts related to subsidence at underground mines are not well known and have not been extensively described.

Different methods are adopted to predict and quantify the subsidence parameters. These methods can be classified into three categories namely empirical methods based on the analysis of the field measurement, Mathematical modelling, and Numerical modelling including Finite Elements, Boundary Elements, and Distinct Elements methods.

IIT (ISM) Dhanbad was engaged to carry out 3D subsidence modelling for prediction of surface subsidence, strain and subsidence slope due to stoping (mining) at Surda Mines, HCL.

This final report mainly depicts the following:

- A brief description of mine highlighting location, layout, mining lease etc.
- A brief description of the geology of the rock type and its strength, hardness, mineable reserve etc. [The required information has been provided by HCL].
- U/G mining stopping method, access to the mine etc. [The required information has been provided by HCL].
- Methodology adopted for 3D Subsidence 3D subsidence modelling
- Results of 3D subsidence modelling using Finite Element Modelling.
- Conclusions and Recommendations.

1.1 Scope of Work

The 3D subsidence modelling for prediction of surface subsidence, strain and subsidence slope due to stoping (mining) at Surda Mines, HCL was awarded to IIT (ISM) vide the PO no. 16031 dated 13.07.21.

The scope of work is mentioned as under:

1. 3D FEM modelling of all the stopes of upper levels and study of their effects on the surface for calibration of the model.
2. Simulation of stoping and study of its effect on surface, i.e. assessment of impact of subsidence on the surface features: forest land, agricultural land, road, villages, rivers, nala and ponds.
3. Suggestions of mitigation of the impact of subsidence.

2. ABOUT THE MINE

The Surda Mine is located between latitude N22032’43.119” - N22o34’17.401”and longitude 86^{o}25’31.849''- E86^{o}26’45.097” in Ghatsila Sub-Division, East Singhbhum district of Jharkhand state in the famous Singhbhum Copper Belt. It is situated 10 km away from Ghatsila Railway Station, S.E. Railway and 45 km from Tatanagar.

The mine was opened in 1930's at a modest scale with available information of ore reserves but production and exploration was suspended later on. After independence, the mine was re-opened in1956. In the year 2003, mine production was suspended again due to high production cost etc. Dewatering, equipment maintenance and other essential activities kept continuing. Production activities re-started again from 14.04.2007.

Indian Copper Complex, a Unit of Hindustan Copper Limited (HCL), a Government of India undertaking under Ministry Of Mines, Govt. of India has the sole responsibility of mining and processing of copper ore in Surda Mine. At present Hindustan Copper Limited (HCL) is engaged for mining at Surda Mine, Kendadih Mine, Rakha Mine and ore processing plant at Mosabani a in the East Singhbhum District of Jharkhand state to produce copper concentrate under Section 3(1) of the Indian Copper Corporation (Taking Over of Management) Act, 1972, the management and undertaking of the Indian Copper Corporation Limited was taken over and stood transferred to vested in the Central Government with effect from 21.09.1972. Vide Gazette Notification dated 25.09.1972 all the properties, assets / liabilities and obligations stood vested in the Hindustan Copper Limited. Today it falls in the state of Jharkhand, under the jurisdiction of east Singhbhum district.

- Surda Mining Lease (part of Mosaboni Mining Lease) initially granted from 16.06.1939 to 15.06.1984
- 1st renewal of Surda Copper Mines was granted with effect from 16.06.1984 for the period of 20 year
- 2nd renewal of the mining lease which was granted by executing a formal lease dated 22.02.2007 with effect from 16.06.2004 for a period of 10 year.
- As per section 8A (8) of MMDR Amendment Ordinance 2015 and as per Ministry of Mines, Govt. of India Order No. 1/2/2015-M.VI dated 06.02.2015, tenure of the three lease has been extended by Govt. of Jharkhand till 31.03.2020. After this a supplementary lease deed was executed for the period of up to 31.03.2020

Total lease area of Surda mine is 388.68 **Hectare**. Out of 388.68 Hectare mine lease area, forest land is 149.03 ha and remaining 239.65 ha is non forest area. Land use of Surda Lease area is given below,

Forest Area	Area, (Ha)	Non-Forest Area	Area, (Ha)
Reserved Forest	88.83	Rayati Land	121.78
		Anabad Bihar Sarkar	107.94
Protected Forest	60.20	Anabad Sarba-Sadharan	6.40
		District Board Land	3.53
Total Forest Area (A)	149.03 Ha	Total Non-Forest Area (B)	239.65
Total Lease Area (A+ B): 388.68 Hectare			

2.1 Geology & Rock Type

The deposit crops out as a NNW-SSE trending ridge parallel to the strike of the rock formations. The immediate hanging wall side of the ore body is a rolling cultivated countryside up to the Subarnarekha River. All the tributary nallahs are seasonal and the Subarnarekha is the perennial source of water in the area. There is no big village in the area. Forest land is only along the hill ridge and hill slope.

The rocks of the Singhbhum Copper Belt are one of the oldest formations of the Indian subcontinent (Pre-Cambrian). The belt is accurate and forms the boundary between older cratonic rocks to the south and younger orogenic rocks to the north. Mineralisation extends over about 60 km. On the local scale, it comprises a thick band of schists and other more granular rocks sandwiched between metavolcanic rock in the southwest and mica schist in the northeast. The belt dips 40º to 50º to the northeast is the area of the mines.

Rock Types

(The information and data in this section have been compiled from a report of "Rock Mechanics IDSCB" Reference (1))

The principal rock type exposed in the underground levels of Mosaboni, Surda and Rakha in approximately order from more granular to more schistose are:

- soda granite,
- epidiorite,
- feldspathic schist,
- chlorite/biotite schist and
- chlorite schist,

Soda granite generally only occurs around Mosaboni and the occurrence is lensiod. It varies from massive to sheared and often contains chlorite/biotite rich foliated zones. It has a range of grain sizes with quartz and feldspar dominant.

Epidiorite is a medium to coarse grained schist similar in texture to the Celdspathic schist. It occurs mainly around Mosaboni.

Feldspathic schist is a foliated granular rock with quartz and feldspar dominant. It is not common around Mosaboni.

Quartz chlorite biotite schist is one of the most important rock types in the Mosaboni – Surda – Rakha areas. It is often mineralized and is highly foliated. It is a medium to coarse grained rock consisting predominantly of chlorite, biotite and quartz.

Chlorite schist generally occurs as bands within other rock types. It is medium grained and comprises chlorite and quartz in various proportions. The rock is very well foliated with parallel alignment of chlorite and flattened quartz.

Schist rocks in Surda mine can be put in three groups

- Schist –quartz
- Schist –biotite
- Schist- chloretic / micaceous

Intact tock strength parallel to schist is high. However, perpendicular to the schist is very high. Quartzite rock are twice as strong as schists. Mean Uniaxial compressive strength (UCS) of all rock types is 71 MPa, mean tensile strength is 10 MPa and modulus of elasticity is 17 GPa. Poisson's ratio is 0.18 and Young's modulus of Elasticity perpendicular to schist is 20 GPa and parallel to schist is 30 GPa.

On the basis of geotechnical mapping of discontinuities in stopes, drives and crosscuts and observation of failure of rock in stopes, rock mass properties estimated in the report (reference 1) are used in numerical model. They are

- Rock Mass modulus = 30 GPa,
- Rock mass uniaxial compressive strength = 23 MPa (one third of intact rock UCS), and
- Tensile strength = 3 MPa.

The rock density has been taken 2500 kg/m^3 for computation of gravity stresses. Poisson's ratio has been taken as 0.25 and internal angle of friction as 30 degrees.

<u>Structure</u>

The general strike of the rocks in the area is NW-SE with dip varying from 30^0 to 50^0 towards NE. The thrust zone maintains a NW-SE trend in this part of the belt. The rock formations have been affected by tectonic movements giving rise to a series of major plunging folds and axes trending approximately ESE-WNW and developed within the shear zone. On the limbs of these folds, S-shaped cross folds have been observed. The Quartzite rocks shows well developed joint pattern. There are three mutually perpendicular tension fractures, and two diagonal shear fractures are observed in the host rocks. The linear structure in the area is represented by (i) Pebble elongation (ii) Slicken-Slide (iii) Parallel alignment of mineral grains and (iv) axes of Micro fold, the lineation normally pitching 45^0 to 500 towards N 50^0 E.

<u>Mineralization & Lode disposition</u>

The copper mineralization is exposed right on the surface of the hill slope in the form of oxidized outcrop and feeble gossans zones exhibiting limonitisation in shades of brown, red and purple colours.

Copper sulphide ores are medium to coarse crystalline with a typical golden-yellow colour. Next to chalcopyrite in order of abundance is pyrite followed by pyrrhotite and pentlandite. Within the shear zone, the intensity of mineralisation is variable and narrow zones of rich mineralisation following shears are known as "Lodes".

In the southern part of Surda Mine, there are three lodes, which are termed as Hanging wall. Inter and Foot wall lodes. In the Central and Bottom sections, number of shoots with intervening lean zones has formed a lode up to 20m wide, at places.

Control

Mineralisation is largely confined to granular-chlorite-biotite-schist and quartzite-chlorite-schist, especially where there are a number of sheared quartzite reefs. These rocks show evidence of crushing, silicification and hydrothermal alteration. Mineralisation occurs as disseminations along foliation, fracture and breccias fillings and also minor replacement patches.

2.2 Method of Mining

Mining methods followed are:

Room & pillar methods for ore body width – 1.5 m to 4 m.
Cut &fill method for ore body width – 4 m to 6 m.
Post pillar methods for ore body width - 6 m and above.

Detail description on the method of stoping is given in as follows:

Room and Pillar Stoping Method: This method is used where the ore body width is between 1.5 and 4.0m. A raise is put along the H/W contact from lower level to upper level. A chute is installed at the lower level, together with an electric scraper engine. A sill pillar of 5m above the lower level and a crown pillar of 5m below the upper level are left as support (Fig.1a).

In this method both faces of a central raise are advanced to a span of 10-15m, with systematic bolting of the roof at a spacing of 1.2m x 1.2 m, 1.5m long 20m dia tor-steel grouted rock bolts are used as conventional support in place of timbers. 1.8m log bolts are also occasionally used for roof support in geologically disturbed area. A rib pillar of 3 to 4m wide is left between two consecutive stopes. Floor stripping is undertaken where width of ore body exceeds 1.6m. Once the mining is completed to the extremities of the stope, back filling of the excavated area is done.

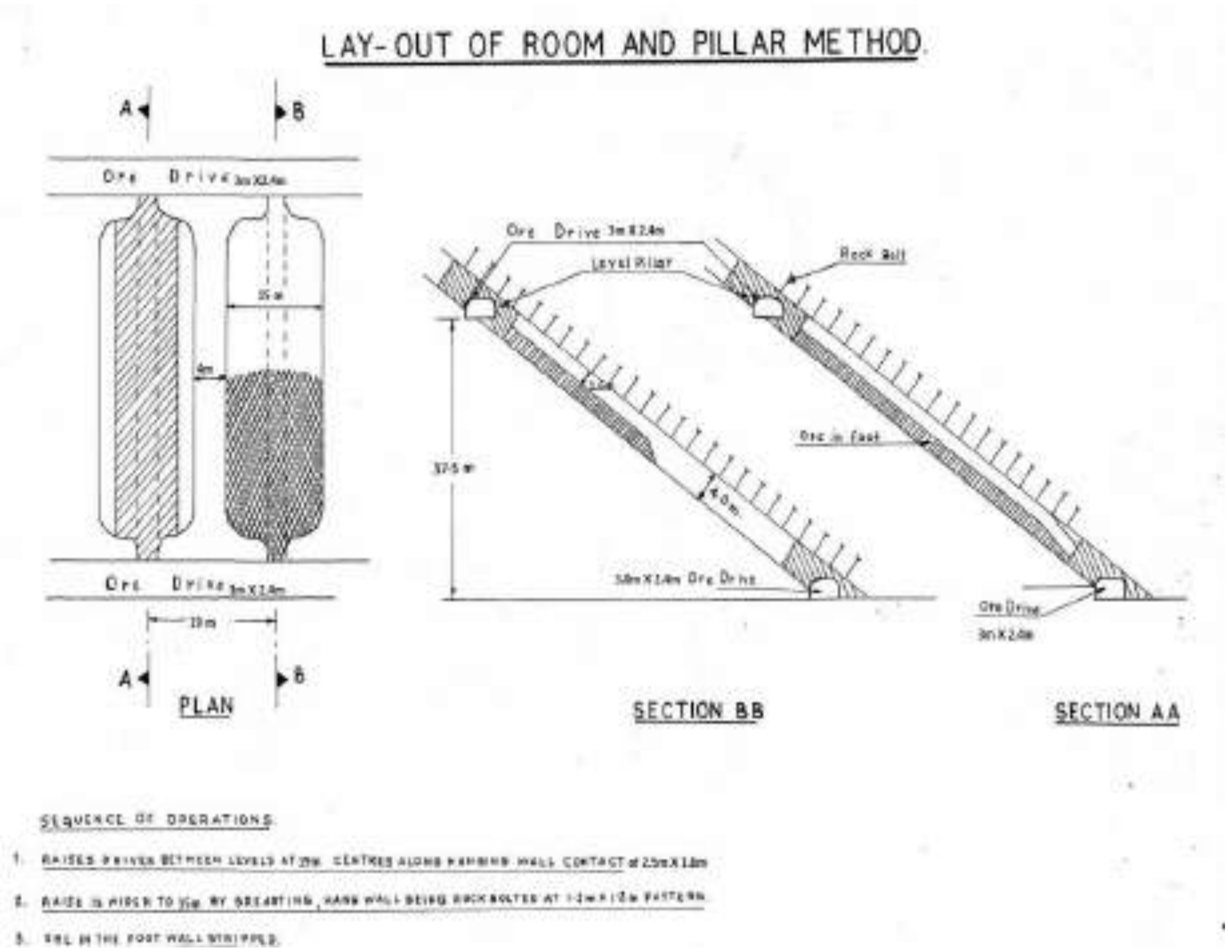


Fig.1a: Room and Pillar Stoping Method Layout

Room & Pillar method is suitable for narrow lodes having thickness of 1.5m to 4.0m which is the case in Kendadih mine. In case the width of the ore body is more other methods may be adopted, which are described as below:

Horizontal Cut & Fill Stoping method: Where the width of ore body is 4-6m Horizontal Cut and Fill Method (HCF) is used. The stoping is started by driving a sill level about 5m above the ore drive and full width of the ore body is exposed for a maximum vertical height of 4.8m. The hanging wall is supported by rock bolts systematically at 1.5mx 1.5m pattern. A F/W haulage is driven on the F/W side of ore body and ore passes are excavated at 50-degree inclination either in waste or ore the stope at intervals of 60m along strike. 1.5m dia ore pass rings made out of 10mm thick steel plates are welded inside the stope to serve as man way and ore pass through the backfill. Cavo 310 or 0.76 cum electric LHDs are used to load and haul broken ore into the operations. Two panels are generally prepared one for production and other being available for filling and consolidation. Back stripping is carried out in panels with 2.4m vertical cut at a time (Figure 1B).

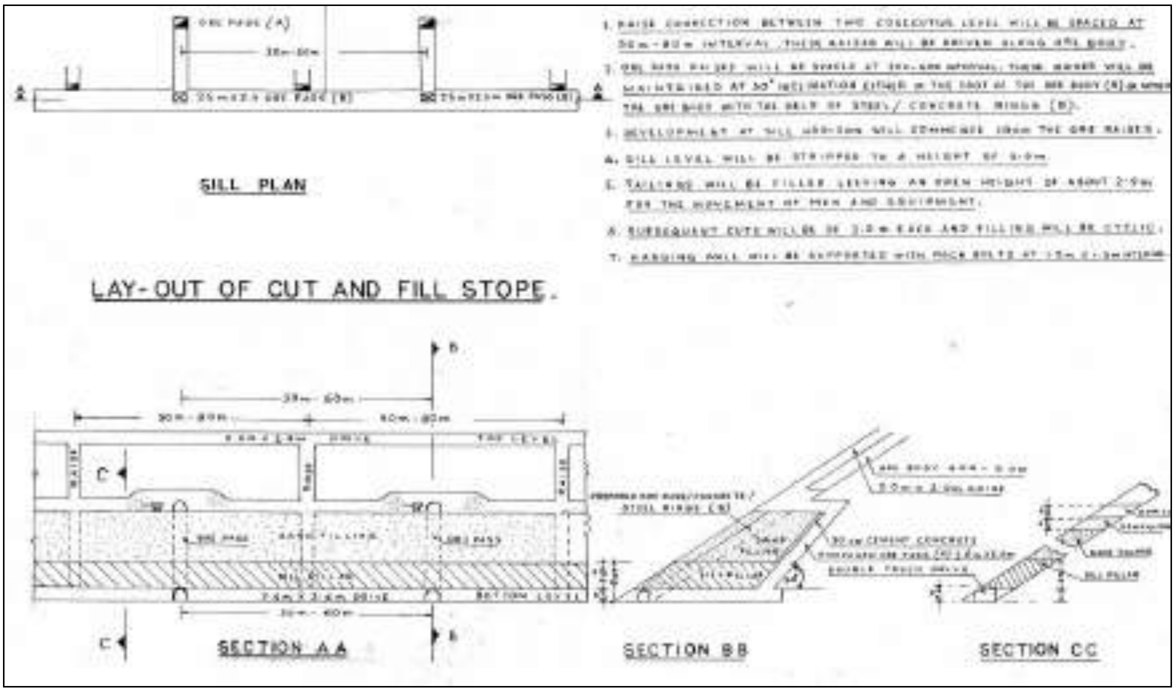


Fig.1B: Horizontal Cut and Fill Method layout

Post Pillar Stoping Method: This method is generally adopted in ore bodies exceeding 6m wide and a minimum strike length of 80m. Basically, it is identical to HCF mining except for the formation of 4m x 4m in situ vertical posts to give additional stability to the roof by breaking long spans excavated. In addition to rock bolting of the roof, the back of each cut in ore is also rock bolted using 1.5m long grouted type rock bolts on 1.5m x 1.5m pattern. The post pillars are spaced at an interval of 13m along strike and 9m across it. Generally, 2.4m high cuts are taken by drilling 2.4 m long by using stope air legs jack hammer. Maximum height of the excavation is limited to 4.8m above the backfill. 0.76/1.5 cum electric LHDs transfer the broken ore into the ore passes from where it is hauled in larger mine cars by locomotive on to the grizzly (Figure 1C).

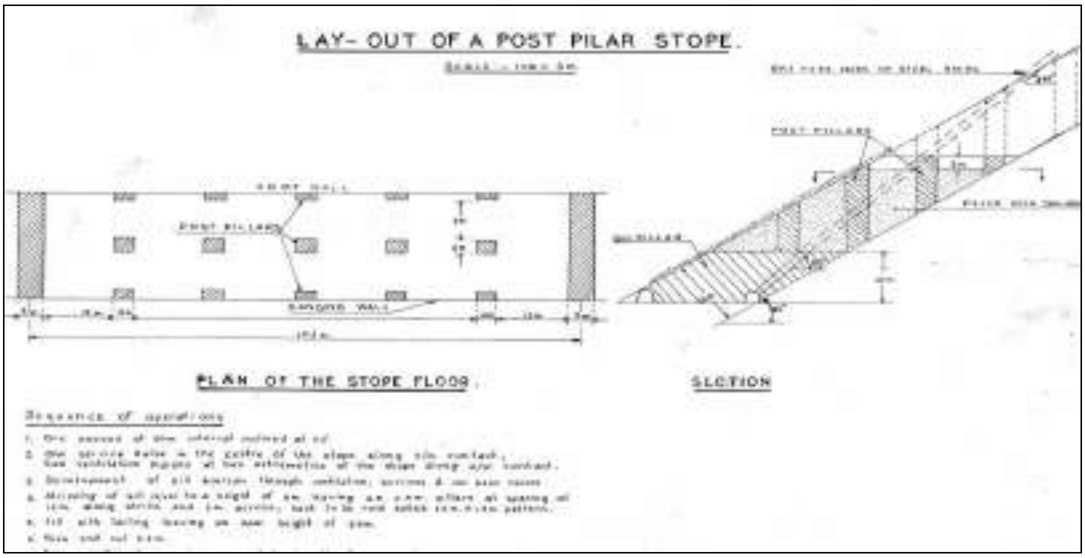


Fig.1C: Layout of Post Pillar Method of Stoping

Sequence of Method:

- The ore drive, approximately 3.0 m x 2.4 m will be developed along the hanging wall contact from one end of the proposed block to the other end along the strike.
- The raises 2.0m x 1.8 m shall be driven at a distance not exceeding 80m along the strike of the ore body to connect the consecutive levels.
- Ore pass raises will be made at 30 – 60 m interval. These raises will be maintained at 50-degree inclination either in the foot of the ore body or within the ore body with the help of steel rings.
- Sill level drive of 3.0 m x 3.0m will be taken along the strike direction having 5.0m vertical pillar from lower level.
- Where the width exceeds 9.0m, post pillars of 4.0m x 4.0m size, as support to the back shall be left in situ and spaced not exceeding 13.0m along the strike and 9m in dip direction.
- The heightening of the sill level shall be taken up for 2.0m such that height of the stope from stope floor shall not exceed 5.0m at any place.
- The slice height in the ore shall be 2.5m vertically.
- The back of the stope (i.e., freshly exposed roof) shall be supported with rock bolts made of TOR steel of 20mm diameter. The spacing of the rows shall be 1.5m and distance in between the rows shall be 1.5m. The length of the rock bolts shall not be less than 1.5m.
- The freshly exposed back and hang wall shall be supported by rock bolting and unsupported span shall not exceed 5m from the face at any stage.

- The de-slimed mill tailings/ sand shall be filled in the stoped out area leaving open height not exceeding 2.5m.
- The extraction and filling shall be cyclic in manner.

3. MINE SUBSIDENCE PREDICTION

Subsidence is a natural and man-made phenomenon associated with a variety of processes including compaction of natural sediments, ground water dewatering, wetting, melting of permafrost, liquefaction and crustal deformation, withdrawal of petroleum and geothermal fluids, and mining of coal, limestone, salt, sulphur and metallic ores (Soliman, 1998). Most subsidence is either created or accelerated by humans (Prokopovich, 1972). Surface subsidence can be caused by a number of activities and mechanisms, the most common being:

- Underground coal extraction.
- Underground mineral extraction.
- Pumping of oil and gas from underground reservoirs.
- Dewatering of sandy or fissured sub-soils.
- Withdrawal of geothermal fluid.
- Erosion or leaching of fine particles in the surface soils and underlying rocks.
- Swelling and Shrinkage of cohesive sub-soils due to changes in moisture content.

Stope mining, combined with the development of adits, drifts and shafts, has historically been the most prolific form of hard-rock metals mining and has been done at both large and small scales. Stope mining is applicable to most vein-type ore bodies typical of base and precious metals deposits. The subsidence created by stope mining is usually the result of unintended cave-ins, inadequate support, pillar robbing, mining too close to the surface, and eventual collapse of the workings over time as the inevitable consolidation of the strata takes place. Most often subsidence is limited to the hanging wall side of underlying stopes.

Several geologic and mining parameters can affect the magnitude and extent of subsidence. These include the thickness of extracted materials; overlying mining areas; depth of mining; dip of mining zone; competence and nature of mined and surrounding strata; near surface geology; geologic discontinuities; fractures and lineaments; in-situ stresses; degree of extraction; surface topography; ground water (including water elevation and fluctuation); mine area; method of mining; rate of advance; backfilling; time; and structural characteristics (SME, 1986).

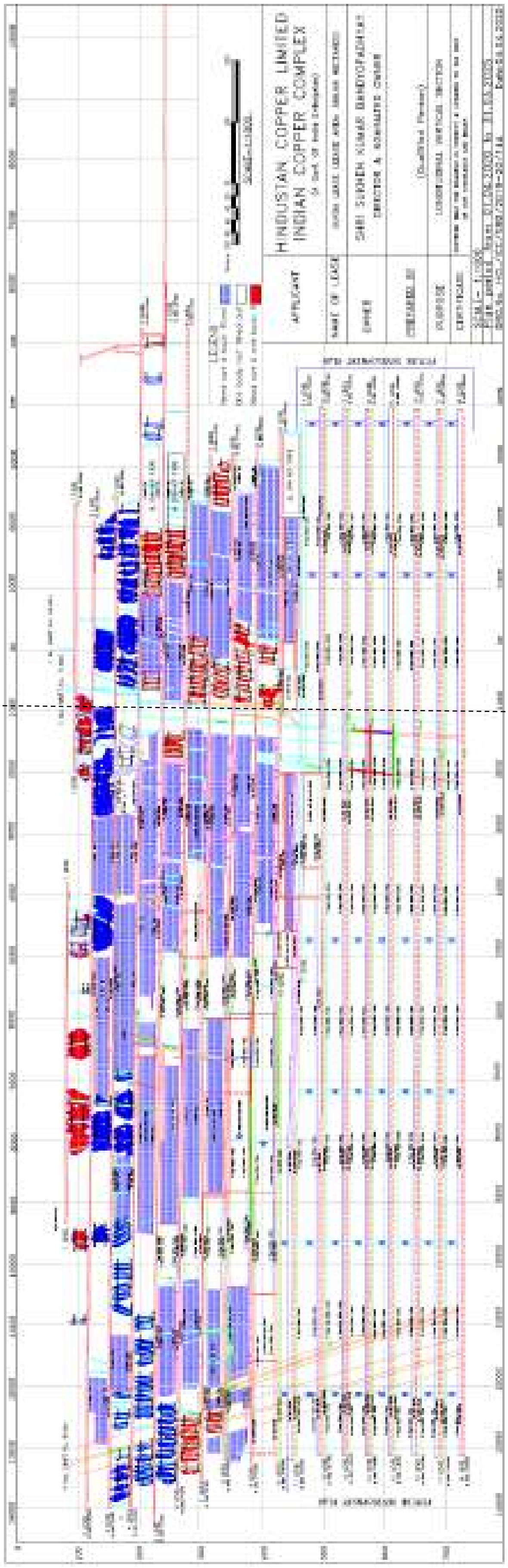
There are two basic methods of subsidence prediction: empirical and phenomenological. However, as many as five principal methods of predicting mining subsidence has been developed: empirical relationships; profile functions; influence functions; analytical models; and physical models (Whittaker and Reddish, 1989). All of these methods fall into the basic categories of empirical and phenomenological.

Empirical methods are based on field observation and experience and are generally applied to regions where adequate empirical data are available. Empirical methods for prediction of subsidence consist of graphical, profile function and influence functions that are constrained by the availability of observed data (SME, 1986). Empirical methods are quick, simple to use, and relatively accurate. These methods provide satisfactory results and are widely used in coal mining. However, the methods are site-specific and are only applicable to areas having identical geological and mining conditions (Bahugana, 1991). Phenomenological methods are based on modelling principles, which use mathematical representation of idealized materials with the application of continuum mechanics. The Phenomenological methods though can give an insight to help in understanding the subsidence mechanism qualitatively but do not give correct quantitative results because of their limitations in correctly representing the complex behaviour of rockmass. Therefore, they do not find wide application for exact predictions of mine subsidence and associated parameters (Bahugana, 1991).

Development in high-speed computing facility has made it possible to predict surface subsidence due to on-going underground mining activities using 3D Numerical Modelling based on numerical approximations of the governing equations, i.e. the differential equations of equilibrium, the strain-displacement relationships, the stress strain equations and the strength-stress relationships. They can simulate nonhomogeneous, non-linear material behavior and complicated mine geometries using Finite element, Boundary element, and Distinct element methods [Elashiry et. al., 2009].

3.1 Numerical Modelling

A Longitudinal Vertical (LV) section DRG. No. HCL/ICC/SRD/2019-20/14A dated 04. 04. 2020 (Fig. 2a) was provided by the mine management in a AutoCAD drawing format file. The LV section contains layout of (a) extracted open stopes, (b) extracted and filled stopes and (c) planned virgin stopes to be extracted in future up to 18 level. Average width of each stope was also provided. Traverse sections showing surface profile were provided as in Fig. 2b.

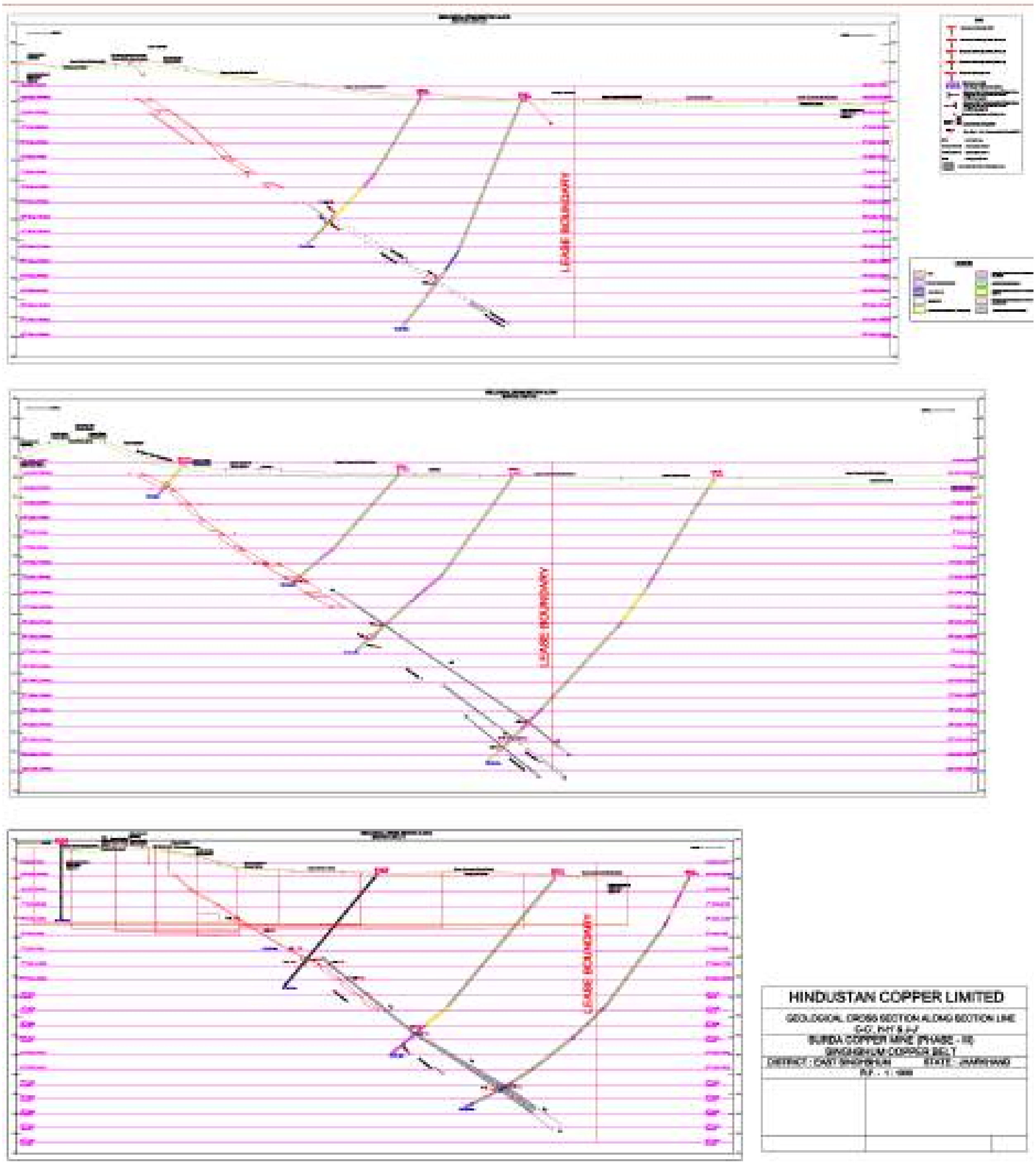


North side

X X

(a)

South side

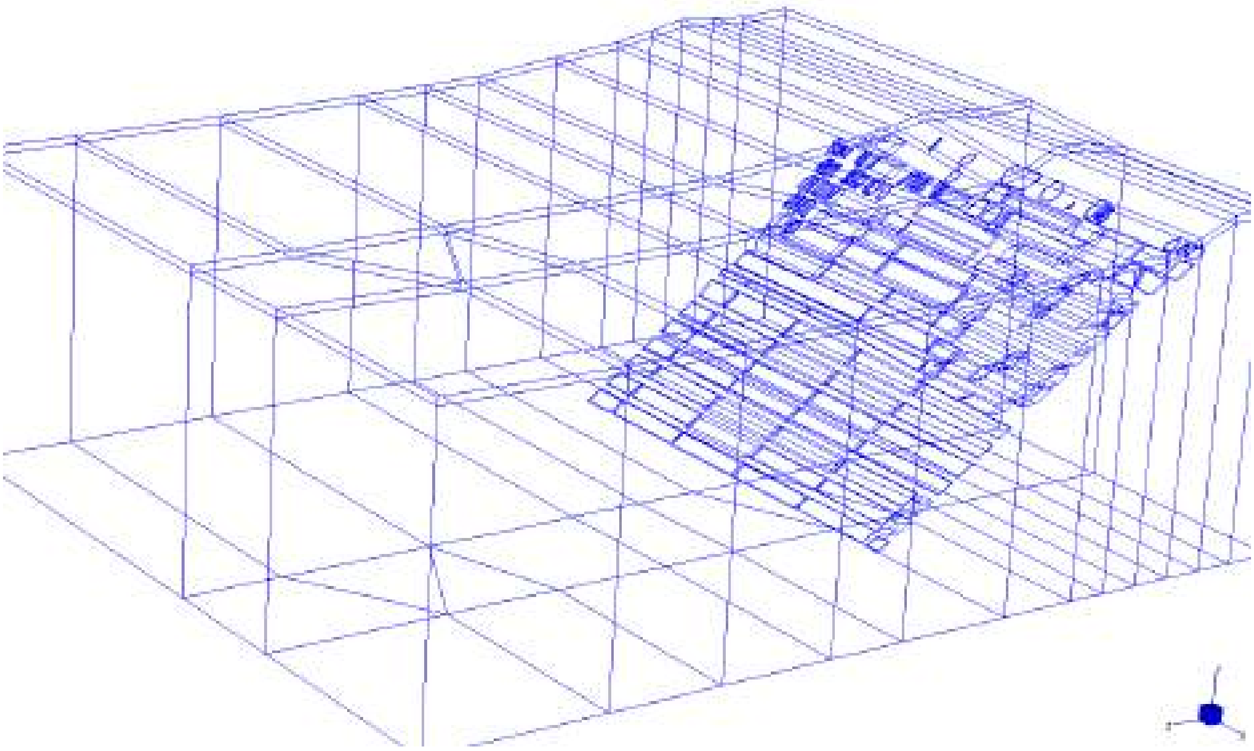


(b)

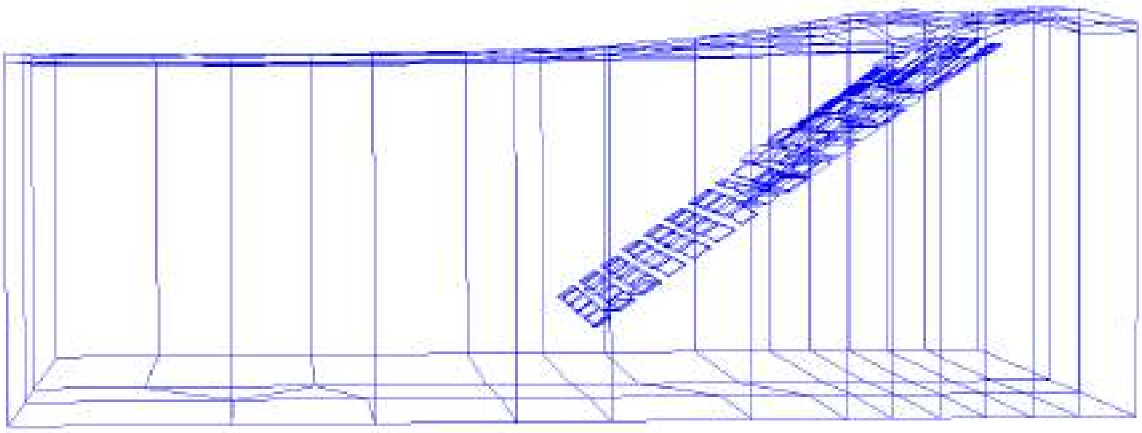
Fig. 2 (a): Longitidinal Vertical section (DRG. No. HCL/ICC/SRD/2019-20/14A dated 04.04.2020) and (b) Crosss sections across the ore body.

A shaft pillar along line X-X in Fig. 2a divides the stopes in two sections: North and south sections. The south side being longer along the strike has been considered for 3D finite element simulation. A plane of symmetry along line X-X and normal to the strike has been taken in the model to simulate north side of the stopes.

The outlines of the stopes saved in .dxf format of the AutoCAD were imported in Strand 7 finite element software package. 3D wire frame model of stopes and domain are shown in Figs. 3a & b. The surface profile of the model was prepared from the vertical cross section given in Fig. 1b. Using these basic geometry data 3D finite element mesh has been created shown in Figure 4a. Figure 4b shows 3D FE mesh of the stopes up to 18 level.



(a)



(b)

Fig. 3 a & b: 3D view of wire frame model of stopes and domain of surda mine (a) looking towards origin of XYZ axis and (b) looking towrds origin along X-axes. (prepared from Longitidinal Vertical section vide DRG. No. HCL/ICC/SRD/2019-20/14A dated 04.04.2020 shown in Fig. 1)

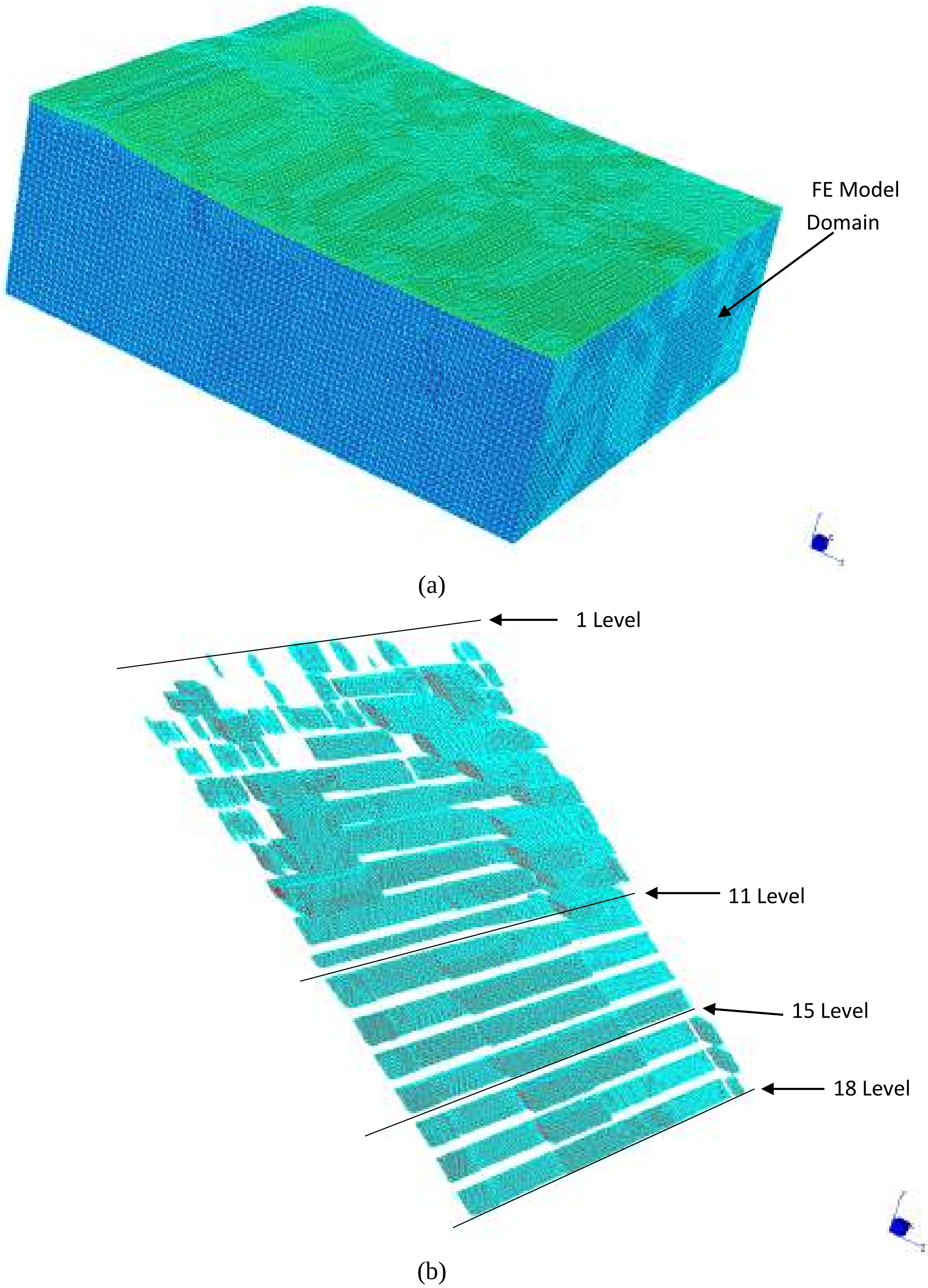


Fig. 4: (a) 3D Finit Element model and (b) model of the stopes showing levels after hiding the domain in (a)

The 3D Finite Element model shown in Figure 4 consists of 1,231,103 brick elements and 222,143 nodes

The ore body has been partly extracted up to 11 level. Some virgin patches ore has been left between the extracted stopes. The extraction of the stopes has been simulated in following stages:

Stage-1: Existing extracted open and filled stopes up to 11 level,

Stage-2: Extraction of virgin stopes between the filled stopes,

Stage -3: Extraction of virgin stopes between 11 level to 15 level

Stage -4: Extraction of virgin stopes between 15 level to 18 level

The boundary conditions adopted for the finite element model are as follows:

- The model base hasn't any movement so that the degree of freedom (DOF) in X, Y and Z directions was restrained.
- The two sides of the model in X-direction were constrained in Z-direction.
- The two sides of the model in Z-direction and extraction face were constrained in X-direction.

The gravity load and in-situ stresses (Table 1) were applied to the model.

3.2 Parameters used in the Analysis

The following parameter were used for the 3D analysis:

Table 1: Parameters and the variables for 3D FEM analysis.

Geometry of HW and FW lodes	As per CAD drawing supplied by mine management
Young's Modulus of Elasticity	20GPa
Density (γ)	2500 kg/m^3
Poisson's ratio (ν)	0.25
Rock mass compressive strength	23 MPa
Internal angle of friction	30 degree
Rock mass tensile strength	3 MPa

Weathered rock at the surface up to 10 m has been simulated by assigning 5 GPa Young's Modules. The compressibility of the fill material has been simulated by laboratory compressive stress-strain experimental curve, Figure 5, of sand.

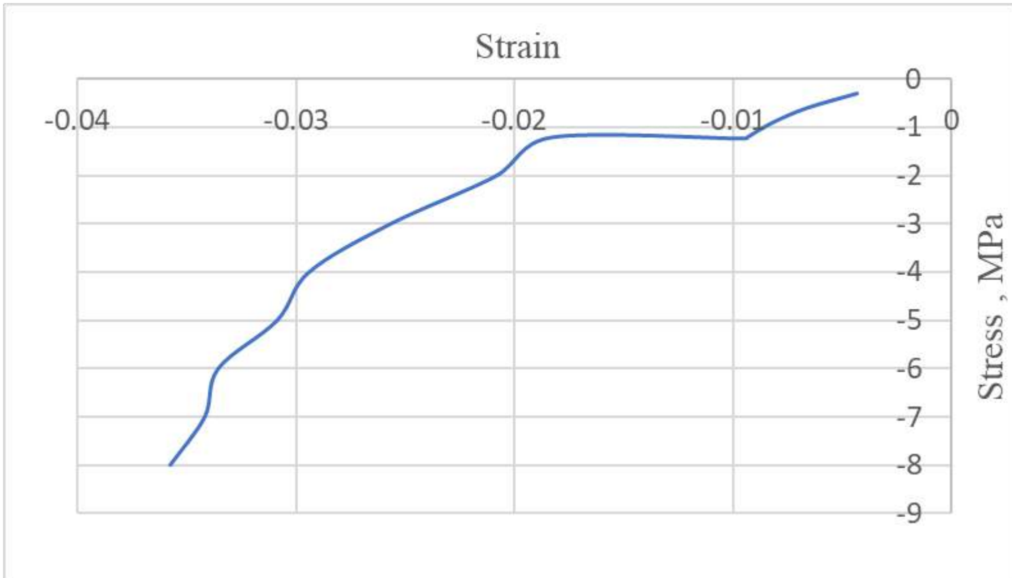


Fig. 5: Compressive Stress strain curve of fill

In-situ stress

(The information and data in this section have been compiled from a report of "Rock Mechanics IDSCB" Reference (1))

Because of the low success rate with the in-situ stress testing, reported in *"Rock Mechanics IDSCB"*, the lack of one complete set of measurements and some irregularities with some tests, a rigorous analysis of the results was not possible. However, selected results from Surda were analyzed from first principles. In general terms the following conclusions may be drawn from the tests for Surda mine.

(a) The *maximum principal stress*, σ_1 is horizontal and oriented sub parallel to strike.
(b) The *intermediate principal stress*, σ_2 is oriented approximately normal to the lode.
(c) The *minor principal stress*, σ_3 is oriented down dip sub parallel to the lode.

The orientation of the stresses is shown in Figure 6 with respect to plane of the ore body.

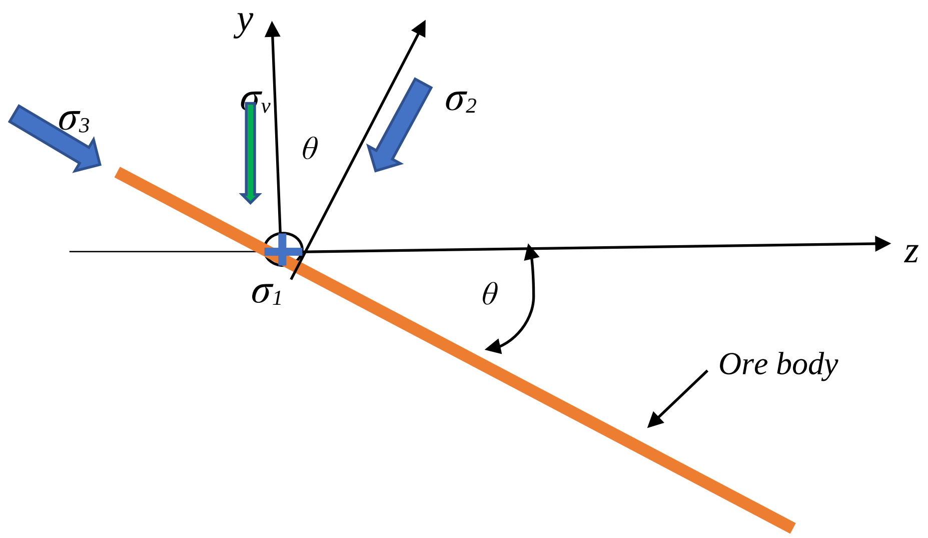


Fig. 6: Axes *x, y and z* associated with ore body plane dipping *θ = 35 degrees along z-axis i.e towards N-E direction,*

The ratio of horizontal to vertical stress is high, but in keeping with other older, eroded Pre-Cambrian shield areas Canada and Australia, the approximate stress ratios appear to be:

$$\sigma_1 : \sigma_2 : \sigma_3 : = 1.0 : 0.5 : 0.25 \qquad (1)$$

Depending on assumptions made and the data set selected, some alternate orientations and magnitudes may be obtained from the test data. However, these results would appear to provide a reasonable match with the observational data, the structure of the area and the geological history.

In order to use the measured and interpreted principal stress ratio (Eq. 1) and direction of these principal stresses shown in Fig. 6 with respect to plane of the ore boy, we need to correlate them with vertical stress, σ_v. The vertical stress, σ_v in MPa, is related to depth for rock density of *2500 kg/m*^{3} as

$$\sigma_v = 0.025 * \text{vertical depth from the surface, } m \qquad (2)$$

Using stress transformation law, σ_v is given referring to Fig. 2 as

$$\sigma_v = \sigma_2 \cos^2\theta + \sigma_3 \sin^2\theta \qquad (3)$$

Using equations 2 and 3, we write principle stresses, shown in Fig. 2, in terms of vertical stress σ_v as

$$\sigma_1 = 2.4\,\sigma_v;\quad \sigma_2 = 1.2\,\sigma_v;\quad \sigma_3 = 0.6\,\sigma_v \tag{4}$$

These in-situ stress data have been used in Numerical simulation for the extraction of the ore body in Surda mine for simulation of surface subsidence.

4. RESULTS

Surface Subsidence

Surface vertical displacement contours is shown is Fig. 7a after present state of stopping (excavating) upto 11 level and the surface displacement is shown in Figure 7b up to 18 level. Comparing Figures 7a & b, it reveals that there will be marginal surface subsidence of 10 mm from the present state of stopping. The variation of vertical surface subsidence across line Z-Z' (marked in Fig. 7b) along the dip direction is shown in graph, Figure 8.

Surface Strain

Contour of surface principle tensile strain are shown in Figures 9a, b & c for different stages of stopping. It is observed in Figure 9a that there occurs initial in situ tensile strain due to applied in-situ stress in virgin state i.e., before any excavation as shown as Fig. 9a. The initial tensile strain of magnitude 1mm/m to 3mm/m occurs in narrow band along the strike. This is due to surface profile and direction in situ principal stresses. The present excavation has led to a marginal increase of 1mm/m tensile strain due to stopping of stage 1, the present stopings (Fig. 9b). Figure 9c shows that after stage 4 stopping, there will be a marginal increase in tensile strain by 2.2 mm/m. Variation of surface tensile strain along the line Z-Z' as shown in Figure 10.

Sill /Crown Pillar Stability

Figures 11 a & b show Factor of Safety (FoS) contour on a vertical plane across a line Z1-Z1' (mark in Fig. 7b). A careful examination of the Figs. 11a & b reveals that factor of safety of all sill/crown pillar pillars are greater than 1.4 except pillars at 16 level and 17 Level. Factor of Safety of sill/crown pillars at these pillars are reduced to 1.1. It is to note that the stopes being filled with mill tailing, they remain stable and continue to transfer stresses.

Parametric Study

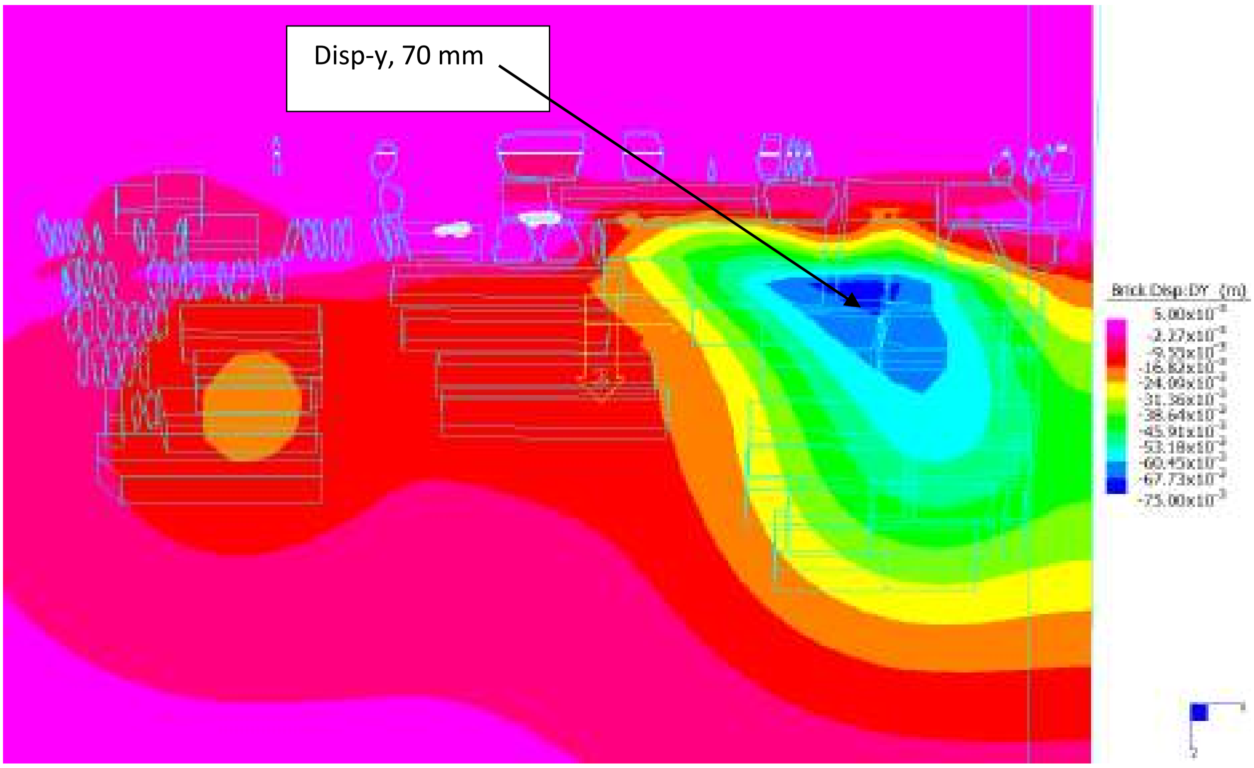
Appendix-1 shows results of parametric study due to following parameters:

- In situ stress only due to gravity load.
- In situ stress as stated in section-2 of the report and all pillars remove between 11 Level11 & 18 Level.

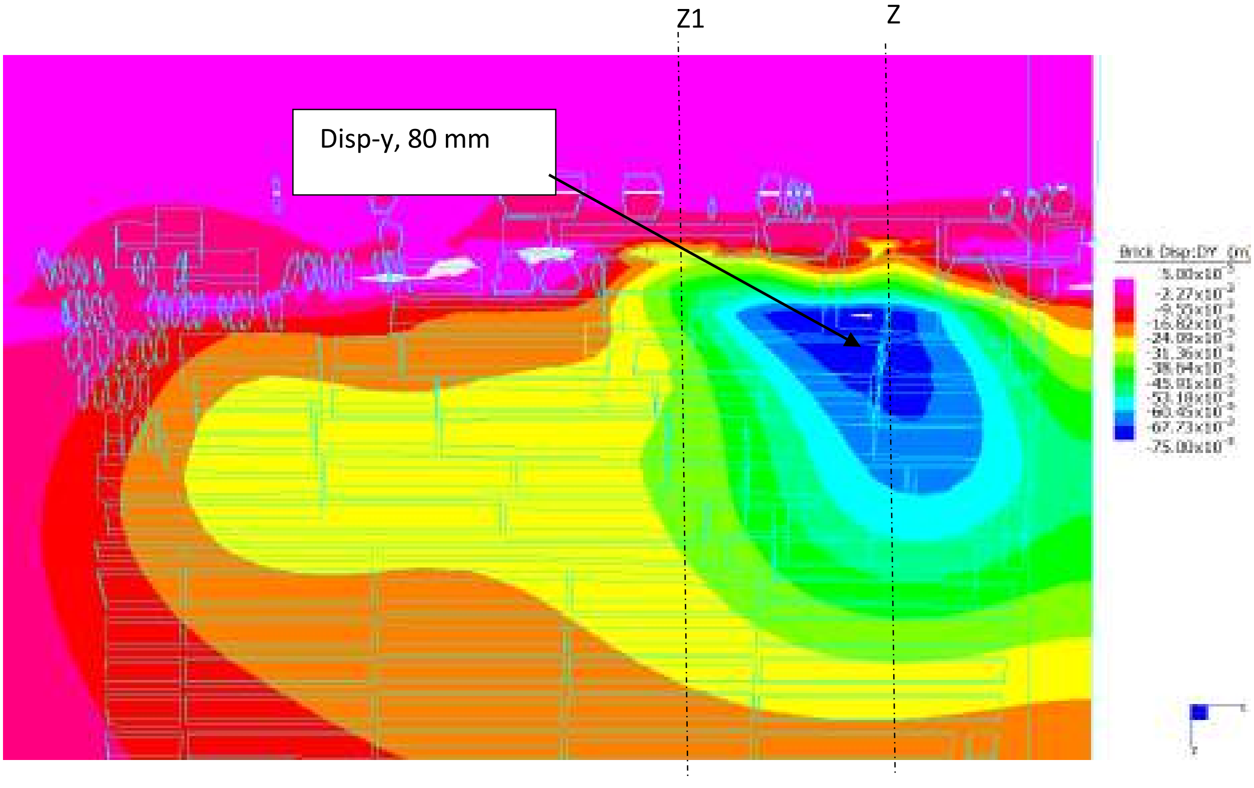
The results of the parametric study are compiled in Table-2

Table 2: Results of variation of parameters A and B for stoping up to Stage-4. Figures are referred to Appendix-I.

	Parameter (A)	Parameter (B)
1. Max surface subsidence, mm	75 (Fig. A.1 and Fig. A.2)	110 (Fig. B.1 and Fig. B.2)
2. Max surface tensile strain, mm/m	0.06 (Fig. A.3 and Fig. A.4)	3.4 (Fig. B.3, Fig. B.4 & Fig. B.5)



(a)



(b)

Fig. 7: Surface plan showing contours of vertical displacement (a) at present state of extraction the ore body up to 11 Level (Stage-1). (b) After extraction the ore body up to 18 Level (Stage-4). Respective extracted stopes are superimposed over them.

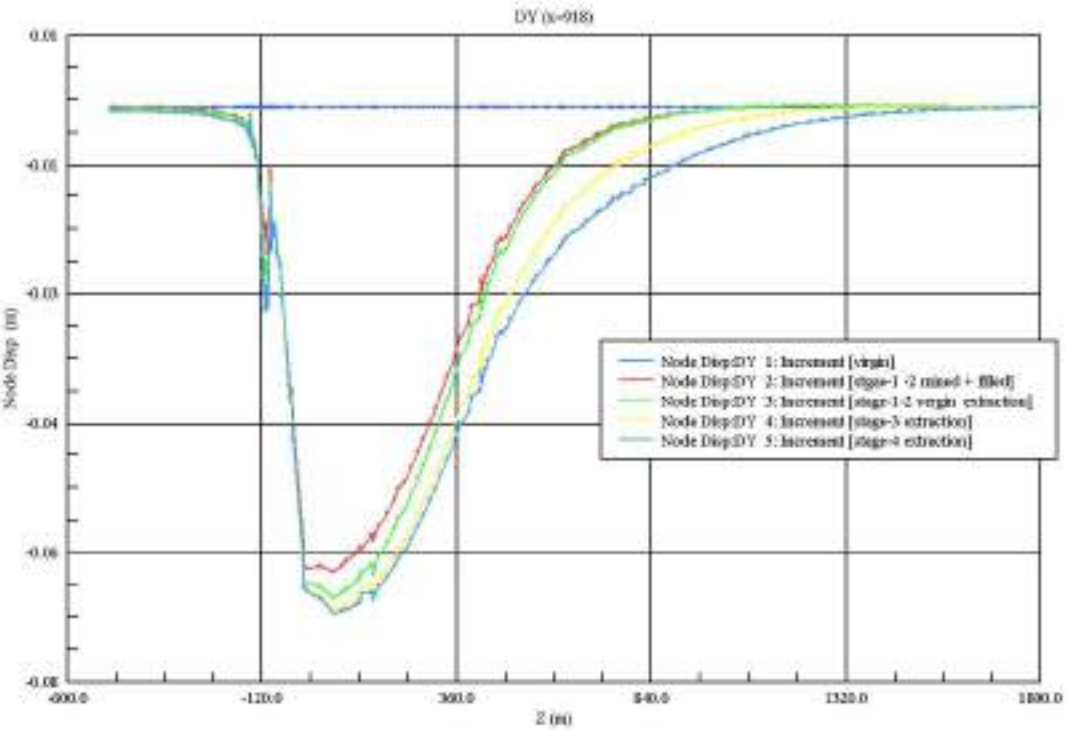
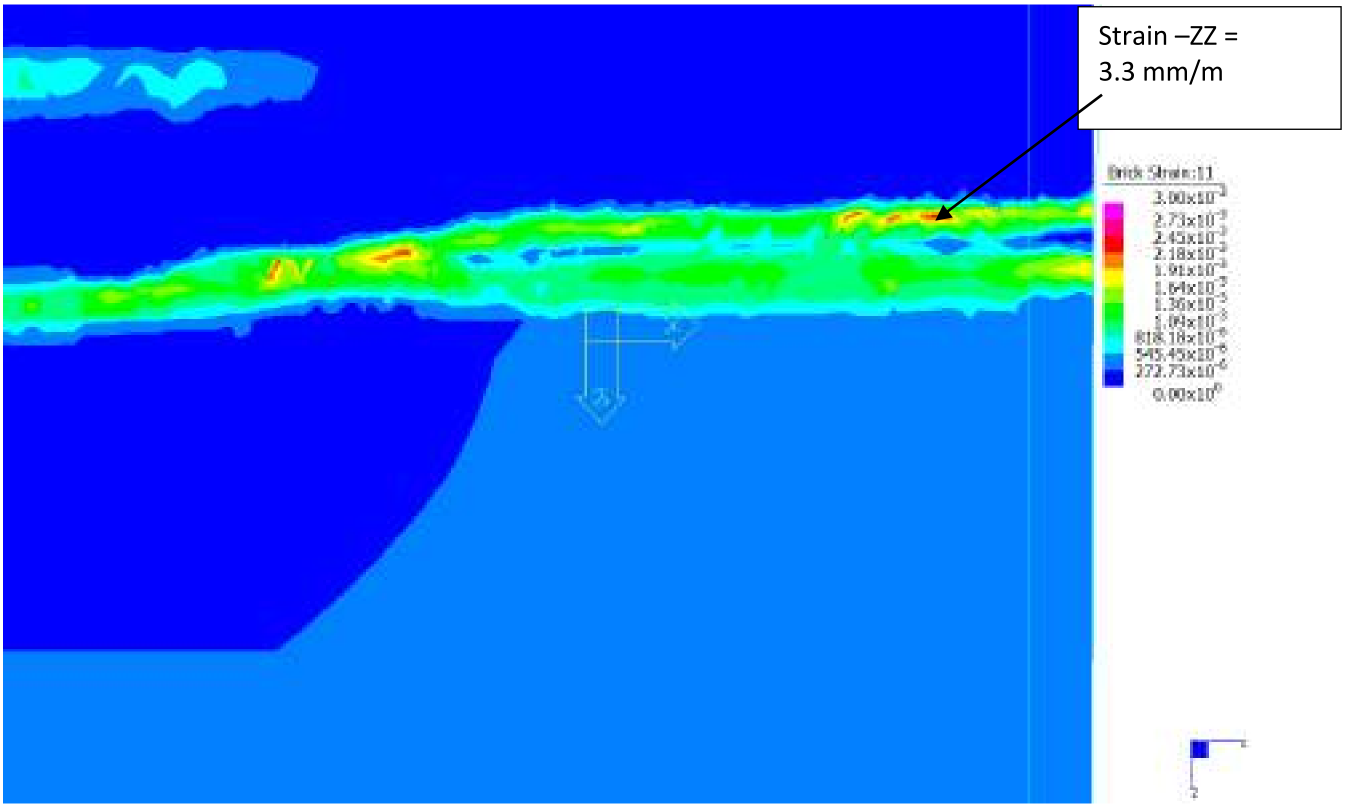
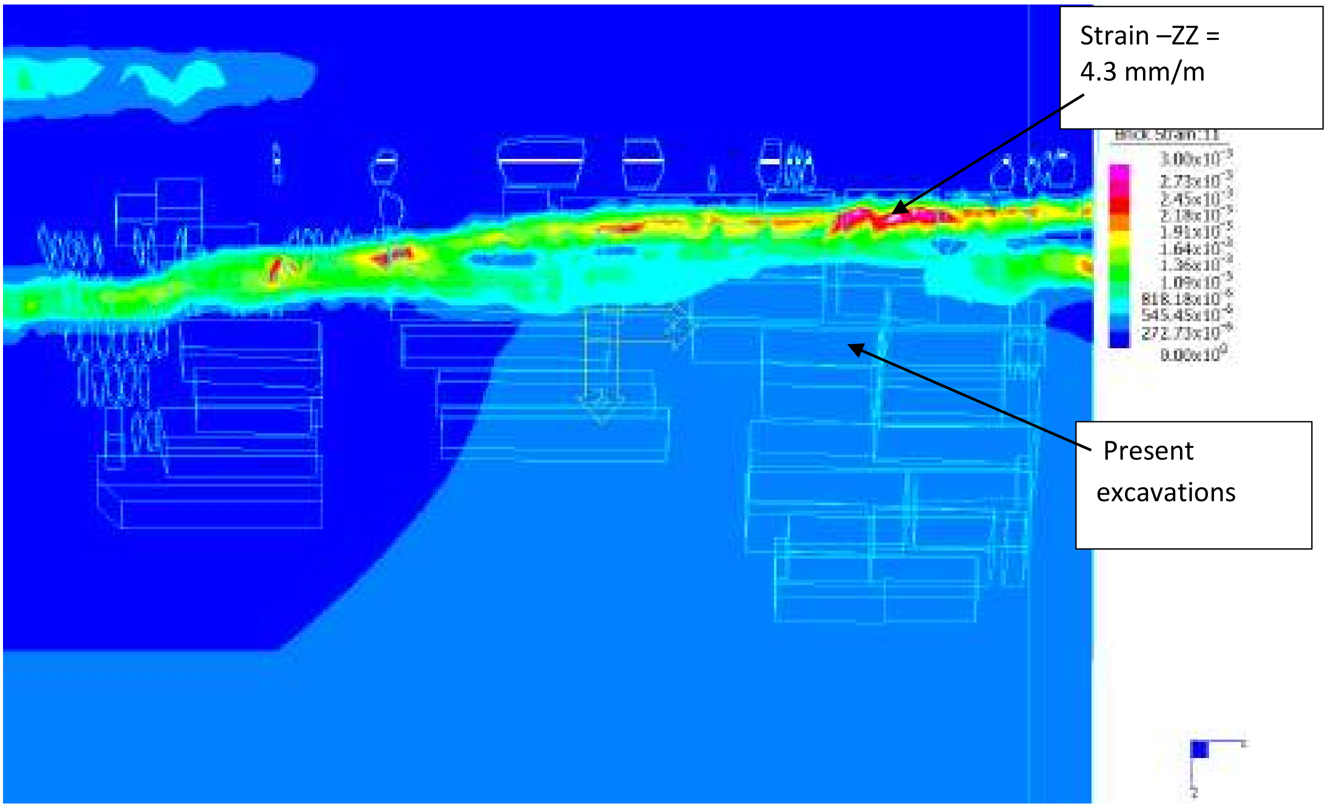


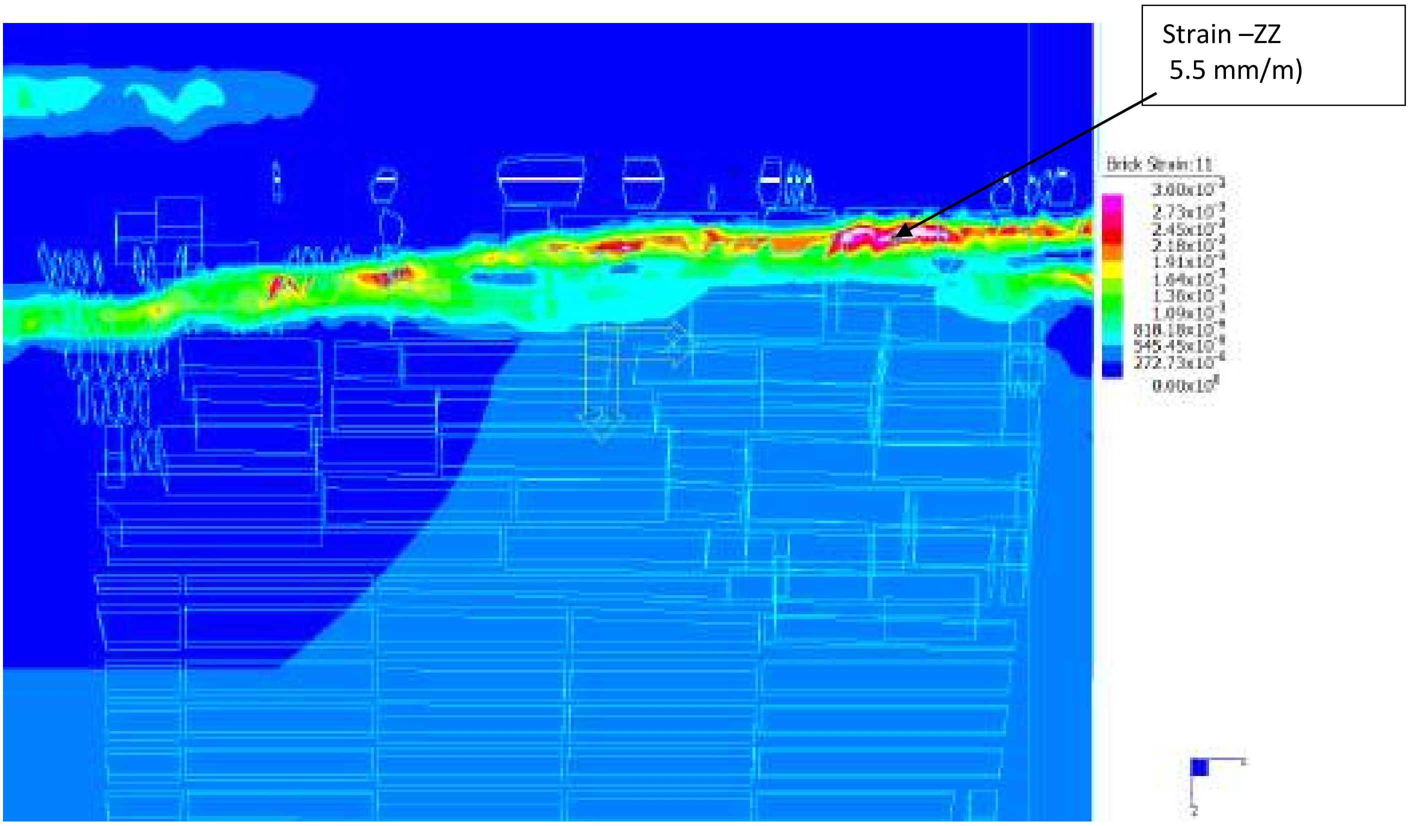
Fig.8: Graph of the vertical displacement, DY, along a line Z-Z' marked in Fig. 7b.


Strain –ZZ =
3.3 mm/m
Brick Strain:11
3.00x10-3
2.73x10-3
2.45x10-3
2.18x10-3
1.91x10-3
1.64x10-3
1.36x10-3
1.09x10-3
818.18x10-6
545.45x10-6
272.73x10-6
0.00x100

(a)

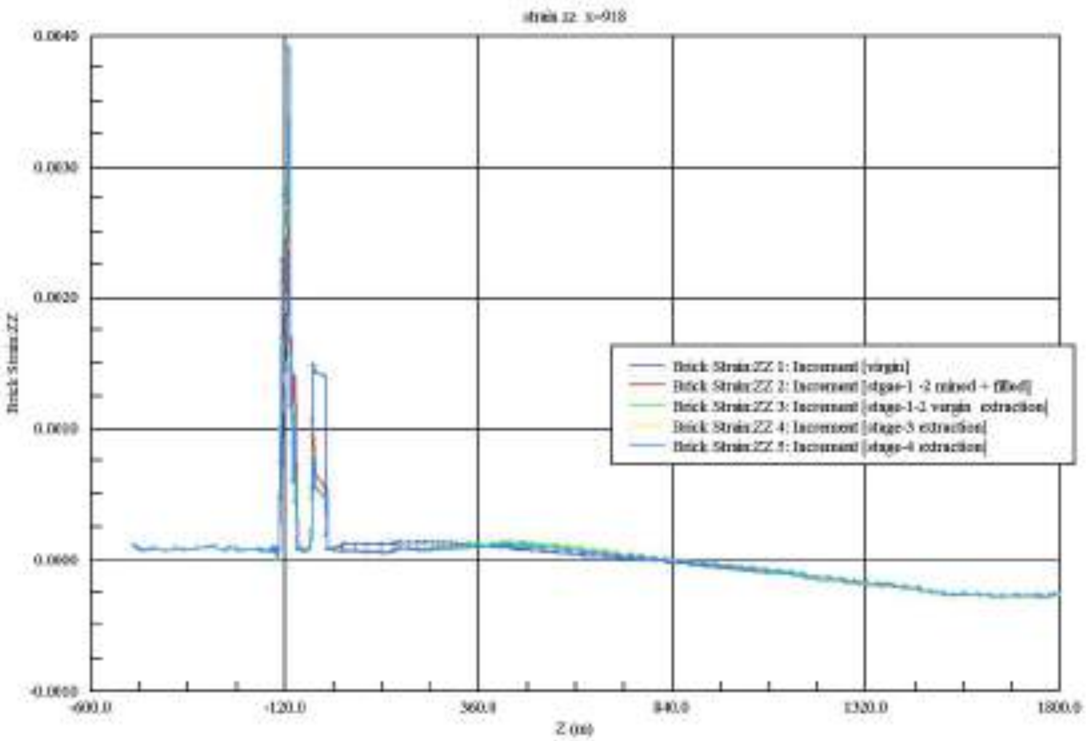

Strain –ZZ =
4.3 mm/m
Present
excavations
3.00x10-3
2.73x10-3
2.45x10-3
2.18x10-3
1.91x10-3
1.64x10-3
1.36x10-3
1.09x10-3
818.18x10-6
545.45x10-6
272.73x10-6
0.00x100

(b)

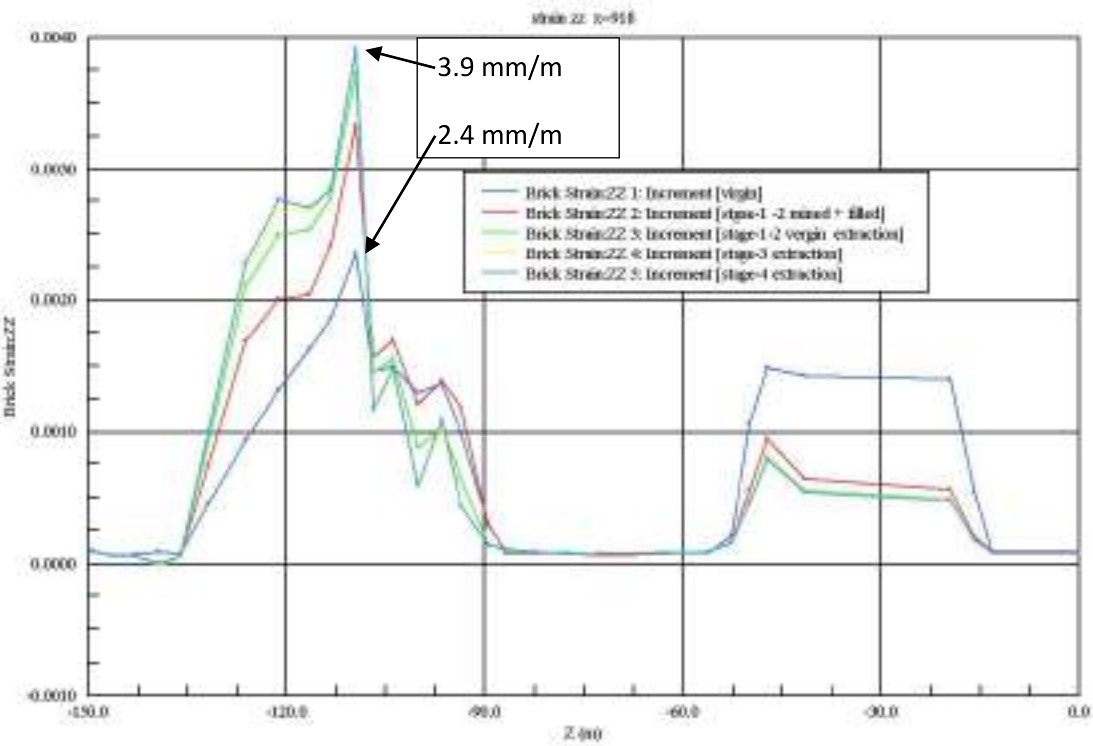


(c)

Fig. 9: Contours of surface strain along dip direction (axis-Z) (a) before commencement of mining, (b) after present extraction the ore body up to 11 Level (Stage-1) and (c) after extraction the ore body up to 18 Level, after Stage-4.

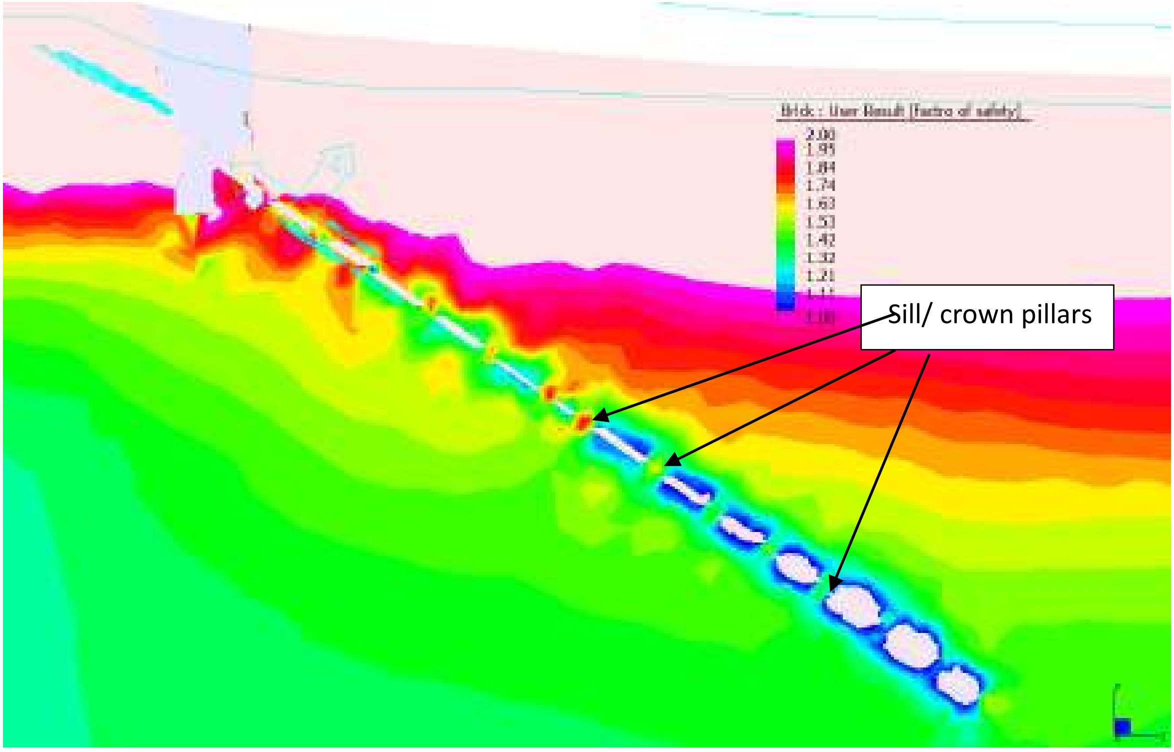


(a)

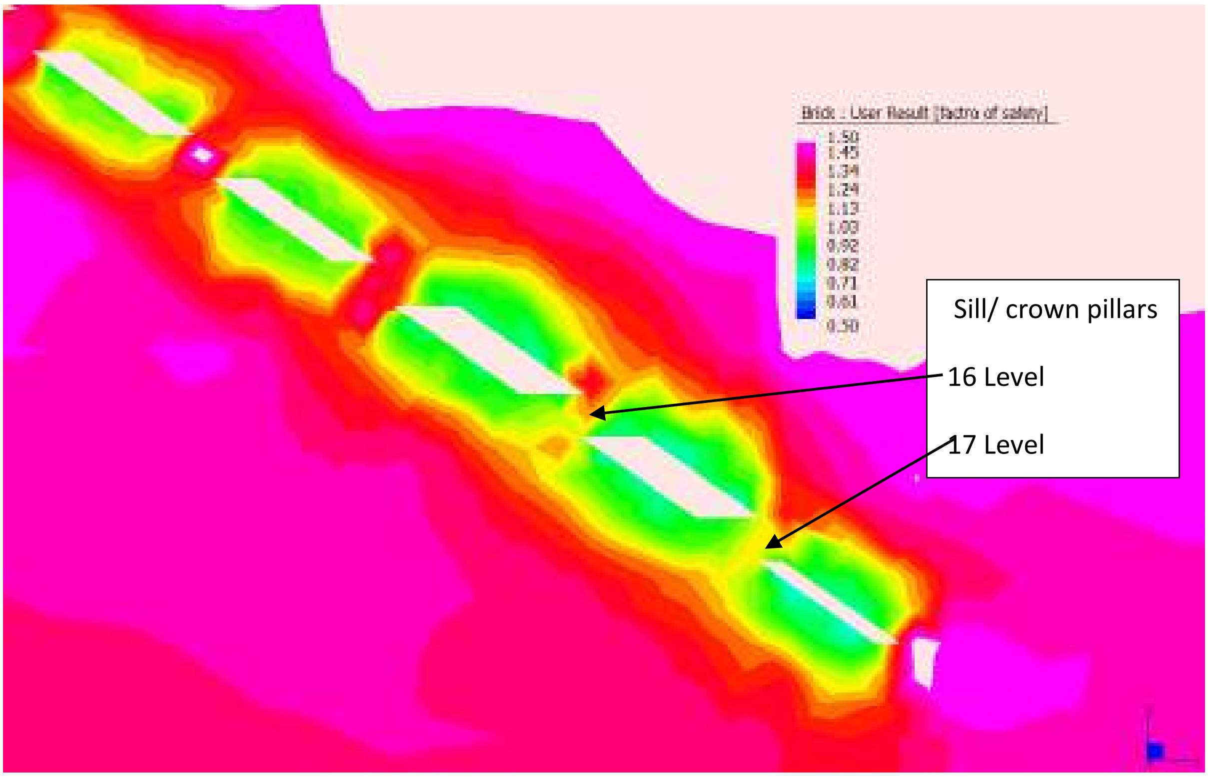


(b)

Fig. 10: (a) Graph of the strain-ZZ, along a line Z-Z' marked in Fig. 7b. (b) Enlarged view near the peak of graph in (a).



(a)



(b)

Fig. 11: Contours of Factor of safety along a vertical cross section of the ore body along line Z1-Z1' marked in Fig. 7b.

5. DISCUSSION AND CONCLUSION

The numerical simulation results shows that the stopes Stage-1 i.e., stopping up to 11 level has led to a surface subsidence 60 mm and maximum tensile strain of 1 mm/m with reference to the initial virgin strain. Excavation in subsequent stages has led to a marginal increase in surface subsidence as shown in Figure 8.

A similar trend exists for the tensile strains too as shown as Figure 10. The results of the parametric study reported in Appendix-I shows that without sill/crown pillars between 11 Level to 18 level, surface strain will be 3.4 mm/m.

On the basis of results, we conclude that

(1) Stages 3 and 4 excavations i.e., deeper excavations have a small influence on the surface compared to the shallower excavations up to Stage-2.
(2) Maximum surface tensile strain of magnitude 2.2mm/m will occur after Stage-4, i.e. 18 Level stopping compared to the virgin state.
(3) The sill/crown pillars remain stable.
(4) Parametric study shows that insignificant damage at the surface may occur in case pillars are removed or crushed at depth.
(5) Tensile strain region exists at the surface along the strike in a narrow band between 1 level to 5 level.

Finally, we conclude in context of damage to the surface that the stopping up to 18 level, as planned by the mine management shown in LV section in Figure 2, will not lead to any damage to the forest land, trees, existing structures, buildings, roads, Nala and agricultural land.

6. SUBSIDENCE CONTROL AND PREVENTION

Four types of measures may control subsidence damage: alteration in mining techniques; post-mining stabilization; architectural and structural design; and comprehensive planning (SME, 1986; Mining, 1997). None of these measures entirely prevents subsidence, and most of the measures address only impacts to man-made structures and facilities and not impacts to land use, including aquatic species, wildlife habitat and human recreation, or water quality and flow.

Post-mining stabilization techniques include backfilling, grouting, excavation and fill placement, and blasting (SME, 1986). The extent to which post-mining stabilization techniques can be relied on to mitigate subsidence damage is uncertain, as they require assessment of long-term stability. But analytical methods to predict the long-term stability of overburden in room-and-pillar (Mine, 1986) and other mining methods need significant improvement.

Back-filling may be done by hydraulic or pneumatic techniques, using a variety of materials including run- of-mine waste rock, milled tailings, or other materials, and may include the use of cement or other modifiers to increase strength. It may also have a beneficial effect on the environment by addressing water quality impacts (such as from acid drainage), reducing waste rock disposal requirements, reducing ground fissuring, and increasing long-term strata stability and providing roof support. Backfilling does not eliminate subsidence entirely, but only reduces the amount of subsidence (Mining, 1997; SME, 1986).

However, without appropriate management sub-surface workings such as stoping can result in changes to the ground surface (including local and regional settlement, cracking, subsidence or collapse) for a variety of reasons including (but not limited to) surrounding geology, general rock mass conditions, size and shape of the excavations and time dependency.

The following measures as listed below can be effective in the Ground Surface stability:

- Selection of appropriate stoping method depending on the specific nature of potential future ore bodies, and management techniques can be used to ensure ground surface stability.
- Geotechnical mapping of ore development drives and detailed characterisation of the rockmass prior to stoping operations to ensure stable stoping spans.
- Prompt back-filling of all stope voids in the mining cycle and some development drives where necessary to ensure long-term stability.
- Selective cable bolting of discrete structures to improve stope stability where structures may affect stability.
- Leaving a sufficiently sized remnant pillar to separate new workings from the ground surface
- Sufficient parting will be left between surface and the stoped out area as a measure against subsidence. Besides, parting among lenses will provide natural support to the strata.

- Post-mining stabilization techniques include backfilling, grouting, excavation and fill placement, and blasting might be adopted.
- Ongoing use of advanced numerical modelling services calibrated with data collected from the monitoring strategy for continued updating of modelling forecasts.
- Sterilisation of ore and/or premature cessation of mining if unacceptable levels of ground surface subsidence are forecasted with numerical modelling or measured through the monitoring strategy.
- Regular monitoring of subsidence on the surface over and around the working area and impact on natural drainage pattern, water bodies, vegetation, structures etc. should be continued throughout life of mining activities.

RECOMMENDATIONS

- Measurement of ground level constitutes baseline data for subsidence study. Therefore, periodical monitoring of the 3D coordinates at the identified subsidence monitoring stations and analysis of result thereafter during the operational phase of mine is mandatory.

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Appendix-I

Results of Parametric study of surface subsidence of Surda Mine, ICC/HCL

A. In-situ stress: due to gravity only

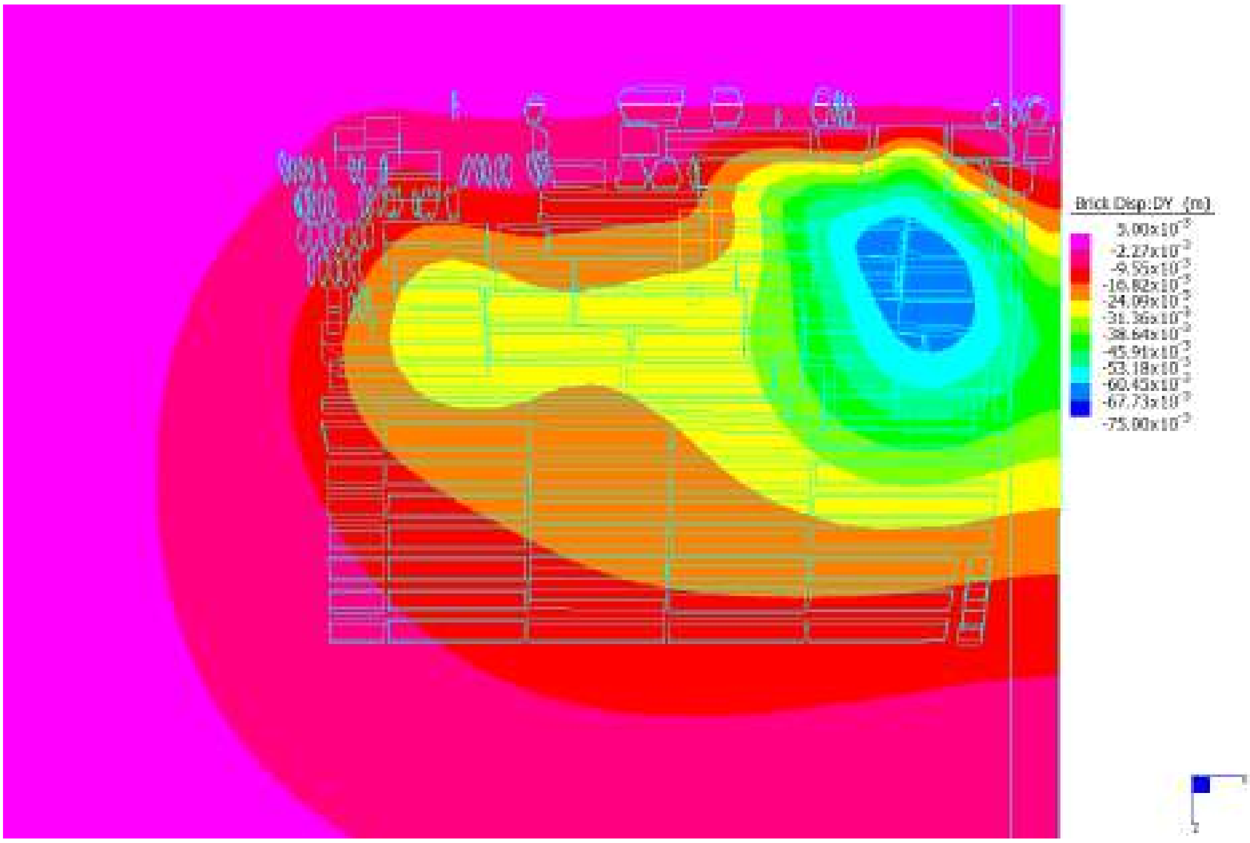


Fig. A.1: Surface plan showing contours of vertical displacement after extraction the ore body up to 18 Level. Respective extracted stopes are superimposed over it.

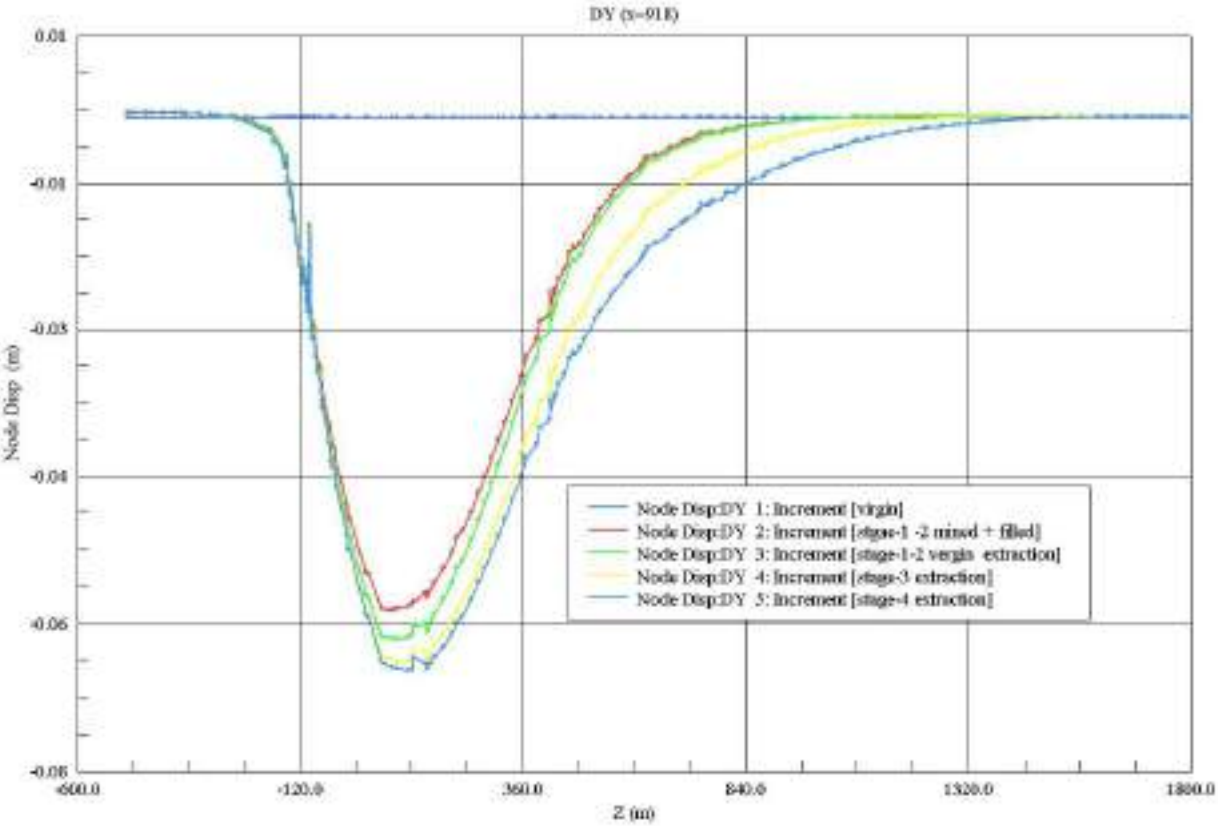
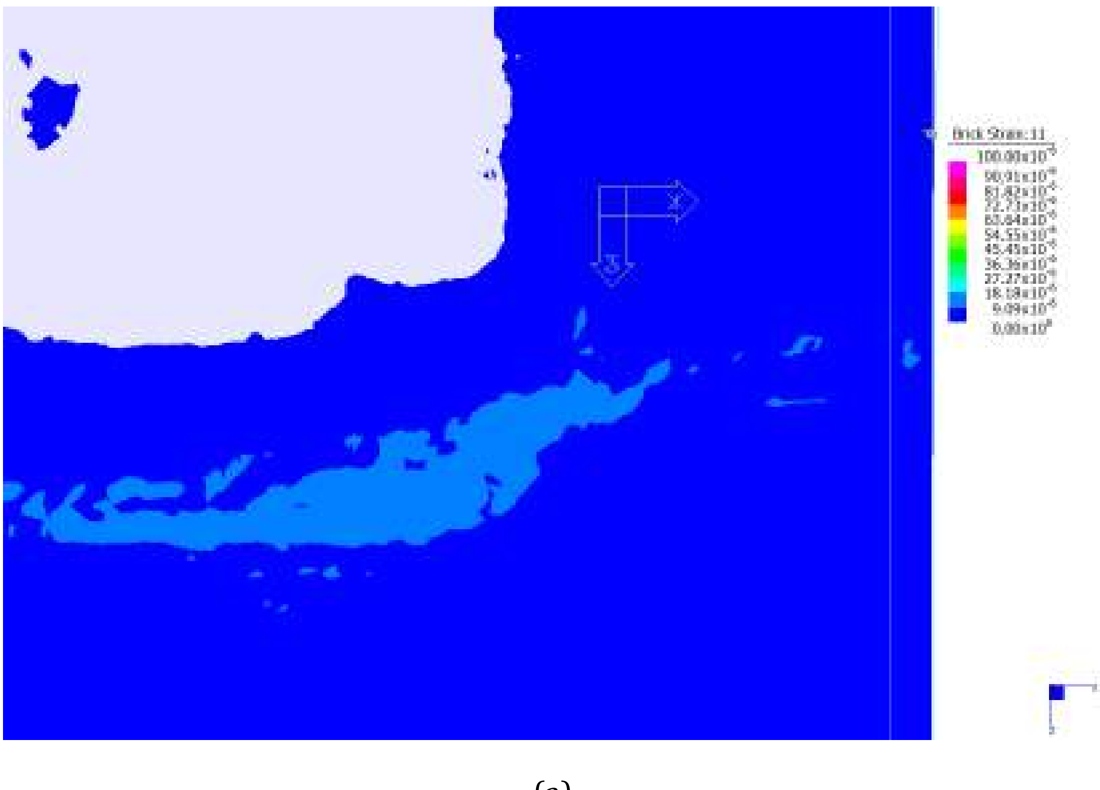
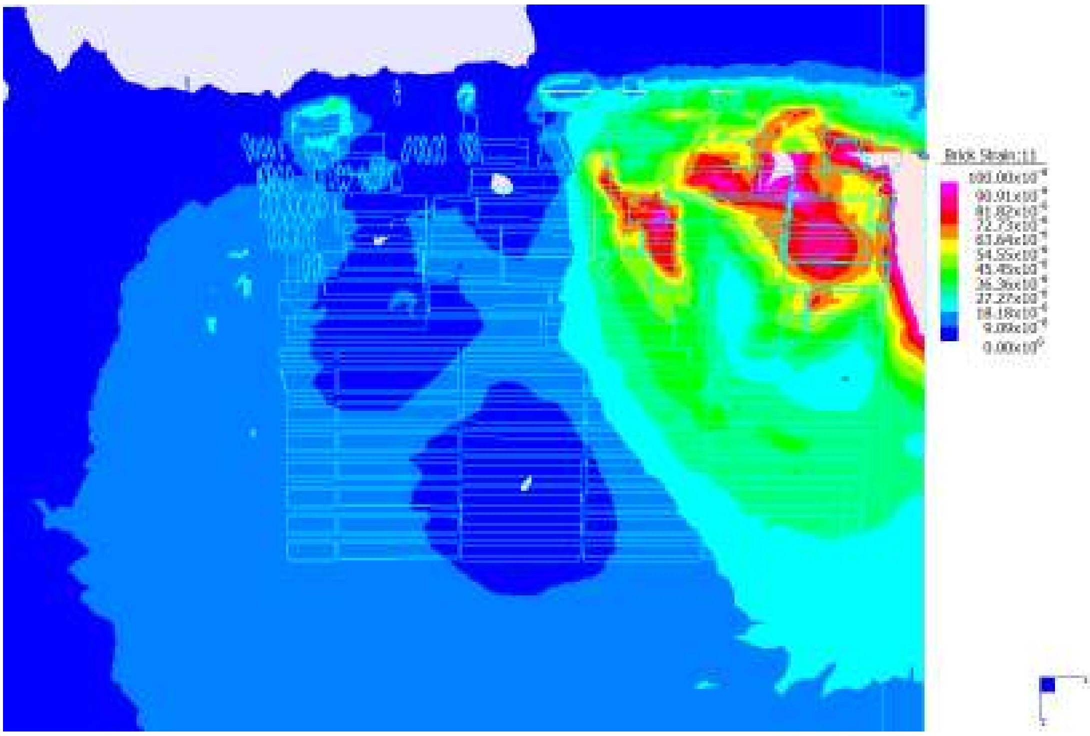


Fig. A.2: Graph of the vertical displacement, DY, along a line Z-Z' marked in Fig. 7b.



(a)



(b)

Fig. A.3: (a) Contours of maximum surface strain before any excavation (b) Contours of maximum surface strain after extraction the ore body up to 18 Level.

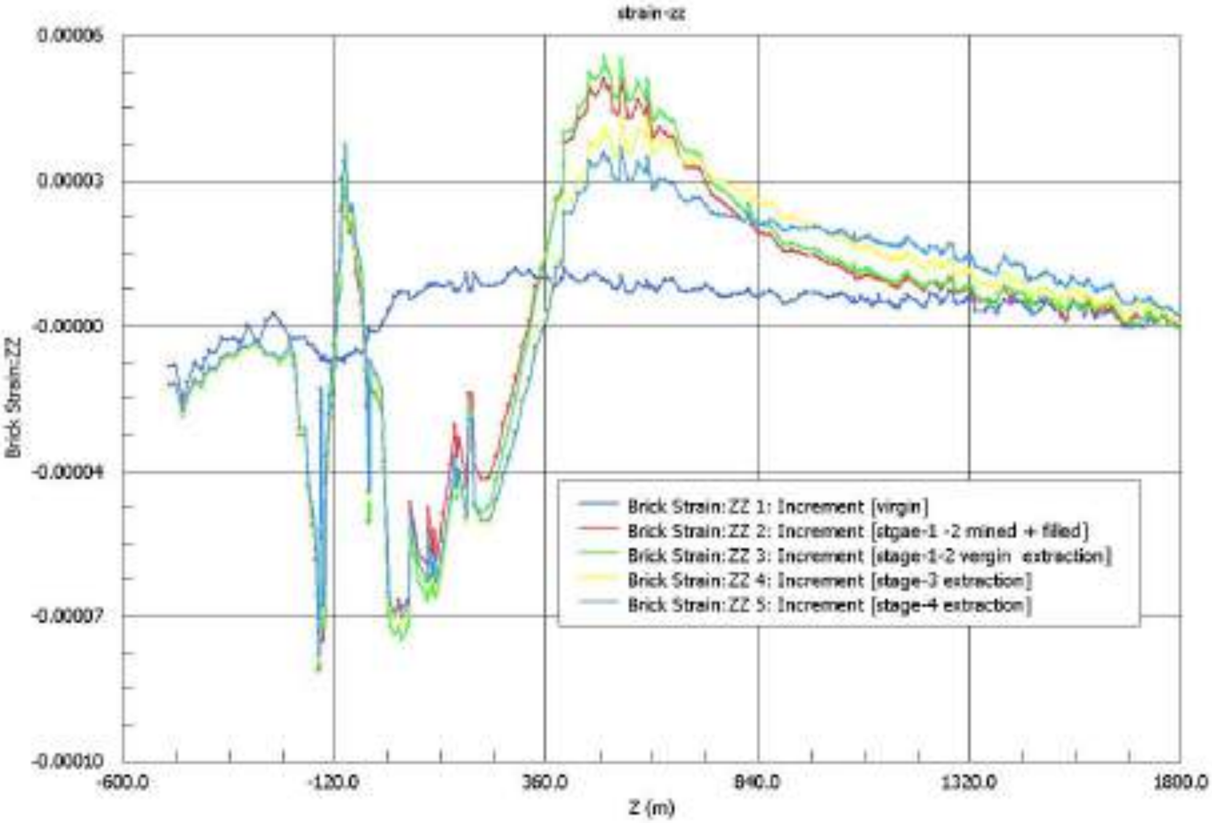


Fig. A.4: Graph surface strain after extraction the ore body up to 18 Level across line Z-Z' marked in Fig. 7b.

B. In-situ stress as per section 3.2 and pillars remove between 11 level to 18 levels

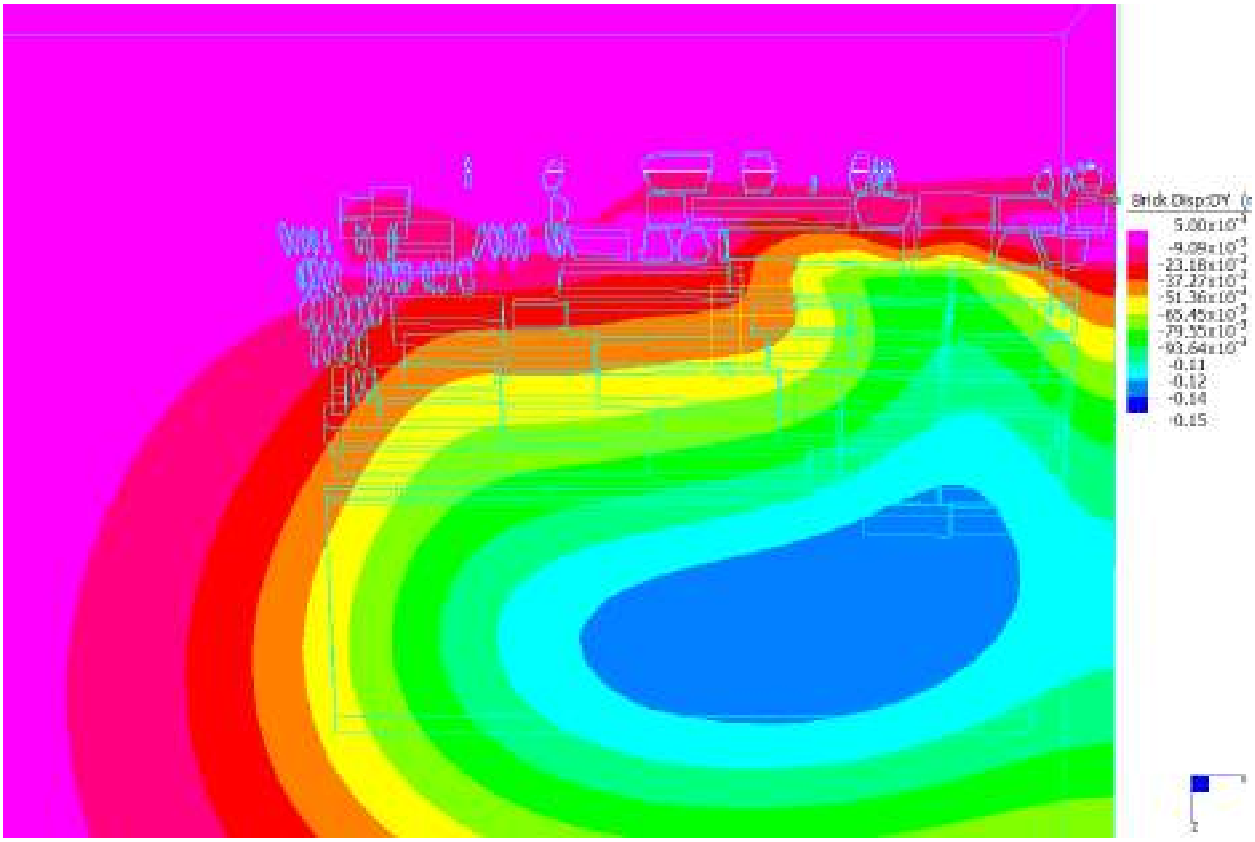


Fig. B.1: Surface plan showing contours of vertical displacement after extraction the ore body up to 18 Level. Respective extracted stopes are superimposed over it.

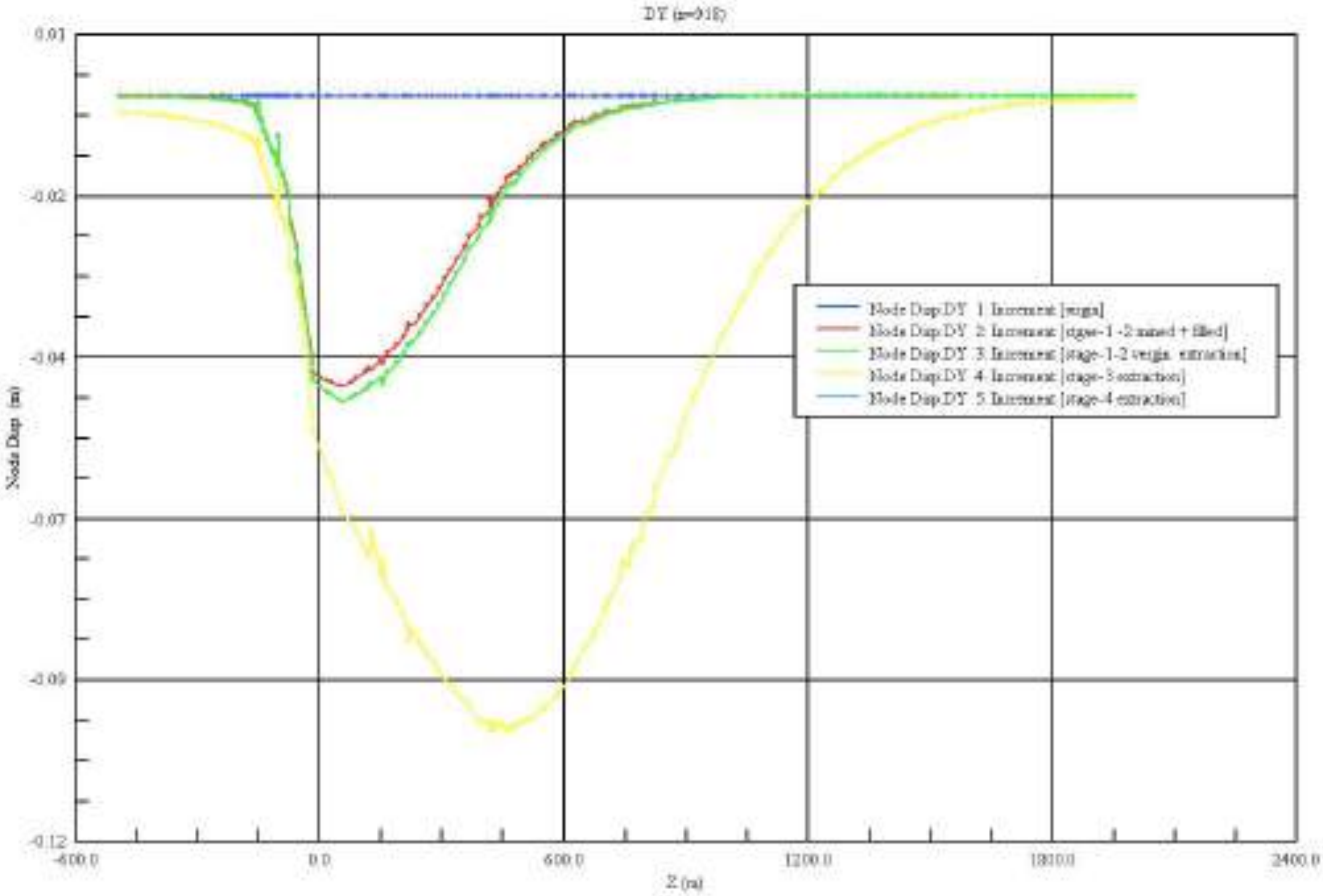
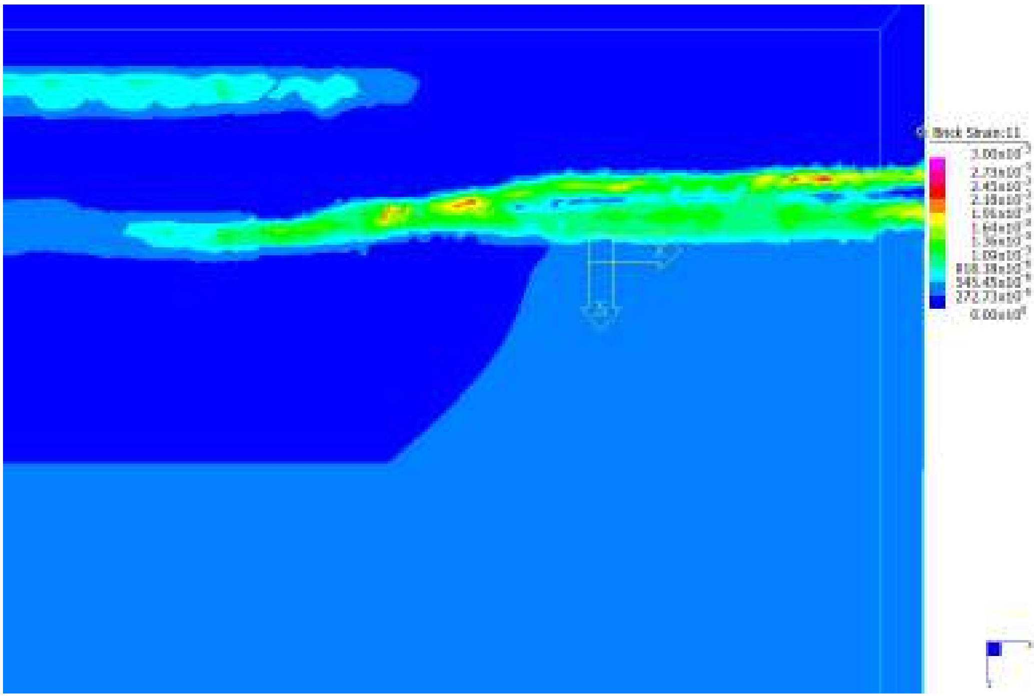
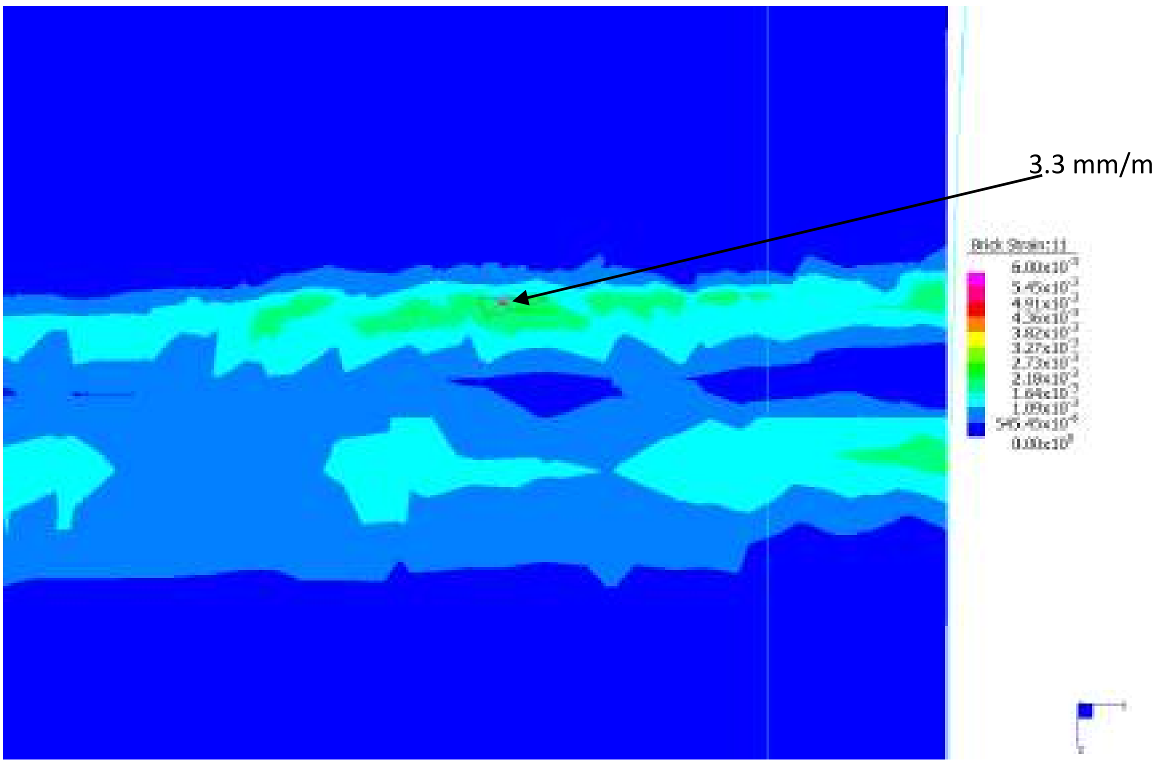


Fig. B.2: Graph of the vertical displacement, DY, along a line Z-Z' marked in Fig. 7b.

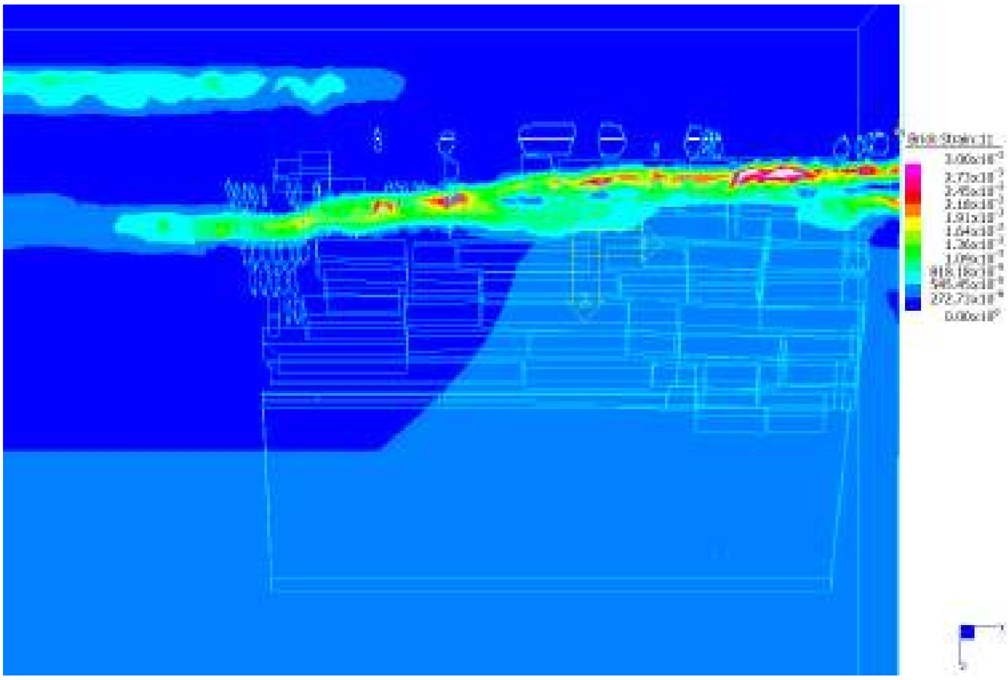


(a)

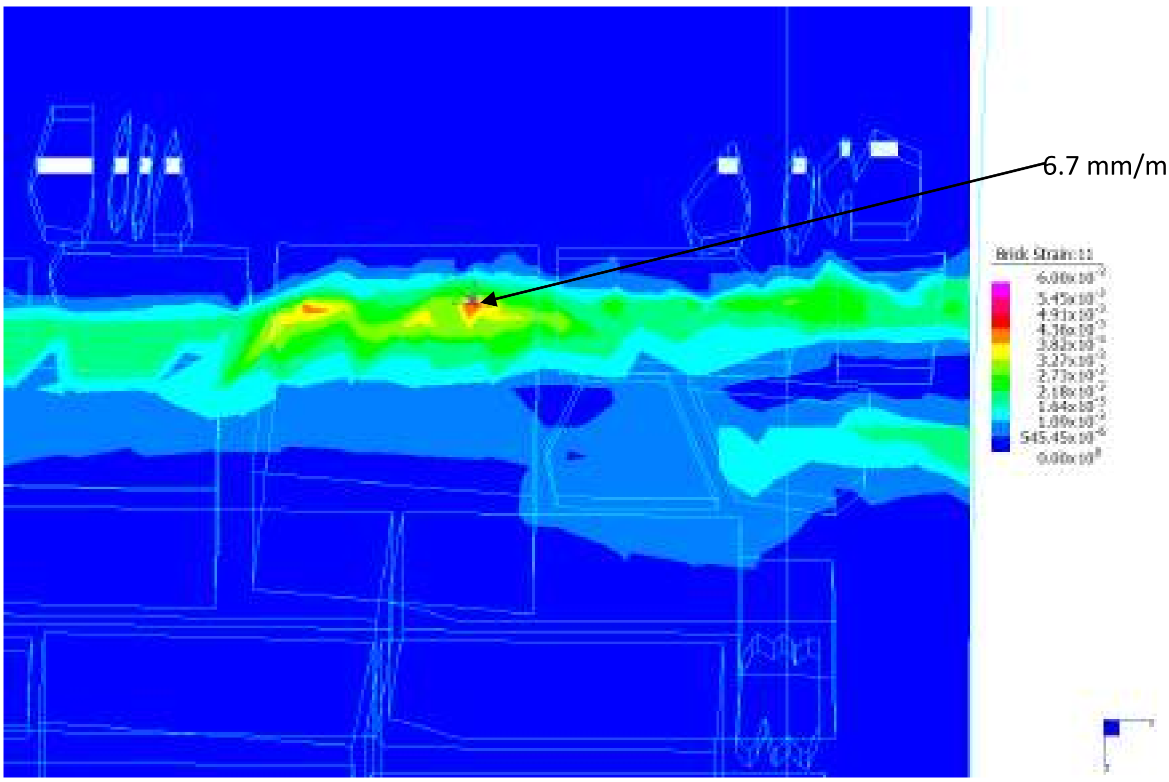


(b)

Fig. B.3: (a) Contours of maximum surface strain without any extraction. (b) Enlarged view near high strain region.

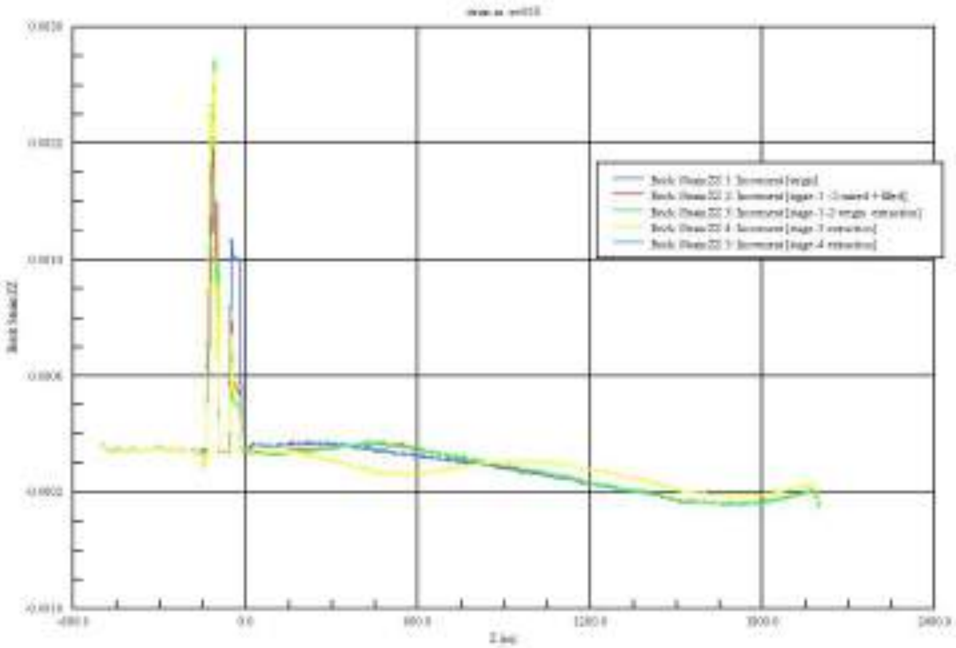


(a)

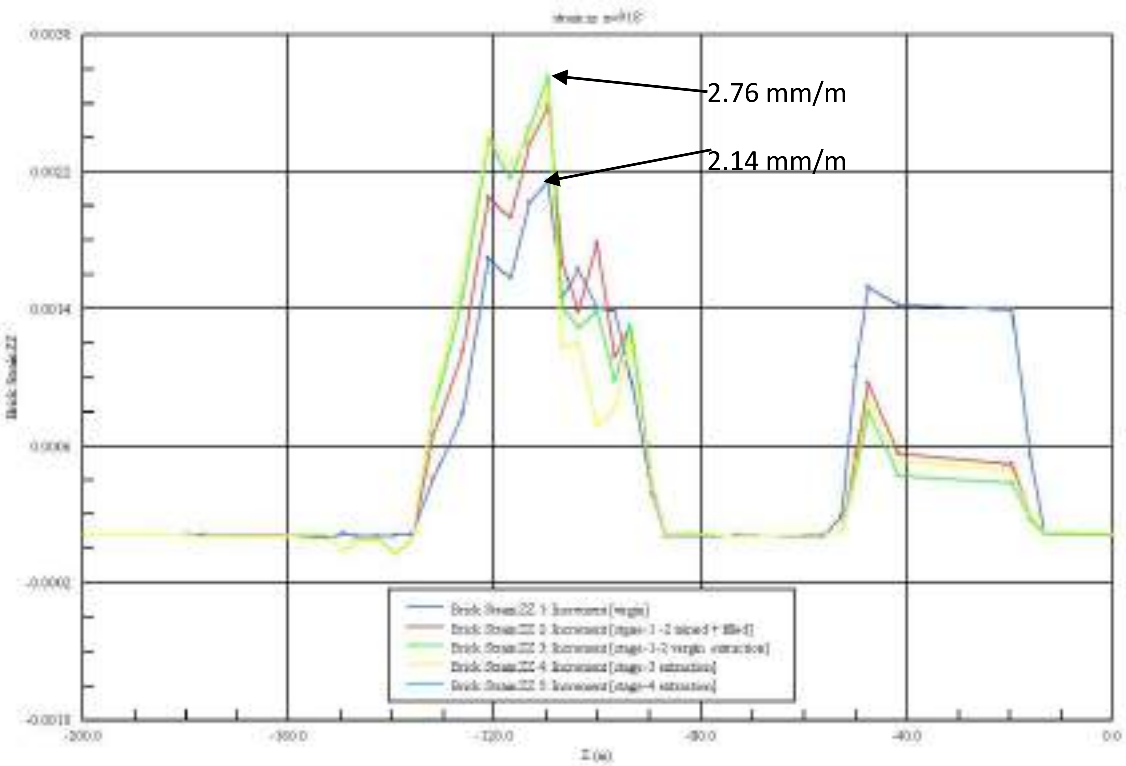


(b)

Fig. B.4: (a) Contours of surface strain along dip direction (axis-Z) after extraction the ore body up to 18 Level. (b) Enlarged view near high strain region.



(a)



(b)

Fig. B.5: (a) Graph of the strain-ZZ, along a line Z-Z' marked in Fig. 7b. (b) Enlarged view near the peak strain.