Field and Numerical Modelling Investigations on the Stability of Underground Strata during Longwall Workings

G Budi
Indian School of Mines: Indian Institute of Technology
Kolikipogu Nageswara Rao (nageswar@cimfr.nic.in)
Central Institute of Mining and Fuel Research CSIR https://orcid.org/0000-0003-3051-2958
Punit Mohanty
Indian School of Mines: Indian Institute of Technology

Research Article

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Posted Date: June 1st, 2021

DOI: https://doi.org/10.21203/rs.3.rs-553348/v1

Field and numerical modelling investigations on the stability of underground strata in longwall workings

G. Budi[1] K Nageswara Rao[2*] and Punit Mohanty[3]

[1] Faculty, Department of Mining Engineering, Indian Institute of Technology (ISM), Dhanbad, 826004 India, e-mail id: anandbudi@iitism.ac.in

[2] CSIR-Central Institute of Mining and Fuel Research, Dhanbad, 826001 India, e-mail id: nageswar@cimfr.nic.in

[3] Former postgraduate student, Department of Mining Engineering, Indian Institute of Technology (ISM), Dhanbad, 826004 India, e-mail id: punit.mohanty@gmail.com

*Corresponding Author: K Nageswara Rao, email id: nageswar@cimfr.nic.in

Abstract

Understanding the behaviour of underground workings is essential for the success of any mining method. The longwall mining method is one of the predominant underground methods to extract coal. Since 1978, in India, 22 underground coal mines of different collieries have been implemented the mechanized longwall method. SCCL is one of that colliery has mixed working experiences with longwall method in their mines. The longwall faces in GDK-10A, JK-5, and VK-7 of SCCL had produced good results, but the faces in GDK-7, GDK-9, GDK-11A, and PVK-5 had suffered due to the geological disturbances and unavailability of real-time information about the strata behaviour. By addressing the previous experiences of longwall workings, Singareni Collieries Company Limited (SCCL) has implemented a high capacity (2×1152T) powered support system in Adriyala Longwall Project (ALP) at a depth of 375m. In this study, extensive field monitoring with different strata monitoring instruments was conducted in ALP to analyze the gate roads convergence, stress variation on longwall and chain pillars at different stages of extraction (i.e., 8m, 25m, 35m, and 45m) and the pressure variation on the powered support systems. It was observed from the results that the

convergence in the gate roads was increasing with the advance of the longwall face and the area of exposure. The pressure of the legs on the dip side was less than the pressure of the legs on the rise side, which implies a stable roof condition over the longwall face. To better understand the behaviour of ALP workings, a numerical modelling study with FLAC 7.0 has been conducted with actual physio-mechanical properties. The computed numerical modelling results have been remarkably well in consistent with the field monitoring results. The stability of chain pillars has been estimated at every stage of extraction by the Factor of Safety (FoS) criterion and it was found that the pillars could be ensured stability in longwall workings.

Keywords: *Longwall workings; Adriyala Longwall Project (ALP); Strata behaviour; field and numerical studies*.

1.0 Introduction

Longwall mining is a mass-mining technology to extract coal from underground mines. The method was first developed in England in the late 17th century [1]. In India, the first longwall face was operated at Narsumuda Colliery around 1880 in Raniganj coalfield. However, it was in 1940 that the longwall mining received attention again when longwall faces with stowing were started in the Raniganj and Jharia coalfields. In 1978, BCCL (a subsidiary of Coal India Limited) had implemented first mechanized longwall mining in India [2]. Singareni Collieries Company Limited (SCCL) has implemented the first its longwall technology in 1983 at GDK-7 mine. It has mixed working experiences with longwall technology in their mines. The longwall faces of SCCL in GDK- 10A, JK-5 and VK-7 had produced good results. However, the faces in GDK-7, GDK-9, GDK-11A and PVK-5 of SCCL had suffered due to geological disturbances and unavailability of real-time information about the strata behaviour [3] [4]. The mine designers must know the initial state of stress to predict the potential block failures or larger areas of instability in underground workings [5]. In longwall mining, the stress distribution could take in several stages, i.e., the initial excavation of roadways, the longwall retreat, formation of the goaf, and finally, the compaction of the goaf [6]. Persistent compressive type roof failures, roof guttering, and roof kinking are the main adverse ground control conditions typically observed at the main gate of longwall workings [7]. Therefore, the chain pillars size between the gate roads needs to be optimized so that the pillars could carry the load imposed firstly by the stress redistribution during roadways development and secondly, by the additional much larger load imposed when extracting the longwall. According to the vertical stress balance theory, the caved goaf is compacted to support the original overburden stress at the center of the longwall panel [8] [9]. Effective ground control designs and accurate subsidence predictions can only be achieved if there is an understanding of strata behaviour response to induced stresses because of mining. Stress distribution ahead of longwall workings is required to understand the failure mechanism and support requirements near the face. Achievement of better advance rate is also dependent on the magnitude and orientation of abutment stress.

2.0 Geo-mining parameters of Adriyala Longwall Project (ALP)

Adriyala Longwall Project (ALP) is located in the Godavari Valley Coalfields of Telangana State, India. The mine has access by "Punch entries" from the neighboring RG OC-II Project. Seam-1 is being adopted longwall technology out of four coal seams of ALP. The thickness of the seam-1 is 6.5m has divided into two sections, i.e., top and bottom sections. The trunk roadways were developed in the top section with stone as a roof, and the gate roadways were developed in the bottom section with coal as the immediate roof. Road headers are being used to develop the gate roads, having a gate roads length of 2333m and a face width of 250m. The depth of the seam is varying from 362m to 457m and the gradient of the seam is 1 in 6. The immediate roof of the gate roadways consists of weak coal with RMR of 41.4. 5m width of gate roads were supported with 2.4m long roof bolts with 1m interval. Rigid meshes were also placed to arrest the skin failures of the weak coal roof. High capacity powered support systems were installed along the face length with the capacity of $(2 \times 1152\mathrm{T})$ with yielding pressure of 450 bar. Figure 1 shows the longwall workings of ALP. The first longwall package was implemented in the longwall panel-1 of ALP. The details of the panel can be seen in Table 1, and the section of the borehole representing the layers of the seam-1 can be seen in Figure 2.

Table 1: The geo-mining details of the selected panel for the study

Name of the seam and panel	No. 1 seam and longwall panel-1
Seam thickness	6.5m (Top and Bottom sections)
Gradient of seam	1 in 6
Working height	3.5m
Depth	Minimum- 362m and Maximum- 457m
Length of panel	2333m
Face length	250 m
Supports in face	$(2 \times 1152T)$ Powered supports

2.1 Field instrumentation results and the assessment of longwall workings behaviour

The gate roads, longwall face, and the powered support system of the longwall panel-1 have been monitored with different strata instruments. Convergence indicators, Telltale extensometers, load cells, PMC-R (Programmable Mining Controller- Roof Support), and stress cells were used in the monitoring study. Figure 3 shows the instruments locations in the longwall panel-1. Round the clock the monitoring was done to observe the periodic weighting phenomenon, induced stress distribution and convergence in the gate roadways. Trigger Action Response Plan (TARP) was prepared for the development to act with the necessary secondary support system to ensure the roof's stability in case of any trigger like more convergence or geological disturbance occurs.

a) Roof weighting phenomenon

Local falls, main falls, and periodic weightings were observed in the panel during retreating of the longwall face. The first local fall occurred after a retreat of 10.75m. The main fall of area 12,215m^2 occurred after a retreat of 39.9m from the mine boundary. Heavy sounds were observed during the main fall in the goaf. A detailed note of such events has given in table 2.

Table 2: Detailed observations of the periodic weighting intervals in the longwall panel-1

Event	Average Retreat (m)	Area of exposure (m^2)	Observations
Local fall	10.75	4,781	-Local fall occurred & the fall area is 3250 m^2 -Sounds were heard in goaf.
Local fall	31.65	10,111	-Weighting observed.
Weighting	31.65	10,111	-Weighting observed
Water seepage	31.65	10,111	-Water seepage from the roof from C44-C55 was observed.
Local fall	35	10,965	-Sounds were heard in the goaf.
Main fall	39.9	12,215	-Sounds were heard in the goaf.

b) Vertical stress variation on longwall and chain pillars

Stress cells were installed at every 100m intervals in the longwall pillar and every 200m intervals in the chain pillars. The in-situ stress at a depth of 375m is 9.35MPa. On longwall pillar, the stress begins drop though after reaching a maximum value of 1010.35 KPa (9.35MPa is being in-situ) at a distance of 13.2 m from the measuring station. Nevertheless, in the case of chain pillars stress readings, it was observed that the stress rises steadily before becoming almost constant at 43.2 m from the face with maximum stress of 580.41 KPa (9.35MPa is being in-situ). The variation of induced stress on the longwall pillar and chain pillar can be seen in Figures 4 and 5, respectively.

c) Convergence of the gate roadways

The roof was monitored with convergence indicators installed for every 25m interval in the gate roads, two-point telltale extensometers were installed for every 50m interval, i.e., at the junctions of cut-throughs, and the monitoring was done on a daily basis.

Main Gate (MG) convergence

From the observations of the instruments, it was reported that the cumulative convergence remains fairly constant and negligible at a distance of 25 m and 50 m from the measuring stations but shows a gradual increase as the face retreats nearer to the measuring stations, as shown in the Figures 6 and 7. A minimum of 1mm convergence to a maximum 12mm convergence was noticed in the MG. The maximum convergence observed in the MG is 12mm after 75m of longwall face extraction, as shown in Figure 8.

Tail Gate-1 (TG-1) convergence

The convergence instruments installed along the TG-1 showed a similar convergence pattern as MG, as discussed in the earlier section. The maximum convergence observed was 8mm at 75m of longwall face extraction, as shown in Figure 11. The variation of convergence at 25m, 50m and 75m of longwall face extraction can be seen in Figures 9 to 11.

Tail Gate-2 (TG-2) convergence

The convergence readings vary from 1 mm to 6 mm at all convergence stations, as shown in Figures from 12 to 14. The convergence readings recorded at TG-2 are considerably less than those recorded at MG. The maximum convergence of 6 mm was recorded after 75 m longwall face extraction.

d) Dip and Rise side pressure observations on Powered supports

The pressures of the chock shields are continuously monitored with PMC-R (Programmable Mining Controller- Roof Support) and from the control center at the surface. All the data will be transferred to the surface to monitor all the chock shields' pressures across the face, and it can store data for each second. Total 146 powered supports installed along the 250m length of the face were divided into three sections as Top section (111 to 146), Middle section (38 to 110), and Bottom section (1 to 37). Among 146 chock shields, three chock shields were selected, i.e., Chock shield no. 5 from the bottom section, Chock shield no. 73 from middle section and Chock shield no. 140 from the top section. The distribution of pressure on these chock shields can be seen in Table 3. From the data obtained from the PMC-R, it was observed that the load developing on the powered supports is not symmetrical along the longwall face. The Middle section of the chock shields will take a greater load than the other two sections. The variation of pressures developing on the powered supports can be seen in Figures 15 to 16.

Table 3: Chock shields pressure (bar) readings along the face

Length of extraction (m)	**Chock no.5**	**Chock no. 73**	**Chock no. 140**
2.85	224	232.5	286
3.2	267.5	225	284
4.45	234	210	260
4.45	240	140.5	241.5
4.45	240	183	239.5
4.75	240.5	181	237.5
5.15	267.5	272	274.5
6.1	229.5	265.5	269.5
8.35	150	206	219
10.75	239.5	82	52
13.5	282.5	282.5	253.5
13.5	252	296	276
14.75	282.5	282.5	253.5
14.75	252	296	276
15.25	282.5	280	275
17.5	252	274	276
20	267.5	268.5	281.5
20.25	238	246	298

20.25	224	257.5	301.5
20.25	299	255.5	302
20.25	223.5	282.5	303.5
20.25	223	281.5	304.5
20.25	283	279	305.5
20.85	283.5	277	306.5
21.05	283.5	281	308
21.05	295.5	281	312
24.2	266	280.5	314
26	266	277.5	283.5
27.5	264.5	271.5	273.5
29	254.5	267	256
31.65	247	320.5	281.5
31.65	219	342.5	259.5
31.65	224.5	359	289.5
31.65	239.5	366.5	284
31.65	266	374	292
33.75	267.5	379	292
35	289.5	334	289
37.4	290	326.5	288.5
39.9	281	333	294.5
39.9	278.5	277	284.5

3.0 Development of numerical models with FLAC 7.0

Evaluating the rock mass behaviour in underground workings can possible by the Numerical modelling technique. In this study, 2D numerical models were prepared by considering the geo-mining conditions of the seam-1 of ALP by using FLAC 7.0 software. FLAC 7.0 of Itasca Consulting Group Inc. [10] is relatively used for solving problems related to tunneling and geotechnical engineering. To understand the behaviour of longwall workings, the side section of longwall panel-1 was considered for modelling. The length of the model is 300m along X-direction and 100m height in Y-direction as shown in Figure 17. 3m thickness of coal is left as the immediate roof for the workings and the truncated load is applied according to the 375m depth of workings (i.e., 375m-(100m-(3.5m+25m))=303.5m, truncated load is 7.58MPa)). In the first phase, 8m width of coal has been extracted for installation of the powered support system of capacity $(2 \times 1152\mathrm{T})$ by considering the parameters as Compressive strength = 8 MPa, Stiffness = 0.5mm per ton. Boundary conditions have been applied to the model as the bottom section of the model is fixed, and roller type boundaries were assigned to Y-direction. To estimate the in-situ stresses, the following formula as suggested by MeSy India was used. This formula was proposed based on the 30 hydraulic fracture tests conducted by them at site 1205 of the Adriyala Longwall Block in the northwestern part of the Godavari coal fields (about 20 km south-east of the town of Ramagundam). Accordingly, the horizontal & vertical stresses were simulated. Seventeen (17) successful hydrofracture tests yielded reliable characteristic hydro fracture pressure data for the determination of a stress-depth profile for the depth range between 77 m and 522 m. The tests demonstrated an in-situ tensile rock strength of 2.9 ± 1.2 MPa. For all of the 17-hydrofracture tests, the orientation of the induced fractures was determined by impression packer tests. Vertical stress = (0.0216 · Z) MPa, Horizontal stress: (a) Minor horizontal stress = 2.05 + 0.0092 (Z, m - 77) MPa, (b) Major horizontal stress = 3.13 + 0.0142 · (Z, m - 77) MPa, Where, Z= depth cover considered is 375m from the surface.

Five different numerical models were developed by considering the lithology and physico-mechanical properties shown in Figure 18. These models were developed to evaluate the displacement profile and stress distribution on longwall workings at every 8m, 25m, 35m, and 45m distances from the mine boundary, as shown in Figures 19, 20, 21, and 22, respectively. After attaining the initial equilibrium position to the model, the coal part's 8m width has been removed from mine boundary by assigning the null model to it as shown in Figure 19.

4.0 Results of numerical modelling study

4.1 Convergence in the gate roadways

After the in-situ model has been simulated, 8m width of coal has been removed to install the support system at the longwall face. After 8m of extraction, no or significantly less convergence in the roof has been noticed. The value of convergence being observed is 1 mm. The same scenario has been noticed up to the width of 25m. The maximum convergence in the roof strata has been observed at 40m coal extraction, i.e., 10mm. The progressive advance of longwall face with powered support system has resulted in less development of convergence in the roof strata. The variation of convergence in the roof strata at different stages of extraction can be seen in Figures 24 to 27.

4.2 Vertical stress observations

The in-situ stress could be developed on the longwall pillar at a depth of 375m is 9.35MPa. At the first stage of extraction, i.e., 8m of coal face advance, the maximum vertical stress developed on the longwall pillar is 10.35 MPa (9.35MPa is in-situ stress). As the face advances further, the vertical stress developing on the longwall pillar is also increasing, as shown in Figures 28 to 31. The maximum stress recorded at 40m of coal face advance is 13.35MPa (9.35MPa is in-situ). It was observed that per meter of face advance, maximum of 0.2MPa of vertical stress increment was noticed. As the observations made from the field and numerical modelling results, the maximum abutment zone noticed on the longwall pillar was 10m to 25m. The variation of vertical stress on longwall pillar during the extraction of longwall panel is shown in Figures from 28 to 31.

4.3 Factor of Safety (FoS) of chain pillars at different stages of face extraction

Natural supports like chain pillars, longwall pillars and barrier pillars in underground workings will play an essential role in keeping the workings stable. Evaluating these pillars' stability at every stage of extraction is crucial for the sustainable extraction of minerals. The stability of pillars can be estimated by the Factor of Safety (FoS) criterion. FoS can be defined as the ratio of Strength of the pillar (S) to the Stress acting on the pillar (P).

$$\text{Factor of Safety} = \frac{\text{Pillar Strength}}{\text{Pillar Stress}} \tag{1}$$

The strength of the pillar can be estimated by the empirical formulae. There is a number of strength formulae developed over the world to assess the strength of the pillars. In this study, PR Sheorey [10] developed empirical formulae, as shown in Equation 1 was used to estimate the strength of the chain pillar. This empirical formula is best suited for Indian geo-mining conditions.

$$\text{Pillar strength } S = 0.27\sigma_c h^{-0.36} + \left(\frac{H}{250} + 1\right)\left(\frac{W_e}{h} - 1\right) \tag{2}$$

Here, S = Strength of barrier pillar in MPa; σ_c = Compressive strength of coal in MPa; h = Height of workings in m; H = Cover depth in m; w_e = Equivalent width of pillar in m, $W_e = \frac{2W_1W_2}{W_1+W_2}$ here the effective width is considered as 45m.

The strength of the chain pillar at 375m depth is found as 34.4MPa. To err on the side of the safety, the vertical stress evaluated from the numerical modelling have been considered (The numerical modelling results overestimating the stress inducing in longwall workings) to calculate the FoS. Therefore, by substituting the findings of strength and stress values in equation 1, the FoS can be obtained as 3.3, 3.2, 3.0, and 2.6, respectively. By analyzing these results, it could be ensured that the chain pillars will be stable to protect the underground workings. The FoS of chain pillars at different extraction stages can be seen in Figure 32.

5.0 Validation of field and numerical modelling results

It is always good to validate the numerical modelling results with field instrumentation results. Convergence noticed in the gate roads and the vertical stress developed on the longwall pillar results were validated. Figure 33 shows the comparison of field and numerical modelling results for convergence of gate roads at different extraction stages. From the validation results, it was observed that the results obtained from both the studies were good in agreement and are encouraging.

The abutment stresses obtained from the field study were compared with the data obtained from the numerical modeling results. They are plotted in graphs to study their nature and interrelation. Figure 34 shows the validation of the vertical stress values in both studies. It was noticed as the numerical modelling results were somewhat overestimating the stress values than the field instrumentation results.

6.0 Conclusions

By addressing the previous longwall failures in Indian coal mines, a high capacity (2x 1152T capacity powered support system) longwall technology has been introduced in Adriyala Longwall Project (ALP), SCCL. To understand the behaviour of longwall workings in ALP, an extensive field instrumentation study was conducted with convergence indicators, telltale extensometers, PMC-R, and stress cells. From the stress cell observations, the maximum stress induced on the longwall pillar was 1010.35 KPa (1.01 MPa) at a distance of 13.2 m from the measuring station. But in the case of chain pillars, it was observed that the stress rises steadily before becoming almost constant at 43.2 m from the face with a stress reading of 580.41 KPa (0.58 MPa). In Main Gate, Tail Gate-1, and Tail Gate-2, the maximum convergence observed was 12mm, 8mm, and 6mm, respectively, after an advance of 75m longwall face. The chock shields pressure readings were evaluated with PMC-R. The observations shows that the load experienced by the middle section of the longwall face is more than the other two sections. The maximum pressure recorded on the chock shield was 439.5 bar, at chock no. 110. Numerical modelling techniques provide great insight into the behaviour of underground workings. In this regard, to better understand the behaviour of ALP workings, a numerical modelling study with FLAC 7.0 has been conducted with actual physio-mechanical properties. The modelling results show that the vertical stress on the longwall pillar and chain pillars varies significantly from the measuring point. The values fluctuated up and down when the extraction was nearer to the measuring point. Peak-induced vertical stress of 13.85MPa (9.35MPa being the in-situ stress) was observed on the chain pillars at a distance of 40m from the mine boundary. Based on the Factor of Safety (FoS) criterion, it was assessed that the chain pillars could provide stability to longwall workings.

7.0 Acknowledgement

The authors are grateful to the management of the Singareni Collieries Company Limited (SCCL) for their help during the study. The views expressed in the article solely belong to the authors and do not represent the institutes they belongs in any form.

8.0 Declarations

8.1 Data availability statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

8.2 Authors contribution

S. No	Author name	Contribution
1	G. Budi	Literature survey, analysis of results, organisation of the manuscript, critical revision of manuscript
2	K. Nageswara Rao	Literature survey, analysis of results, preparation of manuscript, critical revision of manuscript
3	Punit Mohanty	Literature survey, data collection from field site, numerical modelling.

8.3 Conflicts of interests

The authors have no known relevant conflicts of interests

8.4 Funding information

No funding related to this manuscript

9.0 References

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Figures

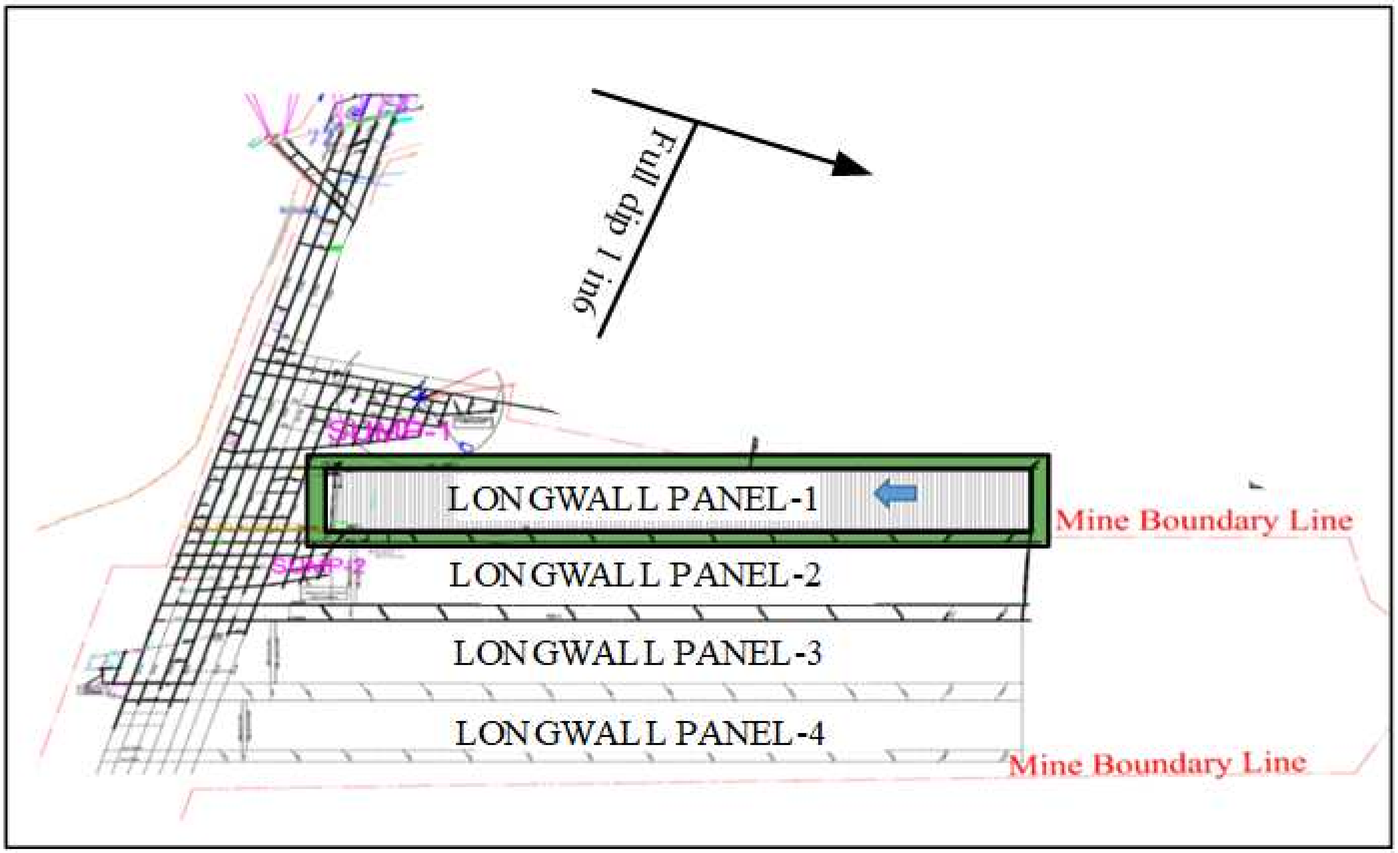

Figure 1

The plan showing the longwall workings in Adriyala Longwall Project (ALP)

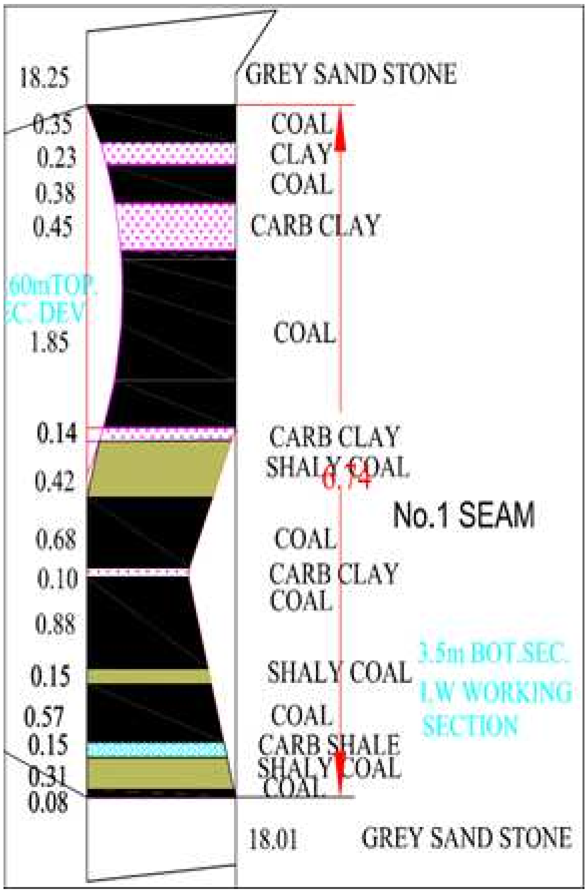

Figure 2

The section of borehole representing the layers of seam-1

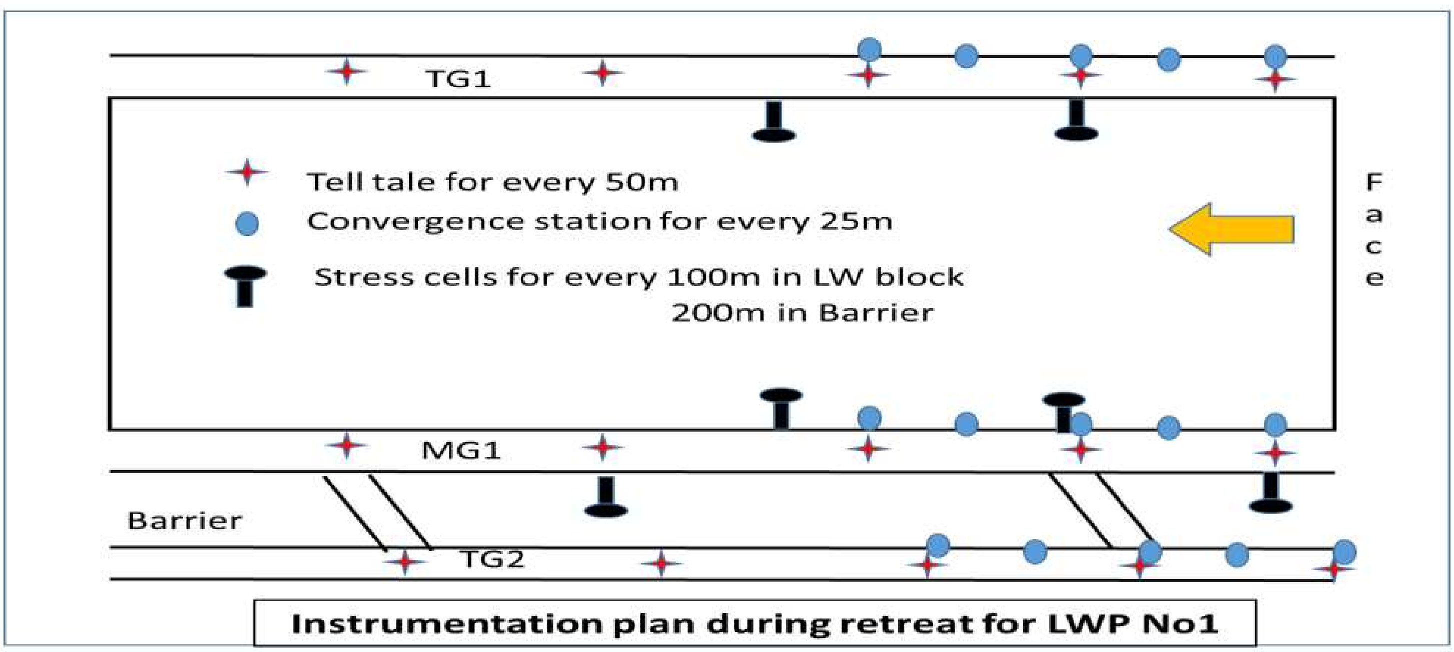

Figure 3

Instrumentation plan during retreat of longwall panel-1

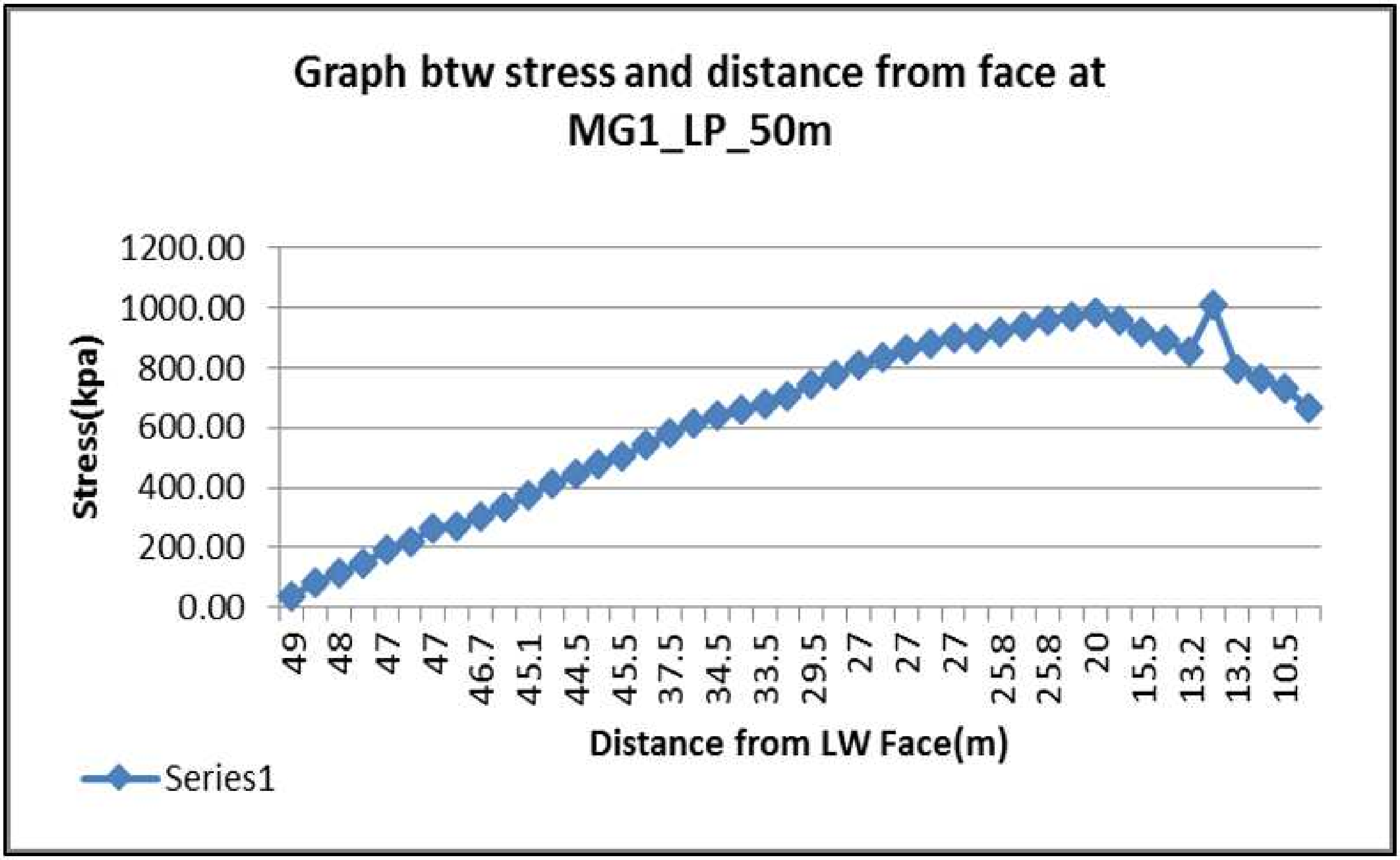

Figure 4

Variation of induced stress on longwall pillar (LP) in MG-1 at 50 m

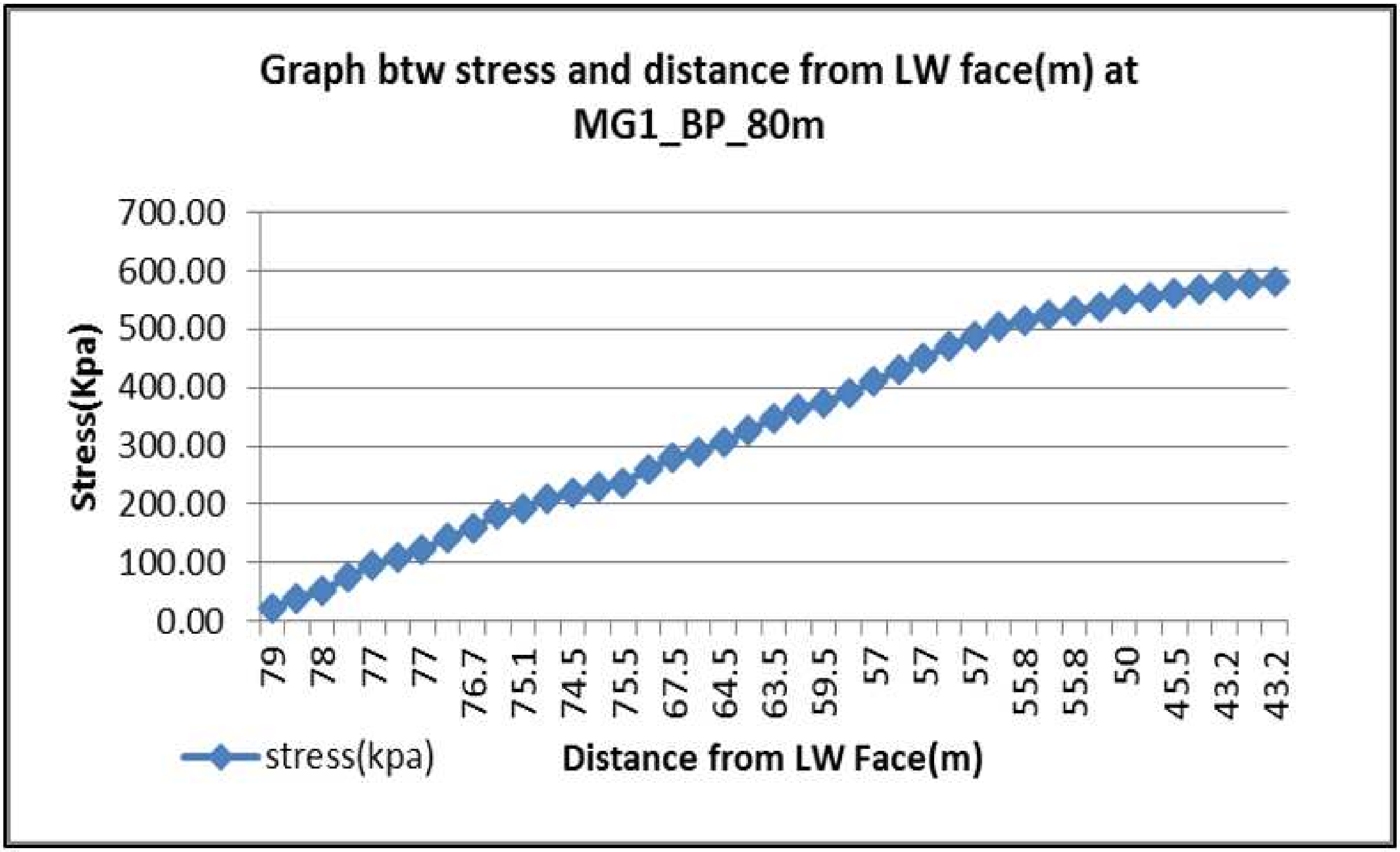

Figure 5

Variation of induced stress on longwall pillar in MG-1 at 80 m

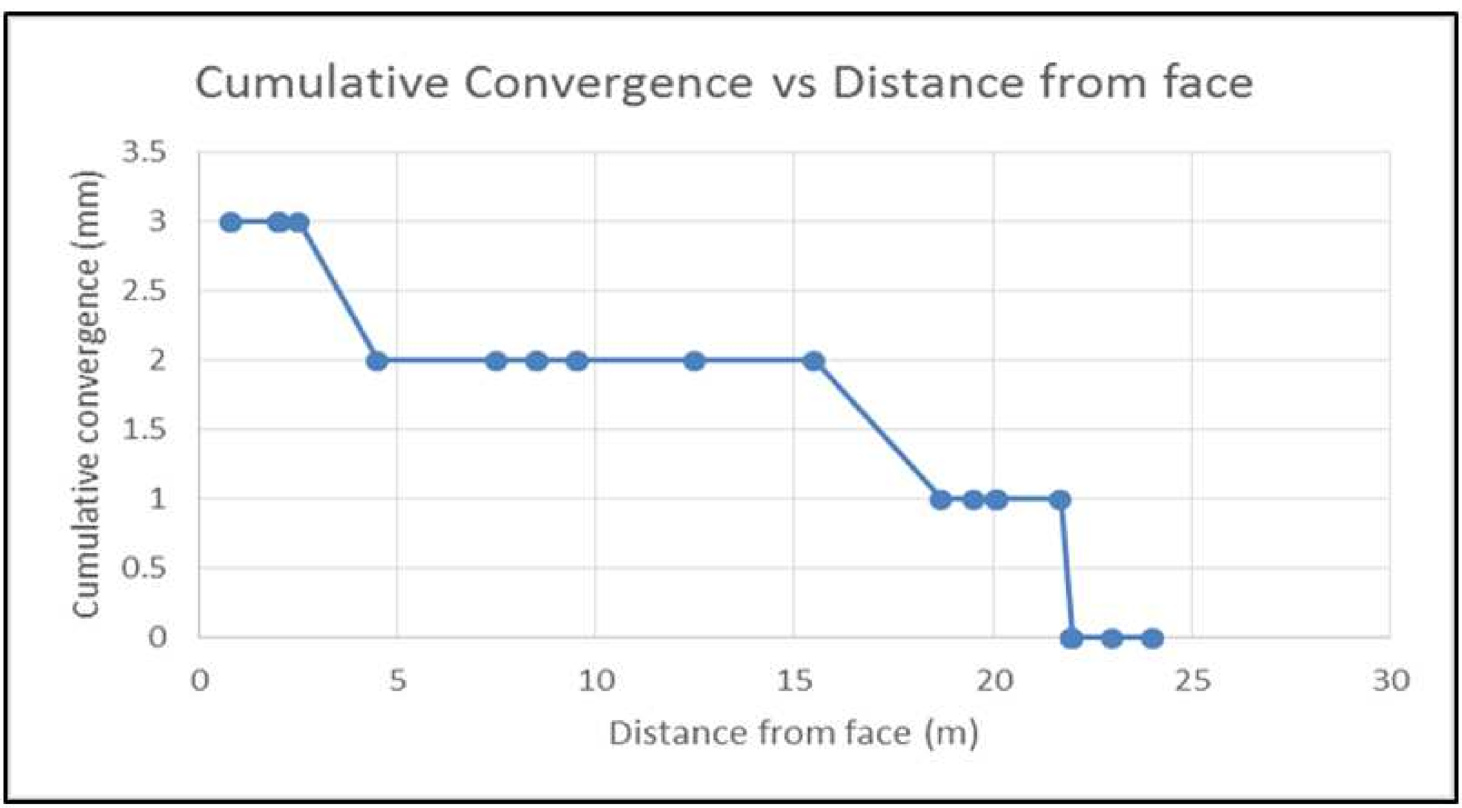

Figure 6

Cumulative convergence vs. distance from the face at 25m from MG-1

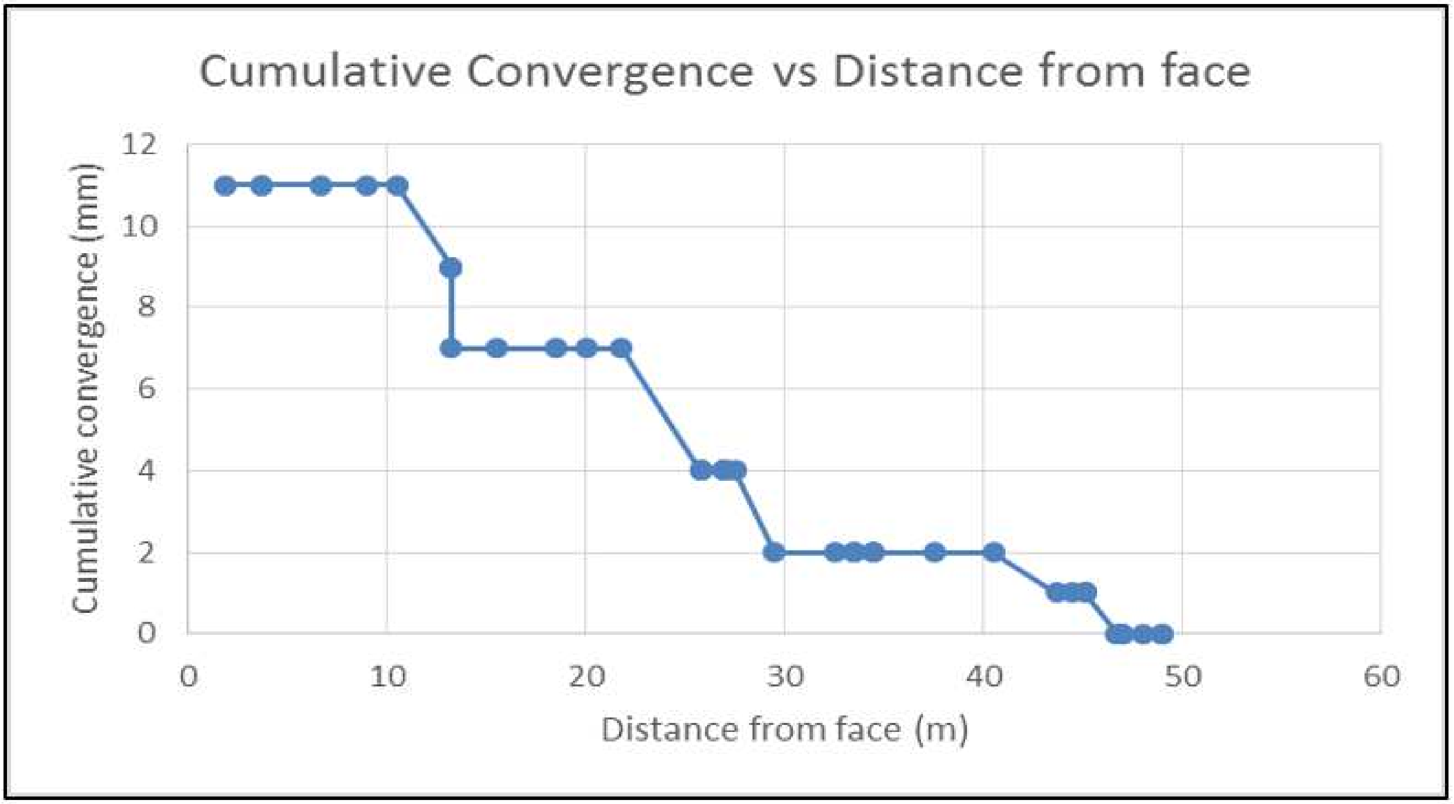

Figure 7

Cumulative convergence vs. distance from the face at 50m from MG-1

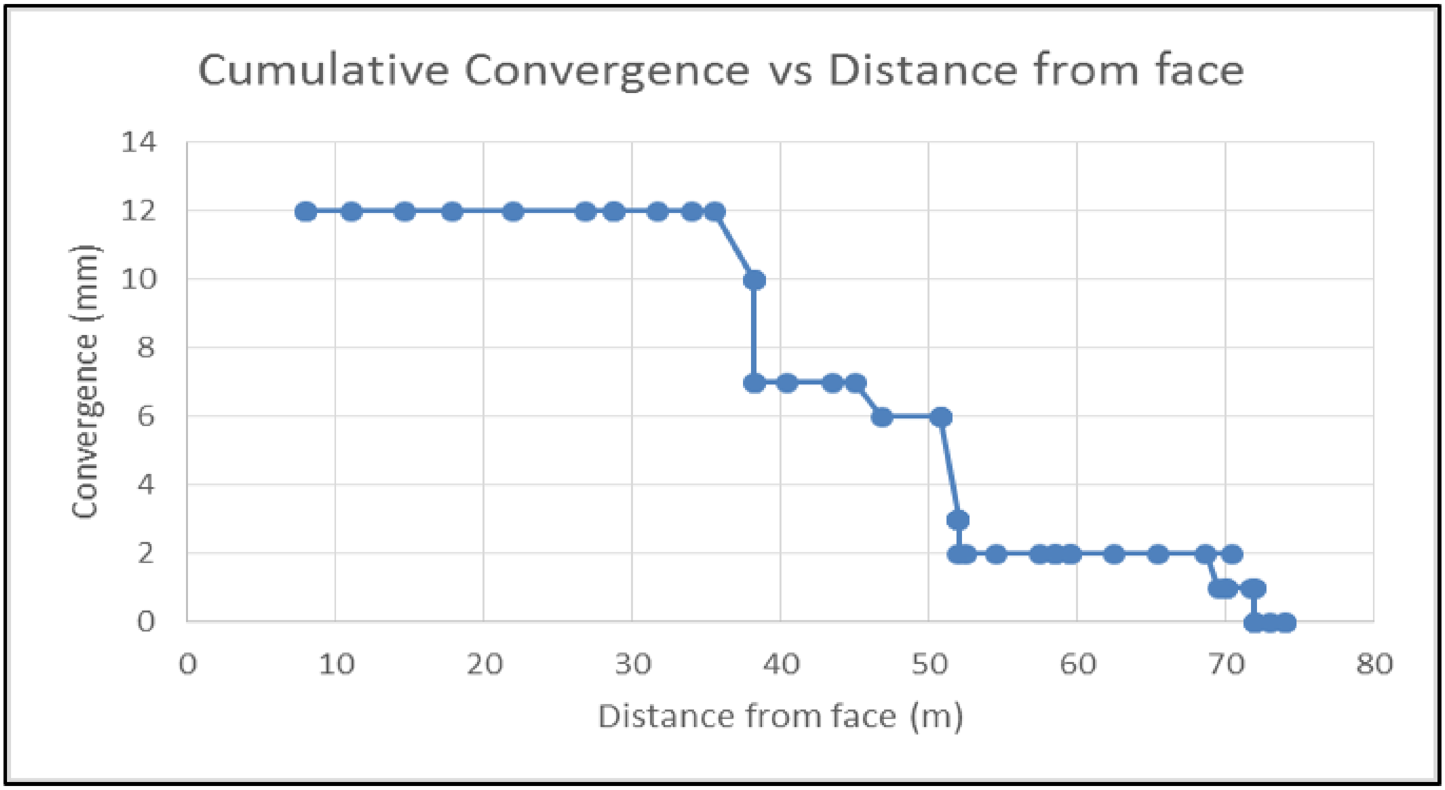

Figure 8

Cumulative convergence vs. distance from the face at 75m from MG-1

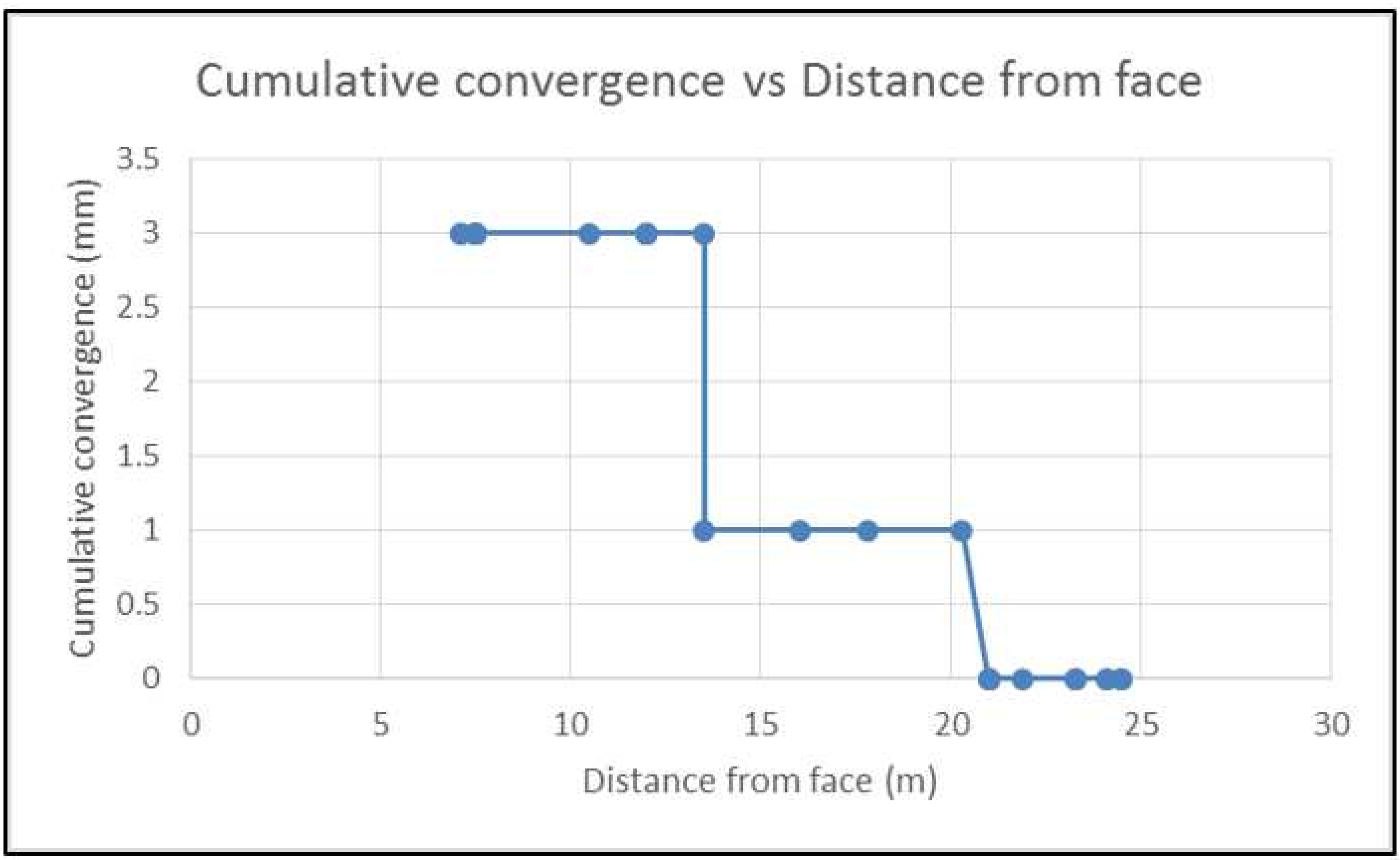

Figure 9

Cumulative convergence vs. distance from the face at 25m from TG-1

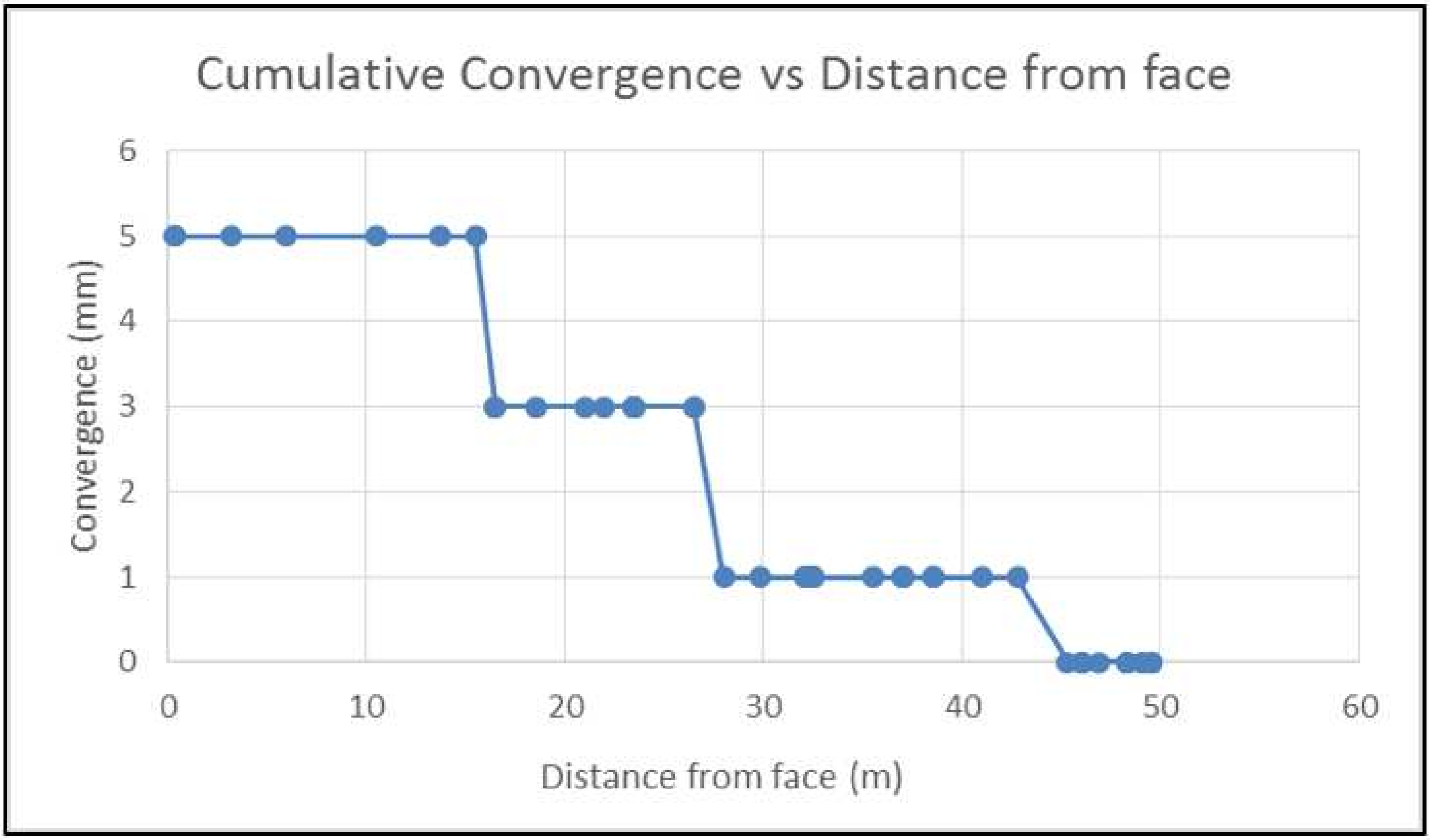

Figure 10

Cumulative convergence vs. distance from the face at 50m from TG-1

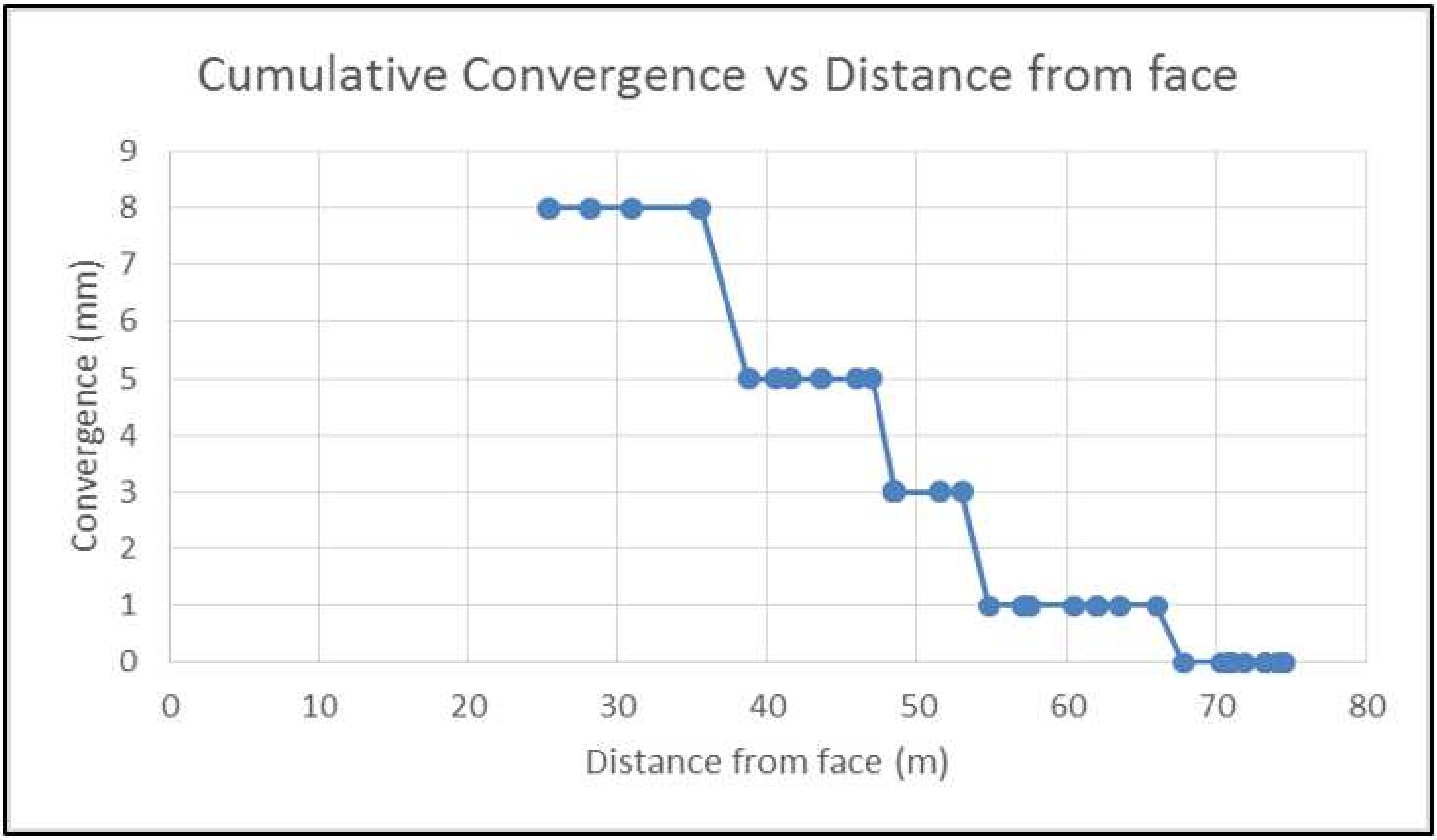

Figure 11

Cumulative convergence vs. distance from the face at 75m from TG-1

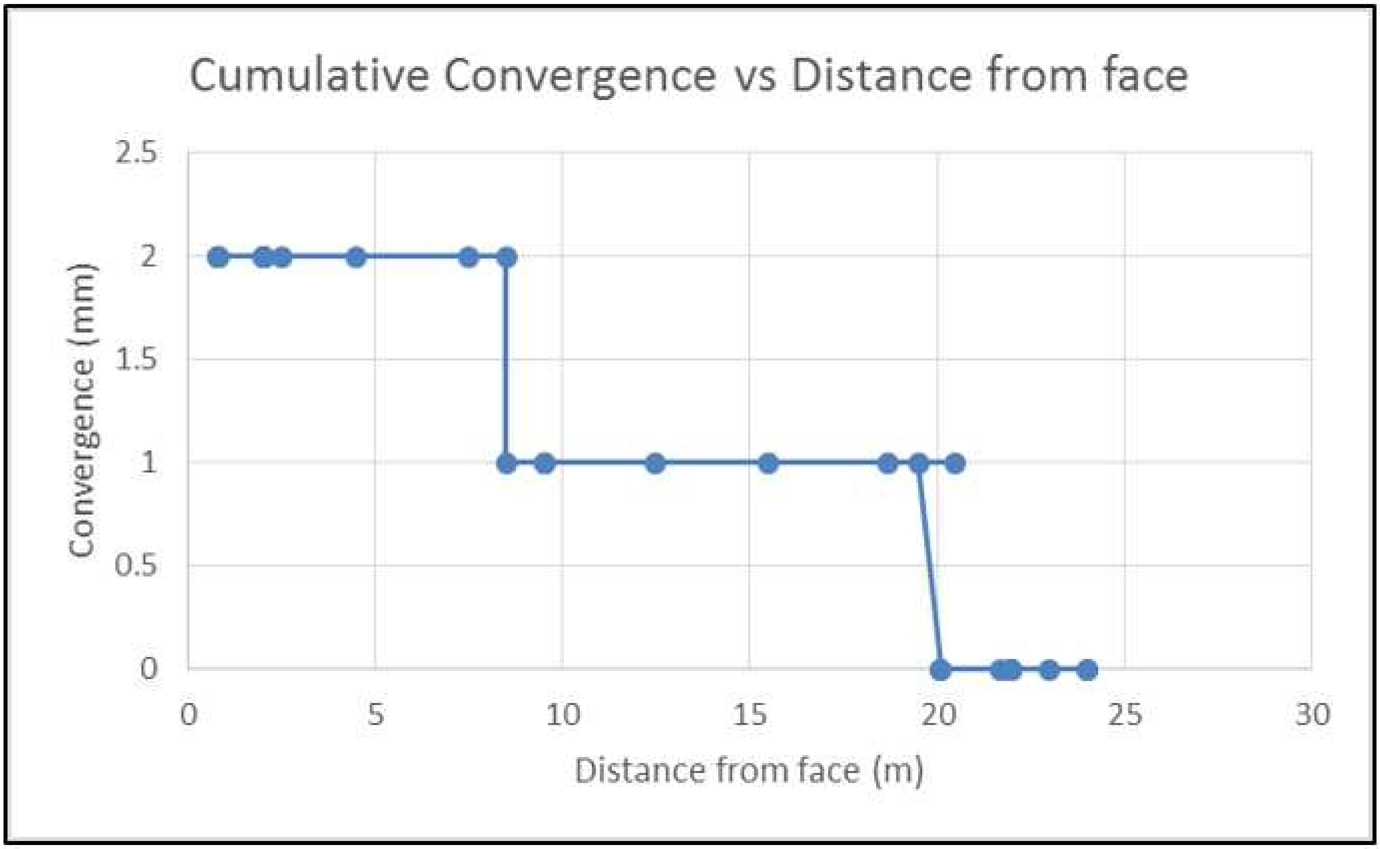

Figure 12

Cumulative convergence vs. distance from the face at 25m from TG-2

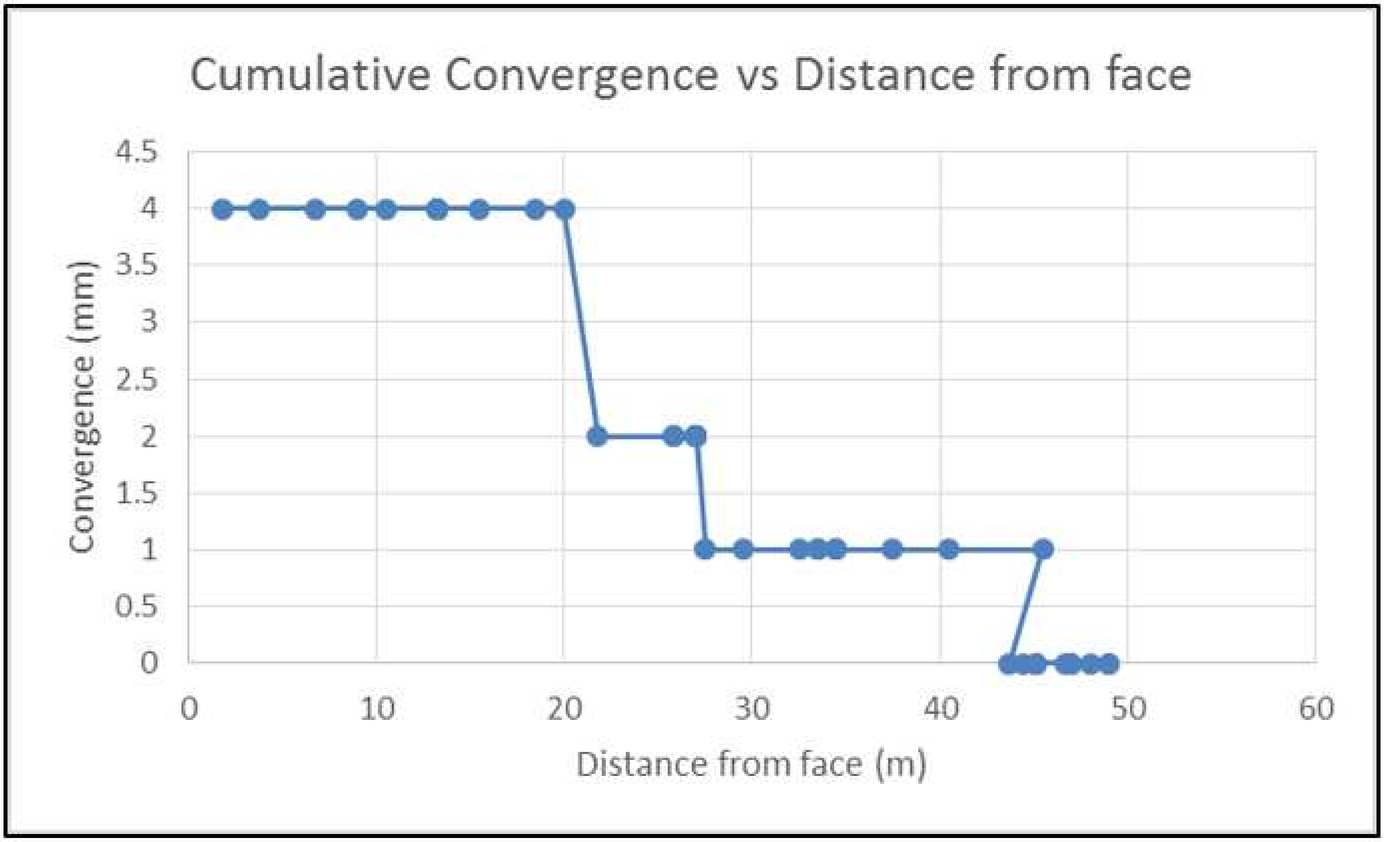

Figure 13

Cumulative convergence vs. distance from the face at 50m from TG-2

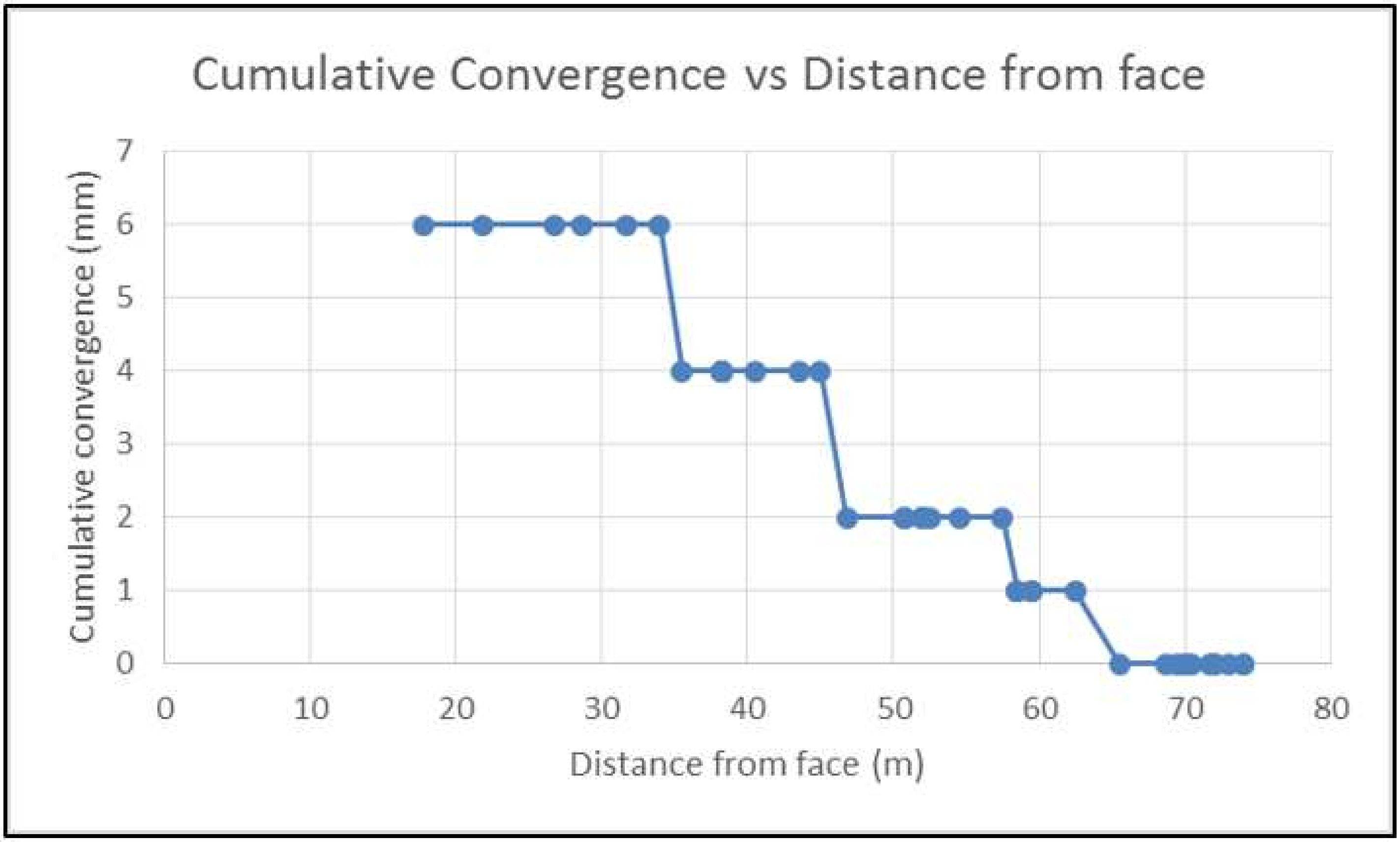

Figure 14

Cumulative convergence vs. distance from the face at 75m from TG-2

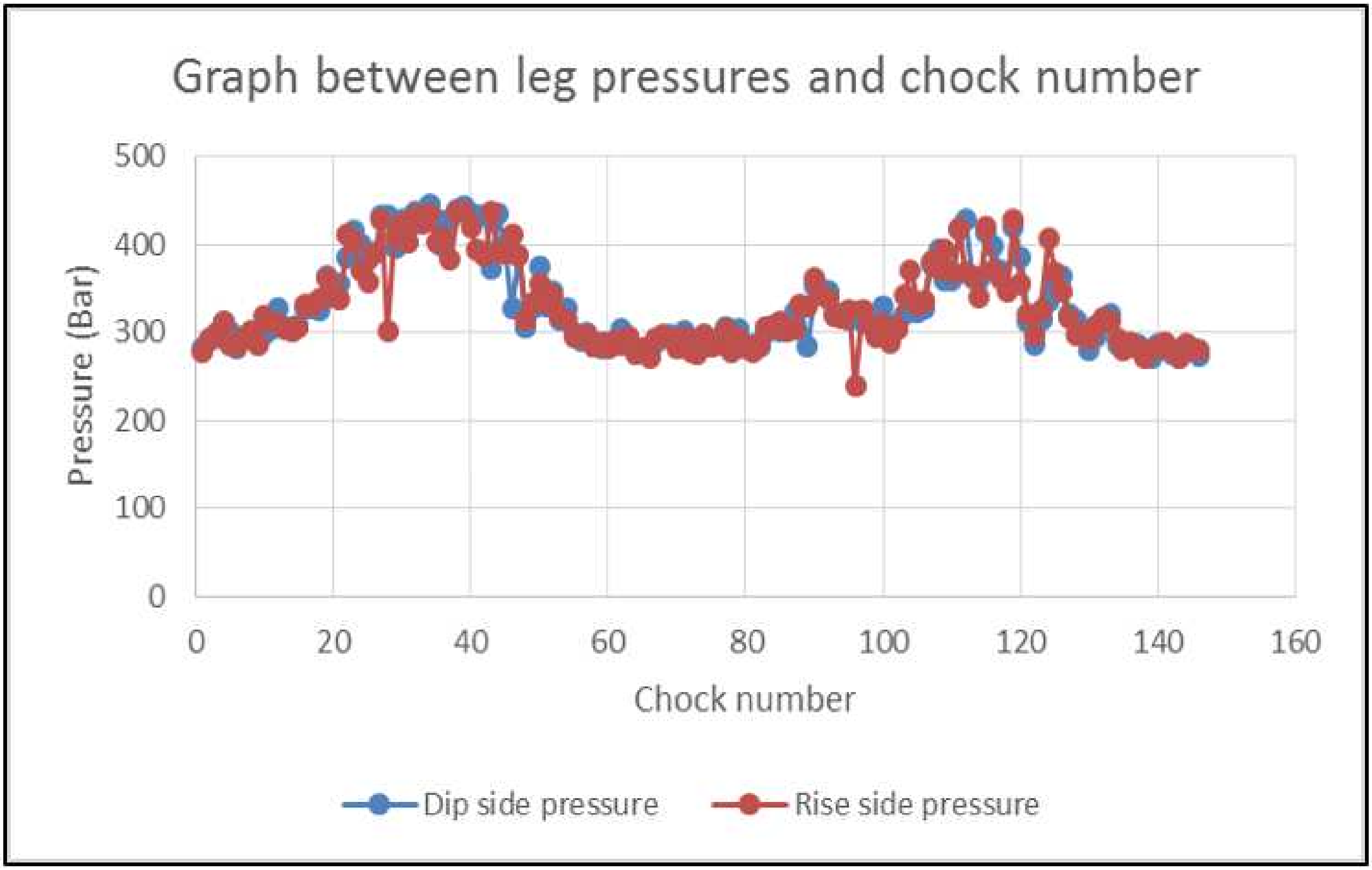

Figure 15

Graph between leg pressures and chock number

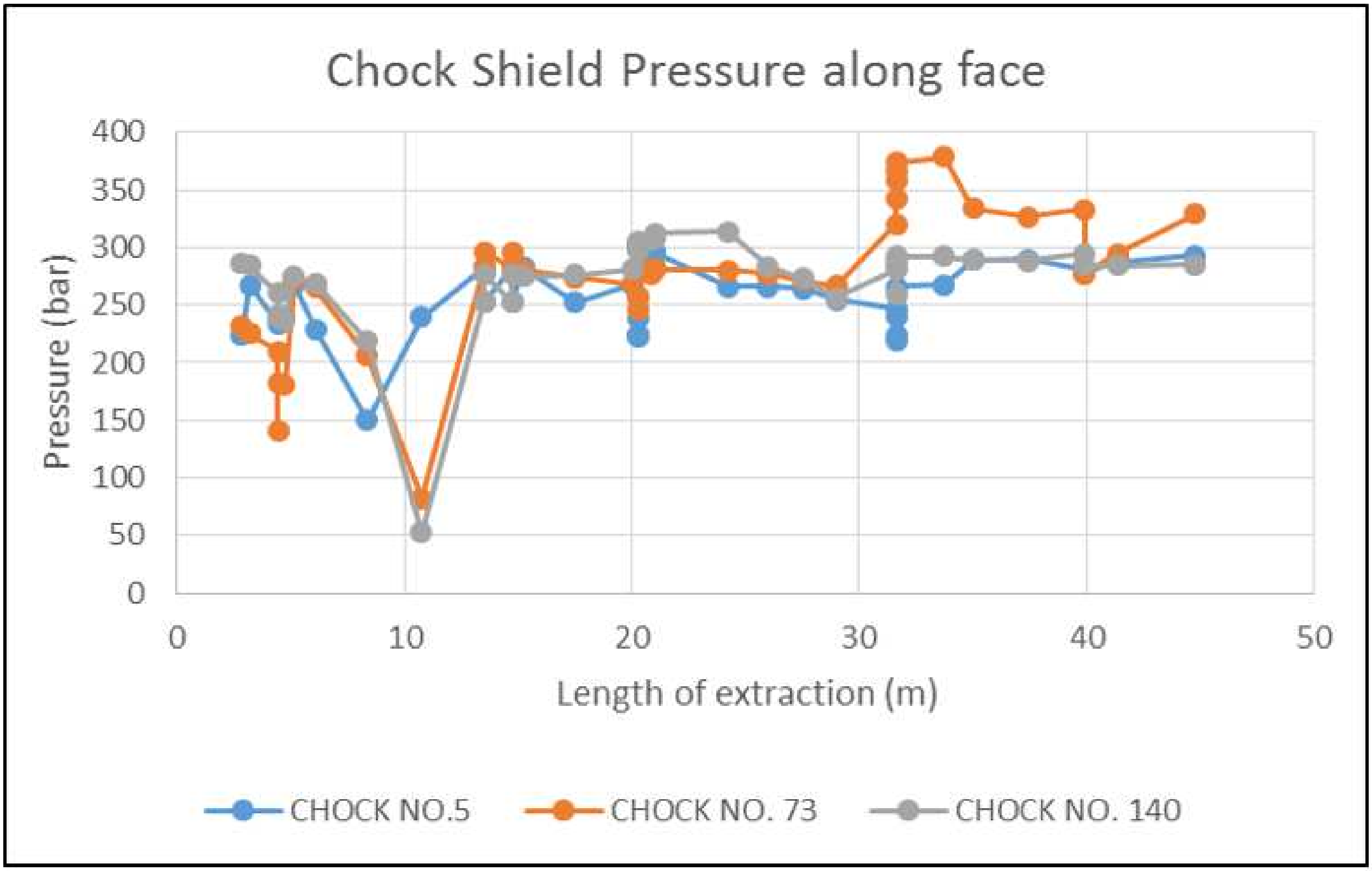

Figure 16

Variation of chock shield pressure along the longwall face

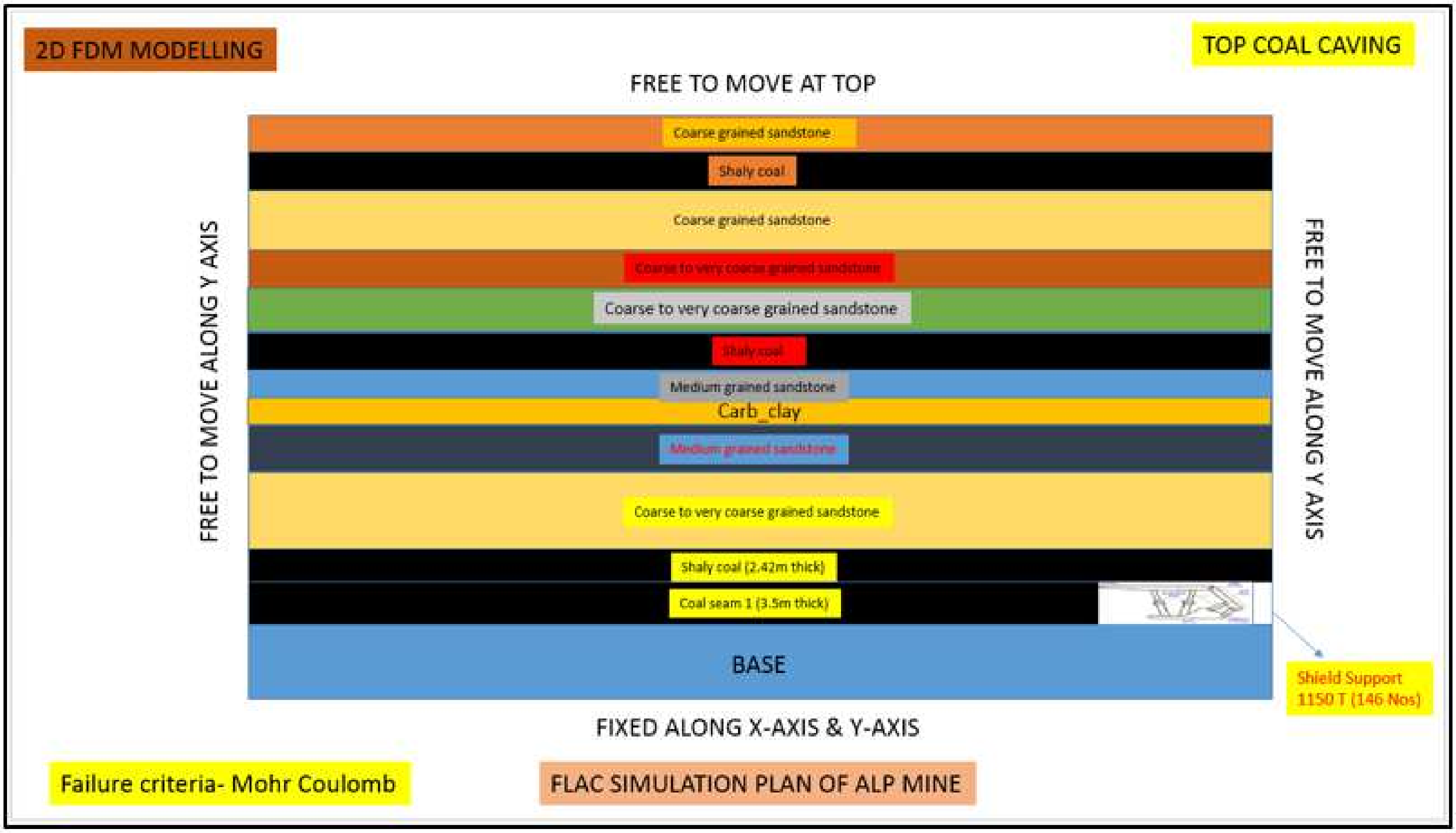

Figure 17

Schematic modelling diagram of Adriyala Longwall Project (ALP)

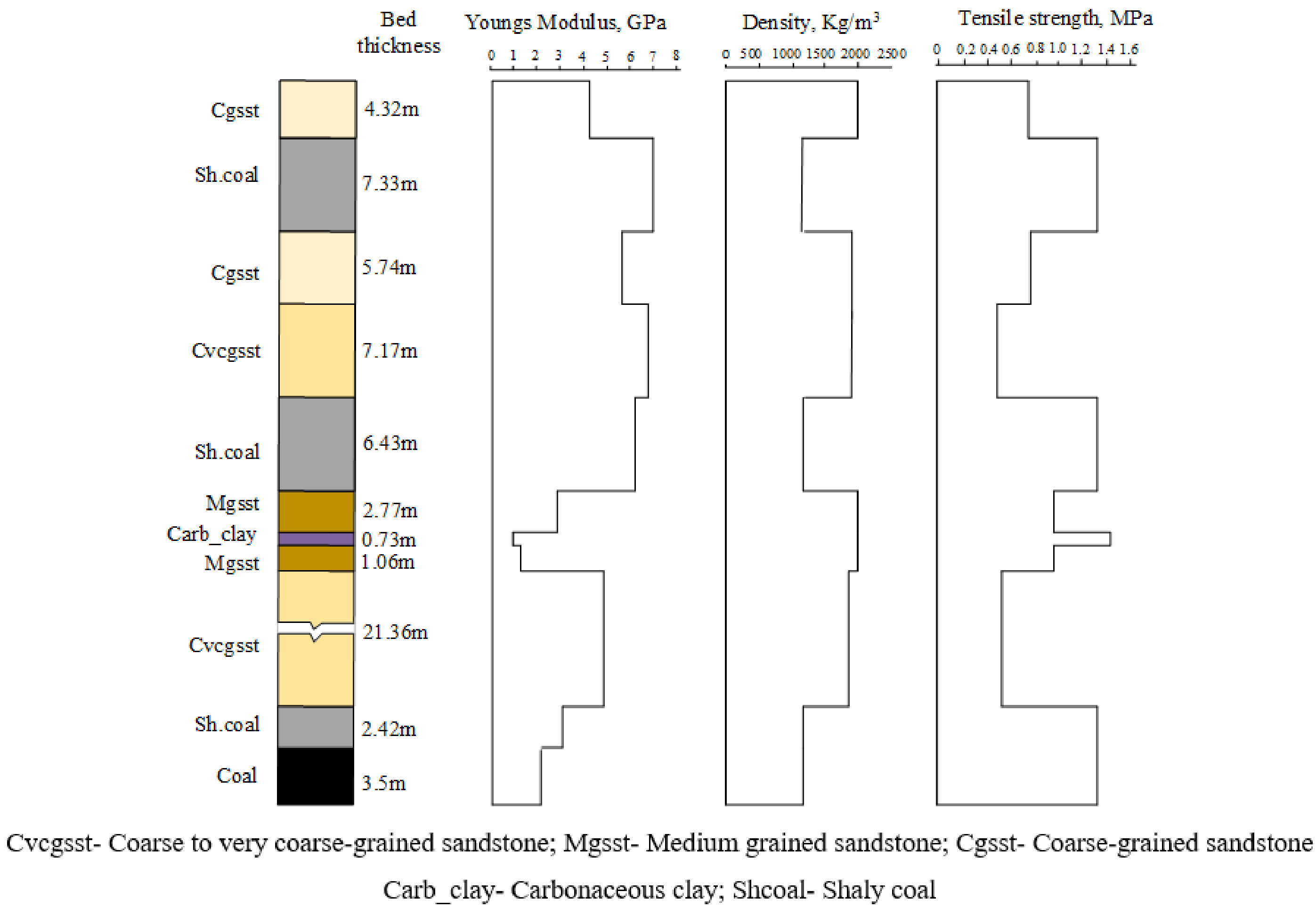

Figure 18

The physico-mechanical properties used on the numerical modelling

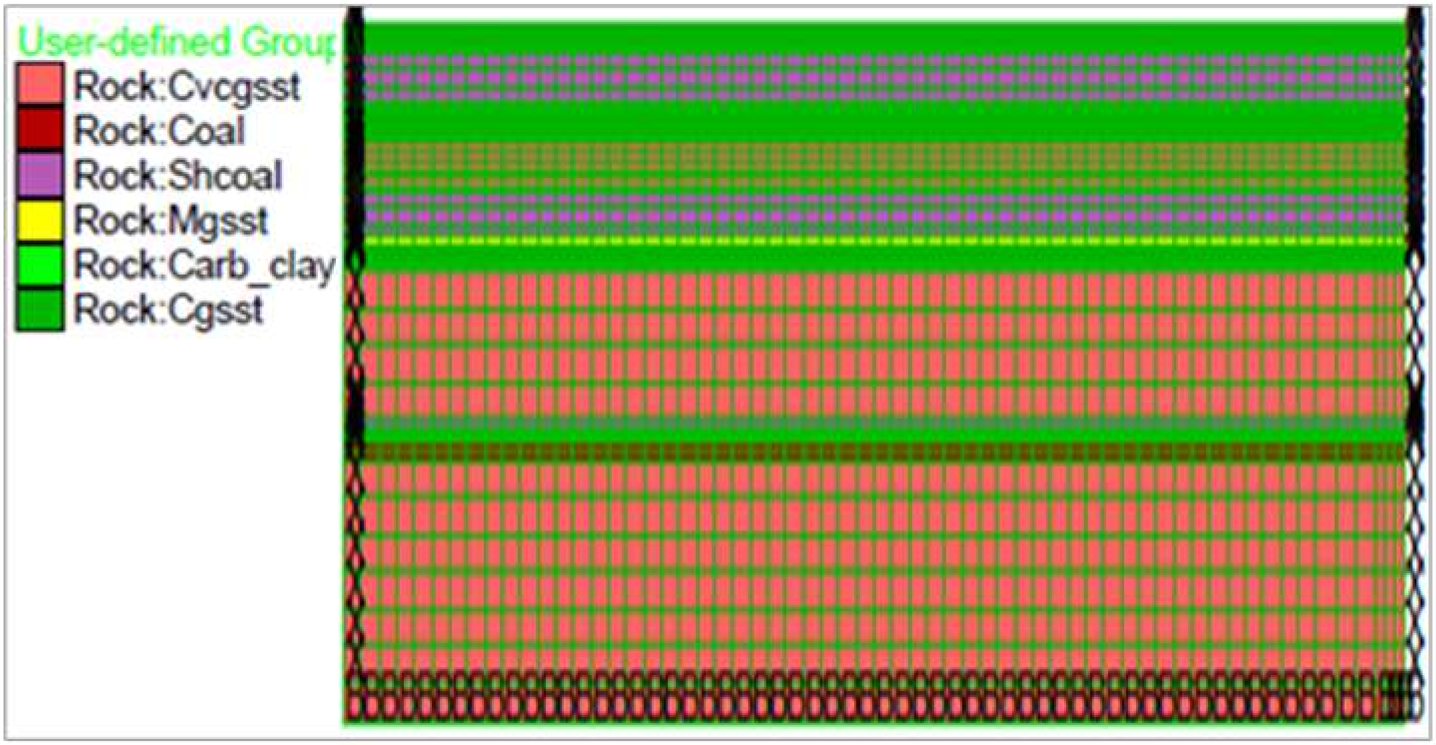

Figure 19

Model of Adriyala longwall project

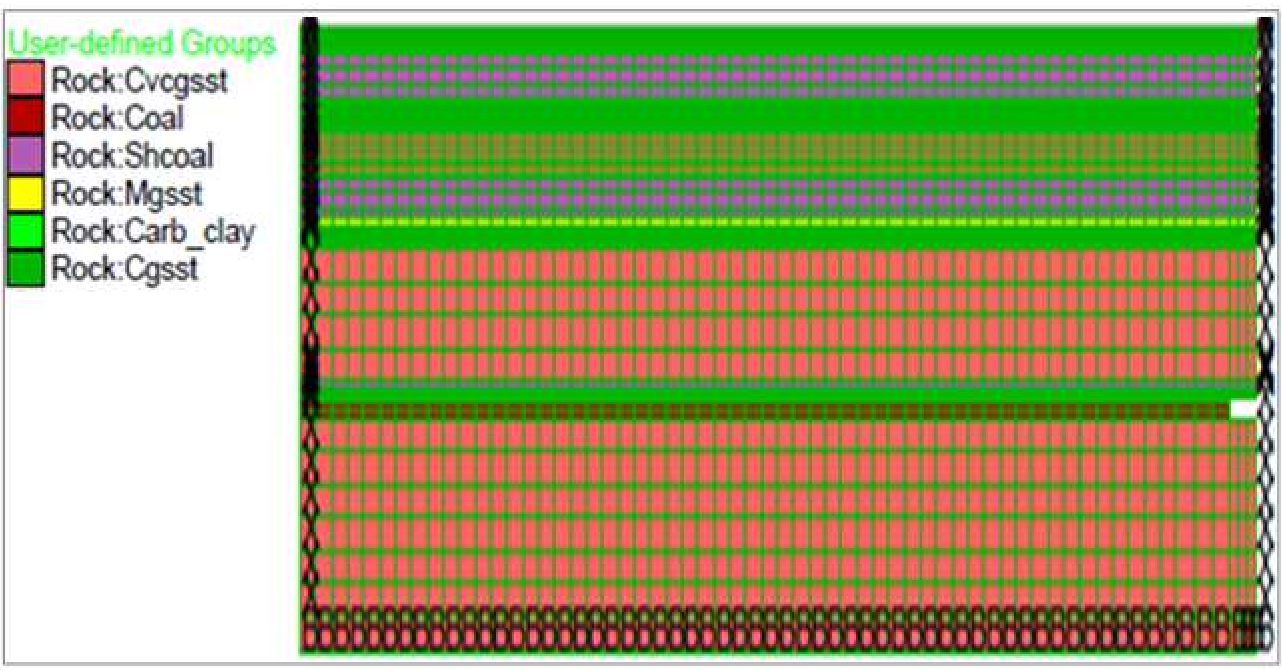

Figure 20

Model developed in FLAC 7.0: after extraction of 8m longwall face for initial setup

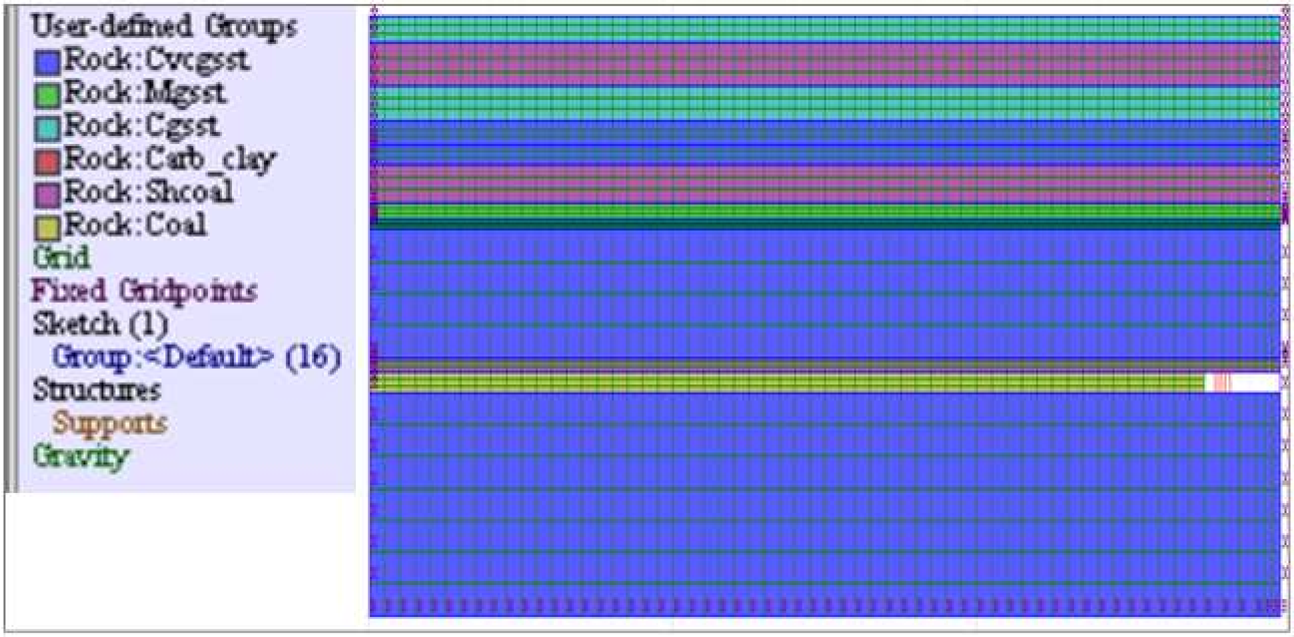

Figure 21

Model developed in FLAC 7.0: after extraction of 25m longwall face

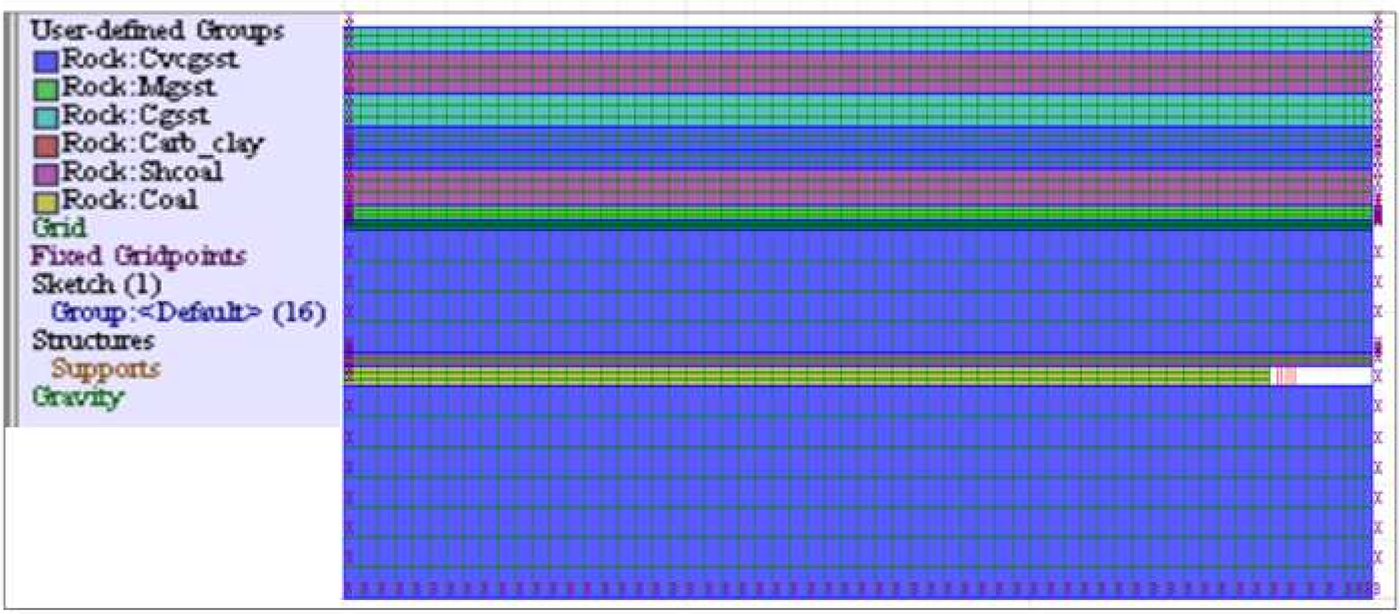

Figure 22

Model developed in FLAC 7.0: after extraction of 30m longwall face

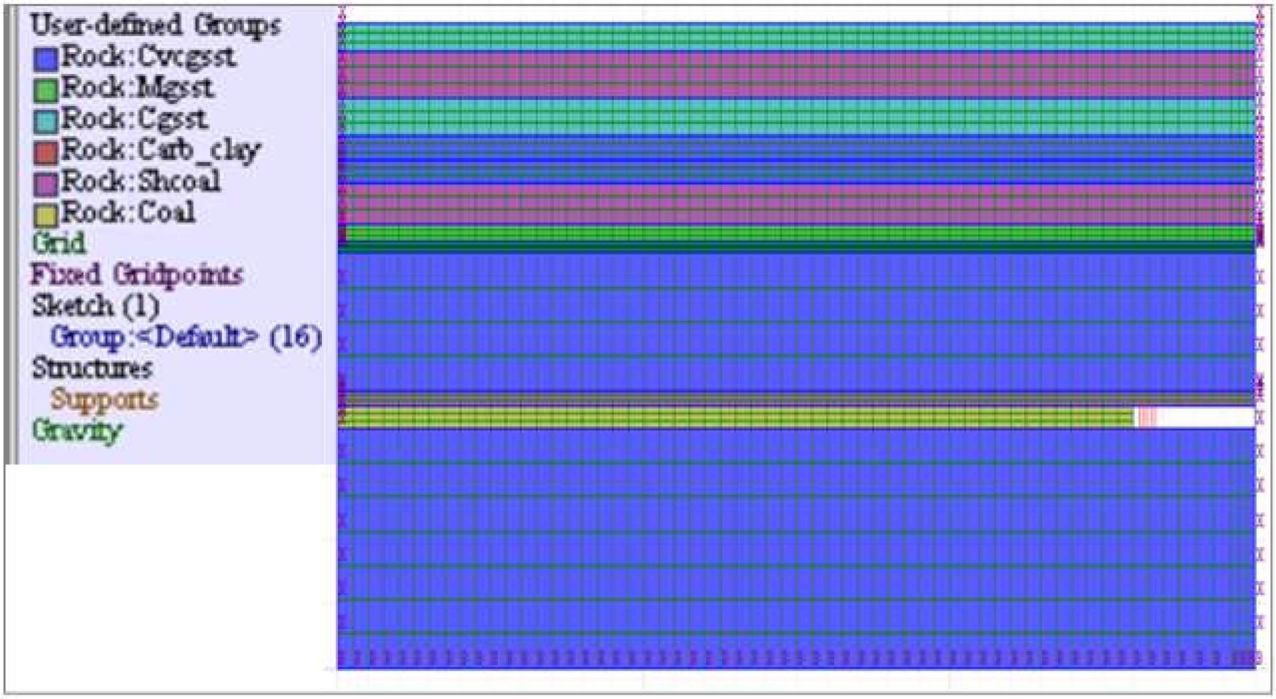

Figure 23

Model developed in FLAC 7.0: after extraction of 40m longwall face

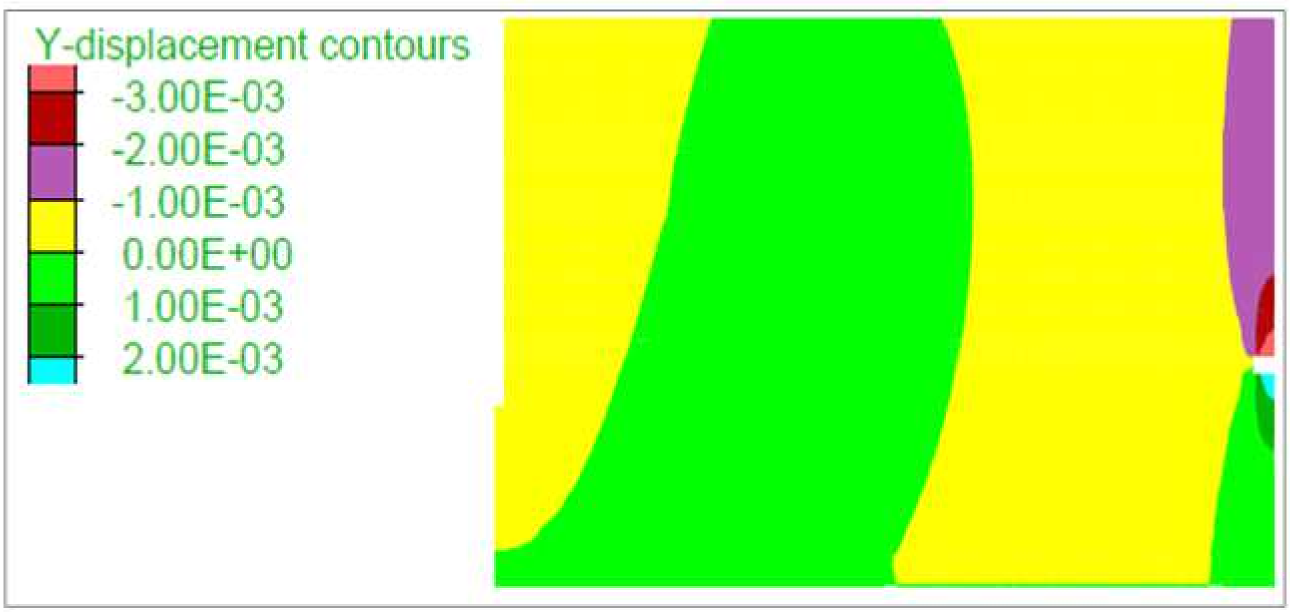

Figure 24

Convergence (mm) after initial 8m extraction

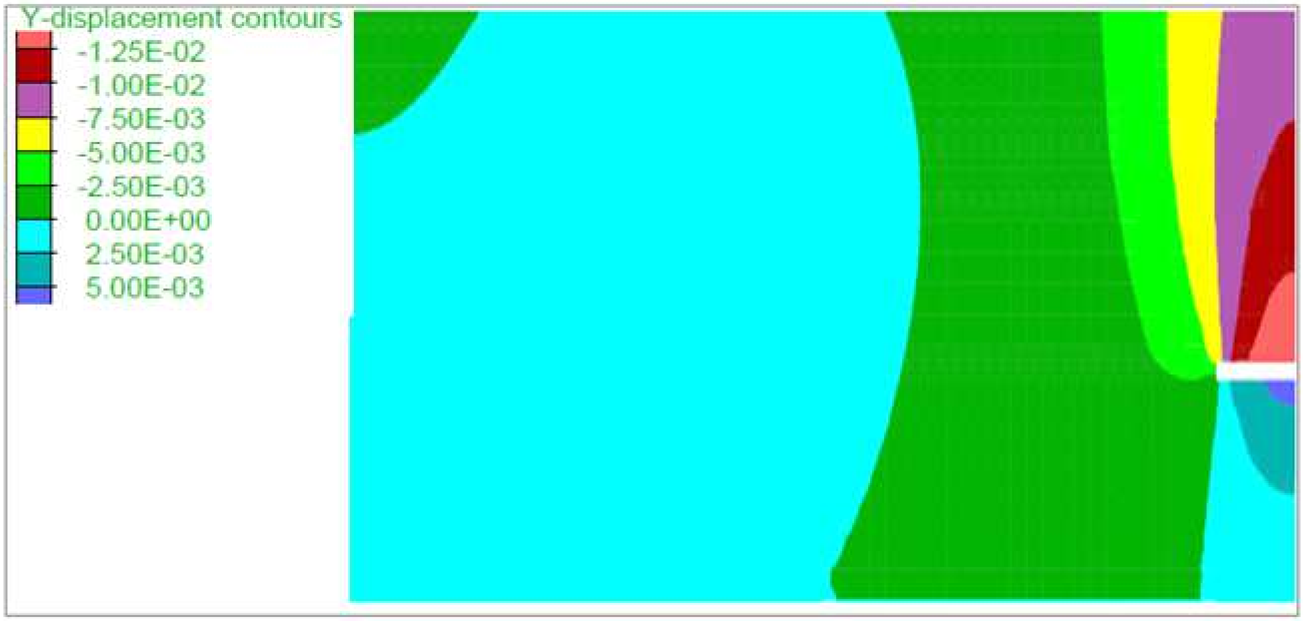

Figure 25

Convergence (mm) after 25m extraction

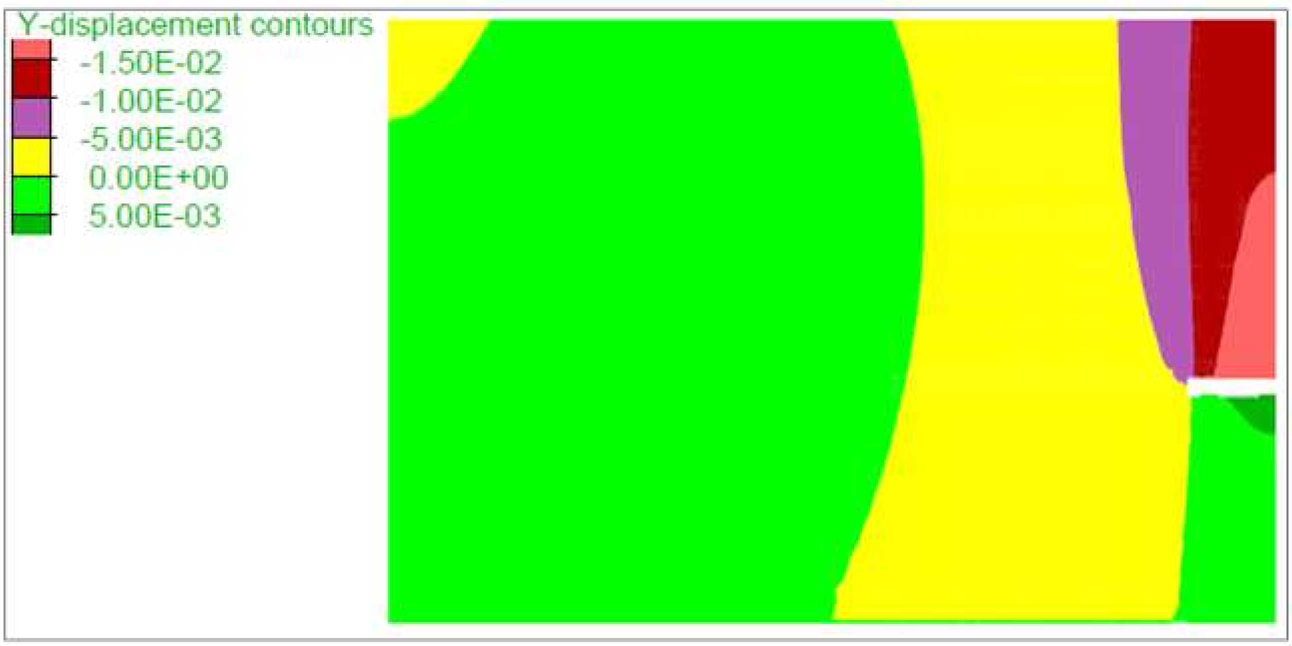

Figure 26

Convergence (mm) after 30m extraction

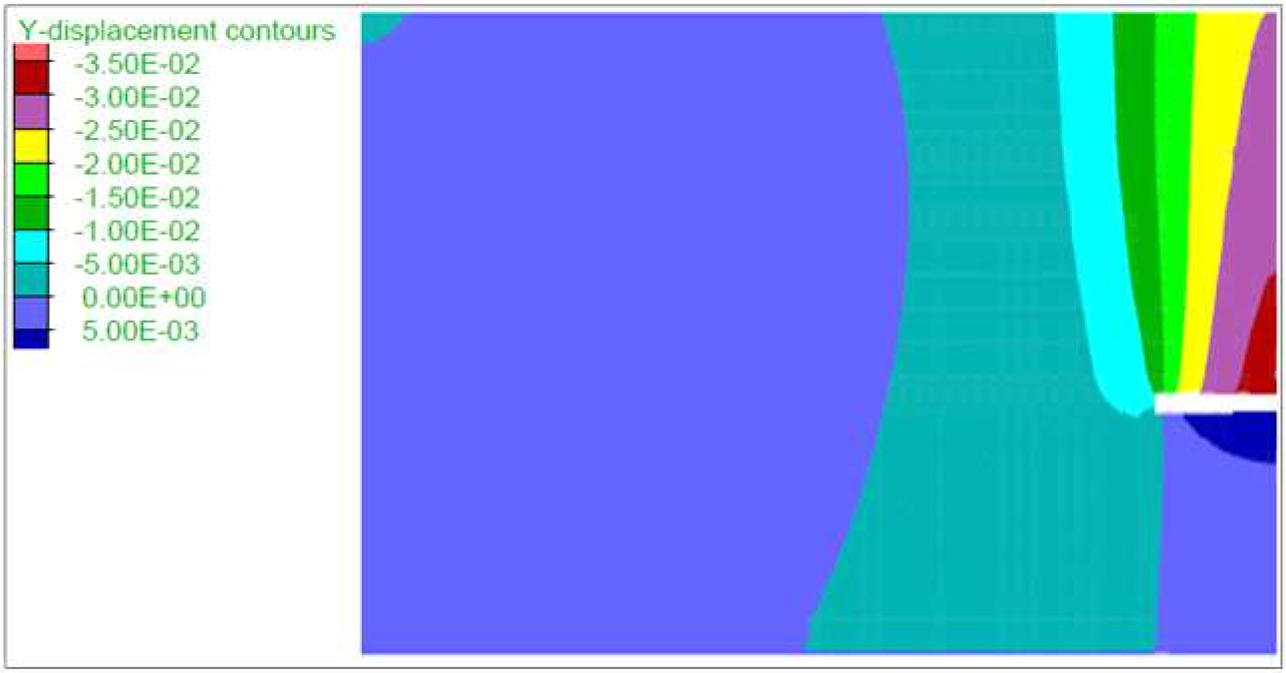

Figure 27

Convergence (mm) after 40m extraction

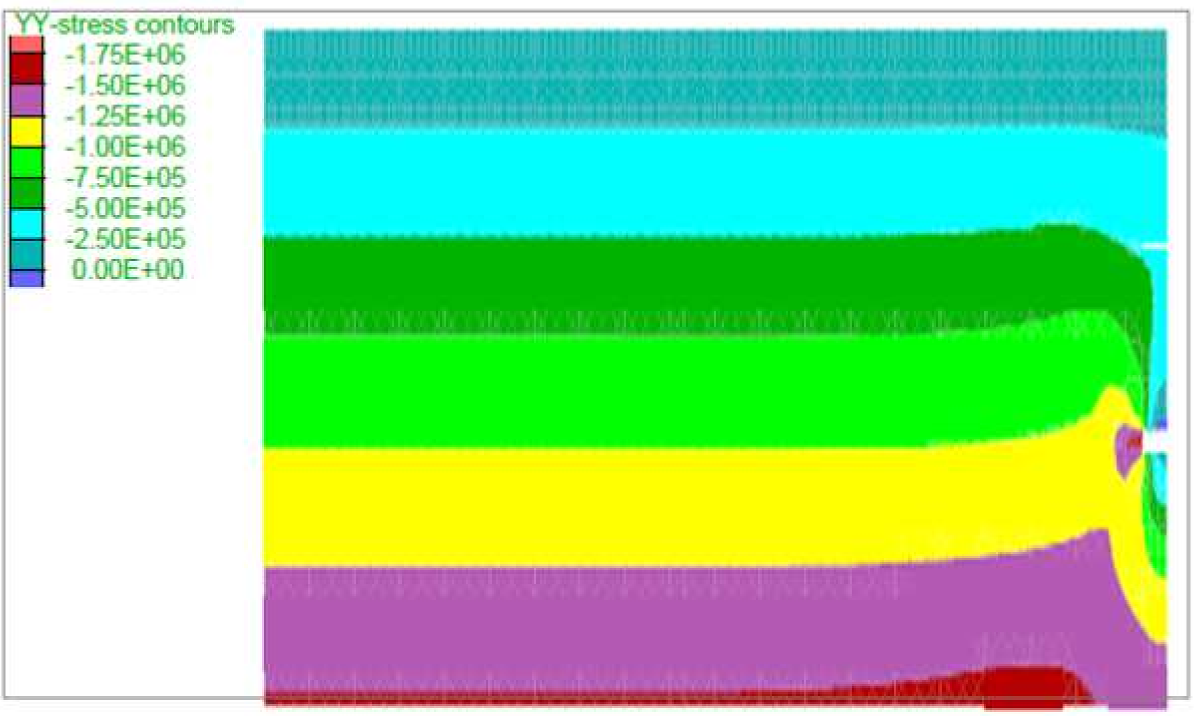

Figure 28

Induced vertical stress (MPa) developed in the panel after 8m longwall face extraction

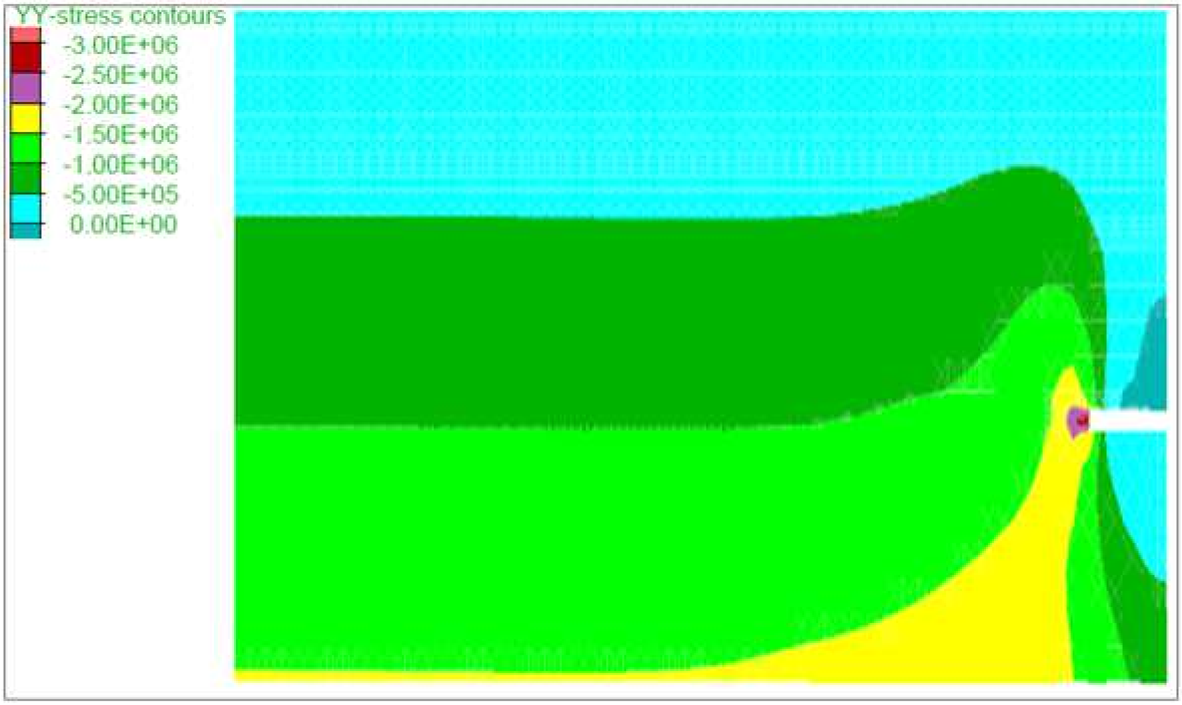

Figure 29

Induced vertical stress (MPa) developed in the panel after 25m longwall face extraction

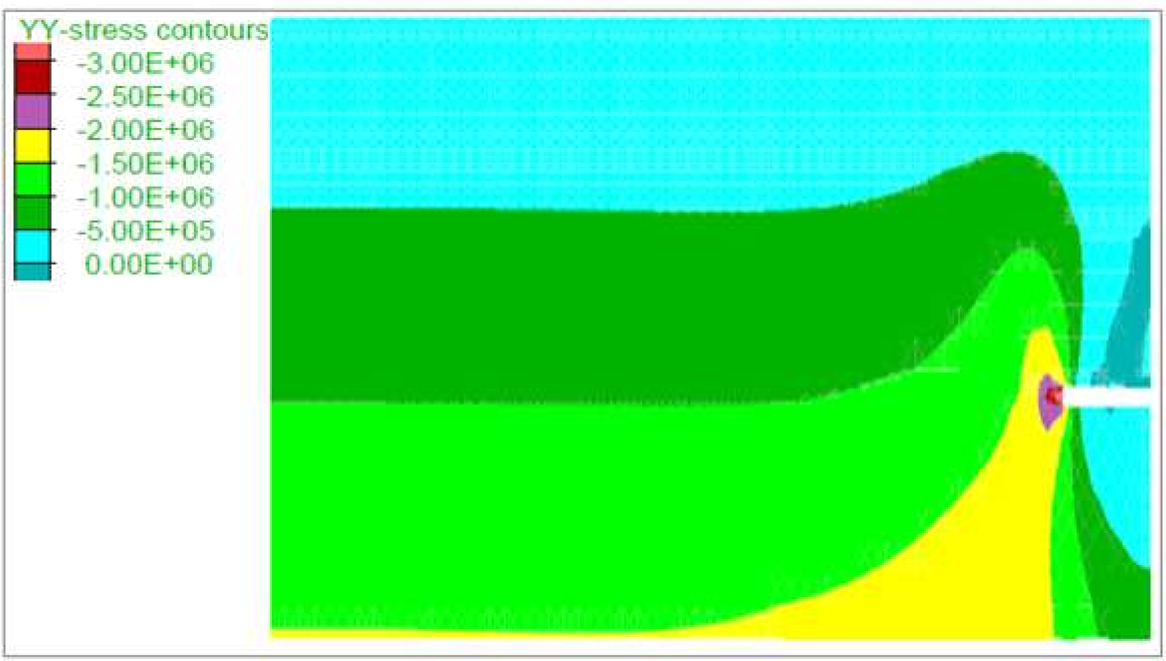

Figure 30

Induced vertical stress (MPa) developed in the panel after 30m longwall face extraction

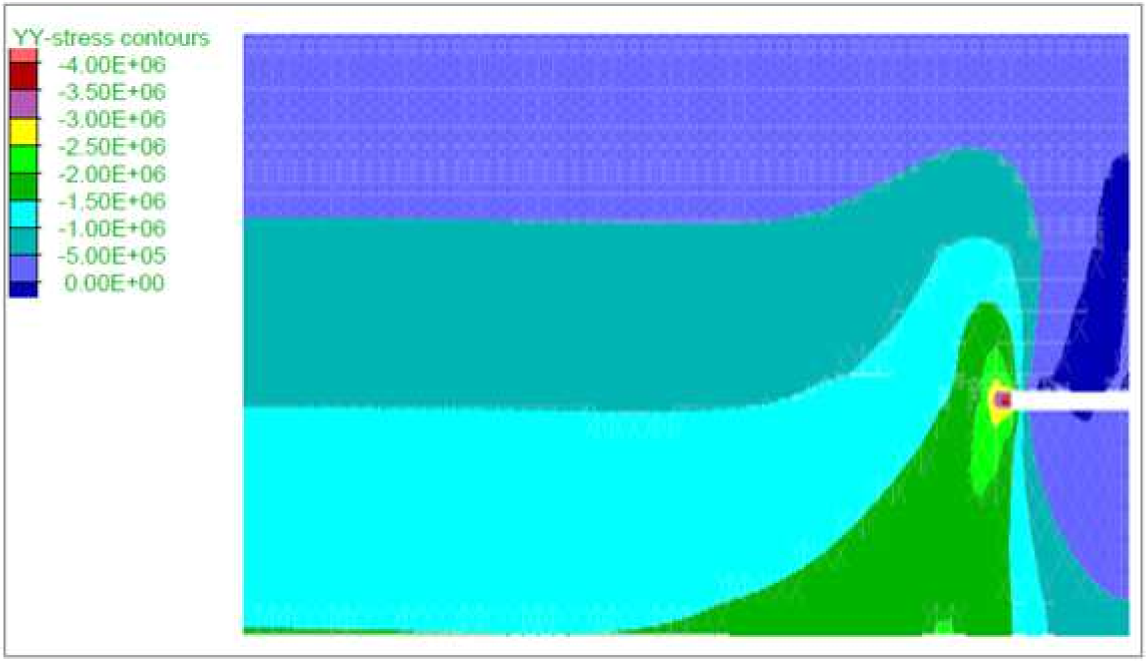

Figure 31

Induced vertical stress (MPa) developed in the panel after 40m longwall face extraction

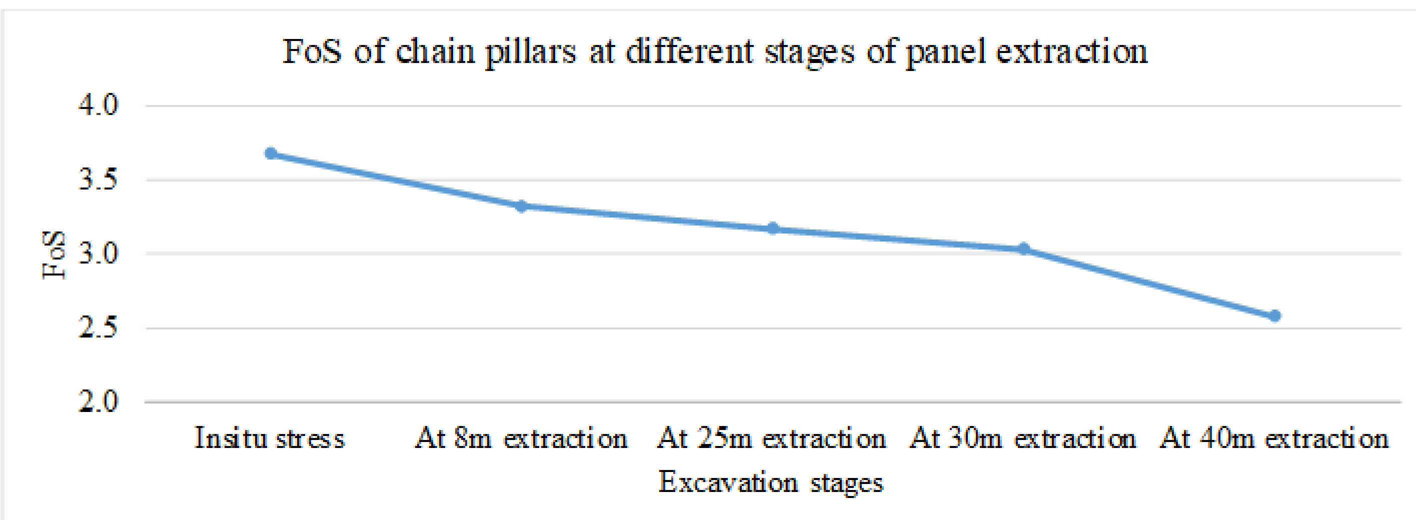

Figure 32

The FoS of the chain pillars at different stages of extraction

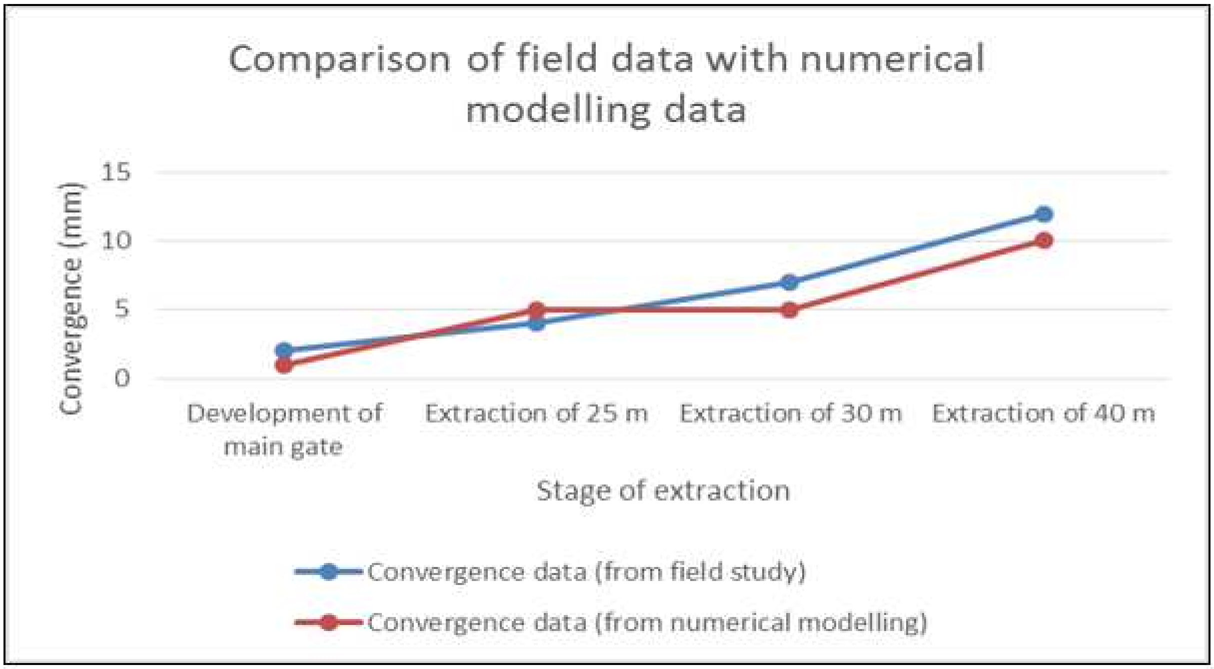

Figure 33

Comparison of field and numerical modelling data for convergence in gate roads

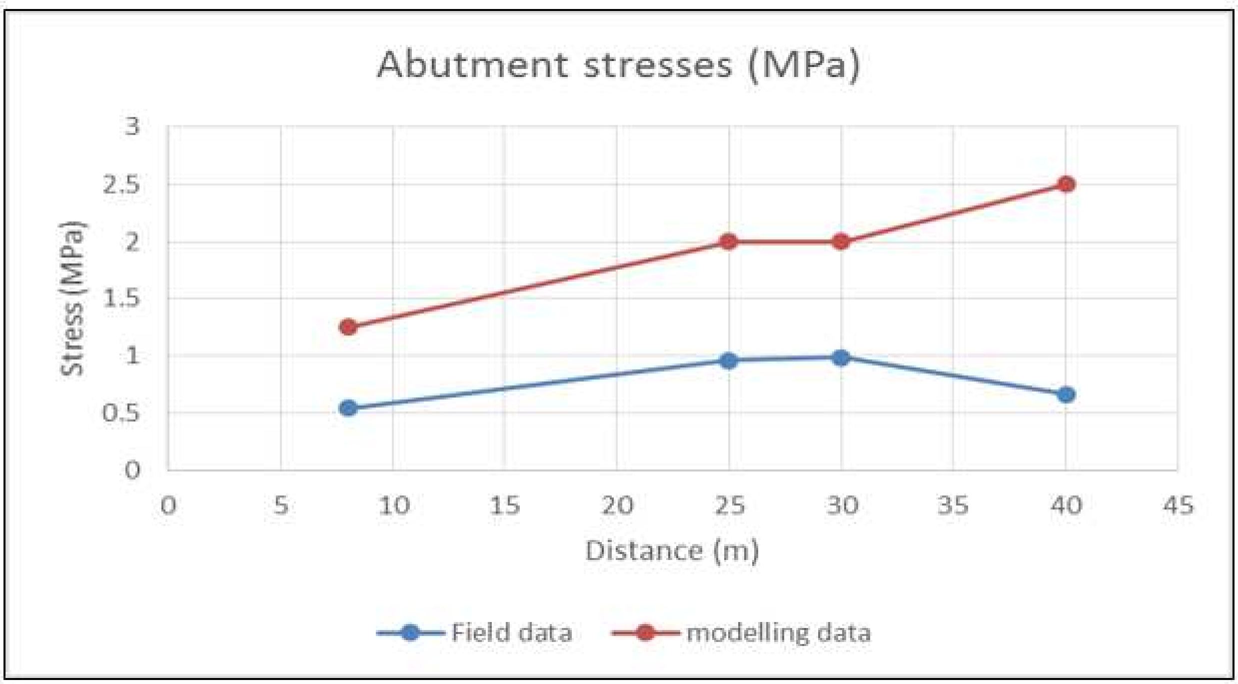

Figure 34

Comparison of field and numerical modelling data for abutment stresses