Chapter 15
Numerical Modelling for Prediction of Ground Subsidence Over Room and Pillar Mining in an Underground Coal Seam

Nisheeth Shekhar , **Supriya Pal** , **Arpan Jaiswal** , **and Pratip Hazara**

Introduction

Coal is the most essential and abundant fossil fuel in India. It accounts for 55% of the country's energy needs. Commercial primary energy consumption in India has grown by about 700% in the last four decades. India's current per capita commercial primary energy consumption is about 350 kg/year (kilograms of oil equivalent per year) (https://coal.nic.in/). Jharkhand, Odisha, Chhattisgarh, West Bengal, Madhya Pradesh, Telangana, and Maharashtra are the major coal-producing states in India (Geological Survey of India). India is the second-largest producer and consumer of coal worldwide, just after China (International Energy Agency, IEA). Among all the mining techniques, the underground mining method dominates the world's opencast method, as more than 60% of the total coal production in the world is extracted from underground mines. However, it acquires less than 10% of overall coal production (Coal Directory of India, 2016–17).

Room and pillar's (R&P) method of underground mining is the most common method used in India. In this extraction method, untouched coal 'pillars' of large dimensions are left to support the overlying strata leaving open areas, i.e. 'rooms and galleries' for the mobility of workers and various mining equipment. The key to successful room and pillar mining is selecting the optimum pillar size. If the pillars are too small, the mine would collapse. If the pillars are too large, then significant quantities of valuable material would be left behind, reducing the profitability of the

N. Shekhar (✉) · S. Pal · A. Jaiswal · P. Hazara
Department of Civil Engineering, National Institute of Technology, Durgapur, West Bengal 713209, India
e-mail: pratik.96.ns@gmail.com

S. Pal
e-mail: supriya.pal@ce.nitdgp.ac.in

mine. The percentage of material mined varies depending on many factors, including the material mined, the height of the pillar, and roof conditions.

The total coal production from U.G. mines in India is around 80% by the R&P method only. Different types of support systems are used to make a safe working condition for the workers. But due to some geomining constraints, only 30–35% recovery of coal is made possible by using the R&P method (developed state), and also a massive amount of energy resources (coal or any other minerals) are left behind in the form of pillars of immense dimensions [1].

Depillaring is coal extraction from pillars and is used, as vast quantities of minerals are left in those intact pillars. It can be done either with (i) caving or (ii) stowing. In depillaring with caving, the roof of the panel is allowed to collapse into the voids or caved area known as goaf. As roof strata are allowed to collapse, the ground surface develops cracks and subsides to a greater extent. In depillaring with stowing, the goaf is completely packed with some incombustible materials like river sand and pond ash. After depillaring for mineral extraction from an underground mine, it is the safest method as the probable subsidence is reduced to the greatest extent.

Despite all precautionary measures, surface subsidence due to underground mining activity is an unavoidable problem as soon as a cavity is formed to extract ores. 70 to 90% of the subsidence occurs immediately, and 10 to 30% occurs in a period of 300 to 500 days for an undisturbed rock mass, whereas for a disturbed rock mass, about 90 to 95% of subsidence occurs during excavation and 5 to 10% occurs in a period of 50 to 100 days [2]. Therefore, the forecasting of surface subsidence due to underground mining activities through numerical modelling techniques would be highly beneficial to the mining authorities in protecting surface properties and, most importantly, to increase the safety of miners [3].

Keeping this in view, the present study was undertaken to assess the quantum of surface subsidence over an underground coal mine at Raniganj coalfield area, Paschim Bardhaman District, West Bengal, India, through the application of numerical modelling techniques. The different cases such as pillar formation, depilating, and stowing were considered in numerical modelling through Plaxis 3D FEM software to assess the ground displacement and probable surface tensile crack formation.

Site Details

In this study, an underground mine in the Raniganj coalfield area, Paschim Bardhaman District, West Bengal, India, has been chosen, which is proposed to be developed by room and pillar mining method. The block lies between the latitudes 23°-38′-10″ to 23°-39′-45″ E and longitudes of 87°-12′-00″ to 87°-14′-10″.

The total area of the mine geological block is 5.85 sq km. The project area of about 2.54 sq km is confined between fault $F1$-$F1$, fault $F3$-$F3$, fault $F4$-$F4$, and the colliery leasehold boundary. The mine area is roughly rectangular, bounded by $F1$-$F1$, $F3$-$F3$, $F10$-$F10$, and $F4$-$F4$, as shown in Fig. 15.1.
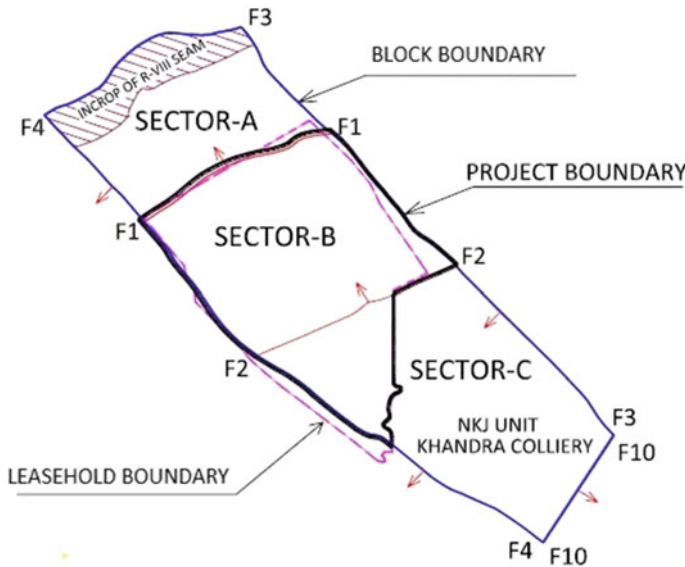
Fig. 15.1 Mine geological block

The roof of a coal seam, considered for subsidence prediction, is located at a depth of 121 m below the ground level. Panel 5 of the seam (as shown in Fig. 15.2) was considered for modelling in the present study. Square-shaped pillars of size 23 × 23 m were made during the development stage. Gallery of width 6 m was made for smooth mobility of mining equipment. The overburden consists of various layers of sandstones and shales with the top 4 m of silty sand. The considered coal seam has a thickness varying from 2.68 to 4.5 m. However, the height of the panel was considered 2.7 m thick for numerical modelling. Figure 15.3 shows the designed plan of the room and pillar developed panel used in numerical modelling.

Numerical Modelling

FEM (Finite Element Method) makes it possible to discretize the structure into single continuous elements. It takes into account the geometry of the structure, boundary conditions, and initial conditions. FEM or FDM-based software is a powerful computational tool for solving many engineering problems in the current scenario. In the present study, Plaxis 3D (FEM-based software) was used for numerical simulation of subsidence prediction over the panel as even the complex topography and geostrata of the site can easily be simulated using this software. The program uses a convenient graphical user interface that enables users to quickly generate an accurate three-dimensional finite element mesh based on a composition of horizontal cross-sections at different vertical levels.

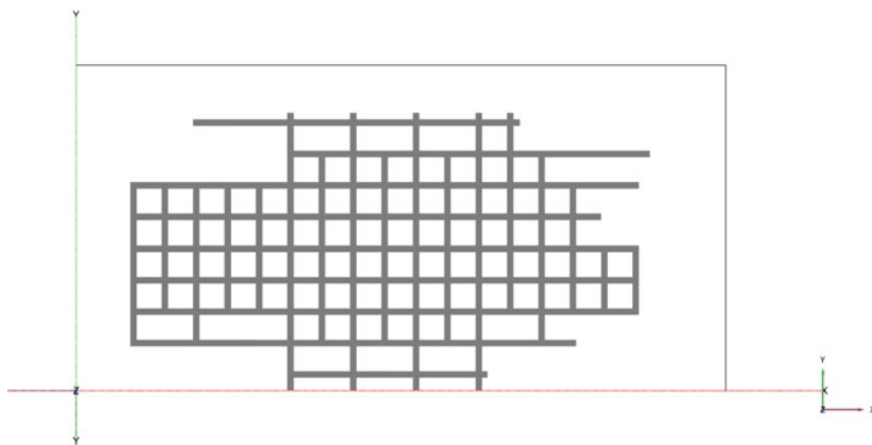**Fig. 15.2** Plan of developed panel 5

Fig. 15.3 Plan of R&P developed panel (white portion: coal; grey portion: voids)

All the overlying layers and coal seams were considered over the panel in numerical modelling in all the cases of pillar development and depillaring with simultaneous stowing. The model geometry is chosen so that it is closest to the actual geometry mine. A rectangular panel of area 600×300 m is considered for subsidence prediction. The linear elastic material model is selected for the overburden layers. Strength parameters of the soil layers used in the numerical modelling are given in Table

15.1. Strength parameters of the fill material (dense sand) used for stowing during depillaring are given in Table 15.2.

Medium quality of meshing was used to generate finite elements for the model. The elements generated by the software for the soil volume are 10-noded tetrahedral elements. Local mesh refinement is done at the surface, and the layer present above the coal seam is considered in the analysis. The mesh generated and connectivity plot of the model are shown in Fig. 15.4.

Table 15.1 Geotechnical parameters of soil layers used in the numerical modelling

Type of soil	E (MPa)	Poisson's ratio (v)	γ_{unsat} (K N/m^3)	γ_{sat} (K N/m^3)
Laterite	710	0.35	20.6	21.2
Alluvium	890	0.31	20	20.5
Loose sand	16	0.3	13.5	16
Sandstone	31.2 e3	0.305	26.1	26.5
Shale	61 e3	0.31	25.4	25.85
Coal	91	0.4	16.85	17.2

Table 15.2 Geotechnical parameters of fill material used

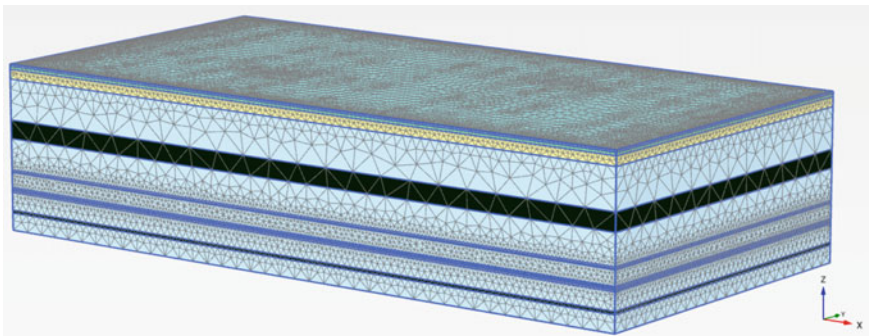| Geotechnical parameters	Value
E (MPa)	20
Poisson's ratio (v)	0.4
γ_{unsat} (K N/m^3)	19
γ_{sat} (K N/m^3)	20

Fig. 15.4 Generated mesh (connectivity plot)

Subsidence Prediction

Subsidence is an inevitable consequence of underground mining because of the voids created due to coal extraction, so the movement of overlaying layers is simulated in different phases.

The numerical simulation for subsidence prediction is done in the following phases:

1. Initial phase: In-situ stresses of the model are considered.
2. Phase 1: Subsidence calculated for the developed panel.
3. Phase 2 (after phase 1): Complete depillaring with caving in the central portion of the panel.
4. Phase 3 (after phase 1): Complete depillaring with simultaneous stowing with a fill material.

Initially, in phase 1, the numerical analysis is carried out for a thoroughly developed panel where the coal pillars are left intact to support the overlying strata. Surface subsidence and coal seam roof movement are calculated.

Further, to increase coal recovery from a panel, complete depillaring is to be done by mining authorities which are analysed by both caving and simultaneous stowing with a filler material (dense sand). Thus, in phase 2, the complete removal of pillars from the central portion of the panel is analysed as an underground cavity. Figure 15.5 shows the cavity formed in the central portion of the panel after complete depillaring.

In phase 3, complete depillaring with simultaneous stowing with a fill material in the cavity is analysed. This is done to support the overlying strata and minimize the subsidence effect at the ground surface. Figure 15.6 shows the panel completely stowed with a fill material in the voids (the stowing material is red). This phase is
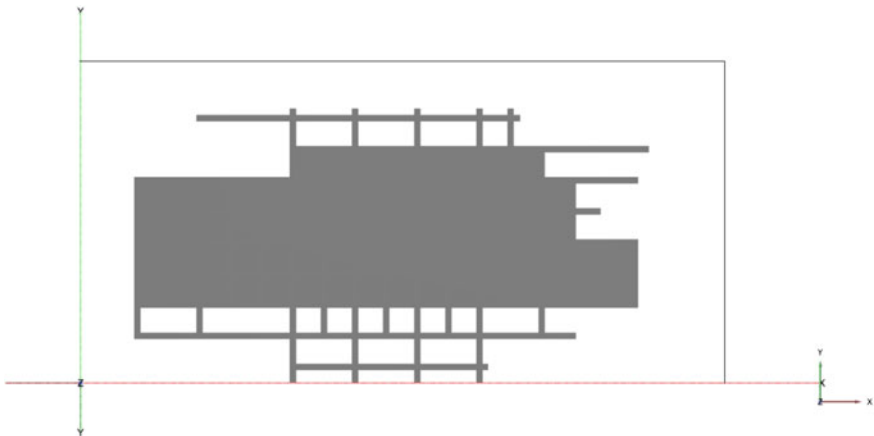

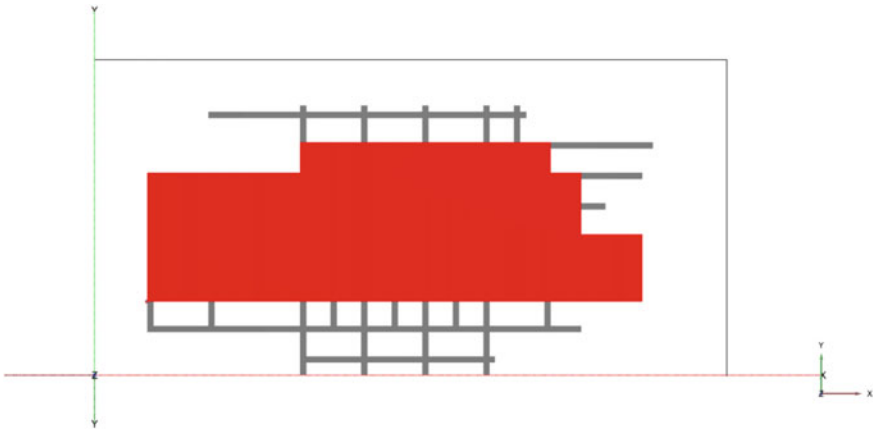**Fig. 15.5** Plan showing cavity formed after complete depillaring

Fig. 15.6 Plan of a panel with stowed material (red portion: stowed material)

executed after phase 1 so that subsidence for both conditions can be compared easily (for phase 2 and phase 3).

Result and Discussion

Figures 15.7 and 15.8 show the vertical displacements shading the ground surface and seam roof, respectively, for phase 1.
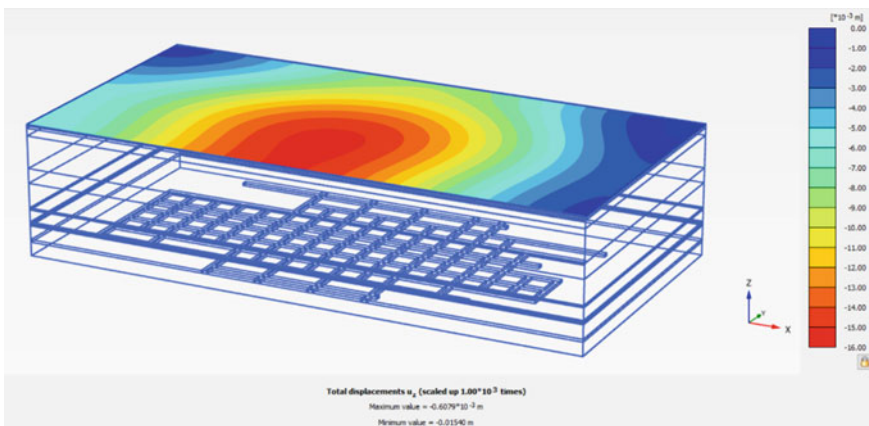
Figures 15.9 and 15.10 show the vertical displacements shading the ground surface and seam roof, respectively, for phase 2.

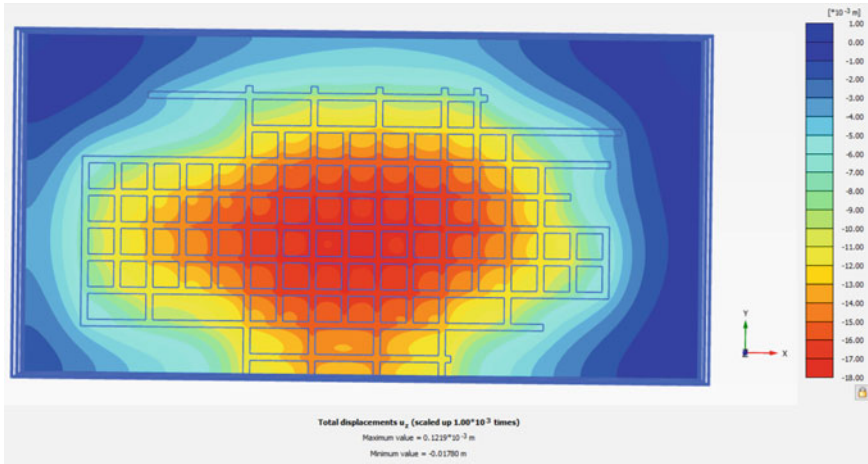**Fig. 15.7** Vertical displacements shading at the ground surface of the developed panel

Fig. 15.8 Vertical displacements shading at seam roof level of the developed panel (top view)
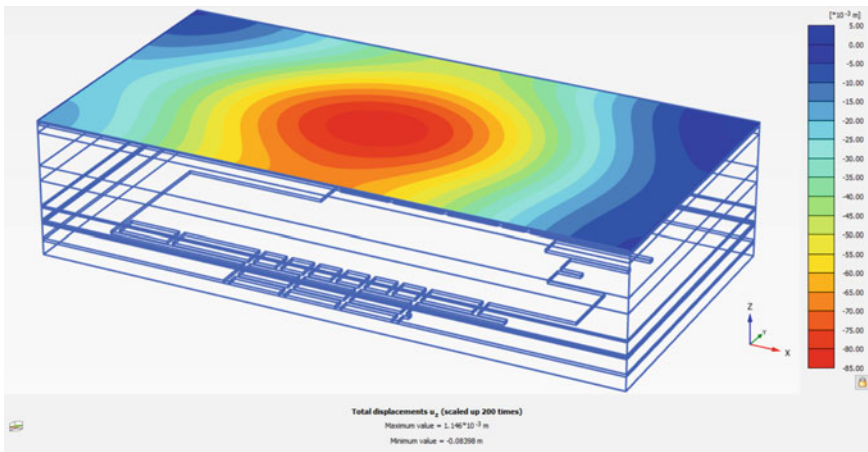

Fig. 15.9 Vertical displacements shading at the ground surface

Figures 15.11 and 15.12 show the vertical displacements shading the ground surface and seam roof, respectively, for phase 3.

From Table 15.3, it can be seen that the vertical displacements at the ground surface and coal seam roof level for the developed panel are 15.40 mm and 17.80 mm, respectively. Since it is stable, to increase the coal recovery from the panel, the complete removal of pillars from the central portion of the panel was analysed as an underground cavity (phase 2). Subsidence estimated at surface and seam roof level is 83.98 mm and 127.50 mm, respectively. But when the same case is analysed as depillaring with simultaneous stowing of a fill material (dense sand) in the voids
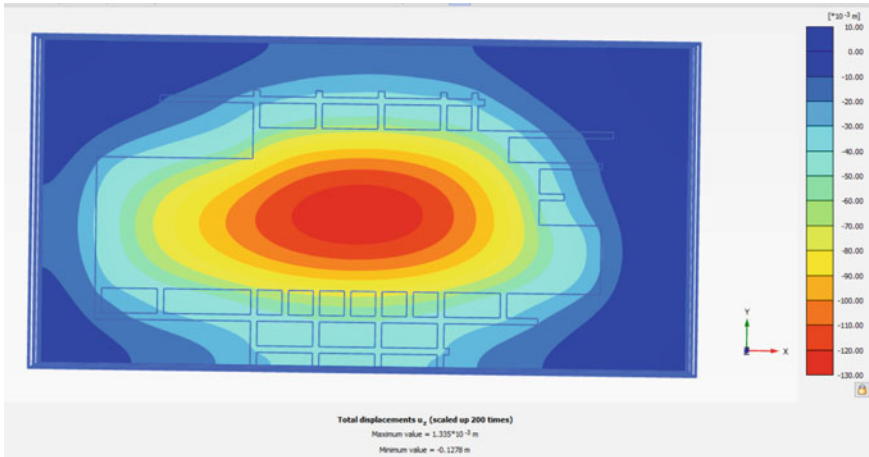
Fig. 15.10 Vertical displacements shading at seam roof level (top view)
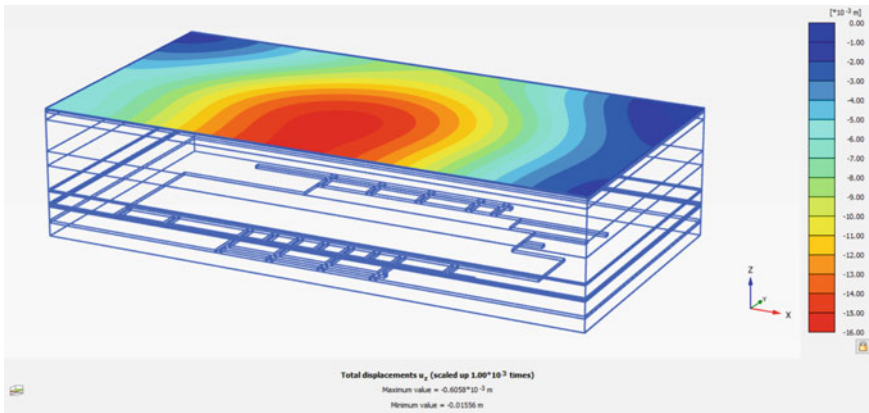

Fig. 15.11 Vertical displacements shading at the ground surface for the stowed panel

formed (phase 3), there was not much increase in the subsidence compared to the developed panel. At the ground surface, it is estimated as 15.56 mm, and at the coal seam roof level, 18.07 mm. Figure 15.13 shows the comparison of estimated surface subsidence for all phases, and it can be seen there is a considerable difference in subsidence for caving and simultaneous stowing.
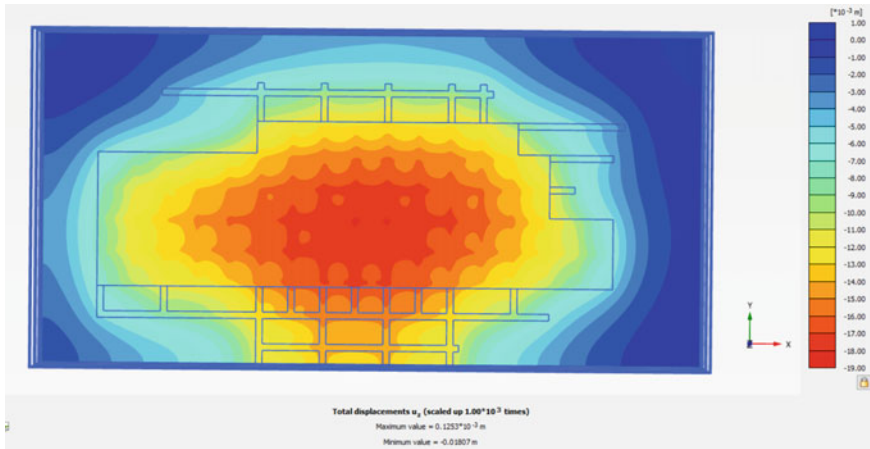
Fig. 15.12 Vertical displacements shading at seam roof level for stowed panel (top view)

Table 15.3 Tabular representation of the vertical displacements calculated

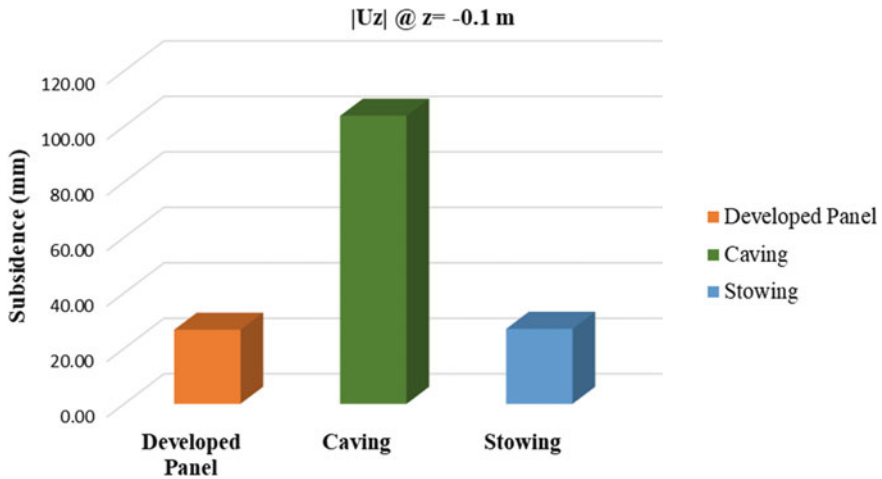| Total vertical displacements $|U_z|$ (mm)			
Calculation phases	Total displacements $|U|$ (mm)	$|U_z|$ @ $z = -0.1$ m	$|U_z|$ @ $z = -121$ m
Phase 1	25.23	15.40	17.80
Phase 2	128.20	83.98	127.50
Phase 3	25.33	15.56	18.07

Fig. 15.13 Comparison of predicted ground surface subsidence

Conclusion

Results from the numerical model indicate that the developed panel is stable with just 15.40 mm subsidence at the surface and 17.80 mm at the roof of the coal seam. Ground surface subsidence for depillaring with simultaneous stowing was estimated at approximately 16 mm. When the same was done with the caving method, estimated subsidence was greater than 80 mm. Following the results obtained from numerical modelling, by adopting a depillaring operation with simultaneous stowing methodology of coal extraction from underground mines, surface subsidence can be arrested, especially for locations where surface topography or infrastructures are protected. By predicting the surface subsidence before the extraction using numerical simulations, we get an idea of the stability, which can be used afterwards with proper roof support systems to ease the coal extraction operations from the pillars of either abandoned or working mines. This study is not just limited to coal mines. It can also be used for other minerals extracted from underground mines with the same mining method. But it is necessary to include the complex geological conditions present in the mining area.

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