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Numerical modeling of longwall top coal caving method at thar coalfield

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Abstract

Thar Coalfield in Pakistan is the largest reserve of lignite coal in the country, which is outlined by thick coal seams. The preferred mining method for these thick coal seams is the Longwall Top Coal Caving (LTCC). The connection of both the top coal caving and its compactness are still rare; therefore, the capability of top coal caving mechanism is the most significant factor in LTCC that must be adequately explained and examined. Moreover, in order to achieve the ideal coal production, a comprehensive modeling of deformation and induced stress is mandatory. In this study, a 12 m thick coal seam with cutting to caving height ratios like 1:2 and 1:3 has been modelled, and the mechanism of longwall top coal caving demonstrated and front abutment vertical stress distribution in front of face line values were computed with the help of UDEC at Block-IX, Thar Coalfield. The results reveal that a thick layer of top coal can be progressively caved behind the face at the ratio 1:3 instead of 1:2 (which explained the incompetent caving progress of top coal). Similarly, the maximum vertical abutment stress of 20 MPa was observed at 6m in front of the face when cutting to caving height ratio was 1:2 and at 3m in front of face with 1:3 (which is comparatively capable for the face advancement), respectively. Therefore, this numerical modeling study proposes the reasonable height of top coal caving at cutting to caving height ratio 1:3 for the efficient production of thick coal seams at Thar Coalfield.

1. Introduction

The Longwall Top Coal Caving (LTCC) is a method that improves the efficiency level of production, especially for thick coal seams [1]. The LTCC was developed by combination of longwall and sublevel caving methods. For thick coal seams, the lower part is extracted by conventional longwall, and the top coal is exploited by sublevel caving (or "driven by the gravity" [2-7]). Coal seams can be classified into thin, average and thick sizes and the cataloguing relating to thickness may differ from country to country, but the acceptable lowest limit thickness is ~ 6 m [8]. Half of the world's coal reserves consist of approximately 70-80% thick-coal seams, which are extracted through underground mining methods [9-10]. China, France, and Poland have adopted identical methods for coal extraction. Nonetheless, disparities may be found due to coal conditions [11,1]. The technical aspect of single-slice long panel shows that the LTCC has been designed to take out thick seams up to the range of 20m that is considered most result-oriented and efficient. The noticeable difference between traditional mechanized longwall mining and LTCC is the caving stage of top coal that performs differently than the normal coal cutting process that is featured in Figure 1.

The LTCC technique was developed in China after 1982 [12], and it is used for the extraction of very deep and thick coal seams [13]. The LTCC is a product efficient and low cost method, but has a significant dependency on the coal seam characteristics [14-15]. The capability of top coal caving mechanism [16-18] and recovery percentage of top coal [19-20] are the most significant factors in LTCC that must be adequately explained and examined [21-22]. These benchmarks – fractured immediate roof, the top coal recovery ratio, and the movement law of fractured top coal affects the compactness of the top coal. The influence of the following parameters (the strength of the immediate roof, cutting depth of the shearer, and the cutting height with top coal caving through numerical modeling)-has been studied by various researchers in their studies [23-28].

The numerical modeling provides useful, quick and authentic results to accomplish the required task. In the same manner, it gives proper information that helps to better understand and address the problem that exists within the LTCC [29]. The vital part of the planning process of longwall mining includes computing the economical yet optimum design of acceptable safety levels and production efficient panel designs [30].

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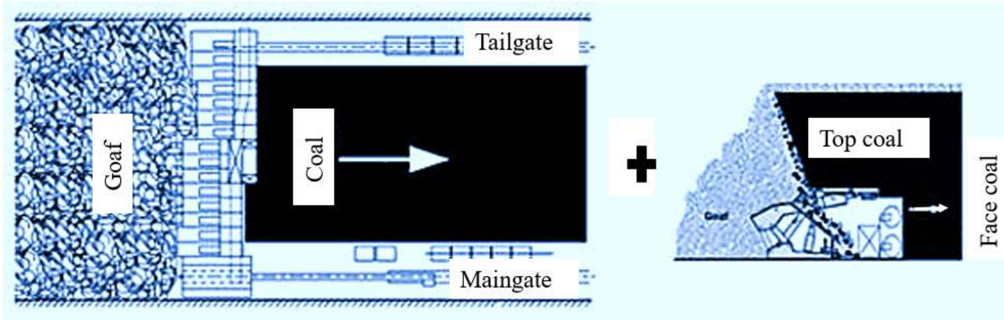

Figure 1. Sketch of LTCC method at Block-IX Thar Coal [31].

This study deals with the connection of both the top coal caving and its compactness, which are still rare and has been not properly focused in the past research studies. Besides, in order to achieve the ideal coal production, a comprehensive modeling of deformation and induced stress is mandatory. Furthermore, some valuable developments can be made based on the above-mentioned researches. In this study, two-dimensional numerical modeling of longwall top coal caving method by using UDEC at 12 m thick coal seam at Block-IX Thar coalfield is conducted. Furthermore, the mechanism of top coal caving is demonstrated, and stress (evaluation of front abutment stress distribution in front of face line) values are computed. Moreover, the cutting to caving height ratio (i.e. 1:2 and 1:3) is also discussed to better understand the reasonable height of top coal caving for the development of LTCC method for the production of thick coal seams at Thar Coalfield of Pakistan.

2. Research methodology

The effective measurement of input parameters of coal and its surrounding rock mass to get reliable output in modeling with UDEC2D is quite important. In UDEC Model, the rock properties of the "contacts and blocks" adjusts the mechanical demonstration of material during modeling. The data was directly collected from the industry professionals and university professors, which was determined by performing the various empirical approaches, laboratory and field experiments [34-38]. For better and effective elaboration, the input parameters of rock mass used for modeling are given in Table 1 [39-41]. Next, a 12 m thick coal seam is modeled in two-dimension by using UDEC version 6.0 at Block-IX, Thar Coalfield. In addition, the two numerical block models with different cutting to caving height ratios like 1:2 (cutting height is 4 m and caving height is 8 m) and 1:3 (cutting height is 3 m and caving height is 9 m) are developed for the effective simulation of the top coal caving mechanism and calculation of maximum front abutment vertical stress in front of the face line. Finally, the reasonable height of top coal caving is recommended for the efficient production at Thar Coalfield in Pakistan.

3. Case study

The Thar coalfield is situated in the district of Tharparkar, in the Sindh province of Pakistan. The Geological Survey of Pakistan (GSP) and the United States Agency for International Development (USAID) have surveyed the area. Thar lignite, Pakistan has been declared the 7^{th} largest coal reserves in the world [42-45].

The discovered coal deposit in Thar, Pakistan is ascribed to the Paleocene and Eocene eras of the classification of rocks. Thar Coalfield was discovered in the joint investigation of Pakistan and other countries in 1991, and it is spread over an area of about 9,000 km^2 containing around 175 billion tons of coal which are sufficient enough to meet the fuel requirements of the country for many centuries.

Thar coalfield is surrounded by dune sand, which extend to a normal distance of 80 m, and is located on an important stand in the eastern part of the desert. The general stratigraphic arrangement in the Thar coal encompasses the basement compound, coal posture Bara formation, alluvial deposits, and dune sand. The cumulative thickness of coal seam at Thar varies from 1.5 m to 42 m.

The Thar coalfield is divided into 12 different blocks as shown in Figure 2(c). The open-pit and the underground mining method can be used to extract the coal of the region. Specifically, Block-II out of the 12 blocks is in under development for the open-pit mining method while Block-I and Block-IX are being prepared for the underground method. This is the first time in the history of Pakistan that the mechanized longwall and the Top Coal Caving method is being proposed at Block-IX, Thar Coalfield. Block-IX is a part of Thar area and the terrain of the Block is similar to that of the entire Thar district. Besides, Thar coalfield is free from any toxic gases, which can be harmful during underground mining. The LTCC has been found to be production efficient with a low-cost development method as compared with other mining methods like the single-slice or multi-slice longwall methods in case of thickness of coal seams respectively.

Table 1. Input material parameters used in numerical modeling.

Rock type	Unit	Claystone	Siltstone	Coal
Density (d)	(MN·m^{-3})	0.022	0.023	0.015
Internal friction (φ)	(°)	36	45	25
Cohesion (c)	(MPa)	1	1.4	0.13
Modulus of elasticity (E)	(GPa)	1.6	1.7	2.2
Tensile strength	(MPa)	2.1	3	0.3
Poisson's (ϑ) ratio	-	0.25	0.25	0.28
Normal stiffness (K_n)	(GPa·m^{-1})	5.1	6	4.7
Shear stiffness (K_s)	(GPa·m^{-1})	3.4	4.7	1.15

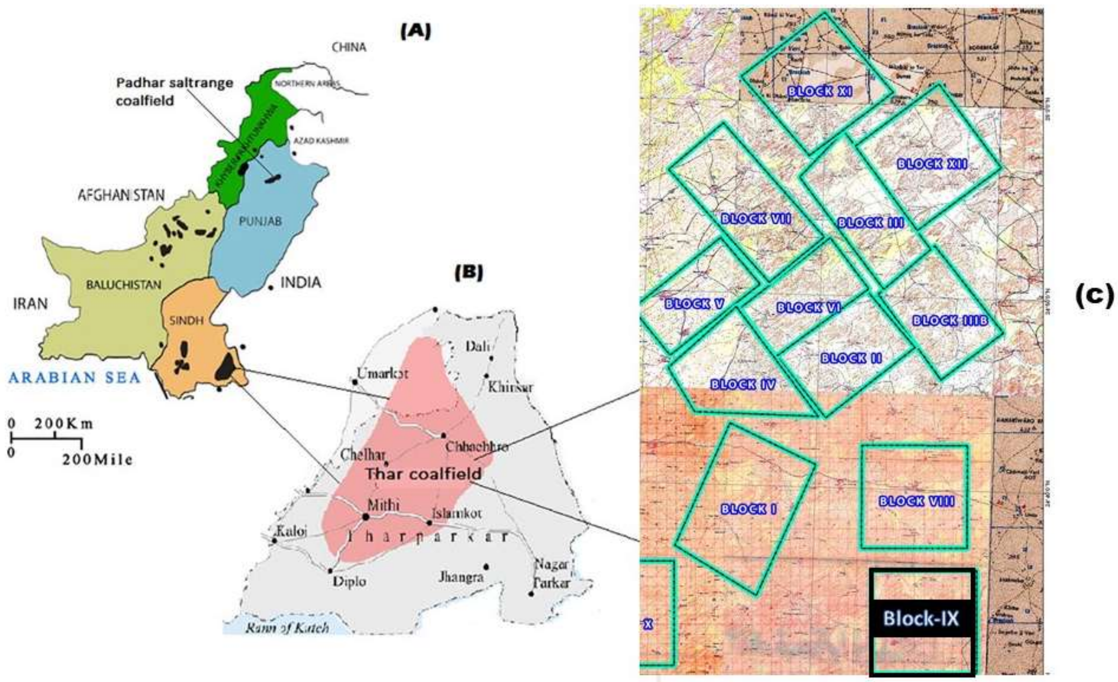

Figure 2. Location map for Thar Coalfield in Pakistan (after [32-33]).

4. The general modeling practice

In several situations, the analysis of underground structures is reflected as challenging and difficult to accomplish. Though, compared with the complex and time-consuming "physical models," the computer based numerical modeling techniques are more convenient, fast and real. The modeling is accomplished by UDEC in two-dimensional frame. The software such as UDEC is commonly used for the simulation of "stress distribution and deformation around the longwall coal surface and underground designs". The UDEC is based on Discrete Element Method (DEM).

The Figure 4 indicates the flow chart of the modeling procedure.

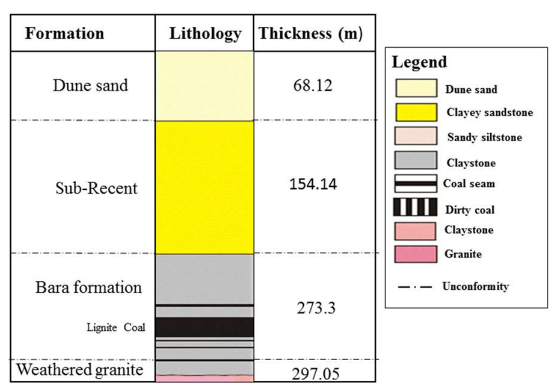

Figure 3. Generalized stratigraphic column at Block-IX Thar Coal.

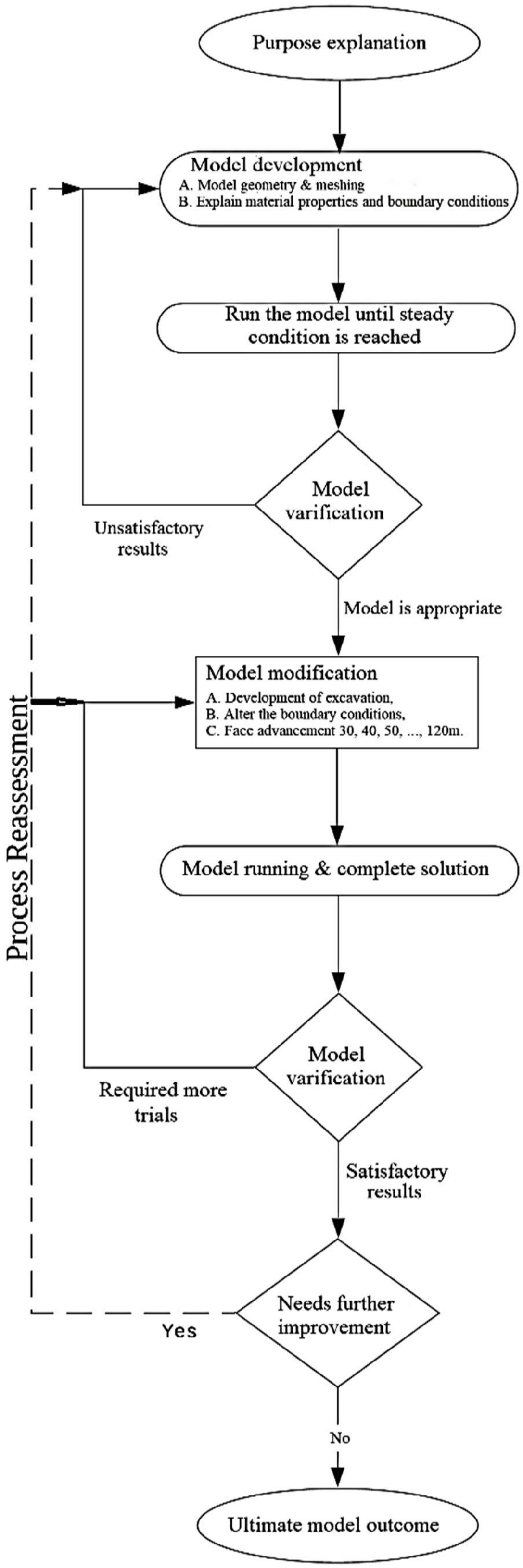

Figure 4. Flow chart of general modeling procedure (after [46-48]).

5. Numerical simulation

In extracting a coal seam that usually exceeds 5m in thickness, LTCC could be the best method. It is also found to be productive and has the potential to become a factor determining the quality of coal and surrounding rock and coal seam conditions. This research study on longwall top-coal caving (LTCC) mining has been conducted because being an important method it has not been properly focus by previous research studies. This research study is considered first time, and its applications in thick coal seams were investigated with the help of numerical analysis using UDEC2D 6.0 at Thar Coal.

6. Development of numerical block model

Two UDEC numerical models are developed, and both consist of 12 m thick coal seam, and each model is divided into 2 parts having different cutting to caving height ratios i.e. 1:2 and 1:3. The ratio 1:2 means that the cutting height is 4 m and the caving height is 8 m. Similarly, the ratio 1:3 measures the cutting height as 3 m and the caving height as 9 m. For convenience purposes, multi-thin layers were not considered, and overburden was designed as identical claystone and siltstone layers. Keeping in view the restraints of computer-based running time and capacity limits, the 118 m high model was taken from the actual height of 297 m with a width of 200 m as clearly specified in Figure 5. This data will be helpful in as failure distribution, ground displacement, and precise stress changes, are measured within the extraction area. This numerical analysis comprises of the input parameters as shown in Table 1. At the initial stage, boundary conditions were set, and the constitutive relationship and material properties were explained. After that, the model was run until it achieved equilibrium stage. In this study, a longwall model was simulated from the left to the right side of the model with the help of stepwise excavation where each stage consisted of 10 m advance. To release the stress and permit the top coal to collapse properly, the satisfactory time steps (8000*n, where n is considered as the cycle number) were undertaken.

7. Results Analysis and Discussion

7.1 Top coal caving mechanism in LTCC

Figures 6 and 7 exhibits the simulated plotting of continuous top coal failure, and the initial phase of coal extraction. It shows that above the mined panel the top coal is unsupported which leads it to deform and fail. At the stage 1 when the face advances 10m, there wasn't any deformation experienced in the top coal (Figures 6 and 7). This also denotes the nature of top coal as extremely competent; therefore, no failure and caving occured and the top seam remained unchanged in this step. However, as the face advances, more cracks were generated and spread became deeper. Here, the top coal acts as a beam and begins to bend downwards at the second step as shown in Figures 6 and 7 with a face advance of 20m. Additionally, it is worth noting that the bed parting started at this particular stage and shear breakage formed. Similarly, when face advances 30 m, the fractures extended deeper and wider into the roof, with prominent separation, as shown in Figure 6 and 7 at stage 3. The fractures extended into the top coal which caved behind the face immediately. As the face continues to advance after stage 3, "the top coal further caves and bed separation occurs, and the fractures extend towards the top of the model". This model clearly shows the toppling of the top coal behind the face immediately, in agreement with 2D discrete modeling results [49].

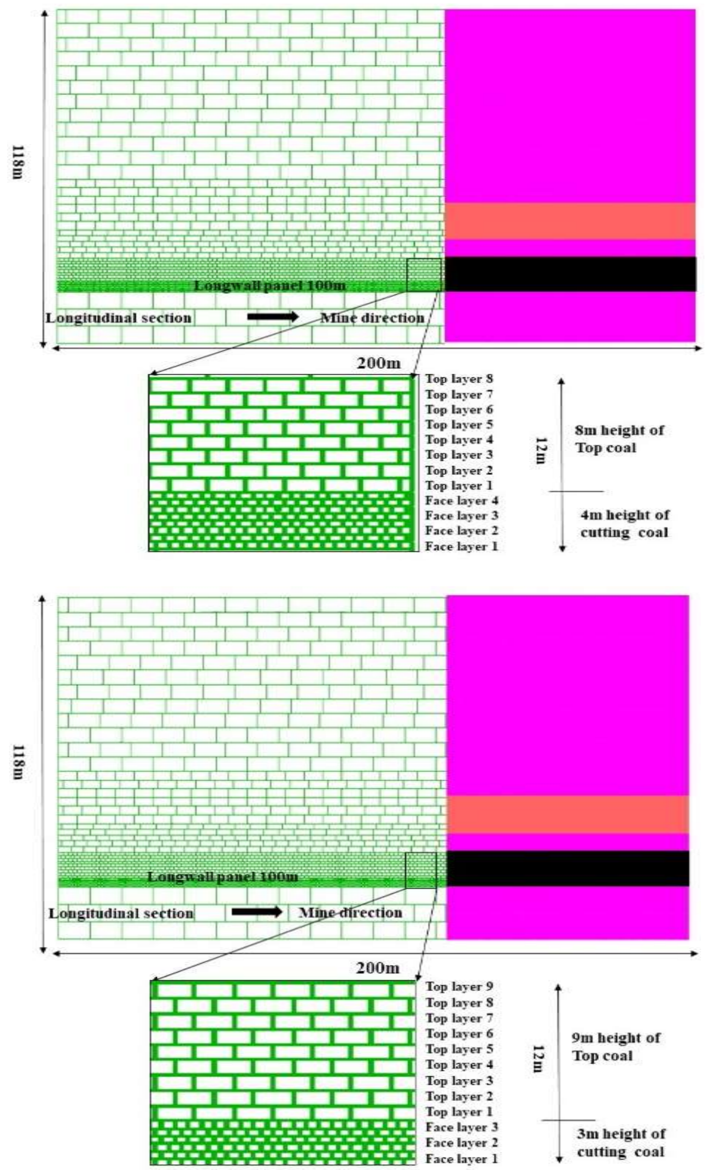

Figure 5. Numerical Block Models with (a) 1:2 and (b) 1:3.

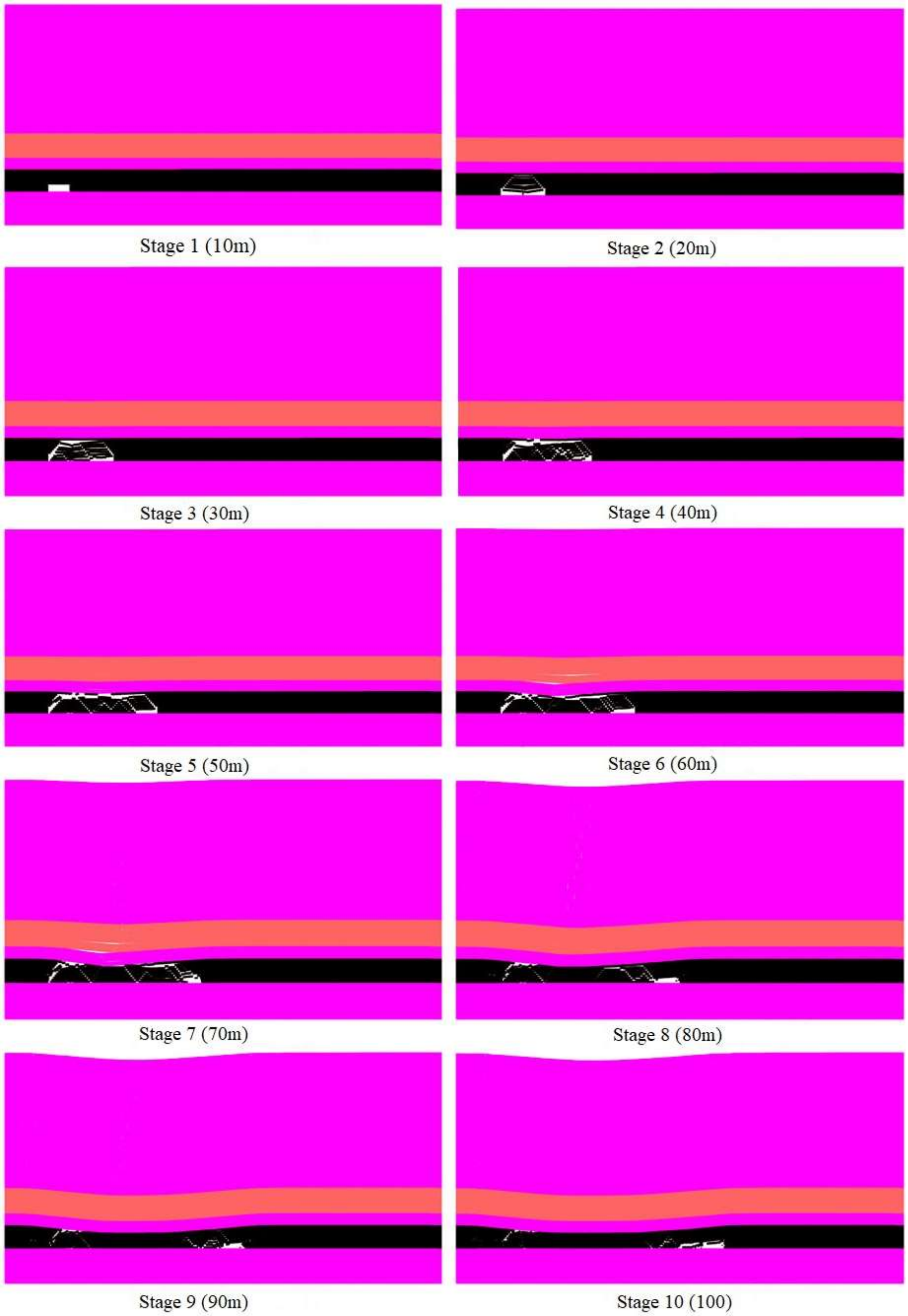

Figure 6. Simulated Progressive Caving of top coal during the extraction of longwall coal face at ratio 1:2.

7.2 Stress changes around the face

The caving of roof and the extraction of coal seam results in stress distribution around the mine openings. For a better understanding of the caving process, understanding the state of stress change is essential for formulating both roadway and face support. In Figures 8 and 9, and Figure 10, the distribution of the vertical and horizontal stress surrounding the longwall face is adequately elaborated, respectively. This mining of coal results in stress concentration in undermined coal and the roof adjacent to the openings. Figures 8 and 9 exhibits the proper distribution/rearrangement of the stresses from the vertical region in the anterior of the lineaments at multiple distances in route to the bearings of the face advance, for example, 3, 6, 9, 12, 15, and 18 m at six multiple levels.

To achieve the realistic stress distribution, the 12 m thick coal seam was divided into different cutting to caving height ratios such as 1:2 and 1:3. According to that, the vertical stress in the top coal and bottom is alleviated and the space of both the stress relief regions and the stress concentration increase with face advancement. It must be taken into consideration that front and rear abutment stress is continuous after prompt roof/roof collapse, in this way, both the rear and front abutment stresses escalate as the face advances.

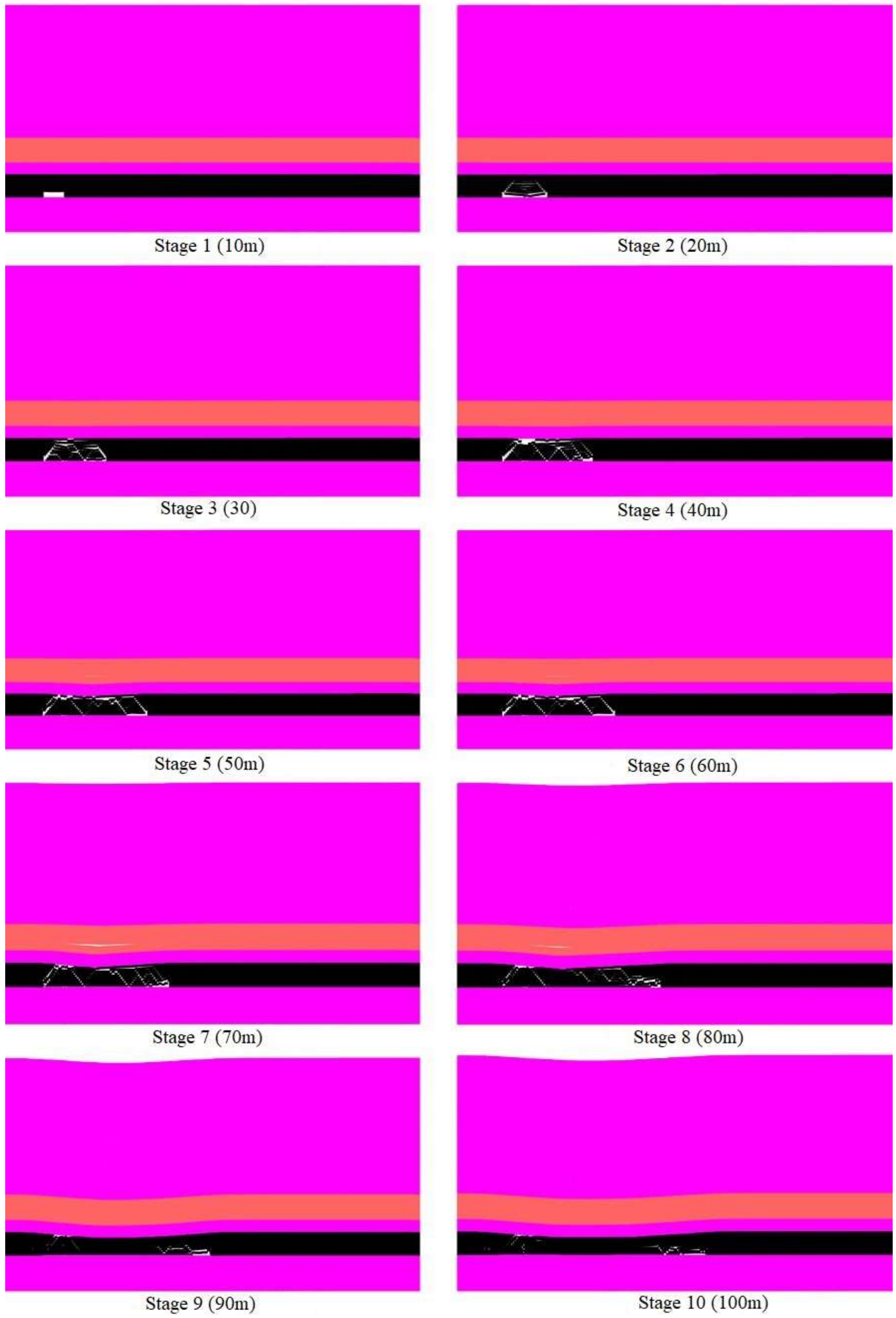

Figure 7. Simulated Progressive Caving of top coal during the extraction of longwall coal face at ratio 1:3.

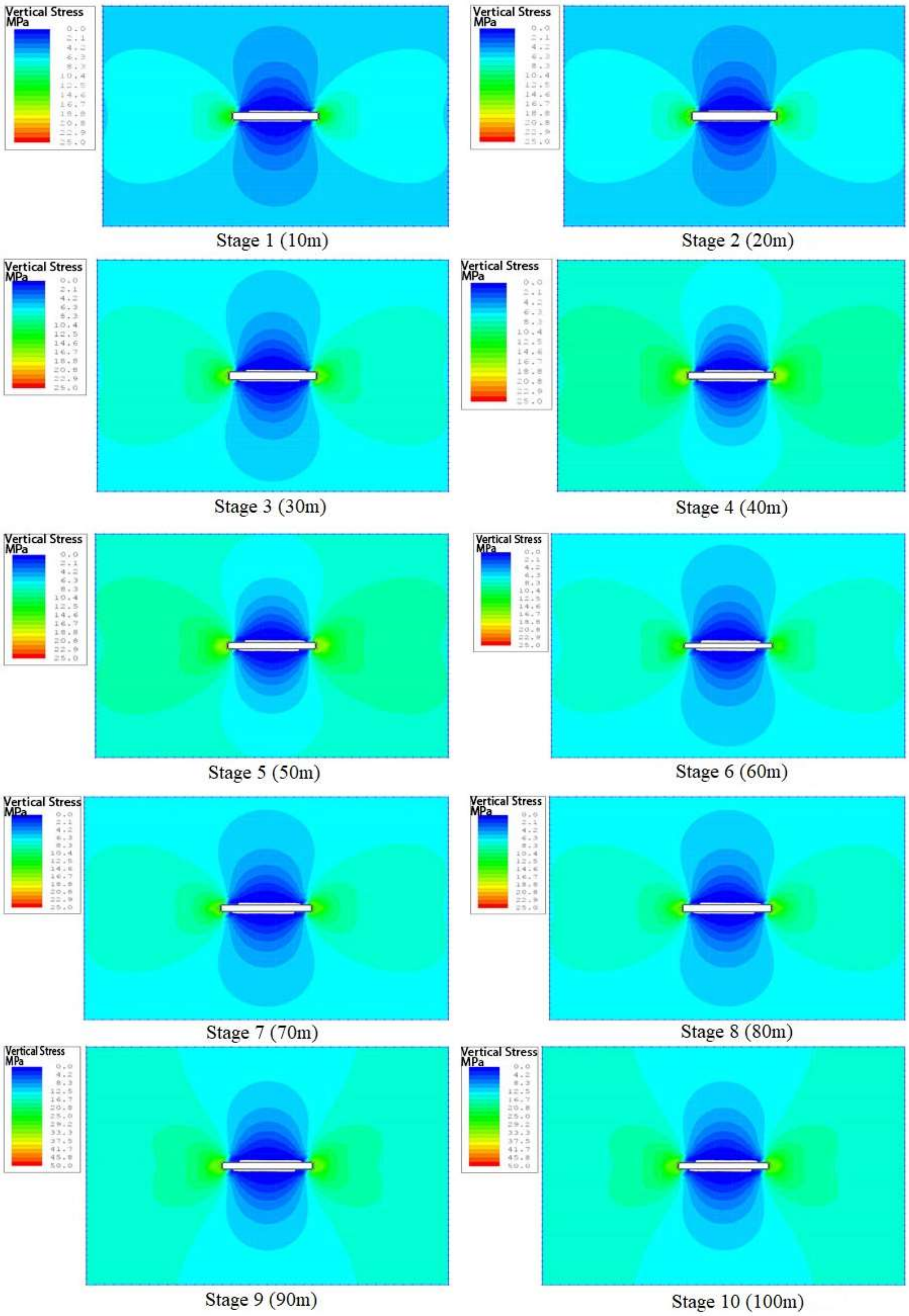

Figure 8. Assumed distribution of vertical stress due to progression of longwall face at 1:2.

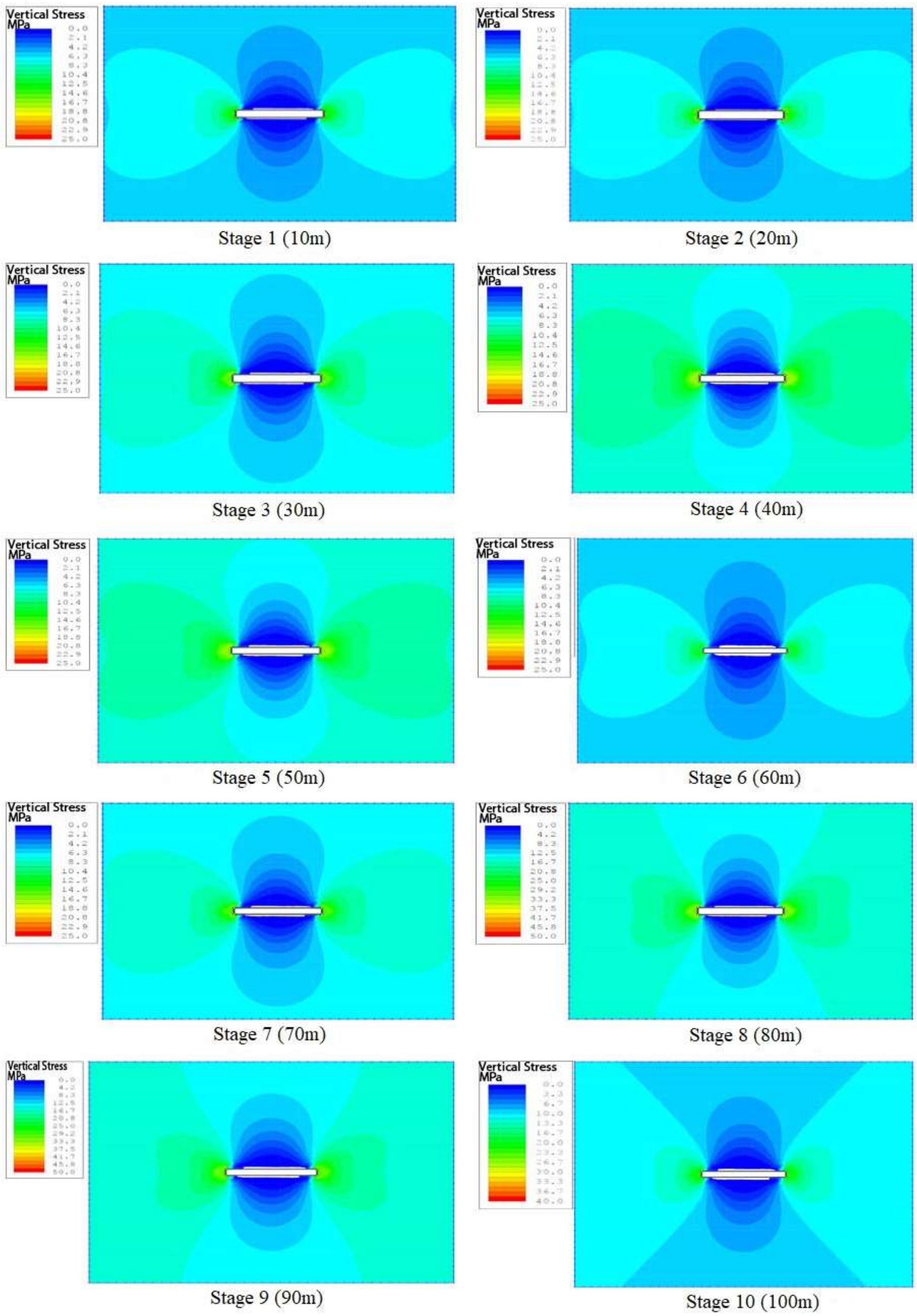

Figure 9. Assumed distribution of vertical stress due to progression of longwall face at 1:3.

Figure 10 indicates the maximum horizontal stresses 3 m in front of the longwall face, i.e. 5 MPa at 1:2 and 4 m at 1:3, respectively. Simultaneously 10 MPa of vertical stresses were found in the same region accordingly. Both cases demonstrate the difference in aspects of stress movement encompassing the longwall anterior. Therefore, the variation in stress was gradually observed in the model after each interval when the face was progressed as 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 m far from the anterior starting line. In parallel, this study has not presented a complete explanation of the modeling results; however, the variation in the movement of vertical stress movement encompassing the anterior depends on the progress of the anterior is concisely discussed.

Various researchers have studied stress distribution surrounding the longwall anterior depending on the consequences of the in situ extensions [50-51]. Follow-on the ultimate falling of coal at the extreme front support space, the maximum stress district would shift to about 2-3 m far ahead of the face. Contrarily, when the coal-seam roof contacts, the vertical stress significantly falls to zero, and subsequently, the slow expansion of the vertical stress is experienced in the goaf area behind the face, depending on the degree of compaction.

The vertical stress distribution regime at the model after 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 m interval from the face advance start line is shown in Figures 11 and 12. The figures clearly show that the aspects of the stress movement around the face acquired by using numerical simulation are in sound agreement with the effects of definite dimensions in underground situations.

In Figures 11 and 12, the corresponding value of vertical stress is noted at different cutting intervals from stage 1 (10 m) to stage 10 (100 m) with 3m to 18 m in front of face in coal at 1:2 and 1:3. Therefore, the findings shows that the stress from the front abutment ameliorates as the anterior moves 6 m at 1:2 and 3 m at 1:3 from the starting point of the face and reaching the maximum value of 20 MPa, which indicates that the top coal caving height at 1:3 is comparatively feasible for the face advancement and the efficient production of thick coal seams at Thar Coalfield in Pakistan.

Modeling results indicate that the 9 m thick layer of top coal can easily cave behind the face. Contrarily, the 8 m top coal at 1:2 shows very confusing results. As the face moves 70 m, the top coal cannot cave behind the face completely. The results acquired from the modeling study indicate that no difficulty will be experienced during the top coal caving at 1:3.

Figures 13(a) and 13(b) indicates the vertical stresses encountered, through numerical modeling, which are appropriate with the consequences of determined measurements in underground circumstances. The degree of original field stress was calculated as ~6MPa.

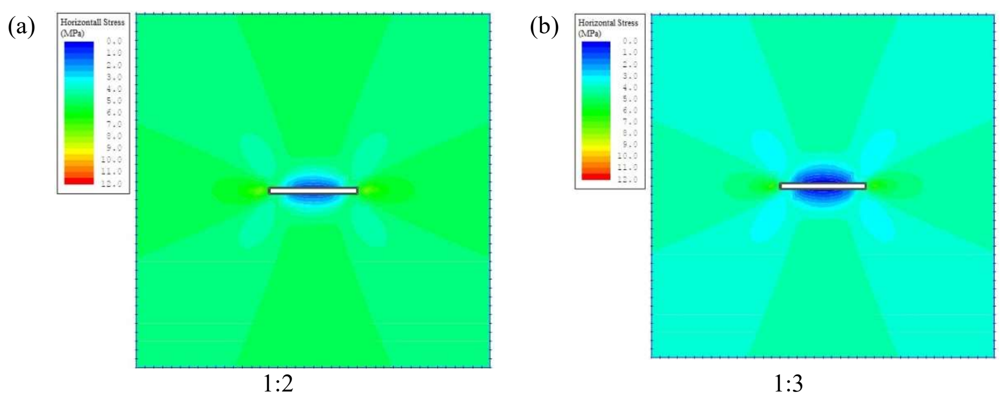

Figure 10. Assumed distribution of horizontal stress encompassing progression of longwall face.

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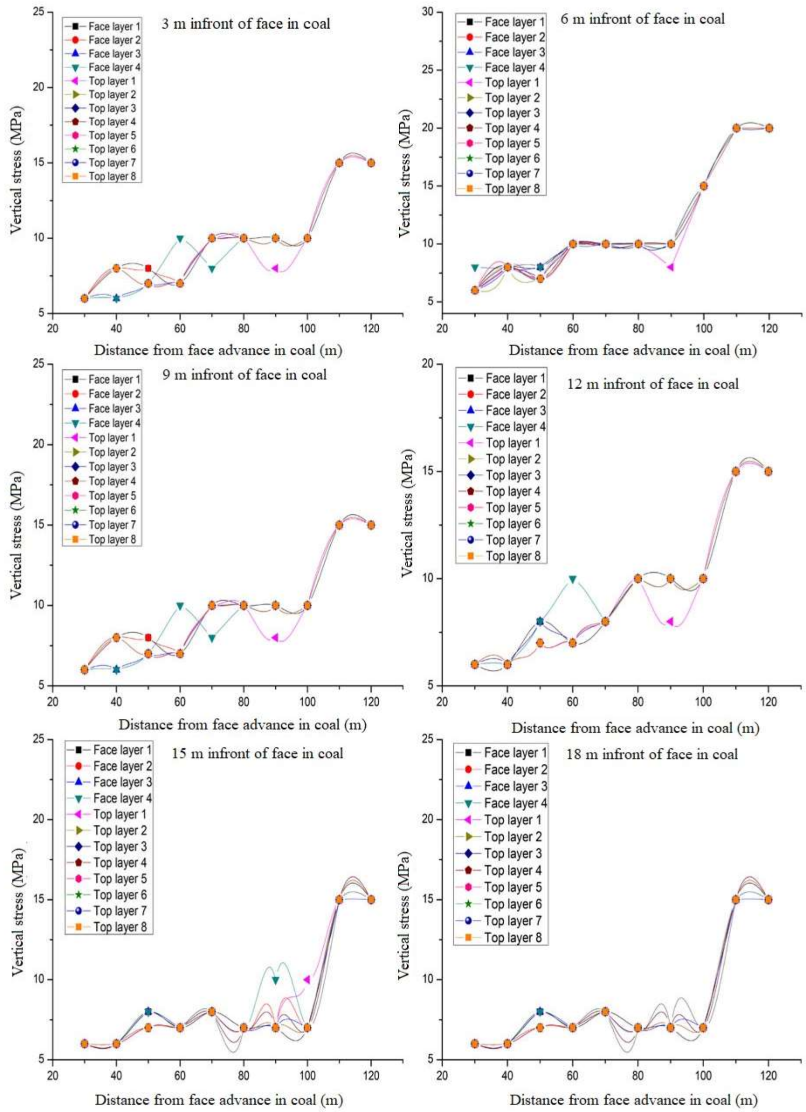

Figure 11. The distribution of vertical stress encompassing the anterior at various intervals 1:2.

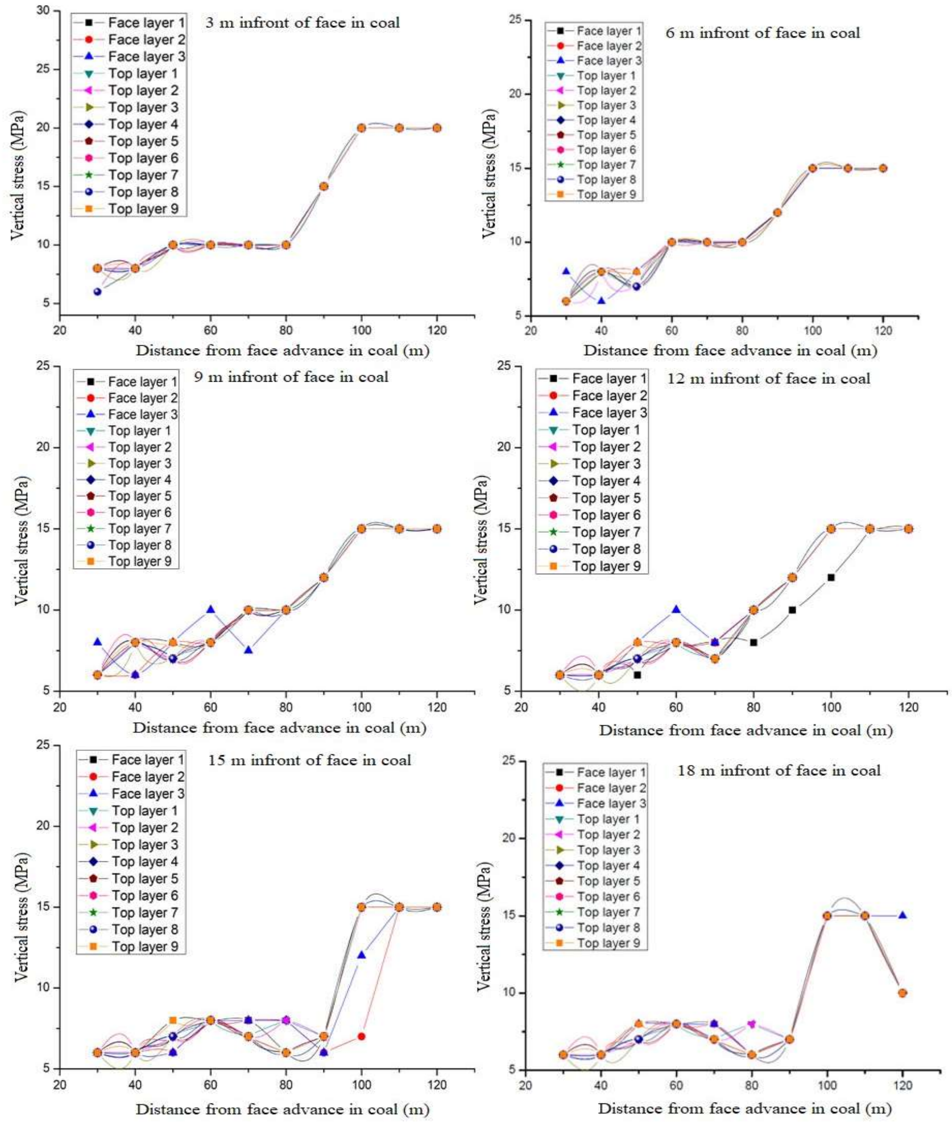

Figure 12. The distribution of vertical stress encompassing the anterior at various intervals 1:3.

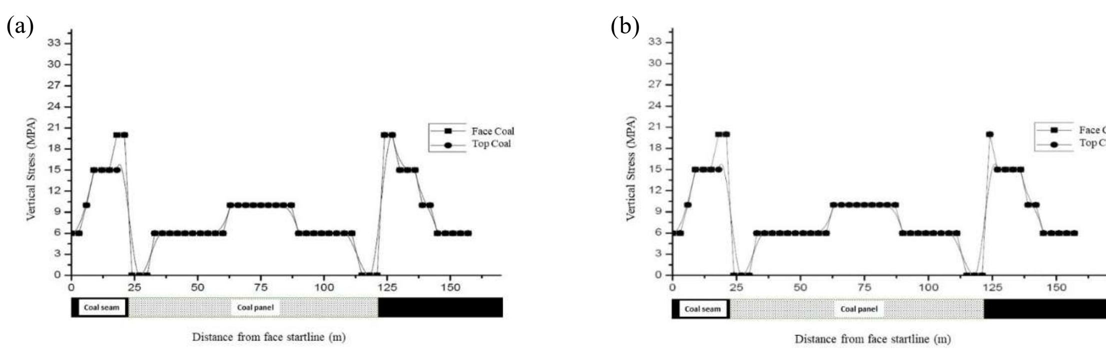

Figure 13. (a) Distribution of vertical stresses around coal face and in goaf at 1:2; (b). Distribution of vertical stresses around coal face and in goaf at 1:3.

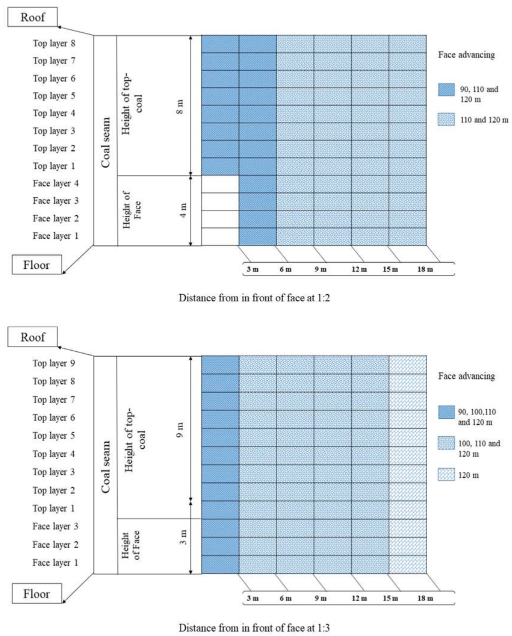

Figure 14. Maximum vertical stress regions in-front of face advance.

As mentioned earlier the maximum front abutment stress was indicated to be at 6 m at 1:2 and 3 m at 1:3 in front of the coal face. Anyhow, the accumulation of maximum front abutment stress in different locations depended on the gap between the face start line and the face. Analysis of various regions of the coal seam shows the same result. Figure 14 shows the stress regions for various conditions of the maximum vertical front abutment.

To find out the location of maximum vertical stress regions inside the coal-seam, a numerical modeling study of Thar Coalfield, Block-IX in UDEC is done. Figures 8 and 9 show different stages of face advance, where the stresses of the vertical abutment have attained their most significant values. For example, the face advance from the face start line is insignificant as the stress of the vertical abutment was observed in the Top layer 1 to Top layer 8 as the face advances 0 m to 3 m and in Face 1 to Face 4, and Top layer 1 to Top layer 8 in coal between 3 m to 6 m from face start line at 1:2. Similarly, the maximum vertical abutment stresses have also been found at Face 1 to Face 4, and between Top layer 1 to Top layer 8 between 0 m to 3m of the face from face start line at 1:3.

The vertical abutment stress values at the remaining intervals were observed almost same in the Face layers and Top layers between 6 to 18 m of the face from the face start line in both cases of cutting to caving height ratios.

Also, in Figure 15, the results of the vertical displacement (at 1:2 and 1:3) are listed in meters (m) like 1.50E00.1, this means that the area of this shade parallel to a vertical displacement quantity of 150 mm. The extraction mode of coal is ellipsoid as given in the figure, and the space of high vertical displacement is known as an ellipsoid of motion. Contrarily, zones with smaller displacement values are called the active zone.

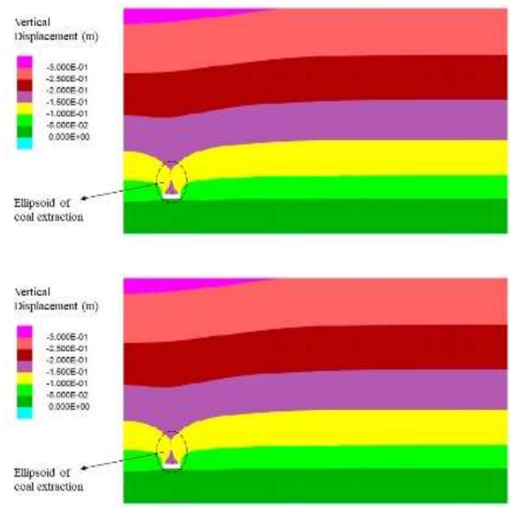

Figure 15. Contours of vertical displacement with (a) 1:2 and (b) 1:3.

8. Suggested cutting to caving height

At a cutting to caving height ratio 1:3, there is an indication of complete failure of the top coal based on numerical simulation, and it is not posing any problem during the caving of top coal as shown in Figure 6(b). However, in the case of 1:2 comparing with 1:3 after 70 m of the face advances, the top coal does not fail entirely, as shown in Figure 16 (from Figure 7), and the distance between 3 m to 6 m from the face results in high vertical stress, which signifies the caving progress of top coal as quite incompetent. Similarly, the observation of top coal failure was infrequent over a period of time as coal was starting to break into irregular pieces. During the instances of this problem, a proper setup for pre-fracturing of the top coal (such as blasting or hydraulic fracturing) is prerequisite to continue the efficient coal drawing operation at 1:2. It should also be noted that both models with different cutting to caving heights were consistent and containing the same material properties. Consequently, a cutting to caving height with 1:2 is time-consuming and costly due to arranging a separate pre-fracturing system before the caving of top coal just after the 70 m of the face advance. Furthermore, at this ratio 1:3, the top coal recovery ratio is computed to be sound like 83.9% [46]. Therefore, it has been strongly suggested that the cutting to caving height of 1:3 is found to be more facilitating in caving phenomena and in good agreement to mining thick coal seam at Thar Coalfield at Block-IX. This condition was confirmed through numerical simulation consequences in this study.

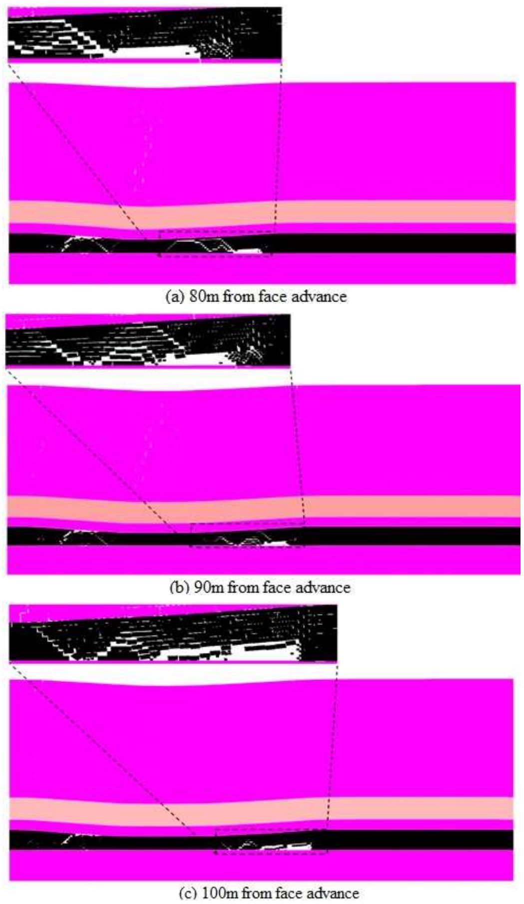

Figure 16. Caving mechanism of top coal from 80, 90 and 100 m of face advance at 1:2.

9. Conclusion

The Longwall Top Coal is a caving method adapted and designed to extract the 12 m thick coal seam at THAR COALFIELD in Pakistan. This method has been applied in this area for the first time and is capable of achieving productive results, especially in the mining of thick coal seam(s).

For realistic modeling of the mechanism of top coal caving, front abutment stresses in front of the face line, displacements results were found by using two-dimensional numerical modeling with advanced software called UDEC 6.0 at Thar Coalfield.

Besides, the input parameters that were used for the modeling were determined by performing the various laboratory and field experiments.

According to the modeling consequences, the top coal completely caved in behind the face at 1:3 as compared to 1:2. A 1:3 ratio means that the conventional longwall face is only 3 m high rather than 4 m high for 1:2. Therefore, the reduced face height denoted the significant face stability benefits in this study.

Moreover, the highest front abutment vertical stress was calculated as 20 MPa at a distance of 6 m in the front of the face with cutting to caving height ratio of 1:2; similarly, the same value of front abutment vertical stress was determined at 3m in front of the face with 1:3. The cutting to caving height ratio of 1:3 showed significant performance in numerical results for the proficient advancement of coal face. Therefore, the cutting to caving height ratio 1:3 is suggested for the development of LTCC method at Thar Coal in Pakistan.

Finally, the results point to the specific condition of Thar Coalfield, for which not many studies have been conducted. Furthermore, 'the overall conclusion' is confirming the previous studies that add to the reliability of this modeling and subsequent results.

10. Future recommendations

The study was conducted with [ratio] 1:2 and 1:3 for the top coal caving phenomenon and computation of front abutment vertical stress in front of the longwall face. Further study can be extended to maximum ratios of cutting to caving height to better understand the simulation of top coal mining method. Furthermore, the results of present study are only based on the numerical modeling in two-dimensional analysis, therefore, the future work can be expanded to this method in three-dimensional analysis with FLAC/3DEC/RFPA and PFC3D. Lastly, the findings of study can be compared with previous research done by various researchers.

11. Acknowledgement

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