

# Longwall Top Coal Caving Design for Thick Coal Seam in Very Poor Strength Surrounding Strata

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## Research

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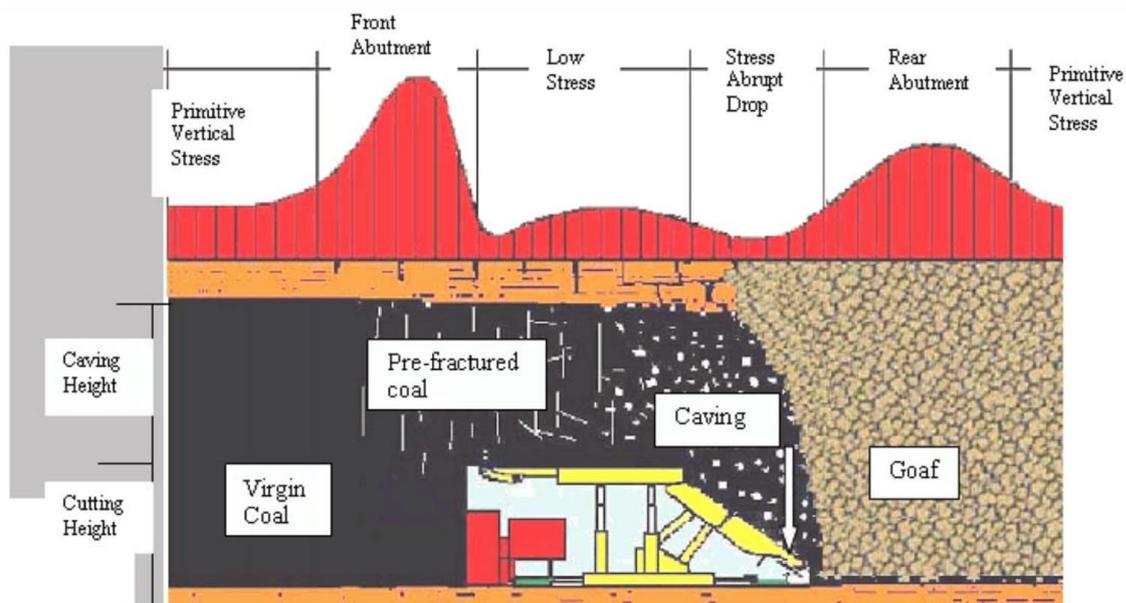
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1 **1. Introduction**

2 Longwall mining is one of the most applicable and effective production methods for  
3 underground coalmines. Longwall mining is attractive for producers due to its high production  
4 rate (Galvin 2016). Mechanized longwall mining requires heavy machinery and equipment that  
5 are shearer for coal cutting, hydraulic shields for roof control, and armored face conveyor  
6 (AFC) for the haulage of the coal. The mechanized longwall mining requires flat-lying coal  
7 seams, in which the dip of the seam should not be more than 20°. The amount of coal for the  
8 production panel must be high enough to cover the initial investment of the mechanized  
9 longwall system. Longwall top coal caving (LTCC) is a part of longwall mining that is  
10 applicable for thick coal seams. China is an important country, which has best practices of  
11 LTCC in terms of high production rates. The production principle of LTCC is similar to the  
12 conventional longwall mining; however, there are two conveyors named as front and rear,  
13 which are used to haul the broken coal cut by shearer and the caved coal from the rear of the  
14 hydraulic systems, respectively (Alehossein and Poulsen 2010). A schematic view of a typical  
15 LTCC practice is presented in Fig. 1. Wang (2014) reviewed the status of fully mechanized  
16 mining technology in detail for China especially for thick coal seams. It was outlined that the  
17 one of the key issue of the mechanized mining defined as complex geological conditions. Wang  
18 and Pang (2017) also presented longwall technology for the interaction between hydraulic  
19 supports and surrounding rock mass properties. Face advance rate which is also very critical  
20 for mechanized longwall mine stability and scheduling has been also investigated as a part of  
21 ground control issues for fully mechanized mining (Aghababaei et al. 2019).



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23

**Fig. 1** LTCC method (Alehossein and Poulsen 2010).

1 Fully mechanized LTCC mining method is a good recovery for ultra-thick coal seams especially  
2 seams above 7 m. Developing technologies increases the recovery rate for LTCC more than  
3 working in slice panels (Wang et al. 2015). Different drawing alternatives effect the recovery  
4 rate of the top coal as also outlined by Wang et al. (2015), and it proposed that one cutting and  
5 one drawing working methodology leads to increase the top coal recovery. However, the low  
6 strength behavior in terms of geotechnical properties of floor and roof strata leads to decrease  
7 the top coal recovery due to the limit of the longwall working height. The relation between the  
8 productivity of coal seam based on geotechnical properties investigated in the study that is the  
9 key factor for the recovery of top coal.

10 Strata movement in longwall mining is generally well described and classified in a caved zone  
11 that is behave as an immediate roof. The height of the caved zone is described by the bulking  
12 factor, which is the ratio of broken rocks volume to intact rocks (Peng 2008). Overburden strata  
13 was categorized into four zones as (1) caved, (2) fractures, (3) continuous deformation, and (4)  
14 soil zone from seam to the surface (Syd 1992). Peng and Chiang (1982) categorized the  
15 immediate roof in three classes, which are unstable, medium, and stable. Peng (2019) also  
16 described the immediate and main roof heights in detail. Ground control is not only related to  
17 the stability of openings, but it is also interested in floor bearing capacity, pillar design, shield  
18 design, and subsidence. The overlying strata is left as a block when the immediate roof is caved.  
19 Required shield capacity can be determined from the gravity forces applied by the separated  
20 block that depends on the immediate roof bulking factor (Barczak and Tadolini 2006). Ofoegbu  
21 et al. (2008) summarized the researches related to the bulking factor in coal mines around the  
22 world.

23 Ground control principles have developed mostly in coal mines due to the weak strength  
24 behavior of coal and surrounding strata in Turkey. Alpu coal mine deposit is a virgin lignite  
25 field having nearly two billion tons of coal. The mine site is divided into the different sectors  
26 and pre-feasibility studies have been carried out individually since 2014. There are plenty of  
27 scope and feasibility studies have conducted for the site and the geotechnical investigations  
28 have shown that the geotechnical features of coal and the surrounding rock mass are the weakest  
29 link in the chain. Although the Turkish coal mining industry gets accustomed to working in low  
30 and fair strength strata, the initial results of the geotechnical investigations indicate that not  
31 only coal itself but also surrounding strata are critical in terms of strength due to its low and  
32 very low strength definitions. The study aims to investigate the applicability of LTCC as a  
33 mechanized underground production method. Caving behavior was simulated for required

1 shield capacity investigations. In addition, floor bearing capacity was researched for the  
2 hydraulic shields and AFC designs. Analytical and numerical methods were also performed in  
3 this study for the design of LTCC in thick coal seam that is seam-A. Furthermore, application  
4 of conventional mechanized longwall mining was investigated for seam-C as an auxiliary  
5 purpose of the study.

## 6 **2. Brief Geology of the Mine Site**

7 Alpu lignite mine is located in the middle of Turkey and it is approximately 14 km east of  
8 Eskisehir province, and 3 km northwest of Ankara Eskisehir main road. The license area of  
9 Esan Company, nearly having 15% of Alpu lignite resource, is approximately 24 km<sup>2</sup>. The  
10 longest distance from north to south is 5 km and from east to west is 6 km.

11 Turkey coal deposits mostly took shape during the carboniferous and tertiary periods. Alpu  
12 lignite mine site is located in Sakarya terrane and Anatolide tauride block, which is separated  
13 by the Intra-pontide suture zone passing through the Bozuyuk-Eskisehir line (Toprak et al.  
14 2015).

15 The basement rocks of the basin are formed by Paleozoic metamorphic rocks and Mesozoic  
16 ophiolites. At the north of the basin, the metamorphic rocks, which contain marbles and blue  
17 schists, are overlaid by the ophiolites. The ophiolitic mélangé is formed by radiolarites,  
18 radiolarian limestones, mudstones, serpentines, diabase, limestone, schist blocks, partly  
19 serpentinized peridotite, and partly metamorphosed diabase and gabbro. Chalcopyrite,  
20 malachite and pyrite mineralization and quartz veins are monitored through the faults and  
21 cracks inside the ophiolitic rocks. Neogene deposits inappropriately overlay the basement rocks  
22 (Asutay et al. 1996). A geological map and a cross-section are given in Fig.2 and Fig. 3,  
23 respectively.

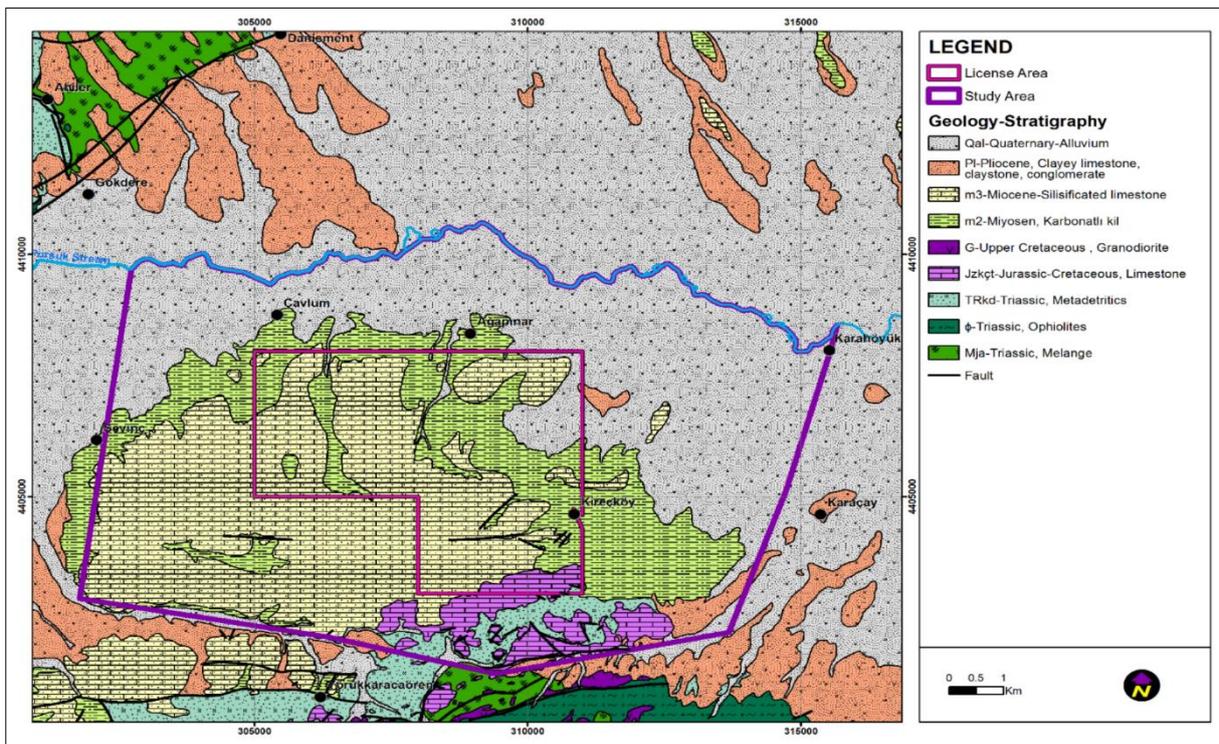
24 The quality of lignite was investigated previously by Turkey General Directorate of Mineral  
25 Research and Exploration (MTA) and the results show that calorific value varies between 1500  
26 kcal/kg and 3000 kcal/kg with the 2050 kcal/kg average. The average values for moisture  
27 content, ash, volatile matter, fixed carbon, and sulphur are 34%, 32%, 21%, 13%, and 1.5%,  
28 successively (Senguler 2013).

29 Alpu lignite field consists of three main seams named as seam-A, seam-B, and seam-C  
30 according to the exploration study. The thickness of the seams varies between 10 m and 30 m  
31 for seam-A, 0.5 m to 1.5 m for seam-B, and 2 m to 4 m for seam-C. Seams are located in 205  
32 m to 450 m depth. It was decided that LTCC is designed as the mechanized longwall mining

1 method for seam-A while conventional mechanized longwall mining method is selected for  
2 seam-C.

### 3 3. Geotechnical Investigations for the Mine Site

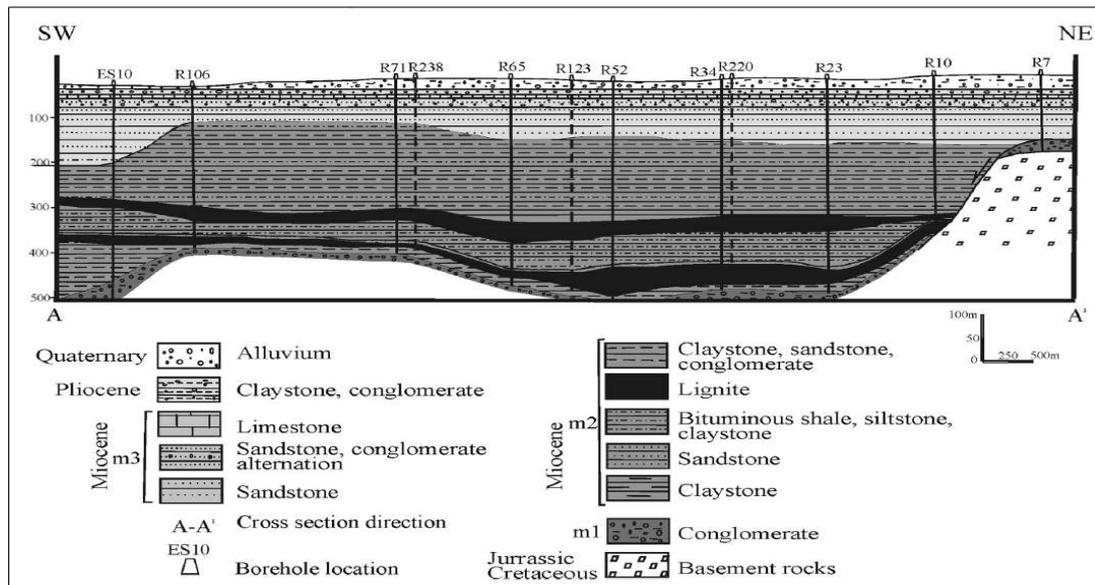
4 Geotechnical classification of coal and surrounding rock masses are performed as the first step  
5 of geotechnical database construction. Four numbers of geotechnical boreholes were used to  
6 proceed with rock mechanics works. First of all, materials were categorized as soil and rock. If  
7 the materials' strength is less than 1 MPa, that is defined as soil and a different procedure  
8 applied for sampling during the drilling works. Then, soil samples were taken as undisturbed  
9 while rock samples were determined separately. The general layout for geotechnical  
10 classification of coal and surrounding strata based on lithology and location of the material  
11 according to the coal seams were presented in Table 1. Intact rock and rock mass properties  
12 were then quantified from the site and the laboratory studies.



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Fig. 2 Geological map of the study area (Yazicigil 2016).



**Fig. 3** Geological cross-section (Senguler 2013).

**Table 1** The general layout of lignite seams and surrounding strata

Geotechnical Classification	Lithology	Abbreviations	Material Type
Seam A roof claystone	Clay & Claystone	SAR	Rock & Soil
Seam A	Lignite	SA	Rock
Seam A Intermediate	Clay & Claystone	SAI	Rock & Soil
Seam A floor claystone	Clay & Claystone	SAF	Rock & Soil
Roof shale	Shale	RSha	Rock
Seam B	Lignite	SB	Rock
Floor shale	Shale	FSha	Rock
Sandstone	Sandstone	SS	Rock & Soil
Seam C roof claystone	Claystone	SCR	Rock
Seam C	Lignite	SC	Rock
Seam C floor claystone	Clay & Claystone	SCF	Rock & Soil

### 3.1. Intact Rock and Soil Quantification

Mechanical and physical properties of the soil and the rock were determined from a series of laboratory tests. Uniaxial and triaxial compression tests, indirect tensile tests, slake durability tests, and physical properties determination tests were applied to the rock samples. Sieve analyses, unconfined compression and undrained unconsolidated triaxial, and direct shear tests were applied to the soil samples.

Uniaxial compressive strength, modulus of elasticity, Poisson's ratio, cohesion, internal friction angle, and Brazilian tensile strength were determined as mechanical properties of intact rock. The average values of the test results are presented in Table 2. Physical properties and slake durability index values can be seen in Table 3.

1 The results are quite interesting due to its very low values. All materials apart from the  
 2 geotechnical classifications are in very low strength. Materials were dispersed in water during  
 3 physical tests except for roof claystone of seam-A and lignite of seam-B. Floor claystone for  
 4 both seam-A and seam-B are very sensitive to water according to the slake durability test  
 5 results. The strength properties of lignite in each seam are also in very poor qualities according  
 6 to the mechanical and physical tests of intact rock.

7 Brief information can be found in Table 4 regarding soil mechanics tests. Soils are mostly found  
 8 in clay content strata in the roof, intermediate zone, floor of seam-A, and seam-B's floor. Some  
 9 parts of sandstone also demonstrate soil properties. The results are critical especially for floor  
 10 clay materials due to their high value of plasticity index that signaled swelling issues.

11 **Table 2** Average mechanical properties of intact rock based on geotechnical classifications  
 12 (Jangara 2017)

<b>Definition</b>	<b>Cohesion (MPa)</b>	<b>Internal Friction Angle (°)</b>	<b>Brazilian Tensile Strength (MPa)</b>	<b>Uniaxial Compressive Strength (MPa)</b>	<b>Elastic Modulus (MPa)</b>	<b>Poisson's Ratio</b>
SAR Claystone	0.64	43.3	0.54	1.5	265	0.28
SA Lignite	0.90	29.9	0.28	3.4	583	0.25
SA Intermediate	0.11	18.9	0.21	1.8	200	0.18
SAF Claystone	0.20	44.0	0.28	5.5	1377	0.24
SB Shale	1.76	30.1	1.22	5.7	364	0.19
SB Lignite	0.90	29.9	1.17	8.8	678	0.33
Sandstone	1.11	38.6	0.32	3.8	998	0.34
SCR Claystone	-	-	0.30	2.2	566	0.35
SC Lignite	0.90	29.9	0.87	5.8	551	0.26
SCF Claystone	0.00	21.4	1.15	5.1	1384	0.26

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1 **Table 3** Average physical properties of intact rock based on geotechnical classifications  
 2 (Jangara 2017)

Definition	Unit Volume Weight (kN/m <sup>3</sup> )	Slake Durability Index (I <sub>d2</sub> ) (%)	Slake Durability Classification		Porosity (%)	Water Content (%)	Water Absorption (%)
			ASTM D 4644	Gamble (1971)			
Seam A roof claystone	20.04	74.03	Type 2 & 3	Medium	26.50	17.96	13.83
Seam A	15.20	-	-	-	<i>Samples dispersed in water</i>		
Seam A Intermediate	14.82	55.23	Type 2 & 3	Medium to Low	<i>Samples dispersed in water</i>		
Seam A floor claystone	20.41	46.10	Type 1 & 2	Very Low to High	<i>Samples dispersed in water</i>		
Shale	13.56	91.74	Type 1 & 2	Medium to Very High	<i>Samples dispersed in water</i>		
Seam B	13.66	-	-	-	32.19	11.04	23.79
Sandstone	21.81	41.35	Type 1 & 3	Medium to Very Low	<i>Samples dispersed in water</i>		
Seam C roof claystone	20.96	-	-	-	<i>Samples dispersed in water</i>		
Seam C	13.11	-	-	-	<i>Samples dispersed in water</i>		
Seam C floor claystone	21.53	34.05	Type 2 & 3	Low to Very Low	<i>Samples dispersed in water</i>		

3  
 4 **Table 4** Average soil properties based on geotechnical classifications (Jangara 2017)

Definition	Natural Water Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Unified Soil Classification System	Unit Weight (kN/m <sup>3</sup> )	Internal Friction Angle (°)	Cohesion (kPa)
SAR Claystone	29.2	72.2	29.4	43	CH - MH	17.7	12.0	78.0
SA Intermediate	23.0	73.7	26.7	47	CH	18.6	23.2	57.3
SAF claystone	24.0	51.0	28.0	31	CH	17.0	15.0	32.0
Sandstone	14.0	33.0	18.0	15	SC	20.3	45.0	111.0
SCF Claystone	22.8	71.8	26.8	45	CH - SC	19.4	21.5	109.0

5

6

1 **3.2. Rock Mass Properties**

2 Rock mass properties are characterized by the rock mass rating system proposed by Bieniawski  
3 (1976). Required data determined from geotechnical boreholes are presented in Table 5. The  
4 average value of rating and calculated RMR are given for each rock mass in Table 6.  
5 Groundwater conditions assume as dripping for all rock masses. The results proved that the  
6 quality of rock masses are mostly classified as poor except for floor claystone of seam-A, roof  
7 claystone seam-C, seam-B, and sandstone in seam-C roof.

8 **4. Mechanized Longwall Mine Design Studies**

9 Geotechnical studies of lignite seams and surrounding strata present that the quality of the rock  
10 materials, soil materials and rock masses are very poor in strength. These results increase the  
11 importance of design studies for mechanized longwall systems. Caving behavior of roof strata,  
12 hydraulic shield working resistance, and required floor bearing capacity were investigated for  
13 the applicability of LTCC and conventional mechanized longwall mining systems. A LTCC  
14 was designed for two different alternatives in seam-A, and a conventional mechanized longwall  
15 system was designed for seam-C.

1 **Table 5** Average properties of rock masses (Jangara 2017)

Definition	UCS (MPa)	RQD	Joint spacing (mm)	Persistence	Separation	Roughness	Infilling	Weathering
SAR Claystone	1.47	32.7	66.67	1-3 m	0.1-10 mm	Slightly rough	Soft Filling <5 mm	Highly Weathered
SA Lignite	3.43	29.7	94.67	1-3 m	<0.1 mm	Smooth	None	Moderately weathered
SAF claystone	7.23	26.7	70.00	3-10 m	0.1-10 mm	Slightly rough	Soft Filling <5 mm	Highly Weathered
SB Shale	5.87	58.0	133.67	1-3 m	<0.1 mm	Slightly rough	None	Slightly weathered
SB Lignite	8.80	32.3	135.00	3-10 m	<0.1 mm	Slightly rough	None	Slightly weathered
SB Shale	5.87	46.3	103.00	1-3 m	<0.1 mm	Slightly rough	None	Slightly weathered
SCR Claystone	4.00	63.7	215.33	1-3 m	<0.1 mm	Slightly rough	Soft Filling <5 mm	Moderately weathered
Sandstone	4.93	34.7	110.33	1-3 m	0.1-10 mm	Slightly rough	Soft Filling <5 mm	Slightly weathered
SC Lignite	1.77	16.0	87.67	3-10 m	0.1-10 mm	Slightly rough	Soft Filling <5 mm	Slightly weathered
SCF Claystone	0.20	16.7	40.67	1-3 m	0.1-10 mm	Slightly rough	Soft Filling <5 mm	Moderately weathered

2 **Table 6** Average rating and RMR values for rock masses (Jangara 2017)

Definition	UCS (MPa)	RQD	Joint spacing	Persistence	Separation	Roughness	Infilling	Weathering	Groundwater	RMR	Rock Mass Class
SAR Claystone	0.7	6.3	7	2.7	4	3	2	1	4	30.7	Poor rock
SA Lignite	1	6.3	7	2.7	5	1	6	3	4	36	Poor rock
SAF claystone	1.7	6.3	7	2	4	3	2	1	4	31	Poor rock
SB Shale	2	11.3	8	4	5	3	6	5	4	48.3	Fair rock
SB Lignite	2	6.3	7.7	2	4.7	3	6	5	4	40.7	Poor rock
SB Shale	2	9.7	8	4	5	3	6	5	4	46.7	Fair rock
Sandstone	1.3	11.3	7	4	4.7	3	2	4.3	4	41.7	Fair rock
SCR Claystone	1	13	10	4	5	3	2	3	4	45	Fair rock
SC Lignite	1.7	4.7	8	2	4	3	3.3	5	4	35.7	Poor rock
SCF Claystone	0.3	4.7	7	2.7	4	3	2	3	4	30.7	Poor rock

3

1 **4.1. Caving Behavior of Roof**

2 Beside the rock mass classification results which Seam-A and Seam-C roof materials are  
 3 classified as poor and fair rock by RMR system (Table 6), rock quality index (L) and coal mine  
 4 roof rating (CMRR) were used to understand and characterize the caving behaviour of the roof  
 5 strata. Rock quality index (L) proposed by Bilinski and Konopko (1973) is used to classify roof  
 6 caving behavior. L is calculated by Equation 1. C is the compressive strength of roof rock while  
 7  $K_1$  is the in situ strength coefficient,  $K_2$  is the creep coefficient, and  $K_3$  is the in situ water  
 8 content coefficient.  $K_1$  is taken as 0.33 for sandstone, 0.42 for mudstone, and 0.5 for claystone  
 9 or siltstone. Similarly,  $K_2$  can be assumed as 0.7 for sandstone and 0.6 for mudstone, claystone,  
 10 or siltstone. Finally,  $K_3$  is 0.6 for sandstone, 0.4 for claystone and mudstone with 50% relative  
 11 humidity.

$$L = 0.0064C^{1.7}K_1K_2K_3 \tag{1}$$

12  
 13 The condition of the longwall roof can be classified according to the value of L (Mangal and  
 14 Paul 2016). Seam-A's roof, seam-A, and seam-C's roof classified and the average results of  
 15 rock quality index and roof classification presented in Table 7. The results present the  
 16 problematic behavior of roof strata for all conditions.

17 **Table 7** Roof strata classification based on rock quality index

Definition	L	Roof Class	Description of Roof Strata	Allowable Area of Exposed Roof
SAR Claystone	0.08	I	Very week, immediate fall of	Approx. 1m <sup>2</sup>
SA Lignite	0.40	I	roof when exposed. Coal	
SCR Claystone	0.02	I	tops recommended for	
Sandstone	0.62	I	safety. Wet, stratified with coal bands clay stone	

18 Apart from roof classification from the rock quality index, CMRR can also be used for a better  
 19 understanding of the actual conditions. CMRR, which is used mostly for bedded coal measure  
 20 rock, is currently applied for different purposes in mine planning such as longwall pillar design,  
 21 roof support selection, and feasibility studies (Molinda et al. 2001).

22 Geotechnical borehole logging or underground face mapping can be used to gather required  
 23 data for CMRR. Rating for the calculation of CMRR is well described by Mark and Molinda  
 24 (2005) and the roof is classified in three ways that are weak, moderate, and strong. Laboratory  
 25 test results and RQD values are used to obtain CMRR scores in Alpu lignite field.

1 Due to the low strength of the rock materials in any location of the lignite field, CMRR rating  
2 is taken as 5 for compressive strength. Rating for discontinuity spacing is calculated by  
3 Equation 2 from RQD. Finally, the overall rating is deducted due to the moisture sensitivity of  
4 the strata. Moisture sensitivity adjustment rating was determined from the slake durability index  
5 of the material. Ratings and the results of the CMRR are presented in Table 8. The results are  
6 similar to the rock quality index's results and roof strata is classified as weak in every type of  
7 the strata.

$$8 \quad DSR = 10.5 \ln (RQD) - 11.6 \quad (2)$$

9 where DSR is discontinuity spacing rating.

#### 10 **4.2. Hydraulic Shield Support and Floor Bearing Capacity for Seam-A**

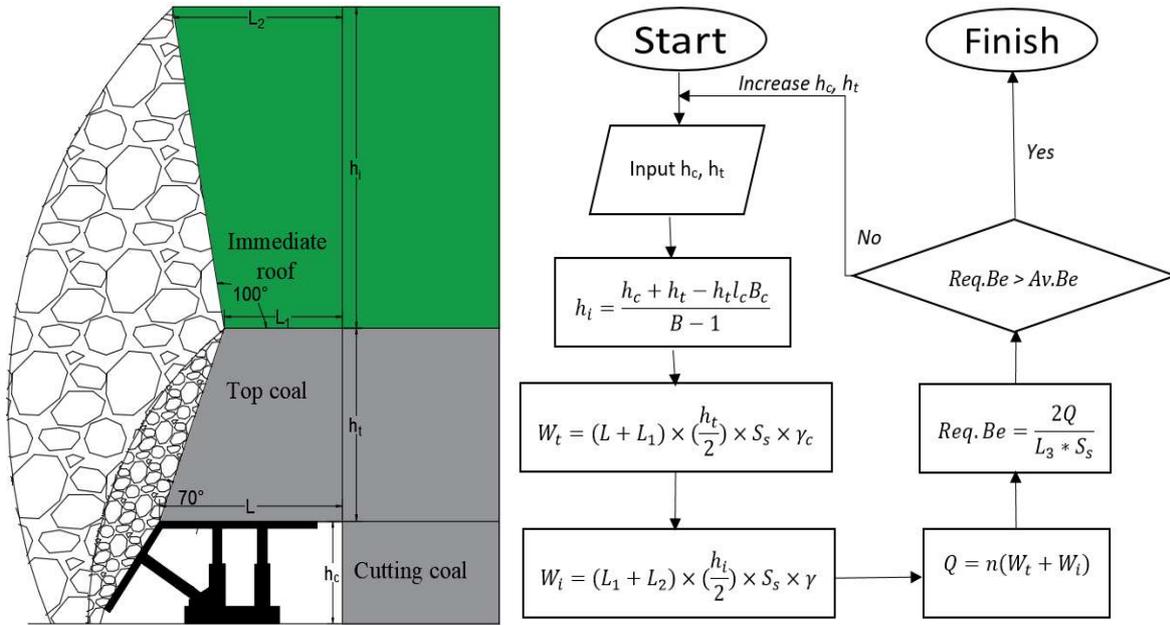
11 Top coal heights are generally three times higher than mining height. Some mines in China  
12 reached a successful geometry to increase mining height for LTCC (Wang et al. 2015).  
13 Similarly, the use of LTCC for dip angle's seams studied and drawing parameters proposed to  
14 improve top coal recovery (Wang et al. 2020). The only good side of the very poor surrounding  
15 rock strata condition for Alpu lignite field is the high cavability of the roof, which will be  
16 helpful for assumed LTCC method. On the other hand, weak materials in base reduce the  
17 bearing capacity of the floor, which can act as a limitation in work resistance of the hydraulic  
18 shield and mining height.

19 Wang et al. (2017) proposed three plies in top coal theory and categorized top coal as “granular  
20 ply”, “bulk ply” and “cracked beam ply” based on the different fracture and caving features of  
21 a lower, middle, and upper ply of top coal in ultra-thick seam. However, in some conditions,  
22 there is only one ply or two plies, depending on the factors such as top coal's thickness, strength,  
23 fracture development, and crustal stress. The top coal portion in the study area is assumed as  
24 one-ply (granular ply) depending on the low strength of the lignite. The high cavability of the  
25 lignite seams reduces top coal thickness in the result of the low floor bearing capacity.

26 There are different methods that can be used to apply for hydraulic shield design such as  
27 detached roof block method, shield leg pressure measurement method, design of powered  
28 support selection model, and yielding foundation model. The existing geotechnical data allows  
29 applying detached roof block model for the study area, which is outlined in Fig. 4. The  
30 parameters used in the method are presented in Table 9, separately. The parameters used in the  
31 design studies are summarized in Table 10 that are determined from coal and surrounding strata  
32 geotechnical properties. [Hydraulic shields' technical specifications can be seen in Table 11 that](#)

1 are collected from the machine and equipment specifications of hydraulic shields, AFC  
 2 conveyor, and shearer are determined from the available equipment in mining industry.

3 The very poor strength of the roof and floor causes to search for different production  
 4 alternatives. Three alternatives were performed in seam-A which are named as LTCC and  
 5 sublevel production, LTCC and sublevel production with pillar, and sublevel conventional  
 6 mechanized longwall mining. The alternatives are illustrated in Fig. 5.



7  
 8 **Fig. 4** Detached block method application parameters and rules (Jangara et al. 2018).

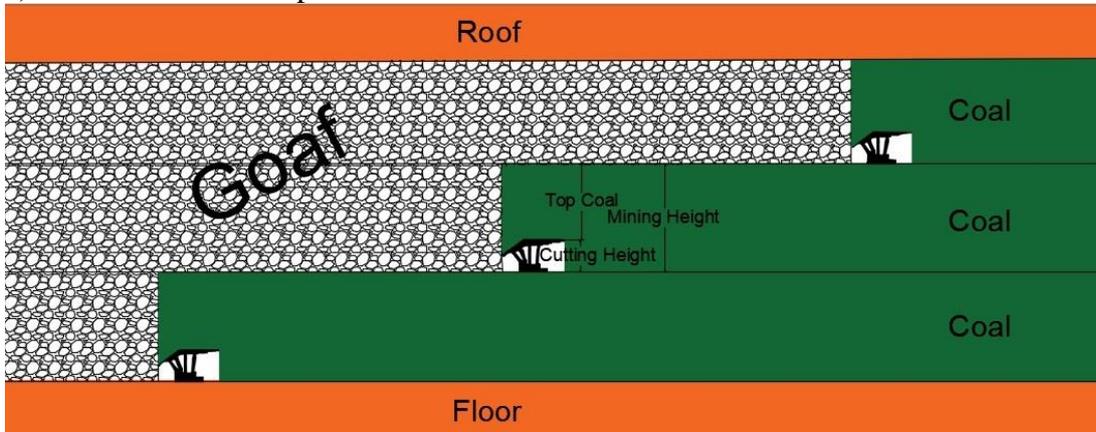
9 The calculations performed to understand the availability of mining heights is the sum of cutting  
 10 (mining) and top coal heights based on the bearing capacity of the floor. Available bearing  
 11 capacity is taken as the average uniaxial compressive strength of the floor materials. It was  
 12 taken as 3.4 MPa for coal and 5.5 MPa for seam-A floor claystone. The results were determined  
 13 from the design studies, which are presented in Table 12.

14 In the second alternative, the upper part of seam-A that contains a lower calorific value (less  
 15 than 1000 kcal/kg) according to the exploration study leaves as a pillar. This helps to decrease  
 16 the amount of weight in the immediate roof that also decreases the load on the hydraulic shield.  
 17 The thickness of the pillar was assumed as 5 m. The same calculation procedure was also  
 18 applied for the second alternative and the results are presented in Table 13.

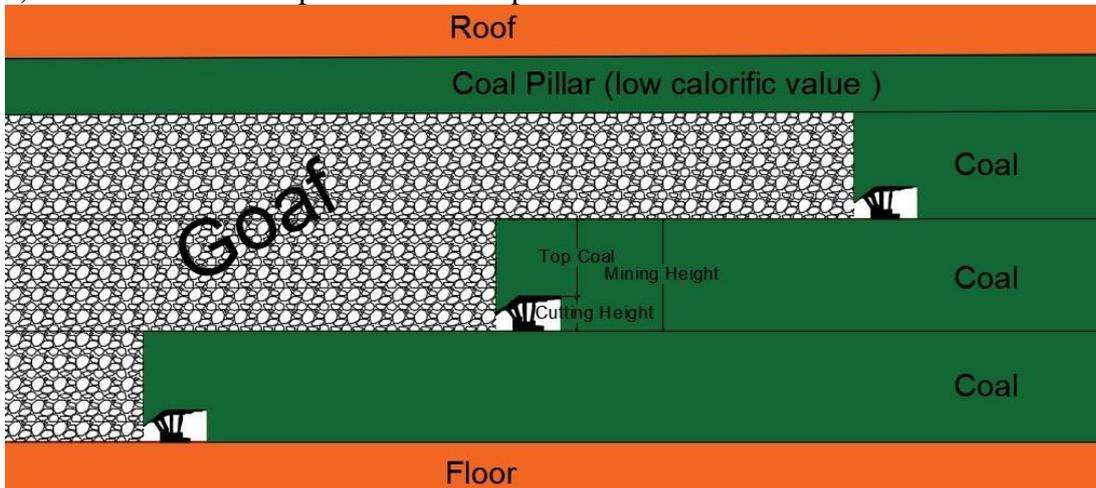
19 Finally, the third alternative was applied for the design of conventional mechanized longwall  
 20 mining application in case of the unavailability of the LTCC method. The production will also  
 21 be applied in sublevels. In other words, slices and the production are only performed in advance

1 instead of the top coal. Different mining heights were studied again and the results are presented  
 2 in Table 14. According to the bearing capacity of the floor for both coal and claystone, the  
 3 available height can be changed from 2 m to 4 m as per the analyses.

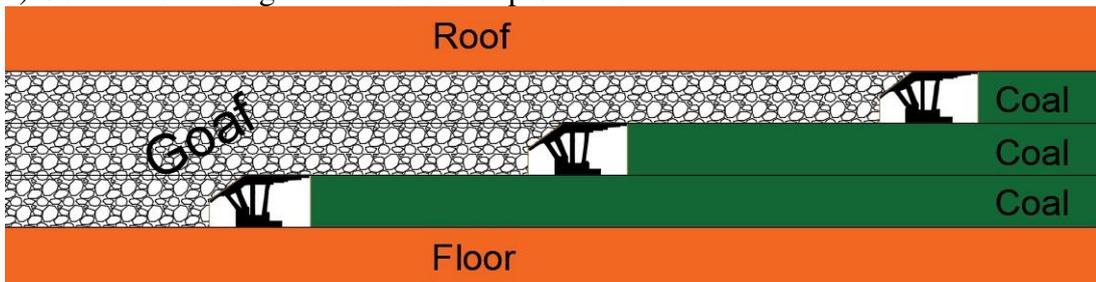
4 a) LTCC and sublevel production



5  
 6 b) LTCC and sublevel production with pillar



7  
 8 c) Conventional longwall and sublevel production



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 12 **Fig. 5** Production alternatives for seam-A (Jangara 2017).  
 13

1

**Table 8** CMRR of roof strata and seam-A

Definition	Average Values of			Ratings for CMRR			Average Values for CMRR		Roof Classification
	$\sigma_c$ (MPa)	RQD (%)	Slake Durability Index (%)	$\sigma_c$	Discontinuity Rating	Moisture Sensitivity	Without Moisture Effect	With Moisture Effect	
SAR Claystone	1.47	32.67	76.20	5.00	24.17	-12.33	29.17	16.83	Weak
SA Lignite	3.43	29.67	-	5.00	22.97	-7.00	27.97	20.97	Weak
SB Shale	5.87	46.33	92.60	5.00	28.57	-4.33	33.57	29.23	Weak
Sandstone	4.07	60.00	41.35	5.00	31.27	-12.33	36.27	23.93	Weak
SCR Claystone	0.60	74.00	-	5.00	33.60	-15.00	38.60	23.60	Weak

2

3

**Table 9** Parameter descriptions in the method

4

Parameter	Unit	Description	Parameter	Unit	Description
$h_t$	m	Coal cutting height	$L_2$	m	Immediate roof upper boundary length
$h_c$	m	Top coal height	$L_1$	m	Top coal upper boundary length
$h_i$	m	Immediate roof height	$\gamma$	kN/m <sup>3</sup>	Immediate roof unit volume weight
B	-	Bulking factor	$W_i$	kN	Immediate roof block weight
$B_c$	-	Coal bulking factor	n	-	Safety factor
$l_c$	-	Top coal loose rate	$S_c$	m	Distance between center of two shields
$W_t$	kN	Top coal block weight	$\gamma_c$	kN/m <sup>3</sup>	Coal unit volume weight
L	m	Working length in face	Req.Be	kN/m <sup>2</sup>	Floor required bearing capacity
Q	kN	Support capacity	Av.Be	kN/m <sup>2</sup>	Floor available bearing capacity
$L_3$	m	Support shield base length			

**Table 10** Parameter values applied in the method (Jangara et al. 2018)

<b>Parameter</b>	<b>Unit</b>	<b>Value</b>
SAR Claystone bulking factor	-	1.3
Lignite bulking factor	-	1.4
Sandstone bulking factor	-	1.3
Immediate roof falling angel	(°)	10
Top coal falling angel	(°)	20
Sandstone unit weight	(kN/m <sup>3</sup> )	21.81
SAR Claystone unit volume weight	(kN/m <sup>3</sup> )	20.04
Coal unit volume weight	(kN/m <sup>3</sup> )	15.2
Top coal loose rate	-	20%
Safety factor	-	2.0

**Table 11** LTCC working face parameters (Jangara et al. 2018)

<b>Parameter</b>	<b>Unit</b>	<b>Value</b>
Shield support distance (S <sub>s</sub> )	(m)	1.6
Shield base length (L <sub>3</sub> )	(m)	3.0
Shield canopy length	(m)	5.0
Width of cut (Web)	(m)	0.8
Tip to Face	(m)	0.8
Rear overhang	(m)	0.0

**Table 12** Required shield and floor bearing capacity in sublevel LTCC for different mining height, Seam-A (Jangara 2017)

Mini ng height	Imme diate roof height	Cutti ng height	Top coal height	Detach ed roof weight	Shield capacit y	Average required bearing capacity at the base	Maximum required bearing capacity at the base	Available bearing capacity
(m)	(m)	(m)	(m)	(kN)	(kN)	(MPa)	(MPa)	(MPa)
5	13.9	2.00	3.00	3,434	6,869	1.43	2.86	3.4
	14.1	2.25	2.75	3,501	7,003	1.46	2.92	
	14.3	2.50	2.50	3,569	7,139	1.49	2.97	
	14.6	2.75	2.25	3,639	7,277	1.52	3.03	
	14.8	3.00	2.00	3,709	7,418	1.55	3.09	
	15.0	3.25	1.75	3,781	7,561	1.58	3.15	
	15.3	3.50	1.50	3,853	7,706	1.61	3.21	
	16.5	2.00	4.00	4,071	8,142	1.70	3.39	
6	16.8	2.25	3.75	4,144	8,289	1.73	3.45	3.4
	17.0	2.50	3.50	4,219	8,438	1.76	3.52	
	17.2	2.75	3.25	4,294	8,588	1.79	3.58	
	17.4	3.00	3.00	4,371	8,741	1.82	3.64	
	17.6	3.25	2.75	4,448	8,896	1.85	3.71	
	17.8	3.50	2.50	4,526	9,053	1.89	3.77	
	26.4	2.00	8.00	6,093	12,186	2.54	5.08	
	26.6	2.25	7.75	6,206	12,412	2.59	5.17	
10	26.8	2.50	7.50	6,320	12,640	2.63	5.27	5.5
	27.1	2.75	7.25	6,435	12,870	2.68	5.36	
	27.3	3.00	7.00	6,551	13,102	2.73	5.46	
	27.5	3.25	6.75	6,668	13,336	2.78	5.56	
	27.7	3.50	6.50	6,786	13,572	2.83	5.66	

**Table 13** Required shield and floor bearing capacity in sublevel LTCC with a pillar for different mining height, Seam-A (Jangara 2017)

<b>Mining height</b>	<b>Immediate roof height</b>	<b>Cutting height</b>	<b>Top coal height</b>	<b>Detached roof weight</b>	<b>Shield capacity</b>	<b>Average required bearing capacity at the base</b>	<b>Maximum required bearing capacity at the base</b>	<b>Available bearing capacity</b>
<b>(m)</b>	<b>(m)</b>	<b>(m)</b>	<b>(m)</b>	<b>(kN)</b>	<b>(kN)</b>	<b>(MPa)</b>	<b>(MPa)</b>	<b>(MPa)</b>
5	13.9	2.00	3.00	3,174	6,347	1.32	2.64	3.4
	14.1	2.25	2.75	3,236	6,473	1.35	2.70	
	14.3	2.50	2.50	3,300	6,600	1.38	2.75	
	14.6	2.75	2.25	3,365	6,730	1.40	2.80	
	14.8	3.00	2.00	3,431	6,862	1.43	2.86	
	15.0	3.25	1.75	3,498	6,997	1.46	2.92	
	15.3	3.50	1.50	3,567	7,133	1.49	2.97	
	16.3	2.00	4.00	3,748	7,495	1.56	3.12	
6	16.5	2.25	3.75	3,820	7,640	1.59	3.18	3.4
	16.7	2.50	3.50	3,893	7,787	1.62	3.24	
	17.0	2.75	3.25	3,968	7,936	1.65	3.31	
	17.2	3.00	3.00	4,044	8,087	1.68	3.37	
	17.4	3.25	2.75	4,121	8,241	1.72	3.43	
	17.7	3.50	2.50	4,199	8,397	1.75	3.50	
10	25.9	2.00	8.00	5,720	11,440	2.38	4.77	5.5
	26.1	2.25	7.75	5,831	11,662	2.43	4.86	
	26.3	2.50	7.50	5,943	11,886	2.48	4.95	
	26.6	2.75	7.25	6,056	12,113	2.52	5.05	
	26.8	3.00	7.00	6,171	12,342	2.57	5.14	
	27.0	3.25	6.75	6,286	12,573	2.62	5.24	
	27.3	3.50	6.50	6,403	12,806	2.67	5.34	

1

**Table 14** Required shield and floor bearing capacity in sublevel longwall, Seam-A (Jangara 2017)

<b>Immediate roof height</b>	<b>Mining height</b>	<b>Detached roof weight</b>	<b>Shield capacity</b>	<b>Average required bearing capacity at the base</b>	<b>Maximum required bearing capacity at the base</b>	<b>Available bearing capacity</b>
(m)	(m)	(kN)	(kN)	(MPa)	(MPa)	(MPa)
6.7	2.0	1,536	3,073	0.64	1.28	
8.3	2.5	1,960	3,920	0.82	1.63	
10.0	3.0	2,399	4,798	1.00	2.00	3.4/5.5
11.7	3.5	2,854	5,707	1.19	2.38	
13.3	4.0	3,324	6,648	1.39	2.77	

2

### 4.3. Hydraulic Shield Support and Floor Bearing Capacity for Seam-C

Seam-C thickness varies between 2.5 m and 4 m roof and floor strata forms by sandstone and claystone. Conventional mechanized longwall mining method, which is also the combined system of hydraulic shields, AFC conveyor, and shearer, designed for seam-C. Roof strata is classified similarly as seam-A and it is classified as high cavability. Floor material that is mostly claystone has different compressive strengths from 0.3 MPa to 34.5 MPa and the average strength is 5.1 MPa. Detached roof method was also applied for the design and the results are presented in Table 15.

**Table 15** Required shield and floor bearing capacity in different cutting height, seam-C (Jangara 2017)

Immediate roof height	Mining height	Detached roof weight	Shield capacity	Average required bearing capacity at the base	Maximum required bearing capacity at the base	Available bearing capacity
(m)	(m)	(kN)	(kN)	(MPa)	(MPa)	(MPa)
6.7	2	1,672	3,344	0.70	1.39	
8.3	2.5	2,133	4,266	0.89	1.78	
10.0	3	2,611	5,222	1.09	2.18	5.1
11.7	3.5	3,106	6,211	1.29	2.59	
13.3	4	3,618	7,236	1.51	3.01	

### 4.4. Evaluations and Discussions

Different production alternatives were investigated for mechanized longwall design in seam-A and seam-C. The outputs of the design studies were discussed below.

Sublevels, which are also called as slices in a longwall panel, are projected in seam-A. The LTCC method was implemented in different alternatives for the production. The average compressive strength of lignite and floor claystone is 3.4 MPa and 5.5 MPa, respectively. The maximum height of one slice is 6 m where cutting height 2 m, and top coal height is 4 m. The total height of the third slice where the floor is claystone can be 10 m, and the cutting height is 3 m. Hence, the total producible thickness for Seam-A reaches up to 22 m in three slices. The second alternative is to leave the pillar in the upper slice to decrease the weight on the hydraulic shields. The results are similar for the second production alternative in seam-A. The only difference is the cutting height that can be increased to 3 m for the sublevels in lignite where the maximum height of the slice can be 6 m. Similarly, the maximum height is 10 m and the

1 cutting height can be taken up to 3.5 m and the top coal is 6.5 m high for the third slice. This  
2 application will decrease the amount of production loss. Finally, the application of conventional  
3 mechanized longwall mining results as the third alternative show that the mining height can be  
4 taken up to 4 m, and three sublevels can be projected up to 12 m coal thickness.

5 The same procedure was applied for seam-C. The producible thickness can be design as 4 m by  
6 conventional mechanized longwall mining method based on the average floor bearing capacity,  
7 which is 5.1 MPa.

8 Recovery rate of top coal limits the applicability of fully mechanized production in longwall  
9 mining in terms of economic aspects. Higher strength of coal and surrounding strata increases  
10 the recovery rate however, it is very low in this case, so the recovery rate of top coal will be  
11 low. Resource modelling and mine design and planning studies should be considered based on  
12 the geotechnical properties and the low rate for recovery especially leaving pillar for strength  
13 requirement needs to be taken care of. The very low strength of the strata also limits  
14 applicability of different drawing and cutting alternatives in the longwall. It's clear that one  
15 advance and one drawing alternative should be the most suitable one for LTCC production  
16 alternative as proposed by Wang et al. (2015).

17 The ground condition for all seams' floor in the study area is in very low bearing capacity. The  
18 design was performed based on the average value of floor material compressive strength,  
19 however, the value was sometimes very low or the material was classified as the soil in some  
20 locations. Thus, geotechnical conditions were assumed as the weakest link for the site and once  
21 the production panel was projected and a geotechnical study must be conducted to understand  
22 the distribution of floor bearing capacity for the applicability of mechanized mining. This  
23 application should be applied for the entire production schedule at Alpu lignite field. Therefore,  
24 the amount of reserve that is defined as the producible amount of mine resource is totally related  
25 to the ground stability of coal seams for the project site. Mine design and planning works should  
26 follow the geotechnical researches. Geo-spatial distribution of floor bearing capacity and roof  
27 strength for strata surrounding coal seams should be modelled prior to mine planning for the  
28 coal mine site similar with Alpu in terms of geotechnical properties. The longwall mine design  
29 will be projected based on the output of the research.

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## 1 5. Numerical Analyses for Ground Control

2 Floor bearing capacity and caving behavior of the roof strata are critical due to the very low  
3 strength in the study area. Similarly, wall failure and/or face spalling can be the other issues  
4 during the working of mechanized longwall machinery. Any failure will cause wasting time,  
5 injuries, or machine failures. 2D finite element method was performed as numerical analysis to  
6 understand the reliability of cutting heights proposed by analytical solutions. Different cutting  
7 heights were applied to understand the wall and face stability.

8 Mohr-Coulomb failure envelope is defined as failure criteria due to the low strength of lignite  
9 and surrounding strata. Vertical stress ( $\sigma_v$ ) for in-situ stress conditions is directly estimated from  
10 the overburden height that is a function of unit volume weight and depth. Hence, it is calculated  
11 as  $0.21H$  in MPa according to Equation 3. Horizontal stress ( $\sigma_h$ ) was assumed as equal with  
12 vertical stress due to the low strength material (Brown and Hoek 1978; Wilson 1983).

$$13 \quad \sigma_v = \gamma H \text{ MPa} \quad (3)$$

14 The complex hydrogeological structure and dewatering solutions have been studied for the  
15 mine site. The scope of dewatering studies to lower the underwater level below the mining  
16 level. Underground water level would be reduced below the mining level and numerical model  
17 was compute in dry condition according to the field and hydrogeological conditions as well as  
18 existing studies. Material properties were used in the numerical models are taken from the  
19 geotechnical database (Table 2). Goaf material properties were estimated from previous  
20 researches due to the unavailability of test material or in-situ testing during pre-feasibility  
21 studies. In order to represent field conditions, goaf properties should be simulated based on the  
22 vertical stresses on the goaf material to gain the precise results (Banerjee et al., 2015). Elastic  
23 properties of the goaf is also a function of time and experimental results can be characterized  
24 according to Equation 4 (Xie et al. 1999).

$$25 \quad E = 15 + 175(1 - e^{-1.25t}) \quad (4)$$

26 Yasitli and Unver (2005) used goaf Poisson's ratio as 0.495 for the Tuncbilek lignite field while  
27 Yavuz (2004) defined unit volume weight as  $0.017 \text{ MN/m}^3$ . Singh and Singh (2011) used unit  
28 volume weight as  $0.018 \text{ MN/m}^3$  and friction angle as  $25^0$  for goaf. Table 16 was prepared to  
29 present the goaf properties used in numerical analyses.

30

31

1

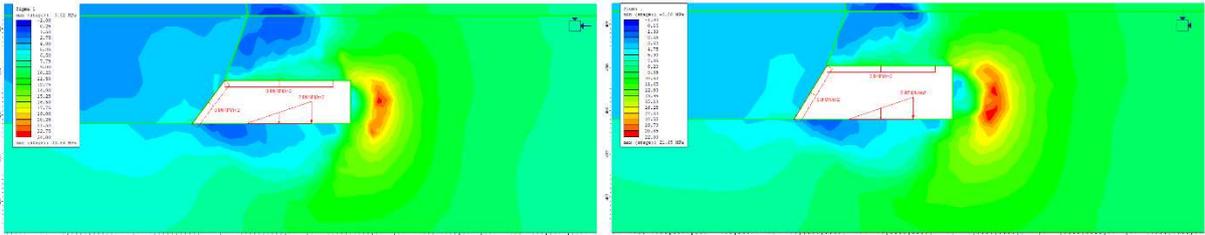
**Table 16** Goaf properties in numerical models

Unit Volume Weight (MN/m <sup>3</sup> )	Cohesion (MPa)	Friction Angel (°)	Indirect Tensile Strength (MPa)	Poisson Ratio	Modulus of Elasticity (MPa)			
					Day 1	Day 2	Day 3	Final
0.017	0.001	25	0	0.495	140	176	186	190

2 RS2 software was used to simulate the condition of the mechanized longwall for the LTCC  
3 method. Stresses, strength factors and yielded elements were taken as output of the analyses.  
4 The boundary conditions were fixed at zero. One of the finite element model was presented in  
5 Fig. 6. The mesh system was used for finite elements. Automatic mesh around the longwall was  
6 generated to model deformations and stresses that were derived from elastoplastic analyses.  
7 Numerical analyses were performed under these conditions. Normal ( $\sigma_1$ ) and horizontal stresses  
8 ( $\sigma_3$ ), strength factor (SF), and yielded elements were determined after a series of iterations of  
9 modeling studies. SF is the ratio between rock strength to induce stress that presents the  
10 adequate support systems. Stresses were investigated the effect of longwall height while SF can  
11 be used to understand caving conditions as well as stability conditions around the openings.  
12 Yielded elements were used to calculate the yielded distance through the face to understand the  
13 unsupported roof availability for the longwall. Four different cutting heights were modeled in  
14 the analyses that are 2.0 m, 2.5 m, 3.0 m, and 3.5 m. Top coal excavation was performed by  
15 caving from the rear of the longwall from hydraulic shields. The outputs of the numerical  
16 analyses, are presented in Fig. 7 for normal stress distribution, Fig. 8 for horizontal stress  
17 distribution, Fig. 9 for strength factor, and Fig. 10 for yielded elements.

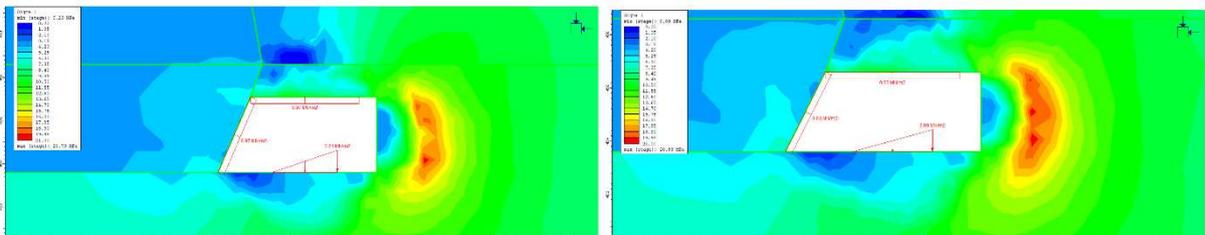
18 [In-situ stress, stress in caving zone at the rear of the shield, and stress in the cutting zone at the](#)  
19 [front of the shield can be compared from the normal stress numerical models. In-situ stress is](#)  
20 [quite similar with the virgin in-situ stress calculated by the Equation 3 and it is around 8 MPa.](#)  
21 [Stress in at the front reaches 24 MPa while it is around 3 MPa.](#) The increasing cutting height  
22 results in the increasing amount of stresses for both normal and horizontal stresses. Increasing  
23 horizontal stress will cause working face instability that limits cutting heights. Caving  
24 conditions can easily be seen in the strength factor distribution for each cutting heights. The SF  
25 values were scattered around 1.0 roof and faced of the longwall for each cutting height. Most  
26 critical outputs determined from the analyses that are the yielded elements and the yielded  
27 depths, which can be seen in Fig. 10. The depth was increased from 1.4 m to 2.5 m by the  
28 increasing value of cutting height. Unsupported span was taken as 0.80 m that is the width of a  
29 typical shearer. Once the shearer cut the face, hydraulic shields should be advanced as early as





Cutting Height: 2 m

Cutting Height: 2.5 m

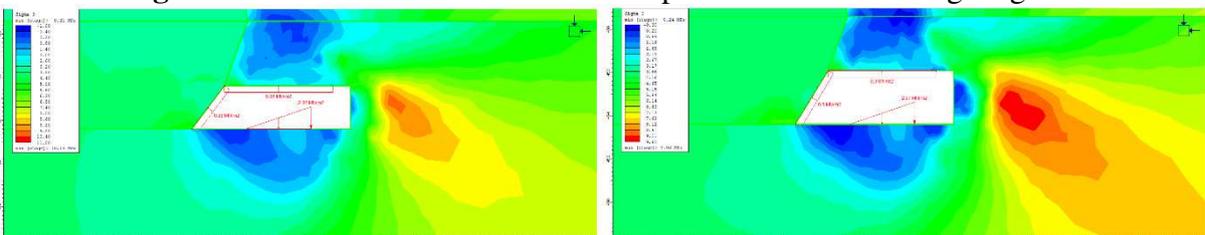


Cutting Height: 3 m

Cutting Height: 3.5 m

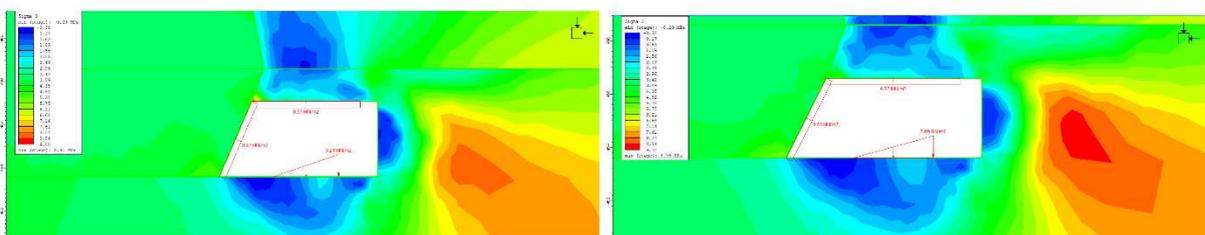
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**Fig. 7** Normal stress numerical model output for different cutting heights.



Cutting Height: 2 m

Cutting Height: 2.5 m

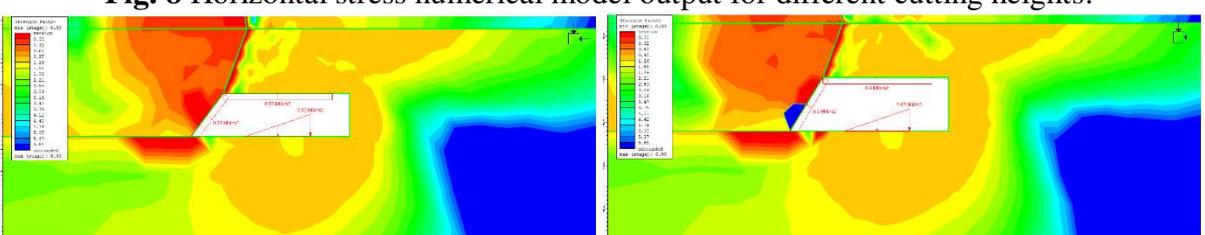


Cutting Height: 3 m

Cutting Height: 3.5 m

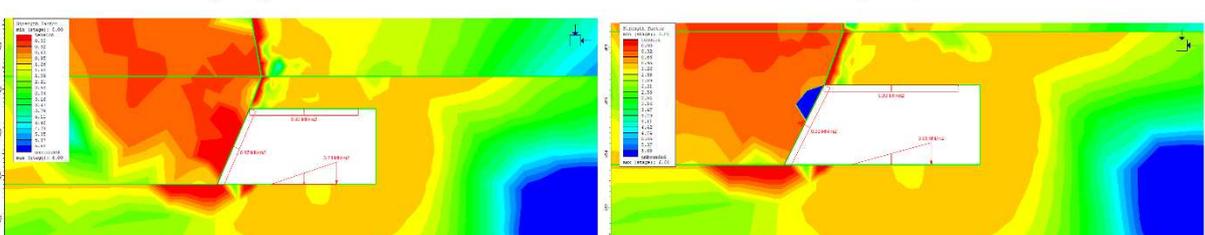
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**Fig. 8** Horizontal stress numerical model output for different cutting heights.



Cutting Height: 2 m

Cutting Height: 2.5 m



Cutting Height: 3 m

Cutting Height: 3.5 m

5  
6  
7

**Fig. 9** Strength factor numerical model output for different cutting heights.

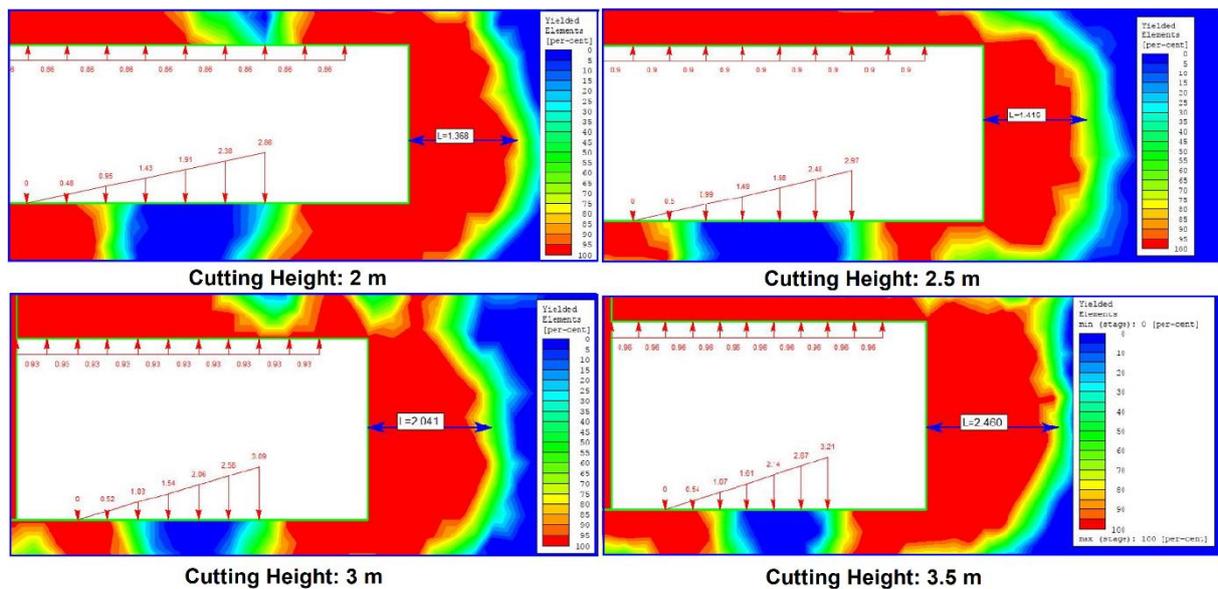


Fig. 10 Yielded element numerical model output for different cutting heights.

## 6. Conclusion

The Alpu lignite coal field with its two billion tons of resources was investigated with respect to the design of mechanized longwall mining systems. The mine site consists of three coal seams in various thicknesses called as seam-A, seam-B, and seam-C. Seam-A has thickness from 10 m to 30 m. The thickness of seam-B is up to 1.5 m while seam-C thickness reaches to 4 m. According to the feasibility studies, a LTCC mechanized system will be implemented for seam-A, and a conventional mechanized longwall mining system is designed for seam-C. Due to the threshold value of thickness, seam-B is not projected for the production. A comprehensive geotechnical analyses were carried out to understand the strength of coal and surrounding structures. The results increases the importance of geotechnical assessment of mine site for mine planning studies due to the low strength value of roof and floor structures. The following main conclusions were drawn from this study as listed below.

- According to the result of the geotechnical classifications, each lignite seam and surrounding strata were classified as very low classes in terms of strength. Rock mass classification results also revealed the condition. The very low strength of the lignite roof causes an immediate collapse in the rear side that increases the loads on the hydraulic shields. Similarly, very low strength of floor bearing capacity also limits the height of the longwall. The very low strength properties of lignite also create a hazard for roof failure and/or face spalling.

- Three different production alternatives were investigated for seam-A. Longwall production will be applied in slices from nearly 30 m thick lignite in seam-A. The height of each slice,

1 cutting, and top coal heights were designed based on the detached block method for each  
2 alternative. Numerical analyses were also performed to understand the face and roof stability  
3 during the production in LTCC. If longwall geometries are not implemented based on actual  
4 site geotechnical condition and design outputs proposed in this study, the low bearing capacity  
5 of floor might result in sinking the machinery and equipment. The low strength of the roof may  
6 also cause instability in the roof and face in longwall.

7 - Only one production alternative that is conventional fully mechanized longwall mining was  
8 applied for seam-C. Similarly, minimum bearing capacity of floor designated in this study for  
9 seam-C for a conventional mechanized longwall mining. If the strata does not meet the required  
10 minimum capacities, mechanized longwall mining cannot be applicable.

11 - The primary outcomes of the study present that Alpu lignite field will be the first example that  
12 will be designed and implemented in the weakest ground conditions among mechanized  
13 longwall mining for both LTCC and conventional mechanized longwall mining.

14 - The bearing capacity of the floor and the strength of the roof can be assumed as the parameter  
15 for threshold in reserve estimation. Once the panel location was projected in the mine,  
16 geotechnical properties of surrounding strata must be determined from a site and laboratory  
17 studies. The mine will be designed for LTCC and mechanized longwall mining in terms of  
18 cutting height, daily advance, top coal height, and sublevel heights based on the machinery and  
19 equipment specifications. If ground geotechnical features do not meet the minimum required  
20 conditions, the resource cannot be accounted for reserve due to the infeasible production. The  
21 required bearing capacity for the longwall cutting and top coal heights as well as the daily  
22 advance rate can be easily predicted based on the output of the research.

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27 for their support and their consent for the research.

### 28 **Conflict of Interest**

29 The authors wish to declare that there are no known conflicts of interest associated with this  
30 publication.

31

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# Figures

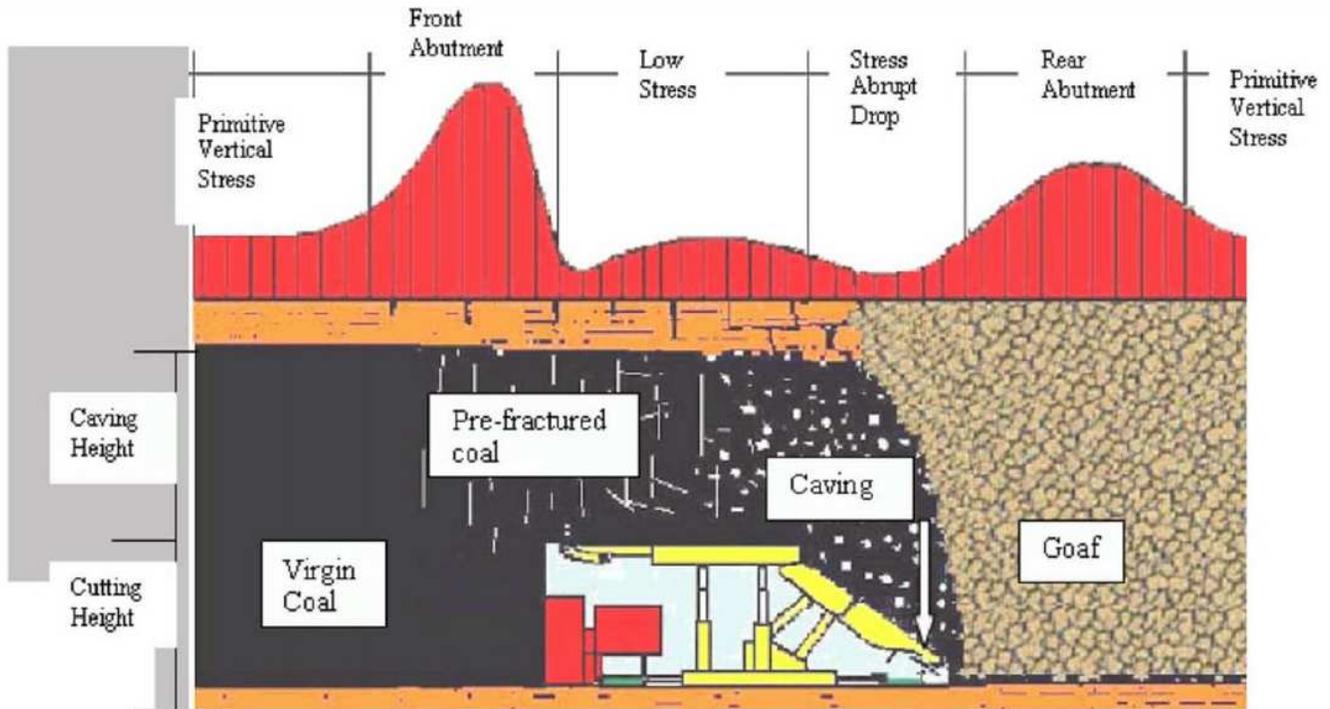


Figure 1

LTCC method (Alehossein and Poulsen 2010).



Figure 2

Project location and an aerial photo of the license area.

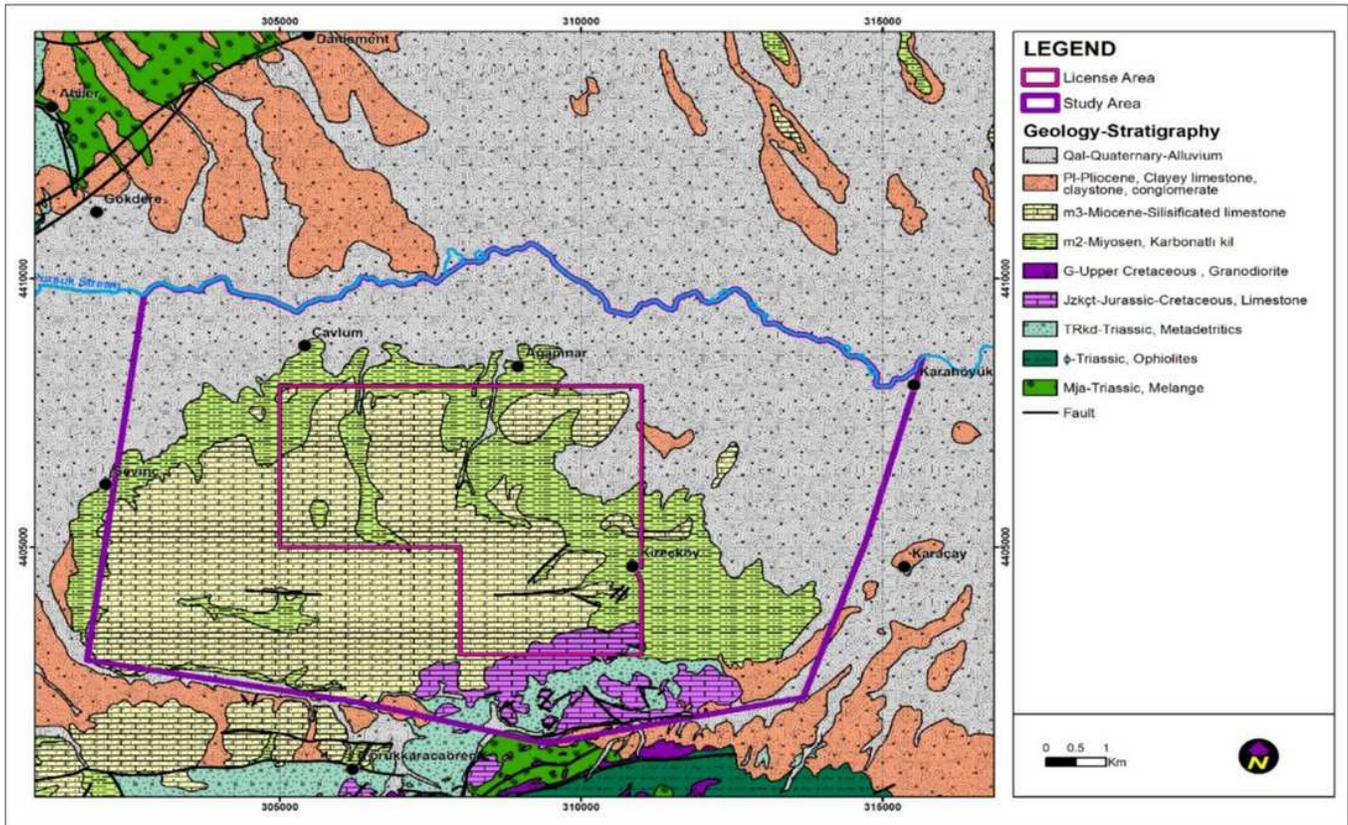


Figure 3

Geological map of the study area (Yazicigil 2016).

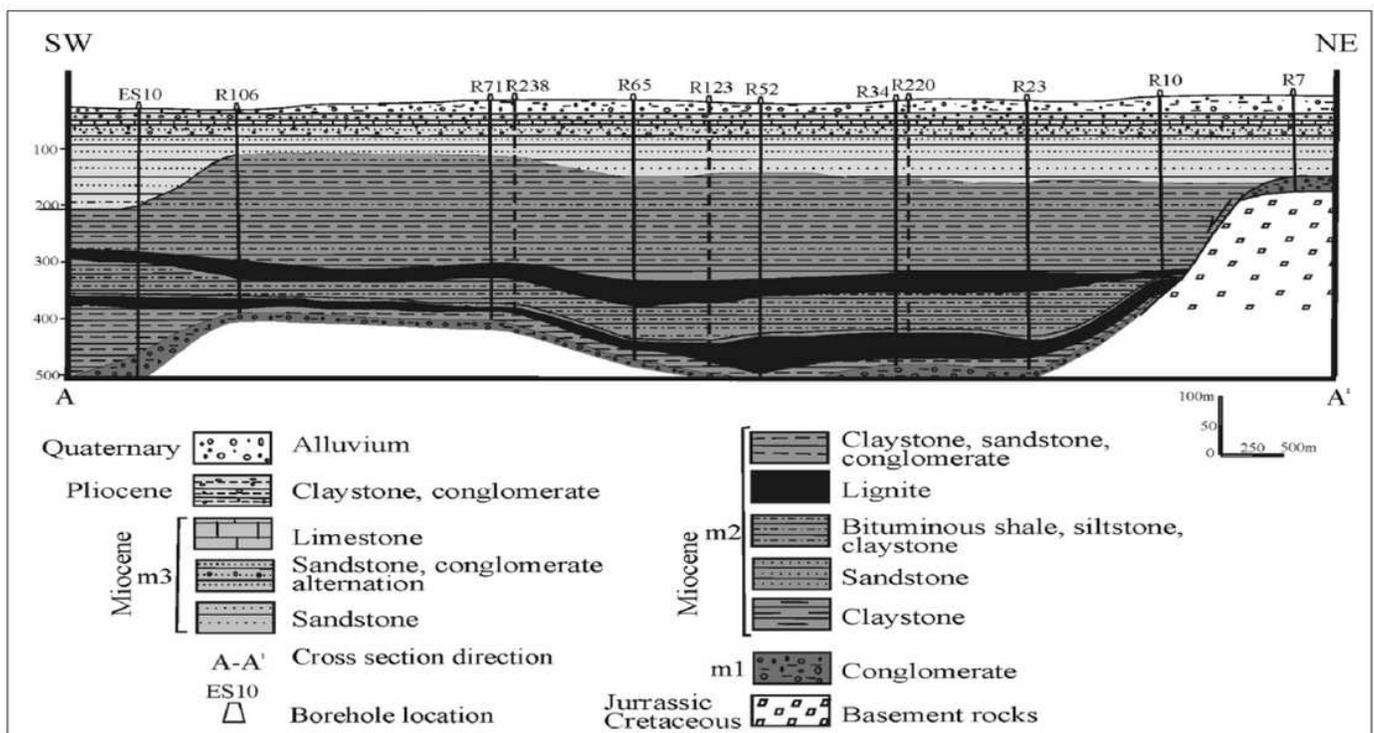


Figure 4

Geological cross-section (Senguler 2013).

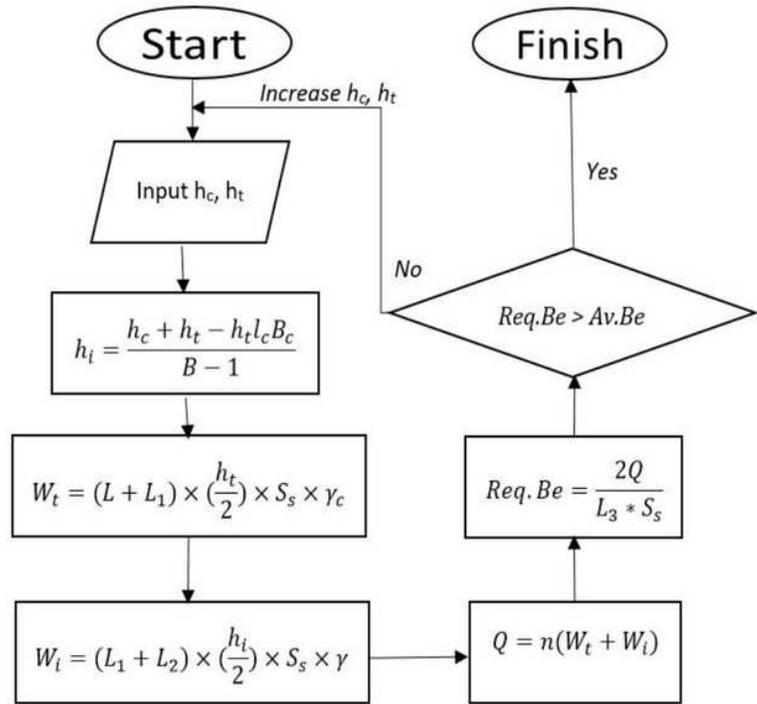
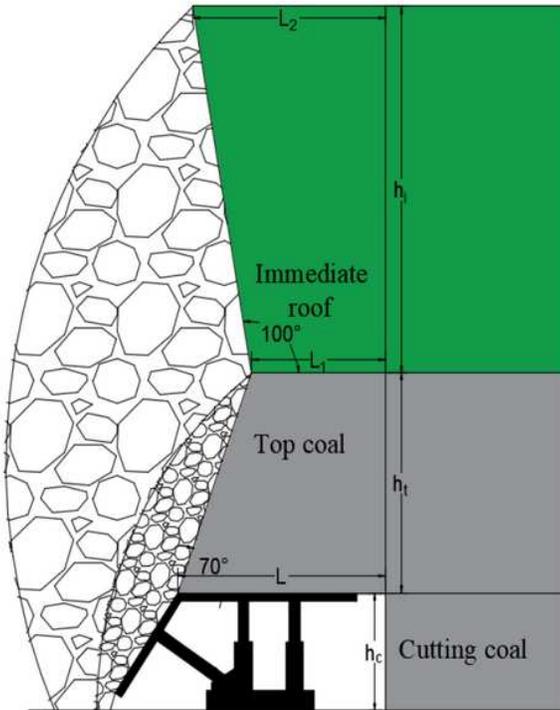
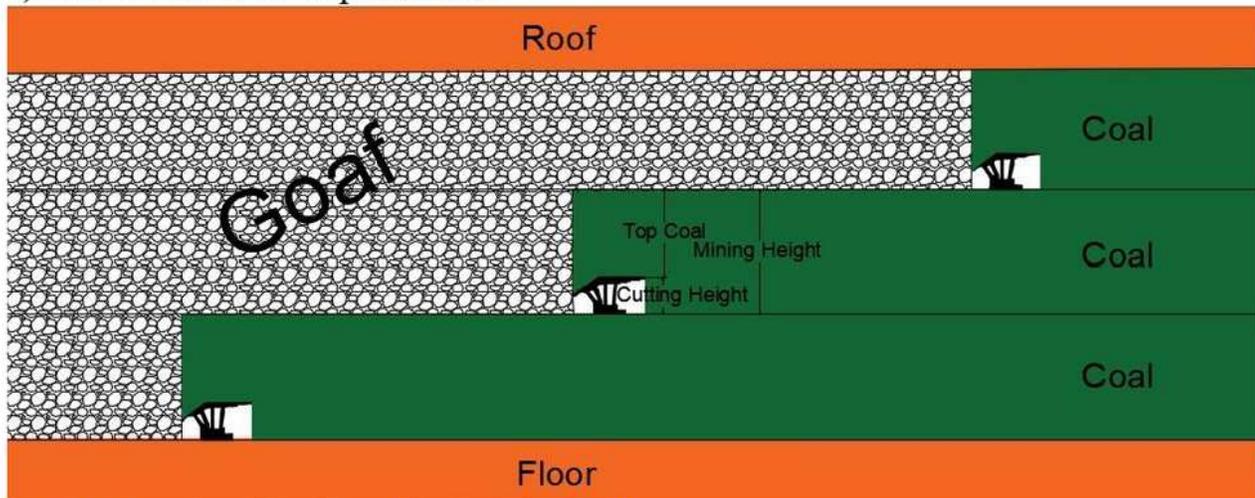


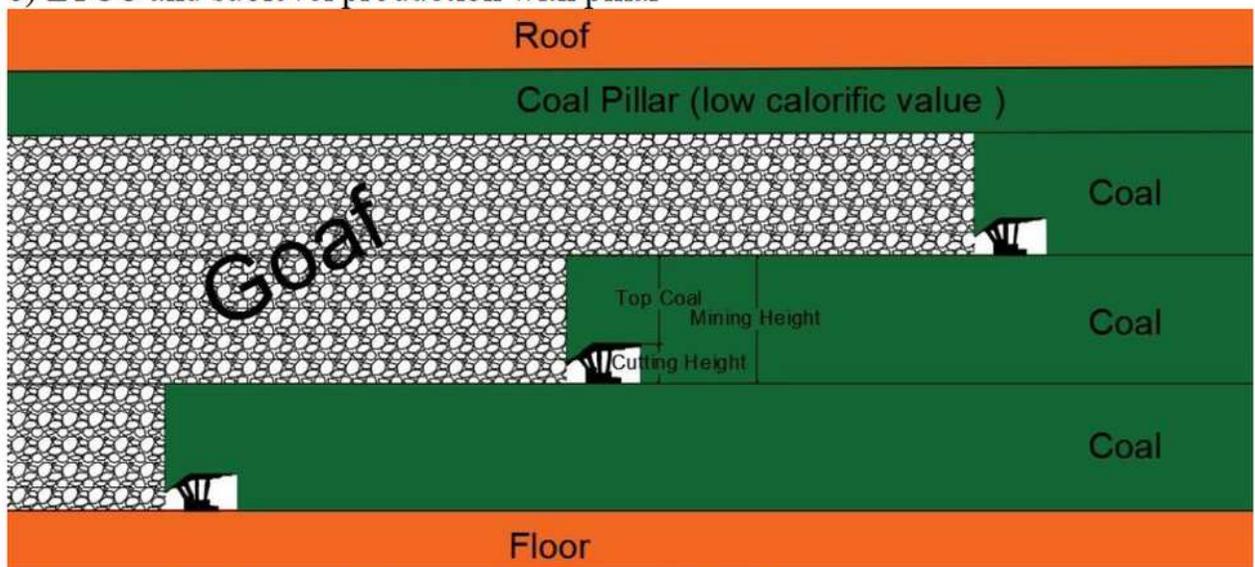
Figure 5

Detached block method application parameters and rules (Jangara et al. 2018).

a) LTCC and sublevel production



b) LTCC and sublevel production with pillar



c) Conventional longwall and sublevel production

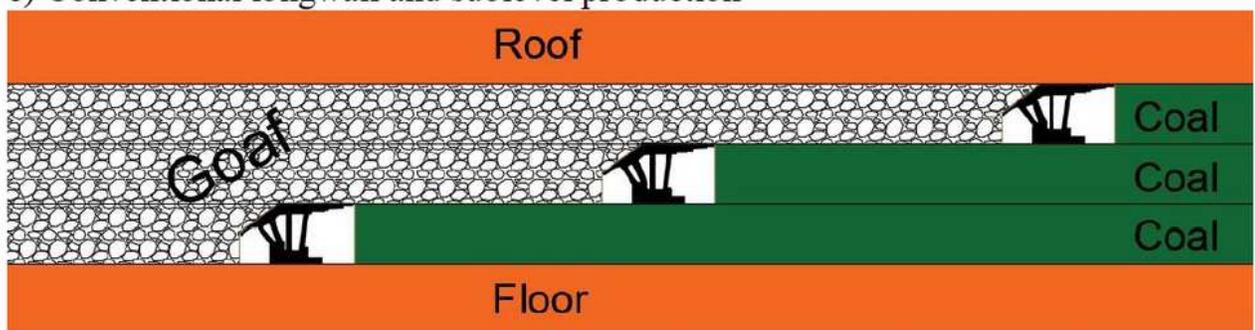


Figure 6

Production alternatives for seam-A (Jangara 2017).

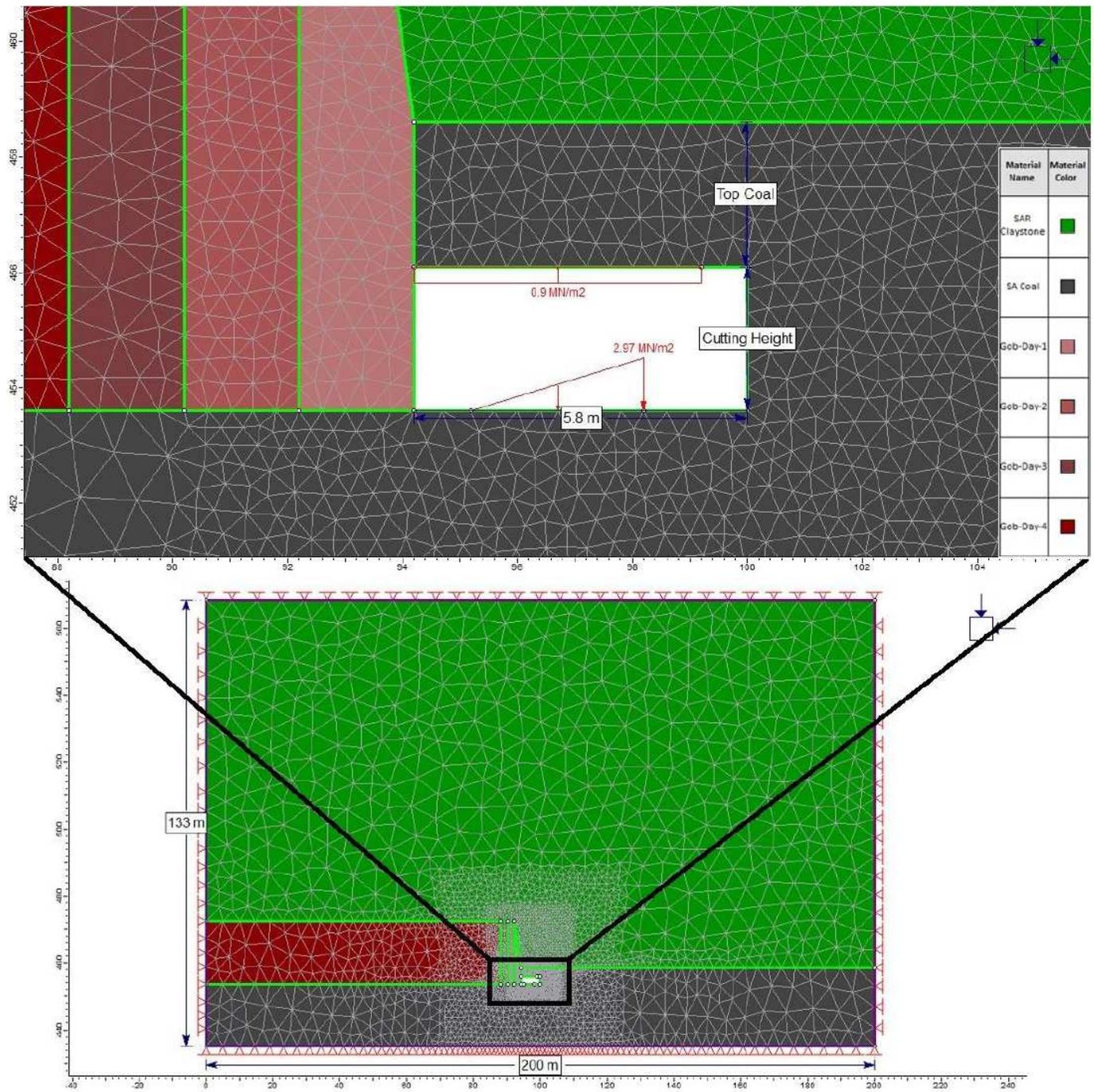
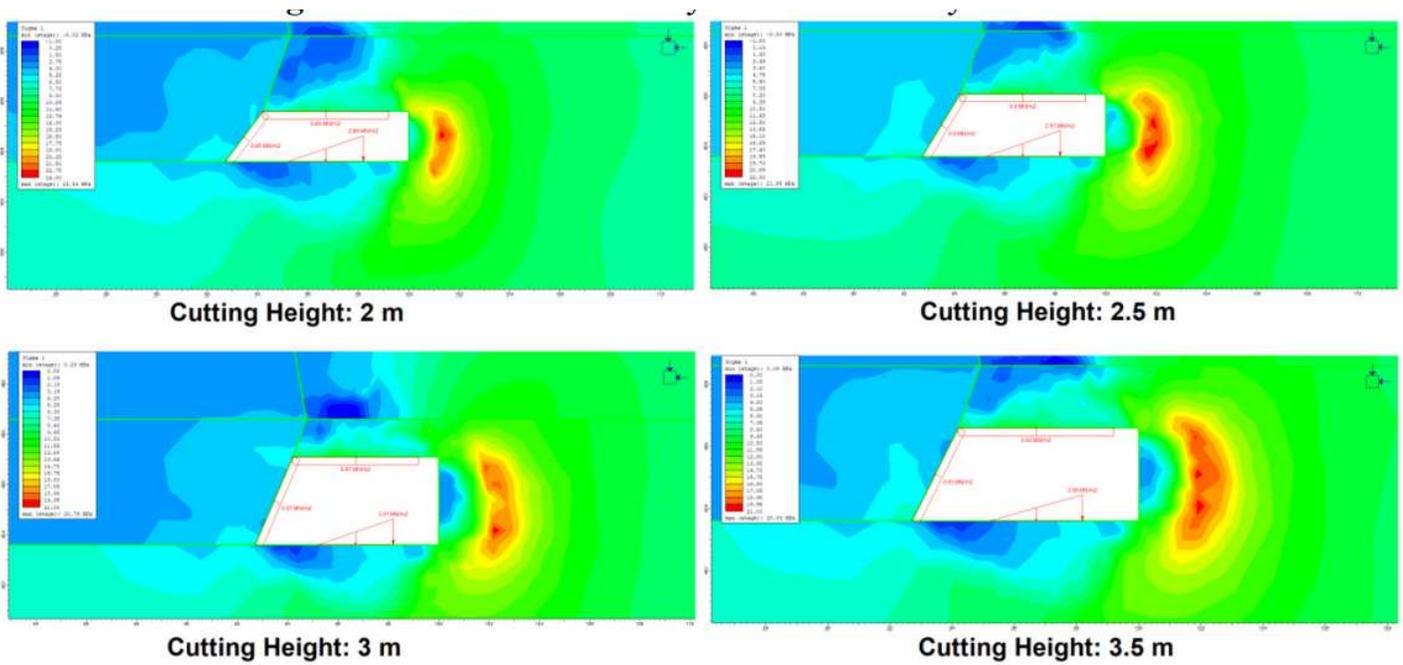


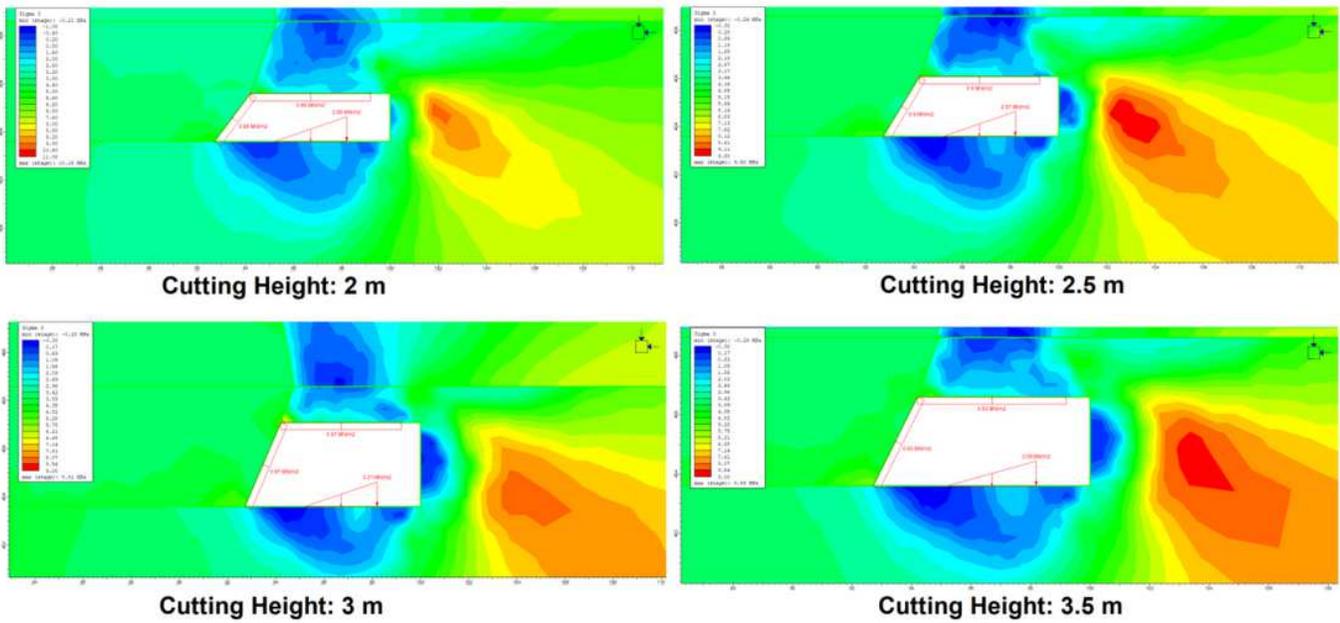
Figure 7

Finite element model layout and boundary conditions.



**Figure 8**

Normal stress numerical model output for different cutting heights.



**Figure 9**

Horizontal stress numerical model output for different cutting heights.

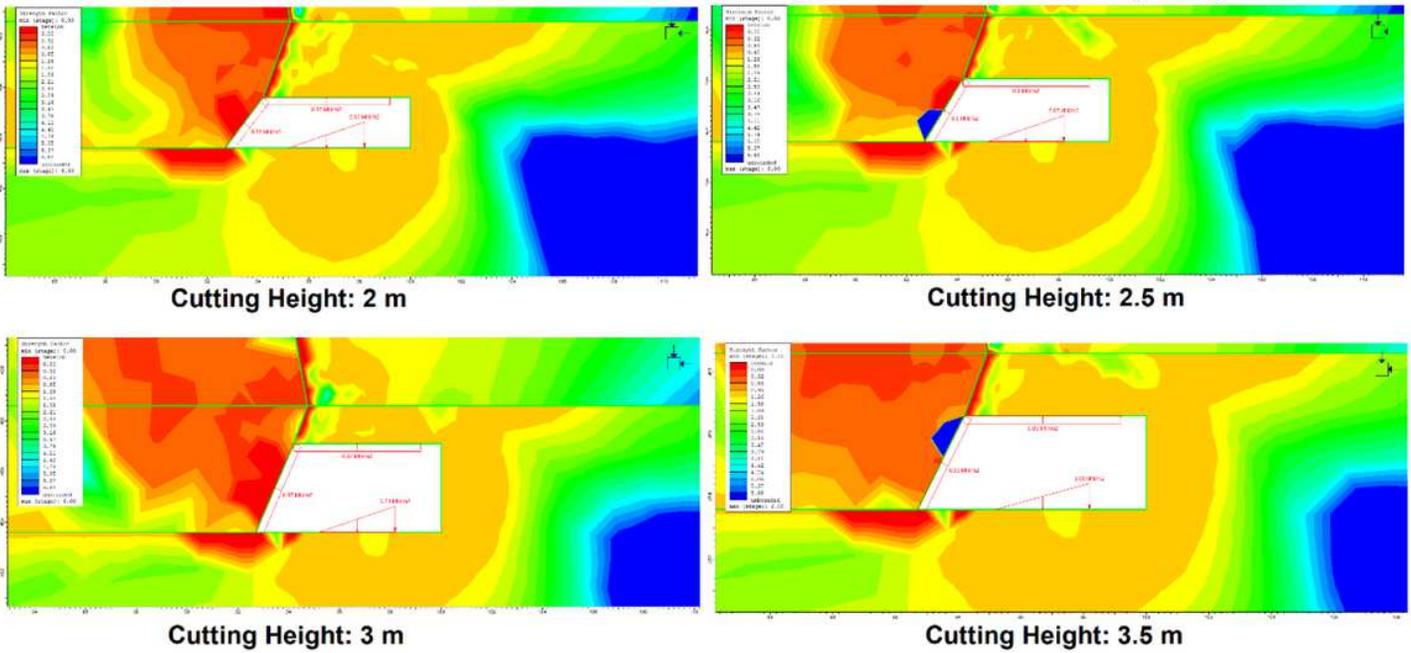


Figure 10

Strength factor numerical model output for different cutting heights.

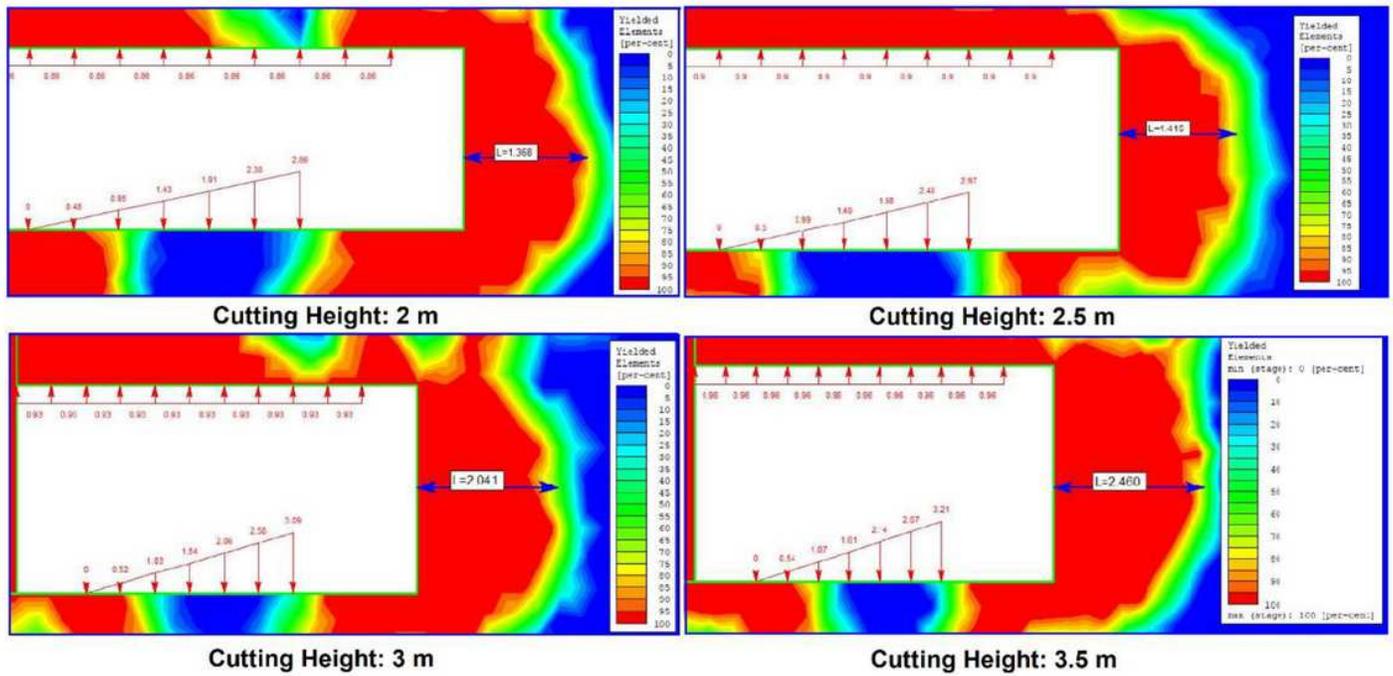


Figure 11

Yielded element numerical model output for different cutting heights.