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Investigation of Top Coal Cavability and Roof Behavior by Ground Response Curves

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Abstract
Longwall top coal caving mines are commonly operated at a depth of 100-400m in Soma Coal Basin located at western part of Turkey. Mining activities will move to a depth greater than 700m in the near future together with the progress in the mine plan. 800m deep and 16m thick coal seam is considered in this study and cavability character of top coal and roof behavior were examined by numerical modelling incorporated to ground response curves in addition to empirical approach. 400m and 800m deep mining activities are compared by utilizing vertical stress distributions, displacements, and ground response curves representing each case.

Keywords: Longwall top coal caving (LTCC), Numerical Modeling, Coal Mining, Cavability Index, Ground Response Curve.

1. Introduction

There are a variety of thick coal seam extraction methods such as multi slice longwall method, blasting gallery method. Among them, longwall top coal caving (LTCC) method gains the highest attention due to low development work per produced coal. Turkish top coal caving experience lies back to early 80s and new thick seam coal mines are being proposed and some of them have initiated production (Doktan and İnci, 1986;1987; Başarır et al., 2015).

Top coal caving method can simply be explained as drawing the coal overlying the powered shield (top coal) at rear canopy flipper of the shield while a conventional longwall production is limited to face cutting. LTCC requires elaborateness in face operations to have a successful production performance. The method provides increased productivity, less development length per produced coal tonnage. When LTCC is compared to other thick coal seam production methods like multi-slice longwall method, it is superior from technical and economical point of view (Vakili and Hebblewhite, 2010; Alehossein and Poulsen, 2010).

Typical single-pass LTCC applications generally work in a coal seam thickness up to around 12m. In coal seams having greater thickness, multi-pass LTCC can be applied in order to achieve better recovery (Başarır, 2015; Aksoy et al. 2015;2016). Still, questions on cavability tendency of the top coal remains hard to be answered accurately. Findings of a top coal cavability assessment may help decisioning on production fashion being either multi slice or single pass LTCC for a greenfield project as being a challenging rock mechanics problem. One of the other challenging part of the problem is the assessment to be conducted for a proposed operation of LTCC under great depth since worldwide top coal caving experiences are generally restricted up to 600m and deeper top coal caving experiences are rare over the world and absent in Turkey.

2. Soma Lignite Coal Basin

Soma lignite coal basin is located at Soma province in Manisa / Turkey. An open cast mine is under operation in the northern region of the basin where the coal seam lies at shallow depth. In neighborhood, underground coal mines are under operation at a depth range of 150-400m. New underground coal mines are being projected having greater mining depth from 700m to 1200m which are owned by government and private companies.

2.1. Geology and Rock Mass Properties

Main coal seam named as KM2 has economic significance and being extracted in the basin. Thickness of KM2 varies between 5 to 30m along the basin. Quality and calorific value of the coal decreases from top to bottom. Around mid-level of the coal seam, clay-claystone content starts to increase and strength of coal and structural quality decreases accordingly. KM2 is underlain by M1 geological unit consisting of poorly cemented clayey conglomerate and sandstones. M1 unit can be encountered having higher clay content in several regions of the basin which is prone to operational problems. In the northern basin, there are zones where coal seam inclination is 25° and it drops to nearly horizontal at southern and south-western regions. It is noticeable that in tectonically affected regions the seam has steep inclinations even though general trend is near horizontal. M2 unit consists of marl and overlies KM2 horizon with a thickness of 30 to 70m and exhibit massive structure with widely spaced beddings and sub-vertical calcite filled joints. A three-meter-thick zone (considered as immediate roof) of M2, overlies the KM2 coal, is structurally more deformed when it is compared to the upper zones of M2. Overburden lying on M2 unit is relatively weaker than M2 unit. Upper zones of overburden mostly consist of claystone, marl, sandstone, pebblestone, limestone intercalations. One of the main character is strong tectonic disturbance over the basin and drastic changes on the structural quality of the rock mass which can be frequently observed in short intervals.

Input parameters are based on laboratory tests and borehole investigations, and final findings are reported. The parameters to be used in the analyses are given below (Table 2). Residual state strength parameters were calculated by assigning rock mass a GSI value for residual state (Cai et al., 2007) and Generalized Hoek-Brown parameters were calculated as described in (Hoek et al., 2002;2013; Marinos, 2014):

Table 2. Rock mechanics parameters of the geological units

	E_{rm} (GPa)	c_p (MPa)	φ_p(°)	σ_{tp} (MPa)	c_r (MPa)	φ_r(°)	σ_{tp} (MPa)
overburden	0.7	0.4	38	0.08	0.2	34	0.04
	E_{rm} (GPa)	σ_{ci} (MPa)	GSI_{peak}	GSI_{res}	mi	$m_{b,peak}$	$m_{b,res}$
M2 Marl	12.325	70	80	28	25	12.239	1.911
M2 Marl immediate roof	7.28	70	60	23	25	5.991	1.598
KM2 Upper coal zone	2.449	30	75	26	10	4.095	0.712
KM2 Middle coal zone	2.449	30	70	26	10	3.425	0.712
KM2 Bottom coal zone	0.319	10	55	20	10	2.005	0.574
M1 Clayey	1.225	15	55	24	10	2.005	0.663
M1 Conglomerate	0.798	25	40	23	12	1.408	0.767

2.2. Longwall Top Coal Caving Method in Soma Basin

Semi-mechanized and mechanized longwall faces are present in northern Soma basin. In northern Soma coal basin, Isiklar colliery is being operated in 20-25° steep coal seam with horizontal long-wall faces, retreating parallel to the strike of the coal at 150-300m depth. Establishing horizontal longwall faces in 20-22m thick and steep coal seam, restrains the face length to 60m. Top coal thickness is adjusted to be in the range of 16-18m in vertical extent. Due to short face length, competent main roof and shallow depth, there is a potential of gathering poor recovery of top coal and standing of main roof were encountered especially for the upper production panels. Production sequence starts from the uppermost slice. Especially in lower consecutive panels, complete caving and drawing (recovery >90%) of the top coal was achieved by the help of pre-fracturing blasting and progressive damage of main roof, successfully. Main roof caving tendency increased and became no longer a problem for further production due to previous production induced damage to the roof. Strong mine induced deformation and stress re-distribution can be observed.

Other coal mines neighboring to the shallow ones, operating in near-horizontal thick coal seams (up to 30m thickness) prefer production of upper most coal slice in conventional longwall method. Operators aim to cave the main roof by conventional longwall mining of the uppermost slice. The rest of the coal seam can be produced in one or two slices of semi-mechanized and mechanized LTCC (Yılmaz et al., 2013; Aksoy et al., 2016) with varied face lengths. In Figure 2, multiple slice top coal caving mining is illustrated.

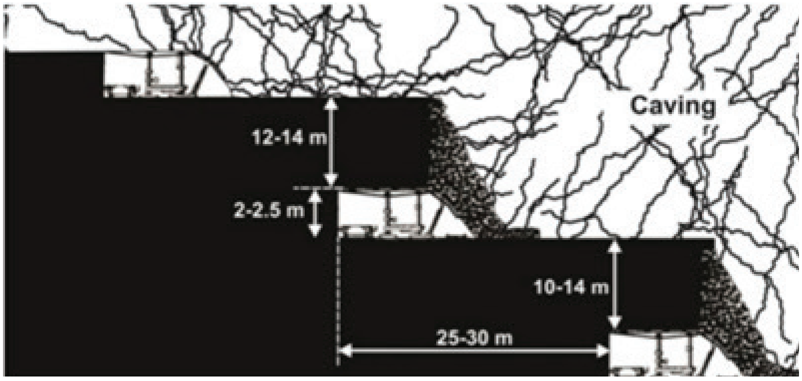

Figure 1. Multiple slice longwall with top coal caving (after Aksoy et al. 2016)

Face lengths are 180-200m and depth varies between 200 and 400m in Eynez, with discrete slicing: mining of the upper slices conventionally and after that second slice mining in the form of LTCC as described in (Başarır et al., 2015). The longwalls are being operated by the way that maximizes top coal recovery (>90%) which is achieved by allowing acceptable dilution.

Southern Soma coal mines are under projecting and development stage. At 700-1200m depth, longwall face lengths are supposed to be at least 160m and restricted by faults and other geological structures. Coal seam inclinations are below 6° with a maximum around 10°. Under great depth and extended longwall face lengths, cavability character is expected to be improved and conditions can lead to single pass LTCC production of a 16m thick coal seam which is beyond the common limits considering high recovery.

3. Cavability Assessment of Deep Coal Seam

Assessing cavability character of top coal can be dealt with several approaches namely numerical analysis and empirical methods which are mentioned in (Vakili and Hebblewhite, 2010; Aksoy et al., 2004). Still, there are limited study on the issue. In case of insufficient caving, pre-fracturing of top coal by blasting can be necessary. Longwall face length, support density, face advance rate, shield alignment, top coal drawing duration-sequence, set pressures of shields and other operational parameters have great impact on top coal caving success. Dattatreyulu et. al. (2012) noted that CSIRO and Chinese y-index cavability studies are based on Chinese mining cases. It should be noted that sample size in several empirical approaches are limited at the time when they were postulated and does not cover great depths.

Another cavability index work proposed by Vakili and Hebblewhite (2010), is based on numerical modelling findings which were carried out by Discrete Element Method codes. The parameters affecting cavability were found to be: deformation modulus, in-situ stress at all axes, seam thickness, spacing of vertical and horizontal jointing. Numerical modelling work was verified by several actual mining cases.

Commercially available Distinct Element Codes namely Itasca PFC, UDEC and 3DEC codes which are capable of handling discontinuum analysis was preferred (Wang et al., 2015; Hai et al., 2015) for top coal caving simulation or problems in top coal caving mines. The codes require input parameters namely discontinuity spacing, orientation, rock block geometry, discontinuity deformability and discontinuity strength in addition to intact rock parameters. Continuum approaches like finite element method, finite difference method are also preferred (Yaşıtlı and Ünver, 2005; Başarır et al., 2015; Alehossein and Poulsen, 2010; Aksoy et al., 2015,2016; Xie et al., 1999) in analyzing the problems successfully, involving top coal caving.

Abutment pressure acting on the face plays an important role in fracturing of the top coal (Alehossein and Poulsen, 2010; Aksoy et al., 2015). Intact coal and roof failure and material fracturing is another essential issue in addition to structurally controlled failures. Treating the rock mass as a continuum and representing the rock mass with simple and basic rock parameters, removed the necessity of detailed input data requirements for rigorous methods. In that study utilization of numerical modelling aims to observe rock material failure in the process and investigation of top coal cavability character by utilizing and comparing convergence-confinement curves for longwall face and failure extents.

3.1. Empirical Approach

For Southern Soma deep coal mines, borehole data is taken into account and due to the absence of in-situ stress measurements, field stress was imposed according to gravitational loading and assuming horizontal to vertical stress ratio equals to unity for deep production levels. Input parameters for the approach are vertical (σv) and horizontal (σh) virgin stress, top coal thickness, modulus of Elasticity of coal (Ei), vertical (Jv) and horizontal (Jh) joint spacing values. Two outputs of Cavability index proposed by Vakili and Hebblewhite (2010) are presented below. Main caving distance (MCD) is the distance of face at a point where all top coal caves to the mined void from initial position. In cavability index, caving of the roof is not taken into account and data input is not required for roof. Top coal recovery (TCR) is the percentage of top coal recovered.

Two different depths are considered in Vakili and Hebblewhite's cavability index. Jointing, deformability values are chosen considering weak and strong sections of the coal seam. Top coal thickness of 13m is taken constant for all analyses in order to be consistent. When stronger coal seam is considered, top coal recovery is around 60% for all depths. Main caving distance (MCD) of top coal lies between 15-25m. Stronger coal seam samples fall into Class III and IV which are fair and poor cavability conditions. Weaker coal samples for all depths are expected to perform good cavability character indicated by Class II and III, good and fair cavability conditions respectively. Current practice of Soma mines include pre-fracturing blasting, slow advance rates of longwall. These practices enable production of stronger sections of top coal. According to the Table 3, even at 800m depth, it is understood that additional measures can still be necessary. This finding is examined again in further sections.

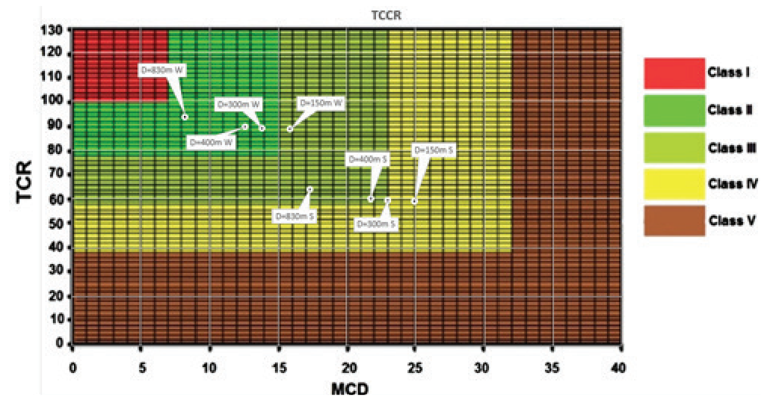

Figure 2. Top coal caving ratings on Vakili and Hebblewhite's (2010) chart

4. Numerical Modelling

Rocscience Phase[2] v.8 plane strain finite element analysis program was used in numerical modelling work in this study, (Rocscience, 2012). The plane strain program was utilized by constructing 2 axes of a longwall panel. The cross-section parallel to the face was used for examination of required longwall face length ensuring successful top coal caving and main roof. Observing tensile yielded element extent at the roof in vertical axis, displacement magnitudes reflect important data on cavability performance. Understanding the relation between numerical modelling and real mine case is essential.

Convergence-confinement curves were utilized in order to compare the top coal caving character which is a beneficial tool when a plane-strain model is in use. Convergence-confinement method is generally used in tunneling analyses (Brown et al., 1983) however, there are several researchers who used the method in longwall rock-support interaction analyses, (Barczak, 2006; Medhurst and Reed, 2005). Second cross-section generated based on the axis parallel to the longwall retreat direction was used in models. That cross-section represents the plane-strain condition in the middle of the face when a sufficiently long longwall face is established and rib side effect is diminished. Finite element mesh model is given in Figure 5.

400m and 800m deep coal seam were modelled based on same geological thicknesses, only overburden material thickness was altered. In Fig. 5, advance steps of a longwall face are visible and totally 85m face advance or retreat were simulated with 5m advance stages assuming a cutting height of 3m. In modelling work, main and tail gates were excluded and only the longwall faces were modelled. Finite element mesh density was increased gradually around the longwall faces, at the area of interest.

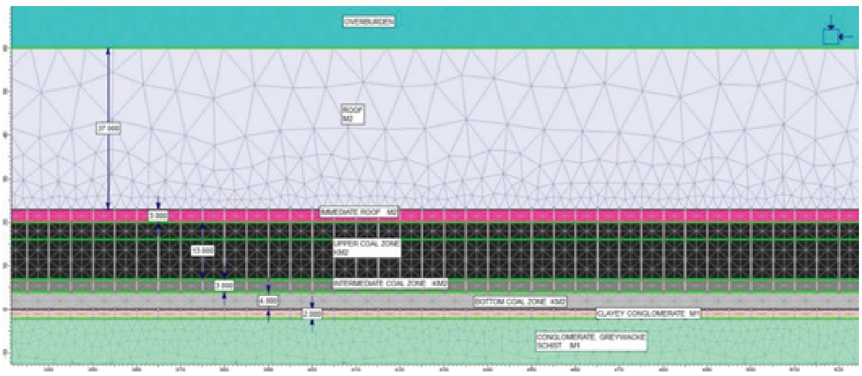

Figure 3. Zoomed view of coal seam numerical model with strata thicknesses and mesh for southern Soma coal mines

4.1. Vertical Stress Distribution, Displacements and Ground Response Interpretation

Vertical stress distribution, abutment stress and stress at face are investigated by utilizing the cross-section parallel to the longwall advance. 400m and 800m deep mining scenarios are modelled with same coal seam and main roof properties the only variable is overburden material which overlies M2 marl unit. Goaf behavior was not covered in this study and a soft goaf material was not imposed to the model. Since the model size is not sufficiently large, goaf material compaction and stress development in goaf are not possible.

Two numerical models were run with cross-sections parallel to the longwall advance: 1. Face coal cutting and removing the elements from the model without top coal drawing. 2. Removing the shearer cut zone and drawing the top coal.

In 400m deep mining case abutment stress is developed at 20m far from the face and around 15 MPa. In 800m case, abutment stress is 40-50m far from the face and between 30-35MPa. Abutment stresses are considerably far from the face which can seem unexpected since generally it is accepted that abutment stress is quite close to the face, (Figure 6). At low vertical in-situ stress and relatively strong coal presence and if elastic material behavior is assumed in order to solve similar problems which will in turn lead to high stressed, sharp vertical stress curves with peak abutment stress is close to the face.

Figure 6 shows stress distribution following a similar path when it is close to the face, since the coal seam mechanical properties and geometry are similar and the variable is depth. The face line falls on to the distance of 90m in the Figure 6. In order to have physical meaning it is better to take relative displacement from face (shield tip) to caving shield (back canopy) which is accepted as 5m for this case. In fact, the distance can be larger due to a new cut by shearer or position of back canopy flippers or equipment model. Relative displacements for conventional models are around 35 to 50 cm for 400 and 800m depth, respectively. If the model is constructed and top coal elements removed (as top coal drawing), relative displacement amounts drop around 10-20cm due to increasing horizontal displacement.

When a coal roof is established at roof in a thick coal seam, conditions considerably change when it is compared to conventional longwall operation. Generally, coal is more compressible and friable than a moderately strong roof. Top coal drawing generates a greater mined void causing difficulties in filling the goaf and compaction of the material. The advantage is, coal drawing absorb energy and cause loosening of the upper zones. If the advance rate of the longwall face can be adjusted, LTCC shields can be more satisfactory operated by means of ensuring support capacity.

Ground response behavior was investigated by considering 3 different longwall face lengths (60, 160,200m) at two different depths (400 and 800m). Plane strain models were constructed based on the cross-section parallel to face. Internal stress reduction was applied on to the boundary of the longwall face. Internal stress reduction was applied in 10 stages.

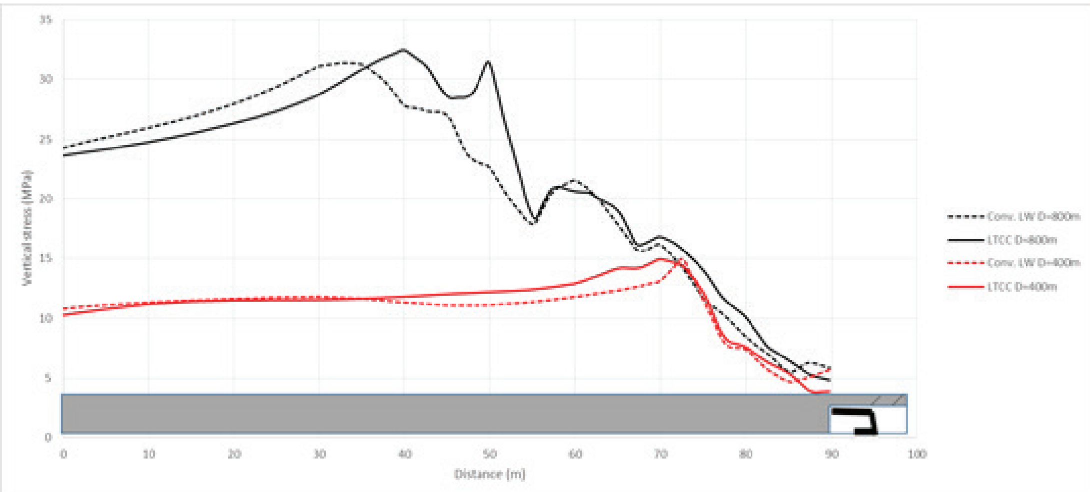

Figure 4. Vertical stress distribution along the mid-face for different depth and mining methods

Ground response curves are plotted for seams having depth of 400 and 800m. Additionally, longwall face lengths of 60, 160 and 200m. Support densities for longwall face supports are generally around 1 MPa or lower. Those support pressures cannot be compared to stress carried by face itself. For the case in this study, vertical stress at face are found to be around 4 to 6 MPa. Then, it is obviously the major supporting element is face itself. Longwall support carries dead rock load, improves bedding interlocking and reducing bedding separation then it ensures stability for the face environment. However, if the roof will converge, it is not totally resistible by typical shield support pressures and then it will finally converge.

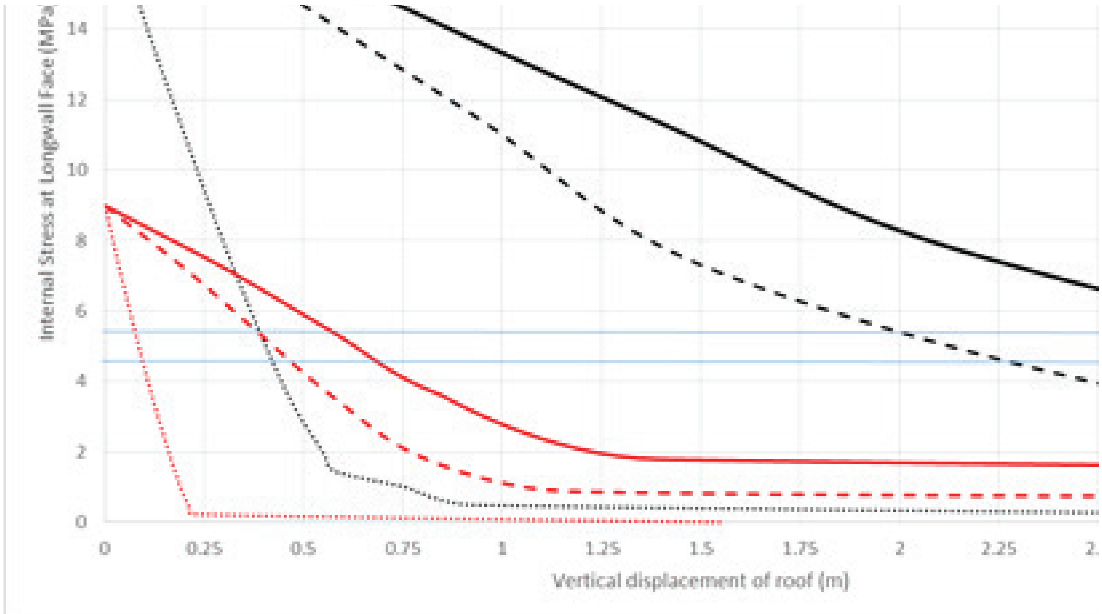

Figure 5. Ground response behavior for 400 and 800m depths and different face lengths

Vertical stress range at face for two different depths are labelled in Figure Below and represents the point on ground reaction curve at face. Previously mentioned empirical approaches does not consider face lengths. When we examine the problem by comparing face lengths, 60m long faces obviously seem to have less deformation potential. For same internal stress reduction on longwall face boundary, deformation attained is considerably small. Same conclusion can be suggested by considering the slopes of the curves in 4-6MPa range. In Soma coal basin, there are many longwalls under operation with 60-80m long faces. Caving of the roof as well as top coal caving are commonly faced problems especially for the first panel of a sector. Current mining activity mostly suggests caving of the roof first by operating a conventional longwall along the upper most slice of the seam. When mine induced deformation and stress have great impact on a particular area, then even in longwalls with short face, roof or top coal caves more easily. Ground reaction curves suggest for 16m thick coal seam, a single pass LTCC operation will not have sufficient top coal caving for both depth cases.

160 to 200m long longwall faces are expected to have similar caving tendency. Other finding is shields may yield up to 35 to 50 cm for 400 and 800m depth, respectively. Of course caving and convergence is strongly related to face advance pace.

5. Conclusions

Ground reaction curves provide valuable data on the relation between face length and cavability character of top coal where empirical approaches do not consider. Same methodology in the study can also be applied in order to foresee roof caving behavior for a conventional longwall. It is obvious that accurate findings can be obtained by construction of a pre-existing longwall and

calibrated data can be imposed to new problem. The methodology is also beneficial in case of utilizing numerical modelling programs assuming plane-strain even though three-dimensional approaches will probably give better estimates in turn more effort and time will be required.
In addition to the scientific facts operational factors have great impact on top coal caving and roof control success. Proper alignment of the longwall shields, optimized caving sequence and interval, clock work of the equipment, absence or presence of malfunctioning or leaking supports and more items are important and have direct effect on the success of a LTCC operation. Another critical parameter is longwall advance rate: slow advance increases degradation of the rock mass increases loads on the supports while it improves caving of top coal. Additionally, during a longwall advance ground stress distribution will change but not immediately. Occasions where peak abutment stress may stay closer to the face when longwall face advance is relatively fast, yielded zone at face may be reduced. In order to simulate that behavior, imposing time dependent properties with extensive calibration effort is necessary.

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