

Coal and Oil Sands

Enhancing the safety of remnant pillar recovery in lignite by numerical modelling

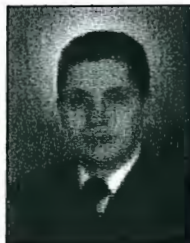
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ABSTRACT

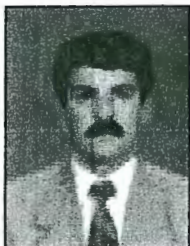
In Turkey, the growing demand for lignite has resulted in increased lignite production and an emphasis on improving underground recovery. This has resulted in a gradual increase in the application of the retreat longwall mining method and also in the extraction of the safety pillars protecting permanent underground structures (drifts, shafts) in mines prior to their abandonment.



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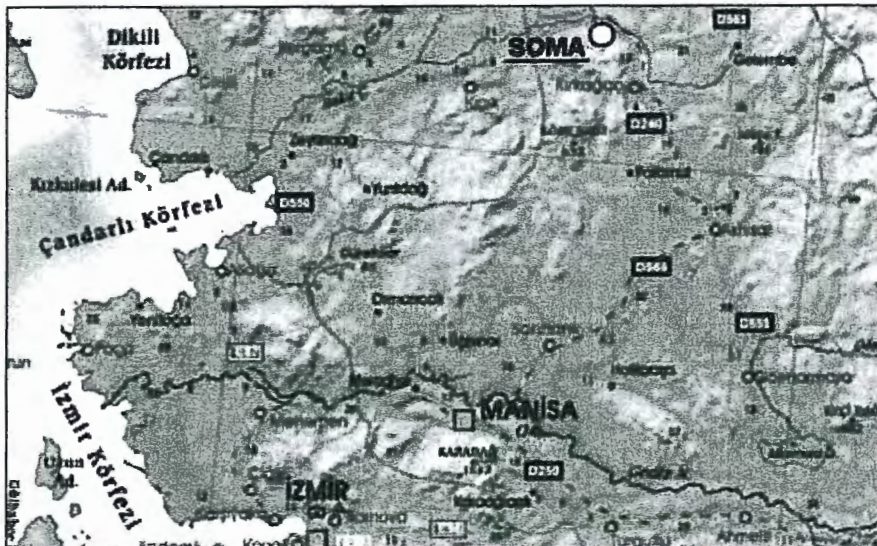


Fig. 1. Location of the Soma mine, Turkey.

Extracting these safety pillars presents a special hazard to mine employees and the stability of the mine. Often subjected to high stresses, the behaviour of these pillars is not always predictable. Special care must be taken to ensure that infrastructure does not collapse prematurely, and that working conditions remain safe. Otherwise the extraction must be halted, and the remaining coal lost.

This investigation reports on a study of the stability of safety pillars during the final extraction phase of the Hustas mine in Soma, Turkey. The model construction was based on mine plans, and material properties were derived from physical properties testing. Observed subsidence effects from other mining events were used to calibrate the overburden lamination thickness.



Keith A. Heasley graduated in 1981 with a B.S. in mining engineering from Pennsylvania State University. He finished his M.Sc. in mining engineering from Pennsylvania State University in 1987, and his Ph.D. in mining engineering from the Colorado School of Mines in 1998. From 1986 until August 2001, he was employed by the former U.S. Bureau of Mines and then the National Institute for Occupational Safety and Health (NIOSH) at the Pittsburgh Research Laboratory. Since August 2001, he has been an associate professor in the mining engineering department at West Virginia University. His research interests are numerical modelling, computer applications in mining, multiple-seam mine design, and ground control.

The model results compared well with surface physical disturbance occurring as a result of mining, as well as with conventional longwall stress redistribution theory and underground observations. The study has shown that properly calibrated models can be useful in assessing mine safety during remnant pillar extraction. The LAMODEL results demonstrate the convenience of this easy to use software.

Introduction

The Hustas Mine Company, founded in the mid-1980s, is the leading lignite mining company in Turkey. The Hustas mine is located southwest of Ankara, 140 km from Izmir, and has been in pro-



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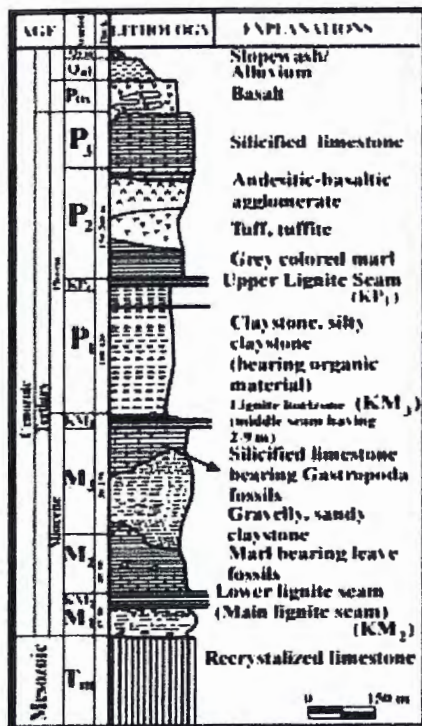


Fig. 2. Generalized stratigraphic section of the Soma District.

duction since early 1988. Figure 1 shows the location of the Hustas mine and Figure 2, the generalized stratigraphy of Soma region.

Between 1988 and 2000, lignite was extracted from various production areas of the mine. The depth of the KM₂ lignite seam, which forms the main resource at the Hustas mine, averages about 200 m and the seam ranges in thickness from 15 m to 25 m with an average extractable thickness of about 18 m.

A manual double-slice longwall mining method is used. In this method, the face area is maintained about 2 m high using hydraulic steel props and wooden posts. The coal is extracted from the face using drill and blast methods and the additional lignite thickness above the supports is recovered as it caves behind the face. Figure 3 shows the chronology of the main production sections and the location of the main drift, mine shaft and associated safety pillars.

Before abandoning the mine, the company planned to extract the final lignite pillars which were originally left as protection for both the main drift and the shaft. The pillar left to protect the main drift contained approximately 2 000 000 t of lignite, and the shaft pillar contained about 500 000 t of lignite (Fig. 3).

The main drift had a cross-sectional area of 12 m² and was developed in the clayey marlstone formation about 35 m above the lignite seam. It was used as the primary transport route for the lignite from the production panels. The main drift started at an

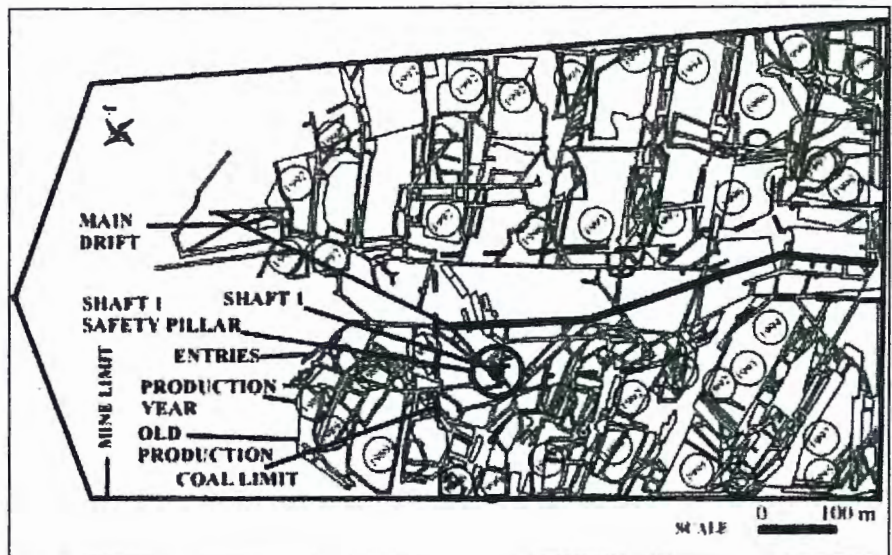


Fig. 3. Chronology of mine extraction prior to safety pillar extraction.

elevation of 330 m in the west and ends at 141 m elevation in the east. The inclination was 12 degrees.

The shaft was located on the west side of the mine and was primarily used for transportation of the workers and staff. It was colared on the surface at an elevation of 368 m and was 148 m deep. The bottom of the shaft was at an elevation of 220 m level, about 30 m above the lignite seam being worked. The lining of the shaft was reinforced concrete with a thickness of 25 cm.

The extraction of the main drift pillar was planned to occur from east to west over a two to three year period. The main drift above it was to be allowed to collapse, but was still required as a haulage-way outby the extraction face. Following the extraction of the main drift pillar, the shaft pillar extraction was planned from south to north. The day-to-day operational use of the shaft was abandoned before this extraction took place, although the shaft remained open for access.

In order to ensure the safety of the mine employees and the remaining mine infrastructure during the extraction of these remnant pillars, numerical modelling was conducted to determine the effects of the extraction on the infrastructure. During extraction, surface and underground observations were made to determine the validity of the model results.

LAMODEL

Both the main drift and shaft pillar extractions were modelled (Aksoy, 2001, 2004) using LAMODEL, a displacement discontinuity model developed for tabular deposits NIOSH. LAMODEL models the

extracted seam as an array of block elements. The properties of each element can be set to represent a variety of materials and material behaviours, and the model can be run in stages to represent in situ extraction sequencing during operations.

LAMODEL is similar to the NIOSH MULSIM program in input requirements, but uses a laminated overburden model which can be used to evaluate the effects of sub-surface interaction and surface subsidence. Because both stress and convergence at seam level are influenced by overburden characteristics, this feature was used to calibrate the model with subsidence observations made on the surface above the Hustas mine.

Laminated Displacement Discontinuity Technique

The displacement-discontinuity variation of the boundary element technique is frequently the method of choice to analyze the displacements and stresses associated with the extraction of large tabular deposits such as coal, potash, trona, and other vein-type deposits. Traditional displacement-discontinuity programs use a homogeneous isotropic elastic formulation which simulates the overburden as one solid material. LAMODEL, a displacement-discontinuity program incorporating a laminated media, was developed by the National Institute of Occupational Safety and Health (NIOSH) to overcome some of the errors inherent in using homogenous overburden models. By treating the overburden as a laminated medium, the LAMODEL program can calculate stresses and displacements at the seam level and at requested locations in the overburden or at the surface (Heasley, 1998).

Table 1. Material properties of intact coal, yielding coal and gob

Coal Elements (for Yield Zone - Elastic-Plastic)		
Element	Peak Stress (MPa)	Peak Strain
A	5.5	0.00228
B	6.9	0.00443
C	8.1	0.00443
D	9.9	0.00491
E	11.3	0.00516
F	12.9	0.00588
G	14.4	0.00660
H	15.9	0.00732
I	17.3	0.00804
J	18.9	0.00876
K	20.3	0.00948
L	21.9	0.01020
M	22.6	0.01092
N	24.0	0.01164
O	25.5	0.01236
P	27.0	0.01308
Q	28.5	0.01380
R	30.0	0.01442
S	31.5	0.01524
T	33.0	0.01597

Coal Elements (for Intact Zone - Elastic-Linear)		
Element	Elastic Modulus (MPa)	Poisson Ratio
V	2000	0.329

Gob Elements		
Initial Modulus (MPa)	Final Modulus (MPa)	Final Stress (MPa)
6.0	153.2	29.7

LAMODEL models the extracted seam as an array of block elements. Arrays up to 400 x 400 elements can be modelled, which usually allows adequate discretisation of the workings. The properties of each block element can be set to represent a variety of materials and material behaviours, and the model can be run in stages to represent in situ extraction sequencing during operations.

Like its predecessor, MULSIM (Zipf, 1992), block elements in LAMODEL can be ascribed properties that allow the development of yield zones in the seam to be approximated. A number of element behaviours can be implemented, including linear elastic, elastic-perfectly plastic, and strain hardening.

In order to model the development of a yield zone around a coal pillar, the LAMODEL formulation determines the peak strength of a model coal element based on an in situ coal strength and its distance from the edge of the pillar using the stress gradient implied by the Bieniawski pillar-strength formula (Mark and Chase, 1997):

$$S_p = S_1 [0.64 + 0.36 \frac{w}{h}] \dots \dots \dots (1)$$

where, S_p is the pillar strength (psi), S_1 is the in situ coal strength (psi), w is the pillar width (ft), and h , the pillar height (ft). This peak strength is then implemented using elastic-perfectly plastic material model (Zipf, 1992).

Table 2. Mine steps with direction

Safety Pillar of Main Drift (East to West)			Safety Pillar of Shaft 1 (South to North)		
Step	Distance from Edge (Grid)	Distance from Edge (m)	Step	Distance from Edge (Grid)	Distance from Edge (m)
1	400	0	1	36	0
2	373	54	2	44	16
3	348	104	3	54	36
4	336	128	4	66	60
5	239	322	5	82	92
6	181	438	6	100	128
			7	113	154
			8	155	230

This general procedure for generating the initial coal properties for elements in LAMODEL fulfills a number of practical requirements. It provides LAMODEL pillars with peak strengths which closely follow the empirically proven Mark-Bieniawski pillar strength formula (Mark, 1993; Mark and Barton, 1997) and stress profiles which closely follow the Bieniawski stress profile:

$$S_p = S_1 [0.64 + 0.54 \frac{w}{h} - 0.18 \frac{w^2}{L^2 h}] \dots \dots (2)$$

where L is the pillar length.

This procedure (using elastic-plastic material) allows the pillars to reach a maximum load-carrying capacity and then realistically

shed additional load to surrounding areas, as opposed to a simple elastic material model with no load limit.

To address gob loading and compaction behaviour, LAMODEL uses a combination of laboratory research and modelling experience. In the laboratory, Pappas and Mark (1993) found that an exponentially strain-hardening material with a tangent modulus that increases linearly with stress provided a reasonable representation of simulated gob material:

$$\sigma = \left[\frac{E_i \sigma_u}{E_f - E_i} \left(e^{\frac{E_f - E_i}{n \sigma_u}} - 1 \right) \right] \dots \dots \dots (3)$$

where, E_i is the initial tangent modulus at zero stress, E_f is the final modulus at ultimate stress (σ_u), and n is the gob height factor.

Table 3. In-put parameters

Formation	Elasticity Modulus (E) (MPa)	Poisson's Ratio (v)	Density (d) (kg/m ³)	Cohesion (c) (MPa)	Angle off Intern. Friction (φ) (°)
Limestone (P2)	23 000	0.24	2650	12	40
Shale and claystone (P1)	5000	0.33	1900	3.2	28
Marl (M3)	14 000	0.27	2100	23.2	35
Marl (M2)	10 000	0.30	1950	20.1	32
Coal (KM2)	2000	0.33	1650	5.2	35
Conglomerate	15 000	0.25	2200	18.4	24
Shaft 1 Concrete	21 000	0.18	2380	25	70

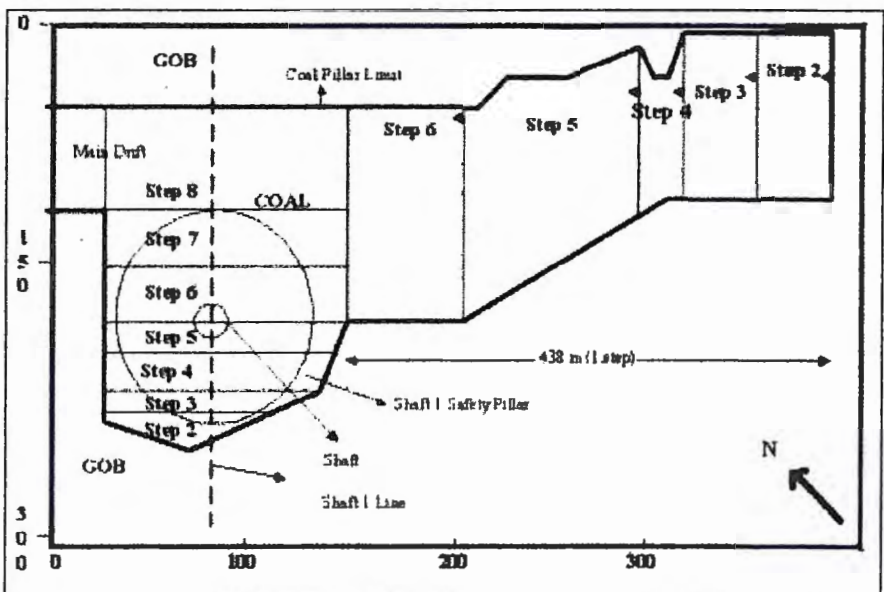


Fig. 4. Mine production map and modelled excavation steps.



Fig. 5. Subsidence cracks developed on the surface above the Eynes-Soma coal mine.

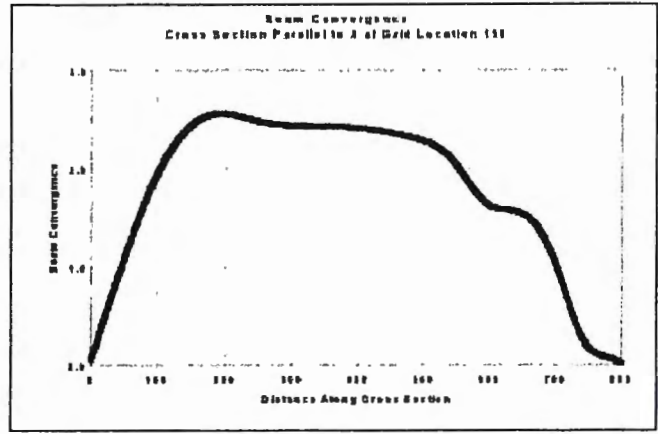


Fig. 6. Seam convergence after main drift step 1.

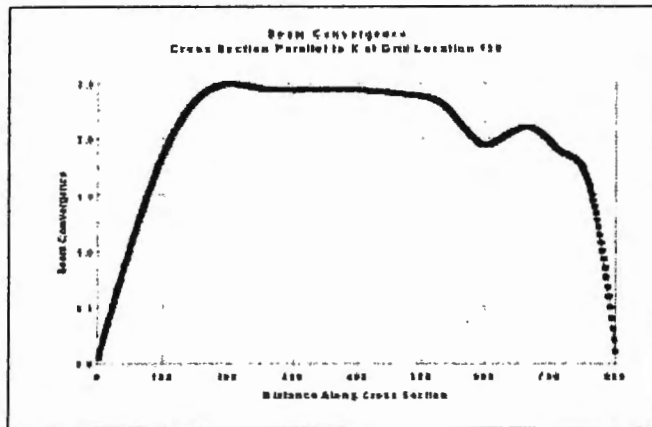


Fig. 7. Seam convergence after main drift step 2.

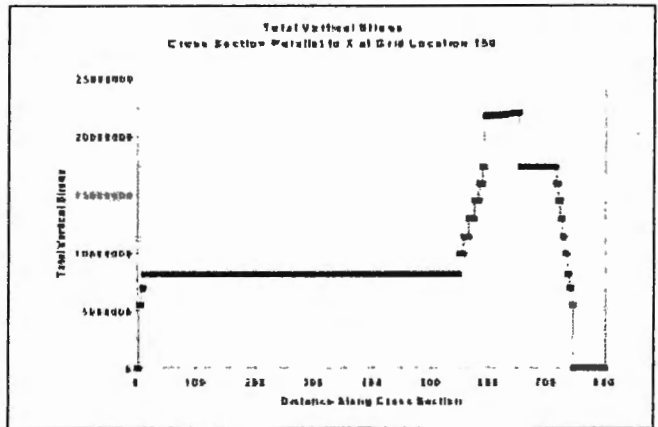


Fig. 8. Vertical stress, main drift step 2.

Parameter values for coal and gob materials used in the modelling work are given in Table 1.

Modelling of the Main Drift and Shaft

In order to define changes in stress, convergence of the excavations, and the effects of subsidence as the pillars were extracted, modelling was conducted over several mining steps, as shown in Figure 4 and described in Table 2. The model geometry was defined from the production map of the Hustas mine (Fig. 3). Model material properties parameters are given in Table 3. The model steps were excavated from east to west in the same sequence as the proposed pillar extraction to simulate the effects of undermining on the main drift, and from south to north to simulate undermining of the shaft.

Model Calibration

As previously indicated, modelled overburden properties have an effect on the development of stress and convergence at seam level. In modelling the Hustas mine extraction, observations of subsidence above similar workings in Turkey were available.

For calibration of the models used in this study, subsidence measurements from previous mining in Turkey were used (Kuscu, 1985; Kose and Onargan, 1993).

The thickness of the extracted seam and low depths of cover result in substantial subsidence development over many Turkish underground lignite mines. Subsidence cracks at the ground surface above the workings were observed above previous extractions at the Hustas mine (Fig. 5). Plotting the location of these subsidence cracks on a map of the mine workings allowed the subsidence angle of draw (break angle) to be determined. The angle of draw (break angle) has been determined as 56 degrees. This is confirmed by other subsidence observations in Turkey.

Based on this published work, the maximum subsidence over the 150 m wide extraction area in the northern half of the mine was predicted to be between 6 m and 8 m. The lamination thickness and properties of the gob material used in the Hustas mine model were adjusted in initial runs of the model so that the resulting surface subsidence matched this estimated value (Heasley, 1998).

The completed, calibrated model was then run over a number of extraction stages

to determine the effects of safety pillar extraction on the main drift and shaft. Six excavation stages were modelled for the main drift to the east of the shaft, followed by eight steps to model the extraction of the shaft pillar (Fig. 4).

Discussion of Results

The results shown are those of vertical stress at the seam horizon, and convergence at the seam horizon. Section lines vary due to the location of the centreline of the main drift in the model, and the vertical scales also vary.

The constraints applied to the model boundaries have a marked effect on the convergence results, emphasized even more by the very large closures resulting from the extraction of 18 m or so of coal. The convergence is constrained to zero at the model boundaries, which makes interpretation of the results somewhat difficult. This is clear from Figures 6 and 7 in which the boundary constraints mask the convergence caused by the face advance, although closer inspection shows about 0.4 m of convergence about 150 m in front of the face.

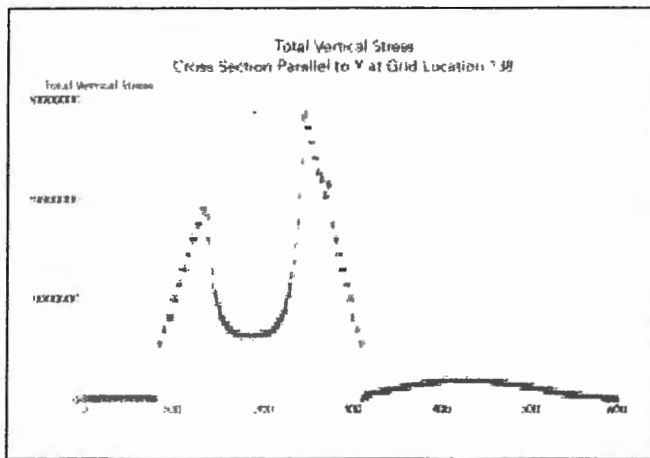


Fig. 9. Vertical stress, shaft step 1.

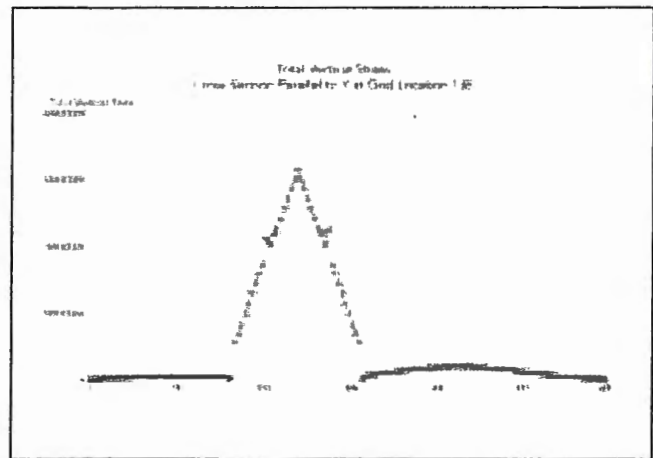


Fig. 10. Vertical stress, shaft step 5.

The two vertical stress plots, Figures 8 and 9, clearly show the contrast between the travelling front abutment associated with the narrow main drift pillar and the typical, almost symmetrical distribution through the larger shaft pillar. In the former, the angle of the section line is not exactly perpendicular to the axis of the pillar, but the characteristic abutment imposed on a fairly uniform background stress level can be seen. In the case of the shaft pillar, the flank abutments protecting the less stressed pillar centre can also be clearly seen. In Figure 10, the entire pillar is stressed, as characterized by the peak over the centre of the pillar.

More detailed analysis of the results models indicated that the main drift collapse followed the seam excavation from east to west by about 10 m to 15 m. The collapse was observed in the mine. Surface subsidence developed almost immediately over the main drift extraction. In contrast, the extraction of the larger, more resistant shaft pillar approached much closer to the shaft before the shaft became dangerous.

Conclusions

The LAMODEL results indicate that the stress increase caused by mining the safety pillar under the main drift results in the generation of very high abutment stresses in the remnant pillar of up to five times the cover load. The effect of these stresses on the very thick and relatively soft lignite results in very large convergence at the seam level. Although less convergence would be expected at the main drift horizon nearly 40 m above the seam, movement would still be considerable. The resulting shear stresses around the main drift would be expected to present severe stability problems. The indication is that the main drift will collapse after the face

has passed below, about 10 m to 15 m behind the face. The actual timing of the collapse will depend on local factors such as face advance rate and local geological features. This was in fact observed in the mine.

The model results show that the stresses experienced around the main drift are similar to those predicted by longwall theory. Behind the face in the collapsed gob the stress did not exceed the cover stress.

Although the calibrated LAMODEL appeared to replicate subsidence values experienced at the surface, the relatively complex model construction process and running time offer no great savings in time or effort than available nomographic methods of determining subsidence. However, the model prediction of areas of stress concentration around the workings compared well with field observations, and shows considerable promise for the determination of the safety of future remnant pillar extraction in Turkish lignite mines.

The LAMODEL construction used in this analysis was fairly simple, and boundary constraints of the model have had a profound effect on the convergence results; zero convergence is generated in gob elements at the edge of the model, resulting in skewed convergence curves. Further modeling of this type of geometry would benefit from either a larger model grid, or a means of reducing the effect of boundary constraints.

Acknowledgments

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