Effect of residual tectonic stresses on roadway stability in an underground coal mine

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Synopsis

Effective strata control is a prerequisite for maintaining an efficient mining operation. If the strata in the vicinity of an opening are not controlled effectively, it is impossible to perform a safe, efficient and economical operation.
In this paper, the reasons and outcome of instability problems observed in roadways opened in clay and marl at the Bolu Colliery of Yeni Çeltek Establishment are investigated. Roadways under examination were located in a syncline causing high residual tectonic stresses. Factors affecting the instability have been studied thoroughly by examining geology and tectonics of the area, establishing convergence measuring stations to understand *in situ* behaviour of supports and laboratory tests to determine engineering properties of samples taken from nearby convergence measurement stations. As a conclusion, a new production strategy and a new support system are recommended to maintain stability.

General information about the mine and aim of the study

Yeni Çeltek Colliery is located in the north west of Anatolia, 36 km from Bolu Province. Total lignite reserve in the mine area is about 6.5 million tons. Because of the presence of tectonic and lithological problems only 1.5 million tons of lignite are suitable for production.

Cores obtained from exploration boreholes were analysed and the following properties related to the coal seam were found:

Ash Content	17.10 %
Moisture Content	4.40 %
Sulphur Content	9.23 %
Calorific Value	4100-5500 kcal/kg

There are several mining methods implemented, namely; retreat shortwall with caving, bord-and-pillar and blasting galleries. Although the coal seam contains a high amount of sulphur and production methods are conducive to spontaneous combustion there has never been any serious mine fire experienced.

Since the sulphur content of the coal is very high, it is not suitable for use as domestic fuel. However, it is very much in demand by nearby brick factories. Strata around the mine had been affected by major tectonic movements resulting in the formation of extensive folds as anticlines and synclines . Main roadways have been driven in marl and clay. There was an asymmetric syncline in the vicinity of main roadways forming a complex stress state. Clay bands surrounding the roadways had different swelling potentials adversely affecting the stability of the roadway.

There has always been a great problem of stability in the mine due to closure in the roadways. Dinting and ripping had to be done frequently to maintain transportation and ventilation functions of roadways.

This study defines and analyses the source and mechanizm of instability problems in the main roadways and to establish the necessary measures to be taken in order to maintain stability.

General and structural geology of mine area

General geology of the area

There are mainly three stratigraphic series of Paleozoic, Mesozoic (Cretaceous) and Cenozoic (Eocene) ages. Paleozoic series (Bolu Massive) are represented by Hornblendeschists, Calcereous-schists and Diorites. Grey coloured calcareous rocks are of Cretaceous age and Eocene series are represented by clay, clayey marl, marl and strong calcareous rocks.

Stratigraphic series including the lignite seam are composed of greenish-gray clay and clayey marl. Above and below this series, there are red and gray marls respectively. Lutesien age lignite bearing series have an average thickness of about 90 metres. A lignite seam that has a thickness of around 2 metres lie

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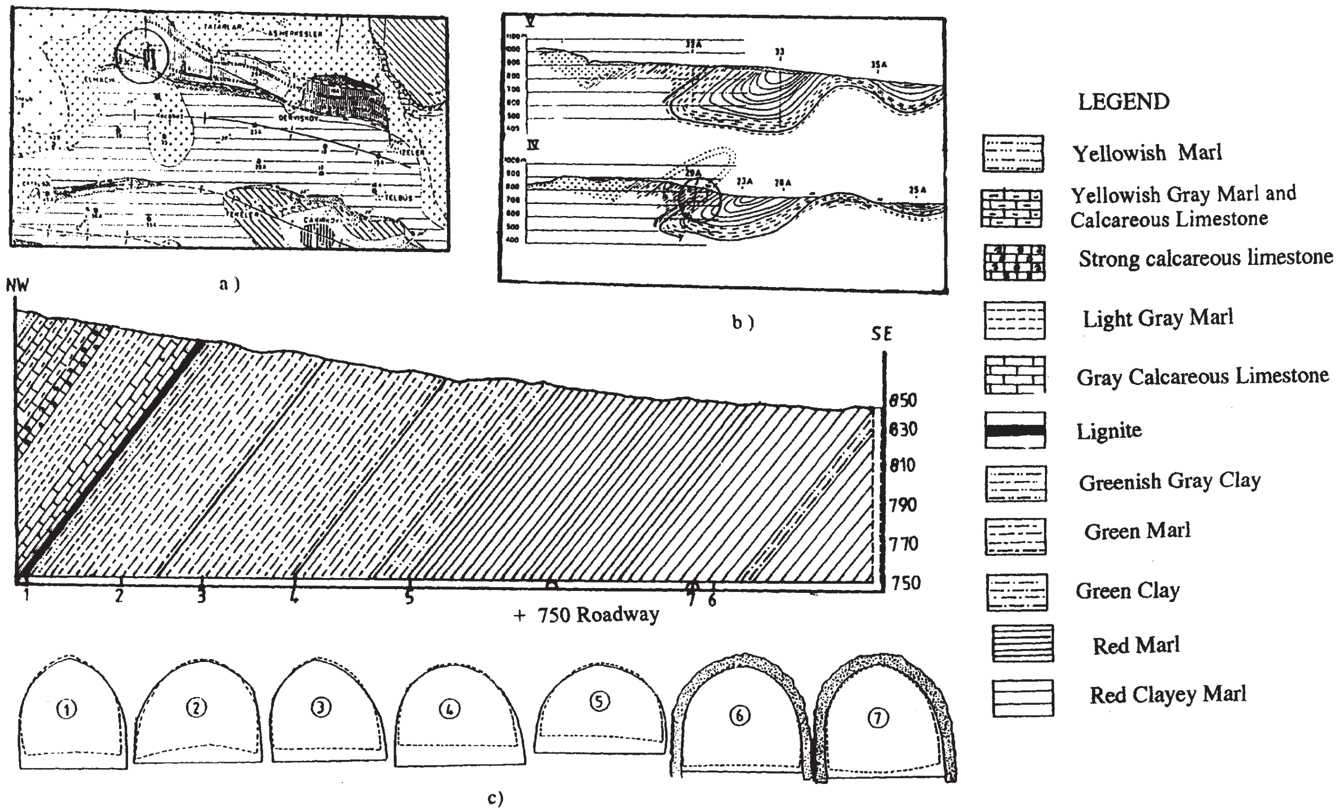


Figure 1—a) Geologic map of mine area, b) Cross-sectional view of mine area, c) Cross-sectional view of +750 roadway, locations of measurement stations and profiles of roadway after deformation

normally below the strong calcareous-limestone. However, due to extensive folding, the lignite seam was overturned forming a geological floor from what was previously a roof.

Structural geology of the area

Strata including the coal seam were tectonically very much disturbed by means of faults and folds. Coal bearing strata together with Eocene series had been thrust towards the south and two synclines, one anticline and one oblique fault were formed. Depending on the general tectonics of the area, faults with axes parallel or diagonal to folding axes were developed during folding.

Analysis of the structure in the vicinity of +750 main roadway

Strata surrounding the roadway

The +750 main roadway was excavated in series containing marl and clay. Geotechnical surveying in the roadway has shown that the strike was in NE-SW direction and the dip of the strata was between 45-55° towards NW.

The direction of the principal stresses, in relation to tectonic activity affecting the roadway

The directions of the principal stresses in relation to the roadway axis is very important for stability and, therefore, support design. Major, intermediate and minor principal stresses are represented by $\sigma1$, $\sigma2$ and $\sigma3$ respectively.

During the formation of folds the side pressure should in general be of the highest magnitude. In other words, the major principal stress must be acting almost parallel to the bedding planes. Figure 2 schematically shows the position of an asymmetric syncline and the roadway together with the directions of principal stresses for a roadway driven parallel and normal to the folding axis.

In order to facilitate the comparison of situations shown in Figures 2b and c, the best and the worst directions of principal stresses in relation to roadway stability are shown in Figure 3.

Effect of principal stress directions on roadway stability

It is well known that directions of principal stresses with respect to tunnel or gallery axes is very important for stability. Tunnels opened in high horizontal pressure zones, are likely to have stability problems in the roof and floor; whereas side stability problems are more likely to be encountered in tunnels opened in high vertical pressure zones (Gale, 1991).

When Figures 2 and 3 are examined carefully, it is observed that the roadway stability was adversely affected when it was driven parallel to the syncline axis, i.e., the major principal stress $\sigma1$ acting from the sides. When the roadway was opened in the direction perpendicular to the syncline axis, the direction of major principal stress would be parallel to the roadway axis. Therefore, shear resistance of the surrounding rock is increased resulting in better stability conditions.

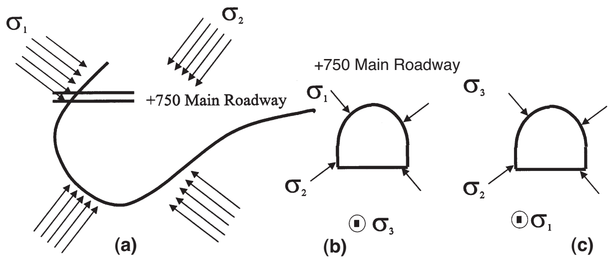


Figure 2—a) Directions of principal stresses for the formation of existing asymmetric syncline and the position of +750 main roadway with respect to syncline, b) Directions of principal stresses affecting the roadway opened parallel to the syncline axis, c) Directions of principal stresses affecting the roadway opened normal to the syncline axis

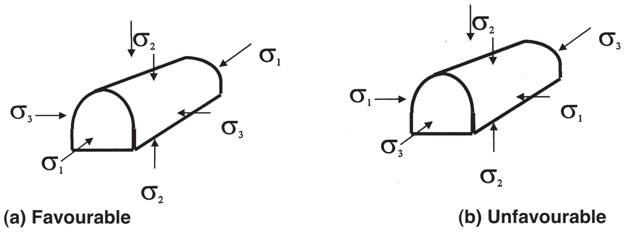


Figure 3—Relationship between roadway stability and the directions of principal stresses

Engineering properties of surrounding rock

Representative samples were taken around convergence measurement stations to investigate whether the movements were due to characteristics of the surrounding rock. Engineering properties of these samples were determined at the Soil Mechanics Laboratory of Hacettepe University. Sampling and testing were done in accordance with ISRM standards. The following engineering and index parameters were determined in the laboratory:

- Specific gravity
- Water content
- Atterberg limits
- Liquid limit
  - · Plastic limit
  - · Shrinkage limit
- Grain size determination by hydrometer,
- Direct shear strength.

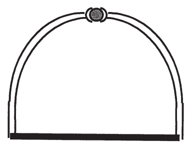
All of the samples taken from +750 main roadway were classified according to their colour and petrologic properties. Summary of test results are presented in Table I.

Support types used in the mine

There is a direct relationship between the stability of a roadway and the geometry of excavation and type of support used. Roof strata movement and deformation are usually higher for rectangular or square cross-sectional galleries when compared to galleries having an arch-shaped roof. It is stated in the literature that convergence in rectangular or square-shaped galleries is three times more than circular galleries for certain stress configurations. Furthermore, closure increases with increasing cross-sectional area[1].

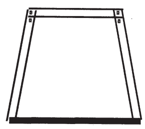
In general, there are three different roadway support types used in the mine. These are moll steel arches, three piece steel sets and steel arches with concrete lining.

Moll type steel arches:



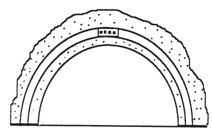
Load bearing capacity: Moll arches have greater load bearing capacity than timber supports. However, Moll arches deform extensively under uneven loading conditions.
Strata control: There is no precaution against floor heave. Therefore, floor heave could be a serious problem.
Labour and cost: Moll arches are easy to set and it is possible to re-use the arches.

Three piece steel set:



Load bearing capacity: Three piece steel sets are stronger than timber supports. However, its capacity is generally limited with the bolt strength used for joining beams.
Strata control: Floor heave can take place. Since most of support load is transferred directly to support legs, penetration problems may arise in soft floor conditions.
Labour and cost: The work involved in setting three piece steel sets is easy and beams can be re-used.

Steel arch with concrete lining:



Load bearing capacity: Steel arch with concrete lining provides a strong support, especially under vertical loading condition. The strength of concrete is critical for load bearing capacity.
Strata control: As applied in the mine, there is no precaution taken against floor heave. However, floor heave could be prevented by constructing an invert arch.
Labour and cost: Steel arch with concrete lining is a very labour intensive type of support. Due to difficulties faced during repairing and side-ripping, moll arch supports are preferred in the mine instead of steel arches with concrete lining.

Convergence measurements and interpretation of results

Convergence measurement stations

Seven different locations were selected for *in situ* measurements of convergence at +750 main roadway. Strata movement and deformational characteristics of support around measurement stations were also determined. Measurement stations are shown on a plan of the mine in Figure 4. Number 1, 2, 3, 4, 5 and 6 convergence measurement stations number were on part of the roadway that is perpendicular to strike and syncline axes, whereas station number 7 was located at the top of a decline which was directed parallel to syncline axis. Locations of

Table I

Engineering properties of samples tested, Kargi[2], Unver and Kargi[3]

Properties		Greenish Gray Clay (1)	Green Marl (2)	Green Clay (3)	Red Marl (4)	Red Clayey Marl (5)
In situ unit weight (gr/cm^3)		1.77	1.78	1.72	1.75	1.80
Grain unit weight, Gs		2.54	2.56	2.37	2.52	2.61
In situ water content, Wn, %		17.90	17.53	18.30	12.23	16.40
Activity, A		High	Low	High	Low	Low
Plastic limit, PL, %		35	35	36	33	29
Liquid limit, LL, %		67	70	71	57	61
Plasticity index, PI, %		32	35	35	24	32
Shrinkage Limit, SL, %		19	23	18	20	22
Shrinkage Ratio, Sr		1.82	1.75	1.83	1.85	1.79
Compressibility index, Cc		0.60	0.63	0.64	0.52	0.56
Grain size distribution	Clay; %	23	2	19	1	8
	Silt, %	67	68	77	62	44
	Sand, %	10	30	4	37	48
Unified soil classification system		OH*	MH**	OH*	MH**	MH**
Swelling potential		Medium	Low	Medium	Low	Low
		> %5	< %1.5	>%5	<%1.5	<%1.5
Triangular chart Classification		Clayey Silt	Sandy Silt	Sandy Silt	Sandy silt	Silty Sand
Internal Friction Angle ϕ (°)		40	34	24	33	27
Cohesion, C (kg/cm^2)		0.51	0.38	0.96	0.32	0.90

* *OH: Organic silt with medium or high plasticity*
** *MH: Inorganic silt*

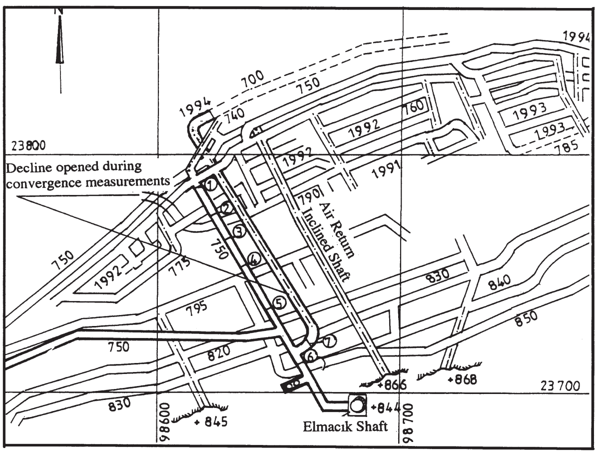


Figure 4—Locations of the convergence measurement stations on the mine plan

measurement stations were selected in different geological conditions for better representation of various surrounding rock parameters. Distances between measurement stations were around 10-15 metres. At the beginning of convergence measurements, it was intended to take closure measurements on a roadway opened parallel to the strike of bedding planes and the syncline axis. Unfortunately, due to positioning the roadway parallel to syncline axis, it was not possible to keep the roadway properly open. Therefore, due to closure, convergence measurements could not be taken in such a roadway.

Method of convergence measurement

A modified version of the convergence measurement method proposed by Whittaker[6] was used for *in situ* measurements Unver[4]. The method of measurement is shown schematically in Figure 5 and is capable of defining deformational characteristics of roadway support by taking measurements in various dimensions. Measurements were made by using a simple steel tape.

Mid-point of a station was marked by suspending a pendulum from the roof and three steel poles were placed on the floor, one in the middle, and two one-metre apart from the mid-point to the left and the right. Side reference points were marked on supports at a height of one metre from the floor. Therefore, it was possible not only to measure the vertical and horizontal displacements, but also displacements between the other reference points that made it possible to obtain the complete profile of the support after deformation

Interpretation of convergence measurement results

Distance measurements between reference points were carried out daily in the first week, and once a week thereafter for a period of 3 months.

By examining roadway profiles after closure, the most important parameter characterizing closure pattern was found to be h_4. Change of the h_4 distance (as an indication of convergence) over a time period is given in Figure 6 for

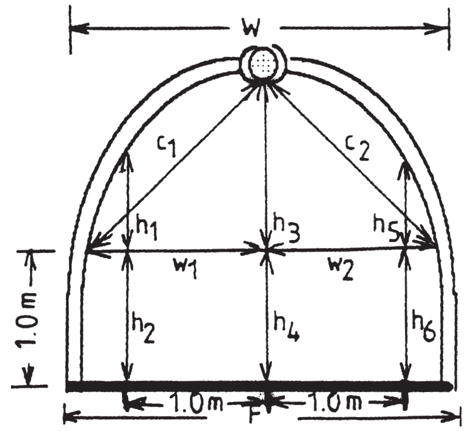


Figure 5—Method of convergence measurement

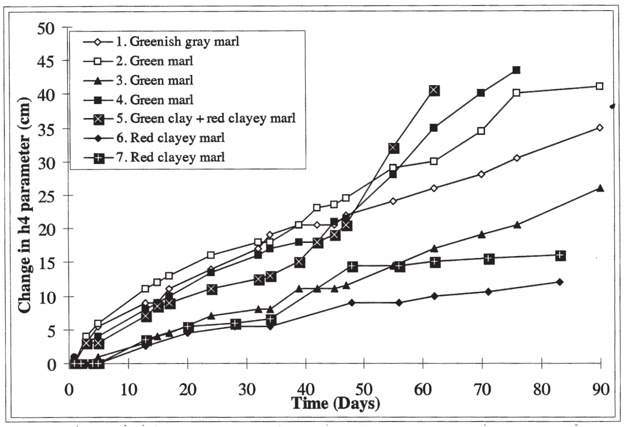


Figure 6—Change in h4 parameter as an indication of vertical closure in a period of three months

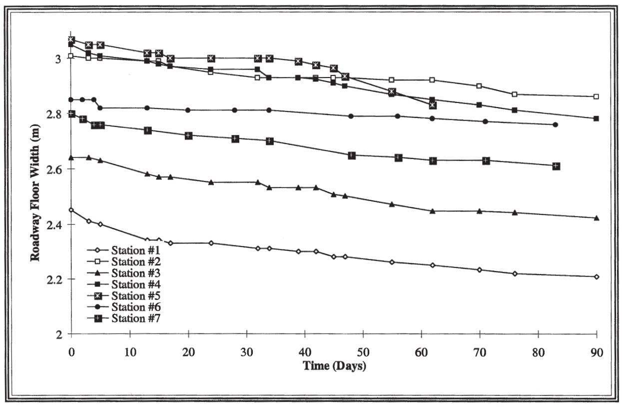


Figure 7—Change in the floor width at different convergence measurement stations in a period of three months

different convergence measurement stations. Convergence measurement results have shown that high amounts of floor heave with some side closure were observed in stations 1, 2, 3, 4 and 5. In stations 6 and 7 which were supported by steel arches with concrete lining, low amounts of floor heave were observed during 90 days of measurements.

Changes of tunnel widths at the floor level at seven convergence measurement stations are presented in Figure 7. The highest side closure at the floor (27 cm) was observed in station number 4. Decrease in floor width was found to be 22 cm in stations 1 and 5, 21 cm in station 3, 19 cm in station 7, 15 cm in station 2 and 9 cm in station 9. After the interpretation of results, no statistically significant relationship between original width and floor closure could be obtained. Floor closures in stations 6 and 7 supported by steel arches with concrete lining, were low as expected. However, floor closure in station 7 which was opened parallel to syncline axis, was higher than that of station 6 which was opened normal to syncline axis.

A rapid increase in the h_4 parameter, (that is an indication of vertical closure) and floor closure was observed approximately 47 days after the beginning of measurements. As it can be seen in Figure 4, a decline from +750 to +700 was being driven during these measurements. A rapid increase of convergence, especially at stations 5 and 4 which were the nearest to the decline, was attributed to interaction between the roadway and the decline. The distance between other stations and the decline increased with the advance of decline. Therefore, no significant effect of interaction was observed at the other convergence measurement stations.

Relationship between *in situ* convergence measurement results, tectonics and mechanical properties of surrounding rocks

A detailed survey on geology and tectonics of the area has shown that, +750 main roadway was driven in an asymmetric syncline with an inclined axis. Therefore, the most important factor governing roadway deformation were residual stresses due to tectonic activities. Tilting of steel sets at about 25-30 cm along the axis of the roadway were observed due to residual stresses acting toward NW direction. Gate roadways of longwall faces were opened parallel to syncline axis and strike resulting in very poor stability conditions due to the great effect of residual tectonic stresses.

Deformations at the concrete lined 6th and 7th convergence measuring stations were significantly different. As surrounding rock and supporting parameters were the same, vertical and side convergence at station 7 which was located parallel to syncline axis were measured twice as much of converge at station 6 which was located normal to syncline axis. This is a good indication of the effect of residual tectonic stresses on stability.

Samples taken from nearby convergence measuring stations were tested in the laboratory to find various mechanical properties. However, no significant relationship between the mechanical properties of rocks and convergence results could be obtained. Engineering and mechanical properties of rocks at different convergence measurement stations were very similar to each other as can be seen from Table I. For that reason, it was concluded that deformational characteristics of the roadway were governed by tectonic stresses rather than surrounding rock parameters.

The red marl of station number 5 was found to have the lowest shear strength. The highest vertical and side closure were also recorded in station 5. In general, the amount of convergence increases in formations that have low cohesion and internal friction angle. Also, when the moisture content of rocks increase, roadway stability decreases.

Clay contents and engineering properties of samples were determined by hydrometer and Atterberg limits tests. It was observed that plasticity of rocks increase with clay content and eventually, swelling potential of rock also increase with plasticity index. The swelling potential of surrounding rock in +750 roadway was thought to be the second most important parameter affecting closure after residual tectonic stresses.

Samples were classified according to their plasticity indices as medium and high organic and inorganic silt. Clay contents of greenish gray clay, green clay, red marl and red clayey marl samples were found as 23%, 19%, 2%, 1% and 8% respectively. Activity values of greenish gray clay and green clay were calculated as 1.9 and 1.8 corresponding to medium swelling potential. Activity values of green marl, red marl and red clayey marl were low since their clay contents were not high. Therefore, swelling potential of green marl, red marl and red clayey marl were low. *In situ* moisture contents of greenish grey clay, green marl, green clay and red clayey marl were determined between 16%-18%, whereas natural water content of red marl was found as 12%. Plasticity index and moisture content of green clay sample were observed to be the highest among the samples tested.

Direct shear strength determinations have shown that red marl had the lowest cohesion (0.32 kg/cm^2) whereas cohesion of red clayey marl and green clay were 0.90 and 0.96 kg/cm^2 respectively. Internal friction angle of green clay was the lowest as 24°.

Conclusions and recommendations to maintain stability of the roadway

Excessive deformations in the +750 roadway and the other roadways especially when they are opened parallel to syncline axis, necessitated floor dinting and side ripping to maintain the functions of the roadways as railway transport, ventilation, etc. It had often been a practice in the mine to be engaged with repair work rather than production. It should be kept in mind that dinting and side ripping would only be a temporary solution. Although repair work was very costly, it promoted further deformation in an accelerated rate. Therefore, a strategy of roadway positioning drivage and supporting should be sought so as to minimize repair work that supplies only a temporary solution at great cost.

Recommendations to maintain stability in the light of *in situ* measurements, laboratory tests and a comprehensive geotechnical study are given below.

- Main roadway should be opened in calcareous limestone at the roof and their axis should be positioned in the direction perpendicular to syncline axis wherever possible.
- In order to minimize floor heave, an invert arch should be constructed.
- Underground water should be drained effectively especially when the surrounding rock has swelling potential.
- Yieldable arches should be used instead of rigid arches.
- The most recent method of maintaining stability in an opening excavated in rock is based on the combination of rock mass and the support as an integrated component. Therefore, the basic idea of supporting of underground openings is to use the surrounding rock mass itself as the support medium. The use of rock bolts is strongly recommended to maintain the stability of gate roadways, since bolts reinforce the medium by constraining movements and increasing frictional resistance between individual blocks Unver[4].
- Instead of three-piece steel sets that contain corners where high stress concentrations and a decrease in the surrounding rock strength occur, deforming arches, and, arch-shaped supports should be preferred.
- In addition to above precautions, struts should be placed under steel sets, and lagging should be performed properly to maintain combined functioning of individual steel sets. Cross-sectional area should be designed to be somewhat larger during drivage to tolerate some deformation. However, it should be kept in mind that larger cross-sectional area may increase the rate of deformation.

This research has indicated that residual stresses due to previous tectonic activity may play the primary role in the overall stability of a mine or an underground excavation.

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