Türkiye 16. Madencilik Kongresi / *16th Mining Congress of Turkey,* 1999, ISBN 975-395-310-0

ADVERSE EFFECTS OF SOFT FLOOR STRATA ON THE STABILITY OF COAL PILLARS

YUMUŞAK TABAN TABAKALARININ KÖMÜR TOPUKLARININ- DURAYLIĞINA OLUMSUZ ETKİLERİ

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ABSTARCT: This study is based on a research program, in which adverse effects of soft floor on the stability of pillars were investigated. For this purpose, a number of two- and three-dimensional physical model tests were conducted. The results of the tests have shown that roof and floor strata conditions play an important role on the stability of longwall pillars with medium and low strength characteristics.

ÖZET: Bu çalışmada, yumuşak taban tabakalarının uzunayak topuklarının duraylığına olumsuz etkileri incelenmiştir. Bu bağlamda, çeşitli sayılarda iki ve üç boyutlu fiziksel model testleri gerçekleştirilmiştir. Çalışmanın sonucunda, tavan ve özellikle yumuşak taban tabakalarının yumuşak ve orta sertlikteki uzunayak topuklarının duraylığı üzerinde oldukça etkili olduğu gözlenmiştir.

1. INTRODUCTION

Strength of pillars have been discussed in relation to their dimensions taking into account the size and shape factors. The effect of these factors on the compressive strength of coal pillars was proven from tests conducted using cubic or prismatic coal blocks in both laboratory and in-situ conditions (Bieniawski, 1968). Although these factors play a significant role on pillar strength, they are found inadequate to characterise the strength of pillars in conditions where the roof and floor include clays or other low strength strata. In such conditions, if the pillar is assumed to be relatively stronger than the rock strata above and/or below it, failure is expected to commence inside the rock strata rather than the pillar. If there is not much difference between the strength of pillar and the rock strata, pillar failure begins from the ribside region, and gradually propagates inside the pillar core. During this process, the effective load bearing area of pillar decreases, and eventually stresses become high enough to exceed the strength of the strata above or below the pillar. Accordingly, confinement which is offered by the roof and floor would be minimal or even negative, and this may cause pillars to yield by tensile rather than compressive failure. As a result, inadequate design may lead to bearing capacity failure of mine floor, collapse of the immediate roof strata and/or failure of the pillar in a localised manner or over extensive areas, eventually leading to surface subsidence.

Floor failure is generally accompanied by floor heave (also referred to as squeeze, lift, creep, or pillar punching) in the entries surrounding coal pillars. The results of numerous underground investigations in coal mines indicate that floor heave is caused or accelerated by the following general factors:

- Weak floor
- High strata pressures,
- Roadway size and shape, and
- Existence of water in the floor strata.

According to Rockaway et al., (1979), heaving mine floors have been observed since 1892, and researchers have generally qualitatively attempted to describe this complex failure process. Some possible techniques have suggested to remedy this complex situation, or at least to mitigate its adverse effects.

2. FOOR BEARrNG CAPACITY ANALYSES

The ultimate bearing capacity of a soil or weak strata is defined as the maximum load that may be applied by a foundation (a pillar in this case) to the supporting strata without failure of the strata occurring. The ultimate load is defined easily if the load-deformation characteristics of the mine floor are known. Bearing capacity failure of the supporting material in soil mechanics are distinguished in the following modes:

- General shear,
- Local shear, and
- Punching shear failure.

These failure modes are commonly observed in foundation problems at shallow depths, and failure of mine floors with one of the modes given above is generally attributed to uniaxial loading conditions. In contrast to the soil mechanics problems, horizontal stresses due to Poisson's effect or other reasons such as frozen or tectonic stresses exist in underground mine strata. Although the confinement against the uniaxial failure of mine floor is supplied by the horizontal stresses, and therefore, the bearing capacity of mine floor is improved, excessive horizontal stresses may also cause buckling type of floor failures especially where the floor strata are composed of thin layers of rock or laminated strata.

As far as the author is concerned, apart from the numerical methods such as the finite element method or finite difference method which are able to solve geotechnical problems by making reasonable assumptions and approximations, so far, only a few number of formulae which yield approximate solutions, have been proposed concerning the load bearing capacity of mine floor. These solutions are mainly based on footing problems in the soil mechanics. In the derivations of these solutions, only single footing problems are considered (i.e. It is assumed that there is a long distance between two footings or only one footing exists). In considering the distance between pillars underground, interaction between two footings is inevitable, and this also complicates the solution of the problem.

In the calculation of the ultimate load bearing capacity of a footing which represents a problem of elasto-plastic equilibrium, an analysis which was first proposed by Prandtl, (1921), is commonly used. In the analysis, a rectangular footing which rests on a semi-infinite soil mass is considered. The strength properties of the soil (C and ϕ) are defined by a straight line of Mohr's envelope. The footing is represented by a uniform load due to the weight of the footing. Prandtl subdivides the failure zone into three distinct areas as shown in the Figure 1. These zones are composed of an active zone (zone 1), a radial shear zone (zone 2), and a passive zone (zone 3). Since the plate is frictionless immediately beneath the footing, the major principal stress is in the vertical direction and the failure surface shown Figure 1 makes an angle at 45 + (0/2) to the horizontal.

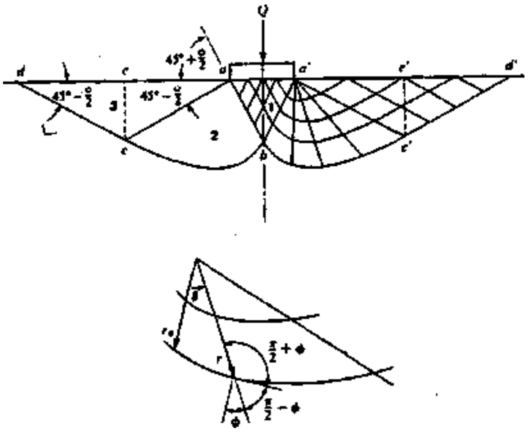


Figure 1 Bearing capacity problem with shallow foundations (Wu, 1976).

Accordingly, away from the footing, i.e. in zone 3, the movement is predominantly horizontal. Therefore, the failure surfaces in this zone makes an angle of 45 + ($\phi/2$) to the horizontal. It is also noted that the two sets of slip surfaces must intersect each other at an angle of 90 + ($\phi/2$). This requirement is met if the curve has the shape given by

$$r = ro \,.\, e^{\theta . \tan \phi} \qquad (1)$$

where ro is the reference radius, θ is the angle between ro and the radius r. This curve is also called as logarithmic spiral. The failure surface varies from an arc for a $\phi = 0$ condition to a logarithmic spiral for $\gamma = 0$ condition. An analytical solution for the general case where a soil has both cohesion and friction, the following formula is used:

$$q_{ult} = C.Nc + \gamma\, D\, Nq + 1/2\, \gamma\, Wp\, N_\gamma \qquad (2)$$

where
Quit= ultimate load bearing capacity,
C = cohesion of the soil,
Wp = pillar width,
D = depth of footing,
ϕ = internal friction angle of the soil,
γ = unit weight of the soil, and
Nc, Nq and Ny are the constants used in the equation, and they can be determined by using the following equations:

$$Nq = (e^{\pi \tan\phi}) \tan^2 (\pi/4 + \phi/2) \qquad (3)$$

$$Nc = (Nq-1)\cot\phi \qquad (4)$$

$$N\gamma \cong 2\,(Nq-1)\tan\phi \qquad (5)$$

The coefficients Ne, Nq, and Ny are called the bearing capacity factors for shallow continuous footings.

Equation 2 include the effect of surcharge on the bearing capacity of floor, since it was first derived for surface foundations. The formula, therefore, can be modified for mine floor as follows;

$$q_{ult} = 1/2\,\gamma\,Wp\,N_\gamma + C.Nc \qquad (6)$$

Working on the similar lines to Prandtl's analysis, Terzaghi, (1943) produced a formula which allows for the effects of cohesion and friction between the base of strip footing (pillar in this case) and the floor. He assumed that the angle (a) in the zone 1 equals to internal friction angle (ϕ). He derived a similar formula given by Equation 2 but the values of the constants Nc and Ny were different. For square and rectangular footings these formulae are given as follows (Smith, 1990).

- for a square footing,

$$q_{ult} = 1.3\,C\,Nc + 0.4\gamma Wp N\gamma \qquad (7)$$

- for a rectangular footing,

$$q_{ult} = C\,Nc\,(1+0.3\,Wp/\,Lp\,) + 0.5\,\gamma\,Wp\,N\gamma\,(1-0.2\,Wp/\,Lp) \qquad (8)$$

where
%lt = ultimate bearing capacity,
C = cohesion of the floor stratum,
Wp = pillar width, and
Lp = pillar length,

Unlike most of the surface foundations, interaction occurs between two pillars due to the short distance which is equal to roadway width. Therefore, shallow foundation solutions given above do not adequately represent the bearing capacity of mine floor.

3. PHYSICAL MODELLING STUDIES

Strata control problems can be investigated by means of different techniques. None of these techniques, however, is unique, i.e. each has its own capabilities and limitations. For example, the physical modelling technique gives better results in observing fracture developments step by step during the loading of modelled structures and determines failure modes such as buckling, fracture propagation, spalling etc., numerical modelling is more convenient for determination of stress magnitudes and directions as well as concentration of stresses and failed areas. For this reason, it was decided to employ two-dimensional physical modelling to investigate adverse effects of soft floor strata upon pillar stability.

In the physical modelling investigation, a number of two-dimensional physical models were prepared. Each model was built with one of four different sized pillars and each size of pillar was tested in two different stress fields. The stress field« varied from a uniaxial field with lateral constraint, to a hydrostatic stress field. The results of these tests show the influence of the stress field on the various pillar configurations, the behaviour of the pillars and the fracture pattern development around the pillars (Figure 2).

Figure 3 illustrates a pillar having a width of Wp and infinite length with two different stress environment, namely dominant vertteal and hydrostatic stress regimes. The floor immediately beneath the pillar is assumed to be under compression similar to a specimen in a triaxial compression test. If the strata beneath the pillar is composed of only one layer, failure would be dependent upon the strength characteristics of the rock mass and the dominant stresses acting in the floor strata. If the prevailing stress regime is that of dominant vertical ($\sigma v = 3\sigma h$), failure is expected to commence beneath the pillar, and propagates through the roadway. This case is similar to the footing problems in soil mechanics. In the hydrostatic stress regime ($\sigma v = \sigma h$), the confinement given to rock beneath the roadway is comparably higher than that from the dominant vertical stress regime. In this case, floor failure is not expected to start beneath the pillar, but it may occur in the rock under the roadway. This is because of the fact that the horizontal stress acting in the region B as the minor principal stress, while the horizontal stress acting in the region A is the major principal stress (Figure 4).

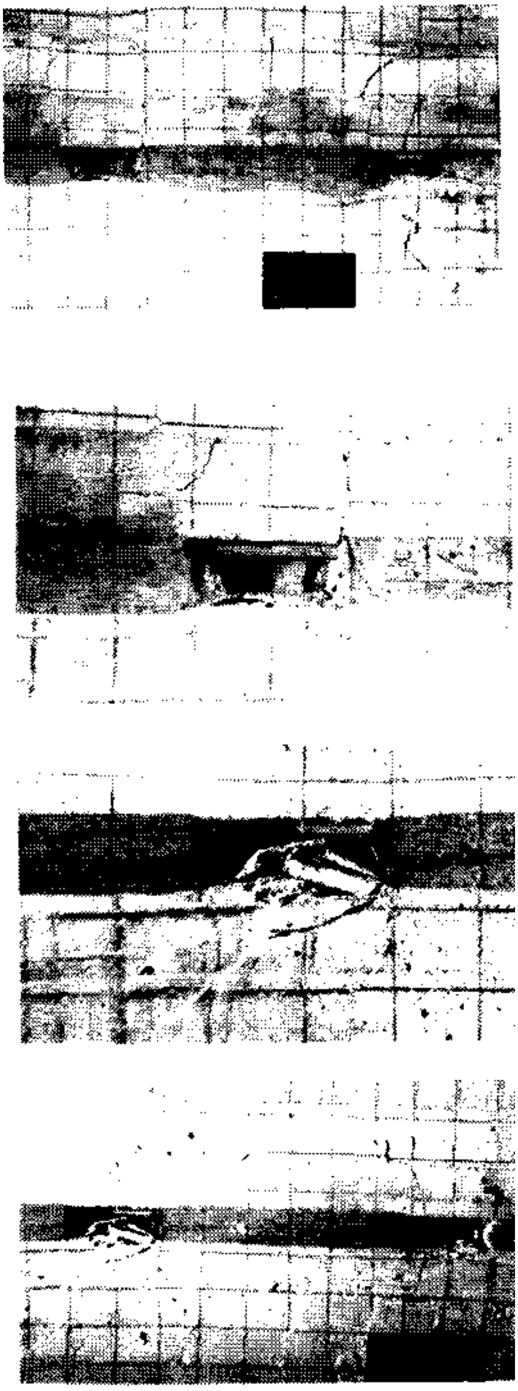


Figure 2 Two dimensional physical modelling test results

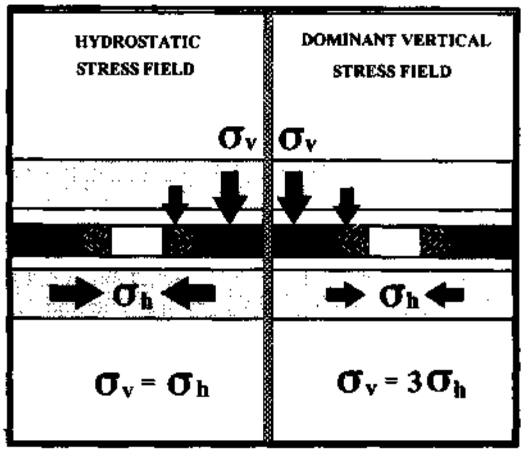


Figure 3 Variation of stress intensity with two different stress fields.

Since the floor immediately beneath a pillar is usually composed of various layers, the effect of floor loading on these layers should be studied carefully. Figure 5 shows the strata beneath the pillar are composed of two layers, these being a soft layer overlying a hard layer and vice versa. In the first case which is illustrated in Figure 5. *a,* the shear will be confined to the weaker material and the stronger will not be involved in the failure. The bearing capacity of the floor should be computed with the strength of the weaker stratum. If a strong layer overlies a soft layer, the thickness of the hard layer plays an important role because loads are spreaded into the soft layer (Figure 5. *b).* In this case, failure occurs by shear in the softer layer as the stronger layer bends down under load.

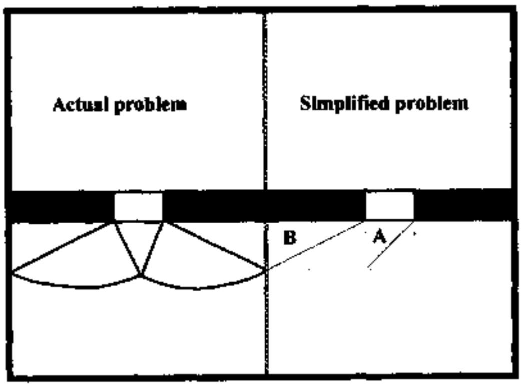
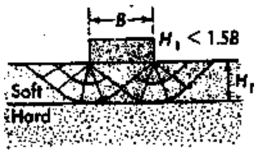
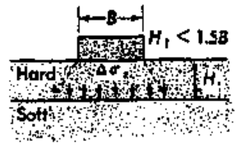


Figure 4 Actual and simplified pillar bearing capacity problem.



a- Soft layer over hard; restricted shear zone



a- Hard layer over soft, load spread out

Figure 5 Bearing capacity of mine floor with two different strata conditions (Sowers, 1970).

Apart from the two dimensional physical model studies, a three-dimensional physical modelling investigation was also carried out to investigate the stability of pillars associated with a twin-entry gateroad system. In the modelling, a strong roof and soft floor strata condition was simulated in particular to observe the effects of the two different confining medium upon the roadway and the pillar stability.

Conventional physical modelling tests have been employed in two dimensions in which it is impossible to investigate some of the important parameters concerning the third dimension (i.e. the yield zone as a unit of area). Therefore, a special three dimensional rig shown in Figure 6 was constructed taking into account important factors such as geometrical scale and the rigidity of apparatus (i.e. good confinement without deformation).

As shown in Figure 6, a small scale gate road chain pillar system and/or room and pillar system was simulated. For reasons of simplicity, symmetry was taken into account so that model dimensions could be kept to a minimum. The model strata properties were selected to represent various layers of coal measures strata (i.e., hard roof-moderately strong coal-and weak floor, and hard roof, moderately strong coal and hard floor). The models prepared were cubes of 65 cm side length and approximately 600 kg in weight. Simulated thickness of roof and floor strata were applied as 25 m deep from the top and bottom line of pillars. Loading was simulated considering deep coal mining conditions (i.e. ~ 1000 m). Since it was impossible to simulate hydrostatic stress conditions with the model rig, the models were tested with uniaxial loading using a 5000 kN loading capacity testing press.

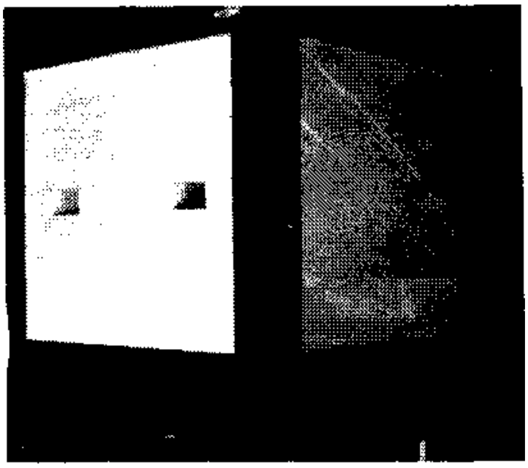


Figure 6 Three dimensional physical model test rig.

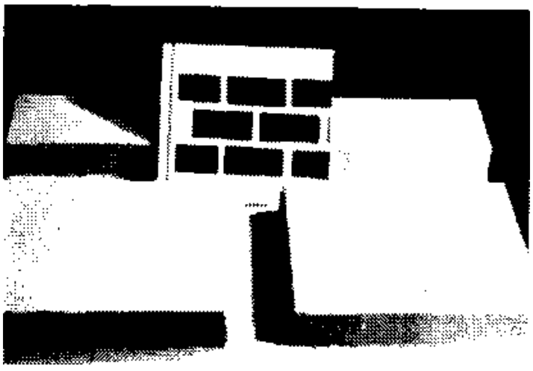


Figure 7 Simulated twin-entry pillar configuration.

4. RESULTS OF THE PHYSICAL MODELLING STUDIES

During the tests, the following aspects were investigated;

O Failure modes in pillars; whether the three distinct zones (i.e., fracture, yielding and intact zones) suggested by Barron, (1984, 1992) are formed as a result of pillar loading),

O The effect of end confinement given by the roof and floor strata upon the pillar and roadway stability,

O The risk of floor heave occurrence in roadways due to the interaction between the pillar and the floor strata with simulating the strong roof and the weak floor conditions, and

O Investigation of the stability of a twin-entry longwall pillar system under uniaxial loading conditions.

The results indicated that the model pillars had three distinct zones these being a fracture zone at the ribside, an intermediate pseudo-ductile zone and an intact zone in the middle. This was concluded after physically examining the failed pillar (i.e. solid pieces but highly fractured in the fracture zone and yielded powdery material between fracture zone and still intact core in the middle) and determining displacements of pre-located points on the pillar (Figure 8).

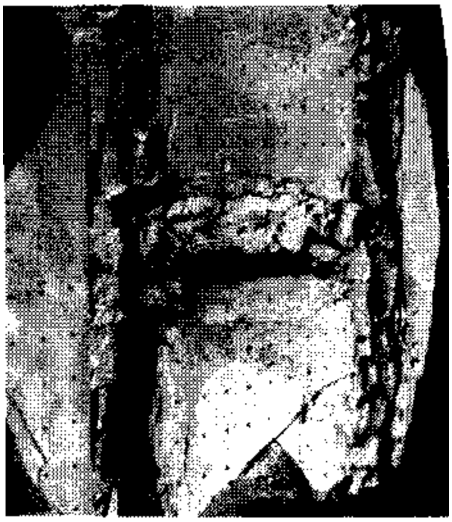


Figure 8 Pre-located measurement points on pillar.

The settlement profile of the floor strata also confirmed the existence of these zones. As demonstrated in Figure 9, an initial settlement of the weak floor strata beneath the pillar occurs when the pillar is in elastic state. Further increment of load brings about commencement of pillar fracturing from the all sides of the pillar. Meanwhile, load transfer occurs from the fractured zone on the solid core. The settlement of the floor continues beneath the intact core due to the load increment but no further settlement takes place beneath the fracture zone since the load taken by the fracture zone is constant (i.e., residual load). Similarly, if the pillar has two more zones (i.e., pseudo-ductile yielding zone and the intact core), secondary and tertiary settlement zones are formed. Although all the three zones were detected in the examined case, two or one settlement zones could have been developed depending upon the amount of load applied to pillars.

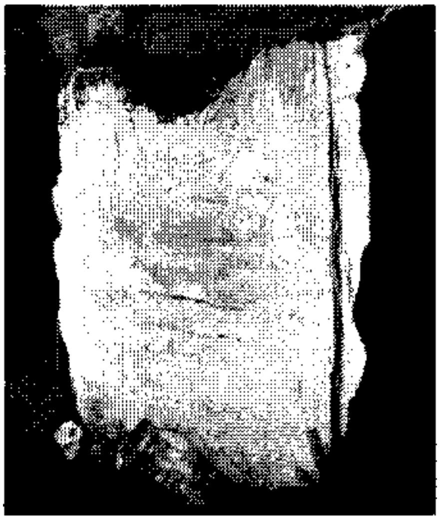


Figure 9 Settlement of floor beneath the pillar.

Figure 10 shows the deformation of roadways and pillars sandwiched between a strong roof and a weak floor. The Figure clearly indicates that the confinement offered to the pillar by the floor strata is negligible when compared to the strong roof strata (i.e., while the pillar was squeezed out at the bottom half of the pillar, there is no indication of pillar expansion at the upper half of the pillar). As a result, the asymmetric deformation of the pillar caused shear failures inside the ribside areas as well as the considerable amount of side closure in both roadways. The contribution of the floor heave to the total roadway convergence is far more greater than that from roof sagging as shown in Figure 10.

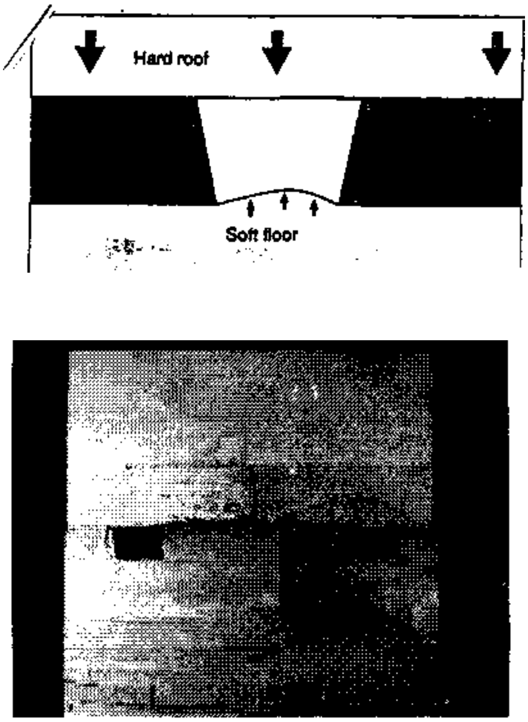


Figure 10 The effect of stiff roof and soft floor on the roadway convergence and rib displacements.

5. CONCLUSION

Two and three dimensional physical model studies showed that relatively roof and floor strata conditions play an important role on the stabilitiy of pillars. When designing underground pillars, possible adverse effects of roof and floor strata should be taken into consideration to minimise the risk of instability of pillars and surrounding openings.

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