OIL SHALE 1994, Vol. 11, No. 3

https://doi.org/10.3176/oil.1994.3.06

J.-R. PASTARUS

FAILURE MECHANISMS IN OIL-SHALE PILLARS

Abstract

Estonian oil-shale mines use the room-and-pillar mining system, where an important problem is the stability of the pillar and the failure process. The investigations showed that the type of failure mechanism which occurs (in vertical or inclined sections) depends on the stress field at the boundary of the pillar. An oil-shale pillar is stronger by the inclined section of failure mechanism.

Estonian oil-shale mines use the room-and-pillar mining system. The field of the oil-shale mine is divided into panels. Panels are sub-divided into mining blocks, each approximately 350 m (meters) wide and from 600 m to 800 m long. The height of the room corresponds to the thickness of the commercial oil-shale bed, about 2.8 m. The width of the room is determined by the stability of the roof. It is very stable when it has a dimension of 6-10 m. In this case the roof must still be supported by bolting. Actual mining practice has shown that it is best to use pillars with a square cross section. The cross-sectional area of the pillar is 30-40 m^2, depending on the depth of the oil-shale bed.

An important problem is the stability of the pillar and the failure process under overburden loading. The design for stability of the pillar requires knowledge about the rock mass itself and the prevailing state of stress near and in the pillar. Here, the theory of plasticity is used almost exclusively for finding upper bounds for ultimate loads. This is done by making calculations on the basis of failure mechanisms. If one knows from tests how a pillar fails, one can develop a good hypothesis for a failure mechanism. An excellent example of this is the failure of a pillar under the overburden loading in an oil-shale mine. Valuable results are obtained simply by considering a failure mechanism.

Mohr-Coulomb [1, 2] assumed that both internal cohesion, which is constant, and internal friction, which is proportional to the normal pressure on the sliding surface, had to be overcome in the sliding surface. This assumption can be formulated as follows [1, 2]:

$$\tau = C + \sigma \tan\varphi \quad (1)$$

where, τ - the shear stress along the sliding surface;

σ - the normal stress perpendicular to the sliding surface;

C - cohesion;

φ - the angle of friction.

By means of Mohr's circles we see that Equation (1) can be written in an x,y-coordinate system as [1, 2]:

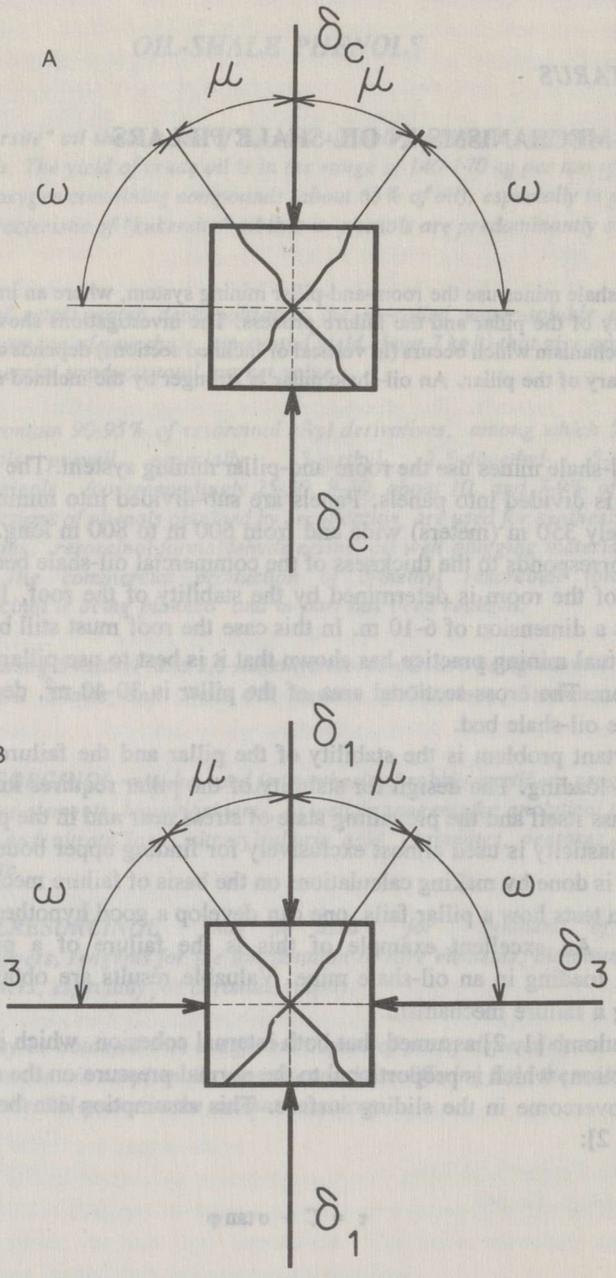


Fig. 1. The failure mechanism in a pillar with (*A*) uni-axial and (*B*) bi-axial compression: $\sigma 1$, $\sigma 3$ - the principal stresses; σc - uni-axial compression strength; μ, ω - the angle of the section, where the failure criterion is satisfied

$$(\sigma xx - \sigma yy)^2 + 4\tau xy^2 = \sin^2\varphi(\sigma xx + \sigma yy + 2C\cot\varphi)^2. \quad (2)$$

If uni-axial compression, σc, is introduced as the stress field, which is defined by $\sigma xx \neq 0$; $\sigma yy = 0$ and $\tau xy = 0$ (or $\sigma xx = 0$; $\sigma yy \neq 0$; $\tau xy = 0$), then the pillar failure is of the type shown in Figure 1*A* [1]:

$$\sigma c = 2C\cos\varphi/(1 - \sin\varphi). \quad (3)$$

In the same way as with uni-axial compression, the bi-axial compression, $\sigma 1$, can be introduced as the stress field. This is defined by $\sigma xx \neq 0$; $\sigma \neq 0$ and $\tau = 0$. Then failure is of the type shown in Figure 1*B*. From Equation (2) we find [1]:

$$\sigma 1 = \sigma c + \sigma 3(1 + \sin\varphi)/(1 - \sin\varphi), \quad (4)$$

where, $\sigma 1$ and $\sigma 3$ - the principal stresses.

According to Mohr-Coulomb's failure hypotheses the middle principal stress has no effect on the carrying capacity. In the case of uni- and bi-axial compressions, the failure criterion is satisfied in the section forming the angle μ between the major principal stress and the angle ω between the minor principal stress (see Figure 1), where [1]:

$$\mu = \frac{\pi}{4} - \frac{\varphi}{2}; \qquad \omega = \frac{\pi}{4} + \frac{\varphi}{2}. \quad (5)$$

This failure mechanism is often seen in the pillars in the centre of mining blocks. There, the major principal stress develops from the overburden loading.

Another type of pillar failure occurs when the failure criterion is satisfied in the section within the right angle between the minor principal stresses (parallel to the major principal stresses). This phenomenon is possible, if the shear stress occurs at the top of the pillar. The calculation method is depicted in Figure 2. It is evident, if the angle α between σxx and $\sigma 1$ stresses is equal to μ, then the aforementioned failure mechanism is possible. The angle, α, can be calculated using the expression presented by [2]:

$$\tan 2\alpha = 2\tau xy/(\sigma xx - \sigma yy). \quad (6)$$

Using Equations (2), (5) and (6), it is possible to forecast the conditions necessary for this failure mechanism.

If the stress field is given by $\sigma xx \neq 0$; $\sigma yy = 0$ and $\tau xy \neq 0$ (or $\sigma xx = 0$; $\sigma yy \neq 0$; $\tau xy \neq 0$), then failure occurs.

$$\tau xy = C; \qquad \sigma yy = 2C\tan\varphi. \tag{7}$$

In this case, if the stress conditions are satisfied, vertical cracks appear in the pillars at the perimeter of mining blocks.

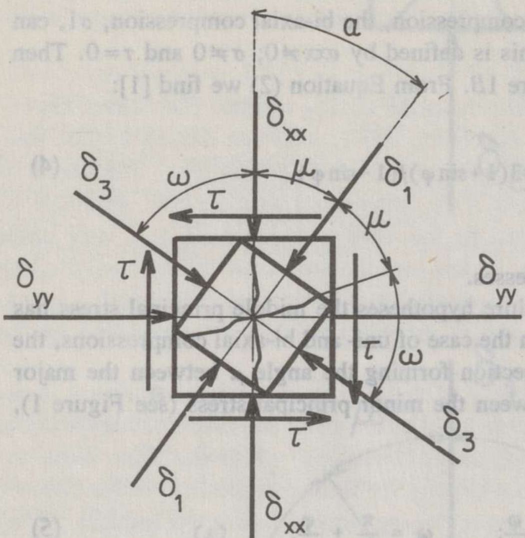


Fig. 2. The failure mechanism in a pillar with shear stress: $\sigma 1$; $\sigma 3$ - the principal stresses; σxx; σyy - x and y component of stresses; μ; ω - the angle of the section, where the failure criterion is satisfied; τ - the shear stress; α - the angle between σxx and $\sigma 1$ stresses

If all components of stress are given, the equation calculations are cumbersome and time consuming. Results for such calculations are presented in Figures 3 and 4. It is apparent that if the value of the friction angle increases, the value of the ratios $\sigma yy/\sigma xx$ and $\tau xy/\sigma xx$ decrease. In the case where the value of C goes up, the ratio of $\sigma yy/\sigma xx$ falls (see Figure 3*A*) and $\tau xy/\sigma xx$ increases (see Figure 3*B*). The influence of the σyy on the value of $\sigma yy/\sigma xx$ and $\tau xy/\sigma xx$ is contrary to the aforementioned behaviour (see Figure 4).

A quantitative example provides some typical conditions for pillar failures. The mechanical parameters of a non-homogeneous oil-shale pillar are as follows:

$C = 4$ MPa;

$\varphi = 37.7^0$.

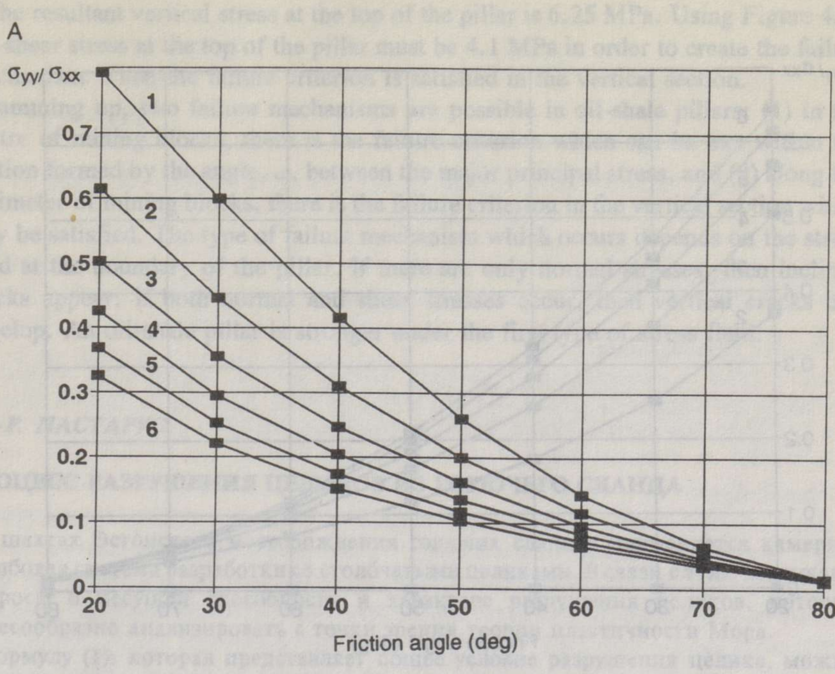
In these calculations, the uniaxial compression is equal to 16.2 MPa. This compression value corresponds to the actual value with the following conditions:

Depth of the mined oil-shale bed - 40 m,

Density of overburden rock - 2.5 10^{-2} MN/m^3,

Pillar cross-sectional area - 36 m^2, and

Width of the room - 9 m.



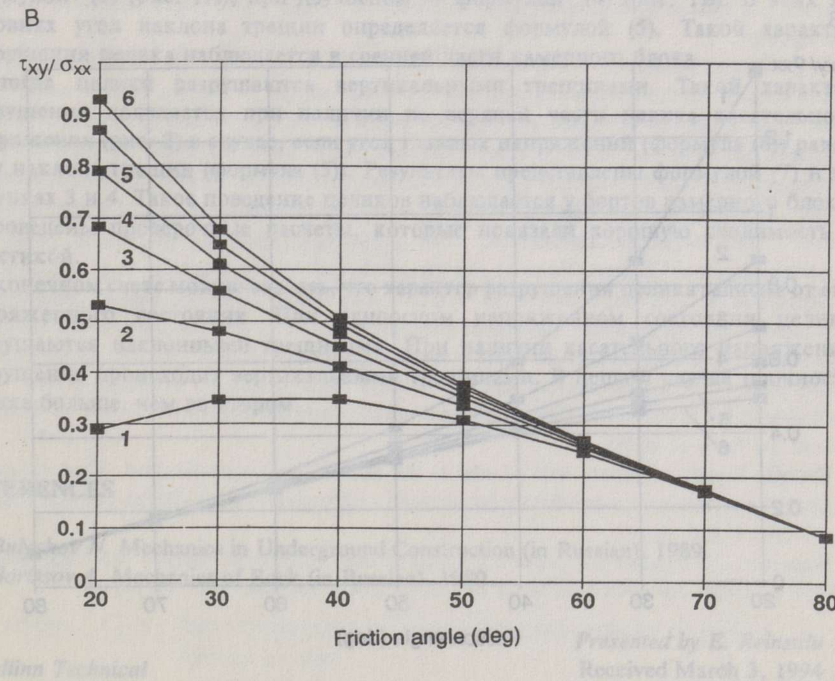


Fig. 3. The dependence of ratio (*A*) $\sigma yy/\sigma xx$ and (*B*) $\tau xy/\sigma xx$ on the friction angle and cohesion ($\sigma yy = 4$ MPa); where cohesion (MPa) is equal to 0 (*1*); 2 (*2*); 4 (*3*); 6 (*4*); 8 (*5*); 10 (*6*)

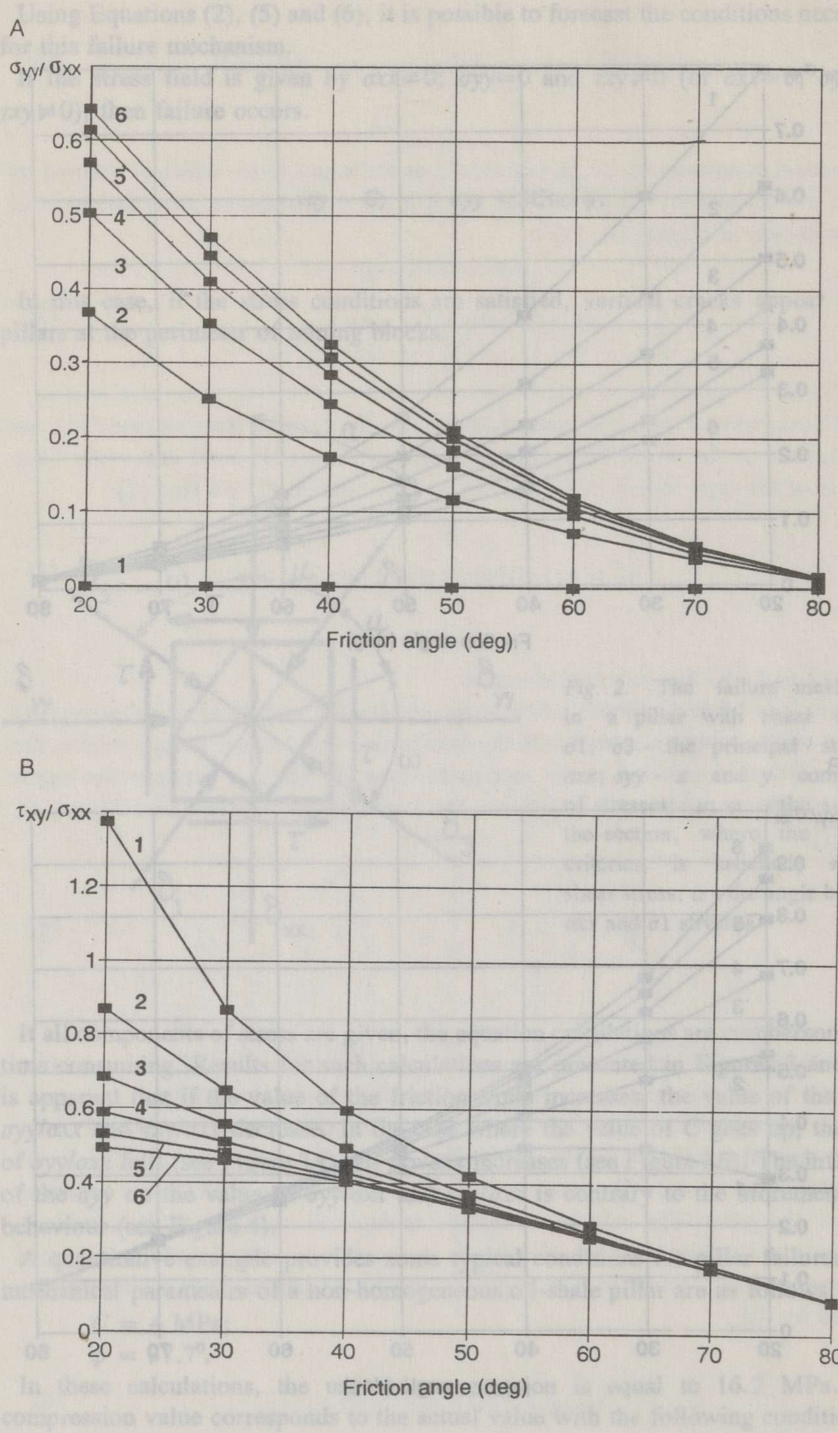


Fig. 4. The dependence of ratio (*A*) $\sigma yy/\sigma xx$ and (*B*) $\tau xy/\sigma xx$ on the friction angle and σyy stress ($C = 4$ MPa); where σyy (MPa) is equal to 0 (*1*); 2 (*2*); 4 (*3*); 6 (*4*); 8 (*5*); 10 (*6*)

The resultant vertical stress at the top of the pillar is 6.25 MPa. Using Figure 4*B*., the shear stress at the top of the pillar must be 4.1 MPa in order to create the failure mechanism. Then the failure criterion is satisfied in the vertical section.

Summing up, two failure mechanisms are possible in oil-shale pillars: (1) in the centre of mining blocks, there is the failure criterion which can be met within the section formed by the angle, ω, between the major principal stress, and (2) along the perimeter of mining blocks, there is the failure criterion in the vertical section which may be satisfied. The type of failure mechanism which occurs depends on the stress field at the boundary of the pillar. If there are only normal stresses, then inclined cracks appear; if both normal and shear stresses occur, then vertical cracks can develop. An oil-shale pillar is stronger under the first type of stress field.

Ю.-Р. ПАСТАРУС

ПРОЦЕСС РАЗРУШЕНИЯ ЦЕЛИКОВ ИЗ ГОРЮЧЕГО СЛАНЦА

На шахтах Эстонского месторождения горючих сланцев применяется камерно-столбовая система разработки со столбчатыми целиками. В связи с этим возникают вопросы о несущей способности и характере разрушения целиков, которые целесообразно анализировать с точки зрения теории пластичности Мора.

Формулу (1), которая представляет общее условие разрушения целика, можно переписать в координатах *x,y* — формула (2).

Условие прочности целика при одноосном напряженном состоянии представлено формулой (3) (рис. 1*A*), при двухосном — формулой (4) (рис. 1*B*). В этих же условиях угол наклона трещин определяется формулой (5). Такой характер разрушения целика наблюдается в средней части камерного блока.

Иногда целики разрушаются вертикальными трещинами. Такой характер разрушения появляется при наличии на верхней части целика касательного напряжения (рис. 2) в случае, если угол главных напряжений (формула (6)) равен углу наклона трещин (формула (5)). Результаты представлены формулой (7) и на рисунках 3 и 4. Такое поведение целиков наблюдается у бортов камерного блока.

Проведены проверочные расчеты, которые показали хорошую сходимость с практикой.

В конечном счете можно сказать, что характер разрушения целика зависит от его напряженного состояния. При одноосном напряженном состоянии целики разрушаются наклонными трещинами. При наличии касательного напряжения разрушение происходит вертикальными трещинами. В первом случае прочность целика больше, чем во втором.

REFERENCES

1. *Bulychov N.* Mechanics in Underground Construction (in Russian). 1989.
2. *Borissov A.* Mechanics of Rock (in Russian). 1980.

Presented by E. Reinsalu
Received March 3, 1994

Tallinn Technical University
Tallinn, Estonia