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THE ROLE OF POREWATER PRESSURE AND SEEPAGE FORCES ON THE STABILITY OF PROTECTION LAYERS

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ABSTRACT

During the study of water inrushes from karstified aquifers into coal mines in Slovenia (NW Yugoslavia) we realised, that for the determination of a safe thickness of the protection layer porewater pressure and seepage forces within the protection layer must be taken into account. The stability of the protection layer can be enhanced with an appropriate drainage of the protection layer.

INTRODUCTION

The basement of the Tertiary coal basins of Slovenia is in many places a higly permeable Triassic dolomite (Zagorje, Trbovlje, Hrastnik, Velenje and others), in others a karstified Cretaceous limestone (Kanižarica). Between the coal seams and these aquifers there is a clayey or marly sediment of variable (0-100 m)and often insufficient thickness to protect the mine workings from water inrushes from the carbonate aquifers. In small mines (Kanižarica) only a passive protection with a protection layer of sufficient thickness is feasible. As there are considerable coal reserves within this protection layer its thicknes must be carefully determined.

In some of the Slovenian coal basins the basement exhibits a very pronounced paleorelief. Above old depressions the coal seams are high above the permeable basement, in other places they overlap the basal Tertiary sediment and are in direct contact with the karstified limestone or dolomite. In these places water inrushes not only from the bottom, but also from a lateral direction are posible.

For the determination of the safe thickness of a protection layer, we have to know the possible processes of its failure. But these processes are not allways well known, as there are only few detailed accountsof heavy inrushes. Usually one of the two following processes is assumed:

- The inrush is the consequence of a sudden total failure of the whole block of the protection layer between the mine workings and the aquifer.
- The inrush is due to some piping processes on the walls or bottom of the mine workings.

On the following pages we consider some factors influencing water inrush risks for simple models of mine workings in the vicinity of aquifers with very high permeabilities. For the aquifer we adopted two extreme models:

- A rock with a perfectly homogeneous permeability. In nature it is approximated quite well by a fractured dolomite.
- A channel in a permeable, fractured zone in an otherwise nearly impermeable rock. This model suits a karstified limestone.

The protection layer, i.e. the rocks between the mine working and the aquifer, must never be considered as impermeable, but exhibits allways some intergranular porosity or is partly fractured. It must therefore be considered as semipermeable.

THE ROLE OF POREWATER PRESSURE ON THE SHEARING RESISTANCE OF THE PROTECTION LAYER

If the rock masses of the protection layer are not subject to piping proceses their stability can approximately be evaluated by determinig the shearing strength of the block between the mine workings and the aquifer. The rocks of the protection layer exhibit allways some porosity and therefore the shearing resistence depends on the effective normal stress

$$\sigma' = \sigma - p$$

The shearing strength which we must take into account is therefore

$$\tau_c = \sigma' \text{ tg}\,\varphi + c = (\sigma - p) \,.\, \text{tg}\,\varphi + c$$

as it is common practice in stability analyses of slopes on the surface. The meaning of symbols in the equations is: σ total normal stress (N/m2), σ' effective normal stress (N/m²), τ_c shearing strength (N/m²), φ angle of internal friction, c cohesion (N/m²), p porosity.

Suppose a mine workings in a horizontal or gently dipping part of the coal seam which ends abruptly against an aquifer. The stability of the protection layer can be approximately evaluted by supposing a sliding of the whole block between the aquifer and the mine workings along two horizontal sliding surfaces, one at the top, the other at the bottom of the mine workings. A change of the porewater presure along the potencial sliding planes will be accompanied by an opposite change of the effective stress.

In cases of a horizontal or gently inclined seam and an aquifer below and parallel to it, the potential sliding surfaces are more or less vertical (fig 1). The effect of a reduction of the porewater pressure on the shearing resistance along the two vertical sliding surfaces in not so obvious. It depends on Poisson's ratio of the rock and on the horizontal component of the hydraulic gradient. We shall suppose that with an adequate system of drainage holes the porewater pressure in the protection layer below the mine workings is locally reduced for the short lifetime of the mine workings from its original value H to the value h. We also suppose that outside the block the porewater pressure retains in a relatively short distance its original value H. The hydraulic gradient (i) will be more or less horizontal. On every unit volume of the rock it will exert a seepage force

$$dF = -\, i \,.\, \gamma_w$$

The seepage force on a sedimental column of unit section between a point A outside the drained block and a point B inside the block equals

$$\int_A^B dF = -\int_A^B \gamma_w \; i \, . \, dl = \int_A^B \gamma_w \, . \, dh$$

$$F = \gamma_w \; (H-h) = \Delta p$$

In this case the reduction of the perewater pressure Δp will therefore also cause an adequate increase of the effective stresses. In reality the flownet in the drained block will not be very regular and the mentioned effect of the drainage is only a rough approximation of the real effect.

Mine workings are usually of great length. Therefore, we can neglect the threedimensional stress field at the ends and consider the equilibrium condition for the planar stress field in the middle part of the mine workings for a slice of unit thickness. The forces are therefore in N/m.

We have to take into account also the weight W of the column of the protection layer between the mine workings and the aquifer.In cases of limit equilibrium the summ of the shearing resistance at the two sliding surfaces 2T and the weight W equals the bouyancy U

$$W + 2T - U = 0 \qquad (1)$$

Knowing the piezometric head of the aquifer and the density of the protection layer, the weight of the rocks W and the buoyancy U can be determined quite accurately. To determine the shearing resistance of the sliding planes we have to know the total horizontal principal stress σ_h which is usually only a fraction α of the total vertical principal stress σ_v. The fraction α was determined in some Slovenian coal basins by pressiometers. The results were $0{,}6\sigma_v \leq \sigma_h \leq 0{,}75\sigma_v$

In the following equations we will adopt the bottom of the protection layer as a zero level, and apply the following notation

P	elevation of the ground level	(m)
H	piezometric head of the aquifer	(m)
h_o	level of the mine workings	(m)
l	level of any point along the sliding surfaces	(m)
a	width of the mine workings	(m)
W	weight of the column of the protection layer	(N/m)
U	buoyancy of the protection layer	(N/m)
T	shearing resistance along one potential sliding plane	(N/m)
γ_w	unit weight of water	(N/m^3)
γ_r	unit weight of rock	(N/m^3)
σ_v	vertical principal stress	(N/m^2)
σ_h	horizontal principal stress	(N/m^2)
σ'	effective stress	(N/m^2)
α	horizontal to vertical stress ratio	
φ	angle of friction	
c	cohesion	(N/m^2)
p	porewater pressure	(N/m^2)

With these notations we have

$$W = a \, . \, h_o \, . \, \gamma_r \qquad (2)$$
$$U = a \, . \, H_o \, . \, \gamma_w \qquad (3)$$

The shearing strength equals

$$\tau_c = \sigma' \; tg\varphi + c = (\sigma_h - p) \; tg\varphi + c. \qquad (4)$$

The horizontal principal stress at the level l above the aquifer is

$$\sigma_h = \alpha \gamma_r (P - l) \qquad (5)$$

The porewater pressure at this point depends on the permeability distribution within the protection layer.

In the follwing we shall evaluate the effect of drainage by analysing the stability of the protection layer for three different porewater pressure distributions.

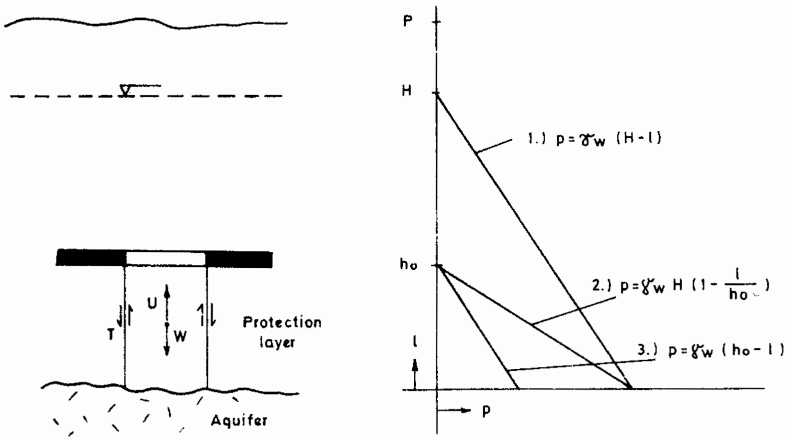

Fig. 1. Model for the evaluation of the stability of protection layers against bottom aquifers.

1. The most unfavorable case is a completely impermeable layer immediately underlying the mine workings. The porewater pressure will correspond to the piezometric level H. At an elevation l above the aquifer the pressure is

$$p = \gamma_w (H - l) \qquad (6.1)$$

2. The porewater pressure decreases linearly from the aquifer,

$p_{l=0} = H \cdot \gamma_w$ to $p_{l=h_o} = 0$ at the mine workings

$$p = \gamma_w H \left(1 - \frac{l}{h_o}\right) \qquad (6.2)$$

3. The protection layer below the mine workings is drained. The porewater pressure corresponds to the depth below the mine workings by the following relation

$$p = \gamma_w (h_o - l) \qquad (6.3)$$

Using (5) and (6.1), respectively (6.2), or (6.3) in (4) and integrating from 0 to h_o we get three different values of the shearing resistance T. Applying these values in the equilibrium equation (1) we have three equations for the minimum thickness h_o for the three assumed casses.

All of them have the following form

$$Ah_o^2 + Bh_o + C = 0 \qquad (7.1)$$

The meaning of the parameters A, B and C is as follws

	A	B	C	
case 1	$(\gamma_w - \alpha\gamma_r)$ tg φ	$a \cdot \gamma_r + 2[(\alpha\gamma_r P - \gamma_w H) tg\varphi + c]$	$- a H\gamma_w$	(7.2)
case 2	$\alpha\gamma_r$ tg φ	$- [a\gamma_r + (2a\gamma_r - \gamma_w H) tg\varphi + 2c]$	$- a H\gamma_w$	(7.3)
case 3	$(3\gamma_w tg\varphi + \alpha\gamma_r) tg$	$- (2\alpha\gamma_r P tg\varphi + a\gamma_r - 2c)$	$+ a H\gamma_w$	(7.4)

Multiplying with the safety factor we obtain the safe thickness of the protection layer above bottom aquifers in rocks not subject to piping for the three mentioned pressure distributions.

The calculation for a mine at a depth P = 270 m, tg φ = 1, c = 0 shows a reduction of the safe thickness of the protection layer from case 1 to case 2 of nearly 50 %, and from case 1 to case 3 of nearly 75 %.

PIPING PROCESSES AND HYDRAULIC GRADIENTS

In rocks subject to piping processes water inrushes can occur at relatively great distances from aquifers. Experiences in Hungarian coal mines show that in these cases there is a strong dependance between the frequency and yield of inrushes on one side and the thickness of the protection layer on the other side (Kesserü, 1982, 95). The most used criterion to express the danger of an inrush is the mean gradient between the aquifer and the mine workings

$$\bar{I} = (H - h_o)/L \qquad (8)$$

which should not exceed a critical value. Instead of the mean gradient its reciprocal value, the specific thickness of the protection layer, $\nu = 1/\bar{I}$ (expressed usually in m/bar) is generally used. Based on experiences in Hungarian coal mines, a gradient $\bar{I}$ = 5 to 6,6 (or specific thickness ν = 1,5 to 2 m/bar) is considered safe enough for the geologic conditions in Hungarian and also in Slovenian coal mines.

The critical region for inrushes accompanied by piping processes is the wall of mine workings. Only here there is room for the beginning of the process. The gradients in the protection layer depend in a high degree on inhomogeneities of the protection layer and can therefore be predicted only in simple cases. To examine the adequacy of the criterion of the critical mean hydraulic gradient let us consider the gradient in a perfectly homogenous and isotropic, semipermeable protection layer for a steady-state flow. If its permeability is much lower than the permeability of the aquifer the hydraulic gradients can be evaluated using the image method. Consider the hydraulic gradient on the perpendicular from the mine workings with a circular cross section to the aquifer. At a distance r from the centre of the mine workings the gradient is:

$$i = \frac{q}{2\pi k \cdot r} + \frac{q}{2\pi k (2L - r)} = \frac{q}{2\pi k \cdot r \cdot (1 - r/2L)}$$

Here is

- q yield of the inrush (m^3/s)
- k permeability of the protection layer (m/s)
- r distance from the centre of the mine workings (m)
- L distance of the mine workings from the aquifer (m)

Introducing the value of Dupuit's formula for q for a well in the vicinity of an aquifer

$$q = 2\pi k \frac{H - h_o}{\ln (2L/r_o)}$$

and inserting for $r = r_o$ (the radius of the mine workings) we have the gradient at the wall of the mine workings

$$i_o = \frac{H - h_o}{\ln \frac{2L}{r_o} \cdot r_o \cdot (1 - \frac{r_o}{2L})} \qquad (9)$$

Substituting $\bar{I} \cdot L$ for $(H-h_o)$ we obtain

$$i_o = \bar{I} \cdot L \cdot \frac{1}{\ln \frac{2L}{r_o} \cdot r_o \cdot (1 - \frac{r_o}{2L})}$$

The average hydraulic gradient (8) decreases inversely to the distance of the aquifer L. The critical gradient on the wall of mine working (9) decreases much slower. The determination of the safe thickness of the protection layer at deeper levels as being proportional to the head difference $(H-h_o)$ can therefore lead to an underestimation of the true critical gradient.

In an inhomogeneous protection layer critical hydraulic gradients at the walls of mine workings can be smaller or higher than the gradients in homogeneous rocks. If the least permeable part of the protection layer lies immediately below the mine workings, the gradients can be very high. If the workings are separated from the impermeable layer by a permeable rock, the critical gradients are smaler than in a homogeneous rock.

The hydraulic gradients in the vicinity of deep underground openings can be very high and of the order of several tens or even hundreds. The seepage force on a unit volume of rock $F = - \gamma_w \cdot i$ can be high enough to cause a failure due to piping processes not only in loose soils but also in soft or fractured rocks. The relative low number of failures of mine workings attributable to high hydraulic gradients must be explained by an increased permeability and an adequate reduction of the hydraulic gradient at the walls of mine workings as a consequence of an increased fracturing of the walls during excavation.

The seepage force on a column of rock between the bottom of the mine workings (width a, level h_o) and any deeper level h can be written (supposing the hydraulic gradient approximately parallel to the column):

$$F = - \int_h^{h_o} \gamma_w \; i \cdot a \cdot dl$$

A failure occurs when this integral exceedes the shearing resistance and the weight of the same column:

$$2T + W = \int_h^{h_o} (2\tau_c + \gamma_r \cdot a) \; dl < - \int_h^{h_o} \gamma_w \cdot i \cdot a \cdot dl$$

As the hydraulic gradients are asually the highest at the mine workings, this condition is often fulfilled for a relatively thin upper part of the protection layer. The failure will therefore begin at the bottom of the walls of the mine workings and will proceed in the direction of the hydraulic gradient (geologists would call it retrograde erosion). This process could be prevented by drainage boreholes reducing in advance the porewater pressure and the hydraulic gradients in the vicinity of mine workings.

HYDRAULIC GRADIENTS DURING UNSTEADY STATE

The analysis in the previous paragraphs considered steady state hydraulic gradients. However, most water inrushes occur while mine workings are advancing and steady state flow does not yet exist. An analysis of unsteadystate hydraulic gradients is therefore appropriate in order to see what differences exist between the steady and the unsteady state gradients distribution around mine workings.

Such an analysis was made for a series of different possible flow geometries, of which two extreme cases are presented in this paragraph.

1. Unsteadystate hydraulic gradients distribution around mine workings in a homogeneous, isotropic medium (fig. 2)

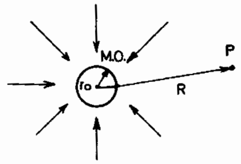

Figure 2. - Radial flow pattern to the mine opening

For such a case the hydraulic gradients distribution as a function of the distance from the mine workings $x = R - r_o$ can be developed on the basis of the Jacob-Lohman (Kruseman, De Ridder, 1973) unsteadystate constant drawdown formula. The mean hydraulic gradient between the mine opening of radius r_o and a point P at a distance x (or of radius R) from the mine opening is:

$$\bar{i} = - \frac{s_o}{x} \cdot \frac{\lg (1+x/r_o)^2}{\lg \frac{2,25.Dt}{r_o^2}} = - \frac{s_o}{(R-r_o)} \cdot \frac{\lg (R/r_o)}{\lg (R_{max}/r_o)} \qquad (12)$$

where:

- $\bar{i}$ mean hydraulic gradient
- s_o drawdown - head difference between static water level and mine workings level (m)
- r_o radius of the mine opening (m)
- R radius to the point P (m)
- R_{max} radius of influence of the seepage process at time t (m)
- D hydraulic diffusivity of the surrounding rock (m^2/s)
- t time since the seepage process started (s)

The figure below represents some results of calculations in which the above equation was applied.

The differential hydraulic gradient di_p at a point P is expressed by basically the same type of formula, with dR being the distance differential at point P:

$$si_p = - \frac{s_o}{dR} \cdot \frac{\lg (1 + \frac{dR}{R})^2}{\lg (\frac{2,25\ Dt}{r_o^2})} \qquad (13)$$

If the critical hydraulic gradient at the mine opening is considered as a function of the radius of influence of the waterinflow area $R^2_{max} = 2,25$ Dt, then the above formula reads:

$$d\,i_{MO} = - \frac{s_o}{dR} \cdot \frac{\lg (1+dR/r_o)}{\lg (R_{max}/r_o)} \qquad (14)$$

Assuming a protection layer of a relatively low permeability and of thickness $L = R_{max}/2$, protecting the mine openings from an aquifer of higher permeability, one can see that the critical gradient changes only as a function of lg $(L/2r_o)$. That is the classical steady state solution.

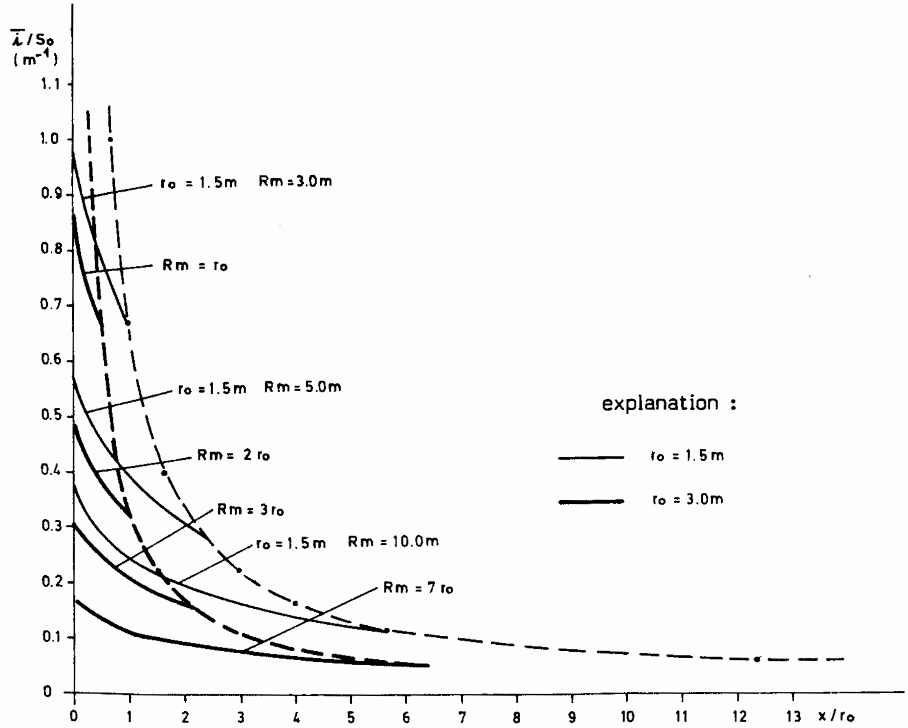

Figure 3.- Mean hydraulic gradient versus distance from the mine opening

2. Unsteadystate hydraulic gradients distribution around mine workings overlaying a karstic channel in a faulted zone.

Figure 4 represents the situation. A protection layer is fracturated by a faulted zone and becomes much more permeable within this zone. A karstic channel exists in the aquifer below the contact of the karstic aquifer with the protection layer. Aquifer's permeability outside the karstic channel can be neglected as well as the permeability of the protection layer outside the faulted zone. This scheme represents an approximation of the situation existing on several locations in Slovenia, Yugoslavia.

After Schneebeli (1966) the drawdown at a point P within the faulted zone is related to the maximum drawdown at the mine opening s_o, distance x from the mine opening, fault zone thickness a, fault zone hydraulic diffusivity D and time t since the seepage process started as follows:

$$s_p \approx s_o \,/\, 1 - \frac{x}{\sqrt{\pi D t}} \,/ \qquad (15)$$

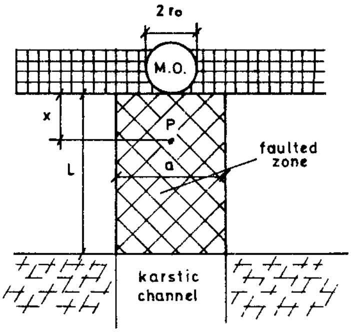

Figure 4. - Mine opening in a faulted zone overlaying a karstic channel

The above approximation is excelent for small values of $u = X/2\sqrt{\tau Dt} \leq 0,1$ and for $X \geqslant a/2$. The resulting mean gradient between mine opening and a point P is therefore:

$$\bar{i} = - \frac{s_o}{\sqrt{\pi Dt}} \qquad (16)$$

The mean gradient can be related to the distance to the karstic channel if we consider that the distance to which the seepage process has advanced is time related as $X = \sqrt{\tau Dt}$. Therefore, the mean unsteady hydraulic gradient in the direction of the karstic channel depend on the thickness $L = X$ of the protection layer as follows:

$$\bar{i} = - \frac{s_o}{L} \qquad (17)$$

It can be further shown that the critical gradient at the mine opening differs from the mean hydraulic gradient only by a factor $2\ a/\alpha_o r_o$, where r_o is the radius of the mine opening and α_o an angle such that $\sin(\alpha_o/2) = 2\ r_o/b$, with b being the floor width of the mine opening. The critical hydraulic gradient therefore reads:

$$d\ i_{MO} = \frac{2a}{\alpha_o r_o} \cdot \frac{s_o}{L} \qquad (18)$$

As a conclusion, we can state that in a faulted zone over a karstic channel, the mean hydraulic gradient and the critical hydraulic gradient are inversely proportional to the thickness of the protection layer. Again, this equals the steady state solution.

Since the seepage force is proportional to the hydraulic gradient, the push exerted by the critical seepage force towards the mine opening in the case of a faulted protection layer overlaying a karstic channel will be inversely proportional to the thickness of this layer. As the faulted zone can be considered to be the mechanically weak and therefore critical zone of the protection layer, this conforms with the statistically proved conclusions of the hungarian authors (Schmieder, 1982), that the probability of the inrush occurence is inversely proportional to the thickness of the protection layer. Outside a faulted zone, however, the effect of the thickness of the protection layer tends to follow the inverse of it's logarithm value.

CONCLUSIONS

It is obvious that the hydraulic gradients distribution within the protection layer depends on the nature of it`s constituents and the degree of their fracturing. The local structure of the protection layer must therefore be carefully examined whenever the mineworkings are approaching high water pressure aquifers and no active water control is feasible; this is a prescription in United Kingdom, for instance (Davies, 1982). Special care has to be given to the exact positioning of the relatively impervious layers within the protection layer, since they predominantly influence the hydraulic gradient distribution around mineworkings.

As discussed already by previous authors (Kesserü, 1982, Schmieder, 1982), the rocks within the protection layer exhibit two basically different behaviours - they are either subject either not subject to the piping process. The mineworkings protection strategy must consider this fact as well.

In the case of a protection layer with it`s rocks subject to piping, we must focus ourselves on the determination of critical gradients starting the piping process. When the passive waterinrush control is applied, these critical gradients must not be exceeded. If all of the protection layer consists of rocks subject to piping, no active control within this layer is possible and the porewater pressure reduction has to be achieved in the aquifer itself.

In the case of a protection layer with it`s rocks not subject to piping process, the stability of this layer under the influence of seepage forces must be examined. Again, this stability analysis should take into account the porewater pressure distribution within the protection layer as resulting from the relative hydrogeologic function of it`s constituents. The stability analysis must be made by integrating the partial effects layer by layer, according to their respective shearing resistance and cohesion. Special care has to be given to the faulted zones, especially where a karstic channel may be expected within the aquifer. We have seen that this is the critical area as well as to the hydraulic gradients distribution pattern, as to the shearing resistance of the rocks. To our opinion, only the residual shearing resistance and no cohesion should be applied in highly fractured zones. This may be considered to be the maximum and perhaps a rather exagerated safety condition. In reality, at least some shearing takes place anew and not only the sliding along the preexisting fractures occurs. Under the passive waterinrush control as well as under the active waterinrush control the stability criterion must be fulfilled. When an active waterinrush control policy is applied, it may be useful to reduce the necessary water pumping rate by means of the protection layer`s own hydraulic resistance. This assumes that the dewatering boreholes are screened within this this layer. When the active control is applied to the small coal basins overlaying karstic aquifers of virtually unlimited hydraulic conductivity, this may be the only economically feasible approach. However, in such a case the protection layer`s stability analysis has to be elaborated for different positions of the screened sections in order to find their optimum position.

The last remark is even more important when the protection layer consists of both the rocks subject to piping and those without such a property. In this case not only the protection layer`s stability, but the critical hydraulic gradients distribution relative to piping must be considered prior to the decision whether the active waterinrush control within the protection layer can be applied.

References

Davies, A.W., 1982, Protection Against Inrushes in the United Kingdom. IMWA Proceedings B, 74-90, Budapest.

Kesserü, Zs., 1982, Water barrier pillars, IMWA Proceedings B, Budapest, 91-117.

Kruseman, G.P., De Ridder, N.A., 1973, Analysis and evaluation of pumping test data , 2 nd edit, ILRI, Wageningen.

Schmieder, A., 1982, The effect and utilisation of protection layers in mine water control, IMWA Proceedings ABCD, p. 175-200, Budapest.

Schneebeli, G., 1966, Hydraulique souterraine, Eyrolles edit., Paris