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EMPIRICAL AND THEORETICAL METHODS FOR DESIGNING SOFT SEMI-IMPERMEABLE PROTECTIVE BARRIERS

Zs Kesserü

Central Institute for Mining Development
Budapest II
Mikoviny U 2-4
Budapest
HUNGARY

ABSTRACT

The paper briefly presents three Hungarian methods of simulating the onset of mine water inrushes through a protective barrier, based on an empirical approach, hydrofracturing technique and hybrid method. The empirical and hybrid methods are based on the empirical distributions of the threshold hydraulic gradients of the protective barriers and can be successfully used for forecasting mine water inflows and for designing water barrier pillars. However they do not necessarily agree with the hydrofracturing phenomenon actually observed in practice.

The hydrofracturing approach of protective barrier design was based on (some) laboratory experiments. The paper presents hydrofracturing test results and rock stress analyses in the area of a mine opening. These results have demonstrated that the necessary conditions for hydrofracture exists in an area 20-40 m immediately surrounding a mine opening owing to the increased minimum normal principal stress component. The true value of the traditional analytical model and the empirically determined threshold values can also be determined on the basis of the hydrofracturing approach. This new model for the design of protective barriers offers the following advantages:

The necessary thickness of the protective barriers can be based on direct measurements instead of the use of mine water inrush experiences of 'analogous' mines.

Water barrier pillars can be better designed and new preventive measures selected based on the knowledge of local rock stress conditions.

INTRODUCTION

Layers of impermeable/semi-impermeable rocks located between reservoir rocks and mine openings capable of the prevention of water inrushes or the limiting of the amount of mine water inflows are termed protective layers or protective barriers. The protective effect of these barriers strongly depends on the rock mass properties, common types of protective barriers are the semi-impermeable formations e.g. clays, marls and shales. Protective barrier evaluations are required for forecasting mine water inflows, designing the dimensions of water barrier pillars and determining the possibility and the selection of possible mining methods of mineral deposits under bodies of water.

PRESENT APPROACHES OF DESIGNING SEMI-IMPERMEABLE PROTECTIVE BARRIERS

Three Hungarian approaches for designing semi-impermeable protective layers are as follows:

(1) The traditional Hungarian approach is based on empirical data pertaining to hundreds of inrushes in Hungarian mines [1, 2, 3 and 4]. According to the evaluation of this empirical data, the onset of an inrush is determined by "the threshold hydraulic gradient of the protective barrier" $(I_p)_t$ compared with the actual hydraulic gradient $(I_p)_a$ [3, 5, 6].

$$(I_p)_a = (I_p)_t \qquad \text{(i)}$$

The actual hydraulic gradient of the protective barries (Figure 1) is given by equation (ii).

$$(I_p)_a = \frac{p_w}{\Sigma m - A} \qquad \text{(ii)}$$

where p_w = the water head in the reservoir rock referred to the level of the mining opening (see Figure 1).
Σm = Total thickness of the protective barrier
A = a constant representing the unknown tectonic dislocations and fracture yield or caving zones around the mine openings [4]

The threshold value of the hydraulic gradient of the protective layers should be regarded as a random parameter represented by a probability distribution $F(I_p)_t$ under the conditions of the given mining method, the local geological conditions and of the given uncertainty of the protective layer thickness. The probability distribution of the threshold hydraulic gradient can only be determined on the basis of empirical data from a large number of inrushes [2, 7, 8]. The average of empirical threshold values are as follows: [2, 3, 4]

$$\frac{1}{(I_p)_t} = 0.8 - 1.5 \text{ m/bar}$$

$$A = 5 - 8 \text{ m}$$

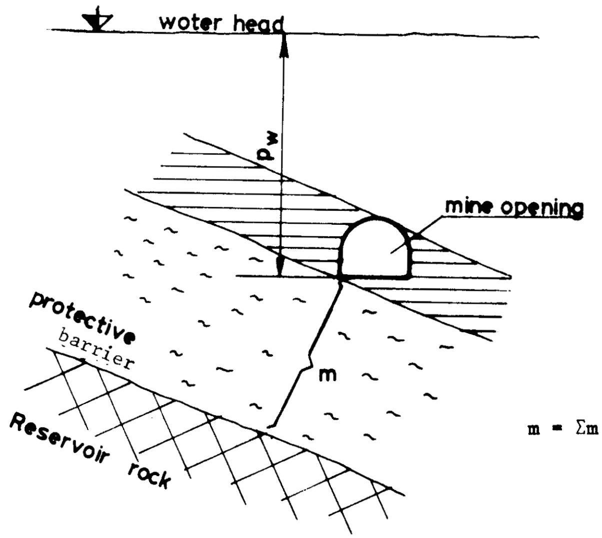


Figure 1 The terminology of protective barriers

This traditional empirical approach is generally used for evaluating protective layers and for dimensioning water barrier pillars in Hungary [1, 2] and some surrounding countries [9]. If necessary a mass of empirical data of analogous conditions is available. The analogy of rock properties and rock stress conditions is necessary [7, 2] and consequently the extrapolation of data for new conditions is difficult and the result may include many uncertainties.

(2) The new approach for evaluating protective barriers may be termed the "hydrofracturing-approach", because direct laboratory tests [7] and some mining experiences [10, 11] seem to show a strong similarity between the onset of an inrush and the process of hydrofracturing.

The hydrofracturing process is well known in high pressure grouting technology [10, 12, 13] and in petroleum reservoir engineering [14].

This approach was first used in the development of the bifurcation model for mine water inrushes [15].

Laboratory testing on fissured or broken compressed clay and marl samples have shown that the protective effect of these samples under conditions of plastic deformation strongly depends on the rock stress conditions [7].

Similar rock stress phenomena were observed during the onset of water inrushes and high pressure grouting operations [10, 11].

According to these laboratory tests and experiences, it seems that under conditions of semi-impermeable protective layers the first phase of the inrush may be a hydrofracturing determined by the following inequality [15]

$$p_w \geq p_{hf} \qquad \text{(iii)}$$

where

p_w is the water pressure of the reservoir rock

p_{hf} is the hydrofracturing pressure

According to many direct and indirect experiences in mining and petroleum reservoir engineering [10, 14] the hydrofracturing pressure p_{hf} is in the range:

$$p_{hf} = 1{:}1 - 1{:}5 \ \sigma_{min} \qquad \text{(iv)}$$

where σ_{min} is the minimal normal rock stress component.

(3) According to the intermediate (hybrid) approaches, both criteria: the threshold hydraulic gradient and the threshold value of rock stress are taken into account sequentially or simultaneously [7, 8, 5, 16]. The most developed hybrid model is the Threshold Energy Equation [5]. The hybrid methods provide the dimensions of water barrier pillars for many different conditions.

Though all approaches are based more or less on past experiences, the comparison of these approaches shows a contradiction.

In many field operations in petroleum engineering, direct hydro-fractured contact could be made between boreholes of distances of 500-1000 m apart, using the proper mixture and volume of fracturing liquid and the proper value of hydrofracturing pressure, which does not depend on the fracturing distance or on the length of the formed fracture [14].

The same phenomenon was detected during clay grouting operations in soft impermeable rocks using higher grouting pressures than the hydro-fracturing pressure.

The movement of the grouting material could not be controlled. The grouting slurry entered into mining openings located 150-200 m from the grouting operation [12, 13, 10].

According to the traditional and the hybrid evaluating models for impermeable protective layers, the hydrofracturing pressure is a linear function of the distance (m) (equations (i), (iii)).

It seems that the traditional and the hybrid evaluating models for protective layers do not agree with the experiences of the hydro-fracturing operations and hence a contradiction between these approaches occurs.

The next section presents the solution of this contradiction by applying the "hydrofracturing model" under existing rock stress conditions to the surrounding area of the mine openings.

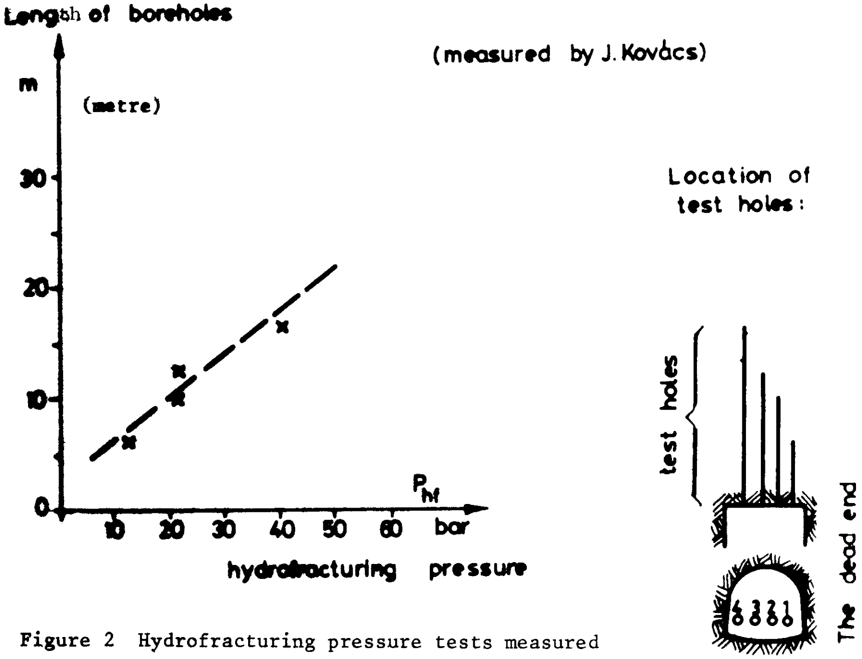


Figure 2 Hydrofracturing pressure tests measured by J. Kovács (Central Institute for Mining Development Hungary) [17]

HYDROFRACTURING PROCESSES IN THE AREA OF MINE OPENINGS

Some hydrofracturing pressure tests were carried on [17] at the end of a roadway (Figure 2) using cement lined holes of different length.

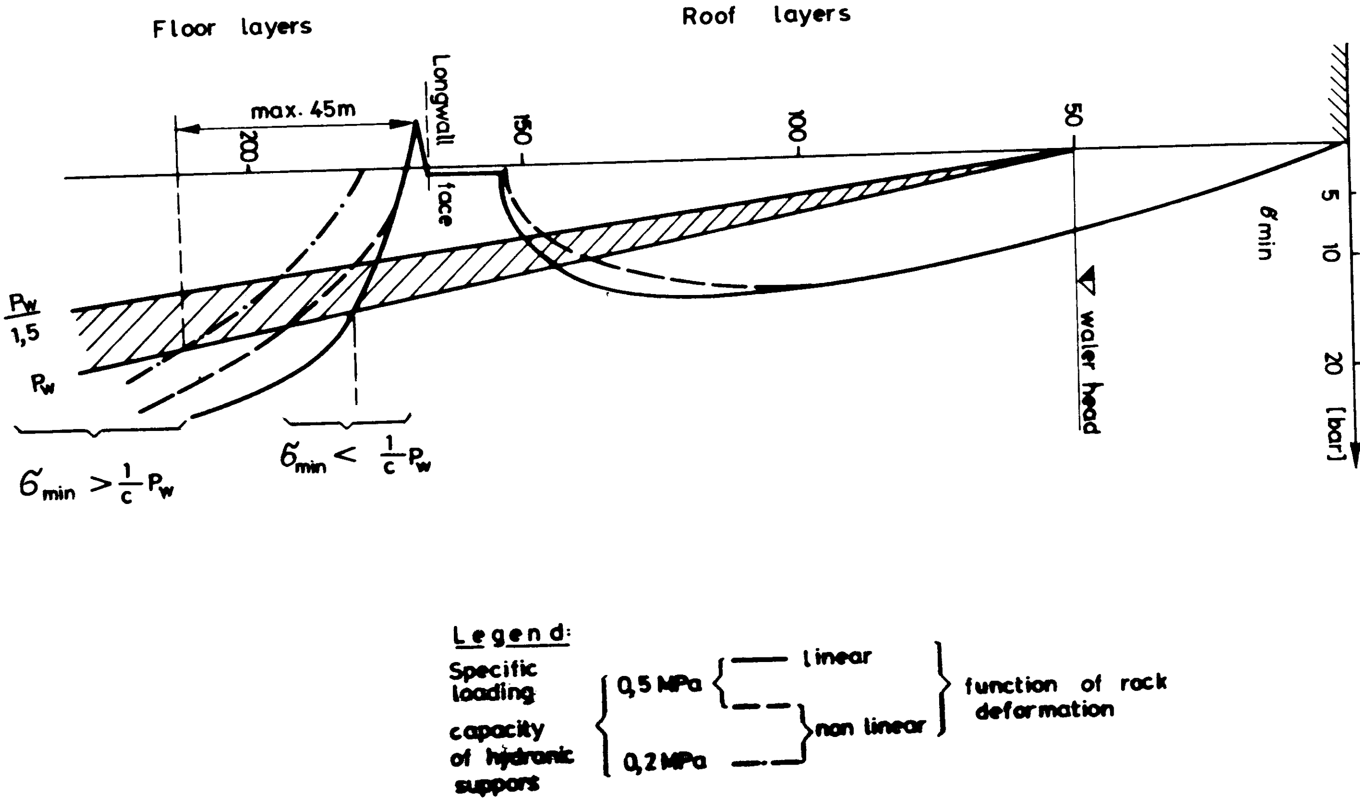
The linear approximation of the measured points represents a similar function to equation (ii).

$$\text{const} = \frac{P_w}{\Sigma m + A} \qquad (v)$$

It seems, that the hydrofracturing pressure can be approximated as a linear function of the distance from the openings, depending upon the given rock stress conditions in the vicinity of the mine openings.

The minimum normal rock stress component (σ_{min}) in the protective barrier should be compared with the water head according to equation (iv). The results of these analyses can be compared with the empirical data obtained from past inrushes.

Figure 3 The possibility of hydrofracturing caused by water pressure of the reservoir rocks in the protective floor layers according to finite element rock stress analyses



The great majority of the Hungarian experiences of mine water inrushes are concerned with aquifers in the floor strata at the coal-fields Tatabánya, Dorog and Várpalota. Therefore the stress analyses are concerned with these formations [2]. No direct stress or hydrofracturing tests were carried on these floor layers, and only finite element stress analyses are available from these case studies [18].

CASE STUDY

Figure 3 shows a case example of similar conditions to the Tatabánya and Dorog coalfields. The depth of the semi-horizontal coal seam is 170 m and the exploited thickness of the seam is about 3 m. Longwall operation is modelled with different loading capacities of hydraulic supports (20 t/m^2 - 50 t/m^2) and with linear and non-linear deformation curves of rocks.

The original water head is about 50 m below the surface. The fitting of the equation(v) is taken into account as

$$\sigma_{min} = \frac{1}{c} p_{hf} = \frac{1}{c} p_w \qquad \text{(vi)}$$

where $1 \leq c \leq 1.5$

Figure 3 shows that the possibility of hydrofracture caused by the water head of the underlying aquifer under existing conditions of m = 30-45 m.

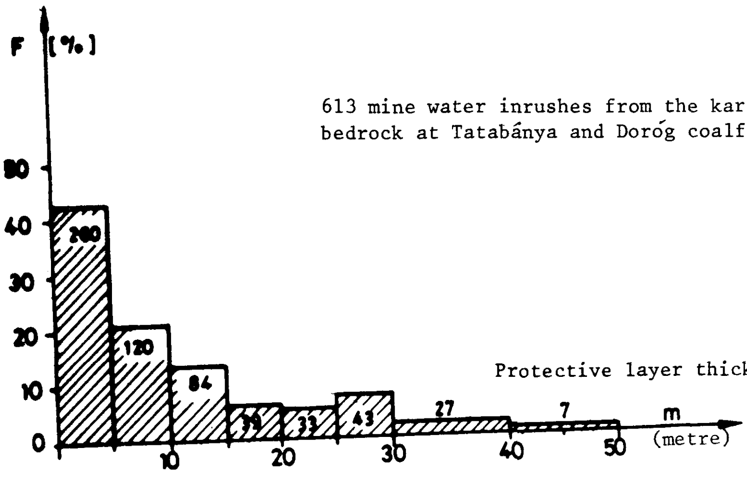


Figure 4 The distribution of protective layer thickness at mine water inrushes from the karstic bedrock (Tatabánya and Dorog coalfields)

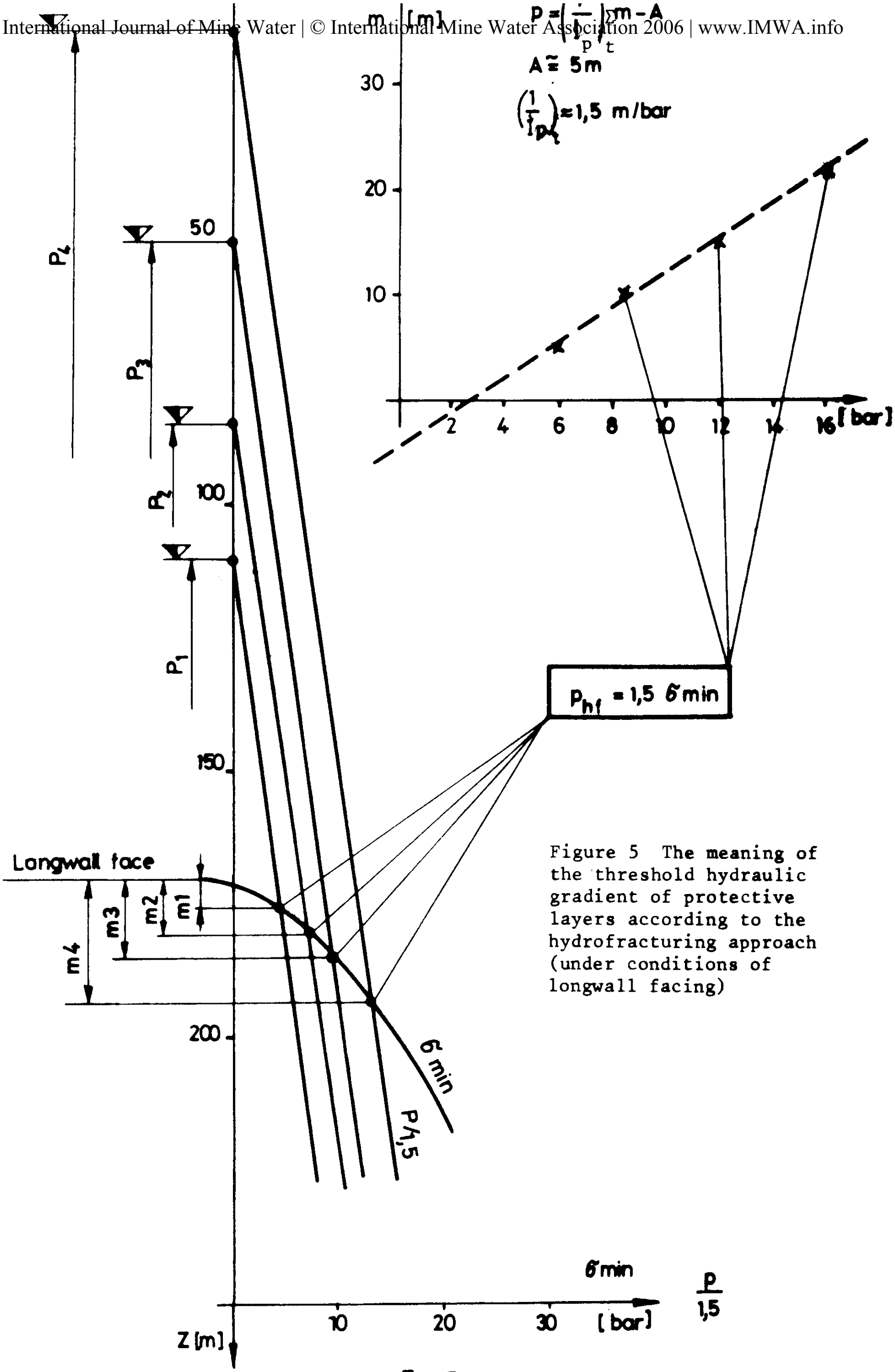


Figure 5 The meaning of the threshold hydraulic gradient of protective layers according to the hydrofracturing approach (under conditions of longwall facing)

Fig. 5

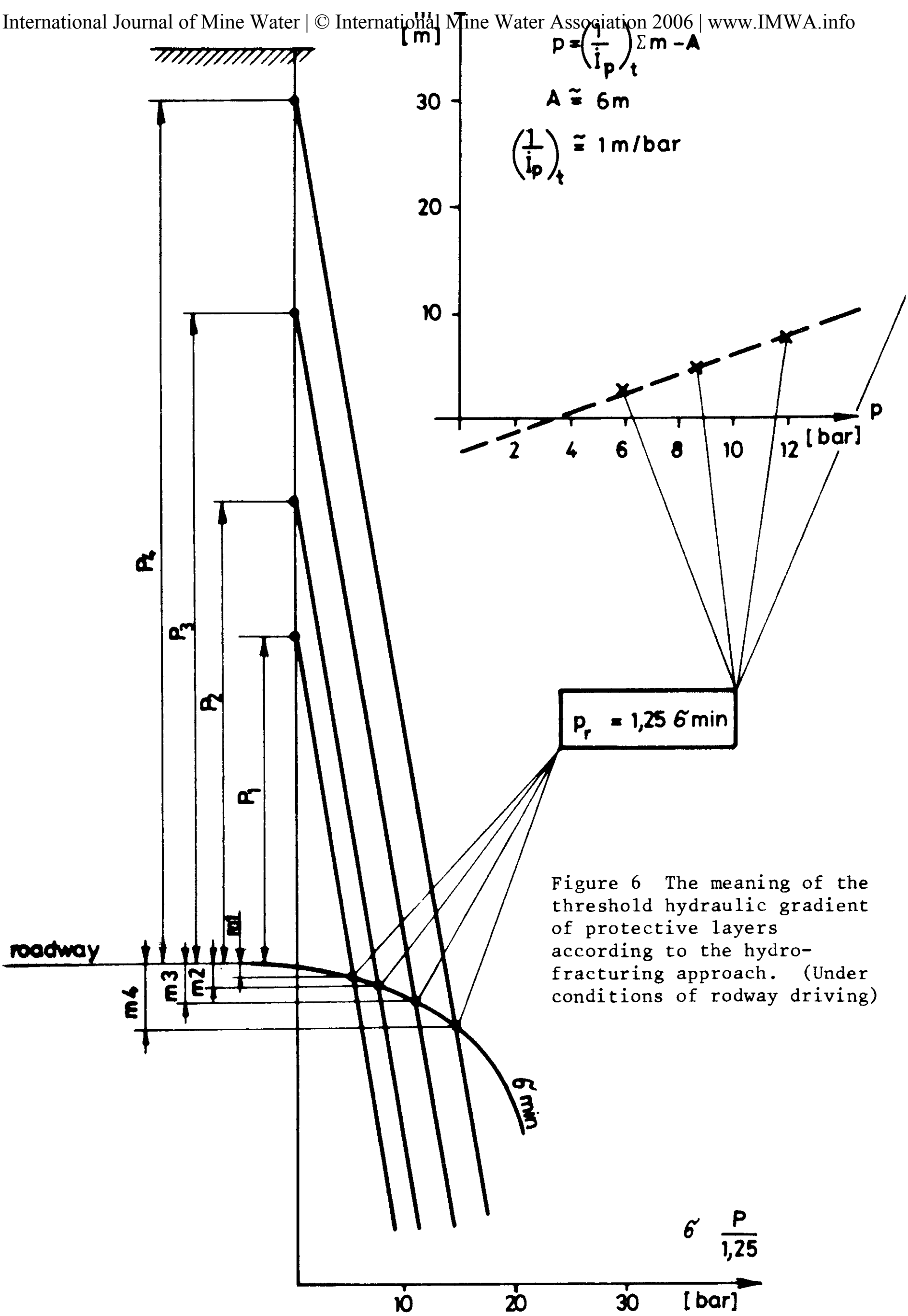


Figure 6 The meaning of the threshold hydraulic gradient of protective layers according to the hydro-fracturing approach. (Under conditions of rodway driving)

Figure 4 presents protective barrier thickness distributions for mine water inrushes occurring up to 1967. A mine water inrush has never occurred if the thickness of the protective layer exceeds 50 m.

The same comparison was carried for the Várpalota region with the same results [10].

Figure 5 presents the fitting of the equation (iv) for different water pressure (p_w).

Figure 6 represents the same fitting on the floor strata of a roadway.

The linear approximation of the cross points (equation (iv)) is strongly compatible with equation (ii), because the average values of $(I_p)_t$ and A are also fitting to the mining experiences of the given coalfields.

CONCLUSIONS

(1) The necessary conditions for hydrofracture caused by the reservoir water pressure exist in the semi-impermeable protective layers in the surrounding area of mine openings because of the increased value of σ_{min}.

(2) The necessary thickness of the semi-impermeable protective barrier can be determined according to the equation (iv) taking also into account the uncertainties on stress conditions, on stratigraphy, tectonics, etc.

(3) The threshold value of the hydraulic gradient of a protective layer represents the conditions of the hydrofracture in the surrounding area of the mine openings, (i.e. σ_{min} is approximated as a linear function of the distance (m) from the opening. The threshold gradient is the ratio of inclination of this approximating line).

(4) The empirically determined threshold values (distributions of the hydraulic gradient can be used only at the surrounding area of mine openings (m = 25-50 m)).

If $\Sigma m > 25-50$ m there is no practical contradiction between the two evaluating methods, although the physical feature of the phenomenon is a hydrofracturing process.

(5) The hydrofracturing pressure can be easily measured in the surrounding area of mine openings (Figure 2). By using direct measurements the necessary thickness of protective barriers can be determined for different mining methods including cave sizes and rock conditions.

Experiences of mine water inrushes of semi-analogous conditions are not required for the evaluation of protective barriers by the hydrofracturing approach.

(6) The hydrofracturing model for protective layers gives a better design approach and permits preventive measures to be adopted based on the prevailing stress conditions in the protective layers [19, 10].

(7) The hydrofracturing model should also be used for sizing water barrier pillars under conditions of semi-impermeable formations. Using this model, more acceptable dimensions can be determined under conditions of great depth and high water head (600-800 m), compared with the hybrid and the traditional methods [1, 8, 16].

Because of the above listed advantages, the new approach is used in some of the present consulting and design projects of the Central Institute for Mining Development of Hungary [10] as well as in other Eastern European countries [19].

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REFERENCES

1. Mine Safety Regulations, Hungarian Mine Safety Authority (1975)

2. Marlos, F. (editor) Schmieder, A., Kesserü, Zs, Juhász, J. and Willems, T. "Mine Water Management" (in Hungarian) Muszaki Kiadó Technical Publishing Co., Budapest (1975)

3. Schmieder, A. "The Protective layers". Proceedings of the 6th Conference on Mine Water Budapest, Vol. 1/2 (in Hungarian) (1976)

4. Kesserü, Zs and Willems, T. "Forecasting of karstic water hazard in mines for determining the optimum level of risk". Proceedings of the 6th Conference on Mine Water Control, Budapest. Vol. II-10 (in Hungarian) (1970)

5. Schmieder, A. "Investigations on mine water inrushes from karstic and fissured reservoir rocks through impermeable layers" Unpublished, C.Sc. Dissertation (1982)

6. Schmieder, A. "Some remarks for better approaches on protective layers" Proceedings of the 6th Conference on Mine Water Control, Budapest (in Hungarian) (1970)

7. Kesserü, Zs. Neue untersuchungen und Beobachtungen über die Schutzschichten. 7th Conference on Mine Water Management Vol. II-6 Mining Research Institute, Budapest (1976)

8. Kesserü, Zs. Water Barrier Pillars. Proceedings of the 1st IMWA Mine Water Congress, Budapest, Vol. B, p. 91-117 (1982)

9. Ahcan, R. "Sanacija vodnego dvora v jami Kanizarica." (Preventing a mine water inrush in Mine Kanizarica) Mettalurski Zbornik Ljubljana Vol. 2-3, p.255 (1977)

10. Kesserü, Zs. Investigations on control of stress conditions of protective layers. Project report of Central Institute for Mining Development, Budapest, under contract of 220.080.20 (in Hungarian) (1982)

11. Zambó, I. Exploitation of quasi-horizontal thick coal seams. Institute for post graduate engineering education of Hungary (1952)

12. Kassai, F. and Benke, I. Sealing water inflows and solidification of rocks by chemical agent. Proceedings of the 1st IMWA Mine Water Congress Vol. B, p. 290-309 (1982)

13. Kassai, F. and Solymos, A. Experiences and conclusions on grouting operations with clay-cement slurry. Manuscript for Tatabánya Coal Company in Hungarian (1981)

14. Selected papers on hydrofracturing in the petroleum engineering (in Hungarian) Documentation Centre of Heavy Industry, Budapest (1978)

15. Kesserü, Zs., Kempf, I., Duckstein, L. and Casti, J. Bifurcation theory model of mine water inrushes. Proceedings of the 1st IMWA Congress of Mine Water, Budapest, Vol. A, p. 346-373 (1982)

16. Water Barrier Pillars. Draft for Mine Safety Standard Centre for Mine Safety Standard of Hungary (1982)

17. Kovács, J. Experiments in Mine "Csordakut" on fixing cementing the conductor lining the holes for grouting. Progress Report of the Central Institute for Mining Development, Budapest (in Hungarian) (1980)

18. Roller, B. and Cserhalmi, I. et al. Project reports on finite element modelling of undermined area. Technical University of Budapest (1976)

19. Kapolyi, L. New trends and researches in protection against mine water. Proceedings of the 7th Conference on Mine Water Management Tom 1. Mining Research Institute Budapest (1976)

20. Kesserü, Zs. and Havesy, I. The roof-water danger at Mine Hrasnik (Yugoslavia) and proposals on prevention and further investigations. Project report (in English) of the Central Institute for Mining Development, Hungary for Revirski Energetski Kombinat Trbovlje, Yugoslavia (1984)