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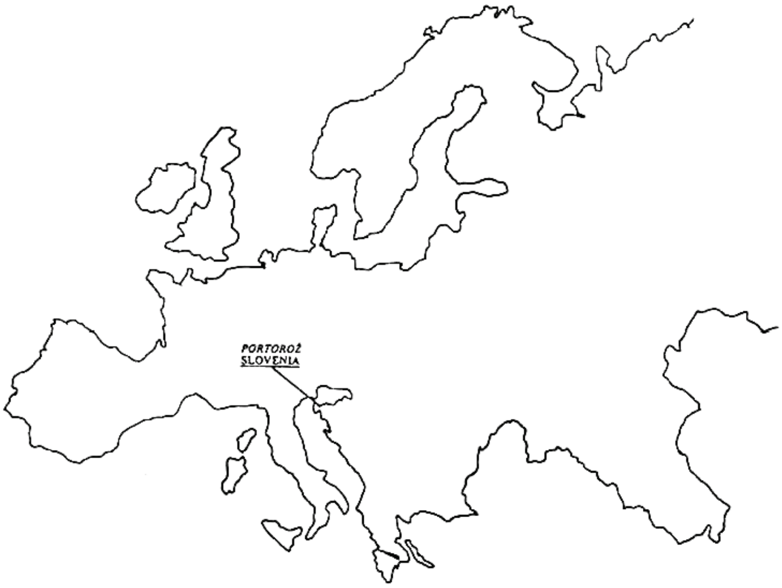

Portorož, Slovenia
September 7 - 9, 1996

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WATER RESOURCES AT RISK
May 14-18, 1995 Denver
American Institute of Hydrology

New Approaches and Results on the Assessment of Risks due to Undermining for Mine's Safety and for Protecting of Water Resources

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ABSTRACT

The risk assessment should fulfil the needs of mine's safety and the protection of the water resources against mining-induced impacts. The overview of the actually used criteria and methods displayed a lot of insufficienties originated from the limited possibilities of observing/understanding the failures in the undermined overburden.

The author passed through the difficulties due to the lack of information on the processes inside the undermined overburden by extending the studies into the water-induced failures of bottom and of lateral barriers and to other engineering areas. The simultaneous study of all barriers discovered and demonstrated the strong dependence of the protective capability on the rock stress and on the water pressure. New criterion has been introduced and tested by in mine experiments and by the experience of undermining. The new criterion is valid for all kind of rocks, for all locations of the geological barriers. The stability of the barrier at inhomogenities and anizotropies and the secondary sources of dander are also interpreted according to the new approach.

A new method for evaluating of the barriers has been developed and implemented into the practice. This method provides improved safety for mines and more accurate risk assessment for protecting of the water resources. The new method also provides appropriate bases to specify the applicability of empirical curves and of empirical criteria for site specific studies. The compact draft-guideline of the mew method, and the experience of the first applications are also presented.

RISK ASESSMENT FOR MINING AND FOR PROTECTING WATER RESOURCES

The impacts of undermining into the surface water bodies and into overlaying underground aquifers have often caused dramatic inflows into the mines. The aquifers often damaged strongly. In spite of the mutual interest of the mine's safety and of protecting the water resources the viewpoints and the requirements differ in some respects.

The risk-estimation governed by the viewpoints of the mining focus first to determine the necessary barrier thickness to prevent against dangerous water inflows into a mining operation of specified parameters, or to specify of the safe parameters of mining operation under the actual overburden conditions. By fulfilling the mine's safety requirements the dramatic impacts into the water resources were/are simultaneously excluded.

Depending to the rock properties the "safe barrier" either prevents against all inflows, or one limits the water seepage. For the second cases the estimation of the water through flow is the next task of the risk-estimation. The yield of inflow from an aquifer should meet with the requirements of mining and of water resource management. The mechanised longwall mining is quite sensitive on the presence of the water. The underground mining (operating close to the economy limits) is quite cost-sensitive. The extra costs of pumping and of water treatments are not warmly welcomed. The mutual interest to minimise the water inflow also exists.

The protection the water resources require more accurate assessment in some respects:

- The mining-induced interconnections between the aquifers and with the surface,
- The risk of the pollution transfer due to mining-induced interconnections and pollution,
- The status after the mine's abandonment, with special regard to the rebuilding of the water regime in the mining impacted area and in its surroundings should also be considered, and foreseen.

Some more aspects (e. g. damages of the vegetation, and the rock compactions due to water withdrawal, the changes of the surface water flow patter due to land subsidence) are not discussed in this paper. The results on better evaluation of undermined barrier may help for better evaluation of the risks due to water withdrawal and for making better decisions on other control measures (e. g. river diversion, sealing of channels)

THE ACTUAL METHODS AND THE CONTRADICTIONS

The actual methods of the risk assessment are based on the experience and on the observations relating to the undermined overburden. The capabilities and the insufficiencies of these methods depend strongly on the sufficiency/insufficiency of this information.

POSSIBILITIES AND DIFFICULTIES ON OBSERVING/UNDERSTANDING OF THE PROCESSES INSIDE THE UNDERMINED BARRIER

Due to the mining-induced deformations/failures direct observations are possible in the boundaries (at the surface, in the close vicinity of the openings, in the bottom of the goaf) and in the zones of modest deformation. [3, 6, 7, 9, 12, 24, 30, 33, 34, 35, 37, 38]

The remote sensing/detecting of the changes on the physical properties inside the rock mass (the geophysical surveying) can provide large-scale picture of state transition, but the information on the processes inside the local inhomogenities is quite poor one. [6, 20]

The observations realised inside the zones of modest deformation are the most important ones for more reasons: The protective capability of the undermined barrier is concentrated surely in the zones of modest deformation. The modest changes on the water resources are important ones for environmental control. The borehole observations directed to this zone provide direct information on the water head/pore-water-pressure, on the axial displacements, on the fissures formed in the open wall of the hole. The geophysical logging can give information on the changes of some physical properties in the vicinity of the hole. The possibilities of the location of such holes are strongly limited ones because the strong deformation usually destroys the very expensive observation-holes [6, 7, 8, 9, 10, 12, 16, 17, 22, 24, 30, 33, 34, 38, 40].

The second focus of the observation directed to the aquifers to be protected. The water wells the piezometers, the springs are all observed to detect the changes. The endangered inland surface waters were/are also observed to discover the losses and pollution [6,7, 9, 33, 35].

The analyses of mining experience are focused usually to the comparison of safe cases (where inflows did not occur), with unsafe ones, where inflows have occurred. In the majority of the cases only the appearance of the water (and mud) and also the chemical/nuclear/biological contents of the waters can be observed [1, 3, 4, 5, 6, 7, 8, 9, 10, 17, 24, 25, 30, 32, 33, 34, 39]. The associated phenomena inside the effective barrier are not visible ones. Appropriate information on the features of the failure inside the effective barrier is usually not available.

THE GENERAL FEATURES OF THE UNDERMINED BARRIERs

According to the common principle of all actual methods, the zone of broken rock pieces and the zone of open fissures must not be regarded as protective barriers. The estimations on the extension of the non"-protective" zones are based on theoretical considerations [7, 30], on borehole observations and on physical model studies [3, 4, 7, 9, 10; 12, 22, 24, 26, 34, 38, 40].

The protective features of the barrier outside the "non protecting" zones depend on the rock properties [5,7, 9, 13, 30]:

- The weak, compact rocks (clay, mudstone) and series with weak compact intercalations are capable to prevent against seepage if their thickness and mechanical status are appropriate one.
- The rigid rocks impacted by undermining are more or less water conducting ones. The conductivity of rigid fissured aquifers increases by one-two magnitude. The rocks regarded as compact ones under virgin conditions became water conducting ones due to undermining. The appropriate thickness of the hard protective barrier is capable to prevent against mud inflows and to limit the water seepage. For estimating the through flow the impacted conductivity/storage parameters should be taken into account.

The reconsolidation of the undermined barrier also rebuild partly the protective features of the barrier.

- In the Carboniferous argilliceous overburden the extension of the non protecting zone can be approximated by hyperbolic function of the slice number [5, 7] The reconsolidation of such series often stops the modest water outflows [33]
- In soft clays the reconsolidated broken clay works as a compact clay breccia [12]
- According to the a number of borehole observations crossed 10~40 years old dry goafs, consisting medium hard clay and marl the height of the not-protecting zone also decreased up to 10-30 % [8]. The recompaction of the wet goafs (of the same

rocks) is more quick process. During the planned floodings of the mines in Hungary the filled volume has been quasi equal with the volume of the roadways.

The impacts of the undermining, (namely the rock-displacements and the mining-induced water seepage) often form "secondary" sources of danger inside the barrier:

- In hard rocks and in weak rocks with thick hard beds the "bed-separation" forms caves and the seepage may fill these caves with water [25, 30]. The inflows from bed separation caves caused dangerous inflows even after preventive depressurizations of the overburden aquifer.
- In weak clay local zones of undrained stress formed, and ones have caused dangerous wet clay inflows. At some sites the local wet clay inflows also initiated more extended pro-gressive failures in the barrier, which one also induced water inflows from the aquifer [16].

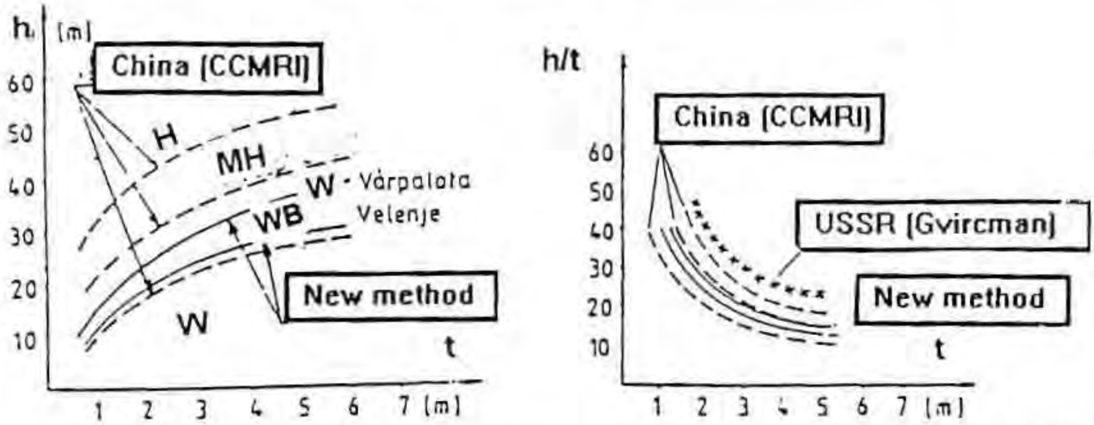
THE SAFE THICKNESS OF THE OVERBURDEN-BARRIER

The "safe barrier-thickness" is a term of mine's safety. The safe thickness means such conditions, where the safety against dangerous inflows is acceptable. Under safe thickness small changes of the aquifers may occur. The safe thickness has been approached by different ways:

- *The barrier has been modelled as a rock beam* loaded by the water pressure, by its own weight [11] and by its rock-surrounding as well [30]. These reasonable assumptions have taken into account the rock properties and the water-pressure as governing parameters of the stability of the rock mass, (the rock beam). The beam models do not provide any information on the stability of the inhomogenities (faults, dykes etc), and on the water-conductivity of the rock beam.
- *The statistical approaches* focus only to the safe/unsafe cases under specified conditions. The safe cases mean such ones, where inflows did not occur, or the inflows have been minor ones, therefore notes have not been taken. The safe thickness of the overburden is displayed in function of the extracted thickness and of slice numbers for specified overburden geology [4, 5, 7, 9] The empirical curves of the Chinese and Russian mining experience are displayed and compared in Figure 1. (See only the empirical curves in Figure 1). The empirical curves and their comparison provide some conclusions:
  - The extension of the non protecting zone is larger in hard rocks, than in weak ones.
  - There is a good fitting between the relating Russian and Chinese curves.
  - The safe thickness of the barrier is not a linear function of the extraction thickness.
  - The dispersion of the cases around the empirical curves may express the importance of the parameters neglected in the statistical approach.

  The empirical curves on the safe barrier thickness can only be used for risk estimation under analogous conditions according to the additional information/considerations drafted above.

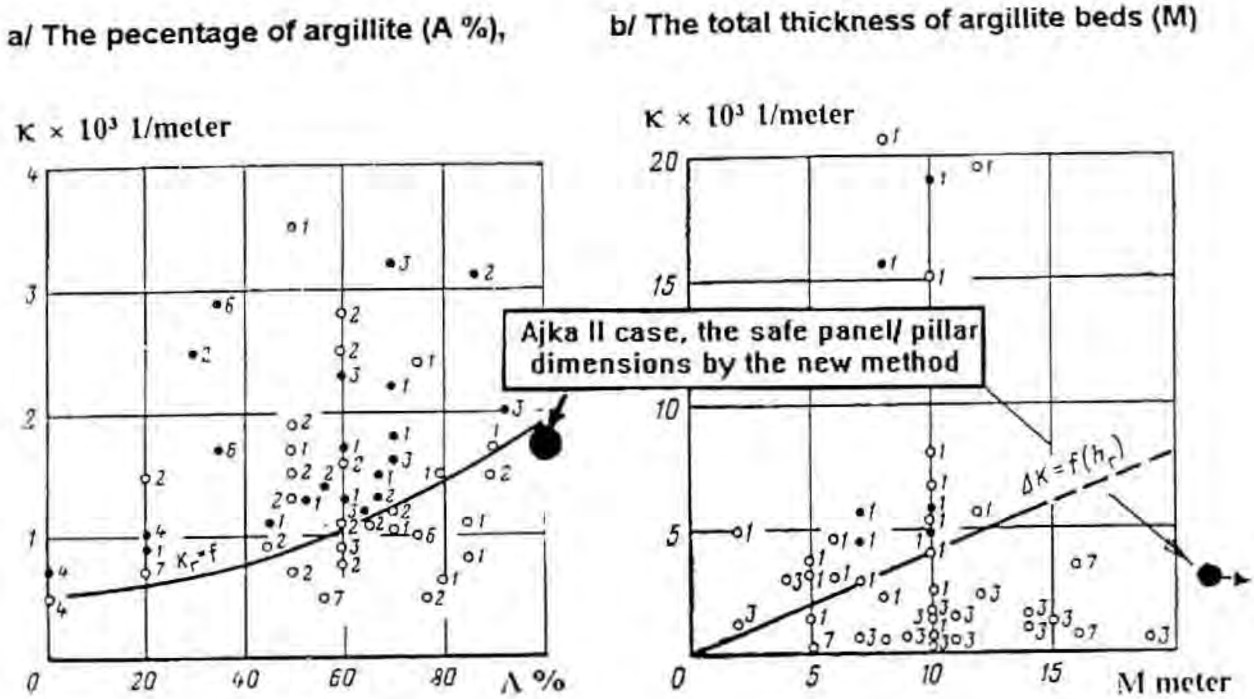
A/ The safe overburden thickness **B/ The safe ratio of the overburden/extraction thickness**



Sympols: W = weak, WB = weak broken reconsolidatec, MH =medium hard, H = hard

Figure 1 Empirical curves (China, USSR) on the safe overburden barrier, and the results of site specific studied according to the new method

- *The more developed statistical approaches have analysed the experience in function of a selected deformation parameter on the undermined overburden. The safe conditions are determined by the safe limit of this deformation parameter (by deformation criterion).* These criteria neglect the water pressure the depth of the barrier.
  - *The British method has selected the tensile strain as the parameter of fracture forming potential in the undermined overburdens. [30,34]* The tensile strain can be determined directly in the surface, and one can be calculated [7,23, 30] or computed [6, 26] inside the overburden. The experience analised at that time have shown 5-15 mm/m tensile strain values for safe cases. Actually 10 mm/m is used/prescribed as one of safety criterion relating to the bottom of the aquifer [34]. This approach is also applied in the Carboniferous coalfields of English-speaking countries with small changes on the safe limit of the tensile strain [1, 6, 26 35] The measurements/calculations of site-specific applications have displayed good coincidences between the tensile strain and water inflows [1, 35] and incoincidencies [37,39] at the faults, dykes. The site specific applications of the tensile strain criterion are often supported by physical model studies on the qualitative picture (fissure propagation, bed separation), [3, 7, 24, 40], and by numerical model studies on the quantitative picture of stress-strain parameters with special regard to the tensile strain and the field of seepage [6, 26, 31]
  - *The Russian method has selected the curvature as deformation parameter [7].* These curves are displayed according to Gvircman [7] in function of the ratio of the argillites and aleurolites in the overburden barrier of the Carboniferous coal seams, and in function of the thickness of clay interbeddings in Figure 2. The curvature can be calculated from the vertical displacements measured in on the surface and estimated inside the rock mass.[7, 23]



Symbols: • = unsafe cases, o = safe cases, 1, 2, 3, 4, 5, 6, 7, are marking coalfields

Figure 2. The safe limit of the curvature at the bottom of the aquifer according to the experience of the Carbonifrous coalfield of USSR.. Aleorolite and argilllite beds are dominating in the Carboniferous overburden. [7]

The safety regulations, based on the above experience/studies prescribe the minimal thickness of the overburden, (with additional specification on the geology), the safe ratio of the overburden and the extraction (h/t), different safety margins against different water bodies, restrictions on the panel sizes, and lateral pilars for the area of insufficient overburden. The requirements on the maximal allowed deformation are inserted in the detailed guidelines.[6, 29, 34].

- *The Hungarian empirical method* [13, 14] applies empirical curves for determining of the non protecting zones and the empirical safe limit of the specific barrier thickness to determine the necessary thickness of the effective barrier outside the non-protecting zone. The empirical curves on the non protecting zone have been given from the international experience (Fig 1) and ones have also been verified with homeland experience/observations. The specific thickness of the barrier is defined as the ratio of the effective barrier thickness along the shortest seepage-pathway and the water pressure (m/bar) This is equal with the inverse of the hydraulic gradient. The safe

limit of the specific barrier thickness has been determined by analysing the experience on the tectonised bottom-barriers. This method take into account the water pressure and the inhomogenities (the tectonics). In lack of analogous experience on the not-protecting zone numerical models fitted by in site measurements have been applied This composited empirical model fits with the trends of the experimemtal curves and also wirh the case histories. [13, 14]
This method is the prescribed one in the actual mine's safety standard of Hungary. According to the actual knovledge this method provides overestimation for cases of high water pressure (over 15 bars) [17]

INSUFFICIENTIES AND CONTRADICTIONS

- Sophisticated considerations have been published on the processes in the overburden [e.g. 30]. The methods applied in the countries of powerful mining [34] neglect important parameters namely: *the depth, the water-pressure and the local inhomogenities.*
- The two deformation criteria are contradicting ones in some respects:
  - Although the location of the maximal tensile strain (ε_{max}) and of the maximal concave curvature (χ_{max} = const) are in quasi-coincidence at the surface subsidence area, the values of *these two subsidence-parameters are represented by quite different functions of the depth and of the extraction height* [7, 23].
  - Supposing the evidence of a constant safe limit for the tensile strain (ε_{max} = const), the proposed approximations for determining the maximal tensile strain [7, 23, 30,] (**ε_{max} = const = c*h/t**) represent linear function between the safe barrier thickness (h) and the extraction thickness (t), and a constant ratio of the depth and of extraction-thickness (h/t). *These trends disagree with the empirical curves in Figure 1.*
  - The maximal curvature can be approximated by $\chi_{max} = a^*t/H^2$ [7, 23]. Assuming a constant safe limit of the curvature (χmax = const), the safe thickness of the overburden is: $h = b^*t^{1/2}$, where the **a** and **b** are constant values. *This trend agrees with the experience displayed in Fig 1, but the dispersion of the cases of similar geological conditions around the statistical safe limit is quite large, (see Figure 2).*
- Both of above deformation parameters reach their maximal values at the final stage of subsidence, (under the reconsolidated stage of the overburden barriers). All of experience and observations have shown partial or total rebuildings of the protective capability of the overburden in comparison with the earlier stages of the subsidence (with smaller deformations). The maximum of the risk and the maximum of the deformation are not linked.
- Both of above deformation parameters represent the crack-forming potential in the surface. The occurrences of large surface-cracks do not mean definitely a free pathway into the mine. At the undermined lakes of Velenje Colliery (Slovenia) the width of the cracks at the bottom of the lake varied among one-two meters, but inflows into

the mine did not occur. At some sites the broken, or fissured reconsolidated overburden also forms effective barrier against water under pressure. *The occurrence of the fissures in the barrier is not equivalent with a free pathway for the water under all conditions.*

- According to the experience and observations on the bottom & lateral barriers hundreds of inflow occurred, where the deformation (at the boundary of the barrier and the aquifer) have been very small, (one-two magnitude smaller, than the safe limits for overburden). Consequently *pathways have been formed across the barrier even under conditions of very small deformations. There is no reason to exclude the risks of forming similar failures in the overburden-barrier.*

The contradictions and insuffitienties called for studies on better understanding the failures in the zones of small deformation with special regards to the inhomogenities and anisotropies.

THE NEW APPROACH AND THE STUDIES

THE PROBLEM APPROACH

The new approach of the author has been based on the following *assumptions:*

- Pathways for water crossflow may be formed by two main ways: Either the impact of the undermining (the rock failure) may open fissures, channels for water crossflow, or the interaction of the rock water system may cause crossflow. Consequently the possibilities of *the failures due to the rock water-interactions should also be considered* in the zones of modest deformation.

- The rock mass of the barrier (impacted by many different geological loadings) should be regarded as a system with inhomogenities, anizotropies. An increased potential of mining- and water-induced failures may exist along these inhomogenities anizotropies. The considerations and investigations on the failures should also *focus to the failures at the inhomogenities and anisotropies.*

- The mechanical-failures of the rock-water system depend only on the water pressure and on the mechanical state of the rock. The failures in the bottom and in the lateral barriers also represent observations, experience on failures under specified status of the rock and the water. The numbers of direct observations on the failure phenomena are available on the bottom inflows. *Same phenomena should occur even in the overburden under same/similar mechanical status & water pressure in the same/similar rocks.*

According to the above assumptions *the steps of the problem approach* were as follows:

- The investigations started with the studies on understanding of the possible ways of failures in the bottom barrier crossed by faults and by micro tectonics. The majority of direct observations related to the failures along the faults or close to faults.

- All possible failure-modes of the rock-water system have been considered and compared with the direct observations. The relating experience of other engineering fields has also been considered.

- Full-scale, long-time, in-mine experiments have been absolved to check the conclusions derived from the observations on the bottom inflows. The mechanical status of the rock and the water-pressure were measured and also modified at all test sites.

- These analyses and experiments have determined the dominant way of failure, the governing parameters and the safety criterion for bottom and for lateral inflows. This criterion relates also to the inhomogenities. The validity of the newly discovered criterion has also been checked by the in site experiments, and by the experience of lateral water barrier pillars.

- The possibilities of the transfer of the above knowledge to evaluating of the overburdens barrier have been investigated by the following manner:
  - The mechanical status of the bottom barrier and the zone of modest deformation in the overburden barriers have been compared.
  - The observed pre-inflow phenomena at the overburden inflows have been compared with the similar ones of bottom inflows.
  - The empirical curves on the safe overburden thickness have been compared with the curves derived by the new safety criterion.

THE TRANSFERABLE EXPERIENCE, OBSERVATIONS AND CONCLUSIONS ON THE BOTTOM BARRIERS

The studied barriers were Tertiary sediments (clay, marl, coal, limestone and sand interbeddings), and also Permian-Carboniferous strata (sandstone, siltstone, mudstone with limestone intercalations). All studied regions are tectonised. Under sufficient barrier thickness the faults are watertight ones. The extension of the mining operations takes many dozens of km². The dept of the operations varies among 50-450 m. The piezometer head of the bottom aquifers varied among 20-350m above the mining operations. The barrier has been sufficient at one part of the mine fields. More than 2000 water inrushes occurred at the fields of insufficient barriers. The studies, the experiments and the conclusions are presented in more pervious papers [15, 17, 19]. Only the most important conclusions and some basic experience are drafted hereto.

The basic experiences are:

- The predominant majority of the inflows occurred at the near vicinity of faults or just at the faults. The inhomogenities have exceptional importance!

- About the half of all inflow cases occurred already in roadways. The coal-getting of the same area induced the second half of inflows. This experience contradicts the beam theorem.

- Some meter thickness of strongly fissured and faulted barrier can protect against water of high pressure under proper rock stress conditions, but much larger barrier of insufficient stress cannot prevent against throughflow. These experience points out the dominant role of the rock stress, (which one is neglected by all empirical criteria).

The conclusions on the possible way of failure fitting to the experience/observations are:

- In cases of barriers without open fissures the predominant majority of the bottom-inflows started with a spontaneous hydrofracturing. The mining-induced changes of the rock stress and the actual water pressure of the aquifer produce the proper conditions for initiating fractures or for opening of virgin discontinuities (faults, intercalations), and of reopening secondary (mining-induced) fissures. Depending on the stress conditions of the barrier either the fractures propagate directly to the opening or the bed separation filled with pressurised water may induce rock failures.
- The liability of this assumption is supported by the experience of other engineering fields. Spontaneous hidrofracturings also occurred in hydrotunnels [21], in embankment dams [27] and in engineered clay barriers [28].
- According to the knowledge of the reservoir and of rock engineering [e.g.36] the treshold equilibrium of a closed fissure against hydrofracture can be expressed as:

$$p_w = [p_{ro}]_{min} \qquad (1)$$

p_w marks the water pressure in the aquifer at the boundary of the barrier.
$[p_{ro}]_{min}$ marks the reopening pressure of that fissure, where the normal total rock stress is minimal.
The fissure-reopening pressure exceeds the shut-in pressure (p_{sh}) of the same fissure. The minimal reopening pressure should occur at fissures perpendicular with the minimal principal total rock stress (δ_{min}). Consequently the safety criterion against spontaneous hydrofracturing can be expressed as:

$$P_w \le P_{sh} \cong \delta_{min} \qquad \textbf{(2)}$$

The shut-in pressure and the water pressure, can be measured directly in boreholes!

THE EXPERIENCE OF THE IN-MINE APPLICATIONS AND TRIALS

The stress dependence of the protective barriers provided also the possibility to transform the insufficient barriers into sufficient ones by proper modification of its rock-stress conditions. Such operations have been absolved at eight bulkheads, where the stress conditions have been modified by using of hydrofrac-grouting with cement slurries. The proper stress condition was specified according to equation (2). The testing of the bulkheads by water pressure and the experience on the long term operation of the pressurised barriers are presented in papers [17, 18, 19]. The bulkhead operation tested both the working hypotheses on the way of failure and the criterion (2). The new laboratory and in site test methods (tailored to investigate the barrier) were also proven. The results are as follows: [17, 18, 19]

- 4~6 meter thickness of properly stressed weak, fissured clays prevents against 26~28 bars. Seepage has not been detected.
- 4~6 meter thickness of properly stressed barrier in fissured coal also prevented against mayor inflows for long period, but permanent small seepage (in magnitude of 1 m^3/d) remained.
- The observations on the watertight feature of clay, and on the limited water conductivity of fissured pressurised coal are in full coincidence with the laboratory test results with a special device. (This one has been tailored to test the features of the fissured barrier under specified stress conditions. Fissured coal and clay samples have been tested [12, 16].)
- Under insufficient rock stress conditions the water started to approach the opening through the barrier. The stress phenomena signed, and the direct borehole observations detected directly the propagation of the hydrofracture inside the barrier. The propagation stopped immediately after decreasing of the water pressure
- During the test period the water pressure exceeded the measured shut in pressures with 3~5 bars. The criterion according to equation (2) represents appropriate safety margin.
- The methods tailored to measure the shut-in pressure in weak, fissured rocks operated properly. About two hundreds of such tests have been absolved by in mine holes.

COMPARISON OF THE EXPERIENCE/OBSERVATIONS ON THE BOTTOM AND ON THE OVERBURDEN

- According to the stress measurements and estimations, bottom-inflows occur only at that thickness of the barrier, where the stress preconditions for initiating the hydrofracture are present [15,17]. The *measurements in the overburden [22] and results of numerical modelling [6, 12, 20] also displayed proper conditions for hydrofracture initiating.* The Figure 3 presents the stress pattern around total and partial extractions at an Australian coalfield according to calibrated FE model studies.[6] The unsafe areas are marked in this picture according to equation (2). (This model relates to typical Carboniferous strata conditions, very similar ones with the "birthplace" of the tensile strain-criterion. This study [6] was fully independent from the author's studies. These are the two main reasons of utilising this figure for demonstrating of the author's statements.)
- Rock stress phenomena have been observed prior the occurrence of bottom inflows. These phenomena are quite similar to the ones associated with hydrofrac-grouting in the vicinity of mine openings. *The author analysed the case descriptions of 56 mayor inflows from the overburden in Ajka coalfield. Rock stress phenomena have been observed in 26 cases.*

Calibrated 2D FE model studies of ACIRL on approching a water body by full extraction and by undermining by partial extraction in New South Wales. Extraction thickness is cc 2 m, fault is crossing the whole series, virgine stress ratio: 1/1/1. **The principal stress vectors in the displaced mesh:**

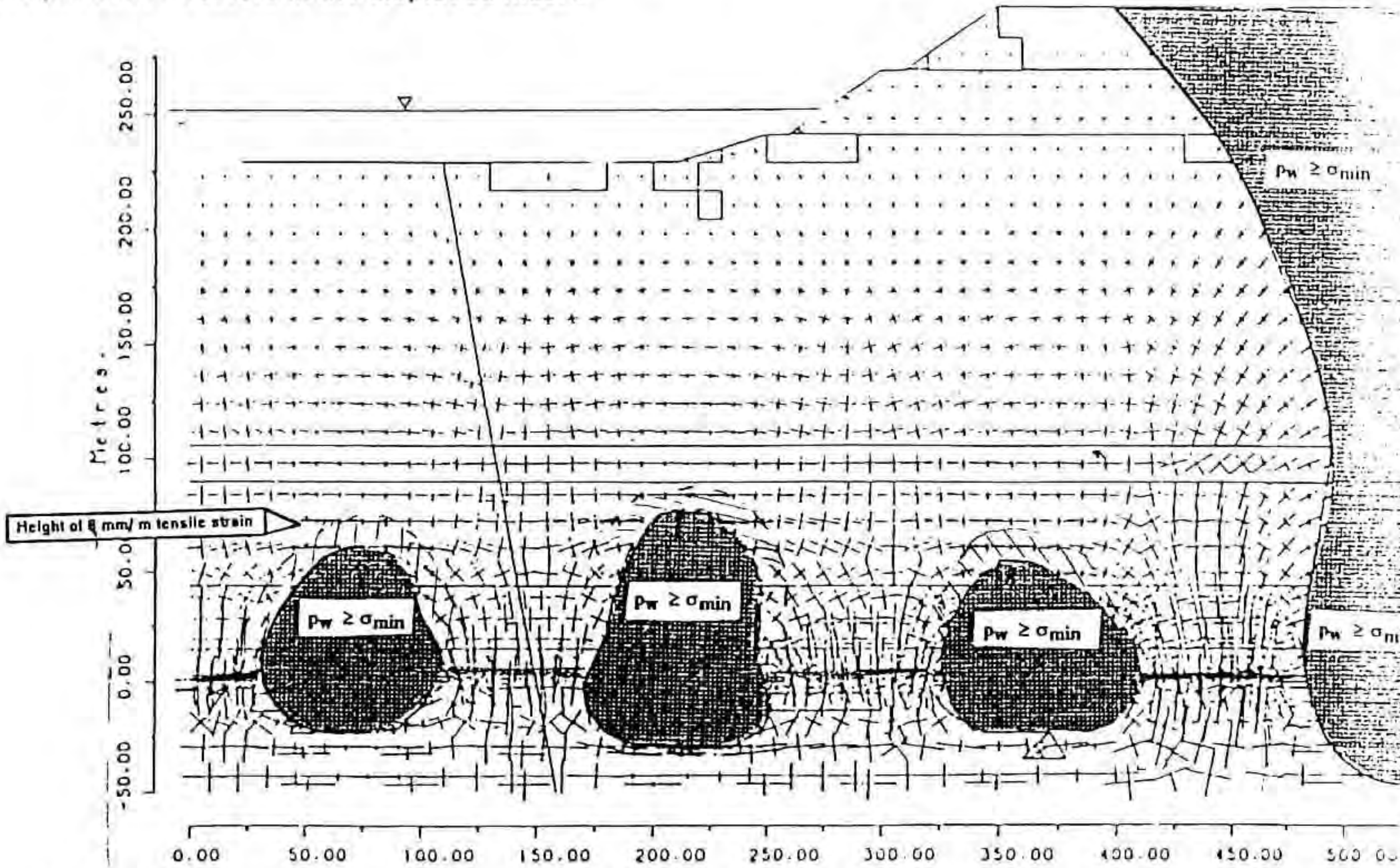


Figure 3 The not-protecting zone, and the appropriate barrier at total and partial extraction according to the new method

- The rebuildings of the rock stress in the barrier increase its protective capability in the bottom and in the overburden as well. The case examples on the bottom are mentioned in [15, 17]. *Under quasi-virgin stress condition 10 meter thickness of reconsolidated broken clay breccia prevented against ten bar water pressure in the overburden as well. The status of the rock and the water pressure have been detected observed directly [13].*
- The empirical criteria on the safe barrier-thickness can also be derived from the safety criterion against hydrofracturing:
  - The safe limit of the specific thickness of the bottom and of the lateral barriers is equal with the linear approximation of the shut-in pressure, versus distance of the opening [15, 17]. Outside the zone of mining-induced stress spontaneous hydrofracturings are not possible. Consequently the specific thickness as an empirical criterion is valid only within the zone of mining-induced stress in those cases, where the quantitative similarities between the mining induced stress fields of the analogous site and of case site also exist.
  - *The site-specific curves on the safe overburden thickness derived from the safety criterion (2) fit to the empirical curves as presented in Figure 1.*
  - *The safety limits of the deformation can be interpreted as equivalent ones with the stress criterion under actual virgin stress and under quasi-constant water pressure*
  - *This interpretation is also supported by quantitative fittings. Some case examples on mechanical modelling of the undermined overburden shows similar or same barrier thickness.* The safe curvature at the Ajka II case of panel-pillar undermining [20] is displayed in Figure 2. The estimation of a British team on the safe dimensions of the panels and the pillars resulted in about the same sizes [2]. The safe boundary against hydrofracturing and the safe barrier thickness according to the tensile strain is displayed in the rock stress picture of a numerical model study relating to a case from New South Wales [6], (see Figure 3). The stress pattern also illustrates the similarities of the stress pattern in the bottom and in the overburdens along the safe-line.

The experience, the observations and the experiments have demonstrated, that the risk of the spontaneous hydrofracturing (as a way of initiating the failure of the barrier) exists even in the undermined overburden. The validity of the safe criterion has also been approved by in mine experiments.

In comparison with other possible ways of the failure the hydrofracture should be the competent one for determining the safe thickness of the overburden, because the hydrofractures also relate to inhomogenities. The all other failure criteria (e.g. forming of open fissures, collapse of a rock beam) require smaller thickness for safety. The quantitative fittings with the empirical curves support this statement.

THE NEW METHOD FOR RISK ESTIMATION

The guideline on the evaluation of undermined barrier is presented hereto in nutshell according to the new approach. The experience of the first site-specific applications [20] and of forming the new guidelines and safety standards are also utilised in this compact "user's guide".

THE CRITERION AND ITS APPLICATION

The candidate barrier should fulfill the criterion (2) in a zone of "proper thickness". The "proper thickness" depend on the relating uncertainties. (If dense network of shut-in pressure measurements is available 5 meters is enough [18,19]. In cases of using verified numerical/physical models for stress estimation we applied 20 m as the "appropriate thickness" [20].) The above stress criterion should be fulfilled during the whole period of the state- transition.

The criterion relates to barriers crossed by faults, fissures, and/or by mining-induced fissures. The rock materials of the barriers are clay, marl, sandstone, siltstone, mudstone, and compact limestone.

If the barrier meets the criterion, one provides appropriate safety against major inflows but limited seepage may occur. The possibility of limited seepage depend on the rock properties and on the actual rock stress conditions. The author developed and implemented into the practice a laboratory device called "triaxial filter cell" to test the above features of large size samples (cut, fissured or broken & reconsolidated ones) under specified rock stress & water pressure conditions. The device and the test method is presented in [16]. During the two decades a lot of rock samples were tested under different conditions. (The weak, broken/fissured clay samples work as watertight ones even in shallow depth. The fissures of the medium hard aleurolites closed fully in medium depth [16].) The necessity of the in-site conductivity tests depends on the situation. If the seepage across the overburden is estimated, the watertight interbeddings may dominate. For estimating the flow conditions in separate beds, parallel with the sedimentation in site tests are necessary to determine the permeability under mining impacted conditions. The water pressure of the permeability test must not exceed the shut-in pressure!

The faults filled with loose, water-conductive material require individual equilibrium analyses taking into considerations the actual rock stress, the pore water pressure and the seepage-induced stress as well. The safe length of seepage along this fault should be determined accordingly.

The water conductive loose interbeddings should be considered as undermined aquifers, because the uncontrolled inflows from a sand lens may provoke sand inrush. The sand inrushes surely cause openings. The redistribution of rock stress du to mayor openings may change the stability against the main aquifer. In these cases the preventive drainage of the sand lenses is proposed.[20]

The safety against inland surface waters, where the water pressure above the land surface is usually negligible ones, the safety against hydrofractures can also be interpreted with some considerations: For these cases the risk estimation should consider first the open fissures at the surface. These open fissures either continue down to the mine, or at the bottom of the deep, water-filled fissures the water pressure may cause fracture-propagation. The safety criterion (2) can answer on the risk of fracture-propagation. The safety against the shallow ground water aquifer should also be considered by applying the equation (2), because the hydraulic connection between the two aquifers may cause indirect inflow from the surface aquifer.

The secondary sources of the danger in the overburden can also be estimated according to the new criterion:

- The risk of forming *bed separation caves* means _**n**_ **0** perpendicular with the strata at an actual stage of undermined overburden. The risk of filling the caves is determined first by the criterion (2). If the criterion is fulfilled, the watertight/water-conducting feature of the fissured rock should be tested under the actual rock stress [16]. Quick increase of the rock stress, may increase the water pressure in the bed separation cavities, with simultaneous increasing of the risk of hydrofracture [25]
- The risk of forming *wet clay inflows* can be evaluated by checking the risk of inflows or seepage through the overburden barrier as described above. If the risk of any seepage exists, the risk on forming of undrained status can be considered by using of the same apparatus as described in [16]. The wet clay inflow (as material-extraction from the barrier) causes stress redistribution, and one may induce progressive failures in the barrier [16].

THE APPLICATION OF ANALOGOUS EXPERIENCE

Analogous experience can also be applied if the analogy on the rock features, on the rock stress pattern and on the water pressure exists.

Partial analogies can also be utilised with additional analyses on the differences. The author also utilised the experience of bottom and of lateral barriers for evaluating of the undermined barrier as discussed above.

The test results, the observations on partially analogous conditions can also be used for analysing the model uncertainties and the parameter uncertainties of the physical/numerical models of a new site specific studies [20]

REMARKS ON THE SITE SPECIFIC ROCK ENGINEERING STUDIES

Site specific studies are necessary either to foreseen the mining impacted status of the overburden or on behalf of transposing of the analogous experience. The site specific studies are usually supported by coupled physical-numerical modelling and by in site measurements, observations. In general the same has been applied to support the new method. Only some small but important differences are mentioned hereto.

The shut in pressure measurements under virgin and under mining-impacted conditions are of exceptional importance. *The shut-in pressure measurements, recordings provide direct information on the protective capability of the barrier under the actual stress conditions.* A network of shut-in pressure measurements excludes the modelling uncertainties at the most critical areas. The spontaneous outflows from piezometer-wells and the newly recovered water head can also be analysed in this respect. The author tailored a measuring device and method for weak, fissured rocks. This one has been applied in cc two hundreds in mine holes.

Information on the other components of the stress-field under virgin and under mining impacted conditions is also necessary to verify the model studies.

The modelling studies should also focus to the stress pattern under virgin and also under mining impacted conditions. The maximal deformations occur at the final reconsolidated stage of the overburden, but this is not the critical status of stress field.

The numerical models should display the total stress under mining impacted conditions. The mining induced components are insufficient to apply the criterion. The stress- disturbances due to faults interbeddings are the basic information to apply the safety criterion. The model should be capable to display the stress status of the intermediate stages. On behalf of better approaching the new requirements, just after the cancellation of the COCOM restrictions against Hungary we installed one of the best numerical models with the necessary hardware.

The new physical models have been also be tailored to model the stress conditions better. The frame is large enough for modelling of more panels. The model is capable to produce specified 3D stress 2D deformation field. The stress sensors are calibrated to the actual model material. The designer and the head of the laboratory has been Mr. G Gajari. In 1993. some model studies on undermining water bodies were absolved for home and for western clients. The improved capabilities of the physical models also help the coupled application of physical/numerical model studies and to verify the model by in site stress measurements. The information on the stress status of the intermediate stages of the overburden-subsidence is of great importance.

THE ADVANTAGES

The new method serves with some advantages:

- The criterion is not site specific one. The same criterion and method are valid for bottom, for lateral and even for overburden barriers, and for all kinds of sedimentary-barrier rocks with fissures and with tectonics.
- The new criterion includes more virgin and mining induced parameters of the site (e.g. water pressure, the depth of the barrier and of the operations) than the other ones.
- It can be used without any local or analogous experience basing only to site specific studies.
- The method is applicable to inhomogenities, anisotropies.
- The criterion gives direct "instruction" on the proper ways of improving the protective capability of the barrier.
- The preconditions of the applicability of analogies are specified. The utilisation of partial analogies (e, g. experience on bottom barriers) is also possible.
- The method provides more accurate estimations on small impacts.
- The governing parameters of the new criterion (the shut-in pressure and the water pressure) can be measured in boreholes both from the surface and in underground openings, even inside the bottom of the sea. This is a direct information on the protective capability of the close surrounding area of measurements. The measured data do not include any modelling uncertainties. The data of these measurements can also be used for model-verification.

THE FIRST APPLICATIONS

The feasibility study on Ajka II coalfield has been the first case. The sizes of the panels and the pillars for undermining a thick karstified aquifer have been determined according to the new criterion by using physical and numerical model studies and the data/observation of the mineral exploration. Site-specific and analogous mining experience were not available. The models were tested by modelling similar cases, where in-mine observations are available. The details on these studies are described in [20].

That time the experimental basements of the new criterion and the fittings with the experience on Carboniferous coalfields were not jet available. The round table discussions with leading British and Russian professionals concluded to propose the simultaneous application of the criterion (2) with conventional ones.

Two years later the Hungarian government commissioned the British Mining Consultants to supervise all mine's feasibility studies. The projects of the new mine have been rejected due to its poor economic efficiency. but the risk estimation was accepted. The British team approved the stress criterion as "the best one for weak rocks". They also pointed out, that it is "not only a criterion but a complete code, applicable one for other cases". (That time the comparison with the experience of the Carboniferous coal basins was not available.) The supervising team also estimated the safe dimensions of the panels and pillars by using the British approach. The results were quite similar ones [2]

These opinions and the experimental & empirical basement encouraged the author to apply the new approach *in other projects for home and for Western clients as well.*

The Coal Industry of China purchased the know-how of the Hungarian empirical method together with the new one including the devices for laboratory and for in site test referred in this paper.

The draft of the new safety standard on estimating of water barrier layers/pillars comprises the empirical method for cases, where analogous experience is available and the new one for other cases. The Mine's Safety Authority already accepted the draft as a professional guideline. The draft as one of the proposed safety standards is in "waiting list". The revision of the general Mine's safety prescription and the new (EEC-conform) Act on Standardisation should be completed and amended first.

CONCLUSIONS

The protective capability of the undermined overburdens surely collapses due to mining-induced open cracks crossing the whole series, but the water pressure opens also the closed fissures, faults under insufficient stress conditions.

The safety of the undermined sedimentary barriers against major inflows is characterised by the safety against spontaneous hydrofracturing. The governing parameters of the equilibrium are the rock's stress and the water pressure. The deformation parameters are in contradiction with the experience in many respects.

The safety criterion against spontaneous hydrofracture with appropriate safety margin is as below. $\mathbf{p_w \leq p_{sh} \cong \delta_{min}}$. The governing parameters: the shut in pressure ($\mathbf{p_{sh}}$) and the water pressure

(p_w) can be measured directly in holes. The validity of the criterion has been demonstrated by the experience and by in mine experiments.

The watertight feature or limited water-conducting features of the fissured, tectonised barrier rocks depend on the actual stress and on the rock feature. Empirically/experimentally approved methods are presented to test the mining impacted barriers in this respect

The safety at the inhomogenities and anisotropies are also specified accordingly.

The possibility of using analogous experience is specified according to the new findings (see above). The new criterion is valid for all situatiuns of the barriers (in the bottom, in the lateral side) as well. This general criterion and the new knowledge on the governing parameters extend the applicability of partial analogies.

The new finding and the new criterion required to implement a new method of risk estimation. The new method provides more safety for mining and more accurate estimations for environmental control.

ACKNOWLEDGEMENTS

The studies have been multilaterally supported. Dr A Schmieder and Mr. Gy. Gajári helped a lot with their strong contradicting, but useful opinions. The Veszprém Coal Company (Mr F. Pera General Director and Mr. Gy. Szentai Head of Mine Water Control) provided the first challenge and financial basement to apply the new method in the practice. The contributors of the projects and of the site experiments have been acknowledged in the papers of the author referred below.

In the frame of round table discussions leading international scientists Prof. R. N. Singh, Dr. Hibberd, and Prof. V. A. Mironenko have given support with comments, with advises and with critics. The supervising team of BMCL Dr Shadbold, and Dr. P. Norton have given the first approval of the new method.

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