Spontaneous Hydrofracturing: a Frequent Way of Failure in Natural and in Engineered Rock/Soil Barriers and New Ways for Process Control

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ABSTRACT

In accordance with the experiences of thousands of mine water inrushes and of special laboratory tests and site experiments the failures in natural rock barriers and artificial isolating liners are often initiated by spontaneous hydrofracturings. The risk of hydrofracturing can be safely excluded if the instantaneous shut-in pressure (p_{sh}) equals or exceeds the water pressure $p_{sh} \geq p_w$). This criterion can be used for evaluating/sizing natural or artificial rock/soil barriers and for preliminary process control by modifying the water pressure and/or rock pressure conditions properly. Some new practical applications of this new approach are also presented. based on the new information the protective capacity of geological barriers of deep waste respiratories was analyzed and compared with the experiences. This analysis has resulted in quite a new conclusion: the strong earthquakes have not caused any dramatic changes in the protective capacity of thick geological barriers.

INTRODUCTION

During the last decade a special mode of rock/soil failure was discovered in several areas of the rock/soil engineering activities: this is the spontaneous hydrofracturing in quasi impermeable rocks/soils due to water under pressure:

• In the field of mine water engineering some laboratory tests, field experiments and a mass of data on mine water inrushes in the Hungarian coal mines have given such preliminary conclusions (Kesserü[11,13]) according to which the natural impermeable layers (clays marls) between the reservoir rocks and mine openings are endangered by spontaneous hydrofracturing in those zone of the rock barrier, where the rock stress conditions changed due to the mining activities. This spontaneous hydrofracturing seems to be the most frequent initiating factor of mine water inrushes through the quasi impermeable rock/soil barriers (Kesserü[11,13,17]).

•• Based on the analyses of cracking cases in embankment dams Sherard[29] discussed that probably hydrofracturings occurred in many cases at the zones of the earth dams, where the stress conditions had been changed due to the compaction differences of the basement.

••• Spontaneous hydrofracturings occurred in some hydrotunnels in Alaska where the water pressure exceeded the reopening pressure of the rock fractures (due to the shallow location of the tunnel) (Kogan[19]).

•••• In engineered clay barriers (of deep waste disposals), the risk of spontaneous hydrofracturing was demonstrated experimentally by Stegentahler[30].

As a contribution to transforming the partial approaches mentioned before into more generalized ones this paper presents:

- additional empirical and experimental studies on the occurrence of spontaneous hydrofracturings in natural and artificially formed isolated barriers,
- new methods for testing, evaluating/sizing of the protective barriers,
- some new ways of process control (with the experiences of the first practical applications), and
- a new approach to earthquake resistance of thick geological barriers.

NEW EXPERIMENTS AND EXPERIENCES IN RELATION WITH THE RISKS OF SPONTANEOUS HYDROFRACTURINGS

During the last six years an intensive research program financed by the Hungarian Scientific Funds was carried out. Due to the pressing needs of practical solutions the new results were immediately introduced in the mine water engineering practice in Hungary by Kesserü, Szentai and others[11,13,14,18,31] and in China by Kesserü[16] as well. Some of the new results are drafted hereto to illustrate the conclusions.

Measurements and experiences

The measurements on the zones of the decreased hydrofracturing pressures around roadways in soft rocks were initiated and carried out by the author and by his colleagues in 1987. One set of measurements is presented in Fig. 1. Similar measurements were conducted by Kvartič, Meža and others[21] in Velenje (Yugoslavia) in the undermined overburden of a longwall face.

In accordance with the above measurements the possibility of a spontaneous hydrofracturing should exist in the zone of modified rock stress around the mine openings. However, one question should be answered: can a hydrofracture cause water inrush through the protective barriers? In accordance with many tests, experiments relating to artificial hydrofracturings the direction of fracture propagation depends on the inhomogeneities of rock (faults, sedimentation inhomogeneities) and on the direction of the rock stress components (e.g. Mizuta, Sano and others[23], Waprinski, Schmidt and others[34]).

Consequently in many cases the fracture propagation should be started in a quasi horizontal boundary surface and the water pressure in the hydrofracture causes the failure of the barrier or opens new fractures crossing the barrier (see Fig. 2).

These processes are indicated by increased rock stress (bottom swelling, convergence, etc.) and the water should appear in the vicinity of a fault. In this case the spontaneous hydrofracturing is the initiating factor of the inrush.

In the close vicinity of the openings the failure the rock often results in a zone of decreased loading ability of the rocks where all of the stress components should decrease. In these zones a hydrofracture on along a fault can also open direct fissure for the water flow into the opening.

The width of the hydrofracture is usually a few millimetres which is enough to initiate a piping process in the faulted zone. In this case increased rock stress phenomena are not foreseen, but the water should appear at a fault.

Let us compare the above statements with the experiences of thousands of mine water inrushes of Hungarian and Chinese mines relating to the bottom barrier crossed by faults. The bottom barriers in Hungary are weak clays, marls and in China they are medium hard mudstones an sandstones.

The summary of the experiences are listed below:

a) The majority of the inrushes are connected with tectonic disturbances in China and in Hungary as well (Kesserü & Willems(7), Li Jinkai(22)).

Due to the fact that the fissure reopening pressure p_{ro} is usually smaller than the fracture initiating pressure of the intact rock, the risk of hydrofracturing on along the faults must be higher (in comparison with the intact rock).

b) If the thickness of the protective layer (m) (interpolated between the boreholes) exceeds a maximum value, water inrushes never occur through quasi impermeable protective layers. This limit value is about 45-50 m in Hungary and in China as well (see Fig. 3).

Taking into consideration of the uncertainties of the real thickness values, this distances do not exceed the area of modified stress in the bottom of roadways and faces. The extensions of the zone of the decreased hydrofracturing pressure around mine openings are of the same magnitude (15-30 m).

c) The empirical data of inrushes show probable but characteristic values of a "threshold hydraulic gradient" (p_w/m) in Hungary (Vigh & Szentes(33), Kesserü & Willems(7), Schmieder(27)) and in China (Li Jinkai(22)). Similar threshold value was obtained from the experiences on water barrier pillars of Wyoming Coalfield. By applying a linear approximation of the hydrofracturing parameters (e.g. the shut-in pressure p_{sh}) in function of the distance from the openings (m) the similar "virtual threshold hydraulic gradient" can be deduced (see Fig.1).

The sealing coefficient introduced by A. Schmieder(27) which represents the risk of water inrushes and the empirical threshold values related to weak clays, marls in Hungary and to mudstones/sandstones in China are compared in Fig.4. For practical purposes the inverse of the hydraulic gradient I/J_o is used/displayed:

$$\nu = \frac{m - A}{p_w} \qquad (1)$$

where A is an empirical factor representing the zone of open fissures (Li Jinkai(22)) in the bottom and the uncertainties of the real thickness of the protective layer between the exploration boreholes (Kesserü & Willems(7)).

In Hungary the factor A varied between 5-8 m, in China between 8-12 m; in Wyoming it was 3 m. The safety values of v (called v_0), related to small inrush risks of 2-3 %, are used as threshold values for mine safety prescriptions. In Hungary v_0 = 2 m/bar has been prescribed for sizing water barrier pillars. The equivalent v_0 value for China is 1.3 - 1.4 m/bar and for Wyoming 1.25 m/bar (Fig.5). This sealing coefficient, which can be deduced also by applying linear approximation of hydrofracturing pressures, belongs to the different values of risks (see Fig. 6).

d) Previously the appearance of the inrush phenomena of increased rock stresses (e.g. moving bottom, broken supports) were detected in China and in Hungary as well in many cases (Kesserü, Szilagyi & Havasy[16], Kesserü[17]) but not in all cases!

e) Similar cases are known in Hungary and in China as well, where the increased rock stress (due to the reconsolidation of the overburden) increased the protective capacity of the barrier.

Results of in situ measurements are also available on water pressure differences loading the protective layers at higher distance and/or under higher stress conditions. Two of such cases are mentioned hereunder:

a) In Velenje (Yugoslavia) 7 m of broken, reconsolidated clay was bored through by us in the course of project implementation (Kesserü[8,10]). The water pressure of the reservoir was 10 bar. Consequently under those stress conditions the specific thickness was 7/10 m/bar. Based on the data of rock stress measurements, quasi-original rock stress conditions may be supposed at the test area.

b) In Nagyegyhaza Colliery a group of piezometer holes were prepared to determine the water flow pattern. In these piezometer holes 17.7 bar pressure difference was measured between the two sides of a bauxite layer of 8.5 m, which bauxite layer is located at 20-25 m m from the bottom of the exploited coal seams. Consequently this specific thickness of 8.5/17.7 m/bar also refers to conditions of higher rock stress (compared with the layers in close vicinity of the mine openings).

These experiences also fit to the "hydrofracturing theory".

As a conclusion of the comparison of experiences and measurements the spontaneous hydrofracturing seems to be the frequent initiating factor of failure in both soft and medium hard impermeable natural barriers.

Due to the well known fact that the governing parameters of these spontaneous hydrofractrings are the water pressure (p_w) and the rock stress parameters, the threshold equilibrium in the barrier can be expressed as:

$$p_w = |p_{ro}|_{min} \tag{2}$$

where $|p_{ro}|_{min}$ is the reopening pressure of those fissures (faults) where the normal stress component is minimal.

Because the fissure reopening pressure (p_{ro}) exceeds the instantaneous shut-in pressure of the same fissure

$$p_{ro} > p_{sh} \tag{3}$$

The following safety criterion may be proposed:

$$p_w = p_{sh} \approx \sigma_{min} \qquad (4)$$

EXPERIMENTS AND EXPERIENCES OF BULKHEAD OPERATIONS

The direct experiences and laboratory experiments (Kesserü[13]) relating to the role of the rock pressures and the considerations, conclusions of Chapter 2 show a new possibility to improve the protective capacity of the rocks by modifying the stress conditions properly. This possibility was realized first during the construction of three bulkheads, where the stress conditions in the surrounding rocks were transformed in accordance with the criterion expressed in unequation (5). The details of the operations, experiments and experiences are presented in an other paper of this Congress (see Kesserü, Bagdy and others). Only the main conclusions relating to the failure process and to the safety criterion are drafted hereto:

- The possibility of a new way of process control by modifying the stress conditions of the barrier properly has been demonstrated.
- A strong coincidence has been detected between the protection effect of the barrier (p_w) and the measured values of shut-in pressures (p_{sh}).
- In relation with the safety criterion (5) the safety allowance was 3-5 bars.
- During those bulkhead tests, when the rock stress was insufficient, and water throughflow occurred, the propagation of the hydrofracture, and the yields of propagating water were measured/detected directly. The magnitude of the propagating water yield (q) and the" propagation velocity" (v_p) were quasi equivalent with the artificial hydrofracturings: (q = 0,050 - 0,2 m^3/min; $v_p \approx$ 1,5 - 10 m/h)

COMPARISON OF THE EXPERIENCES AND THE CRITERIA OF UNDERMINING WATER BODIES WITH THE CRITERION AGAINST HYDROFRACTURING

For the purposes of undermining water bodies, lakes, rivers, the sea and overlying reservoir rocks data of safe and unsafe cases (overburden thickness, exploitation thickness, deformation parameters of the undermined surface, etc.) under conditions of different rocks (hard and soft ones) are available from China, USSR, UK, Australia, etc. (CCMRI[2], Gvircman[4], DSC[3], etc.).

For comparing the safe cases of undermining against hydrofracturing with other empirical approaches two ways have been used. Some results of the detailed comparison are drafted below:

- The empirical curves of direct experiences relating to the safe thickness of the overburden can be compared with similar curves deduced from the safety criterion of hydrofracturing for realizing these comparisons with the mass of experiences of China and USSR are available (Gvircman[4], CCMRI[2]). In the late seventieth the author investigated the safe thickness of undermined water bodies in Velenje (Yugoslavia) and in Várpalota (Hungary) (Kesserü[9,10]). In the course of these studies the mechanical conditions of the undermined overburden were investigated by applying in situ measurements and 2D FEM models verified by the data of in situ stress and deformation measurements. By utilizing the results of these numerical model studies the safe thickness of the overburden was reconstructed by using the criterion $p_w \leq p_{sh} \approx \sigma_{min}$ and a safety reserve of cca 10 m for recompensating the uncertainties of the actual thickness of the overburden and those of the modelled stress conditions. The results compared with the experiences of USSR and China are given in Fig. 7/a and 7/b. In both sites wet clay and water-mud inrushes occurred during sliced exploitation due to the undrained stress conditions of the penetrated undermined reconsolidated overburden (Kesserü[14]). The analysis of the experiences have demonstrated the presence of preconditions ($p_w > \sigma_{min}$) for penetrating the overburden due to spontaneous hydrofracturing in the previous slicing operation for all cases of inrushes (see Table I and Fig. 7/b).

•• To determine the safe thickness of the overburden empirical threshold parameters of the deformations are used worldwide. As threshold limits the horizontal tensile strain is used in English speaking countries ($\epsilon_{max} < 10$ mm/m) and the inverse of minimal curvature I/R is used in USSR. Within the frame of a feasibility study for a Hungarian coalfield (Ajka II) proper partial extraction of undermining water bodies was tailored by using the criterion against hydrofracturing (Kesserü, Szentai & Dosa[31] and others). The equivalent deformation parameters of the safe limit were also available from the numerical modelling of the overburden. The results of the comparison are given in Fig. 7/c and 7/d. Although the deformation criteria are used generally, some unrivalled advantages of our stress criteria should be pointed out. These are as follows;

- σ_{min} and/or p_{sh} can be measured/detected directly in boreholes quite easily, bur the parameters (ϵ_{max}; $(1/R)_{min}$) of deformation criteria cannot be measured directly inside the overburden.
- Experiences of analogous conditions are not very necessary.
- It provides safer criterion against local failures.
- The pressure of the water reservoir (which is an important factor) is also taken into consideration.
- The deformation criteria are not convenient to take into consideration the effects of slicing and reconsolidations.

As a conclusion of the author's experiences and experiments in the field of mine water engineering, spontaneous hydrofracturing seems to be the most frequent risk of failure in soft and hard impermeable geological barriers within the area of modified stress. Consequently a safety criterion against hydrofracturing $p_w \leq p_{sh} \approx \sigma_{min}$ (including a safety margin of cca 3-5 bar) can be used as a general criterion for sizing when protective barriers are evaluated within the zone of modified stress (see Fig. 9).

SOME NEW POSSIBILITIES OF THE PROCESS CONTROL

The hydrofracturing approach opens several new ways also for better process control, because two factors are available for regulation/modification: the water pressure (p_w) and the rock stress (σ_{min}). The water pressure regulation and the regulation of the rock stress conditions provides some new possibilities. Let us list only those, which have already been put into the Hungarian practice:

- Although the water pressure regulation is a well known way of the control, the hydrofracturing criterion gives altering requirements for the necessary size of depressurization as presented in Fig. 9 (in comparison with the former requirements). The new criterion provides more economic sizes for the safety of depressurization.

- By utilizing the load of overburden under reconsolidation in the bottom barrier its protective effect can be increased. Due to this effect the area and the necessary water pressure drop of the preliminary drainage can be minimized (Szentai & Dósa[31]).
- By pressurizing the surrounding rocks around the bulkheads roadways were plugged successfully under extremely difficult rock conditions (Chapter 3).
- The new way of evaluating the protective layers gives us possibility to size proper water barrier pillars for each condition. This know-how has been sold in China and it has already been put into practice in the Chinese Coal Mining Industry (Kesserü, Szilagyi & Havasy[16]).
- A new way of reinjection of mine waters into the underground reservoir of the same mines is based also on the knowledge about the natural protective barriers against hydrofracturing (Pera, Szentai et al.[26]).

EARTHQUAKE RESISTANCE OF GEOLOGICAL BARRIERS

This question has great practical importance in two respects:

- • Do earthquakes initiate mine water inrushes?
- •• Do earthquakes cause dramatic permeability changes in the geological barriers of deep waste disposals, which barrier thickness must be several hundreds of meters to prevent against the long term waste migration?

The second question is the more important one, because the actual requirements of deep waste disposal sites do not allow any risk of strong earthquakes during the whole life period of the respiratories (e.g. IAEG[6]). The fulfilment of these requirements is based usually on the extrapolation of the past earthquake history of centuries in a period of thousand years.

Experiences on earthquake resistance of geological barriers against mine water inrushes

Fig. 3 and 4 give a direct comparison of experiences between the Hungarian mining practice, without strong earthquakes, (maximum MKS intensity was less than 4.5) and three coalfields of China (Jiaozuo, Fenfeng, Zibo) locating in an active zone where on the earthquake map of China (Xie Rui Zhang[35]) medium strong earthquake cases (8-9 MKS) are marked. The hard mudstones and sandstones show better properties in comparison with the protective soft ones in Hungary but no any inrushes occurred exceeding the safety limits.

Individual case analyses of inrushes occurred nearly at the time of earthquakes in Hungary (Bendeffy[1], Monus et al.[24]). In these periods the locations of all inrushes could be identified over insufficient protective layers (5-15 m).

Indirect informations are also available on the earthquake-resistance of the barriers of Kailuan Coalfield (China) impacted strongly by the enormous earthquake of Tanshan. The intensity of this earthquake was cca 10 MKS in the coalfields (Shen Dai Kai & Gao De Quian[28]). Although due to the collapse of the electric supply the pumping stations of mines were flooded, the fact of successful dewatering of the mines demonstrated indirectly that the earthquake did not initiate any rupture of the geological barrier (the thickness of which varied between 270-350 m) because any large water inrush from the karstified bedrock of enormous transmissivity ($T \approx 10^{-1}$ m^2/s !) surely would block any dewatering operations with the available pumping capability.

The experiences of mine water engineering drafted above may give the conclusion that the deep thick geological barriers (of safe thickness against hydrofracturing) were not impacted even by the strongest earthquake. This new conclusion seems to be amended by other geological experiences of overpressurized natural oil and gas reservoirs and of some closed aquifers filled with high pressure water of extreme chemical composition.

The impacts of earthquakes onto the governing parameters of spontaneous hydrofracturings

Due to the limited velocity of fracture propagation the short time changes (elastic waves) cannot cause continuous hydrofracture propagation. Only long term changes (some hours, days) of the governing parameters (see Equation 2) should be considered. (The parameters of the wave propagation should be eliminated, however intensity of the most dangerous Rayleigh-waves also decrease in the function of depth (Yamahara, Hisatomi & Morie[(36)]).

Small changes of pore water pressures (in magnitude of cm or dm) before and after the earthquakes were detected in many parts of the globe (including Hungary). Results of detailed water level recordings were reported by an amateur research group in Japan (Oki & Hiraga[(25)]). The maximal water level rising was within one meter and in one case some meters of water drop were also recorded.

Some in situ measurements on virgin stress are given in Fig. 10 by comparing the magnitude of water pressure values with the minimal principal components of the rock stress in a quiet zone (Forsmark, Sweden) and in a seismically impacted area Tokyo Japan at the boundary zone of the three globe plates (Tsukahara[(32)]). These measurements are representative ones for the areas inside of the continents. Zones of tensile stresses can occur only at some dilative zones of the Ocean bed.

These measurement results may provide such conclusion that under virgin stress conditions the safe relations between the water pressure and the minimal principal rock stress are not disturbed by earthquakes. Consequently, the geological barriers of safe thickness are surely not impacted by the earthquakes. This statement has a more stronger validity for the geological barriers of deep waste disposals, where the retardation of waste migration requires several hundred meter thick barriers.

The direct experiences and the measurement results have given the same conclusion: the deep geological barriers of safe thickness are not impacted even by strong earthquakes. This statement due to its exceptional practical importance in relation with deep waste disposals should be checked repeatedly by other independent experiences.

THE RISK OF SPONTANEOUS HYDROFRACTURINGS IN GROUTED ZONES

In cases of grouting large caves of hard rocks (e.g. karstified caves) by using soft compactible grouting materials (e.g. clay cement slurries, bentonite cement slurries) the stress relaxation in the solidified grouted material may offer proper conditions for spontaneous hydrofracturing through the grouted cave. The engineered barriers around deep waste respiratories are also "unstressed" ones. The risk of Hydrofracturing in the above case was demonstrated by Stegentahler's[(30)] laboratory experiments already.

Our laboratory experiments were focused to find practical ways for preventing spontaneous hydrofracturings. Bentonite-cement grouting slurries infected under high pressure into large caves of hard rocks and engineered barriers of proper sand-bentonite mixtures were tested for the above purposes. The tests have demonstrated the possibility of process control against hydrofracturing. The practical solutions are under application for patent.

CONCLUSIONS

▪ The most frequent failure of thick natural and engineered rock/soil barriers caused by water pressure in spontaneous hydrofracturing.

▪ The safety criterion of spontaneous hydrofracturing ($\sigma_{min} \approx$ pshh $\geq p_w$) can be used for evaluating, sizing natural barriers of any location around underground openings against water inrushes.

▪ By modifying the two governing parameters σ_{min} and/or p_w properly new ways have been discovered and some of them were utilized already for preventing water inrushes even in extremely weak rocks.

▪ The geological barriers under proper stress conditions preserve their protective capacity against strong earthquakes.

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