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Reducing the risk associated with dams through dedicated tracking systems. Selection of options for additional behaviour monitoring for existing dams

Reducerea riscurilor asociate barajelor prin sisteme dedicate de monitorizare. Selectarea opțiunilor pentru monitorizarea suplimentară a comportării barajelor existente

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Abstract: Ensuring the safety of large dams is a legal and ethical obligation that requires continuous assessment of structural behaviour and associated risks. This study proposes a decision-based framework for risk reduction through dedicated behaviour monitoring systems (BBM), emphasizing their role in detecting atypical responses and preventing potential failures. A quantitative method is developed to evaluate the effectiveness (r) of supplementary monitoring interventions by correlating reductions in failure probabilities across distinct failure mechanisms. The framework is applied to the Vidraru Dam (Romania), a concrete arch dam undergoing refurbishment, including a full filling–emptying operational cycle. Historical behaviour data and previous emptying events are reviewed to identify specific vulnerabilities related to thermal, hydraulic, and structural stress variations. Multiple supplementary monitoring options—mathematical modelling, telemeter reactivation, 3D laser scanning, InSAR tracking, hydrogeological boreholes, and inclinometer casing are evaluated based on risk reduction efficiency, implementation cost, and net benefit. Results show that a combined strategy integrating finite element modelling, telemetric upgrades, 3D scanning, and hydrogeological instrumentation yields the optimal balance between safety and cost- effectiveness, achieving the greatest reduction in annual risk rate. The proposed methodology provides a systematic approach for decision-making in dam safety management under atypical operating conditions.

Key-words: dams, safety, BBM

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1. Decision criterion

Reducing the risk associated with dams to a rational minimum is a legal and moral obligation of dam owners as well as authorities. An effective means of reducing risk is to ensure an adequate system for monitoring dam behaviour, capable of detecting atypical behaviour and adverse events that may dangerously evolve towards dam failure. If such a tendency is identified, structural and/or non-structural measures can prevent failure. The behaviour monitoring system, together with the other structural safety measures, ensures risk reduction by decreasing the probability of failure [2]. Most specialists consider that an adequate monitoring system reduces the probability of failure by an order of magnitude [3], going as far as to state that a well monitored dam will not fail (Lafitte, 1996).

The behaviour monitoring system must be well targeted to the relevant safety parameters and must be sufficiently detailed to monitor the whole dam-foundation-lake ensemble. In the case of atypical behaviour or particular operating conditions, the dam behaviour monitoring system shall be supplemented.

The effectiveness of risk reduction through additional behavioural surveillance (or maintenance and restrictions in operational plans) is quantified by the rate of reduction of the annual rate of risk. If P_r is the probability of failure of the existing dam and P_r' is the new probability of failure, reduced as a result of the planned measures, the relationship is used:

$$P_r' = P_r(1-r) \quad (1.1)$$

where *r* is a measure of the effectiveness of the interventions.

The dam may fail by different failure mechanisms depending on the primary events that trigger them. The measures envisaged or the way of supplementing the behaviour monitoring system have different effects on the different failure mechanisms, also reducing the associated failure probabilities differently. For example, pendulum supplementation does not provide relevant information for the prevention of spill rupture and thus has minimal effects on the corresponding rupture probability of this mechanism. Likewise, an additional system of automatic condition checking and control of the hydromechanical equipment reduces the probability of overtopping failure over crest (while maintaining the maximum flow discharge capacity), but has no effect on the probability of internal erosion failure.

If we denote by j $(j = 1, \ldots, n)$ the potential failure mechanisms and by $P_{r,j}$ their associated failure probabilities, then the total probability of failure is given by the relation:

$$P_r = \sum_{1}^{n} \cdot P_{r,j} \quad (1.2)$$

A particular measure expected to increase safety (e.g. increasing the number of piezometers) has different effects in reducing the probabilities of breakage associated with different mechanisms:

$$P'_{r,j} = P_{r,j}(1 - r_j) \quad (1.3)$$

where r_j is the effectiveness of the intervention for mechanism *j*.

From relations (6.1) and (6.3)

$$P'_r = P_r(1 - r) = \sum_1^n P_{r,j}(1 - r_j) \quad (1.4)$$

whence the overall effectiveness of the envisaged measures:

$$r = \sum_1^n j(P_{r,j} / P_r) \cdot r_j \qquad (1.5)$$

The expression (6.5) is a weighted sum of the efficiencies by failure mechanism, the weights being the relative probabilities associated with them.
The annual hazard rate associated with the existing dam has the known expression:

$$R, = P_r \cdot C \qquad (1.6)$$

here P_r is the probability of failure, and C is the quantitative measure of the consequences, this time including damage to the owner.

In the case of dams under the control of the authorities, as in the case of SPEEH Hidroelectrica S.A., the loss of human lives caused by dam failure is minimised to the minimum possible by warning-alarm- evacuation plans. Assuming that, in terms of consequences in terms of loss of human life, all measures are taken to minimise the risk to the limit of tolerable risk, the quantitative measure of consequences C has only a monetary expression. C is the operating cost (actual or potential), as we have seen.
The benefit created by reducing the risk rate by supplementing the behaviour tracking system, BBM, is [1]:

$$b = P_r \cdot C - P'_r \cdot C = P_r \cdot C \cdot r_s \quad (1.7)$$

where r has the expression (6.5), and the subscript s denotes a particular BBM supplementation system or supplementation strategy.
Each strategy has a corresponding annual realisation cost ΔC_s and consequently the net benefit will be:

$$b_n = b - \Delta C_s = P_r \cdot C \cdot r_s - \Delta C_s \qquad (1.8)$$

The selection of the additional BBM strategy is naturally made on the criterion of maximum net benefit (b_n = max.). A suggestive representation is contained in Figure 6.1.8.

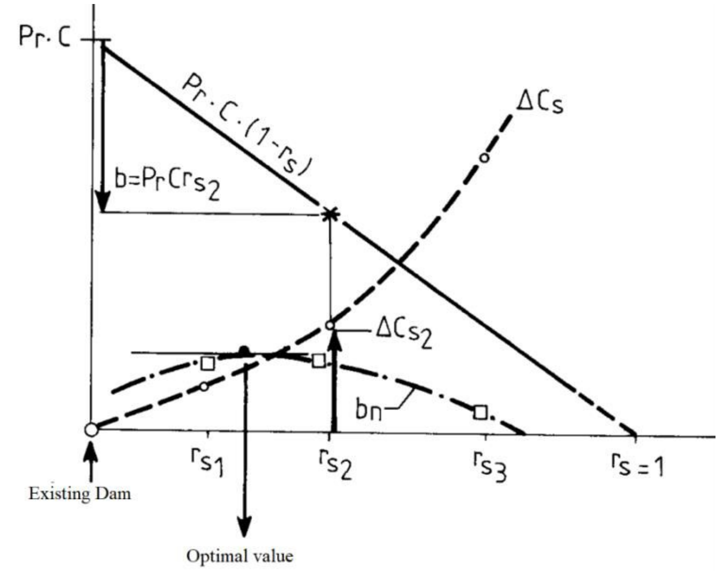

Figure 1. *Optimal variant selection based on net benefit maximisation.*

2. VIDRARU dam case study for the filling - emptying cycle

SPEEH Hidroelectrica S.A. awarded in 2024, the "Vidraru dam refurbishment" project. During the period of the Vidraru CHE refurbishment, the Vidraru reservoir operation mode will include a filling - emptying cycle. As a result, an efficient approach [4] to the monitoring of the Vidraru dam during the period of the revitalisation works is required.

2.1. Presentation of the dam and the existing BBM system

The Vidraru dam is of the "concrete arch" type, with a height of 166.60 m, an arch length at the crest of 314 m and a volume of 470,000 m^3 of concrete. The thickness at the base is 25.0 m and at the crest is 6.0 m; the road on the crest is 10 m wide (with pavements); the crest elevation 834.00 mdM.

The dam consists of 22 plots separated by helical jointed joints so that, for any given elevation of the dam, the lateral faces of each joint are radially oriented and converge in the mean centre of the respective arc. The width of the plots is variable, ranging from 10 to 14 metres each.

The dam has the following construction characteristics:

- canopy height 834.00 mdM
- maximum height 166.60 m
- length at crest 317.00 m
- rope length at canopy 245.00 m
- key thickness at canopy 6.00 m
- thickness at base 25.00 m
- chord to height ratio (L/H) 1.48
- base thickness to height ratio (B/H) 0.15
- volume of concrete 470 thousand cubic metres

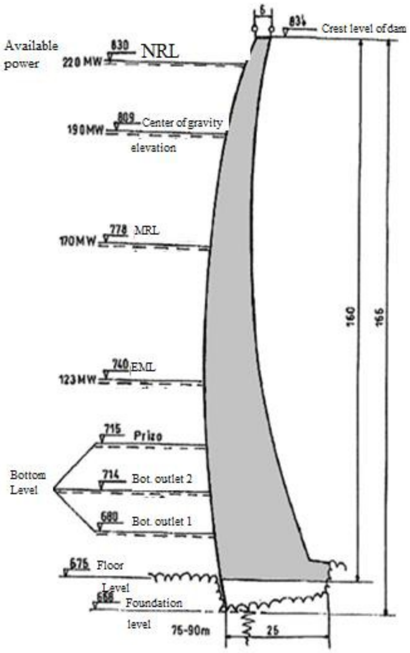

Figure 2. *Main dam section*

The spillways equipping the Vidraru dam have the following capacities (according to the operating regulation):

- Three-field free-flowing surface spillway (832.85 mdMN) = 260 m^3/s.
- Bottom drains: (2 x $80m^3/s$ = 160 m^3/s)
- Hydroelectric power plant: 90 m^3/s.

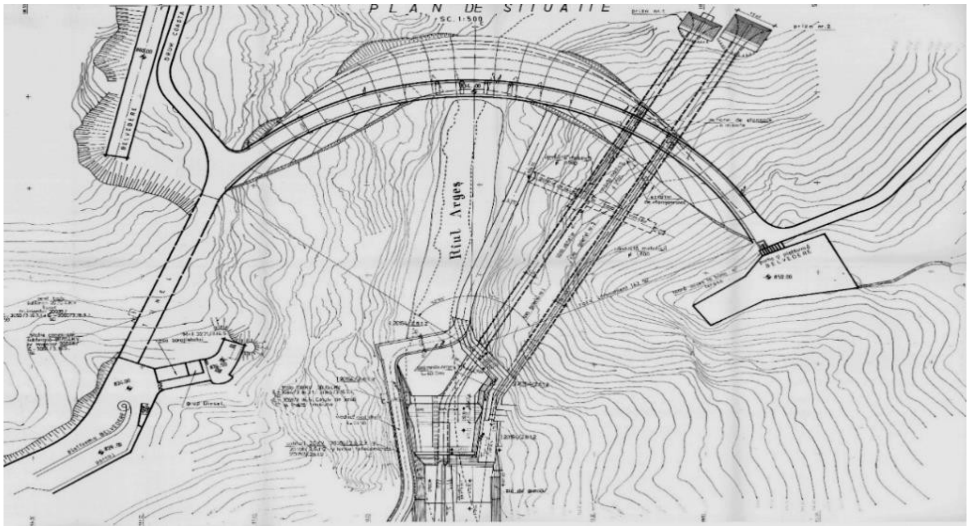

Figure 3. *Situation plan*

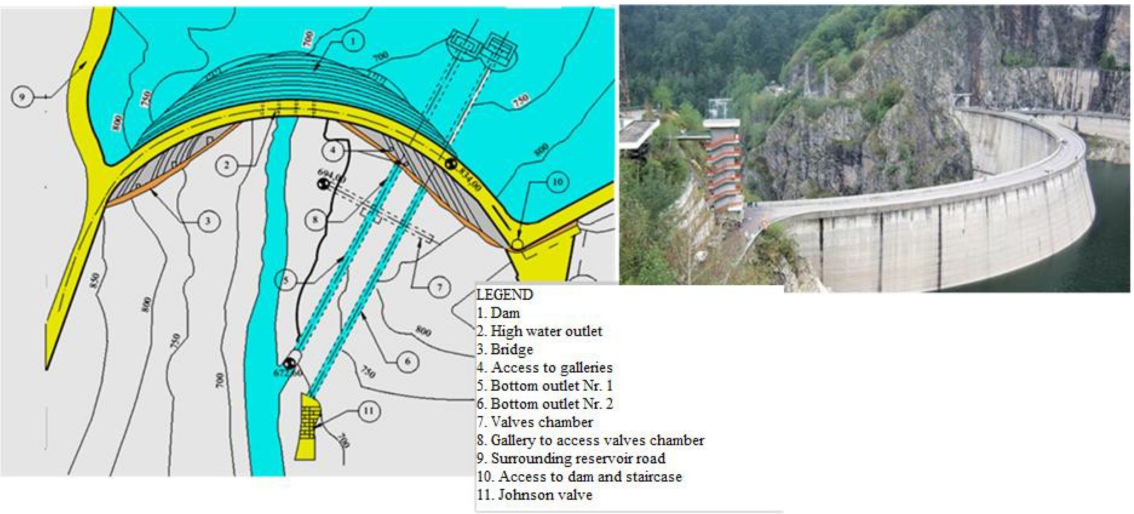

Figure 4. *Components*

The location of Vidraru dam is situated on the gnais ocular of Cozia downstream the tectonic contact.

The main faults in the area of the dam's crest have oblique or normal directions in relation to the bedding, forming angles of 20^0- 80^0. At their intersection and on the main faults there are crushing zones, i.e. breccias 0.5 - 3.0 m thick. These breccias are well cemented, silicified or calcareous. The fissuring, represented by cracks and fissures proper, is characteristic of the surface zone (8 - 10 m deep) and in the depth is more developed on the slopes. They form a complex system both by their orientation in the spaces and by the discontinuity effect they cause in the rock massifs. In areas with faults and cracks, there is a reduction in the physical-mechanical characteristics of the rock, the presence of seepage water circulation and the possibility of detachment of rock blocks on the crack planes with the inclination parallel to the slope of the slopes, which are facilitated by freeze-thaw processes.
The measuring and control equipment at the date of commissioning comprised the following apparatus:

- Reverse pendulum and direct pendulum;
- clinometric bolts;
- deforming bolts;
- discedometers;
- interstitial pressure cells;
- telerocmeters;
- telemeters;
- Triangular displacement gauges;
- levelling protractors;
- micro-triangulation protractors;
- fundamental levelling levelling marks;
- micro-triangulation pilasters;
- drainage boreholes;
- piezometric boreholes.

The present situation of the measuring and control apparatus is:

Table no. 2.1

Nr. crt	Device type	Parameter monitored	AMC No	Location
1	Direct pendulum	Horizontal displacements	5	in plots 2, 7, 12 (2 pcs.), 17
2	Reverse pendulum	Horizontal displacements	4	in plots 2, 7, 12, 17
3	Deformation bolt	Displacements in rost	96	in joints between plots, in galleries
4	Discedimeter	In-row displacements	24	in the joints between studs, in galleries
5	Clinometric bolt	Inclinations	5	in plot 12, in galleries
6	Telerocometer	Foundation rock deformations	4	at contact between dam and slopes
7	Telepiezometer	Water level in slopes	10	at contact between dam and slopes
8	Micro-triangulation marker	Horizontal and vertical displacements	14	on the downstream face of the dam

The monitoring system at the dam is undergoing an extensive modernisation process consisting of the installation of new monitoring devices and equipment (direct and reverse telependulum, telepiezometric boreholes, telemeters, etc.), automatic reading systems on the measuring and data transmission devices. Within the project "Vidraru Dam. Additional AMC installation including BBM data acquisition and processing system " the following devices were installed:

- telependulums, 14 pcs;
- telemeters, 4 pcs;
- telepiezometers, 14 pcs;
- telemeters, 20 pcs;
- discedometers, 20 pcs;
- teledebitmeters, 1 pc, mounted in the gallery at Vana Johnson;
- telemetre and telepluviometer 1 pc. , mounted at the dam house;
- complex seismic monitoring system.

2.2. Lake discharge data

UHE Vidraru is about to enter an extensive programme of refurbishment. This programme also includes rehabilitation works on the hydromechanical equipment related to the bottom drains (flat valves and Johnson valve), which suffered some failures caused by the accident that occurred on the slope in 1974. During the period of operation, the seals of the sluice gates have suffered damage which has increased over time, as signalled by the increase in the flow of water lost downstream of these sluice gates due to the deterioration of the sealing elements of this equipment. The cumulative value of these lost flows downstream of the dam was estimated at around 150 l/s, with small fluctuations, depending on the water level in the reservoir. As part of the upgrading works, an important point for the safety of the bottom drains is the replacement of the by-pass installations for balancing the pressures at the safety valves. These by-pass installations no longer fulfil the functional role for which they were designed, as they are blocked/corroded and no longer safe in operation.

In order to be able to repair/rehabilitate the hydromechanical equipment at the bottom outlet No 1, which has a minimum level of 689.25 mdMN, it is necessary to empty the Vidraru reservoir up to this level. The emptying of the Vidraru reservoir is to be carried out in accordance with the emptying instructions drawn up by the specialised designer. The conditions and stages of emptying (times, discharged volumes, emptying mode - by machining and/or bottom emptying, etc.) between different characteristic heights of the reservoir, as well as the corresponding time periods have been established. Figure 6.5. plots the lake curve over the emptying period.

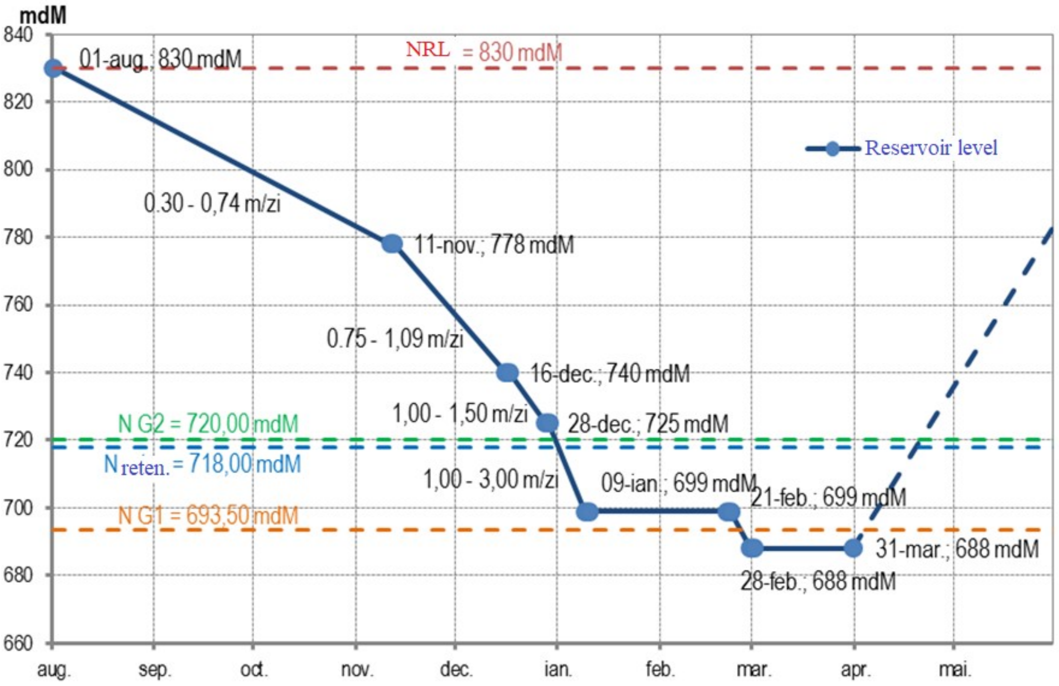

Figure 5. *Proposed emptying programme*

In order to ensure the safety status of the hydro-technical objectives related to the Vidraru PHE during the emptying of the reservoir, the special monitoring programme for the Vidraru dam and reservoir, as well as special instructions for monitoring these objectives by means of measurements and visual observations, prepared by ISPH PD SA, will be followed, even when the dam and reservoir no longer exist.

2.3. Behaviour of the dam at previous embankments

The Vidraru reservoir was completely emptied in the period 1974-1975, after the accident on 05 July 1974. The lake was emptied from the following day from the level of 823.00 mdMN up to the minimum level of 690.25 mdMN, reached in March 1975. This emptying is similar to the expected one, being carried out at the same time of the year (August-March).

Figure 6.6. shows the time evolution of the measured displacements of the direct pendulum in centre plot 12. The values plotted are the displacements of the point at elevation 748 mdM relative to the gallery 712 mdM for centre plot 2.

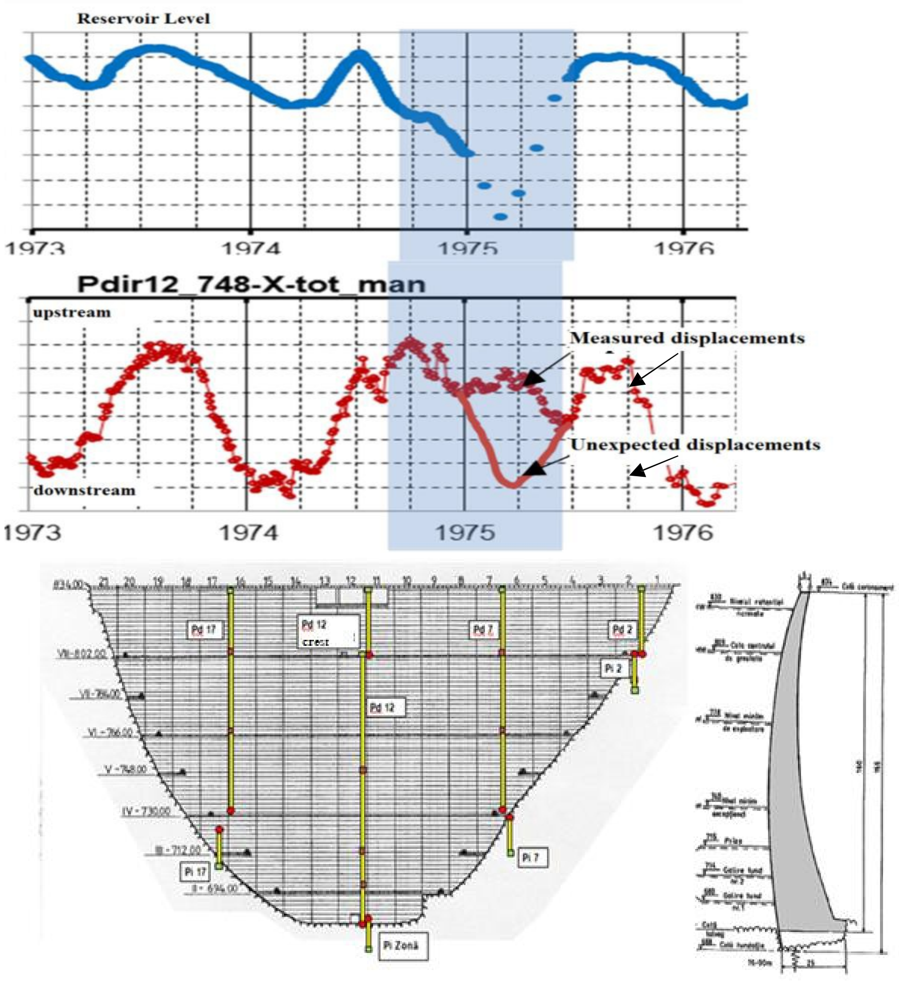

Figure 6. *Dam displacements at 1974 emptying*

Prior to the emptying of the lake, there is a normal upstream displacement due to the air temperature acting on the dam concrete, which is increasing, expanding the horizontal arcs. The emptying of the lake occurs during the autumn and winter when the air temperature is decreasing, which in normal operation mode should have a downstream displacement by shrinking the concrete, but the emptying of the lake decreases the hydrostatic pressure on the upstream face, which induces an upstream displacement. As the two factors acting on the dam (water level in the lake through hydrostatic pressure and air temperature) are in opposite directions, in the end the two causes cancel each other out to some extent, the displacement having a much smaller variation and the downstream displacement no longer occurs.

From the above considerations, it follows that the emptying of the lake during August-February is favourable for the dam safety, the two factors directly influencing the dam behaviour cancel each other out, the dam displacement is predicted to be within the previous limits.

2.4. Specificity of the problem

In the case of the Vidraru dam the approach is similar to the one exposed in subchapter 6.1 but the risk is not associated with the breach defined as uncontrolled loss of water from the reservoir and the formation of a breach wave. We will keep the name breakage improperly to use the mathematical relations related to the adopted decision criterion, but by breakage we mean the loss of the functionality of the reservoir through the long-term forced emptying of the lake for the rehabilitation works imposed by the dam damage subjected to an atypical operating regime.

The breakage cost (**C**) in the given case is defined as the cost of the dam rehabilitation works, plus the cost of the energy not produced during the repairs.

2.5. Damage mechanisms and specific additional tracking systems

In order to select dam failure mechanisms due to atypical stress, potential structural effects upon emptying and refilling of the lake are reviewed.

- Ambient temperature exposure of the upstream face as the level is lowered and as a result the thermal field in the concrete changes, with transient regime and altered boundary conditions.
- Direct exposure of the upstream face to air temperature fluctuations causing in the cold season the joints to open, with the effect of reduced spatial co-operation and increased seepage.
- Alteration of the infiltration regime and interstitial pressures from rock discontinuities in the rock mass of the slopes of the reservoir and implicitly in the slopes of the dam.
- The change in the thermal regime in the slopes resulting in the expansion of the rock, which is felt by the tendency of the valley to close. The details that are necessary are:
- During the long period of exploitation of the lake, with levels of more than 800 mdM since 1996, a saturation of the rock mass occurred, with interstitial pressures corresponding to the water level in the lake. When the lake is emptied, the water stored in the rock flows towards the face of the slopes and at the same time the interstitial pressures are released. The flow spectrum induces gradient-

type infiltration forces, opposite to the direction of flow, which lead to displacements of the lake contour inwards towards the slope. At the same time, the decrease in interstitial pressures leads to an increase in the effective stresses, which are mainly self-weight. These changes in the state of effort also have consequences on the displacements of the slopes, tending to open the valley.

- At the same time, the emptying of the lake also produces a change in the thermal regime of the slopes. In high dams, such as the Vidraru dam, the temperature of bedrock below the mean operating level has a low quasi constant temperature, and below 60 m from the NNR even a constant equal to $4.5^{(0)\ C}$. If the duration of emptying is long and exposes the slopes to warm-season air temperature there is an increase in the temperature of the rock mass over a limited depth. The increase in temperature has the effect of dilation of the rock, which is felt by the tendency of the valley to close.
- Deformation of the slopes upstream of the dam during the filling and emptying phases can affect the structural behaviour and long-term safety. In the first filling phase, the valley tends to converge, and in the emptying phase it tends to open up, especially at the upper reaches of the dammed valley. The dam is subjected to additional loading by the displacement of springs towards or away from the centre section.
- For the filling phase, the effect of "dam ageing" also occurs. If over time there has been a flexibilisation of the structure through joint openings and possibly structural degradation it is possible that the displacements recorded with increasing hydrostatic loading are larger than for previous lake fills (loading and refilling after the 1974 event). Such a situation must be examined from the point of view of the induced stresses in the structure.

Based on the behavioural data presented, the "failure" mechanisms, i.e. the mechanisms leading to the dam being taken out of service, have been established:

- Excessive cracking as a result of a drop in the temperature of the structure due to exposure of the upstream face to the ambient;
- Displacement of the dam's shoulder settlement due to convergence displacement of the slopes;
- Structural wear due to displacements imposed on the foundation contour by slope displacements;
- Landslide of the slopes with blockage of the dam's related outlets;
- Structural degradation and flexibilisation of the structure, accompanied by seepage through the interplot joints as a result of the joints opening in the cold season with the dam empty.

In order to follow the stresses to which the dam is exposed under the conditions of the emptying - filling cycle and respectively the response of the structure to these stresses, the following additions are proposed to the existing BBM system:

- Creation of a finite element mathematical model of the dam structure that takes as input imposed displacements, temperature fields and structural discontinuities
- Reactivation of telemeters, if possible;

- 3D laser scanning of the downstream face of the dam - bedrock system
- InSar tracking of lake basin displacements
- Tracking of interstitial pressures in the slope rock mass by hydrogeological boreholes
- Monitoring the stability of the slopes upstream and downstream of the dam by a network of inclinometer casing.

Clarifications.

In order to monitor the displacements, deformations and stability of the slopes immediately upstream of the dam embedment, it is proposed to carry out geodetic topographic measurements on the slopes using 3D laser scanning technology.

The general view of 3D scanning technology is that it represents a more advanced method of surveying - a more accurate, more detailed and faster method of data acquisition. Whilst all of these properties of 3D laser scanning are true, this technology also brings countless opportunities. 3D scanning provides decision-makers with a tool to assess the progress of construction works, to carry out structural assessments.

A recommended alternative is the use of InSAR technology. Interferometric synthetic aperture radar, abbreviated InSAR is a method of interest here. It uses two or more synthetic aperture radar (SAR) images to generate surface deformation maps. With InSAR technology, millimetre spatial measurement accuracy can be obtained, because the radar signal acquisition mode can simulate a sufficiently large antenna, and most importantly, the measurements are coherent (the phase of the electromagnetic wave is maintained).

2.6. Risk analysis

The decision on the provision of an adequate CCU supplement, based on the maximum benefit criterion, requires knowledge of the risk posed by the dam. It is therefore necessary to assess the likelihood of a failure leading to the storage being taken out of service and also to assess the consequences of the situation created.

In the reports and papers presented at ICOLD congresses and symposia there are no useful reports on the damage caused by emptying-filling cycles in concrete dams. Still less a database that allows statistical processing as exists for breakout cases.

In such situations, the probabilities of an adverse event occurring are assigned on the basis of engineering judgement, which in fact quantifies subjective opinions. Usually the *chance* of occurrence of a particular event is described verbally and numerical equivalences of these judgements are used. Considering the robustness of the Vidraru dam and the behaviour in operation so far, the damage in the case of the emptying-filling cycle can be categorised as "very unlikely". For this categorisation the probability of occurrence of a damage with the effect of emptying the storage is given $P_r = 10^{-1}$.

For the five failure mechanisms inventoried the relative probabilities of occurrence were recognised as:

- ① Excessive cracking as a result of a decrease in the temperature of the structure by exposure of the upstream bulkhead to the ambient ($P_{r,1}/P_r = 0,12$);
- ② Displacement of the dam shoulder rebound as a result of slope convergence displacement (); $P_{r,2}/P_r = 0,10$;
- ③ Structural cracking as a result of displacements imposed on the foundation contour by slope displacements (); $P_{r,3}/P_r = 0,28$;
- ④ Slope failure with blockage of the dam's related manoeuvres (); $P_{r,4}/P_r = 0,32$;
- ⑤ Structural degradation and flexing of the structure, accompanied by seepage through the interplot joints as a result of the joints opening in the cold season with the dam empty (); $P_{r,5}/P_r = 0,18$;

The financial losses as a result of the decommissioning of the storage are the cost of the dam rehabilitation works and the cost of electricity not produced during the rehabilitation works. The rehabilitation works have different costs depending on the failure mechanism.

For mechanisms 1,3 and 5 the works are localised to the structure and consist of injections to restore structural continuity and re-injection of joints. The estimated cost is C_{135}= 12 mil EURO.

Mechanism 2 requires partial restoration of the slope plots and possibly a culee. The construction solutions are demanding and very expensive. The estimated cost of the concreting works is approx. 14 million euros, plus the rehabilitation of the remaining structure, approx. EUR 10 million, which comes to C2 = EUR 24 million

In the case of mechanism 4, the works are intended to stabilise the slope, which has had rock detachments and displacements towards the base. The estimated cost is EUR 14 million.

It should be noted that the cost estimates are rough approximations in the absence of specific rehabilitation solutions. These approximations do not affect the purpose of the case study, the procedure remains valid, of course with the variant selection adjusted in accordance with the correctly evaluated prices.

In order to assess the monetary loss during the period when the hydropower plant is not in operation, it is necessary to estimate the duration of the rehabilitation and restoration works. Assuming a duration of procurement and project preparation of 15 months, a duration of actual works of 20 months and a duration of controlled refilling of the lake of 12 months, a total duration of 47 months, i.e. round 4 years, is given. The annual energy production of AHE Vidraru is 400 GWh/year. SPEEH Hidroelectrica S.A. has put up for sale 5 MW per hour electricity packages, with delivery throughout the year 2025, at a price of 625 lei/MWh. As a result, the cost of the energy not delivered during the period of repair of the damage at the Vidraru reservoir is 50 mil EURO.

The total cost of a damage due to the phenomena associated with the emptying and filling of the reservoir is C = 74 million EURO.

2.7. Effectiveness of dedicated behaviour monitoring variants on the emptying - filling cycle

The analysis of the efficiency of the systems envisaged to reduce the risks for the damage mechanisms inventoried is centralised in Table 6.2. The justification of the values is detailed with reference to Table 6.2.

Damage due to excessive cracking, as a result of the temperature drop of the structure due to exposure of the upstream face to the ambient, can be detected by the existing AMC system to a small extent (0.4), the response quantities being displacements (relative and absolute). By linking to the mathematical model, the measured quantities are translated into efforts which are a measure of the risk of cracking (effectiveness rate increases to 0.80). Reactivation of the telemeters increases the system effectiveness to some extent (0.85). The other measures to improve the BBM system (laser scanner, hydrogeological boreholes and inclinometer casing) do not bring increased efficiency in detecting excessive cracking. Damage due to displacement of the dam shoulder due to convergence displacement of the slopes is poorly detected by the existing BBM system (0.05). The associated mathematical modelling provides an efficiency gain (0.2). The reactivation of the telemeters does not provide relevant information for this damage mechanism. The efficiency in detecting this mechanism is provided by laser scanner measurements and information from hydrogeological boreholes and inclinometer casings (0.44, 0.55, 0.75)

Damage by structural cracking due to displacements imposed on the foundation contour by slope displacements can be highlighted to some extent by the existing BBM system (0.15) and with increased efficiency if the mathematical modelling is added (0.34). The other expected measures have efficiency in detecting the phenomenon by emphasising slope displacements (0.64).

Table 2.2.

Effectiveness of the BBM system

Damage mechanism (j)			$j = 1$ Excessive cracking	$j = 2$ Dislocation of the dam shoulder	$j = 3$ Structural cracking	$j = 4$ Landslide	$j = 5$ Structural degradation	
Relative probability $P_{r,j}/P_r$			0,12	0,10	0,28	0,32	0,18	
Effectiveness risk reduction ( ) R_j			r_1	r_2	r_3	r_4	r_5	Effectiveness Overall $\Sigma(P_{r,j}/P_r)\cdot r_j$
S	Existing BBM system		0,40	0,05	0,15	0,10	0,3	0.226
1	Existing BBM +Mathematical modelling		0,80	0.2	0.34	0.10	0,53	0,3386
2	**Math**	Telemetre reactivation	0,85	0,2	0,40	0.10	0,65	0.383
3		Laser scanner Or	0,85	0,44	0,64	0,65	0,65	0.6502

Damage mechanism (*j*)			*j* = 1 Excessive cracking	*j* = 2 Dislocation of the dam shoulder	*j* = 3 Structural cracking	*j* = 4 Landslide	*j* = 5 Structural degradation	
		InSar						
4		Hydrogeological boreholes	0,85	0,55	0,64	0,85	0,65	0.7252
5		Inclinometer tubing	0,85	0,75	0,64	0,95	0,65	0,7772

Damage by landslide with blockage of the dam's related nozzles cannot be warned by measurements from the existing BBM system, even if the mathematical modelling is associated. The efficiencies have slope scanning (0.65) plus data on interstitial pressures (hydrogeological boreholes 0.85) and inclinometry monitoring (casing 0.95).

Damage by structural degradation and flexibilisation of the structure, accompanied by seepage through the interplot joints as a result of opening the joints in the cold season with the dam empty, can be evidenced to some extent by the existing BBM system (0.3) with a plus in efficiency, if the mathematical modelling is added and with a plus in the activation of telemeters (0.65).

The overall effectiveness is however rather modest (0.7772) despite a consistent supplementation of the existing system due to the complex phenomena involved.

2.8. Choice of the optimal variant

The optimal variant was selected using the maximum net benefit criterion. The calculations are presented in Table 6.3.

For each variant (strategy) of supplementing the existing BBM system the annual costs were first evaluated C.Δ

Table 2.3.

Calculation of benefits per variant

Strategy of BBM system		Cost per cycle ΔC (EURO)	Effectiveness of additionality $r_s=r-r_{existent}$	Benefit $b=P_r\cdot C\cdot r_s$ (EURO)	Net benefit $b-C\Delta$ (EURO)
Mathematical	(1) Mathematical model	40000	0.1126	157600	117600
	(2) Telemetre reactivation	30000	0,157	219800	189800
	(3) Laser scanner Or InSar	315000	0.4242	593800	278800
	(4) Hydrogeological drilling	124000	0,4992	698800	574800
	(5) Inclinometer pipes	235600	0,5512	771600	536000

A cost of $\Delta_{C(1)}$ = 40000 EURO has been estimated for the realisation of a dedicated mathematical model, in line with UTCB's prices. The reactivation of telemeters has been estimated at $\Delta_{C(2)}$ = 30000 EURO, based on the experience of reactivating some telemeters at Paltinu dam. Laser scanner monitoring during the emptying - refilling cycle requires 7 campaigns, 4 during the emptying period and 3 during the refilling period. A campaign with a suitable number of points is valued at 45000 Euro, totalling over the period of interest $\Delta_{C(3)}$ =315000 Euro. Hydrogeological drilling is carried out on a network of 4 profiles on each slope with 3 boreholes per profile. The average depth is 65 metres. With a valuation of 80 EURO / ml of borehole, this gives a cost of $\Delta_{C(4)}$ = 124000 EURO. The inclinometer casing is arranged on a similar network. Given the additional equipment compared to a hydrogeological borehole, taking also into account the higher cost of measurements and processing, a 90% increase in costs compared to the network of hydrogeological boreholes has been estimated, giving a total cost of $\Delta_{C(5)}$ = 148800 EURO.

The maximum financial loss is Max Remediation cost + cost of unproduced energy + 24 + 50 mil Euro = 14 mil Euro. In sub-chapter 6.26 it was estimated that the probability of a failure with the effect of emptying the storage is P_r=10^{-1}.

The effectiveness of the additional variant was calculated by simply subtracting from the overall effectiveness of the additional variant (last column in Table 6.1) the overall effectiveness of the existing BBM system. The benefit and then the net benefit resulted from relations (6.7) and (6.8).

It is noted that the optimal variant (b_n = max) corresponds to a substantial additional BBM endowment, including the creation of a mathematical model, the reactivation of telemeters, the 3D laser scanning of the downstream dam face - foundation ground system and the tracking of interstitial pressures in the rock mass of the slopes by hydrogeolog ical boreholes. The inclinometer casing network is expensive and does not provide an acceptable benefit- cost ratio.

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