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Upgrading criteria for improvement dam monitoring systems

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Abstract. Reducing the risk associated with dams to a reasonable minimum is a legal and moral obligation of dam owners and authorities. An effective means of reducing risk is to ensure an adequate system for monitoring dam behavior, a system capable of detecting atypical behavior and adverse phenomena that may dangerously evolve towards failure. IIn the case of many dams, after a certain period of operation, the need for a supplement to the monitoring system is found, caused either by the insufficiency or defects of the initial system, or by certain characteristics of the dam's behavior that must be specifically monitored. Supplementing the monitoring system inherently involves additional costs, sometimes even very high ones. These costs must be justified by the beneficial effect brought to the dam's safety control. The justification must be made in economic terms, comparing the additional costs with the reduction of the risk rate. The paper develops a decision criterion for selecting the adequate strategy in supplementing a dam monitoring system. The study case dedicated to Vidraru dam demonstrates the correctness of the proposed approach.

Keywords: dam, monitoring system, risk, decision criteria.

1. Decision criterion

Reducing the risk associated with dams to a reasonable minimum is a legal and moral obligation of dam owners and authorities. An effective means of reducing risk is to ensure an adequate system for monitoring dam behavior, a system capable of detecting atypical behavior and adverse phenomena that may dangerously evolve towards failure. In the conditions in which such a trend is highlighted, structural and/or non-structural measures can prevent failure. The system for monitoring the behavior, together with other measures aimed at structural safety, ensures risk reduction by reducing the probability of failure [1].

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The behavior monitoring system must be well targeted to the relevant safety parameters and must be sufficiently detailed to monitor the entire dam-foundation-reservoir assembly. In the event of atypical behavior or in the case of special operating conditions, the dam behavior monitoring system must be supplemented.

The effectiveness of risk reduction by supplementing behavior monitoring is quantified by the annual risk rate reduction rate [2]. 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:

$$P_r^{i} = P_r(1 - r) \tag{1}$$

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

The dam can reach failure following different failure mechanisms, depending on the primary events that trigger them. The expected measures have different effects on the various failure mechanisms, also reducing the related failure probabilities differently. For example, supplementing pendulums does not bring relevant information for preventing failure by spillway and therefore has minimal effects on the failure probability corresponding to this mechanism. Also, an additional system for automatic verification and control of the state of the hydromechanical equipment reduces the probability of failure by spillway over the crest but has no effect on the probability of failure by internal erosion.

If we denote by j (j = 1,…, n) the potential failure mechanisms and the failure probabilities associated with them, then the total failure probability is given by the relationship:

$$. \qquad P_r = \sum_{1}^{n} j \cdot P_{r,j} \tag{2}$$

A certain measure planned to increase safety (for example increasing the number of piezometers) has different effects in reducing the rupture probabilities associated with different mechanisms:

$$P'_{r,j} = P_{r,j}\,(1 - r_j) \tag{3}$$

where is the effectiveness of the intervention for mechanism j.

From relations (1) and (3)

$$P'_r = P_r\,(1 - r) = \sum_{1}^{n} j \;\; P_{r,j}\,(1 - r_j) \tag{4}$$

from which the overall effectiveness of the planned measures is highlighted:

$$r = \sum_{1}^{n} j\,(P_{r,j} / P_r) \cdot r_j \tag{5}$$

Expression (5) is a weighted sum of the efficacies on failure mechanisms, the weights being the relative probabilities associated with them.

The annual risk rate for the existing dam has the well-known expression:

$$\mathrm{R} = P_r \cdot C, \tag{6}$$

where P_r is the rupture probability, and C is the quantitative measure of the consequences, this time including the damages caused to the owner.

The loss of human life caused by the failure is reduced to the minimum possible through warning-alarm-evacuation plans [3]. Assuming that, in terms of the consequences regarding the loss of human life, all risk reduction measures are taken to the limit of tolerable risk, the quantitative measure of the consequences *C* has only monetary expression. C is constituted by operating expenses (effective or potential), as has been seen.

The benefit created by reducing the risk rate by supplementing the behavior tracking system (monitoring), is [2]:

$$b = P_r \cdot C - P_r' \cdot C = P_r \cdot C \cdot r_s \tag{7}$$

where *r* has the expression (5), and the index s signifies a certain monitoring supplement system or a supplement strategy.

Each strategy *s* corresponds to an annual cost of realization and consequently the net benefit will be:

$$b_n = b - \Delta C_s = P_r \cdot C \cdot r_s - \Delta C_s \tag{8}$$

The selection of the monitoring supplement strategy is naturally made on the criterion of maximum net benefit (b_n = max.). A suggestive representation is contained in figure 1.

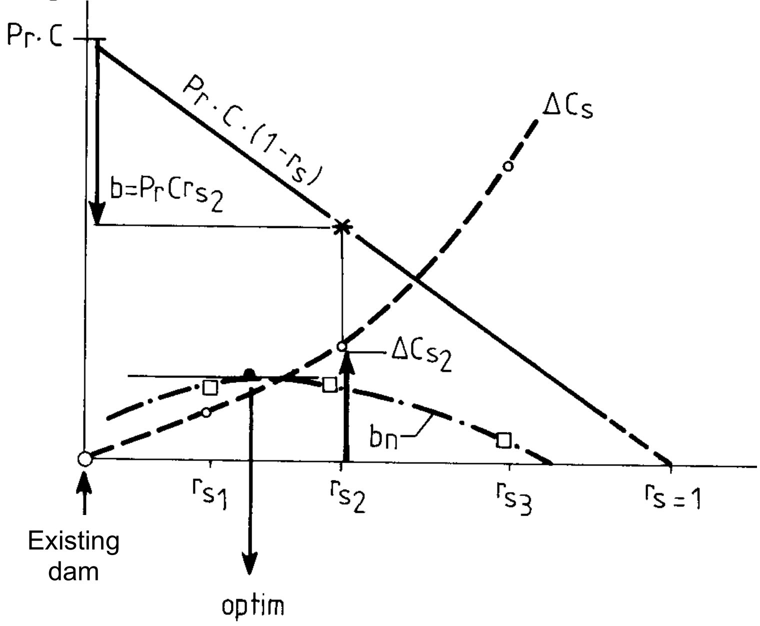

Fig.1. Selection of optimal alternative based on benefit.

2. Case study: Vidraru dam

During the refurbishment of Vidraru Hydro Power Plant (HPP), the operation of the Vidraru reservoir will include an emptying - filling cycle. As a result, an efficient approach [4] is required to monitor the Vidraru dam during the refurbishment works.

2.1. Short description of Vidraru dam and originally monitoring system

Vidraru arch dam on Argeş river with its 166.50 m is the highest concrete dam in Romania and was built between 1961 – 1965. Vidraru Argeş development has main function hydroelectric energy production (P_i=220 MW). The water accumulated in reservoir is used also for water supply of Bucharest city and irrigation. Fifteen runs of river or diversion canal hydropower plants located downstream of Vidraru Argeş hydroelectric development are operated in cascade using multiannual regularization of Argeş river stock in Vidraru reservoir.

The dam has double curvature with circular horizontal arches at both faces having two centers and variable thickness. The main characteristics of Vardaro dam are the followings (Fig. 2):

- maximum height over foundation	166.50 m
- crest length	305 m
- crest width	6 m
- base maximum width	25 m
- Normal Retention Level (NRL)	830 maSL
- dam's crest elevation	834 maSL
- volume of dam body	470,000 m^3
- reservoir volume at NRL	469,000,000 m^3.

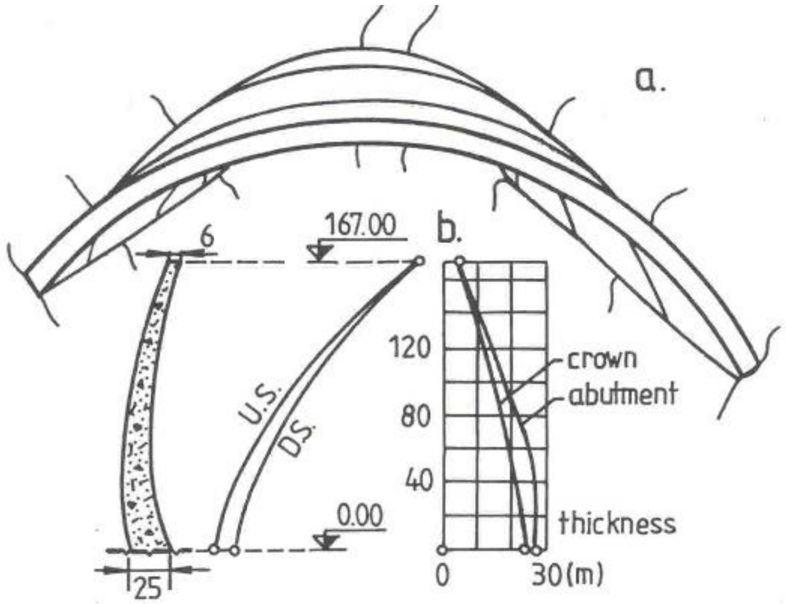

Fig. 2. Vidraru dam:
a – layout; b – central section with main geometrical characteristics.

The dam is located in narrow gorges, the banks having $60^0 \ldots 70^0$ slopes. The rock consists of ocular gneiss with distinct feldspath lens and porphyry gneiss to upstream boundary of the dam site, both types belonging to the crystal area of Cozia gneiss.

Originally, during construction (1961 – 1965), dam – foundation unitary system was equipped with monitoring devices which are presented in Figure 3 [5].

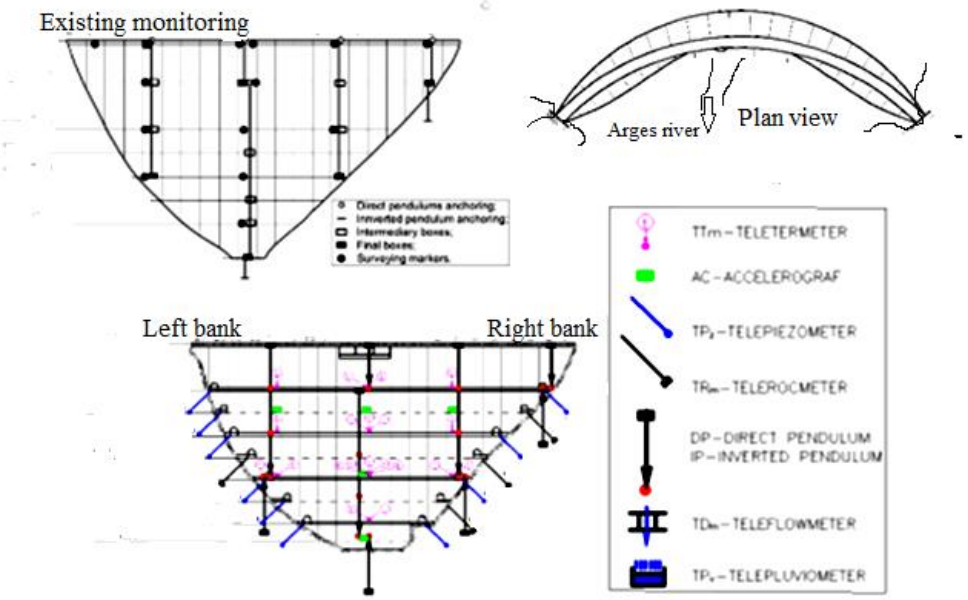

Fig. 3. Vidraru dam monitoring system.

2.2. Specific damage mechanisms and additional monitoring systems

To select the dam damage mechanisms as a result of atypical loading, potential structural effects are reviewed during the emptying and refilling of the reservoir.

– Exposure to ambient temperature of the upstream face as the level drops and as a result, the change in the concrete thermal field, with a transient regime and modified boundary conditions.

– Direct exposure of the upstream face to air temperature fluctuations that produce the opening of joints in the cold season, with the effect of reducing spatial cooperation and increasing infiltration.

– Modification of the infiltration regime and interstitial pressures in the rock discontinuities in the rock mass of the reservoir slopes and implicitly in the dam slopes.

– Modification of the thermal regime in the slopes that has the effect of rock expansion, which is felt through the tendency to close the valley.

The details that are required are:

– During the long period of exploitation of the reservoir, with levels of over 800 mdM starting with 1996, a saturation of the rock mass occurred, with pore pressures corresponding to the water level in the reservoir. When the reservoir is emptied, a flow of water stored in the rock occurs, towards the face of the slopes and at the same time a discharge of the pore pressures. The flow spectrum induces infiltration forces, of a gradient type, with a direction opposite to the flow direction, which lead to displacements of the reservoir contour towards the interior of the slope. At the same time, the decrease in pore pressures leads to an increase in the effective efforts, mostly related to its own weight. And these changes in the state of effort have consequences on the displacements of the slopes, with the tendency of the valley to open.

– The emptying of the reservoir also produces a change in the thermal regime on the slopes. At high dams, such as the Vidraru dam, the temperature of the foundation rock below the average operating elevation has a quasi-constant low temperature, and below 60 m above the NNR even a constant temperature equal to 4.5^0C. If the duration of the emptying is long and exposes the slopes to the air temperature of the warm season, an increase in the temperature of the rock mass occurs over a limited depth. The increase in temperature has the effect of dilating the rock, which is felt through the tendency to close the valley.

– The deformation of the upstream slopes of the dam during the filling and emptying phases can affect the structural behavior and long-term safety. At the first filling, the valley tends to converge, and at the emptying, to open, especially at the upper elevations of the dammed valley. The dam is subjected to additional loads by the displacement of the springs towards or from the central section.

– For the filling phase, the effect of "dam aging" also appears. If over time the structure has become more flexible, through joint openings and eventual structural degradation, it is possible that the displacements recorded when the hydrostatic load increases are greater than during previous reservoir fillings (loading and refilling after the 1974 event). Such a situation must be examined from the point of view of the stresses induced in the structure.

Taking the presented behavior data as a reference, the "failure" mechanisms were established, i.e. the mechanisms that lead to the decommissioning of the dam:

– Excessive cracking as a result of the decrease in the temperature of the structure by exposing the upstream face to the environment;

– Dislocation of the dam shoulder support as a result of the convergence displacement of the slopes;

– Structural buckling as a result of the displacements imposed on the foundation contour by the displacements of the slopes;

– Slippage of the slopes with the blockage of the dam's associated structures;

– Structural degradation and flexibility of the structure, accompanied by infiltration through the interlock joints as a result of the opening of the joints in the cold season with the dam empty.

In order to monitor 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 supplements are proposed to the existing monitoring system:

– Creation of a finite element mathematical model of the dam structure that receives as input imposed displacements, temperature fields and structural discontinuities

– Reactivation of telethermometers, if possible;

– 3D tracking by laser scanner of the downstream dam wall - foundation ground system

– Tracking of pore pressures in the rock mass of the slopes through hydrogeological drilling

– Tracking the stability of the upstream and downstream slopes of the dam through a network of inclinometric pipes.

2.3. Risk analysis

In the reports and papers presented at the ICOLD congresses and symposia, there are no useful reports on damage caused by emptying - filling cycles in concrete dams.

In such situations, the probabilities of an adverse event are attributed based on engineering judgment, which quantifies subjective opinions. Usually, the chance of a certain event occurring is described verbally and numerical equivalents of these assessments are used. Considering the robustness of the Vidraru dam and its operational behavior so far, damage in the case of the emptying-filling cycle can be classified as "very unlikely". For this classification, the probability of damage with the effect of emptying the reservoir is $Pr = 10^{-1}$.

For the five damage mechanisms inventoried, the relative probabilities of occurrence were assumed to be:

① Excessive cracking as a result of the decrease in the temperature of the structure by exposing the upstream face to the environment ($P_{r,1}/P_r = 0.12$);

② Dislocation of the dam shoulder support as a result of the convergence displacement of the slopes ($P_{r,2}/P_r=0.10$);

③ Structural cracking as a result of the displacements imposed on the foundation contour by the displacements of the slopes ($P_{r,3}/P_r=0.28$);

④ Slope slippage with blockage of the dam's aqueducts ($P_{r,4}/P_r=0.32$);

⑤ Structural degradation and flexibility of the structure, accompanied by infiltration through the inter-plot joints as a result of the joints opening in the cold season with the dam empty ($P_{r,5}/P_r=0.18$).

Financial losses as a result of the storage being taken out of service are the cost of the dam rehabilitation works and the cost of the electricity not produced during the rehabilitation works.

Rehabilitation works have different costs, depending on the damage mechanism. For mechanisms 1, 3 and 5, the works are located at the structure and consist of injections to restore structural continuity and reinjection of joints. The estimated cost is C_{135} = 12 million EURO.

For mechanism 2, partial restoration of the slope plots and possibly a concrete block is required. The constructive solutions are demanding and very expensive. The estimated cost of the concreting works is approx. 14 million EURO, to which is added the rehabilitation of the remaining structure, approx. 10 million EURO, which comes to C_2 = 24 million EURO

In the case of mechanism 4, the works are intended to stabilize the slope that had rock detachments and displacements towards the base. The estimated cost is 14 million EURO.

It is specified that the cost estimates are rough approximations in the absence of specific solutions for rehabilitation. These approximations do not affect the purpose of the case study, the procedure remains valid, of course with the variant selection adjusted accordingly but the prices correctly evaluated.

To evaluate the monetary loss during the period in which the hydroelectric power plant is not operating, an estimate of the duration of the rehabilitation and reservoir restoration works is necessary. Assuming a procurement and project development period of 15 months, a duration of actual works of 20 months and a controlled refilling period of the reservoir of 12 months, the result is a total duration of 47 months, i.e. around 4 years. The annual energy production of Vidraru HPP is 400 GWh/year. SPEEH Hidroelectrica S.A. has put up for sale electricity packages of 5 MW hourly, with delivery throughout 2025, at a price of 625 lei/MWh. As a result, the cost of undelivered energy during the period of repair of the damages to the Vidraru reservoir is 50 million EURO.

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

2.4. Effectiveness of dedicated monitoring options for the emptying-filling Cycle

The analysis of the effectiveness of the systems expected to reduce the risks for the inventoried damage mechanisms is centralized in table 1. The justification of the values is detailed with reference to table 2.

Damage through excessive cracking, as a result of the decrease in the temperature of the structure by exposing the upstream facing to the environment, can be detected by the existing monitoring system to a limited extent (0.4), the response quantities being displacements (relative and absolute). By associating the mathematical model, the measured quantities are translated into efforts that are a measure of the risk of cracking (the effectiveness rate increases to 0.80). Reactivation of the telethermometers increases the efficiency of the system to some extent (0.85). The other measures to improve the monitoring system (Laser scanner, hydrogeological drilling and inclinometric piping) do not bring increased efficiency in detecting excessive cracking.

Damage by dislocation of the dam shoulder support as a result of the convergence displacement of the slopes is very little revealed by the existing monitoring system (0.05). The associated mathematical model brings an added efficiency (0.2).

Reactivation of telethermometers does not bring relevant information for this damage mechanism. The efficiency in detecting this mechanism is provided by laser scanner measurements and information provided by hydrogeological drilling and inclinometric piping (0.44, 0.55, 0.75).

The damage caused by structural cracking as a result of the displacements imposed on the foundation contour by the slope displacements can be highlighted to some extent by the existing monitoring system (0.15) and with increased efficiency, if the mathematical model is added (0.34). The other expected measures are effective in detecting the phenomenon by highlighting the slope displacements (0.64).

Table 1. Monitoring System Effectiveness

Failure mechanism (j)			$j=1$ Excessive Cracking	$j=2$ Dam Shoulder Support Dislocation	$j=3$ Structural Cracking	$j=4$ Slope Slipping	$j=5$ Structural Degradation	
Relative probability $P_{r,j}/P_r$			0,12	0,10	0,28	0,32	0,18	
Risk Reduction Effectiveness (R_j)			r_1	r_2	r_3	r_4	r_5	Global effectiveness $\sum(P_{r,j}/P_r)\cdot r_j$
S	Existing monitoring system		0,40	0,05	0,15	0,10	0,3	0.226
1	Existing monitoring + mathematical model		0,80	0.2	0.34	0.10	0,53	0,3386
2	**Mathematical model**	Reactivation of teletermeters	0,85	0,2	0,40	0.10	0,65	0.383
3		Laser scanner or InSar	0,85	0,44	0,64	0,65	0,65	0.6502
4		Hydrogeological drillings	0,85	0,55	0,64	0,85	0,65	0.7252
5		Inclinometers pipes	0,85	0,75	0,64	0,95	0,65	0,7772

Slope failure with blockage of the dam's appurtenance structures cannot be warned by measurements from the existing monitoring system, even if the mathematical model is associated. The efficiency is achieved by scanning the slopes (0.65) by judging data on pore pressures (hydrogeological boreholes 0.85) and monitoring by inclinometry (pipelines 0.95).

Damage through structural degradation and structural flexibility, accompanied by infiltration through the interblock joints as a result of the joints opening in the cold season, with the reservoir empty, can be highlighted to some extent by the existing monitoring system (0.3) with an added efficiency, if the mathematical model is added and with an added efficiency when activating the telethermometers (0.65). The overall effectiveness is however quite modest (0.7772) despite a consistent supplementation of the existing system due to the complex phenomena that intervene.

2.5. Choosing the optimal alternative

The optimal alternative was selected using the maximum net benefit criterion. The calculations are presented in Table 2.

Table 2. Calculation of benefits by alternatives

Strategy of supplementing the existing monitoring system		Annual cost ΔC (EURO)	Additional efficiency $r_s = r - r_{existent}$	Benefit $b = P_r \cdot C r_s$ (EURO)	Net benefit $b - \Delta C$ (EURO)
(1) Mathematical model		40000	0.1126	157600	117600
Mathematical Model	(2) Theletermeters reactivation	30000	0,157	219800	189800
	(3) Laser scanner or InSar	315000	0.4242	593800	278800
	(4) Hydrogeological drillings	124000	0,4992	698800	574800
	(5) Inclinometric pipes	235600	0,5512	771600	536000

For each alternative (strategy) of supplementing the existing monitoring system, the annual costs ΔC were first evaluated. For the implementation of a dedicated mathematical model, a value of $\Delta C1 = 40{,}000$ EURO was estimated, in accordance with the prices charged by geodetic department. The reactivation of the telemeters was evaluated at a cost of $\Delta C2 = 30{,}000$ EURO, based on the experience of reactivating some telemeters in the Paltinu dam. Laser scanner surveillance during the emptying - filling cycle requires 7 campaigns, 4 during the emptying period and 3 during the refilling period. A campaign with a convenient density of points is evaluated at 45,000 Euro, with a total over the period of interest of $\Delta C3$ = 315,000 EURO. The hydrogeological drillings are carried out on a network of 4 profiles on each slope with 3 drillings per profile. The average depth is 65 m. With an assessment of 80 EURO / ml of drilling, a cost of $\Delta C4$ = 124,000 EURO results. The inclinometric pipes are arranged on a similar network. Given the additional equipment compared to a hydrogeological drilling, considering the higher cost of measurements and processing, an increase of 90% of the costs compared to the hydrogeological drilling network was estimated and therefore a total cost of $\Delta C5$ = 148,800 EURO.

The maximum financial loss is Max Remediation Cost + Cost of Unproduced Energy = 14 million EURO. In paragraph 2.3 it was estimated that the probability of a failure with the effect of emptying the accumulation is $Pr = 10^{-1}$.

3. Concluding remarks

The behavior monitoring system must be well targeted towards the relevant safety parameters and must be sufficiently detailed to monitor the entire dam-foundation-reservoir complex. In the case of many dams, after a certain period of operation, the need for a supplement to the monitoring system is found, caused either by the insufficiency or defects of the initial system, or by certain characteristics of the dam's behavior that must be specifically monitored. Supplementing the monitoring system inherently involves additional costs, sometimes even very high ones. These costs must be justified by the beneficial effect brought to the dam's safety control. The justification must be made in economic terms, comparing the additional costs with the reduction of the risk rate. In monetary terms, the risk rate is basically a potential expense caused by the dam's failure. Reducing risk by supplementing the monitoring system reduces these costs, and if the reduction is greater then the costs of additional system the promoting of an improved monitoring is justified.

In the case of Vidraru dam the optimal alternative ($b_n = \max$) corresponds to a consistent additional monitoring equipment, which includes the creation of a mathematical model, the reactivation of telethermometers, the 3D tracking by laser scanner of the downstream dam face - foundation ground system and the tracking of pore pressures in the rock mass of the slopes through hydrogeological drilling. The inclinometric pipe network is expensive and does not bring an acceptable increase in surveillance in terms of benefit - cost.

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