Technical Sciences
Academy of Romania
www.jesi.astr.ro

Journal of Engineering Sciences and Innovation
Volume 6, Issue 3 / 2021, pp. 323 - 334
http://doi.org/10.56958/jesi.2021.6.3.323

E. Civil Engineering and Transport Engineering

Received ***23 Apryl 2021*** *Accepted* ***14 September 2021***
Received in revised form ***17 May 2021***

A procedure for rating the dam safety improvement works

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Abstract. Among the dam portofoliu administrated by an owner some dams show behaviour anomalies, progressive adverse phenomena or deficiencies of the equipment. The owner develops studies establishing the causes of the found phenomena and designs of the rehabilitation works for deficiencies remedy. Financing of the rehabilitation projects, sometimes requiring high costs, is usually provided from the owner's own funds. Naturally, the funds that can be allotted are limited and very often cannot cover the costs required by all the technically approved works. Under these conditions, the funds distribution strategy should select primarily the works that contribute significantly to the dam's safety improvement while in the meantime are bringing maximum benefit to the owner. A decision making strategy is developed in the present paper. Planning the rehabilitation works required by safety improvement is based on the combination of risk reduction and the efficiency of the intervention.

Keywords: risk evaluation, dams, rehabilitation works, decision strategy.

1. Introduction

Following the activity of the dam behaviour monitoring and the periodical safety assessment there is frequently ascertained that some of the dams administrated by an owner show behaviour anomalies, progressive adverse phenomena or deficiencies of the equipment. In such cases, it is the owner responsibility to draw up studies establishing the causes of the found phenomena and designs of rehabilitation works for deficiencies remedy. Financing of the rehabilitation projects, sometimes requiring high costs, is usually provided from the owner's own funds. Naturally, the funds that can be allotted are limited and very often cannot cover the costs required by all the technically approved works. Under these

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conditions, the funds distribution strategy should select primarily the works that contribute significantly to the dam's safety improvement while in the meantime are bringing maximum benefit to the owner.

Repairing, rehabilitation and safety improvement works are aiming in fact at diminishing the risk. Consequently, the assessment of the benefit brought by the safety improvement works is based on the quantification of the reduction of the risk annual rate [1], [2], [3]. The assessments have to highlight both the absolute value of the risk reduction as the relative effect expressed as the ratio between the risk reduction and the cost of the required investment works.

Therefore the establishing of the priorities in promoting safety improvement works should be achieved by a series of criteria based on the evaluation of the risk reduction.

Within a proper approach at least three criteria reflecting the risk quantification and the investment costs assessments as well as the specific social-economic aspects are to be included [4], [5]. Quantified factors are:

ΔR^{PE} - risk reduction rate expressed in monetary units, corresponding to economic losses:

$$\Delta R^{\mathrm{PE}} = \left(P_r - P_r^{'}\right) \cdot C^{\mathrm{PE}}, \qquad (1)$$

where P_r is the total annual probability of failure;

$P_r^{'}$ is the new failure probability, diminished as a consequence of the safety improvement works;

C^{PE} is the cost of total economic losses (own and at third parties) arisen in case of failure.

ΔC - annual rate of recovery of the invested capital in the works required for the safety improvement.

Two among the three criteria usually used are referring to the economic benefit and costs:

- benefit / cost ratio $\left(C_1 = \Delta R^{\mathrm{PE}} / \Delta C\right)$, the benefit being given by the reduction of the risk rate and the cost by the annual rate of the investment recovery;
- net benefit $\left(C_2 = \Delta R^{\mathrm{PE}} - \Delta C\right)$,

while the criterion C_3 is considering the social-economic effects of the work. Primary are considered the reservoirs that are representing unique sources for population water supply or that have major effects on floods control. From economic point of view, the reservoir importance is established by the owner depending on the incomes brought and on the reservoir influence on the basin operation. As case may be, also other rating sub criteria may be used, depending on the own interests: political, of image, of regional development etc.

Rigorous risk quantification requires the establishing of the failure probabilities as well as the assessment of the consequences related to such events. Quantification process is difficult and many times inaccurate, due to the insufficiency of the main data and to the difficulty in defining some measuring units for the consequences[6].

To exceed this inconvenient sometimes an empirical assessment of the risk or of its components is used by risk proportional indices. Within dam's field, during the last period, a specific approach for the risk assessment quantification was developed [7]. This is based on the evaluation by indices of the gravity that the initiatory events may have in triggering the failure mechanisms.

The present paper presents a methodology for establishing the priorities in promoting the safety improvements works for a portfolio of dams. The methodology that is propoposed to Romanian Water Authority for its dams is considering on one hand the criteria of benefit – cost type, and on the other hand, uses scaled numerical indices for the assessment of the importance and urgency of the constructive measures identified as required.

2. Defining the strategy

For each dam selected as requiring safety improvement works, the objects or components that have to be subjected to constructive interventions are identified (structure, water tightening, drainage, spillways, equipment, monitoring, etc). Following a detailed analysis it is then established the extent on which the deficiency of each identified object or component is affecting the dam operation under safe conditions, as well as the urgency in performing the constructive interventions having in mind the predictable unfavourable evolution of the deficiency within the time horizon of the safety analysis [8], [9].

At the same time, each dam requiring safety improvement interventions is characterized by a β importance indicator, reflecting the economic importance of the dam, the dam previous behaviour and the failure consequences, as well as the reservoir social importance.

Starting from these data, each constructive intervention *i*, related to one object or component *k* of a certain dam *j*, can be characterized by a weight coefficient reflecting the intervention importance and urgency:

$$\boldsymbol{p_i = \beta_j \ II_{j,l} \ UI_{j,l}} \tag{2}$$

where:

β_j is the reservoir importance index which the component *i* is belonging to;

$II_{j,l}$ – the importance index of the object/component *l* of the dam *j*;

$U_{j,l}$ – the index reflecting the urgency in promoting the remedial intervention for the object/ component *l* of the dam *j*;

Based on the design of the safety improvement (rehabilitation) works the cost c_i of the constructive intervention for each element/component *i* is established. The available Water Authority budget *B* for the safety improvement works cannot cover the costs of all the inventoried works $B < \sum_1^n c_i$, *n* being the total number of elements/components which constructive interventions works are provided to.

Selection of the components i ($i=\overline{1,k}$; $k \le n$) which funds are allotted for and constructive interventions works are promoted is achieved according to the following optimisation criteria:

- to be selected the most urgent interventions:

$$P_k = \sum_{i=1}^{k<n} p_i \rightarrow \max \tag{3}$$

- under the conditions of the most efficiency using of the funds available:

$$C_k = \sum_{i=1}^{k<n} c_i \rightarrow \min \tag{4}$$

- and under the constrain of the available budget *B*:

$$\sum_{i=1}^{k<n} c_i \le B \tag{5}$$

3. Assessment of indexes and indicators

3.1. Establishing of reservoir importance *β* index

The dam importance is evaluated being considered the class and category of the reservoir importance. Under Romanian norms [10],[11] the class of importance from I to IV is established based on the economic importance of the reservoir (number of inhabitants in the case of water supply, installed power in the case of hydropower, area of irrigated land in the case of irrigation use etc.). Romanian dam safety law provides the dam classification into four categories of importance (from A to C) based on the dam characteristics (type, height, storage etc.), on the dam actual state (monitoring parameters, aging, behaviour incidents etc.) and on the consequences of a potential failure. The importance index β results from the relation:

$$\beta = \frac{CL + CAT + F}{10} \tag{6}$$

where the partial indices are: *CL* – dependent on the reservoir importance class;*CAT* – dependent on the reservoir importance category; *F* – dependent on the reservoir main purpose.

Dependency between the partial numerical indices *CL*, *CAT* and *F* and the dam classification and reservoir purpose is shown within table 1.

Table 1. Partial numerical indices and the dam characteristics

Importance class	Index **CL**		Importance category	Index **CAT**		Main purpose	Index **F**
IV	**2**		D	**2**		Recreation, fish farming	**1**
III	**2**		C	**2**		Hydropower, irrigations	**2**
II	**4**		B	**4**		Flood mitigation	**4**
I	**8**		A	**8**		Water supply	**8**

3.2. Establishing of indicators *II* and *UI*

Importance indicators for objects/components included within the constructive interventions program (*II*) and the indicators regarding the urgency of the foreseen interventions (*UI*), respectively, are established based on the safety inspection reports. The qualitative description from the report is converted into numerical indicator based on the conversion tables 2 and 3.

Table 2. Conversion into numerical indicator regarding the importance

Object / component importance - description	**Importance indicator *II***
Extremely important. Its collapse determines the dam failure	8
Very important. Its collapse severely affects the dam safety	5
Important. Its collapse may trigger a failure mechanism	3
Moderate. Its collapse has as result difficulties of safe operation	2
Minor. Its collapse can partially affect the reservoir operation	1
Collateral. Its collapse has no effects on the dam safety	0.5

Table 3. Conversion into numerical indicator regarding the intervention urgency

Object /component state and intervention urgency - description	**Indicator of urgency *UI***
Critical state, with a high probability to collapse, requires urgent interventions.	12
Bad state, that can lead to collapse, rehabilitation interventions are urgently demanded.	8
It shows damages / defects that can lead to a bad or critical state. Interventions are necessary.	2
It shows minor damages that should be remedied within a defined period of time.	1
Good state, with some ageing. No interventions are needed for safety reasons.	0,5

3.3. Solving algorithm

In order to avoid optimising a multiple function (of bi-objective type), the optimisation criteria (3) and (4) shall be combined, having as result a single objective function:

$$R_k = \frac{P_k}{C_k} = \frac{\sum_{i=1}^{k<n} p_i}{\sum_{i=1}^{k<n} c_i} \rightarrow \max \qquad (7)$$

This way, both optimisation criteria are satisfied. Certainly, in the case of the function (7) the ratio is maximum when the numerator (representing the objective function from the relation (3)), is maximum, simultaneously being fulfilled the condition that the denominator (which is the objective function from the relation (4)), to be minimum.

It is noticed that for $k=1$ from relation (6) it results:

$$R_1 = \max\left(\frac{p_i}{c_i}\right)_{i=1,n} \tag{8}$$

Such selected component *i* is excluded. Within the stage $k+1$ the optimum of the function R_{k+1} is achieved by selecting the maximum of ratios from the right side of the relation (9):

$$R_{k+1} = \frac{P_{k+1}}{C_{k+1}} = \max\left\{\frac{P_k + p_i}{C_k + c_i}\right\}_{i\in I-K} \tag{9}$$

K is the multitude of intervention works selected up to the iteration *k*.
Intervention works to be inserted within the ratios R_k calculation can be achieved also through a very simple heuristic approach. According to relation (7), the first component to be repaired is corresponding to the maximum ratio $\left(\frac{p_i}{c_i}\right)$. Being excluded this component, the procedure of selecting the next object/component based on the maximum ratio p_i / c_i is repeated for the $n-1$ remnant components, and so on up to exhaustion of the whole selected objects/components.
This approach returns, after all, to the function optimisation

$$R_k^{'} = \sum_{i=1}^{k<n} \frac{p_i}{c_i} = \sum_{i=1}^{k<n} r_i \rightarrow \max, \tag{10}$$

$$r_i = \frac{p_i}{c_i} \tag{11}$$

Certainly, $R_k^{'}$, representing the sum of the row $r_{i,\, i<n}$ is maximum when each element r_i is maximum. Consequently, the selection of the intervention works within the rehabilitation program shall be performed in a decreasing order of the ratios r_i. Obviously, the value of functions (6) and (9) will not be the same, but the two functions lead to the same prioritisation of intervention works.

4. Case study

4.1. Description of the dam portfolio

Application is referring to a cascade development, consisting of an upstream main reservoir with a significant storage, realized by a diamond-head buttress dam with a height of H = 100 m and three smaller reservoirs downstream. All the three downstream reservoirs are created by lateral earth dams and concrete spillways, equipped with flap gates and radial gates on the outlets. The lateral dams are made of sand and gravel and are water tightened with reinforced concrete slabs on the upstream face. The foundation imperviousness is achieved by plastic concrete cutoffs down to the marl bedrock

The buttress dam (**BD)** creates a reservoir of which purposes are: hydropower, flood mitigation, water supply (main reserve for a high populated area) and irrigation.

The first downstream dam (**D1),** with a maximum height H = 16 m, creates a compensating reservoir for the irregular discharges of the upstream hydropower station. The length of the side embankment dams is of 4.5 km. The reservoir volume is small and is used for a small hydropower station, for recreation and for fish farming.

The second dam from the downstream cascade (**D2**), with a maximum height of H = 28 m, having side dykes with a total length of 14 Km, creates a seasonal regulating storage, with a significant volume, providing the water supply as main source for a downstream town, electric energy production, irrigation water and recreation area.

The last dam from cascade (**D3**), with a maximum height of H = 14 m, creates a reservoir of medium volume. The length of the side dams is of 6.5 Km. The reservoir provides hydropower, water supply as alternative source of a downstream community, as well as recreation and fish farming.

All the dams were included within the class of importance II. Due to some operation incidents and due to very severe consequences in case of failure, the buttress dam is included within the category of importance A, while the downstream dams have the B category of importance.

4.2 Behaviour incidents and the inventory of the intervention works requirement

Dam BD. In the case of the buttress dam **a *fluctuant increasing of the uplift*** was detected by the measurements at the pressure cells, accompanied by variations of drainage discharges, with excessive increases in certain moments, but with a general tendency of diminishing in time. The identified causes are the breakthrough of the grout curtain, induced by the tensile stresses at the upstream toe and the in time clogging of the drainage system. The proposed ***interventions works*** are the following:

- Rehabilitation of the grout curtain on a length of about 120 m, with 2 rows of inclined drillings, the first one of 25 m and the second one of 40 m deep respectively, at a distance of 2 m on centres, alternatively.
- Extension/rehabilitation of drainage system with new drainage boreholes, at 3 m on centres, inclined towards downstream, with a depth of 30 m, on a length of about 200 m.

A second detected problem is the collapse of some 0f the prestressed anchors in the downstream area of the dam left shoulder, that have the role of stabilizing the rock layers packages. The ***proposed interventions works*** consist in reinstalling of 6 new prestressed anchors of 80 t/piece.

Reservoir D1. Wet and even locally saturated areas are located on the downstream face of the lateral earth dam. The water level in the downstream berm piezometers is high and specific bush vegetation is present. The probable cause is the relatively impermeable nature of the earth fill in the downstream shell and clogging of the downstream prism, which is not draining anymore. ***Intervention works*** consist in performing of draining strips in the wet/saturated areas, discharging in the drainage ditch at the downstream toe. The areas have a total length of about 400 m, with drainage strips at 8…10 m distance.

At the same time the ***sealing of the joints*** of the upstream slabs that is the water tightening provision of the upstream face is partially affected. The bituminous mastic is aged and removed from one face of the joint, especially in the area of level variations. Intervention works consist in replacing of the bituminous mastic with polymeric mastics on a total length of about 7600 m.

Reservoir D2. At the concrete spillway the collected drainage is diminishing in time and the pressure cells indicate an increasing of the uplift pressures immediately downstream of the foundation cut off. Intervention works consist in rehabilitation of the existing drainage boreholes by de-clogging and drilling of new boreholes in the first row of drainage (about 30 boreholes of 7 m depth).

Reservoir D3. Saturation of the downstream prism and superficial slides of the downstream slope of about 40 m occurred at the left bank side dam. Intervention works consist in performing a new draining prism at the bottom of the downstream slope on an area of 500 m (about 800 m^3).

A second detected problem is the local settlements of embankment dam crest and leakages that occurred in the connecting area between the right bank side embankment dam and the concrete spillway. Intervention works consist in grouting the affected area with silicates and cement grout. At the same dam the back-up Diesel unit is obsolete and out of order. Rehabilitation consists in purchasing a new Diesel unit of 80 kVA.

4.3. Establishing of indicators and costs for intervention works

The importance index of each dam was determined based on the relation (5) and is shown in the first column of table 4. Components of the reservoirs showing defects, deteriorations or ageing phenomena as well as the electric equipment being detected with low reliability were analysed from the point of view of their contribution on dam safety. The urgency condition of the interventions was also assessed for each of them. The importance indicators (*II*) and the urgency indicators (*UI*) were established based on this analysis. The costs of the interventions works designed for each component or equipment are also inserted in the same table.

4.4. Prioritisation of interventions works and establishing of those to be promoted

The budget available for the intervention works selected in table 4 is limited to $B = 1.6 \text{ x}10^6$ RON, less than the evaluated requirement $\sum c_i = 2.724 \text{ x}10^6$ RON. Consequently the above described solving algorithm was used for decision making concerning the promoting of the most urgent and efficient interventions.

Table 4. Components or equipment affecting the safety of the dam that require intervention works

Dam **j**	N. *i*	Component or Equipment	**Indicator**		Designed constructive intervention	Cost c_i **RON**
			I I	***UI***		
j=1 **BC** $\beta_1 = 2$	1	Grout curtain	3	2	Rehabilitation of the grout curtain on a length of about 120 m, with 2 rows of 25 m and 40 m depth respectively, at a distance of 2 m, alternatively	800 000
	2	Upstream drainage	8	8	Extension of drainage, with boreholes, at 3 m, with a depth of 30 m, on a length of about 200 m.	700 000
	3	Anchors for the left bank	3	8	Rehabilitation of 6 prestressed anchors of 80 t/piece	450 000
j=2 **B1** $\beta_2 = 1$	4	Downstream face of the earth-fill dams	5	8	Performing of draining strips in the wet/saturated areas. The areas have a total length of about 400 m, with strips at 8…10 m interval.	40 000
	5	Joints between upstream concrete slabs	2	2	Replacing of the bituminous mastic with polymeric mastics on a total length of about 7600 m.	380 000
j=3 **B2** $\beta_3 = 1,6$	6	Concrete spillway	5	8	Washing of the drainage boreholes for d-clogging and drilling of new boreholes from the first row of drainage (about 30 boreholes of 7 m depth).	150 000
j=4 **B3** $\beta_4 = 1$	7	Downstream prism and left bank side dam slope.	5	8	Performing of a draining prism at the bottom of the downstream slope on a area of 500 m (about 800 m^3)	80 000
	8	Dam crest & connecting area dam - the spillway	8	8	Silicates and cement grout in the connecting area.	20 000
	9	Diesel unit	5	8	Purchasing of a new Diesel unit kVA.	104 000

Each intervention work defined in table 4 is characterized by the pairs (p_i, c_i), where the weight p_i is calculated according to relation (1). Based on the weights p_i (reflecting the priorities and urgencies of the constructive interventions) and costs c_i (expressed in RON) the ratios r_i are calculated. Data are shown in table 5.

Table 5. Characterization of component or equipment

I	(p_i, c_i)	r_i
1	(12; 800)	0.015
2	(128; 700)	0.182
3	(48; 450)	0.106
4	(40; 40)	1.000
5	(4; 380)	0.010
6	(64; 150)	0.420
7	(40; 80)	0.500
8	(64; 20)	3.200
9	(40; 104)	0.385

After component arrangement in decreasing order of the reports r_i the values $\left(P_k, C_k\right)$ were determined, according to relation (7), as well as the ratios R_k according to the relations (9), $R_k^{'}$ respectively according to the relation (10).

Table 6. Decreasing arrangement according the reports r_i

$r_k^{decrea\sin g}$	*Component k*	$\left(P_k, C_k\right)$	R_k	$R_k^{'}$
3.200	8	(64; 20)	3.200	3.200
1.000	4	(104; 60)	1.730	4.200
0.500	7	(144; 140)	1.028	4.700
0.420	6	(208; 290)	0.717	5.120
0.385	9	(248; 394)	0.629	5.505
0.182	2	(376; 1094)	0.344	5.687
0.106	3	(424; 1544)	0.275	5.793
0.015	1	(436; 2344)	0.186	5.808
0.010	5	(440: 2724)	0.161	5.818

The reports R_k are noticed to be within the relation:

$$R_1 > R_2 > \ldots\ldots > R_{n-1} > R_n \qquad (12)$$

while the sum $R_k^{'}$ of reports $r_i = \dfrac{p_i}{c_i}$ has increasing values:

$$R_1^{'} < R_2^{'} < \ldots\ldots < R_{n-1}^{'} < R_n^{'} \qquad (13)$$

In both cases the order followed for the component rehabilitation – intervention works- is the same. Depending on the available budget amount the included

$\left(P_k\,,C_k\right)$ are observing the condition $C_k < B$. Component *k* as well as all the components obtained at the previous iterations shall be included within the constructive interventions program.

For the available budget *B* = 1.6 x 10^6 RON the closest value C_k < 1. x 10^6 is equal with 1.544 x 10^6 RON, and the constructive interventions included within the rehabilitation program are the ones with indicators 8; 4; 7; 6; 9; 2 and 3 in table 4.

5. Concluding remarks

Financing of the rehabilitation projects, sometimes requiring high costs, is affected the lack of funds that can be allotted. Under these conditions, the funds distribution strategy should select primarily the works that contribute significantly to the dam's safety improvement while in the meantime are bringing maximum benefit to the owner.

The decision making strategy proposed for planning of the rehabilitation works is based on the combination of risk reduction and the efficiency of the intervention. The methodology is considering on one hand the criteria of benefit – cost type, and on the other hand, uses scaled numerical indices for the assessment of the importance and urgency of the constructive measures identified as required.

Selection of the components which funds are allotted for and of the constructive interventions works is achieved according to several optimisation criteria as the most urgent interventions and the most efficiency using of the funds available, under the constrain of the available budget.

In order to avoid optimising a multiple function (of bi-objective type), the optimisation criteria are combined, having as result a single objective function. Intervention works to be promoted are selected based on a very simple heuristic approach.

The validity of the proposed strategy and of its effivciency is demonstrated by a case study consisting in a cascade development.

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