Breach Forming Scenarios at Concrete Faced Rock-fill Dams

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Abstract. Rock-filled dams with reinforced concrete facing, as the proposed study case of
Bolboci Dam on the River Ialomița, Dâmbovița County, centre Romania, are characterized by
a very high operation safety. On the international level, there is no record of failed concrete
faced rock-fill dams. However, during their usage there have been several incidents mainly due
to the unsatisfactory behaviour of the reinforced concrete masks. Specifically, in an ICOLD
statistic that presented 17 cases of damages to rock-fill dams with reinforced concrete facing,
14 were due to the unsatisfactory behaviour of the reinforced mask. The other 3 cases were due
to piping phenomena or percolation through the dam foundation or the lake's shore. The failure
scenarios of this dam type, Bolboci Dam including, can be as follows: the retaining structure
over-spilling during floods due to an insufficient or poor operation of top and/or bottom
dischargers - the overflow gradually erodes the body of the dam until the breach occurs;
concentrated infiltrations with a high gradient through the dam body as a result of a serious
malfuction in the concrete facing sealing, with material carving in, leading to breaches in the
dam body; piping in the dam foundation / side banks that could finally lead to slippage and
finally dam failure (improbable due to the existing geotechnical conditions); overpassing the
safety guard of the dam's crown leading to the dam over-dischar ging as a result of irreversible
excessive subsidence due to exceptional incidents. There have been studies on three statistical
methods on how characteristic breaches occur: MLM Empirical Method, Washington State
and Froehlich. The Froehlich method has been endorsed and modified, because Bolboci Dam is
a well built, well executed and a well employed dam. The failure hypotheses of the dam were
done with applications using MathCAD software, their algorithm being based on the finite
differences method. It must be specified that the statistical approach of dam failure is a trap,
due to the fact that it is well know they are a work of one of a kind engineering art. This fact
shows the difficulty of the elaboration of the failure scenarios and the need of a sensitivity
study for the comparison of the scenarios. The results show that the failure of rock-filled dams
with reinforced concrete facing is highly improbable and leads to small flows with a sluggish
evolution of the breaches.

1. Introduction
Constructions safety, meaning of hydrotechnical ones, derives from their capacity given by a proper
design based on engineering legal specifications (standards, regulations, prescriptions etc.), to support
the loads they are subjected at and so to work in safety conditions [4]. Acknowledging that water
developments represent ample works of which damage can jeopardize the economic activity and also
the human life, the hydraulic structures safety represents an element of main importance of permanently concern for specialists and specific organisms in the field. The sensitivity for protection aspects places the hydraulic constructions safety problem in a special light as an object of great care and under strict review. Indeed, the material damages and even human casualties registered along time due to some dams failing are at a considerable level. Even if this doesn’t raise to the level of accidents effects in other domains, the psychological shock in case of large dams failing appears larger due to event concentration in space and time and also due to the fact that the victims didn’t deliberately accepted the risk presence.

As about the causes determining failure of embankment dams, a significant percentage – 16…18% – is represented by crest over-spilling and dam down-washing by the developing breach. The failure mechanism of an embankment dam due to crest over-spilling can be noticed in figure 1. presenting the phenomenon developing along the single registered event of such type in Romania [3]. The event took place at Belci Dam – clay core earth-fill dam commissioned in 1962 on Tazlău River (northeast of the country), during the night of 28-29 July 1991 when a high-water wave produced by a torrential rainfall of an exceptional magnitude determined a rapid water level rise in the reservoir.

![Figure 1. Earth-fill dam failure mechanism](image)

2. Description and general data upon the considered water development

Bolboci reservoir [6] is created on the upper course of River Ialomița – about the centre of the country, 10.75km from the water spring, the section between Tătarului and Zănoagei Gorges. The Bolboci Water Development is public domain being managed by the Ministry of Environment and Water Management through “Romanian Waters” National Administration – Buzău-Ialomița Water Branch, Dâmbovița Water Management System.

The reservoir, ensuring a sanitary discharge of 40 l/s, is designed to fulfil the following employments:

- water supply storage for all towns and villages down to Târgoviște, including, and for Bucharest too;
- hydropower gaining by Dobrești Power Station which produces an average electric energy of 22GWh/year at an installed power of 12 MW from an installed water flow of 6.2 m³/s;
- high waters attenuation;
- fishery, recreation and tourism.

At a length of 2.2km and opening a water surface of about 100hectars corresponding to the usual water level, the water reservoir is described by the following main parameters: usual retaining level at 1435mSL, maximum water level (0.1% overpass probability) at 1438mSL, bottom outlet level at 1396mSL, power catchment level at 1400mSL, minimum working water level at 1406mSL, total storage volume of 19.4 million m³, functional water volume of 18 million m³.

The concrete faced rock-fill dam (figure 2.) was commissioned on 1988 with a maximum height of 55m [1]. The retaining structure sealing is accomplished by reinforced concrete slabs laid on the upstream face and sustained at the upstream foot by a continuous hearth that also hosts the monitoring
and grouting/draining gallery. The downstream side of the dam is protected by a dry masonry. The main characteristics of the retaining dam (figure 3.) are as follows: top (crest) level at 1438mSL, thalweg level at 1390mSL, lowest foundation level at 1383mSL, crest length of 455m, crest width (carriageable) of 7m, upstream / downstream side slopes of 1:1.3, maximum spread at the base of 152.6m, rock-fill volume of 920,000m³.

According to the national regulations STAS4273-83 and NTLH-021, the retaining structure corresponds to the II²nd Class of Importance – construction of significant importance – and to the Importance Category B (RB = 0.31) – dam of especial importance which requests special monitoring, respectively.

Regarding the material employed in the dam body, it was harvested from a limestone quarry situated at about 6km upstream of the site. Based on granulometry criteria, the quarry boulders were placed into work as follows:

- the concrete face supporting zone - boulders of maximum 40cm in size, laid in layers of 50cm;
- the midzone of the cross-view - boulders of maximum 75cm in size, laid in layers of 100cm;
- the downstream half of the cross-view - boulders of maximum 120cm in size, laid in layers of 150cm.

As about the main hydrology data related to the considered dam site on Ialomița River, the dimensioning and verification water flow values employed by designer according to the structure importance class are: Q₁% = 220m³/s as the dimensioning water flow, Q₀.1% = 470m³/s (408m³/s) as the verification one. The hydrograph attached to the Bolboci Dam site on the river presents a total developing time of 36 hours, with an increasing time of 8 hours and a shape ratio of 0.28. The base water flow value is of about 10m³/s.
The water discharging appurtenances installed with the retaining dam are of the following capacities:

- the high waters top discharger can evacuate 220 m³/s at a reservoir water level of 1437 mSL and 470 m³/s for a level of 1438 mSL;
- the bottom outlet can evacuate 41.5 m³/s for the reservoir at the usual retaining level of 1435 mSL;
- the evacuation by the hydropower station can release 6.2 m³/s;
- the evacuation by the fault discharger on the headrace towards the hydropower station can release 10 m³/s.

The reservoir attenuation capacity of the 1% high water flow is about 32.6%, while of the 0.1% one is about 32.8%.

According to the former SR 11100/1-1993, the retaining structure site seismicity [6] belongs to a macrozone of I = 71 (MSK) seismic intensity corresponding to a mean recurrence interval of 50 years. Based on P100-92 normative, the area seismic intensity ratio is $K_s = 0.16$, and the edge period is $T_c = 1.0$ sec. The development site is situated at about 100 km away from the Vrancea sub-crustal hypocentre and in the immediate proximity of the Sinaia - Vălenii de Munte crustal hypocentre.

As commissioned in 1988, the development was designed and accomplished according to the technical regulations valid for the time period 1970 – 1988. The general manager of Bolboci Water Development was ISPH Bucharest, while the general contractor was the nowadays S.C. Hidroelectrica S.A. Bucharest.

Along the time passing since its entering in function [6], one could say that the Bolboci Water Development proved a reliable performance, not presenting atypical events – incidents or faults. Structural interventions that would alter the initial design were not needed.

3. Damaging hypothesis considered for estimating the flooded areas according to nowadays national regulations

The estimations were performed according to the prescriptions requested by NP 132-2011, following also the indications of HG no.846/2010 and MMAP/MAI Ordinance no.1422/192/2012. As for the case of Bolboci Dam, bearing in mind the design / accomplishment level of quality and the structure performance under loading from the 1988 commissioning to present times, there was considered that the occurrence risk for failure scenarios is situated in between the usually accepted limits.

The figure 5 presents the area map overlaying the 2D modelling of the flowing domain, pointing out the upstream and downstream border conditions.

The figure 6 presents the digital terrain model highlighting the existing artworks and the characteristic reference cross-paths on the congregating water courses. The affected river sector from the Bolboci Dam right down to the Pucioasa wave receiving valley has a length of 28 km, the distance between the reference (control) cross-paths being of about 1 km. The analysis stretches only to the Pucioasa Reservoir (bottom of figure 5) which, even silted, is still hosted by an opening valley that can largely temper the failure flooding wave.

The geometric characteristics were imported in the HecRas bi-dimensional computation software [7], by the help of which two flooding scenarios were modelled in order to study the wave propagation starting from the hypothetically breached Bolboci Dam.

HecRas [7] is a specialized software that facilitates the either one-dimensional or bi-dimensional analysis of steady and unsteady fluid flow. It also allows the sediments transport or water thermal transfer modelling. The software can develop a system of channels, complex hydrographic receiving basins or a simple water course. The elements of uniform flow are able to model various free surface flow regimes, sub-critic, overcritical or mixt. A combined Results and Discussion section is often appropriate.

Further on the two mentioned breaching scenarios suitable with concrete faced rock-filled dams, as the case of Bolboci Dam type, are to be developed and analysed.
Dam over-spilling during high-water because of dischargers insufficient capacity or poor operation – the overflow gradually erodes the body of the dam until the breach occurs.

The employed statistical method led to improbable results regarding the breach discharge. This was due to the fact that the established regressive equation was actually settled for breaches developing in earth-fill dams, and not rock-fill ones. Consequently, a modified breach evolution time was adopted since we know that the erosion development is slower for rock embankments. As considering the breach development, the mathematical method employed for the hydraulic calculus was the finite differences approach, for a time step of 1 minute.

The breach progressing in time due to failure scenario “i”, together with the water discharge and reservoir level developing with time, are presented by figure 7 [8].

The river sector longitudinal profile pointing out the maximum water level corresponding to the flood wave propagation according to scenario “i” is presented by figure 8. The representative reference cross-paths – potentially affected by the flood wave – in towns and villages are indicated.
Figure 7. Breach progressing with time – failure scenario “i”

Figure 8. Maximum water level along the river sector longitudinal profile – failure scenario “i”

One can notice from figure 9 that there is no flood wave attenuation along the river valley, since it is a narrow one, with no natural storage areas on sides.
Overpassing the safety guard of the dam’s crown and dam over-discharging as a result of irreversible excessive subsidence due to exceptional incidents (e.g. earthquake of large intensity)

The maximum water levels reached along the flood wave transiting the downstream river sector as a result of failure scenario “ii” are presented by figure 10. The reference cross-paths attached to artworks and villages potentially disturbed by the flood wave are also specified.

Commonly, the hypothesis of an earthquake with this level of consequence upon the crest settlement at a rock-fill dam is indeed less probable but given the Bolboci structure proximity to the most important seismic zone in the country, one can realize that it still must be considered for the safety verification calculus.
The resulted effect of this kind of breach development prove a lower amplitude because the reservoir usual retaining level is still three meters below the initial dam crest level. Therefore, even of the breach develops sharply, the discharged water volumes are relatively smaller than those determined along the previous scenario (in correspondence to the presented volume-elevation curve of the Bolboci reservoir).

4. Conclusions
In case the usual methods of breach development estimation are to be considered – the MLM Empirical Method, Washington State, Froehlich 2008 [5] – a breach evolution time of about an hour or less is to be obtained. An evolution time of 8 hours was however employed as a result of rock-fill body resistance to erosion.

A general current problem with breach estimation is the fact that this is usually performed by statistical approach while dams are still of artwork type, meaning unique complex developments, each of them characterized by an important degree of specific achievement and working conditions. Therefore, even if necessary as common approach, the statistical methods need to be refined and accustomed to the specific site and accomplishment conditions of each retaining structure.

It is to be noticed that the dam failure waves corresponding to scenario “i” is considerably similar to the flood wave of 0.01%, an important fact since the two events prove the same probability of occurrence. The economic damaging effects of flood wave determined by failure scenario “i” are greatly significant, but its risk is very small because of its very low probability of occurrence.

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