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Dams Beyond Design Assumptions

Reinhard Pohl

Technische Universitaet Dresden, reinhard.pohl@tu-dresden.de

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Abstract: For the first time, the technical board ‘Dams and Weirs’ of the German Association for Water Wastewater and Waste (DWA) published a guideline on how to cope with loads beyond the design assumption. This implies a need to consider a possible residual risk, which was not so openly discussed in Germany in the past. This paper presents the main issues of the document DWA T1/2017, which gives a guideline how to cope with the risk of large dams and reservoirs.

Keywords: Dams, design assumptions, residual risk, dam safety, dam failure.

1. Introduction

Dams are very safe structures. Until now often the sentence that ‘…dams are safe as far as is humanly possible to tell…’ could be heard. This is not wrong when considering the comprehensive and clear German standards (DIN, DWA, others) for dam design, construction, operation, and maintenance. On the other hand, this can also be understood in a way that the safety is only almost 100 percent and a certain residual risk is remaining. The estimation of this residual risk is also an issue of the German dam standard DIN 19700-11:2004-7.

From many disastrous and spectacular dam failures worldwide during the last four millennia, it can be derived that the consideration of the residual risk is necessary.

In general, it is visible that the number of dams in Germany has been growing rapidly during the last century while the failure probability has been decreasing (Figure 1).

Although no large dams (according to the ICOLD criterion: dam height > 15 m, storage volume > 1,000,000 m³) failed in Germany after 1970, from theoretical mathematical considerations it can be derived that the failure probability is greater than zero. During this period, six medium dams failed (Figure 2). Normalizing this number with the product of the total number of medium dams and the time since construction (dams x years), a failure probability of about $P \approx 0.0001$ is yielded if assumed that the not exactly known number of medium dams is about four times of the large dams.

To calculate the risk $R = P \cdot C$, the failure probability, $P$, as well as the consequences, $C$, (damages) are required. As seldom events mostly produce higher consequences and vice versa, $C = C(P)$ can be displayed as a hyperbolic graph which integral $R = \int_0^1 C(P) \cdot dP$ yields the risk. When (similar to flood statistics) the possible failure event is considered per year and the consequences can be expressed in terms of a currency, the risk will become the expected annual damage in €/a, which can occur or be avoided, respectively. Sometimes this is called the benefit, which is of course not completely exact.

Not every exceedance of the design assumptions and not everything reaching the limiting state (equilibrium between load and resistance) will cause a failure [1]. Due to the normally low number of failures, which is not significant, the ‘true value’ of the failure probability cannot be found exactly by calculation or statistical analysis. What we yield is an estimated value for the relative frequency, which might be considered being close to the failure probability. Depending on the development of the number of large dams in Germany the relative dam failure probability has been calculated for the chart in Figure 1.

With the same procedure, the relative failure probability for nuclear power plants worldwide was calculated considering the major accidents in Chernobyl (1986) and Fukushima (2011). From Figure 1 it becomes visible that the failure probability of medium dams in Germany lies in the same range of about $10^{-4}$ as for nuclear power plants around the world whereas the consequences including life and property losses are magnitudes higher for the power stations. Insofar they generate a very much higher risk but are accepted in the most countries worldwide. The theoretical failure probability for large dams is still lower and amounts some $5 \cdot 10^{-5}$. 

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R. Pohl

1Technische Universität Dresden, Germany

E-mail: Reinhard.Pohl@TU-Dresden.DE

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Figure 1. Development of the relative dam failure frequency (≈ probability) in Germany (blue) and the failure probability of nuclear power plants worldwide (red).

Figure 2. Dam Failures in Germany and dam Categories (grey circles: Large Dams according to ICOLD criteria).
The fire protection and disaster control legislation of the federal states in Germany demand that owners and operators of installations with high-risk exposure have to prepare documents that contain information about the hazard release potential and the possible prone area. Owners and operators are interpreting this lawful claim in a different way. Particularly, the question whether the mentioned documents (primarily hazard maps) have to be prepared or handed over to the authorities without demand is answered in different ways. Also, the question whether the European Flood Risk Framework Directive includes these ‘artificial’ floods is discussed here and there.

From the viewpoint of the author of this paper, four perceptions by dam owners and operators can be seen: the first have prepared and published hazard maps. The second have prepared these documents and are ready to hand over them on demand to the civil protection authorities, but they do not like to publish them to avoid misinterpretations. The third would have the documents prepared after demand and the fourth do not think that their plants and installations might be so dangerous that they were within the scope of these laws.

The authors of the DWA-document T1-2017 [1] felt that the time has come to publish the view on the things as was discussed in the technical committee for dams and weirs (WW4). The intention was to give some thoughts, recommendations, hints and help to the dam owners, operators, consultants, constructors and authorities as well.

2. Design and Dimensioning according to the Technical Standards in Germany

It is the present practice to use the semi-probabilistic partial safety factor concept according to the current European and national standards. The reliability of dams has to be proved corresponding to Eurocode EC 0 (DIN 19700:2004-07, DIN EN 1990:2010-12 [3]) using the following approach:

Reliability = Load bearing capacity + Usability + Durability

![Diagram of Reliability Analysis Concept for Dams](image)

**Figure 3.** Reliability analysis concept for dams based on DIN 19700-11:2004-07 [3] (s. a. Sieber 2009 [10]) and DWA M542 [4].

In general, the basic requirements concerning the reliability are fulfilled when

- Stable and resistant structural systems are selected,
- Adequate building materials are used,
- Appropriate design and analysis methods are applied,
- The barrage and appurtenant works, components, and members are engineered functionally,
- The structure is supervised and maintained.
Corresponding to DIN 19700: 2004-07, the application of the global safety concept is still acceptable. Here the resistant forces must be greater than the load multiplied by a certain safety factor (e.g. \( \eta = 1.3 \)). The younger partial safety factor concept demands that the loads multiplied with a partial safety factor (greater than one) are less than the reduced resistant force (multiplied with a certain safety factor less than one) so that the degree of utilization is less than one. The technical guideline DWA M542/2016 [4] describes a procedure for dams based on the partial safety factor concept which yields approximately the same safety level like the hitherto existing deterministic method.

A full probabilistic analysis using the distribution functions of all loads and resistant forces would provide a very low failure probability (probably in the range from \( P < 10^{-3} \ldots 10^{-6} \)) for every potential failure mode. Often the reliability \( 1-P \) (which will probably take values between 99.9 and 99.9999 percent) is used due to psychological reasons.

3. Possible Loads beyond the Design Assumptions

Dams are exposed to loads that are subjected to natural variations (uncertainty). This is why the design values have to be observed or explored for a long lasting period. This especially applies to design floods, earthquakes, and wind loads. Mainly the following exposures cannot be excluded beyond the design assumptions:

- Extreme discharges and stages (ICOLD 2012),
- Extraordinary overtopping of the barrage (Figure 4),
- Critical surcharge of functional hydraulic structures (Figure 5),
- Unexpected slope sliding in the reservoir area,
- Extreme earthquake (Gruenthal et al. 2009, ICOLD 2016))
- Unexpected seepage and undercurrent with extreme hydraulic gradients,
- Animal burrows,
- Extreme live loads,
- Mishandling, wrong control,
- External impacts, terrorism (Figure 5).

Figure 4. Visualization of Overtopping a Concrete Dam during an extreme Flood beyond the design Flood (HQ\textsubscript{extrem} > BHQ\textsubscript{c}; 3-dimensional hydro-numeric model Keul 2011).

Figure 5. Technical and staff measures to protect critical infrastructure: Watchtower (Sheriff) and Video observation (red arrow), three additional waterways right in the photograph (orographically left) at the Folsom-Dam on the American River upstream Sacramento, CA. (Photograph: Pohl).

Each of the above-mentioned impacts caused disastrous damages in the past. Overtopping due to underestimation of the design flood was the failure reason in about one-third of all observed cases. By means of adequate measures that complete an appropriate design, it is possible to identify weak points, to reduce impacts, or to minimize consequences with

- Periodical visual inspection of the structures,
- Safety reports and thoroughgoing inspection,
• Deficiency analysis,
• Periodical maintenance, inspection, function check,
• Periodical and sufficient measurements and evaluation,
• Risk assessment,
• Instruction and advanced training of the staff,
• Effective organizational structure,
• Building measures at the waterways during low water periods,
• Video observation and motion detection, alert at entering by force,
• Burglar resistant doors, reinforcement of structural members,
• Access control, limited access,
• Protection of communication path (e.g., cable) for data and signals,
• Co-operation of operators with authorities (county-, state-, federal police) in the case of hazard exposure,
• Emergency action plans (EAP).

![Figure 6](image)

**Figure 6.** A tiered approach related to the possible dam failure. Examples of flood exposure. BHQ = Design flood for two design situations.

4. **Adverse Conditions on the Resistance Side**

While the exposure can be unexpectedly high and intensive, on the other hand, a too low resistance is thinkable. This can be due to material properties in the structure as well as in the substratum which do not fulfill the expected standards (material strength (pressure, tension, shearing), soil properties (angle of internal friction, cohesion, permeability, frost resistance, erosion resistance)). Furthermore, malfunction can influence the resistance side adversely (gates or valves of the waterways blocked, drains clogged, colmation, sealing elements in the structure or substratum damaged; ice preventer, concrete cooling systems (especially at arch dams) without function; drives, overload cut-offs, energy
supply, gauges, limit signaling devices, storage level delimiter, overtopping detector, central process control system out of order).

Not every overload will cause a dam failure (see Figure 6) because in the design, analysis, methods, models, materials, safety margins, minimum freeboards, and loads certain reserve is included. This will be activated first and only when this is consumed and the limiting state (equilibrium) will be reached. Partly certain self-regulating forces, e.g. by load redistribution can be observed.

![Diagram](image)

**Figure 7.** Modelling a hypothetical dam failure and its consequences.

5. **Operational Measures in Special Situations and Emergency Action Plans**

Emergency Action Plans (EAP) according to DIN 19700-10: 2004-07 are needed if dangerous situations could appear or were thinkable. For these special situations, instructions have to be given in the related documents. A certain procedure has to be executed systematically when anomalies like distortion, deformation, water release, untypical seepage or similar are observed. This may include an information to the responsible dam professional to give the first assessment and to initiate further measures (like water level lowering with an allowable drawdown rate, alarm message, information of the people downstream and the civil protection) if needed.

Dam owners and operators can be obliged to support the civil protection authorities to establish EAP’s due to the high hazard potential of large dams. This includes the supply of special hazard maps which indicate the potential inundation area in the case of dam failure. These maps should display maximum water levels, water depths, arrival times for flood waves, flood propagation and evacuation paths.

Whenever it becomes visible to the dam operator that the hazard of dam failure cannot be averted any longer, he/she must start the measures schedules according to the EAP.
6. Dam Failure and Impact Assessment

A quantitative analysis of the (hypothetical) case of a dam failure requires some steps of a procedure, which is shown in Figure 7.

As mentioned above, not every extraordinary exposure to the barrage beyond the design assumptions or with calculated exceedance of the limiting state will cause a dam failure. However, if this is the case, the failure modes and breach scenarios have to be described. Embankment dams can suffer overtopping with backward erosion as well as piping due to internal erosion. While the first failure mode is normally linked to meteorological or hydrological events, the piping can occur as a sunny day event. These two failure modes mostly stretch over a period from one to a few hours and can be explained by empirical knowledge or geotechnical models. The failure of concrete, masonry, arch, or vault dams often proceeds relatively quickly and contains either some sections/blocks of the whole structure in very short time. From the breach scenario and the progressive breach development, the outflow hydrograph can be estimated by means of hydraulic models, which will serve as the upper boundary condition for a highly transient hydro numerical analysis. This is normally continued downstream along the watercourse until the water level approaches the level of natural floods. The results of the calculation are copied to special hazard maps from which EAPs or risk maps can be derived (Figure 8).

![Figure 8. Example of a special Dam Break Hazard Map showing the maximum water depth above ground, the inundation area, the flow velocity at control sections and the time of flood wave arrival from the begin x of the break. Additionally, the flow velocity and the intensity h∙v could be displayed (Background Map: OpenStreetMap).](image)

7. Conclusion, Outlook

Dams in Germany are designed, built, operated and maintained according to the generally acknowledged rules of technology, which are communicated within the DIN-, DWA- and other standards. Although they are very safe, a certain residual risk remains. This should be made transparent and identified so that an appropriate reaction can be carried out when first signs of irregularity become visible. The presented DWA-guideline T1-2017 [1] is intended to be a contribution to awareness and preparedness and should help the owners and operators to cope with the improbable case of the residual risk.

Hopefully, more operators and owners will take the initiative to check their installations concerning situations beyond the design assumptions and the related possible consequences. First experiences showed that risk awareness has been improved after the issue of this guideline but due to financial limitation first initiatives of some operators have been suppressed.

The responsibility for flood protection in Germany lies in the hands of the authorities of the 16 federal states. Although most of them have civil protection acts with similar standards, the practice differs from state to state and from operator
It would be desirable to come to a more or less standardized approach to risk assessment and mitigation in the future.

8. Acknowledgement

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