Safety of dams in crisis situations

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Abstract. The safety of dams in crisis situations can be divided into several areas that can affect their functions. The aim of this work is to focus on water crisis situations on the technical infrastructure during emergencies, of which there were many in the world. The protective function of dams can be based on a thorough analysis and their measures. In the article there was risk analysis performed on a dam of choice. The ALARP analysis was used to determine risks that have to be addressed and taken precautions against. According to F-N diagram it was determined that ALARP region is located at frequencies of 0,000 1 (1-in-10 000 years) and number of people at risk at 1 – 1 000. Next there was a benefit-cost analysis performed of mitigation project, that concluded beneficial value of the dam and the costs of the mitigation project and the BCA ratio came out > 1, thus the mitigation project was recommended. In conclusion there was recommended to use both methods in comparative manner.

1. Introduction
Dam safety is very important objective throughout their design, construction and in their operation. The current situation in the field of flash floods makes many experts focus on this topic, such as strengthening water retention in the landscape or building small water reservoirs [1] [2]. Current situation in flashfloods make many professionals focus on this topic. Crisis situation can come during construction; therefore, it is critical to have sufficient information about the dam location, geological base, properties of materials used, technical properties of construction methods and the dam system. Moreover, special characteristics must be taken into consideration. Some waterworks move forwards (such as Dam Vranov, when there are certain parts of the dam moved down the stream because of water pressure) or backwards (due to temperature changes).
In the Czech history the worst dam fail tragedy happened in Desná on 18th September 1916 when the embankment dam breached, and the death toll was 65 people. The reasons of the breach were probably insufficient construction methods, lack of knowledge about underlying rock and forces on low cost of the dam [3].
According to Generel of locations protected for water accumulation issued (hereinafter ‘Generel LAPV’) by the Czech ministry of environment and the Czech ministry of agriculture, there are 65 new dams to be built in the Czech Republic in upcoming years [4]. Therefore, it is critical to adequately consider risks and safety measures to be put up, so the inhabitants in the zone of possible floodwater flow are protected within reasonable means. In this article there are presented major dam failure accidents to stress the importance of safety measures in role of protecting lives during crisis event. Then there is described and compared legislature framework concerning dam safety and outlined main steps in dam risk analysis.
2. Dam failures in crisis situations
Even though most of the people realize the importance of general safety measures used in dam safety, it is important to them in perspective of the catastrophes when the measures were not sufficient or kept at all.

2.1. The Williamsburg Dam, USA
The United States have also had a major dam failure amongst them the Williamsburg dam failure. The causes of the accident were several. Amongst them poor design, poor location (valley properties, the ground rock) and poor supervision. The dam was accepted into operation on the second try and with unknown level of water in the reservoir. The first seven years was the water level held low and in the spring because of snow dissolution the levels were raised significantly. On 16th May 1874, the dam failed because of leakage that caused the dam slide and collapse. The dam failure caused 138 fatalities [5] [6].

2.2. The Desná Dam
In the Czech Republic, the largest dam accident is The Desná Dam failure. On the 18th September 1916 the woodworkers notified the undertaker of the dam about leakage of 2 cm in diameter. It was ordered to empty the dam immediately, but the valve operators managed to open the valves only halfway because the whole dam started to crash. When the water from the failed dam came to village Desná the evacuation was not done yet and it resulted in hundreds homeless and 59 missing [7].

2.3. The Vajont Dam, Italy
In the Europe’s history one of the worst dam failure tragedies is the Vajont Dam failure. It happened at night of 9th October in the year 1963, three years after the dam went into operation. In previous years there has been a concern about landslide accident that would damage the dam. The landslide occurred, but it has not caused any deaths, but special monitoring systems were put in place to monitor the land movements. After the local authorities have issued evacuation order, the inhabitants did not evacuate. On the 9th October after 10 p.m. major rockslide twice the volume of the reservoir occurred and created a huge wave at about 50 million m³ in volume moving both down- and upstream which took a death toll of two thousand people and significant property damage [5] [8].

2.4. The Banqiao Dam, China
On the Ru River there was an extensive system of dams and reservoirs amongst the largest were Banqiao, Boshan, Suyahu. This system was put in place as a flood protection. But after heavy rains of 4-8 August 1975 one in 10 000 years flood occurred which resulted in overtopping and failures of over 60 dams in the Henan province. Resulted death toll was 26 000 people and the economic and environmental aftermath resulted in famines across the province [9].

3. Legislature framework of dam safety and its comparison across countries
Dams are very beneficial for the area they are in. They, however, carry some amount of risk too. Thus, it is important to protect the people, estate, farmland, etc. from the potentially devastating threads that dams may represent [10]. In every country the dam safety is fulfilled in different legislature framework, for example in Moldova there is different framework than in rest of the world [11]. In order to understand the principles used in dam safety it is critical to understand the legislature frameworks held in place in different countries. Therefore, I decided to outline dam safety legislature framework in regard to assessed dam in the Czech Republic.

3.1. The Czech Republic
The dams and the water technical infrastructure in Czech waters are regulated by Water Act, digest no. 254/2001 [12]. The most important obligations from the dam safety standpoint are to keep the water work obligations that were put in place during the authorization process, to obey the operating and manipulation framework, to execute the technical safety surveillance on their own expense, to execute technical check-up once every two years.
Those are the basic requirements from technical safety viewpoint. The Water Act sets out the basis of the problematics and then lower legislation documents work out the problematics to the greater detail. Moreover, there is dam safety classification framework present, which based on possible danger assigns dam safety class. The classification is based on possibility (in which time frame in the crisis situation likely to happen) and amount of damage (death toll, economic damage, environmental damage) as aftermath of the crisis situation.

In the Czech Republic, the methodology used to determine the amount of safety precautions is based on ALARP based methodology

3.2. The United Kingdom - England
The United Kingdom may be considered the world leader in terms of dam safety. Its quantitative risk analysis became an industry standard across the world. The quantitative risk analysis is based on As Low As Reasonably Practicable (ALARP) methodology in order to determine

The dams (and reservoirs) with capacity above 25 000 m$^3$ are regulated under the Reservoirs Act 1975 [13]. In England, the regulating authority is the Environment Agency. The Environment Authority (hereinafter “EA”) must register all reservoirs, then will assign designation of either “high risk” or “not high-risk”. This assessment is made based on impacts of uncontrolled release of water. As a part of designation process the EA uses detailed reservoir flood maps. The flood maps are shared with local authority emergency planners to inform their emergency plans. Inspection and control will follow in accordance with assigned risk designation. In case the reservoir is considered not high risk the reservoir is not supervised. In case the reservoir is considered high risk there are requirements that must be fulfilled in order to comply in the terms of safe operation.

The Reservoirs Act 1975 references the preparation of emergency plans but does not require it. These plans will be specified to each reservoir and will be shared with local authority.

3.3. Switzerland
In Switzerland, the dams and reservoirs regulated by the ‘Stauanlagengesetz’ (the Dams Act) from 1st October 2010 [14]. When a dam is to be built, there will be a meeting of a supervising authority and an owner of the dam, and they will reach an agreement concerning the operational, technical and organizational safety precautions. The dam operational parts must have the ability to be emptied for prophylactic, control and maintenance purposes. The dam must have drainage redundant enough that can in case of crisis situation that it can drain the reservoir in an adequate speed.

The operator of the dam is required to work out the emergency conception. It is stated that the operator of the dam is required to take such precautions that are reasonably practicable or achievable (ALARP) to belittle the danger to the inhabitants, equity and environment to a minimum.

3.4. The United States of America
The US legislation is very complex, because some of the dam safety problematics is regulated on the federal level and some of it is regulated by every state on its own. However, in terms of dam safety there is a federal-wide “Procedure for Estimating Loss of Life Caused by Dam Failure” published by Dam Safety Office under label DSO-99-06 [5]. The methodology used in based on number of people at risk and then determining in what way safety precautions lower the number and then assessing the precautions to lower the number to a practicable and reasonable minimum.

3.5. Comparison
In Europe, the dam legislation is harmonized across the countries in many ways. In general, the dams must be built within strict requirements on the materials and processes. Then there is assigned supervision authority which performs regular checks on safety. The methodology used in Europe is based on England’s quantitative analysis and ALARP principle.

In the USA, the dam legislation can differ from state to state, but there is Federal emergency management agency and the US bureau of reclamation that harmonize the safety requirements and methodology. The focus is put on number of people at risk and the safety precautions are raised to lower the number to a practicable and reasonable minimum.
4. The dam safety assessment steps, methodology and principles

As it was mentioned in the previous chapter the methodology used in every country differs a bit, but in general the efforts are the same. Apart from engineering best practices the most widely used methodology is the ALAPR (“As Low As Reasonably Practicable”). In this chapter there will be described the use of ALARP methodology and other steps in dam risk analysis.

4.1. Determining dam failure scenarios

Firstly, it is critical to work out basic dam failure scenarios. They will be used in further risk evaluation. The necessary scenarios to take into consideration are those: a) dam failure with full reservoir, b) dam failure in case of flood and overtopping.

In the last decade there has been a great change to climate. In the past there were not considered rapid changes to climate with aftermath to dam management and whole waterflow. Changes to forestation (resulting in deforestation) [15], flash rains are participating in creating new set of risks which must be considered [16].

4.2. Determine for which time frames the analysis should be made

Depending on the potential risk that the dam bears there are different time frame for which should be the analysis made and precautions taken.

In the Czech Republic there are four safety categories of dams that are assessed depending on how much people and property are at risk. In Table 1. there first two categories of the four where there is expected loss of lives. In the Czech Republic there is in accordance with ALARP principle stated that risk of loss of lives is acceptable at likelihood of $10^{-4}$ in a given year when ALARP is exercised as seen in Chyba! Nenašiel sa žiaden zdroj odkazov..

| Water work class | Possible damages in case of crisis scenario | Assessment viewpoints in case of crisis scenario | Required safety (crisis scenario in N years) |
|------------------|--------------------------------------------|-----------------------------------------------|-------------------------------------------|
| Overall damages  | Potential loss of lives                    | Likelihood of crisis scenario in given year   | Required N of years                       |
| I. Severe damages| Severe economic damages, damages to environment and social aftermath on a state scale | Expected | 0.000 1 | 10 000 |
| II. Extensive damages | Extensive economic damages, damages to environment and social aftermath on a regional scale | Expected Not probable | 0.005 | 2 000 |

4.3. ALARP application and safety measures recommendation

ALARP analysis is recommended to be applied always when there is loss of lives risk above 100 [21].

4.3.1 F-N diagram. For each dam there should be F-N diagram (see Chyba! Nenašiel sa žiaden zdroj odkazov..) calculated based on historical data of the country or ideally the watercourse the dam to be built on. The F-N diagram determines adequate values of dam failure to number of lives at risk [21].
4.3.2 Calculation of costs in case of crisis situation. There are many ways how to estimate the costs that would rise in case of crisis situation. There must be included dam repair estimates, then according to flood plans: housing damages, environment impacts, farmland damages, traffic impacts, damages to other infrastructure, losses of potable water, etc. Then there must be calculated loss of live toll. This calculation depends on judicature of each state and purchase power of each nation.

4.3.3 Major factors influencing Loss of Life. Major factors influencing loss of life are following:
   a) dam failure origin and severity,
   b) total number of people in the area,
   c) time advance of official warnings and evacuation of the area,
   d) volume of water released influencing depth and velocity of wastewater [5].
The major factors are the ones to be the most concerned about and should have the most attention paid.

4.3.4 Safety measure decision-making. When deciding about putting up a safety measure there must be a benefit cost analysis used. Thus, it must be calculated whether the investment is adequate to difference in the costs of crisis situation after the safety measure is put up and after and before when the probability of event is considered.

5. Dam safety method evaluation
In this chapter I am going to choose one Czech dam and apply different safety methods and then evaluate their results.

5.1. Dam Boskvice

5.1.1. General data
   Location: Boskvice, The Czech Republic
   River: Bělá, km 7,40
   Undertaker: Povodí Moravy, s.p.
   In operation since: 1990
   Major repairs: 2020

5.1.2. Reservoir data
   Total capacity: 7,373 million cubic meters
   Minimal capacity: 0,425 million cubic meters
   Water storage capacity: 6,375 million cubic meters
   Emergency retention capacity: 0,796 million cubic meters

5.1.3. Dam data
   Type of dam: embankment dam
5.1.4. Spillway
Number x diameter of spillway valves: 2 x 800 mm, capacity: 2 x 5 m³/s

5.1.5. Emergency spillway
Capacity: 85 m³/s

5.1.6. Hydrological data
Average long-term inflow: 0.356 m³/s
Q₁₀₀: 33.5 m³/s
Q₅₅days: 0.030 m³/s.
Data source: undertaker official website [22].
The undertaker discloses that the dam is able to withstand one-in-thousand years flood.

5.2. ALARP analysis
According to ALARP analysis and the F-N diagram (see Figure 3.), we have to focus on 1-in-10 000 crisis situation. The dam is designed to withstand 1-in-1000 years crisis situation, so the risk is negligible here. However, during 1-in-10 000 crisis situation there is a possibility that the dam will overflow or fail. Thus, it is important to determine endangered area and work out safety solutions that minimize the risk as reasonably practicable. Thus, it is important to put in place emergency solutions that will warn and evacuate area at risk in a short amount of time. In case of 1-in-100 000 crisis situation the risk is lowered by ALARP region precautions and remaining danger is socially acceptable and costs are not adequate to the benefit.
5.3. Benefit-cost analysis
Benefit-cost analysis (hereinafter BCA) analysis is a tool to determine mitigation projects. Concerning the Dam Boskovice suggested mitigation project is for 1-in-10 000 crisis situation. BCA analysis was made in accordance with the U.S. Federal Emergency Management Agency methodology (hereinafter FEMA).

| Table 2. BCA analysis of 1-in-10 000 crisis situation damages mitigation project. |
| --- |
| **Cost estimation** |
| Useful life before major investments | 100 years |
| Annual maintenance cost | 20 000 000 CZK |
| **Benefit estimation** |
| No. of people protected | 1 000 |
| Daily value of unit of service (according to FEMA) | 1 218 CZK |
| Total annual value of service | 444 570 000 CZK |
| **Expected damages before mitigation** |
| Recurrence interval | 10 000 years |
| Damages estimate | 900 000 000 CZK |
| **Expected damages after mitigation** |
| Recurrence interval | 10 000 years |
| Damages estimate | 500 000 000 CZK |
| **BCA analysis** |
| Mitigation project cost estimate | 200 000 000 CZK |
| **B/C ratio** | 2 |
| **RESULT** | B/C ratio > 1, thus recommended |

6. Discussion
Both methods used have their advantages and disadvantages. ALARP method is very useful at identifying which risk has to be minimized and regions in the F-N diagram to focus on. However, it does not provide any information to be used in safety measure decision making. On the other hand, this is where the BCA provides really helpful insights on the matter. Therefore, it is recommended to use both methods in synergy.
Firstly, it is important to identify risks that has to be minimized and crisis events leading up to them by performing ALARP analysis. If there are any low-cost safety measures that can be applied they must be applied immediately without hesitation.
Secondly, if there are any more costly solutions BCA analysis should be performed. The BCA provides information whether the benefits of the measure outweigh the costs. If the B/C ratio comes out greater than one there should be put best effort to put up the measure. The drawback of the ALARP method is mostly its morality, whether statistical protection of lives is good enough to physical protect people. This was widely discussed in the academical society, but there were not any final conclusions made.

7. Conclusion
In this article there were stated major dam failures in order to accent the importance of dam safety. Then there were dam safety legislation frameworks compared and concluded that across Europe the legislation is harmonized. There were outlined major steps in dam safety analysis, then ALARP method use and benefit cost analysis in safety measure decision making.
There has been ALARP analysis and benefit cost analysis performed for the dam Boskovice. The ALARP analysis identified risk region which should be focused, and the BCA was used in safety measure decision making using FEMA BCA calculator.
In collusion, based on the evidence we recommend that it is critical to use these two analyses (ALARP and BCA) together comparatively and focus on their ethicality with accent on engineering best practises.

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