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Consequence estimation in risk analysis

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ABSTRACT: Damages produced by a dam failure are usually very severe, leading to high economic impacts and in many cases loss of life. When performing a Quantitative Risk Analysis, these consequences must be estimated for several dam failure scenarios. In order to be able to work with incremental risks, no-failure consequences must also be estimated.

This article classifies the different types of consequences and discusses the available methods for their estimation and how these results can be incorporated into a Risk Model in a Quantitative Risk Analysis. Lastly, results for several case studies are presented.

1 INTRODUCTION

When a dam Quantitative Risk Analysis is performed, a proper consequence estimation for several dam failure scenarios is necessary since they are one of the components of risk. Dam break consequences may be very important, especially the loss of life that they can produce in downstream urban areas.

Dam break consequences are very diverse; some examples are societal and economic disruption, damage to the government and environmental losses. In general, they can be divided in direct or indirect, if they are directly produced by the flood wave or not. They can also be divided in tangible or intangible if they can be quantified in economic terms or not (Jonkman and Vrijling 2008).

This paper discusses the estimation of loss of life and economic consequences (direct and indirect), since these consequences can be easily quantified and incorporated into a Quantitative Risk Analysis. Other dam break consequences like social trauma, historical and cultural losses and environmental losses may need an independent qualitative analysis.

The situation of consequences in a Quantitative Risk Model is shown in Figure 1. They may depend on dam break hydrographs (in the cases of dam break consequences) and outflow

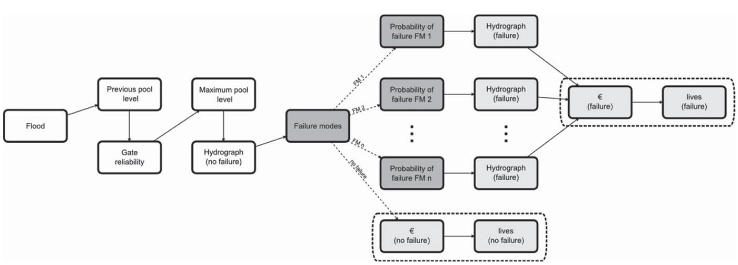

Figure 1. Integration of consequences in a Quantitative Risk Analysis.

hydrographs (in the cases of non-break consequences). For each situation, consequences in the cases of dam break and non-break are subtracted to compute incremental consequences, which are used to compute dam incremental risk (Serrano-Lombillo et al., 2011).

Therefore, the first steps of a consequences analysis are the dam breach parameter estimation and the hydraulic modeling of dam break flood wave. Some recommendations can be found in the bibliography to correctly make these steps (Froehlich 1995, ICOLD 1998, MMA 2001), so this paper will be focused on loss of life and economic consequences estimation when flood characteristics in each affected area are known.

2 ESTIMATION OF LOSS OF LIFE

Loss of life usually is the consequence with the highest social impact of a dam break. Several methodologies have been developed to estimate dam break loss of life (Graham 2009), with a high variation in the level of detail. In general, all these methodologies give a high importance to the warning time, which is the time available from the beginning of the warning to the population to the arrival of the flood wave.

A widely used method to compute dam break consequences is the method proposed by Graham (1999), which computes an average mortality rate that must be applied to the population at risk in downstream areas. This mortality rate depends on warning time, flood severity and population's flood severity understanding. This methodology is commonly used because it is simple and based on historical data.

Some methodologies have been developed based on the one proposed by Graham. An example is the one proposed by the USBR (2006), which includes the speed of dam breach formation as a parameter to estimate the mortality rate. Another methodology is the one proposed in the SUFRI project (Escuder-Bueno et al., 2011), which divides the degree of understanding of flood severity in 10 categories depending on education and coordination of population at risk and governments.

Another proposed methodology based on mortality rates is the one developed by Jonkman (2007). This methodology has been developed for any kind of flood and gives a high importance to warning time and evacuation procedures.

Furthermore, it is important to also emphasize other methodologies which are based on modeling the physical processes occurring during a flood event. One example is LifeSIM (Aboelata et al., 2003), which includes simulations of people at risk behavior during the flood and also has a simplified version (Needham et al., 2009). Another example is LifeSafety (BC Hydro 2006).

Loss of life estimation is a complex process, since it depends on many circumstances and parameters. In general, before deciding the methodology to use, it is necessary to analyze the available data, in order to apply it correctly. In this sense, Emergency Action Plans are an important source of information, since they define the most important affected downstream areas and the flood wave characteristics.

3 ESTIMATION OF ECONOMIC CONSECUENCES

Dam break economic consequences are also very useful data in Quantitative Risk Analysis, especially to justify measures that may be implanted to reduce risk. Economic consequences depend on conditions of downstream urban areas and local economy. In general, the estimation of these costs is divided in direct (produced directly by flood wave) and indirect (due to disruptions in local economy).

In general, the methodologies to estimate direct consequences are based on the proposal of Kates (1965). They are estimated as a combination of the cost of total destruction of the land use and depth-damages curves, which define a relation between depth of inundation and percentage of produced damages. Costs of total destruction depend more on local conditions whereas depth-damages curves can be more easily generalizable, depending on land use.

Some examples of these methodologies developed to estimate flood consequences in Spain are explained in PATRICOVA (COPUT 2002) and INUNCAT (ACA 2009).

Regarding indirect consequences, they are usually estimated as a percentage of direct consequences, which can vary depending on the importance of the local economy in the region. Currently, more detailed approaches are being studied (Bockarjova et al., 2004), with Input-Output models to estimate the flood long term impact on economy. Furthermore, when estimating the costs of destruction of the dam structure two approaches can be followed. One would be to estimate the lost project benefits. The other one would be to estimate the cost of reconstruction. References provide some recommendations to estimate them (Ekstrand 2000).

4 CASE STUDY

Dam break consequences have been estimated for a portfolio of 27 large dams located in the same river basin. This estimation has been based on the information available in their Emergency Action Plans and the hydraulic models used for their elaboration. Therefore, the degree of detail of results depends on the quality of the information available in each dam. There is a high variation in the types of the dams, from large arch and earthfill dams to small gravity dams, so a high dispersion in the results has been obtained.

4.1 *Loss of life*

Loss of life has been estimated using the SUFRI project methodology (Escuder-Bueno et al., 2011). In each dam, the current situation has been analyzed in order to evaluate the degree of flood severity understanding in the population, in this sense, most of the dams have an Emergency Action Plan written but it has not been implemented yet.

These mortality rates have been applied to population at risk, which has been obtained using the INE database (INE 2011). Furthermore, seasonal and daily variations in the population have been obtained, so a different loss of life has been obtained for day and night and for summer and winter. This population at risk has also been corrected depending on the average number of floors in the buildings of each urban area.

Then, combining the mortality rate and the population at risk in downstream areas, loss of life is directly obtained for different dam failure scenarios. These consequences have been related to the peak break discharge in the dam, obtaining a curve that can be introduced in a risk analysis model. In Figure 2, an example of these curves is showed.

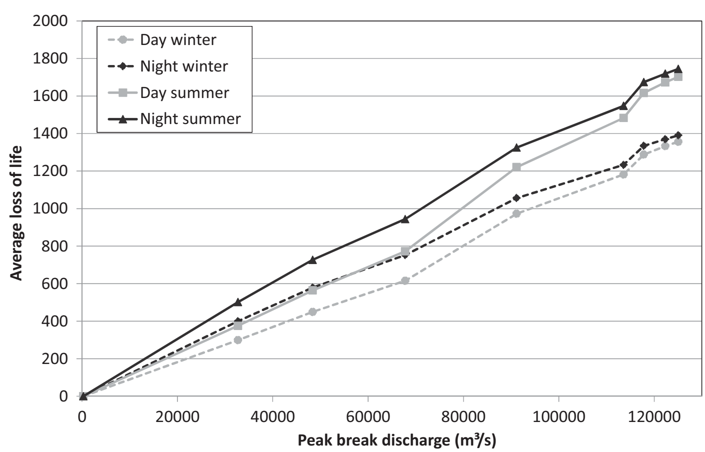

Figure 2. Example of relation between loss of life and peak break discharge in the dam 4.

Although the analysis of the individual results of each dam is interesting, the main focus for the rest of the paper will be on the comparison of the results between the 27 dams, in order to know which dams have a more vulnerable downstream area. In these dams, the efforts to communicate and educate the population relating to flood risk must be higher. In Figure 3, the maximum dam break consequences in each dam are shown. As can be observed in this graph, there are big differences in the results of the different dams. Furthermore, there are three dams that do not produce significant loss of life when they break.

The consequences when the dam does not break have also been computed to estimate the incremental consequences. In general, these consequences are much lower than dam break consequences, although in some cases, like small dams in large rivers, they have a similar magnitude. The results obtained in this situation are also shown in Figure 3.

Warning time has been a parameter with a very high influence on the loss of life results. Therefore, a sensitivity analysis has been done in order to analyze how the loss of life changes in one dam break scenario depending on the moment when warning to the populations is initiated. The results are shown in Figure 4. As can be observed in this graph, the moment of beginning of warning has a high influence on loss of life results, so it is really important to correctly analyze when the warning time to the population will be initiated in a dam break situation.

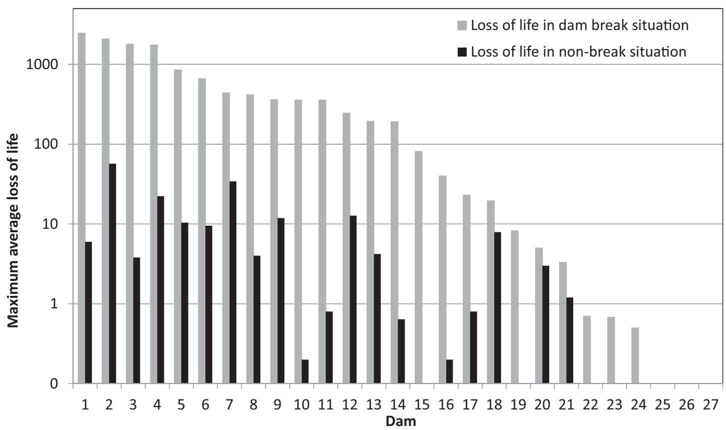

Figure 3. Maximum average loss of life in the 27 dams analyzed.

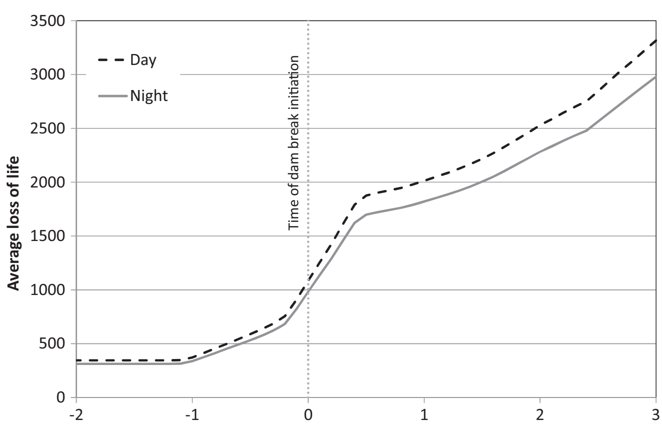

Figure 4. Relation between loss of life and time of beginning of warning to the population in the dam 4.

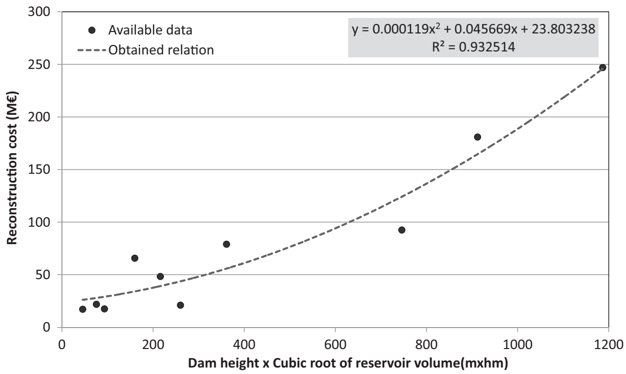

Figure 5. Relation obtained to estimate dam reconstruction cost as a function of dam height and reservoir volume.

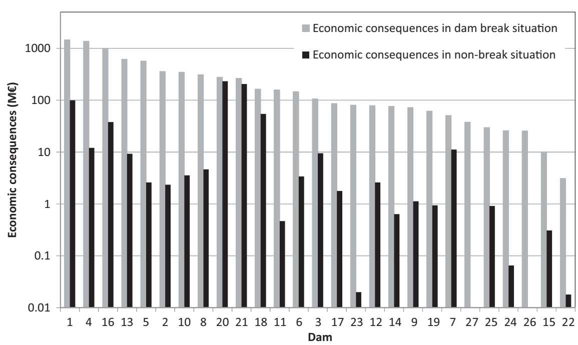

Figure 6. Maximum economic consequences in the 27 dams analyzed.

4.2 *Economic consequences*

The flood economic consequences have also been computed for the dam break and non-break situations in the 27 dams of this portfolio. The direct economic consequences, produced by the flood wave, have been computed using the methodology proposed in PATRICOVA (COPUT 2002). Following these recommendations, the indirect flood consequences have been estimated as a fixed percentage of the direct consequences. This percentage has been defined for each land use, depending on local economy characteristics.

The next step has been to estimate the cost of reconstruction of each dam. This cost has been computed using available data about cost of construction of recent dams projects. Then, a relation between these costs and the dam height and the reservoir volume has been obtained, producing a good adjustment to the available data (Figure 5). The cost of reconstruction is only taken into account in the dam break case.

Applying these methodologies, economic consequences for each dam have been obtained, getting a relation between the economic consequences and peak break discharge, similar to the relation shown in Figure 2. This relation can be directly included in a risk analysis model. In Figure 6 the maximum consequences in break and non-break cases are shown for all the dams.

5 CONCLUSIONS

The main conclusion obtained after computing dam break consequences in 27 different dams in the same portfolio, is that it is a complex process with many parameters and variables involved. Therefore, it is really important to estimate consequences in a consistent and structured way, in order to be able to compare the obtained results between dams.

Furthermore, it is necessary to check available data to estimate consequences correctly. In this sense, Emergency Action Plans are a very useful source of information which can be applied to make a consequence assessment. Furthermore, consequence estimation produces useful information for dam safety management, for instance it informs about the most vulnerable urban areas downstream and the effectiveness of emergency procedures in minimizing loss of life.

Regarding loss of life, warning time is the most important parameter to minimize flood fatalities, so improvements on warning procedures and task forces coordination are really important to reduce dam risk. Furthermore, some aspects to improve population severity flood understanding, like education programs and flood drills can also be very important.

Finally, economic consequences are highly dependent on local economic conditions, so it is important to analyze in each case the flood consequences on local economy.

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