Protections 2016 Ft. Collins, Colorado, USA, 7-9 September 2016
2nd International Seminar on
Dam Protection Against Overtopping
ISBN: 978-1-1889143-27-9 DOI:

Dams and Overtopping: A Polyhedral Relationship

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ABSTRACT

This paper discusses the different elements playing a role in causes and consequences of dam overtopping: the river basin, the reservoir, the dam and the spillway, the riverbed and the territory downstream of the reservoir. The risk is presented as the key concept linking all these elements, causes and consequences of the dam overtopping. The perspective of the different stakeholders is also considered, especially that of the dam owner, who is responsible for making a decision about what to do if a dam overtopping problem arises. The different attitudes of the dam owner are mainly characterized by the definition of the damage adopted when considering the risk as a basis for an informed decision taking. The social and economical risk are defined as characteristic of the extreme opposite positions, considering only damage to others, casualties and environmental damage (social risk), or considering only the cost for the dam owner, including cost in compensation for casualties and environmental damage, (economical risk). The legalist position is also considered, of the dam owner that seeks to comply with the regulations, irrespective of the risk except in the countries where risk considerations are already part of the legal framework for decision-making. Three key questions that the dam owner must answer to solve an overtopping problem are analyzed: a) Do I really have a problem? b) What different ways can I solve my overtopping problem; and, c) How do I choose the best solution for me? Finally, an ideal process for solving an overtopping problem on a rational and informed way is proposed, including the perspective and position of the particular dam owner. The general process should be adapted for every particular case in order to be feasible in practice and as efficient as possible.

Keywords: *overtopping, overflow, dam, risk, damage, failure probability*

1. INTRODUCTION

Dam overtopping and the hydrological safety problem it causes involve a great number of factors and stakeholders. The interaction between them and the unavoidable uncertainties complicate dealing with this complex problem in a rational and systematized way. There is not a holistic and generally accepted methodology for stakeholders, mainly the dam owner and the dam safety authority, to take rational decisions on particular cases of dams threatened by overtopping. This paper is an attempt to understand the complexity of the dam overtopping problem, a call to a holistic and systemic view, and also an attempt to rationalize the decision making.

The problem of dam overtopping may be seen as a polyhedron with many faces observed by the stakeholders from different perspectives, so that every stakeholder has a different image of the problem. This polyhedron is not empty; on the contrary, it is completely full of wires connecting the multiple faces. So the polyhedron is not a simple device. Knowing the complete polyhedron, the many faces and connections between them, and being aware of the multiple perspectives, are necessary conditions for dealing with hydrological safety in an informed and rational way.

Therefore we should first tackle the analysis of the elements and factors affecting dam overtopping problem and relations between them (the faces and wires of the polyhedron). After that, we should identify the stakeholders and their possible attitudes (perspectives). Finally, a general procedure for dealing with hydrological safety should emerge from this holistic analysis of the dam overtopping problem, applicable by any stakeholder and taking into account his specific attitude.

2. DAM OVERTOPPING: ELEMENTS AND CONECTIONS

Accumulation of rain water and water emergent from the subsoil in the river basin, upstream of the dam site, form the floods. Flood routing through a reservoir raises the reservoir's water level and may cause dam overtopping. On the other hand, flood routing is affected by the dam's spillway in the upper part of the reservoir, and sometimes also by the dam's other outlet works (although not significantly in most cases). Damage that overtopping causes on the dam body, the probability of a catastrophic failure and, if it occurs, the failure hydrograph shape and size, greatly depend on the type of dam and its particular site characteristics. Areas flooded in the case of dam failure depend on the riverbed topography and hydraulic features. Finally, casualties and economic and environmental damage are conditioned by land use downstream of the dam. Therefore, the river basin, including its climatological conditions, the reservoir, the dam body and spillway, the riverbed downstream of the dam and the territory may be proposed as the main significant elements related to dam overtopping.

The river basin and the reservoir are elements related to the causes of the potential dam overtopping event, while the riverbed downstream of the dam site and the territory are connected to the consequences of dam failure. The dam body and the spillway are in the middle, between causes and consequences, since they condition the overtopping occurrence and also may potentially be damaged if overtopping happens.

2.1. Causes of Dam Overtopping

The river basin and the reservoir are causes of dam overtopping in the sense that they influence the dam overtopping occurrence. Features of climate and topography on the river basin area determine the intensity and the spatial and temporal distribution of rainfall which, together with geological and vegetation characteristics of the river basin govern the formation of floods, that are routed through the fluvial net to reach the reservoir. The formation of floods is the main and most evident contribution of the river basin to dam overtopping. However, it is not the only contribution, since solid deposit (sediment) in the reservoir over time also depends on the geological configuration, slopes and vegetation on the river basin. It meanwhile may influence the reservoir level over the operation period, and so the occurrence of dam overtopping. The effect of sediment deposit on the dam overtopping threat may be negligible in many cases, but relevant in some of them.

The most evident influence of the reservoir on the dam overtopping threat is through its topographical configuration, expressed via the "characteristic curve" that links reservoir storage capacity with water level; and, also the initial water level when the flood reach the reservoir has an important effect. The result of the flood routing through the reservoir highly depends on both, the initial water level and the "characteristic curve". The evolution of the water level in the reservoir is governed by water demand and operation criteria. Additional phenomena can be identified in the reservoir with influence on the dam overtopping threat. Evaporation of water from the reservoir surface also has an effect on the reservoir level. Although small, it is not completely clear that this effect can be considered negligible in all cases, since a small difference in water level may imply a significant difference in overtopping flow discharge. The fraction of sediment entering the reservoir that leaves downstream through the spillway and outlet works depends on the topographical configuration of the reservoir and the operation criteria of the outlet works. Finally, waves can be generated in the reservoir due to wind, seismicity or landslides that may cause dam overtopping, although of a quite different type and effect on the dam.

The spillway governs the water discharge flowing out of the reservoir over a flood episode, so spillway influence on the dam overtopping threat is evident. In the case of gated spillways, operation criteria have an important impact on the water level evolution over a flood episode. Also the possibility of one or several gates breaking down, or partial or complete clogging of the spillway (due to vegetation and other debris), should be considered in a complete analysis for the assessment of the hydrological safety level of a dam.

Finally, crest elevation determines the available freeboard for the flood to leave the reservoir without overtopping. This way, the dam body greatly affects the hydrological safety of the dam. Freeboard is the most popular factor in addressing the dam overtopping problem. Different values for the freeboard are prescribed in the regulations as the minimum vertical distance from the crest to the maximum water level in different flood scenarios and to the maximum level in normal operation scenario. The word "freeboard" will generally be used in the context of this paper to refer to the difference in elevation between the dam crest and the maximum normal operation level, which is the only completely objective freeboard that can be measured in the dam. Freeboard related to a given flood level depends on the assumptions adopted when computing and routing the corresponding flood. The word "freeboard" will sometimes also be used as a general concept, not related to a particular reference level.

For the assessment of the probability of dam overtopping, the above-mentioned factors should be taken into consideration. An informed analysis of a particular dam could disregard some factors if it is clear that they are negligible.

2.2. Consequences of Dam Overtopping

The dam, the riverbed and the territory play a role in the consequences of dam overtopping, once it occurs. The damage to the dam and danger of a catastrophic failure is the first consequence. The failure can be considered catastrophic when the damage causes the release of a significant quantity of water stored in the reservoir. However, we must be aware that all dams are overtopping resistant up to a certain overflow discharge and duration that depend on the particular features of the dam and are certainly difficult to determine. Also the damage to the dam provoked by overflow strongly depends on the specific characteristics of the dam and foundation. Therefore, the probability of dam failure must be estimated on a particular basis. It is well known that concrete dams resist overflow much better than do earth and rockfill dams. However not so well understood are the deep differences of overflow resistance and failure process between earth and rockfill dams. The breakage process is essential for the assessment of the failure hydrograph, especially for reservoirs of small storage capacity, for which water level changes substantially while the dam is still breaking. In spite of the difficulty, informed decision making regarding a dam overtopping problem should be based on the best possible analysis of the dam resistance to overflow and failure process, and so the best possible estimation of the dam failure probability.

Riverbed topography, hydraulic features and even erosion and deposition dynamics govern the failure hydrograph routing downstream of the dam, and so the delimitation of the flooded areas and the computation of the flow depth and velocity at different affected locations. Although not easy, to model the failure hydrograph routing implies less uncertainty than the failure hydrograph estimation. The type and extent of the flooded inhabited territory, its uses and occupation, influence the casualties and the economical and environmental damage. The distance from the dam to the inhabited areas and the availability of effective emergency plans for the eventuality of dam failure also strongly affect the number of casualties, but scarcely the economical and environmental damage. Although usually not properly considered, the dam failure process may have a significant impact on the number of casualties. The failure of the dam takes some time. It is unrealistic to assume that the water reservoir release, the failure hydrograph, initiates with the overtopping. Failure time is different from one type of dam to another and depends on the particular features of the dam. For example, the failure of a rockfill dam may be much faster than the failure of an earth dam of cohesive material; also the failure of a high rockfill dam may be much slower than the failure of a low dam of the same type, all other factors being equal. The dam failure time is an opportunity for a threatened population to escape from the areas that will be flooded; actually, it is the only opportunity for population centers downstream in the close vicinity of the dam, unless a good flood forecast system is available that allows the evacuation of the population before the dam is overtopped. The most realistic estimation of casualties and economical and environmental damage should consider all the factors and mutual interactions.

2.3. The Risk and the Stakeholders' Perspectives

There are many stakeholders involved in the dam overtopping problem: the dam owner, the dam safety authority, the environmental authority, the dam user who obtain a benefit from the dam, the potential casualties or population economically damaged in the case of dam failure, the population damaged by the construction of the dam, different citizen groups with interests in the affected area, the politician somehow affected by the dam construction and operation, and for the potential failure... we might even consider the perspective of an objective observer with no particular interest on the subject, not benefited and not damaged by the dam.

The perspective and position of the stakeholder shape the risk perception, at least regarding the damage. Different types of damage may be considered: a) casualties and environmental damage are a not economically quantifiable type of damage from a human and social point of view; however, they can be measured from an economical point of view as the sum to pay by the owner in compensation, if responsible of the dam failure; b) damage to the dam and the dam owner properties and also to the properties of others are economically quantifiable.

The risk is accepted to be the product of the failure probability and the damage (Altarejos-García et al. 2012), so that the risk is null if the failure probability or the damage is null, and the risk equals the damage if the failure is certain. In the case of dam overtopping, the failure probability is the product of the overtopping probability and the dam failure probability once overtopping occurred. Therefore, the concept of risk links causes and consequences of dam overtopping.

The stakeholders may adopt different attitudes, depending on how they define the damage. Let us consider the dam owner perspective, since he is finally the stakeholder that must take a decision about acting or not on the dam, conditioned by the rest of stakeholders, and fund any dam modifications as well as pay for damage if failure occurs. The *social, ethical or altruist attitude* leads the stakeholder to consider just economical damage to properties of others, because he tries to limit the risk imposed to others to a value accepted by the society. We can define the *social risk* imposed to others by the dam as the product of the failure probability and the economical damage to properties of others. Of course, the dam owner with a social attitude seeks to limit the risk of life loss among the downstream population and the risk of environmental damage to values also accepted by the society, admitting that it cannot be economically quantified. At the opposite pole is the *economist attitude*, that leads the dam owner to consider exclusively the cost that he is forced to assume: damage to his own properties (mainly the dam) and the sum to pay in compensation to others due to economical damage, and also due to casualties and environmental damage. The product of the failure probability and the total cost for the dam owner may be termed *economical risk*. A range of attitudes may be found between social and economical extreme positions, but all of them involve a rational approach, and also are conditioned by necessarily complying with the applicable dam regulations. Given that many regulations were developed with an approach mainly based on freeboard criteria, they may be a sever obstacle to adopt the most adequate solution to an overtopping problem with the risk approach. In fact, the dam owner, strongly conditioned by the dam safety authority, frequently shows a *legalist attitude*: just to comply with the dam regulations, irrespective the economical or social risk generated.

3. THREE KEY QUESTIONS

Solving an overtopping problem in a rational way requires answers to three key questions that we shall consider from the dam owner perspective: a) Do I really have a problem? b) What different ways can I solve it? c) How do I choose the best solution? The answer to each question is not easy, but it is worth considering the opportunities and limitations that arise when trying to respond.

3.1. Do I Really Have a Problem?

The dam owner may have different types of additional problems derived from an overtopping threat. If the *economical risk*, as defined above, is much greater than the cost for reducing it to an acceptable level, then the dam owner really has an economical problem, and he should try to find a solution for an economical reason. Let us remember that the damage used to determine the economical risk is just the cost for the dam owner. But he must define the solution and determine the cost to be able to find out if it is greater than the economical risk or not, and therefore if he really has a problem or not. So the initiation of the study should be based on a suspicion, based on clues: the freeboard is lower than required by regulations, water level reached elevations near the crest in some flood events, or even overtopping has occurred. Private companies, whose main objective is to produce an economical benefit, are very sensitive to economical risk.

The dam owner has an ethical problem if the *social risk*, considering the economical damage to others and also the potential casualties and environmental damage, is greater than accepted by society. Public dam owners are particularly concerned about the *social risk*. The ethical problem may become a different kind of problem if the dam safety authority, or other stakeholders as ecological groups or population threatened by the dam failure, press to lower the risk.

If dam regulations are not fulfilled, typically because the freeboard is insufficient, the dam owner has a legal problem. It should be noticed that a legal problem does not necessarily imply that the social or economical risks are unacceptable. A legal problem is, in principle, just a legal problem, that may be traduced in economical terms by the potential fine and probable lost of profits if the dam safety authority imposes restrictions to the dam and reservoir operation. So a new type of risk may be defined: the *legal risk*, the product of the dam failure probability and the costs derived from the failure to comply with the dam regulations, even if failure do not occur. Legal and economical risks are usually alternatives, although the economical risk may include a possible fine in the case that dam regulations were not fulfilled before the dam failure. To find out if a legal problem implies a social or economical problem it is necessary to assess the social and economical risks.

As may be inferred from the complexity of the dam overtopping problem mentioned above, it is not easy for the dam owner to find out if he really has an economical or social problem, which are real problems for the dam owner and for the rest of the stakeholders; however, it is fairly easy to identify the legal problem if regulations are based just on a freeboard requirement, as usual. Freeboard criteria were adopted as a rather conservative and simple to implement way to guarantee the hydrological safety of the dam and the population and properties downstream of the dam. Nonetheless, new dam failures due to overtopping occur every year, although most of them are quite small dams. Although reasonable, in the absence of the tools and means for a deeper analysis of the overtopping problem, the freeboard approach is quite limited. Minimum freeboard values required in different countries have a notable arbitrariness component, since they are not founded on a rational quantitative argument or method.

On the other hand, the most important weakness of the risk analysis is the difficulty to determine the probability of failure on solid and reliable quantitative methods. In the case of dam overtopping, it is now possible to make a reasonable estimation of the probability of overtopping, and the main obstacle is the estimation of the dam failure probability, once overtopping occurs. However, a great research effort is nowadays being done to properly modeling the dam failure process. Any contribution in this area brings us closer to an effective understanding of the real problems originated by dam overtopping, and so allows the dam owner to find out if he really has a problem, different from the legal one.

3.2. What Different Ways Can I Solve my Overtopping Problem?

If the dam owner really has a social, economical or legal overtopping problem it implies that: a) the probability of dam overtopping is too high; or, b) assuming that the overtopping occurs, the dam failure probability is excessive; or, c) assumed that the dam fails, damage downstream is too elevated; or, d) the dam fails to comply with dam regulations, usually the freeboard is lower than required. The alternative solutions for a dam overtopping problem may therefore be classified according to the particular issue they act on. We are going to begin the analysis by considering the last issue; i.e., considering a conventional approach.

<u>How to comply with the dam regulations with a conventional approach</u>

The most conventional and prevalent solution nowadays for an overtopping problem is to reduce the threat of dam overtopping by increasing the dam’s freeboard and prevent overtopping for the design flood. I avoided here the word "probability" because this concept is not managed in this conventional approach. The dam is considered threatened when the freeboard is lower than required by regulations, and dam safety is considered restored when the dam’s freeboard is equal or greater than required. The increase of the freeboard by conventional solutions usually implies a significant investment. If the necessary budget is available, the problem may be solved, but frequently it is not, especially when this problem happens in an important number of dams of the same owner. Three alternatives arise in this scenario: a) not doing anything, and maintain the dam regulations violation; b) lowering the maximum storage water level, and so reducing the storage capacity of the reservoir and its functionality; it implies a cost that may sometimes be huge and inconveniencies for the user; and, c) turn to unconventional solutions of lower cost than conventional ones. The strong conservatism and resistance to change in the dam field often results in the rejection of the "c" option, and only "a" and "b" options are considered, regardless of the significance of the overtopping threat or the cost and inconveniencies of lowering the reservoir level.

The need to increase the freeboard arises usually as a consequence of the updating of the design flood due to new data available or by changes in the regulations. The most frequent conventional solutions for increasing the freeboard are: a) the raising of the dam, elevating the dam crest, while the ogee spillway in maintained unchanged (though the spillway chute and basin must also be refurbished to receive a greater flood discharge); b) the construction of a new additional spillway, to maintain the same flood level while the maximum flood discharge is greater; and, c) the change of the ogee crest to a labyrinth weir may nowadays be considered an accepted solution (it also allows to the flood level to be maintained in spite of the higher flood discharge; the refurbishment of the spillway chute and the basin are also necessary in this case).

There are also unconventional solutions to increase the freeboard. They are discussed at the same time as discussing the risk analysis approach in relation with dam overtopping.

<u>How to reduce the probability of dam overtopping</u>

Increasing the freeboard, which is also the most conventional solution, is still the most obvious option to lower the probability of overtopping based on risk analysis. However, there are two essential differences between the risk analysis and the conventional approaches: a) required freeboard is a beforehand value, of dubious justification, for the conventional approach, while freeboard is a result of the analysis for the risk approach; its value is that needed to lower the risk to an acceptable level by reducing the overtopping probability; b) with the risk approach, the needed freeboard depends on the dam features, which condition the dam failure probability, and damage downstream, while it is a fixed value from the conventional approach perspective, although a different value is required for concrete and embankment dams.

Regardless of the approach followed, the freeboard may be increased using the above-mentioned, clearly accepted conventional solutions, and also by means of less conventional and widely accepted alternatives. Although infrequent, there is a number of cases of these unconventional alternatives all over the world. Among them we can mention: a) labyrinth or flat fusegates, which fail and fall when the reservoir level reach a prescribed elevation (Falvey and Treille 1995); b) for gravity dams, increase of the ogee crest length by demolition at both sides; highly convergent chutes are designed on the downstream dam face to convey the water coming from the extended zones to the central basin (Morera et al. 2015); c) piano key wires (PK-weires), evolved from labyrinth weirs, with parallel faces and sloping bottom that reduces the necessary space for the base, which is favorable for the installation on the body of concrete dams (Erpicum et al. 2013); and, d) different types of concrete spillways on the body of earth and rockfill dams. The latter have the following features: the maximum storage water level is maintained below the crest elevation, with an adequate freeboard, unlike the overtopping protections that will later be mentioned; the spillway usually takes up just a part of the dam crest; the bottom of the spillway chute may be formed by conventional slabs of reinforced concrete (Alves and Morán 2015) or by precast wedge shape blocks (WSB) (Hewlett et al. 1997) (Morán and Toledo 2014); and, RCC solutions are also feasible for this type of spillway (Hansen 2003). These unconventional solutions may be particularly adequate for emergency spillways, acting only during floods of high return period.

The probability of overtopping for dams with gated spillways or outlet works with high discharge capacity may also be reduced by improving the early warning of flood development. It may sometimes be less expensive than undertaking structural works on the spillway, although the reliability and probability of failure of the early warning system should also be considered.

<u>How to reduce the probability of dam failure in an overtopping scenario</u>

Protection techniques against overtopping are the solution to reduce the probability of dam failure, once overtopping occurs (FEMA 2014). Let us focus first on embankment dams. Although there is not a rule, these techniques are generally more adequate to manage a moderate overflow discharge, because of the problem of protecting the contact between the dam and the abutments, specially the dam toe, and also avoiding the initiation of failure in the dam crest. Protections are also a good solution for cofferdams. If the overflow discharge is large and the dam is not temporary, it may be advisable to avoid overtopping. It should be noticed that the word overtopping implies water passing over the crest of the dam, which is different from water passing through a spillway, although on the dam body. In this case the flow is maintained far from the abutments and a stilling basin or ski jump is designed to properly return the flow to the river.

It is rather unusual to accept the possibility of overflow for a flood smaller than the design flood, in whatever way it may be defined, denying the possibility of designing the dam to resist overtopping. But it is a fact: overtopping occurs, and a conventional dam is not protected against that real threat. Of course, it is an option to implement dam protection measures against overtopping as additional safety measures, with an extra cost, besides the required freeboard. But now we are considering the dam protection techniques in the frame of a risk approach, trying to solve the problem and provide the required safety level in the most efficient way.

When maximum flood water level is below the crest elevation and overflow occurs only due to wind waves it is usually doubtful that the damage on the dam will provoke a significant incident and even less a catastrophic failure. Costly remedial measures are not usually justified in this case, although regulations generally do not make any difference regarding overtopping type. Relevant damage to the dam should not be expected either if the overtopping discharge and duration are very small, but again regulations do not make any difference regarding the importance of the overtopping event.

Soft or hard protections may be considered mainly depending on the dam typology and maximum overflow discharge. It is well known that earth and rockfill dams are more vulnerable to overtopping than concrete dams. Many of the highest dams in the world are rockfill dams, so let us consider first this typology. For a moderate overflow discharge a simple rip-rap of adequate stone size should be enough to avoid the particle dragging (Taylor 1991), but mass sliding may occur due to the pore pressure inside the downstream rockfill shell (Toledo 1997). It may be avoided, up to a certain overflow discharge, with a rockfill toe berm (Morán 2015), or by increasing the downstream slope up to a value that guaranties stability (Toledo and Morera 2015 a,b). Also the crest and shell-abutment contacts should be treated to avoid the initiation of failure there. For any kind of protection, a proper treatment of the crest, shell-abutment contacts, and dam toe is critical.

Different types of vegetative cover have been used in low height earthfill dams as a protection for small discharges. Geomembrane liners and geocells have also been used for moderate discharges (FEMA 2014). Reinforced rockfill and gabions have been designed, mainly for protecting cofferdams, not limited to a moderate overflow discharge (Shercliff 1990). Repairing may be necessary after important overflow episodes for this type of protection (Shackleford et al. 1970). Different types of precast concrete blocks allow the evacuation of significant overflow discharges, as the cable-tied and interlocking block systems. Precast wedge shape blocks (WSB) and conventional reinforced slabs that allow the evacuation of important overflow discharges, are generally used to build spillways on the embankment dam body. However, these solutions are also available as protection techniques if the contact between the dam body and the abutments, and also the dam toe are properly treated. RCC has been widely used in the USA, both as a protection and to build the spillway on the dam body, as a robust solution to overtopping that allows notable discharges.

As a summary, protection systems are available for any overflow discharge. Some unconventional systems may be very cost-effective compared to conventional solutions.

<u>How to reduce the damage downstream in dam failure scenario</u>

The last way to lower the risk generated by a dam is to reduce the economical and environmental damage and the number of casualties downstream. The ideal option is to avoid or limit the occupation of the potentially flooded areas in the case of dam failure, but it is usually not feasible in practice, or even reasonable given that the water may flood areas of the territory with a high economic value. Of course, it is always a good idea to limit the occupation of floodplains, but this can be quite difficult. The usual situation is that the dam owner finds the territory occupied, and has no way to act on that occupation.

Economical damage to most properties fixed to the ground is unavoidable. You cannot escape with your house or farm land in the case of dam failure. Although you can take your car or your farm tractor, the economical value of properties that you can carry while escaping is relatively modest, and better you should try to leave the flooding area as soon as possible. If the dam fails, the environmental damage is also unavoidable. However, the number of human casualties, which is the most negative consequence of a dam failure, may be highly reduced in different ways.

The development and implementation of an emergency plan may be very successful in saving human lives. For the emergency plan to be effective, it must be realistic in its assumptions, communication and coordination between the different parts implied must be guaranteed, and the threatened population must be trained. The last point is particularly delicate, given that the dam owner tends to prefer to keep the risk hidden, and training makes population more aware of the risk and may provoke a reaction against the dam. Although being aware of the risk and trained to properly react in the case of emergency will improve the safety level, and while this planning is generally well accepted in the case of fire, for example, there is a lack of that culture in the case of dam failure threat.

The state of the art in the understanding of the dam failure process, from the dam particular features, makes difficult the development of realistic emergency plans. For example, the assumptions about breach formation and failure process duration specified in regulations for rockfill dams are usually far from reality. It may have a relatively small effect on finally flooded areas for high capacity reservoirs, but the time for the failure hydrograph peak to reach the different affected areas may be quite different from that estimated in the emergency plan. The available time to evacuate population is usually greater than assumed, given that the failure process takes time, sometimes a considerable period, but it is often assumed that failure initiates just in the moment that water reach the dam crest and overtopping begins.

The period of time available for the evacuation of the population determines what you can do in the different areas that will be flooded, and a proper assessment of that time would help to plan the most efficient way to proceed. The failure process has a particularly important impact on the available time for evacuation in the reach of the river near the dam where, with the assumption of the emergency plans, there may be little time for warning, insufficient for the evacuation of the threatened population.

Protection measures against overtopping, even in the case that they do not finally avoid the dam failure, greatly increase the period of time available for evacuation, and so may be very effective to greatly reduce the number of casualties, or even avoid them. Taking into account that some of the protection techniques are very cost effective, it may be concluded that protection of the dam against overtopping may be advisable although a total effectiveness is not guaranteed, if combined with an emergency plan.

3.3. How do I Choose the Best Solution for Me?

Given a dam overtopping problem, there are plenty of possible solutions, although the best alternative for the dam owner depends essentially on his attitude and availability of budget to solve the problem. In the worst case, more frequent than desirable, the dam owner has no budget for solving the problem. Even in this extreme scenario the dam owner must choose between different alternatives: a) with an indolent or apathetic, and of course irresponsible, attitude, the dam owner may do nothing, and even ignore the importance of the problem; and, b) he may lower the reservoir level as necessary to limit the social risk (ethic position) or the economic risk (economist position) to an acceptable value, or in order to comply with the regulations (legalist position). As previously mentioned, the lowering of the reservoir level may have an important economic and social cost, because of the reduction of the reservoir functionality that would justify taking active measures if the budget for them was available.

Assuming that the dam owner has a given budget availability, two scenarios arise: it may be more than enough for the remedial measures needed or, it may be a limited and insufficient budget. Unfortunately, the second scenario is quite common. The dam owner with an ethic position chooses the less costly solution that lowers the social risk to an acceptable value. Economical, environmental and social costs must be considered when evaluating an alternative. If the available budget is not enough, he adopts the alternative that is feasible with that budget and allows the greatest reduction of the social risk. Although the dam owner cannot afford the optimal solution, investing the budget available may be justified to reduce the amount of reservoir level lowering needed to reach an acceptable value of the social risk.

Something similar may be said about dam owners with an economist or legalist position. They will try to implement the least costly alternative that solves their respective objectives but, if this is not possible, they will at least try to partially solve the problem with the budget available and move to a safer situation.

Another curious position is sometimes adopted by some dam owners when they implement an alternative more expensive than needed, and perhaps safer than demanded also, although not in all the cases. This attitude may be described as magnanimous, if the money comes from the dam owner activity and the benefit goes to him, or irresponsible if the money comes from the taxpayers, for example, or the benefit goes to a group of shareholders of a private company. At the opposite pole is the stingy position, also irresponsible, of the dam owner that spend less budget than available, and leaves the problem unsolved and with the same insufficient safety level.

When speaking about "available budget", we have been referring to an amount of money available to solve a dam overtopping problem, however the resource allocation may have already been done. Another problem, not treated here, is to prioritize the budget allocation for solving different problems of a group of dams of the same owner. Nevertheless, the same reasoning done for a dam, may be done for a group of dams, and the same archetypical attitudes may be found for the dam owner. It should be noticed that the attitudes considered are not exclusive. A dam owner may have an ethical concern about risk imposed to others and at the same time be concerned about the economical risk assumed by his company and desire to comply with regulations. In the case of conflict between different objectives, the dam owner will be forced to establish priorities.

Large and solvent companies, typically the electric companies, tend to exhibit a strong legalist and economist position, less commonly an ethic position, and really rarely a magnanimous-irresponsible position. Public institutions, sometimes owners of a large number of dams, are at risk of spending more budget than necessary, if the budget is available, or doing nothing, if the budget is not enough for developing conventional solutions, due to an extreme conservatism, and so incurring an irresponsible attitude. Both private and public institutions and companies with a weak economic capacity usually do nothing, unless there is a clear and imminent threat of a legal action against them.

Several key conditions must be met for the dam owner to reach his goals in the most efficient way when facing a dam overtopping problem, : a) A holistic approach, considering causes and consequences as close to reality as possible; b) Consider all the solutions available nowadays and sometimes take advantage of the experience gained in the unconventional alternatives; c) Clearly define your position, objectives and priorities as a dam owner; d) Incorporate optimizing methods into the design of the most promising alternatives, whenever possible, with the objective of reducing the risk, or complying with the regulations, and dealing with the restrictions reflecting the dam owner priorities.

4. SOLVING A DAM OVERTOPPING PROBLEM

As discussed before, a dam overtopping problem must be firstly diagnosed and, if needed, can be solved in many different ways. In the absence of inexhaustible economical resources, which is the most probable scenario, the efficiency when applying the available budget is essential to reach the maximum feasible safety level. An efficient budget appropriation requires to remain as close to reality as feasible. On the other hand, when dealing with safety for human lives, it is forced to remain on the safe side. Therefore, a reasonable general criterion for dealing with hydrological safety would be to remain as close to the real conditions of the problem, but always on the safe side. We should be aware that accepting hypothesis on the safe side further from the real conditions than feasible take us away from the most efficient solution, subtracts budget for solving other safety problems and lead us to a lower general safety level.

An ideal general process may be defined, according to all the previously exposed ideas, to diagnose and solve a dam safety problem. It is the task of the team in charge of the study to assess and decide which parts of the general process are significant or negligible, feasible or not in a particular case. A probabilistic approach is suitable if feasible for every study of the process. For existing dams, any dam overtopping analyses has two phases: diagnoses and, if a problem is identified, solution.

The objective of the *diagnosis stage* is to assess the overtopping probability, the dam failure probability and the damage to properties and environment and casualties, remaining as close to real conditions as feasible, on the safe side. That should allow the most accurate estimation of the risk possible, again on the safe side. Looking at the *river basin*, the flood generation and the production and transport of solids to the reservoir should be firstly investigated.

Flood generation: A set of floods should be defined with different return periods and so probability of occurrence. Seasonal and even monthly distribution of the floods should be investigated, given that the flood occurrence must be combined with the reservoir water level to determine the overtopping probability. The quality of this study has a notable impact on the risk assessment goodness.

Solid production of the river basin: If the space occupied in the reservoir by the deposition of these solid particles is forecasted to be important and may have a not negligible effect on the hydrological safety, then the most realistic assessment of the solid production should be tried.

The role of the *reservoir* is considered through the study of the reservoir regulation, flood routing through the reservoir, landslide danger and wave generation.

Reservoir regulation: The water level elevation when a flood reach the reservoir may have a notable impact on the danger of overtopping, so significant effort should be devoted to assess the evolution of the water level elevation over the year. Results of the *study of solid production of the river basin* are an input for this regulation study. It should be noticed that annual overtopping probability can depend on the space of the reservoir occupied by deposited solid particles. Therefore, that probability becomes higher over the operation period, and the risk may be initially acceptable, but become unacceptable due to solid deposition. Of course, the role of solid deposition is secondary or even negligible in many cases. Also changes in the water demand or operation criteria induce a change in the water level evolution, and should be taken into consideration if this effect is considered significant.

Flood routing through the reservoir: The result is a set of overflow hydrographs with an associated probability. Every flood should be routed considering different reservoir levels with different associated probabilities. Therefore, the result of the reservoir regulation is an input for the flood routing study. The probability of every resulting overflow hydrograph is the product of the probability of the flood and that of the reservoir level. Current computation capabilities allow the combination of the set of flood hydrographs and reservoir levels to obtain a set of overflow hydrographs with the correspondent probability associated.

Landslide danger: This study is of a geotechnical nature, and a probabilistic approach is relatively easy to implement if an appropriate number of data is available. The result of this study is the probable sliding of a certain mass of soil or rock into the reservoir water. The landslide is associated to a rapid descent of water in the reservoir to a certain elevation, which probability should also be investigated to estimate the most realistic probability of the landslide.

Wave generation: It may be due to wind, a seismic episode or a landslide. Waves may be dangerous only if the water level is high, near the maximum storage water level. Therefore, the probability of different water levels should be considered in order to assess different overflow scenarios due to waves. The probability of the wind, the seismic episode or the landslide should be combined with the water level probability to estimate the wave overflow probability.

At this stage of the diagnosis study a set of overflow hydrographs with a different probability associated should be available. The goal of the next stage is to estimate, for every overflow hydrograph, the failure probability and, if fail occurs, the correspondent failure hydrograph.

Dam failure process: It is a critical issue for several reasons. Even the most vulnerable dams resist overtopping without failure until a certain overflow discharge and duration are exceeded, so the probability of dam failure and the associated risk may be close to cero for minor overtopping episodes. Overflow does not automatically imply dam failure. Assessing the failure threshold, if feasible, may be quite useful for avoiding costly expenses in unnecessary remedial measures. Additionally, as mentioned above, the initiation of failure, failure duration and failure hydrograph peak and shape, depend on the failure process, and so the flooded areas and travel time to reach every affected zone. There is at present a rather limited capability to model the failure process, but we must be aware of the notable impact of that uncertainty on the resulting risk estimation, and try to get as close as possible to real failure conditions for every particular dam.

Flooded areas and casualties danger: The topographical configuration, roughness and other hydraulic conditioning features of the *riverbed*, as the existence of bridges or other obstacles, downstream of the dam, should be properly defined before modeling the failure hydrographs routing. We use the plural because at this stage a set of failure hydrographs with different probability associated should be available. For every failure hydrograph, a map of flooded areas and also a map of zones of potential casualties, taking into account depth and velocity of the flow, can be prepared. Casualties are potential because a properly designed and managed emergency plan may avoid a great number of casualties. The accuracy of the topographical map should be adequate for the expected depth of water, ground slope and territory occupation.

Damage to properties and environment, casualties and associated costs: Damage to properties and environment, and associated costs, correspondent to a failure hydrograph may be inferred directly from the map of flooded areas without a significant lost of precision. However, for an estimation of the number of casualties as close to reality as feasible, several factors should be taken into consideration: dam failure duration until the water stored in the reservoir, and not flood flow, is released; travel time of the failure hydrograph to every inhabited flooded area; the availability of an emergency plan and, if so, the expected effectiveness depending on the plan quality and training, and the easiness to escape from the flood according to the site conditions. It is clear that these factors do greatly influence the number of casualties, and ignoring them may lead to a notable overestimation of the real risk. Additionally, implementing an emergency plan implies a cost, higher for a better plan, including training. It should be justified by a quantified risk reduction. It is important to notice that the objective is to assess the damage and casualties *due to the dam failure*, so it is the incremental damage over the one that the flood would have caused if the dam did not exist. Therefore, damage and casualties due to the flood in the absence of the dam must also be assessed. It is also instructive information for the population downstream, to know the damage and casualties that the dam is avoiding in the most probable scenario of good dam behavior.

The risk: It is the glue that holds together the causes and consequences of a dam overtopping problem, and forces a holistic view. If we remained as close to the real conditions, on the safe side, as feasible over the whole process, the result is the best estimation of the overtopping probability, of the dam failure (assumed overtopping), and of the damage and casualties (assumed dam failure), and therefore the best estimation of the real risk, on the safe side. The concept of potential risk, based on potential casualties, on an envelope of the most unfavorable peak flow discharges due to dam failure all over the world, on an almost immediate failure, considering always the reservoir full when the flood reach the reservoir... is an enemy of an efficient allowance of economic resources and, given a set of dams, leads to a lower overall safety level, unless an unlimited budget is available. Managing the concept of potential risk often leads to paralysis or wasting money on solving problems that do not exist, because they are not a real problem.

The dam owner will be able to decide in an informed way if there is really a dam overtopping problem from the estimation of the social, economical or legal risks, depending on his own sensibility and perspective. If the conclusion of the dam owner is that the risk is excessive, according to economical, social, or legal criteria, and a solution is needed, a study of alternatives must be addressed.

Qualitative analysis of a great number of alternatives: Firstly all structural and non structural, conventional and unconventional solutions should be considered to reduce the overtopping probability, the dam failure probability or the damage and number of casualties, and so the real risk. As discussed before, there is a great number of possible alternatives, and a mainly qualitative systematic analyses of advantages and handicaps of every solution must be addressed. As a result of this first stage, a small number of promising alternatives for the particular case can be selected for a deeper quantitative comparison.

Quantitative study of the few selected alternatives: The most promising solutions must be defined with a proper degree of accuracy to make a valid comparison. For the comparison to be meaningful the desired value for the risk or the available budget should remain constant for all the alternatives. Solutions with different cost and risk value are difficult to compare. However, if the risk value remains constant, the cheaper solution is preferable, or the safer alternative, with the lowest risk value, for a given available budget. Therefore an aim should be defined at the beginning of the study: minimum cost for a given risk value, or minimum risk, maximum safety level, for a given available budget. The selected aim can be achieved by trial and error, for every alternative, or preferably by some optimization method, if possible. For that, the solution should be defined by a manageable set of parameters and the calculations involved be low time consuming to allow many repetitions, with different values of the parameters involved. This requirement may force the use of simplified models for the optimization stage. The perspective of the dam owner is included in the process by means of the type of risk considered when defining the objective. Of course, the objective could be to guarantee a certain prescribed freeboard, irrespective of the associated risk. The results of this study are the base for the dam owner to take an informed decision about the most appropriate solution to the problem.

Detailed design of the selected solution: Once the dam owner selects an alternative, founded on the comparison of optimized solutions with the same risk or cost, the chosen alternative must be designed with detail and a construction project must be developed.

5. CONCLUSIONS

The main ideas to highlight are:

- Dam overtopping is a complex problem with many faces and relations, and looking just at a part of the elements involved makes difficult to take the most convenient decision.
- A systemic holistic approach, however, allows the consideration of all the factors and links between them, as a basis for an informed decision taking.
- Causes (flood generation, water level in the reservoir...) and consequences (dam failure process, damage to properties and environment, casualties...) of dam overtopping should be considered as close to the real conditions as feasible, remaining on the safe side, in order to make an efficient allowance of the available economical resources, and so reach the highest general safety level.
- The concept of risk links causes and consequences of dam overtopping, and this way leads to a desirable holistic approach.
- On the contrary, an approach based on a fixed required freeboard simplifies the overtopping problem, breaks the link between causes and consequences, and makes impossible a rational informed decision taking.
- The weakness of the risk approach is the somehow arbitrary or at least subjective estimation of some of the probabilities involved. While the probability of dam overtopping, and the damage to the properties and casualties may be reasonably estimated, based on particular data of the case, there is much to improve in the dam failure probability estimation. An effort should be made for developing objective methods based on the particular features of the dam.
- The perspective and position of any stakeholder, and particularly that of the dam owner, may be objectively included in the analysis through the specific definition adopted for the damage when estimating the risk.
- Discerning if there is really a dam overtopping problem (not just a legal problem, because the freeboard is lower than required) forces any stakeholder to analyze the real (not potential) conditions of all the elements involved in order to have a better estimate of the dam failure probability, and to assume a position regarding the definition of the damage, that should also be estimated as close to the reality as possible.
- Many different structural and non structural measures may be taken to increase the safety level, dam protection against overtopping among them. It is essential to consider all of them in a first stage for efficiently solving a dam overtopping problem.
- Whenever feasible, including optimization techniques while roughly designing the most promising alternatives guarantee that the design responds to clear objectives, and that comparison is between the best design for every alternative, and is fair.
- When comparing different promising alternatives, it is essential to maintain constant for all of them the cost or the risk, depending on the restrictions of the particular case. Solutions with different cost and risk are not easy to compare in a fair and objective way.

We come from the *mythological era* of dam overtopping, when the only thing we knew about it was that overtopping, like a devastating Greek God, causes the dam failure and therefore it must be avoided by all the available means. We are going towards a *rational era* of dam overtopping, when we will know how to manage this threat in the most rational and efficient way. Nowadays we are halfway, but we must work to face the overtopping problem without fear and with confidence on properly founded solutions and methods.

6. ACKNOWLEDGEMENTS

My deepest gratitude to the many colleagues and friends with whom I had the opportunity to extensively discuss so different issues related to overtopping, with an special mention to Alfonso Álvarez, who many years ago opened my eyes to this fascinating subject.

This paper was made possible with funding support from de *Ministerio de Educación, Cultura y Deporte* of Spain over the last years through the research projects XPRES (BIA2007-68120-C03-021), and eDAMS (BIA-2010-21350-C03-03) and also with funding support from the *Ministerio de Economía y Competitividad* of Spain through the research project HIRMA (RTC-2016-4967-5).

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