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HOLISTIC APPROACH TO SELECTION OF DESIGN FLOODS FOR LARGE DAMS

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HOLISTIC APPROACH TO SELECTION OF DESIGN FLOODS FOR LARGE DAMS

By Kamran Emami[1],

Abstract:

This paper describes the crucial importance of balanced and rational criteria for selection of the design flood for large dams in developing countries (where the main risk from dam failure may be from floods) and to the world as a whole from the viewpoint of both safety and economy. This is followed by a summary of key problems that arise in developing and establishing such criteria. Solution to these problems will above all require a holistic approach and dependence on risk based approaches and recognition of effectiveness and adaptability of nonstructural risk reduction measures. When plausible threats are examined with a broad view of possible ways to detect problems or warn the downstream population, then risk reduction may be accomplished with a holistic, balanced, and, therefore, cost-effective approach. Accordingly it appears that in many developing countries faced with grave social and economic challenges, the structural safety should be determined by Economic Risk Analysis. Minimizing the residual risk should be achieved by efficient nonstructural approaches and by increased structural resistance by low cost means (such as overtopping protection or unlined spillways). Considering the dynamics of numerous factors involved in dam safety, and the potential enhanced use and effectiveness of nonstructural options in coming years, the paper concludes that the overall risk accepted should be based on a shorter time step rather than 100 years commonly assumed for the life cycle of a dam (incremental risk acceptance).

Key words: Hydrological safety, design flood, dam safety, criteria, risk analysis, spillway design.

1. Introduction

The selection of the design criteria is perhaps the most important activity in the process of the design and construction of a dam (ICOLD, 1988). Since the overtopping of 14 m high Sadd Kafra in Egypt 4600 years ago, floods have steadily posed the highest risk to dams and the criteria for selection of the design flood has always been debatable. Magnitude of the chosen design flood has probably more impact on dam safety than any other hydrologic parameter. There has been a definable trend towards using large, more remote design floods for dams whose failure would pose a threat to life. Three generations of criteria have been recognized (Berga, 1998):

The first generation criteria were based on empirical and general considerations; applicable to any dam and in any situation, without taking into account its size, typology, volume of the reservoir, nor the downstream hazard.

The second-generation criteria are based, in general, on the Dam Hazard Classification. Although there exists a wide variety of formulations for dam classification, in the majority of cases the tendency is towards taking downstream hazard as the basic and fundamental criteria. Design flood and safety check flood have been increasingly used in the second-generation criteria. The design flood standards used in different countries lead to very different requirements from the 200-years flood in Japan and Poland to the PMF in the U.S. and India.

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The second-generation criteria used from 1980's supposed an important and positive change in the field of hydrological safety, but have been subjected to various criticisms. The most important of these criticisms are the high cost and over-conservatism of PMF criteria, the need for incremental evaluation of damages downstream and the qualitative nature of the classifications. (Berga, 1998)

The third generation criteria use risk-based assessment. Risk analysis is the systematic development of input to aid in decision-making under uncertainty that is ubiquitous in the life cycle of dams, perhaps more than any other civil structure. Risk assessment can be used despite the individuality of each dam. A cause of failure is not an easily predictable event, nor is the consequence an easily predictable result. Low probabilities of extreme events can hardly be defended by predictive concepts and failure consequences tend to depend on human actions, which are difficult to predict too. Because of this high degree of uncertainty, risk analysis is an appropriate tool. It is a sequential and conceptually concise approach, which gives a stepwise insight into an equally sequential risk development. (Kreuzer, 2000). By risk assessment of different failure mechanisms, a balanced safety can be approached.

It is observed that the evaluation of three generations of the design flood criteria is closely associated with increased holistic thinking.

2. ICOLD Recommendations

After the 16th international congress on large dams in which Question 63 discussed hydrological safety, was held in 1988, ICOLD Bulletin 82 was published on "Selection of Design Flood". The main recommendations of the Bulletin are as follows (ICOLD, 1992):

- Inherent uncertainties associated with determination of extreme floods by various methods should be recognized. For major projects a combination of various methods should be employed.
- Utilizing a design flood and a safety check flood is recommended.
- A large number of dams do not threaten human lives, and, in such situations, Economic Risk Analysis can be an effective means for determining the design flood. Otherwise when absolute safety is demanded, the economical analysis appears to be an unattainable ideal.
- Reliability of data, downstream hazard, public opinion, dam and spillway type, freeboard, storage for routing, and the presence of an upstream or downstream dam can affect the selection of the design flood.
- Effective safety is usually much larger than the one associated with the design flood.
- Seasonal varying storage of the reservoir can account for seasonal variation of the design flood.
- The exceptional circumstances causing extreme floods and the associated widespread catastrophic damages must be emphasized.
- Studies should be initiated to improve existing knowledge in hydrology and hydrometeorology.
- In the final analysis, human life is of great value and our most important asset.

3. Economic Risk Analysis

Recommendations have been made for the use of Economic Risk Analysis to select a design flood of least total cost. The process of formally determining an optimum design flood through risk analysis is well established. The use of the process for two dams in California was demonstrated for the case when loss of life would not be expected (Cassidy, 1988). A 1973 report published by ASCE recommended a rational analysis for determination of an optimum design flood when damages due to failure of a dam include loss of life (ASCE, 1973). On the other hand, to provide a lesser design flood than PMF would likely make the designer legally and financially liable should dam failure occur due to an inadequate spillway capacity. Many engineers will not take such risk with their professional reputation and financial future. Consequently engineers' reluctance along with near outrage on the part of sociologists and humanists over the use of "monetary values for loss of life" resulted in rejection of the 1973 proposal (Cassidy, 1993). Ever since, thousands of costly spillways with $\Delta B/\Delta C$ of less than 0.1 (See Appendix 1), have been constructed all over the world especially in developing countries. This paper presents information that illustrates that this trend provides little incremental safety and has required huge investment while more effective and low-cost alternatives are feasible. It should be pointed out that acceptable and appropriate levels of risk are critical issues that must be dealt with based on input from communities and regulatory authorities, and it is not the responsibility of the engineers. Considerable deliberation within the profession and society is needed to pay proper attention to acceptable risk. While there is no such thing as zero risk, people and organizations usually have some limit to the level of risk they are willing to accept. This limit is often unstated and among the general public rarely stated in precise quantitative terms. Nevertheless, it is the limit to risk acceptability that must be at the heart of any risk philosophy. Figure (1) shows only a representative sample of the most usual factors but it clearly illustrates the need for holistic approach for determination of the socially acceptable risk (SAR) which is the basis for selection of the design flood. In this regard, engineers could give advice, but the final decision about the acceptable risk lay with politicians.

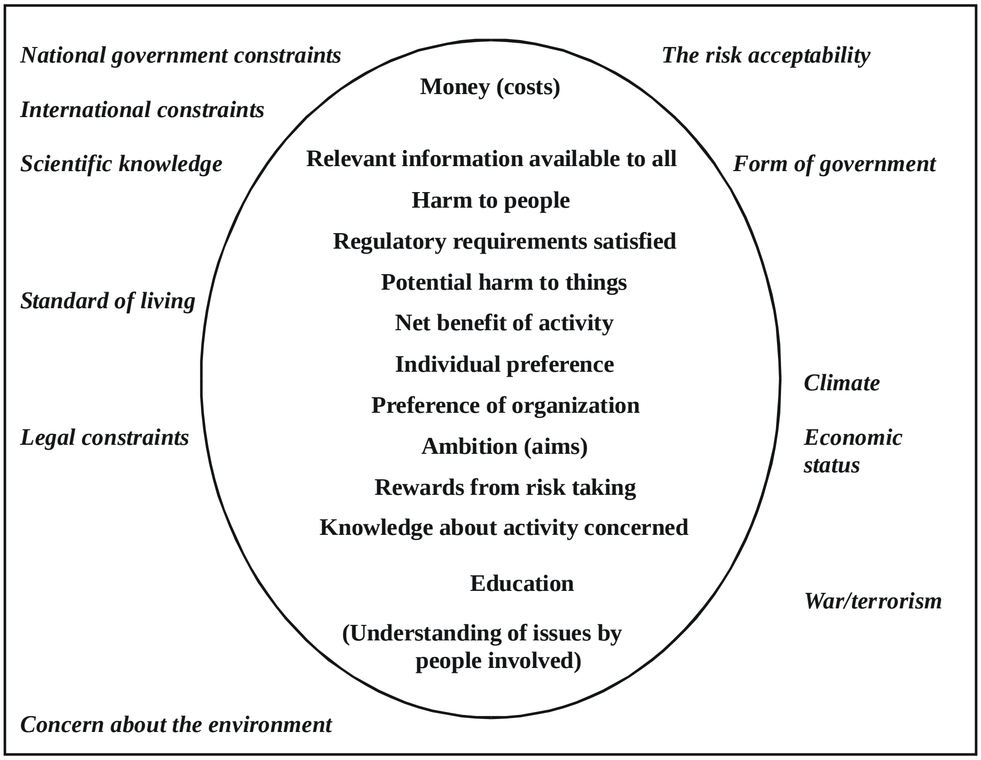

Figure 1: A specific risk acceptability set

4. Uncertainties of Determination of Extreme Floods

Although the study of hydrology has advanced greatly over the three past decades, it is far from an exact science; so many variables influence the timing and quantity of runoff that it is unlikely that hydrology will ever become a precise science in the foreseeable future. The shear magnitude of our current ability to analyze data is sometimes mistaken as an increase in accuracy (Cassidy, 1993). This is best illustrated by a few examples:

- In Switzerland, despite long and reliable records of precipitation and discharge, the determination of the PMF is considered highly problematic and 1.5 times the 1000-years flood is used for the safety check flood (Biedermann, et al., 1988).
- As a consequence of high precipitation in 1978 (return periods approximately 500 years) thousands of trees were uprooted in the catchment area of Palagnedra reservoir in Switzerland and were transported to Melezza river. The trees blocked the flow openings at several bridges that had relatively small pier spacing. Due to successive failure of these kinds of “timber dams”, a flood occurred at Palagnedra dam with a peak flow of at least 1.5 times of the thousand years flood (Biedermann, et al., 1988).
- In 1963 a huge rockslide into the reservoir of Vaiont dam in Italy, caused a wave that overtopped the dam to a height of 122 m and killed 2300 people in downstream. The experience indicated that in some cases the wave resulted from a landslide with a probability of 10^{-3} may be much higher than the one associated with the PMF (Janson, 1983).

- In India from 62 dams studied by dam safety authorities, 33 dams were recognized as hydrologically unsafe with up to 650% increase in the design flood (Sharma, et al., 1997).
- The 1965 flood event in Plum Creek, Colorado, was about 22 times larger than what had been experienced in the previous 23 years of operation of Louviers gauge (ICOLD, 1992).
- According to U.S. Bureau of Reclamation, use of PMF as the criterion was, by experience, to select a standard which had a history of change, usually yielding larger PMF's every decade or two (Parrett, 1993).

This inherent uncertainty is the main reason for risk aversion of many dam engineers and explains why they go to extremes to ensure "absolute safety" which is an unattainable ideal. Actually it is the heavy of a burden to be placed on the engineers. In practice the criteria should reflect the desired level of safety by the countries as a whole. Still not only the risk aversion tendency is more or less incorporated in many of the established criteria, but also designers seldom exercise any freedom given in the criteria especially in developing countries (Sharma, et al., 1998). When there are no formal criteria in a country, the tendency is to go for the most conservative criteria from other countries. Even in these conditions the nature of the selected criteria is not exactly practiced. For example, for many concrete dams designed in Iran, safety check flood is assumed to be equivalent to a flood overtopping the dam to height of 1.5 m above the crest. Actually the structure is far from imminent failure that is the inherent feature of safety check flood. In short, rational criteria are absent where they are needed most, in the developing countries constructing most of the world dams.

5. Does Probability of Loss of Life Justify $\Delta B/\Delta C$ <0.1 for Spillways?

Determination of Benefit to Cost ratio for the spillways is not customary, but if overall safety of the structure is considered, for many dams, especially the concrete ones, $\Delta B/\Delta C$ would be much smaller than unity (An example is given in appendix 1). It is not surprising considering the fact that economy had not been the basis of determination of the design flood in the first place because of the probability of loss of life. But does probability of loss of life justify $\Delta B/\Delta C<0.1$ for the spillway? Solution of the loss of life versus economy problem will above all require a holistic approach as follows:

1) Total number of people that have died as the results of dam breaks in the world in the past 130 years is about 10000. About 7000 people died in only 3 dam failure disasters: Vaiont (Italy, 1963), South Fork (United Sates 1889) and Macchu (India 1979). The number of people that have died in dam breaks in 1.3 century equals to the worldwide deaths in:

   - 6 hours from water borne diseases;
   - 4 days from car accidents;
   - 5 months from floods;
   - 3 months from natural disasters;
   - 8 years in air crashes.

   Undoubtedly in comparison to other sources, dams do not present major risk to the public especially if the number of deaths is converted to "present day situations" (i.e. the failure of South Fork dam in 2003 would probably cause lesser number of deaths than the one that occurred in 1889). Increased population downstream calls for enhanced safety of dams. Respect for human lives mandates using the limited resources in the most effective way to reduce risk to life. Based on statistics of the fatalities from human activities, the concept of socially acceptable risk (SAR) was developed. It addresses the society's need to quantify involuntary risk and it is a mean to assign importance to life loss without resorting to monetary units. SAR is generally depicted in so-called F/N diagrams, with F generally the cumulative failure probabilities of scenarios with loss of life, and N the number of lives lost in these scenarios. Presently F/N charts are used in Australia, US, South Africa, and the Netherlands. These charts include criteria for loss of life up to 1000 and 10000 (Kreuzer, 2000). In fact the strategy should be to compare loss of life to loss of life instead of assigning units. Iran serves as an illustrating example:

- About 20000 people die in road accidents in Iran annually. This poses a risk of about $3*10^{-4}$ to every Iranian and much more to those who travel by land regularly. Some 40000 people died in Manjil earthquake in 1990 that is the fifth worst catastrophe in the world (1970-1996). Even in the capital Tehran, a disastrous earthquake with a return period of a few hundred years, would kill half a million people. In this situation should the government invest in large spillways with very poor economic parameters or build new roads that not only are economically justified but also would save lives of many people? While the risk of dying from road accidents is about $3*10^{-4}$, is spending huge sums of money on spillways with the goal of reducing risk to, say 10^{-8} mean much increase in safety for the people of the country?

2) Risk is the product of a probability of recurrence and a consequence value. High-probability events may render higher risk than low-probability ones. The risk of a 100-year flood inundating 50% of a city is 500 times of a 10^{-5} event (PMF or dam break) inundating the whole city (assuming comparable damage to inundated area). Often, the risk protection achieved during natural flooding far outweighs the risk imposed by the impoundment of the reservoir. Accordingly in most cases flood management of 50-200 years floods would be the first priority and the rule curves and forecasting models used can also reduce the design flood peaks. Even for the dam itself, "uncommon" or high-probability primary failure causes may render the highest risk. Examples are clogging of spillway openings at a moderate-frequency flood, blocked dam access during a medium flood to impede gate operation, any kind of human errors, e.g. increasing trends of leakage at a dam with deficient surveillance (unobserved development of critical conditions). A case of risk analysis for Alouette dam in British Columbia demonstrated that the failure probability contribution derived from a flood exceeding one in 250 year frequency is 12 times the probability from floods 100-130% of PMF (Nielson, et al., 1994).

3) A balanced approach to safety considering different modes of failures and loadings requires that differences in criteria for different failure modes should be limited. In practice the probability of hydrological failure should not be many times smaller than the overall probability of dam failure because the increased effort to minimize the hydrological risk would not mean increased safety for the dam itself. This would limit the conservatism that rationally can be applied in hydrological safety. For example the risk analysis performed in gravity section of Three Gorges dam in China gives the probability of sliding at the interface of rock and concrete in the range of $2*10^{-5}$ to $5*10^{-5}$ (FU, 2000). This range may serve as an approximate upper limit to the conservatism that can be applied for each failure mechanism.

4) A balanced safety criteria should consider different phases of the project (construction, first impoundment and operation). If loss of life is the critical governing criteria, PMF may need to be used for design of the diversion system for the cases that poses a threat to the life. In 1981, Oros Dam in Brazil failed as a result of a flood during construction. Because the failure could be predicted days in advance, it was possible to warn a population of 100,000 people in a large area and to prevent major loss of life. The Guhuo dam failure (China, 1993) indicated that even failure of a 3 MCM reservoir could cause 350 deaths (ICOLD, 2001). The first impoundment has proven to be particularly dangerous. The consequences of a dam failure in the last year of construction is close to that of the completed dam, but normally the capacity of the spillway is much smaller than the final design and consequently the hydrological risk to the downstream in the last year of construction may actually be more than the risk imposed by the dam during it's useful life especially if the client is eager for the early impoundment of the reservoir. It appears that many engineers are reluctant to ask a certain risk during operation while they are willing to accept a larger risk during construction (Fahlbusch, 1999).

5) According to the ICOLD Bulletin No. 73 (1989), at most sites the risk of fatal accidents to the workmen during construction is greater than the risk from the dam failure and statistically, therefore, failure of recently built dams causes much less than one victim per dam (ICOLD, 1992b). Accordingly an uneconomical spillway constructed solely on the basis of saving lives in practice is likely to increase the risk to life instead of reducing it. Furthermore large projects would invariably cause many fatal accidents during construction (for example Tarbela construction resulted in 117 deaths (ICOLD, 1992b)). If the risk of loss of life is the main criteria, many dam projects should never be constructed.

6) If today's emergency plannings and communications had been available, there might have greatly reduced the loss of life during the South Fork failure (United States 1889), the Machu failure (India 1979), and the Guhuo failure (China, 1993) (ICOLD, 2001). A forewarning time of 3 to 5 hours in many cases may minimize the risk of loss of life due to failure (Parrett, 1993) and this is the main basis of the criteria for selection of the design flood in Thailand (McClung, et al., 2000). Good emergency planning might be reasonably expected to make the difference between catastrophic loss of life and minimal loss of life for the same event (ICOLD, 2001).

7) Increased spillway capacity for accommodating PMF may mean reduced routing effect on smaller floods that in fact pose most of the flood risk to the downstream. According to the U.S. Bureau of Reclamation, if a decision to modify an existing dam for a new, larger PMF is not done with care, the protection provided to the downstream population for the more likely to occur floods may be reduced (Parrett, 1993).

8) The illusion of complete protection may in practice increase the vulnerability. Titanic experience is a good example. Too much confidence in the "unsinkable" ship safety resulted in inadequate number of boats for emergency and 1500 lives were lost.

9) 52 and 84 percent of dam failures occurred in first 5 and 20 years of the operation (ICOLD, 1995). For other failure mechanisms more risk in the first years of operation is expected. But considering the stochastic nature of floods, it is expected that roughly 5 and 20 percent of the failures occur in the first 5 and 20 years of operation respectively. The differences of expected and observed values are very large and it can be concluded that most of the dam failures due to overtopping occurred during floods much smaller than PMF or 10000-years flood. So it may be concluded that most of the overtopping failures were resulted from blunders in design, operation and crisis management. This is

supported by the fact that none of the dams higher than 100 meter has been overtopped by natural floods apparently due to the fact that larger dams are designed and operated more carefully.

10) Extreme effort to reduce risk may make the project infeasible and require society to forego the benefits of the project. On the other hand, extreme conservatism may not be as effective as it looks because there is always a residual risk from other failure mechanisms such as reservoir landslides similar to the Vaiont disaster in Italy in 1963.

6. Non-Structural Risk Reduction

In 1990's, the non-structural approaches to flood management were established in many countries and sole dependence on structural methods for flood mitigation was regarded as ineffective. (ICID, 1999). The same trend is developing in dam engineering. The Committee on Costs of ICOLD presented a paper entitled "Nonstructural risk reduction measures; Benefits and costs for Dams" emphasizing the capabilities and cost-effectiveness of nonstructural measures for reducing the risk of dams in Beijing conference in 2000. The committee has published a bulletin on the subject in 2001. According to the bulletin those responsible for dams and their operations should continually search for ways to minimize risk because of the great consequences of dam failure. There is also a responsibility to provide and operate storage facilities in an economical manner. It may be possible to achieve desirable risk reduction through application of nonstructural measures as less costly alternatives to structural modifications. The bulletin focuses on risk analysis, training, structural monitoring, emergency planning, early warning system, and modified operation (ICOLD, 2001).

7. Holistic Design 0f Adaptive Hydraulic Structures

In 1998 a doctoral dissertation entitled 'holistic design of adaptive hydraulic structures' was presented at Sharif University of Technology in Iran (Emami, 1998). The dissertation emphasizes the vital importance of reducing construction time and costs of hydraulic structures in solving the most important problems of humanity; water crisis, sustainable development and flood mitigation in 21st century (Frederiksen, 1996). In this context, inherent uncertainties of water engineering in a non-stationary climate and hydrosystems have been highlighted. The main principles of holistic design are to:

- Ensure a flexible and adaptive design in view of hydrosystem changes and the inherent uncertainties of water engineering.
- Establish the interdependence of hardware (structures) and software (management and knowledge) in design.
- Adapt to the stochastic nature of river flow by integration of seasonal characteristics and river forecasting.
- Design hydraulic structures to adapt to extreme events far larger than design parameters and remain inherently safe (structural ductility).
- Base the design on comprehensive management and flexibility.
- Enhance safety by 'designing' crisis management preceding the events and in real time for the structure and downstream population centers.
- Monitor hydrosystem and structures on a continuous basis.

The interdependence of structural and non-structural options in design is established in order to achieve an optimum configuration. The conclusions of the bulletin of the Cost

Committee on "Nonstructural risk reduction measures" are quite similar to those of the holistic design. The main difference is that the Committee of cost has focused on application of nonstructural risk reduction measures in constructed dams while holistic design calls for integration of structural and nonstructural measures in design in addition to the operation. It is interesting to note that the holistic design is applicable for flood management structures (such as levees) in addition to dams.

To implement the tactics of holistic design of dams, expert system KURIT was developed based on worldwide experience (Kurit is a 60 m high dam near Tabas, Iran which had been the highest dam in world for 550 years till early 20th century). KURIT is designed to prevent overlooking of fundamental principles of holistic design of hydraulic structures. KURIT presents strategies and guidelines for enhancing dam safety, optimum reservoir sizing selection of the design flood and initial reservoir elevation and reducing the conflicts in multi-purposed projects.

8. Initial reservoir elevation

The design flood is generally assumed to flow into an already full reservoir spilling long term average daily inflow combined with the stipulation for conserving freeboard with a gate assumed to be jammed shut during a routing of the design flood. This represents a very high degree of protection, even if not very precisely defined. (ICOLD, 1992a). In practice this degree of protection is dependent on:

- Purpose of the dam;
- Seasonal flood characteristics of the river;
- Flood hydrograph: volume and peak;
- Expertise of the dam manager and operators;
- Effectiveness of flood warning system;
- Reservoir volume;
- Seasonal rule curves;
- Long-term discharge forecasts;
- Discharge facilities to draw down the reservoir;
- Importance of the management of the floods in the downstream.

Risk-based approaches can be utilized to estimate the extent to which a reservoir would retard and attenuate the design flood and it is one of the merits of the third generation criteria compared to the previous generations.

A study on seasonal flood characteristics of 50 rivers in Iran, grouped them as follows:

- Group A: In most of the Iranian rivers, the largest of floods occur in spring.
- Group B: For the rivers located in the south of the country, the largest of floods occur from mid autumn to mid winter.
- Group C: There are a few rivers in North and south of the country where the summer floods are the most critical ones.

As a result of the low precipitation in the country, generally the volume of the reservoir are larger than the annual run off the river. For the rivers of group A, using snow cover reservoir drawdown can be effectively used to free flood control volume for storage of the spring floods. For the rivers of Group B and C, a large part of the reservoir would be available for storage of the floods as the result of the irrigation demand and little rainfall in summer and early autumn (Emami, 1998).

The experiences of routing of extreme floods through the cascade reservoirs of Volga River have shown that with proper forecasting of flood characteristics up to 40 percent in reduction of the peak flow of the 100 years flood in the cascade reservoir was achieved in 1979 (Asarin, 1998).

9. Structural Ductility

According to the holistic design, in view of uncertainties and economical considerations, during extreme events far larger than design parameters, the structures should be "designed" to enhance ductility and safety. Overtopping protection by RCC is an illustrating example (Hansen, et al., 1999). A protected earth dam with a 1 in 100 years flood spillway may be substantially safer than an earth dam with PMF spillway. Based on the worldwide experiences, overtopping resistance of concrete dams has greatly contributed to their proven hydrological safety.

It is interesting to note that most of the overtopping failures have been in small dams and overtopping protection is most effective for these dams. The experiences of overtopping protection of 70 old dams by RCC overlays in United States are very encouraging. Unfortunately the great potential of the method for enhancing safety of new earth dams has not been fully recognized. Finally the integration of non-structural options and structural ductility could enhance the safety of the dam and the downstream considerably. This is one of the most important merits of the holistic design of hydraulic structures.

10. Incremental Risk Acceptance

Comprehensive rating of risk acceptability is based on risk of failure in the life of the project (Checken, et al., 1998). Many historical dams have been in operation for more than 2000 years (3600 years for Mala'a dam in Egypt)(Schnitter, 1994). So life cycle of a dam may be substantially longer than 50 or 100 years normally assumed especially if sustainable development principles are incorporated in design.

Considering the dynamics of numerous factors involved in dam safety, including inherent uncertainties of the design floods and development of the downstream in one hand and enhanced effectiveness of non-structural options in coming years on the other, the paper concludes that the overall risk accepted should be based on shorter time step rather than 100 years assumed for the life of the dam (for example 10 or 20 years). For example for a large project a total risk of 10^{-3} may be accepted during its life cycle. If a time step of 20 years is used, it means that the annual acceptable risk would be five times the one associated with the life cycle of 100 years. In 20 years, based on the latest information and technologies, the most appropriate options for minimizing the overall risk would be adopted. In this context, managing a dam is very similar to raising a child (Iarossi, 1993). By breaking the life of the dam and consequently the associated risk into parts, the responsibility of dam safety would be shared by the designer and the operation management through continuous design and management, which is the key to increased safety and reduced cost.

In 1997 the American scientists for the first time in the history of mankind predicted the floods in California six months in advance. These predictions were based on ESNO in the Pacific Ocean. In the last 5 years Internet has revolutionized the natural disaster management. In this context, the effectiveness of the non-structural options may be enhanced beyond imaginations and expectations. The nonstructural alternatives may be the most effective and feasible means that mankind can use in view of the challenges of 21st century. The problems of hydrological safety of dams are very complex, nonlinear and dynamic and to solve them, we need a holistic approach and incremental risk acceptance above all.

11. Case studies

Since 1990's, design and construction of more than 100 dams has been initiated in Iran. In this period, floods have been the most important hazard to Iranian dams:

- Jiroft dam experienced a 500-year flood during its first impoundment in 1992 (Rashidi, et al., 1998).
- Marun cofferdam failed after 3 hours of overtopping in 1993 (Emami, 1998b).
- The spillway of 200 m high Karun Dam was destroyed during the spring floods of 1993 as the result of cavitations.
- Karun III cofferdam failed during the spring floods of 1998. The cofferdam initially designed as an RCC one but during construction an earthfill cofferdam was built. The failure caused extensive damage to the construction machineries and equipments in the absence of an effective flood warning system.
- The downstream cofferdam of 2000 MW power plant of Masjed Solyman Dam failed in 2000 during the first impoundment, resulting in considerable delay in completion of the project.
- An extreme flood occurred during summer of 2001 in the basin of Golestan Dam, in the north of Iran, exceeding the calculated PMF for the dam by 25 percent. After three years of drought, the Golestan reservoir was almost empty when the flood occurred and the inflow of about 3000 m^3/s was reduced to 300 m^3/s. The dam prevented a major disaster downstream. 500 people were killed upstream of the dam but the magnitude of the disaster could have been much larger without the dam.
- A flood in early 2002 overtopped the downstream cofferdam of Salman Farsi gravity arch Dam in Fars province.
- Two floods, one in Dec. 2001 and the other in Jan. 2002 overtopped the upstream and downstream cofferdams of Delvari project near Busher (Emami, et al., 2002)

The experiences of the extreme floods at Golestan Dam in 2001 and 2002 and overtoppings of Delvari Cofferdam would be presented here.

11.1 Occurrence of 125% PMF in Golestan Dam

In 2001 the Golestan Dam in northeast of Iran, suffered a flood with a peak flow of 1.25 times the peak of calculated PMF. The maximum observed flood at the site before 2001 flood was about 400 m^3/s. The hydrologic and hydraulic parameters of the dam are as follows:

- Peak of PMF: 2389 m^3/s
- Reservoir Volume at NWL: 86 MCM
- Peak of 10000 years flood: 1703 m^3/s
- Spillway Capacity: 1550 m^3/s

The reservoir was almost empty when the extreme flood of August 2001 occurred. The impounding began just a year before the flood and the initial volume of the reservoir just before the flood was 10 MCM and consequently the peak inflow of 3000 m^3/s was reduced to about 300 m^3/s as shown in the figure 2. About 500 people were killed upstream of the dam but the reservoir prevented a major disaster downstream. As the result of the flood, thousands of trees were uprooted in the catchment and were transported to the river. The trees blocked the flow entrance of the bottom outlet of the dam. The trees were cleared with the serious effort of an emergency task force. On the anniversary of 2001 flood, another flood with a peak flow of 600 m^3/s entered the reservoir. Again the reservoir was nearly empty with a volume of 20 MCM (compared to 86 MCM at NWL) and the maximum outflow from the reservoir was just 60 m^3/s.

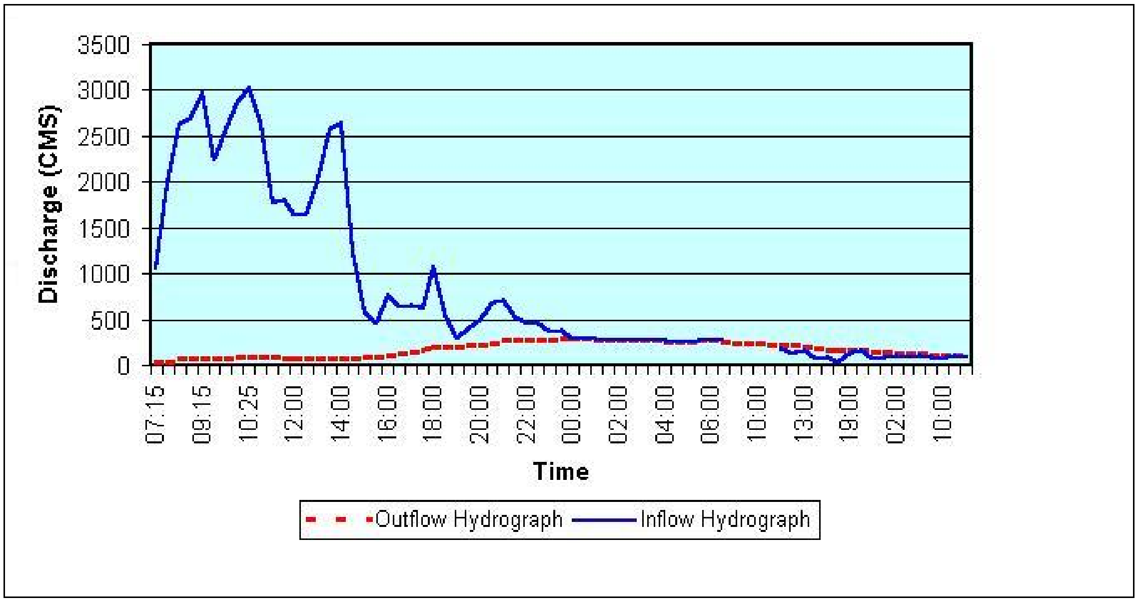

Figure 2: The inflow and outflow hydrograph of 125% PMF flood in 2001

The lessons learned from the floods of 2001 and 2002 in the Golestan reservoir are as follows:

- In some cases a large part of the design flood can be retained in the reservoir resulting in substantial increase in safety. This fact should not be overlooked during the hydrological safety studies. For the Golestan reservoir, the largest floods occur in the mid summer when the reservoir volume would be small.
- Golestan Dam prevented a major disaster downstream. Often, the risk protection achieved during natural floods far outweighs the risk imposed by the impoundment of the reservoir. In this context, with the limited resources, construction of 4 dams with 1000 years spillways may save more lives than 3 dams with PMF spillways and with equivalent total cost.
- The Golestan reservoir was impounded just 1 year before the extreme flood of 2001. What would have happened if the construction time had been longer 15 months? It can be noted that adopting very conservative approaches in practice may increase the construction time and the risk. The example clearly indicates the merits of holistic approach to risk management.

- The expectations from hydrology should be limited and reasonable especially in view of hydrosystem changes. Uncertainties involved in determination of design floods can be beyond imagination especially in the developing countries.
- Residual risk exists in all projects. Emergency concept should be developed to deal with it.
- A high degree of hydrological safety can be achieved with minimum costs with overtopping protection of earthfill dams.
- Competent people are essential to the effective monitoring and crisis management of the dams.
- Non-structural risk reduction measures should be employed for all dams irrespective of the degree conservatism employed in design. These measures are very effective for enhancing the safety of the constructed dams.
- If the capacity of Golestan Dam spillway were 3000 m^3/s instead of 1550 m^3/s, the outflow of the reservoir in the flood of 2001 would have been about 500 m^3/s and this flood could have caused serious damages in the downstream equivalent to 2 or 3 times the total cost of the dam.

Figure 3: The spillway of Golestan Dam after the 2002 flood

10.2 Overtoppings of Delvari cofferdam in 2001-2

Delvari double arch Dam is being constructed in South-West of Iran. The dam would be 100 m high. The 10 years flood was used as the design flood of the concrete cofferdam. In December 2001 and January 2002 the cofferdam experienced two overtoppings (Emami, et al., 2002). In the first event the height of the overtopping was about 1.6 m. Following extreme precipitation in the basin, (Bushehr 230 and Borazjan 330 mm/day), a historical flood occurred at the dam construction site in January 2002. The peak of inflow into the reservoir was determined by reverse flood routing and is estimated to be about 2400-2500 m^3/s, 10 percent smaller than the historical flood of Dec. 1986 assumed as a 100-years flood. The flood overtopped the cofferdam for 20 hours to the maximum height of 4.7 m (figure 4). The return period of the flood is estimated to be around 80 years. Currently an investigation on stabilizing the natural stilling pool of Delvari dam is going on. With stabilized stilling pool, the cofferdam designed for 10-years flood can withstand a 100 or 200 years flood. This can be appropriately called structural ductility. The lessons learned from the floods of 2001 and 2002 are as follows:

- The structural ductility exhibited by the Delvari cofferdam during the Dec. 2001 and Jan 2002 floods was the key to coping with inherent hydrological and hydraulic uncertainties and economical limitations. In view of these uncertainties, it is prudent to construct overtopping resistant cofferdams for increased safety and reduced costs.
- In both events flood warning based on the information acquired from Internet ensured that no additional damage should occur during the flood event to machineries. It can be foreseen than Information Technology (IT) would be increasingly used in dam engineering.
- It is interesting to note that 1.5 m of overtopping is assumed to be the condition for safety check flood for design of Delvari Dam spillway. As a result the cost of the designed spillway would be more than 20 percent of the dam cost that for an arch dam is rather high. In practice, overtopping to a height of 4.7 m did not cause failure of the cofferdam or even any major structural damage. It appears that excellent overtopping resistance of the concrete dams and especially the arch ones is not properly used to minimize the spillway costs in many cases.
- Considering the disastrous nature of dambreaks in populated areas, it seems that overtopping protection of the earthfill dam itself, may increase the safety substantially for a normally small cost. Even if the overtopping protection can not prevent the failure, it can ensure complete evacuation of the downstream in the case of the dambreak.

Figure 4: Overtopping of Delvari Cofferdam to maximum height of 4.7 m (Jan. 2002)

Figure 5: Delvari Cofferdam after the second overtopping (April 2002)

10. Conclusions

1) When plausible threats are examined with a broad view of possible ways to detect problems or warn the downstream population, then risk reduction may be accomplished with a holistic, balanced, and, therefore, cost-effective approach. Consequently it appears that in many developing countries faced with grave social and economic challenges, the structural safety should be determined by Economic Risk Analysis. Minimizing the residual risk should be achieved by efficient risk reduction by non-structural approaches and by increased structural ductility (such as overtopping protection for earth dams).
2) Solution of the problems of hydrological safety of dams will above all require a holistic approach and will require dependence on risk based approaches and recognition of effectiveness and adaptability of non-structural risk reduction measures.
3) Risk assessment can provide for consideration of the full range of risk reduction options available including those that are nonstructural. Consequently, comparison of effectiveness and costs of structural and non-structural alternatives would be feasible through risk analysis and based on the value engineering approaches.
4) Appropriate criteria for selection of the design flood are absent where they are needed most, in the developing countries.
5) Incremental risk acceptance might be appropriate for dynamic and nonlinear problems of hydrological safety.

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Appendix-II:

- $\Delta B/\Delta C$ for increasing the safety check flood from 10000 years flood to PMF

Assumptions:

- DC=Dam Cost
- ΔC= DC/10 (cost associated with increasing the safety check flood)
- Dam break incremental damages in the downstream=10*DC
- Discount rate= 10%
- Probability of PMF$\approx 10^{-5}$
- Case 1: (safety check flood= 10000 years flood)
- Case 2: (safety check flood= PMF)
- Present value of probable damages (case 1)=$10.9*10^{-4}*(DC+10*DC) \approx 1.2*10^{-2}*DC$
- Present value of probable damages (case 1)=$10.9*10^{-5}*(DC+10*DC) \approx 1.2*10^{-3}*DC$
- $\Delta B=(1.2*10^{-2} - 1.2*10^{-3})*DC \approx 1.08*10^{-2}*DC$
- $\Delta B/\Delta C= 1.08*10^{-2}*DC/0.1*DC \approx 0.11$

Considering the beneficial effect of flood warning systems, possible attenuation of the flood in the reservoir, and overtopping resistance of concrete dams, there would be many cases with $\Delta B/\Delta C<0.1$.