Dam-break Problems, Solutions and Case Studies

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In memory of

Costantino A. Fasso
(1920 – 2008)

Hon. Vice President of ICID
Professor Emeritus of the Politecnico of Milano
Scholar, Teacher, Author, Friend

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Introduction

A dam is an engineering structure constructed across a valley or natural depression to create a water storage reservoir. Such reservoirs are required for three main purposes: (1) provision of a dependable water supply for domestic and/or irrigation use; (2) flood mitigation and (3) generation of electric power.

In providing water supply, the reservoir storage is filled during the periods of above-average stream-flow. For flood mitigation, the storage reservoir is kept nearly empty during drought and periods of low rainfall, so that when rainstorms occur, the storage volume available in the reservoir provides a buffer against severe flooding events. For power generation, the storage reservoir provides a head of water upstream of the dam and the potential energy of this water is converted first to kinetic and then to electrical energy.

A large dam has two essential requirements. First, it must be reasonably watertight. Second, the dam must be stable. Movements and deformations of the dam and its foundations cannot be eliminated, but they must be predicted and allowed for in the design.

Because of these requirements, the location and design of dams are undoubtedly influenced to some extent by structural and/or geological features. It therefore follows that geological factors, and the proximity of construction materials are elements of overriding importance in determining the type of dam constructed at a given site. Once a site has been selected for a dam, consideration has to be given to deciding which type of dam is most suited to the site. Anyway, at any site, several types of dam should be considered. In general, three factors control this final decision: (1) the topography of the dam site and reservoir area; (2) the strength and variability of the foundations and (3) the availability and suitability of construction materials.

These factors are largely controlled by the geological structure and history of the site, and an informed decision requires a great deal of geological data analysis, particularly for the second and third factors, presented in a manner that planners and engineers can use in design calculation and procedures.

When designing a large dam, the engineers have to abide by two main goals: (1) the dam must be stable and (2) the structure must be constructed as economically as possible. The two objectives are against each other: ensuring stability by over-design increases the costs, while cost-cutting methods could lead to unsafe structures.

On a worldwide scale, it is clear that the objective of constructing stable dams is not always achieved. During the 1900–1965 period, for example, about 1% of the 9000 large dams in service throughout the world have failed, and another 2% have suffered serious accidents.

It might be expected that progressive advances in dam design and construction techniques would result in lower incidence of failures. This, however, does not appear to be the case, for two main reasons.

First, with any technological advance there are always likely to be unforeseen factors that can produce unexpected problems. Second, most of the easy dam sites around the world have been utilized. This means that future dam construction will be necessary at progressively more difficult and geologically complex dam sites, which increases the probability of dam failure accidents. It is therefore clear that if dam failures and accidents are to be minimized in the future, the role of advanced technology must be enhanced during the investigation, design ad construction of dam.

Records of the world's dams are kept by the International Commission Of Large Dams (ICOLD) in Paris.

Dam troubles are usually reported with terms neither comparable nor classified, which can, sometimes, generate misunderstandings. According to ICOLD (1986) a failure is defined as: *"collapse or movement of part of the dam or its foundations, so that the dam cannot retain water. In general, a failure results in the release of large quantities of water, imposing risks on the people and/or property downstream"*.

To the term "*incident*" is assigned the task of covering all the troubles occurred to a dam, but not degraded in "*failure*", due to the timely recourse to remedial measures. The term "*accident*", even if not officially codified, is used to represent the anomalies of the behaviour of the structure that could have been evolved to "*incidents*" or also to "*failures*", but whose timely diagnosis avoids any further negative progress.

An imperfect accordance between design hypotheses and reality represents, often, the decisive factor of failures. Also natural processes, such as flash-floods, rock or landslides, earthquakes or deliberate human actions, as terrorist or war attacks, can lead to dam-break events. Examples of major dam-break flooding disasters are the 1959 Malpasset dam failure in France, the 1975 Banqiao dam-break in China and the 1985 Stava dam failure in Italy.

Failure of a dam (dam-break) can result in a major disaster with devastating losses of both human life and property. The phenomenon is time-dependent, multiphase (water–soil interaction), and non-homogeneous (different materials, various degrees of soil compaction, and so on). Hydraulics, hydrology, sediment transport mechanics, and structural and geotechnical aspects are all involved in dam failures. Erosion of an earth-dam can be primed by low or weak points on the crest or on the downstream face, by piping or overtopping. Progressive erosion then widens and deepens the breach, increasing outflow and erosion rate.

Dam-break hydraulics and hydrology are topics of increasing interest in the field of water resource planning, environment protection and ecology management, given the potential occurrence of extreme meteorological events due to climate change and the catastrophic nature of historic dam failures. Prediction of the shape, magnitude, and timing of a flash flood resulting from a dam failure is important for evacuation planning and safe management of reservoir operations.

Over the recent decades, there have been continuing efforts to enhance the understanding of the theoretical background and the practical aspects involved in dam failures. Because real-time field measurements are difficult to make, the majority of dam-break studies have been carried out in laboratories. It is well-known, however, that physical experiments are largely constrained by the comparatively small spatial scales that can be realistically accommodated in laboratories and thus may not be able to fully reveal the long-term mechanisms of these processes. This applies not only to early dam-break experiments over fixed beds, but also to the recent mobile-bed laboratory tests.

As far as computational studies are concerned, most have been developed for fixed bed cases, without considering the undoubtedly strong eroding capability of the transient flow and the related morphological evolution of the channel bed. However, a dam-break flow can generate extensive debris or encounter floating debris in the valley downstream of the dam and trigger the formation of surges and shock-waves. Different methods have been proposed for the prediction of the flow depth, grain-size specific near-bed concentration, and bed-material suspended sediment transport rate in sand-bed rivers.

Debris flow always has uncertainties in variables and model parameters. The properties of the moving fluid mixture of debris and water are very different from those of purely water floods. The traditional approach to debris flow studies using a physically hydraulic-based model is limited. In spite of advances made with this approach major problems and barriers exist in debris flow studies. Therefore, efforts to develop new tools for debris flow forecasting are needed.

Despite the increasing safety of dams due to improved engineering knowledge and better construction quality, a full non-risk guarantee is not possible and an accident can occur, triggered by natural hazards, human actions or just because the dam is loosing strength capacity due to its age.

Legislation and safety criteria for dams vary quite significantly throughout the world. The majority of the contemporary safety legislation and technical guidelines promote and support dam-break flood risk management, which is a practical and important issue for public safety along the valley downstream of dams as well as for the protection of economical and environmental resources.

There are two important phases in dam-break risk management: predicting the losses or damages and their likelihood, through risk assessment, with the support of specific methods; and finding the appropriate mitigation measures, when residual risks are not acceptable.

Dam-break risk assessment defines the magnitude of the flood hazard that may occur due to a dam failure, estimates its main consequences and evaluates its significance. To assess this type of risk, it is, generally, necessary to undertake an integration between risk analysis and dam safety procedures, to evaluate the probability of dam failure, as well as numerical dam-break flood simulations. Predicting the effects through flood simulation allows the identification of flood prone areas, the flood path and magnitude and aims to assess valley vulnerabilities as well as losses and damages.

Hazard mitigation aims at organizing the prevention measures, namely safety control requirements, to be enforced at the dam site, and emergency preparedness measures, to be implemented in the downstream valley. Issues to be addressed in this last area are: safety monitoring of dam, emergency planning and preparedness, early warning systems, rescue, relief.

These procedures introduce several problems to all organizations involved in dam exploitation as well as in dam and valley safety and civil protection.

Private dam owners face a responsibility towards society in what concerns the internal dam procedures that will avoid a dam-break or diminish the probability of a dam-break flood should an abnormal event or action occur.

Civil protection authorities on downstream valleys face a responsibility to diminish the probability of human and economic losses should a dam-break event occur. To mitigate the risk along the valley, defence passive procedures should be implemented as land-use control according to flood risk zoning. These procedures can cause local political resistance.

Emergency planning, and effective warning systems, are now mandatory issues in modern dam safety regulations. However, these procedures need to be implemented with the support of local authorities and with adequate public information and participation according to the risk perception level of the population at risk.

Evacuation planning needs to be well prepared and trained and in almost all real cases the alarm needs to be switch on as soon as a failure is predicted, in order to evacuate a large number of inhabitants. This condition implies:

- advanced monitoring systems with real time capability to predict with more accuracy a dam accident;
- good coordination between dam owners, dam safety authorities and civil protection authorities in order to be sure that emergency and evacuation plans are effective;
- good public information in order to guarantee a good response to flood crisis.

Dams play an important role in meeting people's needs. Benefits include flood security, expansion of road and other infrastructures important for micro- and macro-economic development. But the last fifty years have also highlighted the social and environmental impacts of large dams. They have fragmented and transformed the world's rivers, displaced millions of people and often hardly provided protection against floods. Among the main reasons why in many places and so often dams fail to serve their purposes is that traditional evaluations of dams and similar public infrastructure investments often ignore related spatial–temporal risk profiles and potential negative consequences.

Thousands of dams have cost much more than the original contract price; unexpected geological and hydrological features, many of which could often have been identified by more thorough investigations , are the cause of expensive problems during construction. Too many dam sites are under-investigated, and the resultant extra cost of construction is far greater than the additional expense that would have been necessary to carry out a thorough investigation. Moreover, purely engineering evaluations of a dam are not able to account for public regulations and management of low probability – high consequence risks that exist in other human activities. Planning dams for economic development and social welfare requires the development of new spatial–temporal integrated models and decision support procedures, with the evaluation of dam safety, socio-economic, and environmental changes and developments.

With reference to these issues, the book aims to give an up-to-date review on dam-break problems, along with the main theoretical background and the practical aspects involved in dam failures, design of flood defence structures, prevention measures and the environmental, social, economic, and forensic aspects related to the topic. Moreover, an exhaustive range of laboratory tests and modelling techniques is explored to deal effectively with shock waves and other disasters caused by dam failures. Disaster management refers to programs and strategies designed to prevent, mitigate, prepare for, respond to and recover from the effects of these phenomena.

To manage and minimize these risks, it is necessary to identify hazards and vulnerability by means of a deep knowledge of the causes, which lead to dam failures, and to understand the flow propagation process.

Knowledge and advanced scientific tools play a role of paramount importance in the strain of coping with flooding and other dam-break problems along with the capacity building in the context of political and administrative frameworks. All these aspects are featured in the book, which is a comprehensive treaty that covers the most theoretical and advanced aspects of structural and hydraulic engineering, together with the hazard assessment and mitigation measures and the social, economic and forensic aspects related to subject.

The book contains the following chapters:

- Dam Failure
- Laboratory Experiments
- Dam-break Wave Routing
- Dam-break Flood Routing
- Dam-break Flow Against Obstacles and Through River Bed Singularities
- Dam-break Risk Management and Hazard Mitigation
- Economic Evaluation of Dams for Flood Protection: an Integrated Safety Approach
- Case Histories: a World-Wide View

The Editors are grateful to all the Authors for their excellent contribution as well as to the Staff of the WIT Press Officers for the review of all the chapters included in this Book. The quality of the material makes the Volume a most valuable and up-to-date tool for professionals, scientists and managers to appreciate the state-of-the-art in this important field of knowledge.

The Editors
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