

Strategies for Dam Safety Risk Management in Mexico

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Abstract

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Safety protocols for dams worldwide are currently based mainly on: understanding possible failures; quantitative risk assessment; justification of risks taken (with reference to accepted standards and good practices); historical records of dam performance; new criteria and state-of-the-art designs; the need to prioritize research; solutions to known problems; better communication of risks to the public, civil organizations and decision-makers; and the improvement of risk management through clearly defining and assigning responsibilities (Bowles, 2013). In addition, these protocols are equally applied to dam owners, regulatory organizations, insurance companies and consulting companies. This article discusses the current framework used to evaluate dam safety at the international level and proposes a specific methodology to evaluate existing dams in Mexico. It also discusses the urgent need to study the possibility of removing dams that present unacceptable risks and for which rehabilitation is not cost-effective.

Keywords: Risk analyses dams, dam removal, dam rehabilitation.

Resumen

Botero-Jaramillo, E., Ossa-López, A., & Flores-Berrones, R. (mayo-junio, 2015). *Estrategias para la gestión de riesgos de seguridad de presas en México*. *Tecnología y Ciencias del Agua*, 6(3), 5-14.

Alrededor del mundo, actualmente los protocolos de seguridad de presas se basan de manera principal en el entendimiento de las posibles fallas; evaluación cuantitativa del riesgo; la justificación de los riesgos que se toman (con referencia a las normas aceptadas y buenas prácticas); catálogo de desempeño histórico de presas; nuevos criterios y el estado del arte de los diseños; la necesidad de priorizar la investigación; soluciones a los problemas conocidos; una mejor comunicación de riesgos para el público, las organizaciones civiles y los que toman las decisiones; y la mejoría de la gestión de riesgos, a través de la definición clara y la asignación de responsabilidades (Bowles, 2013). Además, estos protocolos se aplican de igual forma a los propietarios de las presas, organismos reguladores, compañías de seguros, compañías y empresas de consultoría. Este artículo discute el marco actual para la evaluación de la seguridad de presas en el plano internacional, y se propone una metodología específica para la evaluación de las presas existentes en México. También se discute la necesidad urgente de estudiar la posibilidad de retirar las presas que presentan riesgos más allá de lo tolerable y cuya rehabilitación no es rentable.

Palabras clave: análisis de riesgo en presas, remoción de presas, rehabilitación de presas.

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Introduction

Traditionally, dam safety has been considered merely a technical matter. This has led to regulatory decisions based exclusively on engineering standards. This is not wrong, but over time, in countries such as the United States, Australia and the United Kingdom, decision-making has evolved with some independence in different sub-disciplines. This is in contrast to a comprehensive, integral examination of the global security of a project being carried out by only one organization (USSD, 2006; Hughes *et al.*, 2000; Brown & Gosden, 2004; Cooper, 2013). This evolution has taken place, in general, in isolation from other fields of engineering and industry. As a result, the risk levels associated with dam safety norms may significantly vary according to the possible failures considered, their consequences and the country where they are applied.

In this context, it should be considered that dam safety must be judged based on technical norms and good practices (common sense, rational operation of structures, coherent actions, efficiency and expeditiousness of decision making, etc.), in addition to an understanding of the failure modes and tolerable risk criteria (safety-life). Additionally, the full range of load events and all significant and physically feasible failure modes must be taken into account. Decision-making related to risks and structural loads must be based on engineering criteria through the characterization of failure risk and the estimation of the potential consequences.

Due to the issues raised above, it is necessary to propose a portfolio of possible risks for each dam. The safety of one structure may compromise others (downstream) through possible interdependence of dam failures, mainly due to large floods, which may affect dams in the region or basin. Major earthquakes (design and/or maximum credible) may also pose a threat. This interdependence can be directly related to time, due to the possible deterioration of the dam (progress of internal erosion, loss of operational capacity of the appurtenant structures,

faulty filters, creep, aging of the construction materials, etc.). Additionally, the consequences of the failure may be subject to external changes through time (population growth downstream of the dam, changes in the use of the soil, climate change, etc.).

Finally, this article discusses the current framework for the evaluation of dam safety at the international level, and a specific methodology for the evaluation of the existing dams in Mexico is proposed. We also discuss the urgent need to study the possibility of removing dams that present risks beyond what is tolerable and are not cost-effective to improve.

General Context of the Problem of Dam Safety

Historically, the development of dam infrastructure has been tied to the premise that “infrastructure follows floods and people follow the infrastructure” (Snorteland, 2013) carrying out their daily activities around it, and developing their houses and works near to the water resources. For this reason, the importance of the study of dam safety increases on a daily basis, due to the direct tie between population growth and the continually-increasing demand for energetic resources and resources for the sustenance of human activities.

In the last twenty years, significant advances have been achieved in dam durability. The technical and scientific foundations that have been developed make it possible to define the levels of safety that dams and temporary constructions must have. A more complete and complex scientific basis has been laid out for the understanding of geological and hydrological phenomena, the nature and behavior of materials, the types of load, the cycles that dams undergo and the appropriate operation procedures (Marengo, 2011).

In developed countries (Snorteland, 2013; McClenathan, 2013), the construction of new dams has substantially diminished. Currently, work in this field is focused on rehabilitation, extension of useful life, increasing safety, updat-

ing the original design characteristics to adapt to climate change, permanent closing and, in some cases, the removal of infrastructure and remediation of the zone affected by sediment. In Mexico, due attention has not been given to these recent trends. The main focus has been the construction of new dams for the water supply and for hydroelectric energy generation. This does not mean that a particular implementation of the aforementioned measures should begin, due to the high average age of the dams.

Dam Safety Management Program

At the international level (ICOLD, 2005; FERC, 2005; ANCOLD, 2003), permanent programs for the management of dam safety cover mainly the following aspects:

- Maintenance and safe operation of the dam, within the safety levels considered in the design.
- Verification that design expectations are met and identification of possible deviations in safety levels, through monitoring and vigilance.
- Periodic reviews of the existing dam and of its performance in order to identify safety issues, including the analysis of potential modes of failure and the development of a remediation strategy.
- Planning for the management of possible incidents at the dam, including action plans, drills and the determination of affected and high-risk zones.
- Prioritizing which safety issues or existing problems may require immediate attention, and which may be handled through a continued dam safety improvement program.

In accordance with these points, it must be considered that all decisions on dam safety can be categorized in terms of the answers to the following questions:

- Determination of tolerable risks: How safe is it to continue operating the dam?

- Uncertainty management based on available information and on the determination of paths toward risk reduction: How can one justify the current risks, and how, in a given period, can the safety goals for each dam be reached?
- How can we maintain and guarantee adequate safety levels, and what are the tolerable and acceptable levels of risk for the affected population, throughout the life cycle of the dam?

In response to these questions, a variety of options for the reduction of risk can be included in the portfolio. The most widely used in some countries (USD, 2004; AS/NZS, 1995) are related to the following considerations:

- Avoiding risks. This option must be considered before building a dam (at the stages of feasibility, planning and design), or perhaps in the closing of an existing dam. Additionally, it is possible to decide against the construction of a dam if the risk is too high. Risk tolerance levels have diminished in the last few decades as a direct response to the increasing amount of information and the formulation of laws, which protect the communities present in the zones where the project will be carried out.
- Reduction of the probability of occurrence of these incidents (prevention and control) in general, through structural measures for dam safety management, such as control and surveillance, instrumentation, periodical inspections or operational restrictions.
- Risk transfer to a third party through contractual agreements or the sale of the dam. This transference must involve a third party with technical and economical capabilities that allow them to carry out the necessary rehabilitation of the structure in order to reduce the level of risk, or to carry out the final removal of the dam.
- Remnant risk (acceptable or tolerable). After the risk level has been reduced or transferred, some residual risks remain,

and these may require risk financing for future repairs, rehabilitations or catastrophe response (insurance).

The aforementioned aspects are presented within an ideal framework of risk evaluation, remediation and control for existing dams. However, the majority of engineers who work in dam safety, as in the specific case of The United States, are not —according to the guidelines for the evaluation of risks put forth by the regulatory bodies of the country— experts in risk evaluation techniques. Thus, there is a need to educate dam safety engineers in the concepts and methods required for a real and opportune risk assessment, in accordance with the local normativity (Snorteland, 2013). There is much to learn: workshops and courses must be offered to train the person in charge of the dams. Finally, a culture must be developed in which risk evaluation is considered to be a valuable tool for the dam safety engineers.

The Case of Mexico, Risk Management and Reduction

General Approach

In Mexico, there are approximately 4 462 dams built by government agencies and private enterprises, with an approximate storage capacity of 150 billion m³. Out of these, 667 (15%) correspond to large dams and 52 are classified as main dams (Conagua, 2011), which have a combined storage capacity of approximately 79% of the national total. The majority of the dams in the country are close to the end of their operational life. The service life range is normally estimated to be from twenty to fifty years; 71% of the existing dams are more than twenty years old, and the average age is 36 years. In addition, among the dams for which information is available, 28% exceed 50% of their sediment capacity, and only 2% (96) have instrumentation (inclinometer, piezometer, water level gauges, etc.). This translates to a loss of capacity in the reservoir due to sediment, pollution, possible

deterioration as a result of poor maintenance, unknown risks, important changes in location and population density of the communities located downstream, etc.

Another problem with dam management in Mexico is the change of initial purpose for several dams. In some cases, they were initially constructed for irrigation, supply of drinking water and/or electricity generation. However, some projects that were developed for surface water are now handling wastewater, which is detrimental to the concrete and reinforcement steel that were used for construction and which negatively affects the safety factor.

Problems with the Management and the State of Dams

In Mexico it is necessary to consider, for several of the existing dams, the potential problems related with the management and the status of such dams that might increase the risk of flooding, which might happen under the following circumstances:

1. When an earth dam with a clay core shows transverse or longitudinal cracks, and an exceptionally strong storm occurs, the risk of collapse increases. The flood resulting from the collapse of a dam is one of the most destructive type of floods that can be experienced by the downstream valley.
2. When the dam has not performed adequately during an emergency, in a situation of rapid volume changes (fast emptying or filling). When the floodgates have suffered mechanical damage and have yet to be repaired, and the appropriate measures have not been taken, the risk of flood damage for the communities living downstream is increased.
3. When the dams generate an optimistic risk perception in the face of flooding (inaccurate perception of safety on the part of the regulating entities and the general population), the settling of communities in areas prone to flooding is encouraged. In that case, it is important to clarify to the communities

what level of protection will be provided and to explain the contingency plans that are in place.

4. When the dams are almost filled to capacity and when prolonged rains occur, the flood-gates must be opened to their maximum.
5. Uncertainty in the face of meteorological phenomena produced by climate change, and the change of frequency, duration and intensity of the storms that produce flooding. There is a real risk that climate change may modify the hydrological base on which many dams were designed decades ago. This may lead to inadequate capabilities for handling the higher volumes of water that will most likely be produced by climate change. This has been observed repeatedly during extreme weather in Mexico in recent years.

Portfolio for Risk Management in Mexico

The National Water Commission, Conagua (Conagua, 2012b; Arreguín, Murillo & Marengo, 2013), currently have a database that allows knowing the relevant data of each curtain, such as spillway, levees, galleries, outlet works, gates and valves. This information is constantly updated. In the last 3 years, Conagua has made about 2 200 revision of dams. The current base information consists of 5 166 dams. These studies provide an appreciation of the general conditions of each dam and determine whether any required special attention is needed in terms of operation or repair. Related with the operational aspects, there exist a Technical Committee of Operation of Hydraulic Works, CTOOH, which is a multidisciplinary group (Federal Electricity Commission CFE, National Water Commission CNA, Institute of Engineering II UNAM, Secretariat of Agriculture, Livestock, Rural Development, Fisheries and Food SAGARPA and the National Meteorological Service SMN) composed of trained personnel in hydraulic works, geotechnical engineering, geology, power generation, irrigation, risks, potable water, and flood control. Its mission is

to dictate policy management of reservoirs, by discussing the state of the dams and the short and medium-term forecast adaptations and adjustments required.

In addition, of the above aspects, it is proposed an implementation of risk management portfolios for dams in Mexico that will allow more updated risk information with the purpose of improving the safety management of each dam (or group of interdependent dams) with a common owner or operator. For this purpose, is necessary to consider that the creation a portfolio for risk management will not be an additional activity to be incorporated into the safety program of an existing dam. It will have to consist of a global perspective of the full safety program on the part of the owner or the operator (Bowles, 2006). It is estimated that this focus (USSD, 2004) may be an important and acceptable approximation for the prioritization of the cost-benefit relation in the implementation of corrective safety measures, and for the development of further research for the improvement of the safety of the dam, or group of dams. In addition, this perspective should provide ideas for the improvement of information for the owners and should provide information about the present and future implications and responsibilities entailed by their dams.

Of the approximately 4 500 dams currently in Mexico, 836 are taller than 15 m, and only 27% are federal property (Bowles, 2013; Conagua, 2011; Arreguín *et al.*, 2013). A methodology for the development of a risk portfolio is proposed for existing dams; this methodology considers the definition and management of risk and decision making and must encompass at least dams with a height above 15 m. Furthermore, in the development of such a risk portfolio, it must be considered that an important fraction of the dams are private property and/or have been abandoned. Those dams require special judicial measures. Figure 1 shows a flow diagram for the proposed method for storage or control structures taller than 15 m.

For the first aspect related to safety inspections (1 to 4), the guidelines mentioned in the

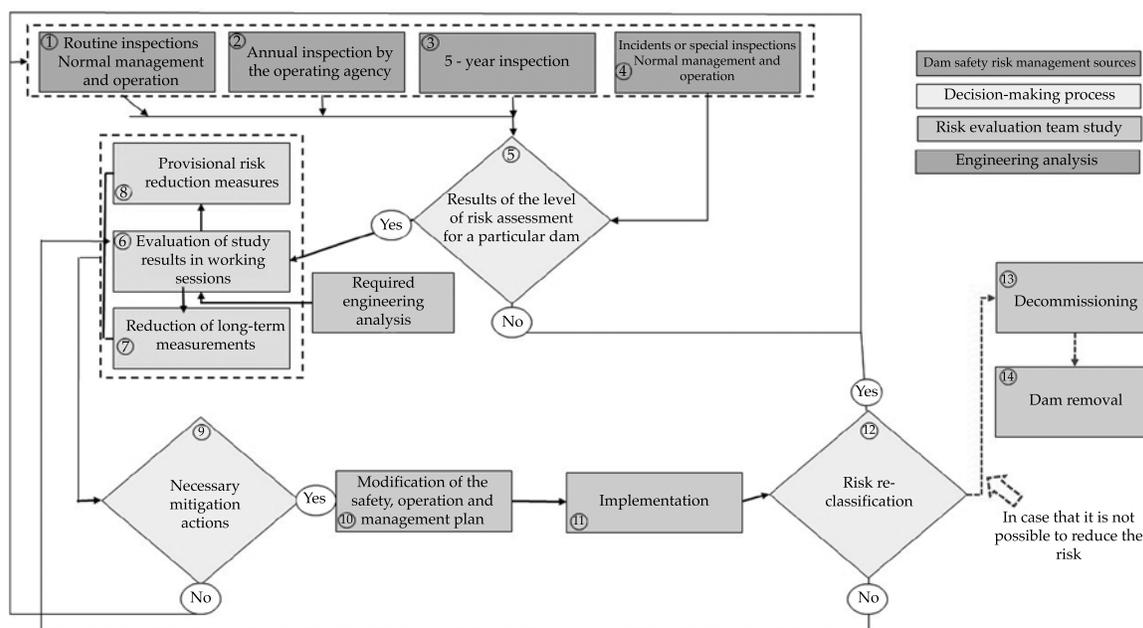


Figure 1. Flux diagram of the proposed method for structures taller than 15 m (modified of Cooper, 2013).

following points must be taken into account (ICOLD, 1989; ANCOLD, 1983; Conagua, 2012a y 2012b; Conagua, 2000; Arreguín *et al.*, 2013). It is necessary to consider that the routine and annual inspections by the organization in charge will be centered on the operational and behavioral aspects in the short term, whereas the 5-year inspections must lead to a detailed analysis of the state of the curtain and to the determination of possible major corrective action. Finally, the analysis of special incidents or inspections may be centered on specific events that merit special study due to an extraordinary event. The aspects to be considered in these inspections are the following:

- Compilation of the information on the dam, as a starting point for the revision. Subsequently, it is necessary to carry out inspection visits that encompass the crest, embankment or wall facings, galleries, inspection and drainage tunnels, abutment slopes, reservoir and channel, spillways, intake discharge works, and the electro-

mechanical mechanisms of intake and control.

- Knowledge of the dam behavior under normal and extraordinary service conditions, obtained by recording data from the instrumentation that should exist in the dam.
- Review of the hydrological safety, considering the transit of the design flood discharge by the reservoir, for the given return period with the criteria of the regulatory body. The physiographic characteristics of the basin, annual flood discharges, geometry of the excess works (it is also necessary to keep in mind that some of the existing dams lack these structures), elaboration of the topo-biometric curve of the basin and the operation policy.
- Due to the effects of climate change, the information from meteorological stations must be periodically updated, and information on rain and the duration of rain cycles should be distributed hourly.
- Review of the stability of the curtain and appurtenant structures by means of topo-

bathymetric surveys in order to determine the sediment level against the curtain; material resistance tests for rigid curtains and geotechnical explorations for flexible curtains, in order to determine mechanical properties; and geophysical explorations to build stratigraphic profiles of the hillsides and the foundational terrain. These tasks are complex because many curtains do not have construction blueprints and there is no historical archive that allows one to know a priori which materials were used, how they were distributed, what construction methods were used and what the placing and quality of the materials were. Because of this, the field explorations—in cases that call for it—will have to carry out surveys of the curtain bodies as well as laboratory tests.

- Timely detection of problems and deficiencies in the behavior of the dam and its foundations during construction and operation and the determination of the appropriate time for a correction, in accordance with the level of risk presented.
- Evaluation of seismic risk, including determination of the operating basis (OBE) and maximum credible (MCE) earthquakes, according to the seismicity of the zone, attenuation laws and seismic sources. In addition, the historical seismicity must be reviewed, and deterministic as well as probabilistic seismic risk analyses must be carried out to determine the responses and uniform risk spectra, respectively, in addition to the corresponding synthetic accelerogram.
- Determination of the safety factor for the established flux conditions, rapid emptying and earthquake, and determination of the condition of limit equilibrium for the reservoir at the high water mark (HWM), in rapid emptying with the reservoir at the maximum or minimum ordinary high water levels (MOHWL and MINOHWL, respectively), and the dynamic stability with the reservoir at the MOHWL.

- Calculation of the stress and strain states of the dam, pore water pressure, filtration pressure, freeboard loss, localized or generalized landslides and liquefaction potential.

The evaluation of the results from different inspections must lead to the determination of failure risk levels of the dam (5). If the dam has not presented protalbeblems historically or in recent inspections (1 to 4), it may be chosen to continue with periodic inspections. In the opposite case, the risk must be initially established (Botero & Romo, 2014; Bowles, 2013; Conagua, 2011; IMTA, 2001) through a process of delimitation of risk zones, which will have as a priority the determination of the flood zones downstream in accordance with the established risk types (*e. g.*, extraordinary discharge, collapse of the dam, sudden landslides within the basin, etc.). The zoning must also be permanently considered, so that active or structural measures may be taken, including protection works against floods as well as passive, non-structural measures. This is in addition to considering the possibility of the relocation of settlements, limitation of the growth of settlements that may be vulnerable and the periodic censuses of the vulnerable population. The risk levels can be defined according to table 1 (modified from FERC, 2013).

Remediation actions (9), safety plans, operation and management (10) and the implementation of the necessary measures (11) for the improvement of the stability and safety of the existing curtains will directly depend on the risk category, the type of problem that may occur and the types of damages and losses that may occur in the event of a collapse, as well as the speed with which the necessary actions will have to be implemented.

At the end of this continuous process, it must be determined whether success has been achieved and whether the evaluated structure presents a sufficient increase in safety and trustworthiness such that it deserves to be re-classified (12) as a safe structure. If it is not

Table 1. Risk levels for a dam.

Risk category	Description
Remote	The physical conditions for the development of a problem are non-existent, or unlikely to exist. A series of events would need to occur simultaneously or in sequence in order to trigger the failure. Furthermore, the majority of the necessary events are themselves unlikely. A flood or an earthquake with a return period of more than a million years would be necessary to trigger the failure.
Very low	The possibility cannot be disregarded, but there is no convincing evidence that suggests that it has ever happened, or that there may exist a situation that could lead to the development of the failure. Nevertheless, a flood or an earthquake with a return period between one million and 100 000 years could trigger it.
Low	Causes of defects are known. Indirect evidence suggests it, and it is possible, but the evidence strongly indicates a low probability of occurrence. Nonetheless, a flood or an earthquake with a return period between 100 000 and 10 000 years may trigger it.
Moderate	The fundamental conditions or defects that may produce the failure are known, and indirect evidence suggests that it is possible. However, there is more compelling evidence that it is improbable. A flood or earthquake with a return period between 1 000 and 10 000 years could trigger it.
High	Substantial evidence—direct or indirect—exists, that suggests that such an event has happened or is likely to happen. It is also likely that a flood or an earthquake with a return period between 100 and 1 000 years would trigger the potential failure.
Very high	There is direct evidence that indicates that the problem is being actively produced, or that it is most likely going to happen. A flood or earthquake with a return period of less than 100 years will most likely trigger the potential failure.

found to be safe, the evaluation must be carried out again, with the goal of determining which aspects continue to negatively influence the minimum safety parameters. If the situation is not remedied after this subsequent study, it will be necessary to carefully consider the possibility of removing the dam. This aspect is of great importance because in Mexico only two large dams and approximately 100 dams (< 15 m) has been removed (SMIG Dam Committee, 2013), but is necessary to considered it as a realistic necessity to remove a greater number of old dams. It is essential to create policy that allows and encourages (through incentives) the safe removal of the curtains, the remediation of the storage basins, the management of sediment and pollutants contained in the basins and the restoration of wildlife.

Finally, an Official Mexican Dam Safety Norm (NOM) must be created and must clearly state the responsibilities of the owners and operators with respect to the operation, maintenance, surveillance and risk reduction for the

consequences of a possible failure of the dams. Most dams are the property of user associations, private parties or state governments; and only 440 dams are operated by CONAGUA and 54 by CFE (Arreguín, Hungsber, & Alfaro, 2005).

The future of dam management in Mexico

For future dams in Mexico, it is necessary to incorporate the established guidelines for safe management and continued operation, be it through federal, local or private operators. In addition, the following points must be considered (Marengo, 2011):

- Ensuring the introduction of the World Bank guide.
- Adapting geotechnical research to feasibility studies in all types of dams.
- Resolution of the recommendations, before finalizing the design.
- Provide security measures that guarantee the safety of the project.

- Co-finance packages that allow for the financing of project safety.
- Introduction of realistic programs.
- Resolution of the issues detected during construction.
- Continued presence of professionals in the project.
- Training of the local staff on the dam safety and monitoring program.

Conclusions

In this article, the different factors that may cause the failure of a dam have been indicated, and the existing risks in terms of damage and loss of human life have been explained, with an emphasis on the current situation around the world, and especially in Mexico, as a result of climate change.

In particular, the flood risks for settlements located downstream of the dam are laid out. There is a need for updated contingency plans, and aid must be provided to the aforementioned communities in case of flood.

Additionally, a method for a safety review of dams is proposed. Such a review would cover the hydrological aspects, curtain stability, structural integrity under different conditions of load, seismic activity and stability of the reservoir hillsides. It would also address overflowing, waterproofing of the foundations and the curtain and problems due to internal erosion in the case of embankment dams.

The necessity of shutting down dams, or removing abandoned dams in Mexico, is proposed, with an emphasis on the dangers and risks taken by not doing so.

The development of numerical methods and computational techniques allows for a better global view of these aspects. To date, the safety factors have been redefined, and human error has been significantly reduced by submitting and updating the design criteria of international consensus.

Dams are unique, and for that reason, it is necessary to study and control each one of them individually.

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