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Dam Safety: General Considerations

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Abstract

Dams construction is an old art practiced by man since thousands of years. History of dams shows great innovations in this field, but failure cases, however, indicate gaps in human knowledge of safety measures that could have stopped such failures. Available statistics show of a great boom in building dams during the past century and indicate at the same time large number of failures associated with losses in human lives and material damage. Uses of these dams during this period, apart from flood control and storing water for irrigation were also for hydropower generation, navigation, drinking water supply, recreation and in mining operations as tailing dams. Reduced dam safety leading to failures, accidents and higher safety hazards were caused by insufficient knowledge of the geological conditions and in using wrong or deficient foundation treatment. Dam safety was compromised in cases of insufficient hydrological data and design of inadequate spillways. Misinterpretation of the seismic conditions of the area and adopting seismic criteria compatible with such seismic conditions is also added as one more reasons of failures. Human mistakes and errors have undermined safety in many cases in the operation of dams leading to grave safety issues including many failures. Safety hazards also were exasperated by increasing population and land use in the downstream areas of dams and by failing to do necessary inspection and maintenance or upgrading works. More emphasis over dam safety measures is needed now in our existing dams and in their future development of dams if they are to continue delivering their benefit without causing harm to human communities.

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1. The early beginnings

Dams are man-made structures that are primarily used to store and/or divert water. Other uses such as power generation and recreation were added to those uses in the last century. The benefits of dams were known to the ancients since thousands of years, and so we see that old civilizations had discovered these benefits and had built dams to harness large rivers and store water for the use, mainly in irrigation and produce the food they needed. Some other dams were built to divert water but to serve irrigation in the end also. Those people had used trial and error coupled with intuition in order to achieve this, but in many times met with failures and undoubtedly paying the price in human lives.

Recorded history and archeological findings show that the oldest dam in the world dates back to 3000 BC; this was the Jawa Dam in Jordan, which was actually the largest in a series of dams that were all parts of one reservoir system. This dam was 4.6m high, 24.4m long, with a base of 4.6 m, and It created the Jawa Reservoir that had a capacity of more than 30,000m^3. The dam itself was so well designed and constructed that the ancient structure stood till just few years ago, when it was partially ruined due to human intervention, Figure 1, [1].

Most ancient dams were simple gravity or earth fill dams, the Jawa Dam, however, was constructed from gravel reinforced with rock fill behind the upstream wall in order to protect the wall from the water pressure breach. This feature reflects the awareness of the ancient constructors of safety measures that could be incorporated in the design to protect the structure. In similar case, we may mention the Nimrud Dam which was built on the Tigris River in Mesopotamia, now Iraq, during the Chaldeans time of the New Babylonian era (330-612BC) which was meant to divert the flow from the Tigris River to the Grand Nahrawan Canal and it remained in service until its final collapse in the thirteen century. Sir William Willcocks, the late nineteen century British engineer spoke of this dam saying:

“The construction of the Grand Nimrud Dam and the Great Nahrawan Canal involved colossal volume of work and great deal of planning and surveying works. In considering the size of the “Grand Nimrud Dam’ we should remember that this dam had to be of such volume and workmanship as to resist Tigris floods which from hydrological calculation can reach up to 12,000 m^3/second. The dam continued to function for about three thousand years and its destruction and progressive abandonment lasted from the mid-10th century onwards mirroring the Abbasid Caliphate's decline”.

It is unfortunate that the remains of this dam are no longer in existence; being washed away by the Tigris River, which had changed its course. But from the words of Willcocks it may be inferred that, apart from the skills and workmanship used in its construction, the dam must have had many safety features in its design, [2].

Figure 1: Remnants of Jawa Dam in Jordan [1].

History furnishes us with many cases of mixed success and failure; one such example is the case of Marib Dam in the kingdom of (Sheba) in Yemen, which was built around 750BC. In its good days, the dam supported a flourishing agriculture and prosperous communities. Notwithstanding the dam good construction, it had been overtopped several times during its history, but always had been repaired. In the recurrent overtopping, severe flooding had occurred and the dam proved to be a constant hazard to the communities living in the downstream and led to the abandonment of towns and cities. After the last failure, the inhabitants were forced to leave the area for their safety, and this caused serious mass migration to Syria and Mesopotamia. The final collapse of the dam occurred most probably in 575AD, after more than 750 years of service [2], [3]. Remnants of the dam are located about 150km east of Sana'a where a modern dam has been constructed lately, Figure 2, [4].

Figure 2a: Ruins of Marib Dam [4].

Figure 2b: Artist impression of the ancient Marib Dam [4].

Another example of failure is the case of Saad el-Kafara, which was masonry-embankment dam on Wadi al-Garawi 10km southeast of Helwan in Egypt. The dam was built in around 2650BC by the ancient Egyptians for flood control, and it was the oldest dam of such size in the world. The dam was 14m high, with a base width of 98m. It was originally 113m long, but now there are only the remains of construction on both sides of the wadi, and it is estimated that it was necessary to excavate and transport approximately 100,000m^3 of rock and rubble for its construction. No mortar was used in the dam: since ancient Egyptians did not use mortar as a cementing material. Considering the construction methods and technology available at that time, and considering the volume of gravel and rock fill that had to be transported from the wadi terraces to the dam's core and facing, the construction can be estimated to have taken 10-12 years. In cross-section, the Sadd el-Kafara dam consisted of three construction elements of a total width of 98m, which differ in composition and function: these were, i) An impervious central core of essentially calcareous silty sand and gravel, ii) Two sections of rock fill on either side (upstream and downstream) of the core which support and protect it. The fill consists of rocks, usually 30cm thick, but these also range in thickness (10-60cm). The quarried fill material was dumped down haphazardly, and the cavities between these rocks were not filled with gravel or debris, iii) upstream and downstream slope protections of blocks/ashlars placed in steps on the slopes of the rock fill, Figure 3, [5], [6]. The total volume of the reservoir when fully impounded to an elevation of 125(m.a.s.l) is about 620,000m^3. Below elevation 123.5(m.a.s.l) about 465,000m^3 could be stored. The purpose of the dam is still controversial, for such a large-scale reservoir may have been needed either to fulfill a heavy demand, such as for irrigation, or to protect the downstream area from flooding, but there is no evidence of cultivated land around the dam. Also, the absence of spillways in the dam indicates that the reservoir was not built for irrigation. On the other hand, geographical and geological conditions prevailing in the catchment area of the Wadi Garawi indicate that sudden and heavy rainfalls can lead to flash floods with disastrous effects in narrow valleys. Flood discharge can be estimated anywhere between 50 to 250m^3/sec, and even nowadays inhabitants in the region report the recent occurrence of floods several meters high, which have destroyed villages and claimed lives. So, in all probabilities the dam was intended for the retention of the rare but violent floods in the valley of wadi el Garawi.

Figure 3: Remains of the Sadd el Kafara dam (about 2600BC), on the right bank of the wadi Garawi one of the oldest known large dam in history. View from upstream (photo of G.Albecht), [5].

Evidence shows that Sadd el-Kafara dam was never completed, as there are no signs of siltation in the reservoir. Most probably the dam was partially completed when a sudden high flood occurred and washed away the central part of the dam. There is evidence also that the upstream rock fill was almost (or fully) completed, but a gap still remained in the middle section of the downstream rock fill, and perhaps also in the core, when the flood occurred. The inadequately protected core could not withstand the gush of the water overtopping it and was carried away causing the central part of the dam to collapse. Modern assessments of the dam's stability lead to the conclusion that the design was basically correct, though conservative [6]. This example shows that the builders of the dam took a considerable risk for not providing an escape for the flood water during construction, which is something that has been taken care of in constructing modern dams. But even in some recent cases, however, serious failure of coffer dams during construction occurred showing underestimation of the floods adopted during diversion. In both cases this is due to hydrological miscalculation and bad judgment causing serious safety hazards.

Development of the skills for dams' construction grew from damming small streams to building diversion weirs needed for diverting irrigation water by the use of materials that were available at hand. In ancient Sumer, in Mesopotamia, 3000BC, people placed rolls of mats woven from palm trees fronds and impregnated with bitumen in the stream and then dumping earth behind them to create the required barrier. Later on, such weirs were built from burnt clay brick masonry cemented with various types of mortars, and proper gravity dams exceeding 15m in height were built also from cut stones masonry for river diversion, irrigation, and flood control. As examples to be noted are the old Diyala dam and the old Adhaim dam, which were most probably built by the Chaldean king of new Babylonia, Nebuchadnezzar II (605–562BC) which bear witness, and they were complementary to the works of the Great Nahrawan canal. The two dams continued to function until their collapse, due to lack of maintenance and conflicts, in 912AD and 1150AD respectively. Trial and error and the accumulation of experience helped in the building of larger dams by the use of different materials and for many more uses other than only irrigation.

Of all the dams that were built during many thousands of years, many of them can be described as being unsafe dams. We have to admit that history is silent on catastrophes related to loss of lives, which occurred from dam failures, but we can assume that such losses occurred. The major weakness of those dams was their incapacity to withstanding high floods due to inadequate knowledge of hydrology, or weak foundation due to misjudgment of the foundation conditions or maybe being subjected to seismic events. Some of the dams which had passed these tests collapsed finally after long years of service due to aging. Aging remains up to this moment as a major cause of failure, and therefore many old dams, which are still in operation may pose safety hazards to communities living downstream of them and require special thought for decommissioning them.

2. Evolution of Dams' Design and Construction

While construction of dams continued for ages, development in the design and types of these dams evolved. The need for building more dams increased with the development of human societies and their increased use of water and enhanced knowledge of hydraulics. In this development the Romans may be regarded as pioneers for their advances in hydraulic engineering, which led them to build higher dams and develop new types. They were creative and abundant in dam construction, and during the height of the empire, they built large number of gravity dams, most notably the Subiaco Dams.

The Subiaco Dams were a cascade of three gravity dams on the Aniene River in Subiaco, Italy, that were built during the reign of Nero (54–68AD). The largest of these dams stood 165 feet tall and was the tallest dam in the world until its destruction in 1305; which was due to mismanagement, [7]. The Romans also constructed the world's first arch dam in the province of Gallia-Narbonensis, now modern-day southwest France, in the first century BC. The remains of the Glanum Dam, the first recorded true arch dam in history, were discovered in 1763. Unfortunately, a modern arched gravity dam replaced the ancient structure in 1891, and all remnants of the Glanum Dam were lost. The Romans were also responsible for constructing the world's first buttress dam. Many such dams were built in the Iberian Peninsula, although they tended to fail due to their too-thin construction. As a consequence of the industrial revolution and the increased demand for water during the modern times, large dams began to appear especially after the introduction of concrete in their construction. Major advances in concrete dam design were made from 1853 to 1910 by British and French engineers. During this time, understanding of the relationship between the precise weight and profile of gravity dams and the horizontal thrust of water increased extensively. In 1910, further advances were made as engineers began to take a more three dimensional approach to dam engineering, examining the effect of individual stresses and deflections on multiple points rather than on the structure as a whole.

By recognizing the complexity of the structure and understanding its interconnectedness, engineers were able to make exponential advances in dam engineering. The world’s largest and most complex dams have all been built within the last century due to engineering as well as technological advances. In addition to supplying water and controlling flooding, modern dams are often constructed to provide hydroelectric power. Striking examples of advanced engineering are found in such dams as Hoover Dam, a concrete arch-gravity dam constructed on the Colorado River in 1936. The massive dam, which impounds Lake Mead, is 726 feet (224 m) tall and has a reservoir capacity of 28,537,000 acre feet (> 35 billion m^3). Hoover Dam however lost its title as the highest in the world to other dam’s long time ago.

3. Present day Statistics on Dams

The numbers of all dams in the world has exceeded 800,000 dams in 2007, out of this about 40,000 were large dams [8]. The register of the International Commission on Large Dams (ICOLD) indicates today a dramatic increase within the past thirteen years to about 60,000 large dams, Figure 4 [9]. Many of these dams serve multipurpose while other serve a single purpose as shown in Table 1. The first twenty highest dams in the world today are listed in Table 2, [10].

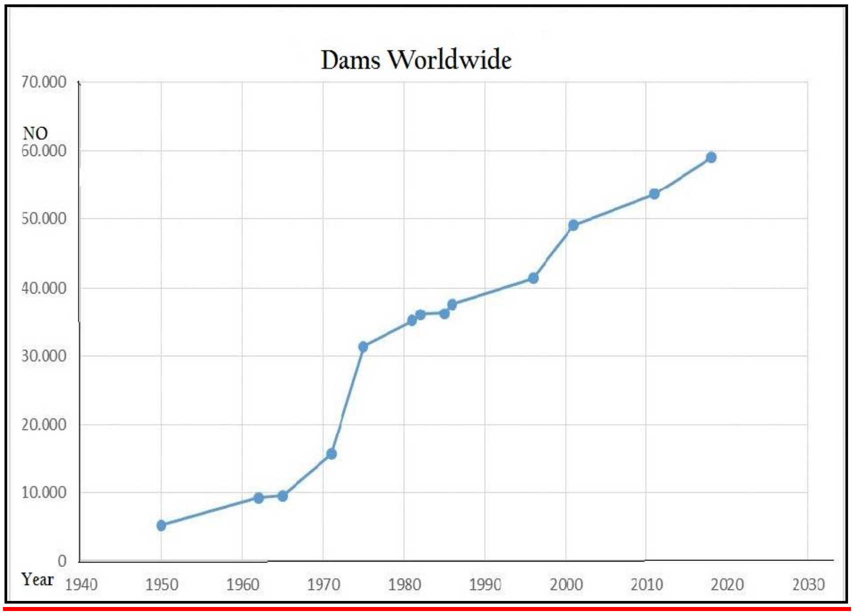

Figure 4: Growth of Numbers of Dams in the world (1950-2020) [9].

Table 1: Number of large dams in the world showing their purpose [10].

Code	Desecription	Number of Dams with Sole Purpose	Number of Multiple-Purpose Dams
C	Flood Control	2524	4778
F	Fish farming	41	1395
H	Hydropower	5786	3932
I	Irrigation	14562	5954
N	Navigation	97	580
R	Recreation	1350	2942
S	Water Supply	3285	4330
T	Tailing	63	8
X	Others	1540	1214

Table 2: The twenty highest dams in the world, their purpose and country [10].

Dam name	Height (m)	Purpose	Country
Rogun	335	HI	Tadjikistan
Bakhtiyari	315	HC	Iran
Jinping 1	305	HC	China
Nurek	300	IH	Tadjikistan
Lianghekou	295	H	China
Xiaowan	294	HCIN	China
Xiluodu	286	HCN	China
Grande dixence	285	H	Switzerland
Baihetan	277	H	China
Inguri	272	HI	Georgia
Diamer-bhasha)	272	HIS	Pakistan
Yusufeli	270	H	Turkey
Manuel Moreno Torres (Chicoasén)	262	H	Mexico
Nuozhadu	262	HCN	China
Tehri (thdc)	260	IH	India
Hacixia	254	H	China
Mauvoisin	250	H	Switzerland
Laxiwa	250	H	China
Deriner	249	H	Turkey
Mica	243	H	Canada

4. Dam Safety and Dam Hazards

The great number of dams which have been built already in the world today or those to be built in the future have been subject of special emphasis on the questions of dams' safety and their hazards. The terms "Safety" and "Hazards" are interrelated; the first means the quality of averting or not causing injury, danger, or loss; the second may be said to denote something unavoidable, danger or risk. The question of dam safety concerns the dam only, while the term dam hazard is much wider as it encloses in addition to losing the dam itself the risk of flooding of the downstream valley causing life loss, material and property losses and environmental damage. In this case, the reservoir behind the dam is called into play as an essential element in deciding the magnitude of the hazard.

Dam safety is normally controlled by the owner through proper selection of the site, ensuring good design, proper construction followed by competent management, applying appropriate inspections and repair measures; all these actions are to be done following recognized specifications, codes, laws, and regulations. The dam hazard question however, must be followed by national authorities and governments whose responsibility does not stop at issuing the required laws and legislations but also ensuring the correct following of them by the dams' owners, and this extends to give serious thoughts to the possibility of failure of the dam, even if the probability of such an event is infinitesimal. Planning for such a remote possibility includes the performance of dam break studies as a prerequisite to any work concerning flood zoning, early flood warning, evacuation plans, and rescue and salvage measures to reduce the damages to the minimum possible level. Emergency Action Plans (EAP) to meet all these must always be available, updated, and ready, and a certain level of preparedness shall be kept always to meet emergencies. The failure of a dam and the hazards it involves could take the dimensions of a national catastrophe in the absence of such measures.

In summary, the objectives of all this, as put by ICOLD, are the following:

i. To control the release of damaging discharges downstream of the dam,
ii. To restrict the likelihood of events that might lead to a loss of control over the stored volume and the spillway and other discharges,
iii. To mitigate through on-site accident management and/or emergency planning the consequences of such events if they were to occur [11].

These fundamental objectives and principals of dams' safety and mitigation of their safety hazards should apply to all dams and their associated reservoirs throughout their lifetime, whether during planning, design, construction phase, or their commissioning and operation, and having always in focus minimizing any loss or damage downstream in the event of uncontrolled accident or failure.

5. Dam Failure

Dam failure is the sudden and rapid uncontrolled release of water impounded by the dam due to collapse of the dam itself or, in some cases due to an upstream land slide into the reservoir with or without the collapse of the dam. Such an uncontrolled release of water may result from insufficient or faulty design, inferior construction procedures, malfunctioning of one or more components of the dam, or as in the case of landslides, insufficient investigation of the stability of the reservoirs`` slopes. Insufficient design in its turn may be caused by one of the following:

i. Misunderstanding of the geological conditions of the foundation of the dam. This leads to wrong or deficient foundation treatment, and seepage controls arrangements, or unexpected deformation of these foundations.
ii. Erroneous calculation of the inflow designed flood. This can result in overtopping of the dam due to insufficient spillway capacity and/ or

insufficient free board.

iii. Misinterpretation of the seismic conditions of the area and adopting seismic criteria which are not compatible with such seismic conditions.

Faulty design may include among many other things the use of improper factors of safety and method of stability analysis, selection of inappropriate construction materials, insufficient drainage arrangements of the foundation and the dam body. Similarly, inferior quality control during construction is an obvious cause which can lead to failure of a dam and needs no further comment.

Mismanagement in the operation of a dam can lead also to complications as far as safety is concerned. This may reflect on daily operation of the various components of the dam, or during flood events or maybe after a seismic event. Ensuring good management requires the service of experienced and seasoned personnel that are not only familiar with such routines but who will also carry out all required inspections and detect any anomaly in the behavior of the dam at an early stage and apply the proper remedies or report the problem to the higher technical level if it is beyond their available means.

Table 3 highlights some of the registered major dam failures in the world showing year of occurrence, the country, and number of fatalities during (1950-2019).

Table 3: List of major dam failures in the world (1950-2018), excluding Tailing dams` failures and those failures with fatalities less or equal 10, [12].

Dam	Date Fa Date	Location	Fatalities	Details
Machuchu-2 Dam	1979	Morbi, India	5000	Heavy rain and flooding beyond spillway capacity
Val de Stava Dam	1985	Tesero, Italy	286	Poor maintenance and low margin for error in design. Outlet pipes failed leading to pressure on dam
Kantale Dam	1986	Kantale, Sri Lanka	180	Poor maintenance, leakage, and consequent failure destroyed over 1600 houses and 2000 acres of paddy fields
Zeyzoun Dam	2002	Zeyzoun, Syria	22	2000 individuals displaced and over 10,000 directly affected
Shakidor Dam	2005	Pasni, Pakistan	70	Sudden and extreme flooding caused by abnormally severe rain
Gusau Dam	2006	Gusau, Nigeria	40	Heavy flooding. Approximately 500 homes were destroyed, displacing 1,000 people
Situ Gintung Dam	2009	Tangerang, Indonesia	98	Poor maintenance and heavy monsoon rain
Kyzyl-Agash Dam	2010	Qyzylaghash, Kazakhstan	43	Heavy rain and snow melt. 300 people were injured and over 1000 evacuated from the village
Patel Dam	2018	Solai, Kenya	47	Failed after several days of heavy rain
Xe-Pian Xe-Namnoy Dam	2018	Attapeu Province, Laos	36	Saddle dam under construction collapsed during rainstorm. 6600 people homeless, 98 missing
Note: For a more comprehensive list of dam failures, reference can be made to [12].				

Some major failures were excluded from this table as the number of fatalities was less or equal to ten, although they had caused extensive material losses. The case of Teton dam failure mentioned above is worth considering. The low number of fatalities of only 11 was due to early warning and efficient evacuation of the people who were at risk. The dam was located on Snake river, Idaho, USA, and it was an earthfill dam 100 meters high completed in 1976 and collapsed during first filling. Its failure caused the release of 296,000m^3 of water; fortunately, 30,000 people were evacuated from the downstream flooded area, and the number of human losses was only eleven. The failure was due to insufficient protection against foundation seepage and the misinterpretation of the characteristics and properties of the filling material. According to the data of the National Performance of Dams Program (USA), the number of failures and height of the failed dams from 1848 until 2017 in the United States are as shown in Table 4.

Table 4: NPDP Dam Failure Database summary (USA) [13].

Data Summary	**Value**
Period of Record	1848-2017
Number of Dam Failures All Dams < 15 m Dams > 15 m	 1645 1546 99
Number of States Having Dam Failures	50
State with the Most Failures	Georgia
States with the Fewest Failures	Hawaii Louisiana
Earliest Known Dam Failures	1848

Further data from the same source give more details on Dam Failure-Fatality statistics in USA as indicated in the following Table 5 for the period 1850-2016.

Table 5: Summary of the Dam Failure-Fatality Dataset (USA) 1850-2016 [14].

Parameter/ Summary	**Value(s)**
Period of Record	1850-2016
Number of years of Record	167
Number of Dam Failure Resulting in Fatalities	63
Frequency of Occurrences per year of Dam Failure Events	38%
Range of the Number of Fatalities that occurred over the Period of Record	1-2,209
Total Number of Fatalities that occurred over the Period of Record (A range is shown based on the variation of the estimates of the number of fatalities that occurred)	3,432-3,736
Average number of Fatalities per Year over the Period of Record	20.6-22.4

It is evident from these data and field investigations that the number of fatalities that may result from dam failure is function of number of factors; these include (but are not limited to):

i. Size of the dam and reservoir.
ii. Severity (depth, velocity, and arrival time) of flooding that occurs downstream.
iii. Population at risk at the time of the failure (time of year, time of day).
iv. Location of the population at risk downstream of the dam and in the area that is inundated.

v. Location of safe havens.
vi. Effectiveness of local emergency management services.

6. Dam Incidents

Dam incidents, contrary to dam failures, are events, which occur during the lifetime of a dam which threatens its safety, but they are manageable at an early stage, and the dam may be saved. So, dam incidents have considerable engineering and safety value in that they provide insight into the structural and functional integrity of dam systems and their operation.

Such events may be experienced in case of an earthquake event resulting in large settlement or the appearance of distress signs on the dam body and the appurtenant structures and/or the mechanical and electrical equipment, similarly these can happen during very high floods causing damage to the water ways or jamming of one or more gates, or even the uncontrolled release of water causing damage to the downstream.

Incidents may happen even during normal operation such as landslides into the reservoir without causing overtopping, ether because the volume of the slide is not so large or the reservoir level being low during the event, in which cases these mark near misses.

More incidents may happen due to errors on the part of the operators by not following the prescribed rule curves and the operation instructions. In this, category falls the early filling of the reservoir not anticipating further flooding and the very fast rate of drawdown which could affect dam stability; and even in some cases affecting the reservoir slopes stability due to saturation of the soil mass increasing its weight while stabilizing forces i.e. balancing water pressure and resisting friction force are reduced suddenly. Negligence and bad maintenance are another human failing, which may lead to the deterioration of the dam's materials, equipment and essential safety devices such as drainage systems.

Documenting and reporting all incidents even the minor of them is essential to ensure dam safety; and keeping log books of all observations and events are most important allowing proper diagnosis in similar future cases. Immediate actions by the operators must be undertaken to execute the necessary remedies or report the issues that are beyond their capacity to the higher technical levels. Besides repairs, modifications of the design may have to be done in serious cases. An example to such case is modifications made to increase the spillway capacity or raise the dam itself. Stabilizing landslides or rockfalls that shows signs of danger may have to be treated to increase their stability; an example to such a case is Derbendikhan Dam landslide in Iraq.

Drilling new drainage holes to replace clogged once, or performing remedial grouting works may also prove necessary during operation, and it takes diligent operators to first diagnose the need for such works through careful follow up of the instrumentations readings and their intelligent interpretation.

Keeping records of the frequency and impacts of events related to the general performance of dam is of prime value. Of such events; the occurrence of very high waves generated by violent winds, impacts of such winds on the operating systems, ice sheets jamming waterways, trash, and debris, which clog trash racks or intakes. Such reports help in finding and implementing technical solutions so that the dam safety as a whole is not compromised in similar situations.

Importance of the human factor and the value of training in enhancing “Dam Safety” play a very important role in avoiding dam incidents, which can lead to inadequate risk management. This is highlighted by the following paragraph quoted from a recent article on the importance of the human factor:

“Inadequacies” in risk management may be classified into three types:

1. Ignorance involves being insufficiently aware of risks. This may be due to aspects of human fallibility and limitations such as lack of information, inaccurate information, lack of knowledge and expertise, and unreliable intuition. Complexity can also contribute to ignorance.
2. Complacency involves being sufficiently aware of risks but being overly risk tolerant. This may be due to aspects of human fallibility and limitations such as fatigue, emotions, indifference, and optimism bias (“it won’t happen to me”). Pressure from non-safety goals can also contribute to complacency.
3. Overconfidence involves being sufficiently aware of risks, but overestimating the ability to deal with them. This may be due to aspects of human fallibility and limitations such as inherent overconfidence bias, which results in overestimating knowledge, capabilities, and performance”

The article goes on to state:

“Counterbalancing” the drivers of failure noted above, the human factors contributing to system capacity for safety generally emanate from what is routinely referred to as “safety culture”. The general idea of safety culture is that individuals at all levels of an organization place high value on safety, which leads to a humble and vigilant attitude with respect to preventing failure. For such a safety culture to be developed and maintained in an organization, the senior leadership of the organization must visibly give priority to safety, including allocating the resources and accepting the tradeoffs needed to achieve safety”, [15].

While all of this is well said and true; it is of paramount importance to realize that training in safety awareness and procedures is one of the most important factors in creating this “safety culture”, and it must be realized that such training is required at all organizational levels, not only on the level of operators of the dam, but the whole hierarchy up to decision makers at the top.

7. The question of loss of life and its evaluation

Loss of life due to dam failures has been experienced for a long time over history. Although, Table 1 shows some of the important registered cases of failure with their corresponding number of fatalities since the middle of the last century, other registered data indicates considerable life losses even before that [12], not to mention those cases which were left unregistered. The question of life loss did not take the full attention of societies before for many reasons. First, not such a great number of dams were built at the time, which meant also that not so many possibilities of failures existed. Second, many failures went unnoticed by the public due to poor communications or limited public news media; Third, the exponential growth in dam building activity since the beginning of the last century.

In spite of the advances in knowledge and construction technology, frequent failures and accidents did happen which were associated with loss of life, and the wide reporting of human fatalities drew much more attention to the question of dams as threats to human societies.

The worth of building new dams came to be examined not only by investors and banks but also by environmentalists, welfare societies, health organizations and insurance companies, and the question of loss of life became central in the evaluation of dam risks. Governments and owners in addition to other stakeholders started to take a keen interest in this question which led to the formulation of new methods of assessing dams’ safety and their risks especially oriented towards life loss.

Of the many governmental bodies and dam owners who have taken a keen interest in this question were the United States Bureau of Reclamation (USBR) and the United State Army Corps of Engineers (USACE). Their approach involved quantifying the failure likelihood category level of any dam as a function of both the critical loading conditions leading towards failure and the chance of its occurrence. A chance of occurrence probability of 1:10,000 as the threshold separating moderate likelihood from high likelihood zones of failure was accepted by both entities as a reasonable criterion for acceptable loss of life [16]. The concept of acceptable risks to human life has been the subject of research conducted by the Health and Safety Executives, UK (HSE) since the 1970’s. Although their research was mainly oriented towards risks in the industrial and nuclear sectors it had contributed to the definition of tolerable risk and acceptable risk in general in other areas such as dams. In this respect, HSE reckons that the individual risk/annualized failure probability guideline is generally taken as 1 in 10,000 per year. In the water resources industry, this threshold seems to describe an agreeable guideline. Further work was done to relate this concept to dams and their risk assessment by the Construction and Industry Research and Information Association, UK (CIRIA). Their work and findings were issued in the UK as a report in 2000 “CIRIA 568, Risks and Reservoirs”.

To quantify the risk paused by any dam to life and property, a matrix has been suggested by the USBR and USACE, shown in Figure 5. The location of dam under consideration on this matrix is obtained after thorough examination of the dam conditions so that the likelihood of failure is estimated with the help of indicators outlined in Table 6, and similarly the category or level of consequences is be obtained by referring to Table 7 where estimating of these consequences is based on loss of life taken as a measure of the risk posed by the dam [17].

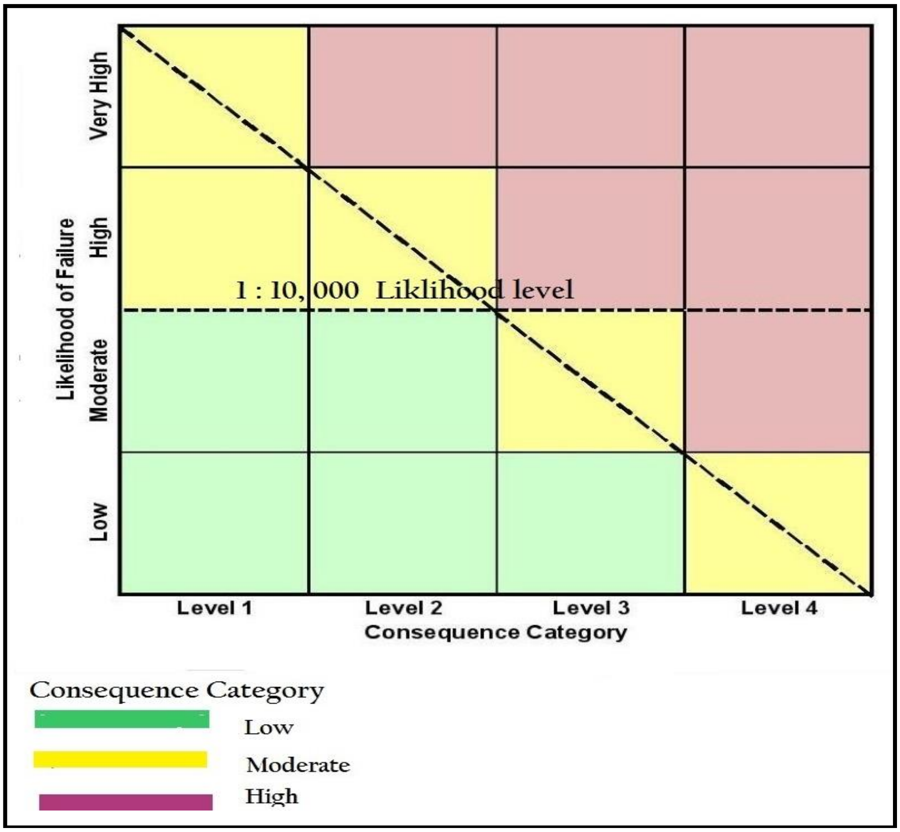

Figure 5: Quantitative Risk Matrix Format.

Table 6: Failure likelihood Categories.

Category Name	Description
Low Likelihood	The possibility cannot be ruled out, but there is no compelling evidence to suggest it has occurred or that a condition or flaw exists that could lead to its development (e.g., a flood or an earthquake with annual exceedance probability more remote than 1.0 x 10^{-5}/yr would cause failure)
Moderate Likelihood	The fundamental conditions or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily towards unlikely than likely (e.g., a flood or an earthquake with annual exceedance probability between 1.0 x 10^{-5}/yr and 1.0 x 10^{-4}/yr would likely cause failure)
High Likelihood	The fundamental conditions or defect is known to exist; indirect evidence suggests it is plausible; and key evidence is weighted more heavily towards likely than unlikely (e.g., a flood or an earthquake with annual exceedance probability between 1.0 x 10^{-4}/yr and 1.0 x 10^{-3}/yr would likely cause failure)
Very High Likelihood	There is direct evidence or substantial indirect evidence to suggest it has occurred and/ or likely to occur (e.g., a flood or an earthquake with an annual exceedance probability more frequent (greater) than 10 x 10^{-3}/yr would likely to occur.

Table 7: Consequences Categories (numbers refer to casualties).

Category Name	Category Description
0	No significant impacts to the downstream population other than temporary minor flooding of roads or land adjacent to the river
1	Although life threatening flows are released and people are at risk, loss of life is unlikely
2	Some life loss is expected (in the range of 1 to 10)
3	Large life loss is expected (in the range of 10 to 100)
4	Extensive life loss is expected (greater than 100)

8. Conclusion

History of dams' construction is full of mixed cases of successes and failures, and the chances of more failures still exist even today. The great number of dams that have been built during the last century and the ones being constructed in the two decades of the twenty century have resulted in a tremendous increase in the number of these dams all over the world. Such increase was dictated by the increasing demand for producing food to the growing populations, and their need for electric power. The need for flood protection is also demanded by the growing populations inhabiting river valleys. The risks posed by these dams to people, and material properties have grown in lieu of the large number of these dams. Even with the vast improvements in the ways of collection of data used, the much improved methods of design and the more refined methods of analysis, the probability of failure of dams, even if it is reduced, remains as a threat to human societies. This leads to concentrate attention on "Dam Safety" as a way of reducing dangers to human lives and material properties.

Dam Safety issues, as we visualize them, are not only taking care of the proper design and good construction of dams only, but extending this to their safe management and operation, in addition to more understandings of the natural hazards impacting them such as floods and earthquakes. The increasing number of aging dams adds another worry to dam owners due to the reduced competence of these dams as result of passage of time and deterioration of their materials and ancillaries, which merits special attention.

There exist now tremendous volume of records documenting case histories of dam incidents and failures. Lessons learned from these case histories have led to improved guidance and technical understanding, and ultimately to safer dams.

ICOLD (1995) listing shows that dam failures had continued over the previous four decades with less than 0.5% of the 12,138 large dams built between 1951 and 1986 [18]. However, this is still 59 failures around the world. Judging by the magnitude of losses resulting from these failure it is a clear that such statistics are misleading unless they are qualified with statistics of human fatalities and property damages associated with them which in these cases were. tremendous.

Long-term concerns over improving dam safety include, among other things, taking seriously future "Climate Change Impacts" on dams and the decommissioning of aged dams.

More emphasis over the need for safety measures and diligence in the future developments of dams need no further explanation. With the growing need for water for the expanding industry and agriculture to satisfy, the increased population dams will continue to be built and raised in height exasperating the need for stringent "Safety Measures".

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