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Dam Safety and Dams Hazards

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Abstract

Dam safety hazards towards human communities have increased tremendously during the last decades. They have resulted from dam safety problems leading to failure and being exasperated by the large losses at downstream areas due to increasing populations and land use. In this work, an attempt is being made to review the procedures being followed to reduces these hazards by improving dams safety standards. Classification of dams by their potential hazards are explained as used today for prioritize remedial actions in various countries of the world. The guiding principles of these classification are indicated and they are based on height of such dams and their storage and linked to the potential damage and harm they can create. Normally such classification and follow up actions are supported by various legislations and regulations issued by the respective governments. Moreover, conventions signed by riparian countries promote cooperation on mitigating safety problems of dams on transboundary rivers. Examples of such legislations and conventions are mentioned. Looking for having safer dams is an objective continually which is being pursued as more dams are needed in the future while existing dams continue to serve their objectives. Therefore, using lessons learned from previous failures is recommended taking the question of loss of life as a main doctrine.

Keywords: Dam Safety, Dam Hazards, Dams Classification, Potential Hazard, Loss of life.

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1. Introduction

Dams have served mankind since ancient times. Irrigation of agricultural land was the main drive for building dams in those days, and it remains as a very important tool for such use until today. By damming a river and controlling its flows this will harness flood waters of the wet seasons to utilize it in the dry periods. Flood control function of dams has saved humanity from great losses of lives and spared rich lands from inundation and damage. The importance of dams grew in the last century due to the need for electric power needed in industry and human applications such that a large percentage of the world electric power is generated by dams nowadays. According to dam's statistics of the International River Organization, there were in 2007 the following numbers of dams:

Global number of dams: c. 800,000

Global number of large dams: >40,000

Global number of major dams: >300

The same reference states that there was in 2007 more than 50,000 dams higher than 15m or more, and that some of them dated back to centuries, but most were built after World War II. About 5,000 dams have heights of 60m or more; another 350 of such giants were under construction in 2014 [1], [2].

Although dams are a blessing to the countries rich with rivers, they create hazards to population living in their downstream flood plains. The subject of dam safety, therefore, must be approached with caution and prudence. Dam safety cannot be concerned only with the structure itself, but it should be considered in relation to the population at risk in the downstream flood plain.

2. Dams Classification according to their size and their potential hazards

Different authorities have different classification systems for dams with respect to safety hazard`s evaluation related to them. These classifications serve either design, or licensing purposes, or may be used for other goals such as prioritizing remedial actions and budgeting planning. Most of these systems adopt criteria based on dam's parameters such as height or size of reservoirs and/or the potential hazards causing loss of life and economic losses. Few of these systems are presented here to introduce the philosophy behind dams safety procedures currently applied in the world today.

2.1 Classification of the International Congress on Large Dams (ICOLD)

The International Commission on Large Dams (ICOLD), considers any dam is large dam if its height is 15 meters or more measured from the lowest point of foundation to top of the dam. Dams with a height of 10 m or more are considered as high dams, if they satisfy one of the following criteria or a combination of more than one of them as set out in Table 1.

Table 1: ICOLD large dams classification criteria for dams >10 m in height [3].

Criterion	Requirement
Length of crest	> 500 m
Volume of reservoir	> 1 million m^3
Design flood	> 2000 m^3/sec.
Geological conditions	Difficult
Other considerations	Unusual Design

In considering the question of potential hazards posed by dams, ICOLD has modified these basic criteria to link the size of a dam to the hazards it could create and has adopted modified criteria based on the French Committee on Dams and Reservoirs' guidelines [3]. These guidelines consider the two parameters (H), the maximum height of the dam in meters, and (V) which is the reservoir's volume in m^3 in defining a numerical index $H^2\sqrt{V}$ to rate the Potential Hazard Classification (PHC). The relationship may be obtained by using semi-log paper; (V) on the X-axis and (H) on the Y-axis as shown in the chart given in Figure 1, this chart may be read in conjunction with Table 2 for obtaining the Potential Hazard Classification (PHC) for small dams not exceeding 25m in height and having reservoir volume not more than 100 million m^3.

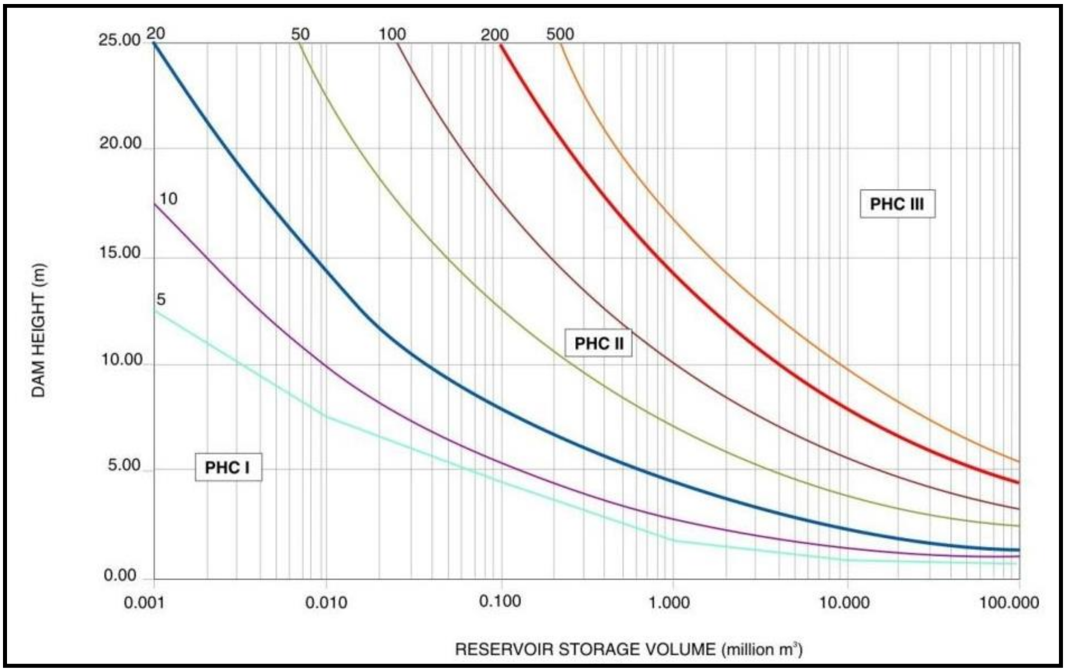

Figure 1: Relationship $H^2\sqrt{V}$ for small dams [3].

Table 2: Potential Hazard Classifications (PHC) [3].

Component	**Potential Hazard Classification (PHC)**		
	Low- (I)	Medium- (2)	High- (III)
$H^2 \sqrt{V}$	$H^2\sqrt{V} < 20$	$20 < H^2\sqrt{V} < 200$	$H^2\sqrt{V} \geq 200$
Life Safety Risk (number of lives)	~ 0	< 10	≥ 10
Economic Risk	Low	Moderate	High or extreme
Environmental Risk	Low or Moderate	High	Extreme
Social Disruption	Low (rural area)	Regional	National

This guideline; however, modifies ICOLD's definition for small dams given in Table 1, and qualifies them to be high dams if they follow the criterion shown below: Dams with height 5< H < 15 m and V>3hm^3.

Accordingly, the differentiation of small dams from large dams follows the boundaries in Figure 2. This classification is related directly to hazards posed by these dams and therefore, it is a better classification system than the original ICOLD classification.

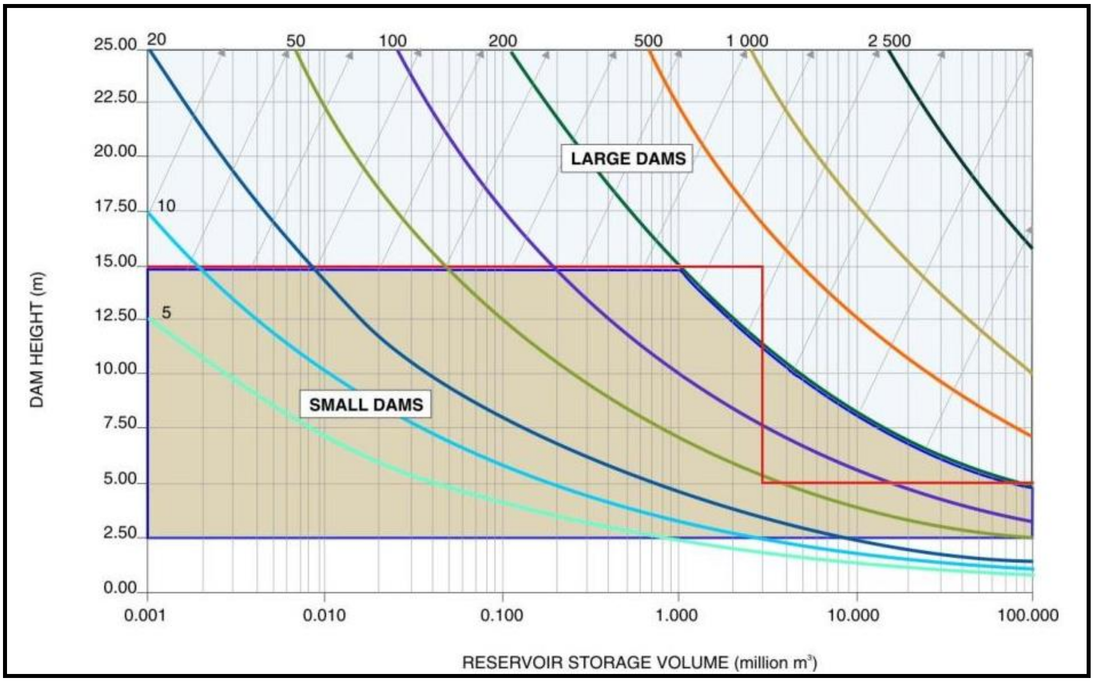

Figure 2: Classification of small and large dams [3].

2.2 Classification of the Federal Emergency Management Agency (FEMA) [4].

This agency was established in the USA in April 1979 with the objective of protecting people from hazards associated with nuclear power plants, the transportation of hazardous substances in addition to protection from and mitigating hazards associated with natural disasters. Enhancing public safety that is caused by dams became also one of its main concerns.

The classification of dams adopted and used by FEMA follows two criteria:

- Loss of life
- Economic, Environmental and Lifeline losses

Three classification levels are used, which are: LOW, SIGNIFICANT, and HIGH, listed in order of increasing adverse incremental consequences. The classification levels build on each other, i.e., the higher order classification levels add to the list of consequences for the lower classification levels, as noted in Table 3, and described below.

Table 3: Classification of dams according their hazard potential [4].

Classification	Loss of Human Life	Economic, Environmental, Lifeline losses
A- Low	None Expected	Low and Generally limited to Owner
B- Significant	None Expected	Yes
C- High	Probable, one or more expected	Yes

A. Low Hazard Potential

Dams assigned to the low hazard potential classifications are those where failure or miss- operation results in no probable loss of human life and low economic and/or environmental losses; but losses are principally limited to owners' properties only.

B. Significant Hazard Potential

Dams assigned to the significant hazard potential classifications are those dams where failure or mis-operation results in no probable loss of human life but can cause economic loss, environmental damage, disruption of lifeline facilities, or can impact other concerns. Significant hazard potential classified dams are often located in predominantly rural or agricultural areas but can be located in areas with population and significant infrastructure.

C. High Hazard Potential

Dams assigned to the high hazard potential classification are those where failure or mis-operation will probably cause loss of human life in addition to economic, environmental and lifeline losses.

This Hazard Potential Classification System recognizes that the failure or mis-operation of any dam or water-retaining structure, no matter how small, represents a potential danger to downstream life and property. Whenever there is an uncontrolled release of stored water, there is always the possibility, regardless of how unexpected, of someone being in the path of the discharge. The difference between the Significant and High Hazard Potential Classification levels is the loss of life criterion; whereby a high hazard dam may cause probable loss of human life and in a significant hazard potential dam such loss is not expected.

2.3 Other Classification Systems

Many States in the United States have their own systems of classification for dams, but all these dams fall under the jurisdiction of the Federal Emergency Management Agency (FEMA). These systems are mainly intended for licensing the construction of new dams, regulating the construction procedures, and setting rules for the operation and maintenance of such a dam. All have in view public safety and the reduction of the hazards posed by these dams to the public [5], [6]. Countries such as UK, Australia, Canada, and most of the European countries also have their classification with the same objectives. In Table 4, a summary of guidelines adopted by the Australian National Committee on Large Dams (ANCOLD for the classification of the potential hazards of dams is given. These guidelines introduce the term Population at Risk (PAR) as the criterion on which hazard classification is built. Population at Risk means all the population in the downstream flood plain, which is subjected to dam failure hazards [7], [8].

Table 4: Dam Hazard Categories according ANCOLD [7], [8].

<table>
<tr><th rowspan="2">Population at Risk (PAR)</th><th colspan="4">Severity of Damage and Loss</th></tr>
<tr><th>Negligible</th><th>Minor</th><th>Medium</th><th>Major</th></tr>
<tr><td>0</td><td>Very Low</td><td>Very Low</td><td>Low</td><td>Significant</td></tr>
<tr><td>1-10</td><td>Low
Notes 1 and 4</td><td>Low
Notes 4 and 5</td><td>Significant
Note 5</td><td>High C
Note 6</td></tr>
<tr><td>11-100</td><td rowspan="3">Note 1</td><td>Significant
Note 2 and 5</td><td>High C
Note 6</td><td>High B
Note 6</td></tr>
<tr><td>101- 1000</td><td rowspan="2">Note 2</td><td>High A
Note 6</td><td>High A
Note 6</td></tr>
<tr><td>>1000</td><td>Note 3</td><td>Extreme
Note 6</td></tr>
</table>

Note 1: With a PAR of 5 or more people, it is unlikely that the severity of damage and loss will be: Negligible.
Note 2: "Minor" damage and loss would be unlikely when the PAR exceed 10.
Note 3: "Medium" damage and loss would be unlikely when the PAR exceeds 1000.

Note 4: “Change to *significant* where there is the potential for one life being lost is recognized.
Note 5: Change to High where is the potential for one or more lives being lost.
Note 6: Refer to section 2.7 and 1.6 of ANCOLD Guidelines on the consequences of Dam Failure for an explanation of the range of High Hazard Categories.

In the previous table the likelihood of occurrence of hazardous incidents causing medium or major damage and loss is classified into categories of:

i. High A; Almost certain. The event is expected to occur in most circumstances,
ii. High B; Likely. The event will probably occur in most circumstances and,
iii. High C; Possible. The event could possibly occur at some time

It follows from all this that Public Safety is looked at in almost all countries in most careful and scrutinizing eyes. Concerning dams, they should be classified according to their potential impacts on the communities downstream as explained already. Such classification must be adopted and put into application; for new dams, this is done by thorough investigations and studies, safe designs, and proper construction procedures, which are commensurate with the class of the dam. For existing dams safe operation and routine safety checking and maintenance must be conducted as required by their operation and maintenance manuals and even by introducing new innovations in these fields such as new types of monitoring systems i.e. new instruments and/ or remote sensing methods. In the case of any anomaly is being discovered then all required corrective actions should be performed promptly to upgrade the safety conditions of the dam under consideration.
Thousands of dams have been built during the last 100 years and some of them are suffering from clear signs of aging and becoming serious threats to the Public. If corrective measures seem to be impractical or very costly, then the question of decommissioning them should be addressed seriously.

3. Dam safety legislations and Dam Safety Program

In great number of countries dams safety classification and required measures of public safety protection are defined by legislations in the form of laws, regulations, and guidelines. The classification systems mentioned in the previous section or very similar ones are embodied in such legislations in many countries such as USA, UK, France, Australia, and the latest bill on dam safety in India (2019) [9].
In many other countries such as Turkey, no specific legislation for dam classification and their required safety measures are available but the general requirements are identified following many laws and regulations, such as Protection against Flooding Law (1943), Civil Defence Act (1958), Measures and Assistance Regarding Natural Disasters affecting General Public Life Precautions Act (1959), DSI Regulation on Protection against Flooding (1982), The Environmental Law (1983), and Regulation on the Environmental Impact Assessment (2003) [10].

Other countries, Iraq for example, unfortunately have no classification system of their own on which dam safety legislation are based in spite of the numerous dams they own and the fact that they threaten the safety of millions of people. It is therefore time to sound the alarm so that the respective governments of these countries pay heed to this important question.

In Riparian countries sharing large transboundary river the classification and safety legislations of dams on transboundary rivers in the form of conventions and mutual cooperation take special importance as any safety threat in one of these countries will have its implications on the other sharing countries. Many such conventions have been developed and signed for river basins in the world. One example is the "Danube River protection Convention (1998) between fifteen European countries sharing the river basin which stipulates among other important issues preventive measures to control hazards originating from accidents involving floods, ice, or hazardous substances [11], [12].

In the Eastern Nile sub-basin spanning Egypt, Ethiopia, Sudan, and South Sudan, thirty transboundary dams operate in the region, including, Roseries in Sudan, Aswan in Egypt, and many smaller dams no higher than 15 meters, with a combined storage capacity of 210 billion cubic meters. More, including on the mighty Blue Nile, are being built such as the Renaissance in Ethiopia. Attention to dam safety is critical issue which concerns the design or the inadequate monitoring and maintenance which can increase the risk of dam failure and have significant flood consequences and affects river bank settlements, fisheries, power generation, agriculture, the environment, and the overall regional economy.

Through its dam safety program, the Nile Basin Initiative carried out by the Eastern Nile Technical Regional Office (ENTRO) with support from World Bank's Cooperation in International Waters in Africa program and CIWA works to build technical capacity and establish national and regional safety norms through national dam safety units so these countries can standardize dam safety management, safeguarding against such threats as dam breaches that put at risk a Nile Basin population that may double in 20-30 years.

CIWA is the Cooperation in International Waters in Africa program which is a multi-donor trust fund representing a partnership between the World Bank and the governments of Denmark, the European Union, Norway, Sweden, the Netherlands, and the United Kingdom.

Additionally, the collaboration among countries in the dam safety program allowed technicians across the region to discuss technical operational issues beyond dam safety, further increasing trust among the participating countries [13].

4. Dams Hazards and the Question of Loss of Life

Hazards caused by dams are now quantified by the loss of life that could result from their failure. Classification of dams according their potential hazards was treated in a previous paragraphs. But these hazards, as it can be seen, are not dependent only on the dam structure itself, but they are also linked to the nature of the downstream flood plain; its topography and its extent. Other important factors in this respect are the level of occupancy of the flood plain by people and how many of them are directly exposed to the danger of drowning. These hazards can be also modified by the administrative procedures and regulations which have been enacted to deal with such emergency, and the degree of preparedness for dealing with natural disaster events particularly related to flooding due to dam failures. Therefore it may be said that loss of life is influenced by the following factors:

i. The number of people occupying the dam failure flood plain,
ii. The severity of the flooding,
iii. The time available to warn people to the incoming flooding, and,
iv. The degree of preparedness to deal with such an emergency.

The procedure for estimating loss of life due to dam failure has been developed to great extent in the United States and it is based upon data from U.S dam failures. This procedure is composed of seven steps which are:

i. Determination of dam failure scenarios to evaluate.
ii. Deciding on time categories for which losses of life estimates are needed.
iii. Determination when dam failure warnings would be initiated.
iv. Finding out the area flooded for each dam failure scenario.
v. Estimating number of people at risk for each dam failure scenario and time category.
vi. Estimating the number of fatalities by applying empirically based equations or methods.
vii. Evaluating uncertainty.

According to Graham [14], each of the above steps is explained, which are as follows:

Step 1: Determination of dam failure scenarios to evaluate;

Loss of life may need two scenarios; failure of the dam with full reservoir during normal weather conditions and failure during large flood that overtops the dam.

Step 2: Deciding on time categories for which loss of life estimates are needed;

Normally, the number of people at risk in the downstream changes according to the season, and to the week and the day. So, the study must be repeated for selected time categories according to the varying occupancy of the flood plain. In the time category studies (Day) and (Night) estimates shall be made. The degree of occupancy can vary considerably between (Day) and (Night) due to the number of computers who are present at their works during the day but leave the area to outside locations for the night which changes the degree of occupancy. The initial time of sounding the alarm must be repeated in such studies since people are more likely to respond to this alarm during daytime than during night.

Step 3: Determine when dam failure warnings would be initiated;
The most important factor affecting loss of life is when the warning of the incipient failure has been initiated. Based on data collected from dam failures in the U.S since 1960 and data from Vajont Dam failure in Italy, Malpasset Dam failure in France and St. Francis Dam failure in California it is found that alarm sounding is less likely during the night than during the day, that timely sounding of the alarm for dams, with smaller reservoirs with little flood storage and smaller catchment basins, are also less likely. Limited data also shows that timely warning is less likely for concrete dams than for earth dams. Table 5 shows guidelines, which help in estimating warning time to be used in loss of life studies resulting from dam failures. The data are for earth fill dams and based on actual collected data.

Table 5: Guidelines for estimating warning time in loss of life studies for dam failure scenarios (Earth fill Dams).

Mode of Failure	Special Considerations	Time of Failure	When Would Dam Failure warning is initiated	
			Many Observers at dam site	No Observers at dam site
Overtopping	Drainage area < 260 km^2	Day	0.25 hrs. before dam failure	0.25 hrs. after fw* reaches populated area
	Drainage area < 260 km^2	Night	0.25 hrs. before dam failure	1 hrs. after fw reaches populated area
	Drainage area > 260 km^2	Day	2 hrs. before dam failure	1 hrs. before dam failure
	Drainage are> 260 km^2	Night	1- 2 hr. before dam failure	0- 1 hr. before dam failure
Piping (full reservoir, normal weather)		Day	1 hr. before dam failure	0.25 hrs. after fw reaches populated area
		Night	0.5 hr. after dam failure	1.0 hr. after fw reaches populated area
Seismic	Immediate Failure	Day	0.25 hr. after dam failure	0.25 hr. after fw reaches populated area
		Night	0.5 hr. after dam failure	1.0 hr. after fw reaches populated area
	Delayed Failure	Day	2 hrs. after dam failure	0.5 hr. before fw reaches populated area
		Night	2hr. after dam failure	0.5 hr. before fw reaches populated area

Notes: “Many observers at Dam” means that tender lives on high ground within site or the dam is visible from the homes of many people or the dam crest serves as a used roadway. These dams are typically in urban areas. “No Observer at Dam” means there is no dam tender; the dam is out of site. These dams are at remote areas.
The Abbreviation * “fw” stands for flood water.

Step 4: Finding out the area flooded for each dam failure scenario.
Inundation map or other description of the flooded area is needed for each scenario. For such a requirement existing dam break studies and maps are useful.

Step 5: Estimating of number of people at risk (PAR) for each failure Scenario and time category. PAR is defined as the number of people occupying the dam failure flood plain prior to the issuance of any warning. Normally, this number varies during a 24 hours period. This is most likely dependent on the time of the year, day or week and time of the day during which the failure occurs. Sources of such data can be census data, field trips, aerial photographs, telephone interviews, topographic maps, and any other source that gives a realistic estimate of flood plain occupancy and usage.

Step 6: Estimating fatalities rates from empirically based equations or methods.
Suggested rates for estimating life loss should be obtained from Table 6, which was developed using data obtained from approximately 40 floods, many of which were caused by dam failure. The 40 floods include nearly all U.S. dam failures causing 50 or more fatalities as well as other flood events that were selected in an attempt to cover a full range of flood severity and warning combinations. Values of fatality rates given by this table are subject to the following factors:

i. Flood Severity,
ii. Available warning time to population at risk,
iii. The degree of understanding of the flood severity by those issuing the warnings (refer to notes given above below Table 6).

Number of fatalities may be obtained by multiplying the applicable fatality rates obtained from Table 6 by the numbers of population at risk PAR for each scenario of dam failure, which has been obtained from the previous step 5.

Table 6: Recommended Fatality Rates for Estimation Loss of Life Resulting from Dam failure.

Flood Severity	Warning Time (Minutes) see note (2)	Flood Severity Understanding See note 3	Fatality Rate	
			Suggested	Suggested Range
High When flood sweeps the area clean. High flood should be used only for locations flooded by the near instantaneous failure of a concrete dam.	**No Warning**	**Not Applicable**	**0.75**	**0.3 – 1.00**
	15 to 60	Vague	Use the values shown above and apply to the number of people who remain in the dam failure flood plain after warning is issued. No guidance is provided on how many people will remain in the flood plain	
	More than 60	Precise		
Medium Homes are destroyed but trees or mangled homes remain for people to seek refuge in or on. Use medium flood severity if most structures would be exposed to depths more than 3.3 m or if DV* is more than 4.6 m^2/s	**No Warning**	**Not Applicable**	**0.15**	**0.03 to 0.35**
	15 to 60	Vague	0.04	0.01 to 0.08
		Precise	0.02	0.005 to 0.04
	More than 60	Vague	0.03	0.005 to 0.06
		Precise	0.01	0.002 to 0.02
Low No buildings are washed away off their foundations. Or most structures would be exposed to depths of less than 3.3 m **or** if **DV** (1) rate would be less than 4.6 m^2/s	**No Warning**	**Not Applicable**	**0.01**	**0.0 to 0.02**
	15 to 60	Vague	0.007	0.0 to 0.015
		Precise	0.002	0.0 to 0.004
	More than 60	Vague	0.0003	0.0 to 0.0006
		Precise	0.0002	0.0 to 0.0004

Notes:

1. The parameter DV is used to separate areas that might receive Low Severity Flooding from those areas expected to receive Medium Severity Flooding. DV is computed from:

$$DV = \frac{Qdr - Q2.33}{Wdf}$$

Q_{dr} is the peak discharge at a particular site caused by the flood wave.
$Q_{2.33}$ is the mean annual discharge at the same site. This discharge can be estimated, and it is an indicator of the safe channel capacity.
W_{df} is the maximum width of flooding caused by dam failure at the same site.

2. Warning Time: The warning time categories shown indicate the time interval from beginning of the flood wave at the dam break to the time people in downstream become aware of the coming flood. The fatality rate in areas with medium severity flooding should drop below that recommended in Table 6 if the warning time increases well beyond one hour. Repeated dam failure warnings, confirmed by visual images on television showing massive destruction in upstream areas, should provide convincing evidence to people that a truly dangerous situation exists and of their need to evacuate. This should result in higher evacuation rates in downstream areas and in a lowering of the fatality rate.
3. Flood Severity Understanding: The flood severity understanding categories are as follows:
   i. Vague Understanding of Flood Severity means the warning issuers have not yet seen an actual dam failure or do not comprehend the true magnitude of the flooding.
   ii. Precise Understanding of Flood Severity means the warning issuers have an excellent understanding of the flooding due to observations of the flooding made by themselves or others. Warning in case (ii) will be weak and the response of people will also become weak. In case (ii) the warning will be strong, and the response of people will be expected to be also become strong.

Step 7: Evaluating Uncertainty

Various types of uncertainty can influence loss of life estimates. To ensure more reliable results it is necessary to perform the following actions:

Action 1: The suggested procedure for this action is to develop separate loss of life estimates for each dam failure scenario. Various causes of dam failure will result in differences in downstream flooding and therefore result in differences in the number of people at risk as well as the severity of the flooding.

Action 2: It suggests that the dam failure be assumed to occur at various times of the day or week. It is recognized that the time of failure impacts both when a dam failure warning would be initiated as well as the number of people who would be at risk.

Action 3: It focuses on when a dam failure warning would begiven. This warning initiation time could be varied to determine the sensitivity to this assumption.

From the preceding it may be seen that dam failures can result in death of innocent people. In the dam failure records there are plenty of cases of such occurrences that could not be avoided. But, it is important to carefully examine case histories and infer new knowledge of the causes, and find ways to avoid such failures. Nobody would think that it is possible to eliminate the probability of failure and bring it to zero value. Therefore, it is most important to secure the downstream population to the maximum limit by estimating the dam hazards and implement procedures to reduce loss of life through;

i. Flood zoning of the potential inundation area,
ii. Installation of warning systems that can give enough warning, train dam tenders to be vigilant and observant and act in the proper time,
iii. Preparation of emergency evacuation plans ready to meet such events.

5. Historical Dam Failures and Their Consequences

Studying case histories of dam failures help to understand why dams have failed and to stress caution in dealing with existing dams in order to enhance their safety and reduce their hazards towards the downstream areas.

In an attempt to verify the conclusion of the previous chapters one sample of 25 dam failure cases is selected for examination.

The sample is compiled from historic dam failure cases, which resulted in a significant number of fatalities. ICOLD data base was utilized [15], additional information are added on the causes of failures. To make the size of the sample reasonable the selected cases fatalities ranged between 2200 and 100 in spite of the fact that hundreds or even thousands of cases have resulted in fatalities less than 100; while catastrophes like the case of 1975 failure of Banqiao and Shimantan Dams in China (about 23,000 deaths) are considered as special cases of multiple dam failures in Domino Action, and therefore, they are not included.

In the prepared Table 7, selected dams are arranged in descending order of fatality numbers. Date of failure is included to indicate the standard of knowledge or state of the art in dam design and construction during the time of failure. Causes of failure are listed in addition to the heights of the dams (H) and volumes of reservoirs (V). By inspecting this table it becomes clear that although the height (H) and volume (V) play prominent roles in causing fatalities, they are not the only effective factors. The failure of South Fork Dam in USA, which had 18 million cubic meters of storage, killed 2200 people, while Iruhaika Dam failure in Japan, which had the same storage, killed 1200 persons only.

Mode of failure can cause higher fatalities, as they tend to happen at faster rate than the other modes of failure as in case of overtopping during high floods and intensive storms.

Table 7: Dam Failure Cases, Cause of failure, Type of dam, Volume of reservoir and number of fatalities.

Dam	Country	Year of Failure	Cause of Failure	Type of Dam	Height of Dam (m)	Volume of Reservoir (hm^3)	Number of Fatalities
Vajont	Italy	1963	O	A	262	Not relevant	2400
South Fork	USA	1889	O	E/R	21	18	2200
Machu	India	1979	O	E	26	101	2000
Iruhaika	Japan	1868	-	E	28	18	1200
Möhne	Germany	1943	H	M	40	134	1200
Khadakwasala	India	1961	FL	M	33	137	1000
Tigra	India	1917	FL	M	25	124	1000
Panshet	India	1961	I	E	49	214	1000
Gleno	Italy	1923	O	E	35	5	600
Puentes	Spain	1802	O	M	69	13	600
St. Francis	USA	1928	S	GR	62	47	450
Malpasset	France	1954	F	A E	66	47	420
Dale Dyke	GB	1864	I	E	29	3.2	230
Sempor	Indonesia	1967	I	R	60	56	200
Fergoug 1	Algeria	1881	FL	A	33	30	200
Gotvan	Iran	1980	-	-	22	-	200
Vega de Terra	Spain	1987	O	B	33	7.3	140
Mill River	USA	1874	-	-	13	-	140
Hyogiri	Korea	1961	-	E	15	0.2	139
Walnut Grove	USA	1890	O	R	31	11	129
Kantilla	Siri Lanka	1986	O	E	27	135	127
Zerbino	Italy	1935	S	GR	16	10	100
Eder	Germany	1943	H	M	48	200	100
Nanak Sagar	India	1967	I	E	16	210	100
Heiwalke	Japan	1951	-	E	22	0,2	100

Nomenclature:

Cause of Failure	Internal Erosion	Spillway Defect	War Hostilities	Overtopping	Stability	Foundation	Flood
	I	S	H	O	S	F	FL

Type of Dam	Masonry	Earth Fill	Rock Fill	Multiple Arch	Arch	Gravity	Buttress
	M	E	R	MA	A	GR	B

The conclusions that may be drawn from dam failure studies may be summarized as follows;

i. Mode of failure, whether sudden or takes some time contribute to the number of fatalities.
ii. Population at Risk (PAR) is very important. High population in the flood plain exposed to the danger of drowning increases the number of fatalities.
iii. Warning the (PAR) in very short time or failing to do so increase the number of fatalities and vice versa.

The technical safety of the dam on which point (i) above depends is the responsibility of the dam owner and his personnel on site, but ensuring the safety of downstream population referred to in point (ii) and point (iii) is the duty and responsibility of the communal authorities and government departments of the area or zone in which the dam is located and, which falls under their jurisdiction. This duty encompasses such things as, flood zoning planning, preparation of Emergency action plans (EAP), and finally installing good alarm systems

6. Conclusions

Due to the increased public awareness of the hazards that could result from dams failures of old dams or even new ones, procedures and actions are needed to reduce the threats they cause to communities living in the downstream flood plains. Based on actual failure cases and the related number of casualties new dam safety classification systems are adopted; these are linked directly to the potential losses of lives and properties. It is also recognized that DAM SAFETY has two major issues; these are:

i. The safety of the dam structure itself,
ii. The safety of the population at risk (PAR).

The first issue; for new dams the construction of such dams should be allowed only after fulfilling all safety requirements of thorough geological and hydrological investigations and deep analytical studies, preparation of safe designs, and by following proper construction procedures, which are commensurate with the class of the hazard classification of the dam under consideration. Thorough knowledge of case histories of dam failures helps in avoiding previous mistakes and results in safer designs. For existing dams safe operation and routine safety inspections and maintenance must be observed and followed. In the case of any defect is being discovered then corrective actions should be performed. One lesson learned from some case histories is that budgeting issues should not compromise needed corrective actions. Prioritization of the required repairs may help but without undue neglect or delay even for small issues. Aging dams form other source of threats due to their degradation and state of their materials deterioration. Safety of these dams must be reviewed regularly, and all necessary repairs and corrective actions must be applied promptly, or if this appears, unpractical or not economical, then one single moment must not be wasted, and they should be decommissioned

immediately. These technical and managerial decisions must be handled by competent staff should they be design engineers, operators, or dam owners.
In dealing with the second issue related to minimizing the dam safety hazards towards the (Population at Risk), no one would think that it is possible to eliminate the probability of failure and bring it to zero value in spite of all efforts in this respect. So, it follows that maximum effort must be directed towards reducing dam hazards towards this. Population through regional planning and flood zoning of the potential inundation areas, installation of efficient warning systems that can give enough warning time, increase public awareness of necessary actions in case of a catastrophe, employing trained and vigilant dam operators and to have one or many of them stationed at the site at all times, and above all to have at hand proper and workable emergency evacuation plans ready to meet such events. An example of such a successful plan was witnessed during the Oroville Dam crisis in 2017, when 200,000 people were evacuated [16].

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