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Dams and Floods

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ABSTRACT

The possible mitigation of floods by dams and the risk to dams from floods are key problems. The People's Republic of China is now leading world dam construction with great success and efficiency. This paper is devoted to relevant experiences from other countries, with a particular focus on lessons from accidents over the past two centuries and on new solutions. Accidents from floods are analyzed according to the dam's height, storage, dam material, and spillway data. Most of the huge accidents that have been reported occurred for embankments storing over 10 hm^3. New solutions appear promising for both dam safety and flood mitigation.

1. Introduction

Floods are and will continue to be a key problem in many countries and especially in the People's Republic of China, where rain intensity and flood discharge per square kilometer are close to the highest in world data. China has a great deal of experience in flood mitigation and has built a large portion of the world's dams since 1950, including very large dams and dams with many efficient innovations by Chinese engineers.

This paper, however, focuses on the dams of other countries; it is mainly devoted to lessons from dam accidents linked to floods over the past two centuries, and to possible improvements based on recent technical progress. It is predominantly based on the reports and bulletins of the International Commission on Large Dams (ICOLD). ICOLD classifies large dams as those that are higher than 15 m or that store over 3 hm^3 [1].

The analysis below is separated into embankments and concrete dams. Floods from ice and snow melt are not studied because such floods are very specific and cause only a small proportion of dam accidents. No reference is made to tailing dams, which have specific risks.

2. Basic data on extreme rains and floods

Many studies have been devoted to extreme flood evaluation, especially in the past, and have used various theories and methods. The results vary with the method used and with the people using the methods; a significant number of dam failures have been linked with huge under-evaluations. No method of evaluation has had full success, and all appear to be questionable on some points. A reasonable conclusion is that a serious uncertainty exists for evaluating flood values of very low probability. Although this uncertainty currently seems to be less important for yearly probabilities of 1/100 or 1/1000, the impacts of climate change may seriously affect these probability values. It is likely that all flood evaluations will remain very uncertain, aside from yearly floods.

Therefore, it seems advisable to use several solutions in order to avoid significant under-evaluations by a single method. For extreme floods, it is possible to have a range of magnitude if referring to extreme world data on rains and floods according to the catchment area; Chinese data (Table 1) are very close to the world maxima (Table 2) [2].

The duration of an extreme flood increases with the catchment area: usually 2–3 h for a catchment of 1 km^2, 5–20 h for a catchment of 100–1000 km^2, or several days for a catchment over 100 000 km^2. The extreme rain depth corresponding to an extreme world flood has been found to be about the same irregardless of catchment area, and is reported as being in the range of 500 mm for various catchment areas (Table 1). Extreme flood

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volume per square kilometer of catchment area has been found to be in the range of 0.5 hm^3, but the duration of such floods varies considerably. For such volumes, almost all the floods included waterflow from rainfall; for a catchment area of 1 km^2, the extreme world rain volume of 0.5 hm^3 is in accordance with a peak of 100 $m^3 \cdot s^{-1}$ and a flood of a few hours.

Thus, for a catchment area under 1000 km^2, a very rough preliminary evaluation of extreme floods may be given, according to the catchment area and to the extreme rainfall registered in the climatic area as compared with the extreme rainfall world values. Such an evaluation may at least favor comparisons between dams of the same country or climatic area while avoiding huge under-evaluations. Simple adjustments may be made according to the catchment shape. The formula $q = k \cdot S^{0.75}$, with k as a regional coefficient and S as the catchment area, may give a preliminary evaluation [2,3].

3. Embankments (beyond those in China)

3.1. Existing dams

Existing dams may be classified according to the following criteria [1]:

- **Height:** About 5000 dams are higher than 30 m, 15 000 are between 15 m and 30 m high, and hundreds of thousands are between 5 m and 15 m high.
- **Storage:** Hundreds of dams store over 500 hm^3, 5000 store between 10 hm^3 and 500 hm^3, and over 100 000 store between 0.1 hm^3 and 10 hm^3; of the latter, 15 000 are classified by ICOLD as "large dams" because they store over 3 hm^3.
- **Material:** About 2500 dams are rockfill; most are higher than 30 m. Within earthfill dams, the quality of material has varied considerably, with a significant impact on flood risk. Since 1950 in industrialized countries, and since 1980 in other countries, most large earthfill dams have included wide sections of well-compacted clay materials, which better withstand overtopping; the breaches from floods widen slowly. Before 1930, the quality of earthfill was rather poor in many dams. Key progress was first made in the US, with better theoretical knowledge and efficient equipment for compaction. However, the low cost of labor in many Asian countries led to many medium- or low-height embankment dams being built without heavy equipment—and thus with questionable earthfill quality—up until 1980. For those dams, breaches from overtopping could extend widely and quickly.
- **Spillway:** The choice of spillway varies with the discharge as well as with the country, traditions, and regulations. According to the ICOLD world register of dams [1] and bulletin No. 83. [4], most dams with a discharge of under 1000 $m^3 \cdot s^{-1}$ have a single free-flow spillway. A majority of dams with a discharge over 1000 $m^3 \cdot s^{-1}$ have a single gated spillway. Accordingly, the reservoirs for most dams storing over 10 hm^3—which requires a catchment area of hundreds or thousands of square kilometers and which thus indicates significant flood values—are gated, while most reservoirs storing about 1 hm^3 and requiring small catchment areas have a single free-flow spillway. Few existing dams associate a gated and an un-gated spillway, except in Italy, due to a specific regulation there.

3.2. Flood failures of embankment dams in operation and remedies

The following data are mainly from ICOLD bulletins [3,5,6] and from the 1974 ICOLD report [7]. They refer to large dams—that is, dams higher than 15 m or storing over 3 hm^3. There are about 25 000 large embankment dams (not including dams in China), of which 10% were built before 1930.

Although some dam failures by flood were structural spillway failures, most were by crest overtopping and erosion of the downstream face and toe. The time for creating and widening a breach varies with the dam's material:

- Well-compacted clay materials may withstand a 0.5 m nappe depth for hours, and the breach may widen slowly.
- Poorly compacted materials may be breached by a 0.3 m nappe depth in one hour, and the breach may widen quickly.
- Rockfill may withstand a 1 m nappe depth for hours, but a breach may widen quickly.

The duration of overtopping is thus a key element of risk. Failures of 70 large dams in operation by flood have been reported. Many may not have been reported; however, this value very probably includes the great majority of failures of large reservoirs or failures with many fatalities.

The rate of failure has thus been 0.3% or 0.4% for an average life of 50 years, which is equivalent to an average yearly probability of about 6×10^{-5}. This rate is about the same for dams higher than

Table 1
Chinese rainfall data (mm).

Duration	Area (km^2)							
	Point	100	300	1 000	3 000	10 000	30 000	100 000
1 h	401	185	145	107	41			
3 h	550	447	399	297	120			
6 h	840	723	643	503	360	127		
12 h	1 400	1 050	854	675	570	212		
24 h	1 673	1 200	1 150	1 060	830	435	306	155
3 d	2 749	1 554	1 460	1 350	1 080	940	715	420
7 d	2 749	1 805	1 720	1 573	1 350	1 200	960	570

Table 2
World maximal floods registered.

Catchment (km^2)	1	10	100	1 000
Flood peak ($m^3 \cdot s^{-1}$)	100	700	4 000	15 000
Flood peak (km^{-2})	100	70	40	15