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Analysis of earth dam failures: A database approach

L.M. Zhang[a]*, Y. Xu[a] and J.S. Jia[b]

[a]*Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong, China;* [b]*China Institute of Water Resources and Hydropower Research, Beijing, China*

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A dam may fail when the loading exceeds the resistance against overtopping, internal erosion, slope instability, sliding/overturning, excessive deformation etc. To investigate the causes of failures, it is necessary to study characteristics of the dams which have experienced failures. In this work, more than 1600 dam failure cases throughout the world excluding China are compiled into a database, including details of the dams, the reservoirs, the triggers and the failures. This paper focuses on failure of earth dams, which make up 66% of the failure cases in the database. A statistical analysis of the failure characteristics is conducted. According to dam zoning and corewalls, earth dams are divided into four typical categories: homogeneous earthfill dams, zoned earthfill dams, earthfill dams with corewalls, and concrete faced earthfill dams. Further analysis of the failure modes and causes of the four types of earth dams is carried out. Potential locations at risk are also described to provide the reader with a better understanding of earth dam failures.

Keywords: dam safety; disaster; failure; seepage; flood risk analysis and management

Introduction

In recent years, dam safety has drawn increasing attention from the public. This is because floods resulting from dam failures can lead to catastrophic loss of life and property, especially in densely populated areas. For instance, the breaching of the 62 dams in Henan Province of China in August 1975 during an extreme storm caused a regional death count of about 26,000 (Ru and Niu 2001). A robust understanding of the characteristics of dam failures is of critical importance to dam risk mitigation. In this paper, the failure of a dam is identified according to the following definitions of failures type 1 and type 2 by the International Commission on Large Dams (ICOLD) (1974). Failure type 1 is a major failure involving the complete abandonment of the dam while failure type 2 is a failure that at the time may have been severe but has since been successfully repaired and the dam has again been brought into use.

A number of studies have been devoted to investigating dam failures. The ICOLD has reported statistics of dam failures (ICOLD 1974, 1995). The United States Committee on Large Dams (USCOLD) has made two surveys of incidents to dams in the United States (USCOLD 1975, 1988). Many researchers also conducted analyses of dam failures using statistical methods (e.g., Howard 1982, Silveira 1984, Foster *et al.* 2000). Yet, few attempts have been made to characterise the failure modes and causes for specifically classified earth dams.

In this study, more than 1600 dam failure cases throughout the world excluding China are compiled into a database. A total of 1065 failure cases of earth dams in the database are utilised to study earth dam failures through statistical analysis. Based on the database, the failure modes and causes of these earth dams are analysed according to dam and material types. Potential locations at risk are also described to provide the reader with a better understanding of earth dam failures. Owing to page limit, this paper only discusses the failure causes based on information of past failures; mechanistic analyses are not included.

Establishment of database

More than 1600 dam failure cases have been collected from the literature (e.g., Vogel 1980, USCOLD 1975, 1988, Singh 1996, Stanford University 1994) and compiled into a database. Details of the characteristics of the dams and the failure information were collected. The cases comprise earth dams, concrete dams, masonry dams, rockfill dams, and so on. Figure 1(a) compares the percentages of these types of dams and shows that 66% of all the cases are earth dams. The failure cases are from over 50 countries, including the US, India, and the UK, but excluding China. The dam failures in China are compiled in a

*Corresponding author. Email: cezhangl@ust.hk

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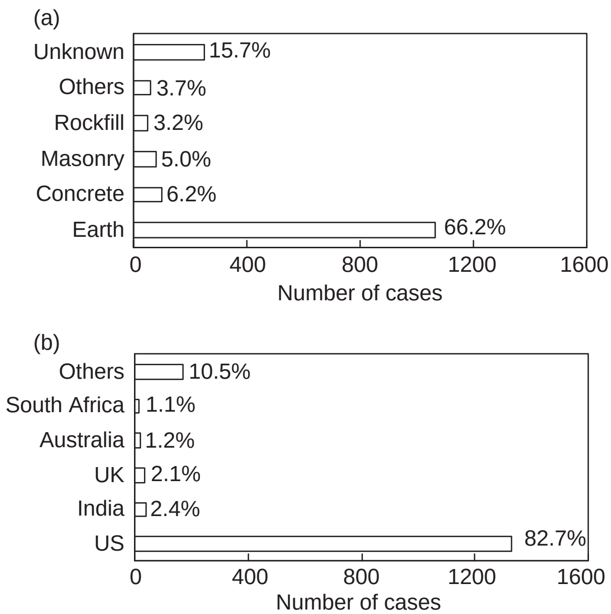

Figure 1. Statistics of (a) dam type and (b) geographic distribution of dam failures.

separate database by the China Institute of Water Resources and Hydropower Research (IWHR) (IWHR 2008) in a cooperative research. Figure 1(b) shows the geographic distribution of the failure cases. The US reported the most amount of cases, about 83% of the total population. Note that the reported numbers do not necessarily reflect the amount of dam failure cases that actually occurred. The database has three primary functions: information searching, statistical analysis, and system management for editing and updating.

Statistics of earth dam failures

Characteristics of earth dams

As indicated earlier, 1065 out of over 1600 failure cases are earth dams. Table 1 shows the reservoir capacities of the failed earth dams. Among the cases with known capacities, most reservoirs have capacities less than 1×10^8 m^3. Table 2 shows the heights of the failed earth dams, of which more than half are less than 15 m high. Table 3 presents the construction time of the failed earth dams. The dams constructed during two periods, 1910–1919 and 1960–1969, appear to have suffered the highest rate of failure. Table 4 further shows the ages of the earth dams at the time of failure. It is indicated that a dam is most likely to fail within its first five-year service, especially during the first year after construction.

According to dam zoning, earth dams are classified into four major categories as sketched in Figure 2: homogeneous earthfill dams, zoned earthfill dams, earthfill dams with corewalls, and concrete faced earthfill dams. Homogenous earthfill dams are composed almost of the same material throughout the cross section. Zoned earthfill dams are composed of

Table 1. Reservoir capacities of the failed earth dams.

Capacity range ($\times 10^6$ m^3)	Number of cases	Percentage (%)
>1000	7	0.7
1000-100	20	1.9
100-10	71	6.7
10-1	59	5.5
<1	112	10.5
Unknown	796	74.7
Sum	1065	100.0

Table 2. Heights of the failed earth dams.

Height range (m)	Number of cases	Percentage (%)
>100	3	0.3
100-60	10	0.9
60-30	53	5.0
30-15	186	17.5
<15	659	61.9
Unknown	154	14.5
Sum	1065	100.0

Table 3. Construction time of the failed earth dams.

Construction year	Number of cases	Percentage (%)
Before 1800	8	0.8
1800–1849	10	0.9
1850–1859	10	0.9
1860–1869	15	1.4
1870–1879	7	0.7
1880–1889	22	2.1
1890–1899	32	3.0
1900–1909	43	4.0
1910–1919	55	5.2
1920–1929	41	3.8
1930–1939	35	3.3
1940–1949	23	2.2
1950–1959	42	3.9
1960–1969	59	5.5
1970–1979	37	3.5
1980–1989	9	0.8
After 1990	2	0.2
Unknown	615	57.7
Sum	1065	100.0

Table 4. Ages of the earth dams at failure.

Age range	Number of cases	Percentage (%)
Under construction	32	3.0
0–1	89	8.4
1–5	80	7.5
5–10	38	3.6
10–15	38	3.6
15–20	26	2.4
20–30	36	3.4
30–40	21	2.0
40–60	36	3.4
60–80	22	2.1
80–100	10	0.9
100–150	10	0.9
>150	4	0.4
Unknown	623	58.5
Sum	1065	100.0

several materials, each for one zone (e.g., zones A and B consist of two different types of soil in Figure 2(b)). An earthfill dam with a corewall contains earth fills and a low-permeability wall (e.g., clay or concrete), which is often built vertically or inclined towards the upstream of the dam. A concrete faced earthfill dam is composed of earth fills and an impermeable concrete facing on the upstream slope. Table 5 shows the subdivision of the failed earth dams in terms of the dam types in Figure 2. Note that the information available only allows the identification of the types of 129 dams.

Causes of dam failures

Many causes of dam failure have been identified (e.g., Johnson and Illes 1976, USCOLD 1988, ICOLD 1995). Several causes are often involved in a single failure and these causes are interrelated with each other. This study follows a similar classification of failure causes as proposed by the Ministry of Water Resources of the People's Republic of China (MWR 1993). Natural or manmade disasters are also considered as a typical cause because disasters are likely to become more frequent in the future. Table 6 presents the detailed categories of dam failure causes. Note that 'piping' in Table 6 is a general term that describes internal failure mechanisms related to seepage.

Table 5. Subdivision of failed earth dams in terms of dam type.

Dam type	Number of cases	Percentage (%)
Homogeneous earthfill	61	5.7
Zoned earthfill	45	4.2
Earthfill with corewall	21	2.0
Faced earthfill	2	0.2
Unknown	936	87.9
Sum	1065	100.0

Figure 3 shows the percentages of causes for earth dam failures. Most of the cases are caused by either overtopping or technical deficiencies. These two causes led to over 80% of all failures. Figure 4 shows specific percentages of technical deficiencies leading to dam failures. It is clearly seen that 64% of technical deficiencies are associated with piping. Overall, the most common causes of earth dam failures are overtopping and piping. The principal influence factor on overtopping is insufficiency of spillway capacity. The single most adverse factor for piping is cracks, which can be caused by differential settlement, shrinkage, interfaces with abutment or embedded structures, and hydraulic fracturing.

Analysis of four types of earth dams

As shown in the previous section, four types of earth dams are considered: (1) homogeneous earthfill dams, (2) zoned earthfill dams, (3) earthfill dams with corewalls, and (4) concrete faced earthfill dams (See Figure 2). Table 7 shows a summary of failure causes for the four types of earth dams based on 129 cases. For homogeneous earthfill dams and zoned earthfill

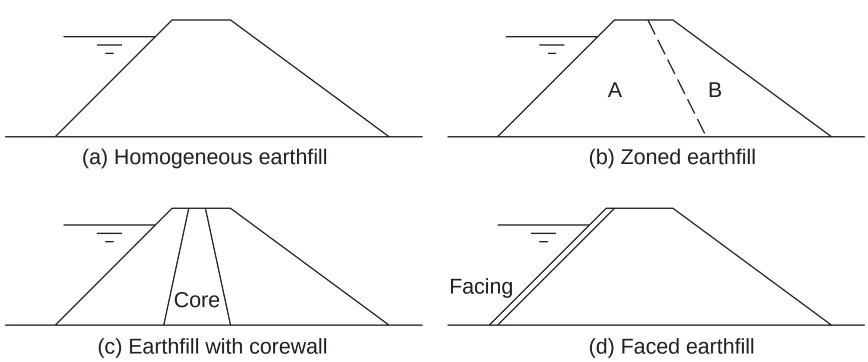

Figure 2. Sketches of four typical types of earth dams.

Table 6. Categories of dam failure causes (Modified based on MWR 1993).

No.	Causes
1	Overtopping
	(1) Insufficient spillway capacity
	(2) Extreme flood exceeding design criteria
2	Technical deficiencies
	(1) Piping in dam
	(2) Sliding of dam
	(3) Piping in foundation
	(4) Piping around spillway
	(5) Quality issues in spillway
	(6) Piping around culverts and other embedded structures
	(7) Quality issues with culverts and other embedded structures
3	Poor management
	(1) Loss of reservoir capacity for flood control due to over storage prior to flood season
	(2) Poor maintenance and operation
	(3) Temporary heightening of spillway crest not removed in time
	(4) Organisation issue: unclear responsibility for dam management
4	Disasters
	(1) Earthquakes
	(2) Wars and terrorist attacks
	(3) Breaching of upstream dam
	(4) Reservoir landslides
	(5) Rodent den
5	Others
	(1) Spillway blockage due to bank slide in reservoir
	(2) Excavation on dam for discharging
	(3) Poor design options
	(4) Poor planning of project layout
6	Unknown

dams, overtopping and piping are the two dominant failure causes. In contrast, for earthfill dams with corewalls, failures are mostly attributed to overtopping whereas piping appears to become less important. It is evident from the comparison that the corewall plays a key role in preventing piping in the dam. In practice, one or two layers of filters are usually constructed on the downstream side of the corewall, which help prevent piping failure in the core. Owing to insufficient data (only 2 cases), the failure causes for concrete faced earthfill dams are not conclusive in this study.

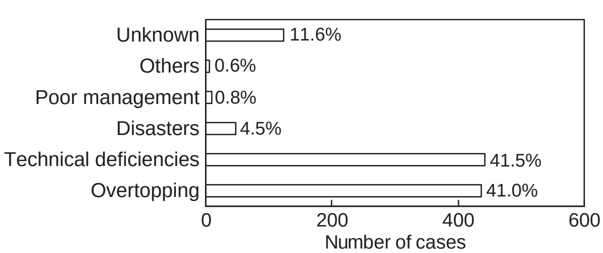

Figure 3. Percentages of causes for earth dam failures.

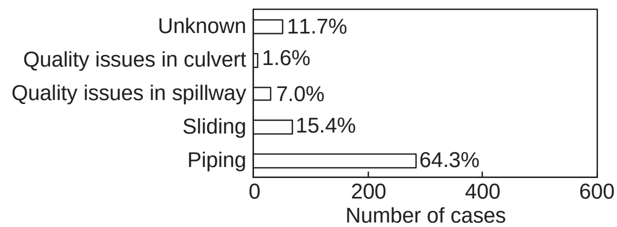

Figure 4. Percentages of technical deficiencies for earth dam failures.

In order to better characterise the failure modes and causes, a dam system can be divided into several parts, called ‘potential locations at risk’, as shown in Figure 5. Note that ‘at risk’ in this paper means possibility of a failure mode associated with a specific potential location. For instance, the overtopping failure may be due to insufficient capacity of the spillway in a dam system. The two primary failure causes, overtopping and piping, can be discussed in relation to these potential locations at risk. Homogeneous and zoned earthfill dams are grouped together owing to their similar failure causes, as indicated in Table 7.

Homogeneous/zoned earthfill dams

Dam failures owing to overtopping often occur in the flood season. As presented before, insufficient spillway capacity is a major reason for overtopping. Therefore, the most important potential location at risk is at the spillway. The second potential location at risk is the downstream slope. The erodibility of the downstream slope material is one of the controlling factors for the erosion process over time, and hence determines whether a dam eventually fails or not. The foundation may be another potential location at risk. This is because the settlement of dam is often attributed to a weak foundation and the foundation settlement will cause the settlement of the dam crest and reduce the freeboard of the dam. In summary, spillway, foundation, and downstream slope are believed to be potential locations at risk in terms of overtopping failure. Given these potential weaknesses of a dam, however, whether overtopping occurs or not depends on the loading (i.e. floods).

For dam failures owing to piping, the impact of inflow floods does not seem to be extremely significant, although floods do increase the possibility of piping occurrence by causing larger hydraulic

Table 7. Summary of failure causes for four types of earth dams.

Earth dam type	Technical deficiencies: Overtopping	Technical deficiencies: Piping	Technical deficiencies: Others	Poor management	Disasters	Sum
Homogeneous earthfill	23	26	5	1	3	3
Zoned earthfill	18	17	6	–	1	3
Earthfill with corewall	13	6	1	–	1	–
Concrete faced earthfill	–	2	–	–	–	–

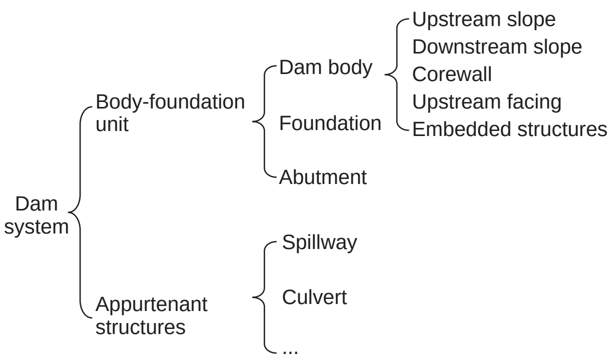

Figure 5. Potential locations at risk in a dam system.

gradients. Whether piping occurs or not primarily depends on the dam system itself, including the configuration, filter design, and construction quality of the dam, as well as the geologic conditions and connections of the dam with the abutment slopes or any embedded structures. Compared to overtopping failure, more potential locations at risk are found for piping failure, which can be any part of the dam system, as shown in Figure 5. For instance, a faulty foundation can lead to piping failure in several ways. In the first scenario, if the abutment bedrock is too steep or contains faults not adequately treated, an adverse seepage through the foundation can develop. In the second scenario, soft soils in the foundation can lead to differential settlement cracks in the dam, resulting in piping through the dam. In the third scenario, weak seams left at the interface between the dam and the foundation, or between segregated fill layers, can result in contact seepage along the interface (Zhang and Chen 2006). Any of the above scenarios may be accompanied by the other two. Therefore, it is rather difficult to detect the piping paths.

Earthfill dams with corewalls

Failures of earthfill dams with corewalls due to overtopping are similar to that in section 4.1 for homogeneous/zoned earthfill dams, except at the location of corewall. The corewall often consists of less erodible materials, such as masonry, asphalt concrete, or clay. The erosion process of the corewall zone is relatively slow, allowing more time for warning and mitigation of losses, and taking actions to limit the extent of dam failure.

For dam failures caused by piping, appreciable differences exist between homogeneous/zoned earthfill dams and earthfill dams with corewalls. The corewall has a good control of seepage through the dam body; the piping paths are more likely to be associated with the foundation, the abutment, or their interfaces with the dam. This does not mean that the dam body is absolutely free from piping. Instead, hydraulic fracturing is a common phenomenon that creates preferential flow paths in the clay corewall (e.g. Zhang and Du 1997). As a result, the corewall clays erode as water flows along the hydraulic fractures. It may be concluded that foundation, abutment, or their interfaces with the dam body are noticeable potential locations at risk for earthfill dams with corewalls; while piping may develop through the dam, owing to either hydraulic fracturing of the corewall or poor contact with any embedded structures.

Table 8. Summary of potential locations at risk for typical types of earth dams.

Earth dam type	Overtopping: High risk	Overtopping: Low risk	Piping: High risk	Piping: Low risk
Homogeneous/zoned earthfill	Spillway; Downstream slope	Foundation	Dam body; Foundation; Abutment	
Earthfill with corewall	Spillway; Downstream slope	Foundation; Corewall	Foundation; Abutment	Dam body

Potential locations at risk

The locations at risk in homogeneous/zoned earthfill dams and earthfill dams with corewalls are summarized in Table 8. These potential locations at risk are ranked in two levels: 'High risk' and 'Low risk'. The classification is somehow judgemental, of which 'High' and 'Low' are simply based on frequency of occurrence in the dam failure database.

Conclusions

Based on 1065 cases of earth dam failures, a statistical analysis of the failure characteristics has been conducted. The modes and causes of failure for carefully classified earth dams, as well as potential locations at risk, have also been studied. Several conclusions can be drawn:

(1) The most common causes of earth dam failures are overtopping and piping, particularly for homogeneous earthfill dams and zoned earthfill dams.
(2) For earthfill dams with corewalls, failures are mostly attributed to overtopping, whereas piping appears to be less likely because the corewall materials are less erodible and well-designed filters are present.
(3) For homogeneous earthfill dams and zoned earthfill dams, spillways, foundations, and downstream slopes are believed to be potential locations at risk for overtopping failure; while any part of the dam system can be a potential location at risk for piping failure.
(4) For earthfill dams with corewalls, the progress of overtopping failure is slower as the corewalls may erode slowly. Piping failure often occurs at foundations, abutments, or their interfaces with the dam body, which are noticeable potential locations at risk. However, piping may still develop in the dam owing to either hydraulic fracturing of the corewall or flows in discontinuities along embedded structures.

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References

Foster, M., Fell, R., and Spannagle, M., 2000. The statistics of embankment dam failures and accidents. *Canadian Geotechnical Journal*, 37 (5), 1000–1024.

Howard, T.R., 1982. Statistical analysis of embankment dam failure. *Proceedings of 19th Annual Engineering Geology and Soils Engineering Symposium*, Pocatello, ID, USA, 1–17.

ICOLD, 1974. *Lessons from dam incidents*. International Commission on Large Dams (ICOLD), Paris.

ICOLD, 1995. *Dam failures statistical analysis, Bulletin 99*. International Commission on Large Dams (ICOLD), Paris.

IWHR, 2008. *Chinese dam failures database*. China Institute of Water Resources and Hydropower Research (IWHR), Beijing.

Johnson, F.A. and Illes, P., 1976. A classification of dam failures. *Water Power and Dam Construction*, 28 (12), 43–45.

MWR, 1993. *National inventory of reservoir dam failures*. The Ministry of Water Resources of the People's Republic of China (MWR) (in Chinese), Beijing.

Ru, N.H. and Niu, Y.G., 2001. *Embankment dam-incidents and safety of large dams*. Water Power Press (in Chinese), Beijing.

Silveira, A., 1984. Statistical analysis of deteriorations and failures of dams. *In*: J.L. Serafim, ed. *Safety of dams*. Netherlands: A.A. Balkema, 55–60.

Singh, V.P., 1996. *Dam breach modelling technology*. Boston: Kluwer Academic Publishers.

Stanford University, 1994. *National performance of dams program* [online]. Available from: http://npdp.stanford.edu [Accessed 30 April 2008].

USCOLD, 1975. *Lessons from dam incidents, USA*. Committee on Dam Safety of the United States Committee on Large Dams (USCOLD), New York: American Society of Civil Engineering.

USCOLD, 1988. *Lessons from dam incidents, USA II*. Committee on Dam Safety of the United States Committee on Large Dams (USCOLD). New York: American Society of Civil Engineering.

Vogel, A., 1980. *Bibliography of the history of dam failures* (CD Rom). Risk Assessment International, Vienna, Austria.

Zhang, L.M. and Chen, Q., 2006. Analysis of seepage failure of the Gouhou rockfill dam during reservoir water infiltration. *Soils and Foundations*, 46 (5), 557–568.

Zhang, L.M. and Du, J.C., 1997. Effects of abutment slope on the performance of high rockfill dams. *Canadian Geotechnical Journal*, 34 (4), 489–497.