Dam Disasters: An Assessment

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Dam Disasters: An Assessment

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Introduction

In a paper entitled *The Philosophy of Estimating Spillway Design Flood,* published in the January, 1969 issue of the *Engineering Journal,*[1] it was reported that very little, if any, research has been conducted on the causes of dam failures. The present paper reports some of the results of the research on dam disasters that is being currently conducted by the authors.

The design criteria for dams have improved considerably over the last 100 years, but, even now, there are too many assumptions, approximations and unknowns involved in computations. For example, the importance of uplift pressure was realized only toward the end of the nineteenth century, the grouting technique has come into being within the last 45 years or so, and the technique of foundation drainage is of still more recent origin. Also, dams, like other structures, are subject to decay and deterioration with the passage of time, and, hence, it is not surprising to find that dams do fail occasionally. But, unfortunately lessons learned from past mistakes have often been forgotten. To cite an example, one of the earliest recorded dam disasters was that of the Sadd el-Kafara in Egypt (between 2950 and 2750 B.C.), which failed because there was no provision for a spillway. But, unfortunately, this elementary error has been repeated innumerable times, even to the present century, because designers did not always realize that a spillway is an essential feature of any impoundment. Both Schnitter[2] and Biswas[3,4] have discussed in detail the early history of dam engineering and dam failures.

Failure Statistics

Details of dam failures, with the possible exception of those from western countries, are rather difficult to obtain since the authorities concerned are rather reluctant to discuss and advertise the failures of the structures administered by them. Gruner[5] and Babb and Mermel[6] have prepared a fairly comprehensive bibliography of literature currently available on dam failures. However, detailed results of investigations of failures in many cases are non-existent, and, even if they exist, they are not available for perusal. Also, it has to be realized that the determination of the exact causes of dam failures is an extremely difficult task. It means reconstruction of conditions that existed prior to the failure on the basis of data available, before and after the disaster, which are often insufficient. Even when causes can be attributed to a failure, they do, to a certain extent, depend on the experience and judgement of the engineers investigating the catastrophe. For example, if a dam fails because of insufficient cut-off, the failure can be attributed to improper design and construction, or to foundation problems, or to insufficient grouting, or to percolation, or to some combination of these factors. Also, the distinction between failures due to human errors or to *force majeure* is often quite arbitrary.

In 1961, the Spanish Publication *Revista de Obras Publicas* listed 1,620 dams and noted 308 serious accidents between the years 1799 and 1944, a period of 145 years. Among the structures that failed, 163 were earthen embankments, 14 were dykes, 70 were concrete gravity dams, 9 were arch dams, and the rest 52 were other types. The causes for the failures, as listed in the publication, were as follows:

Foundation problems	40%
Inadequate Spillway	23%
Poor Construction	12%
Uneven Settlement	10%
High Pore Pressure	5%
Acts of war	3%
Embankment Slips	2%
Defective Materials	2%
Incorrect Operation	2%
Earthquakes	1%
Total	100%

Table 1
Failures of dams of more than 15m height built in Western Europe and the USA since 1900 (only failures leading to storage releases, but excluding acts of war)

Year of Completion	Total No. of Dams	Failed Dams No.	Failed Dams %	Name of Failed Dam (Year of Failure)	Deaths (Failures(2))
1900-1909	190/100(3)	9/9(3)	4.7/9.0(3)	Scottdale (1904), Hauser (1908), Zuni (1909), Jumbo West (1910), Austin (1911), Hatchtown (1914), Sepulveda (1914), Long Tom (1916), Lake Toxaway (1916)	100
1910-1919	280/220	12/12	4.3/5.5	Stony River (1914), Horse Creek (1914), Hebron (1914 and 1942), Lyman (1915), Plattsburg (1916), Mammoth (1917), Schaeffer (1921), Bully Creek (1925), Wagner (1938), Sinker Creek (1943), Swift (1964)	10(3)
1920-1929	430/280	8/6	1.9/2.1	Apishapa (1923), Gleno (1923), Moyie (1925), Lake Lanier (1926), Diandi (1926), St. Francis (1928), Balsam (1929), Sella Zerbino (1935)	1,010(5)
1930-1939	450/280	1/1	.2/.4	La Fruta (1930)	0(1)
1940-1949	390/240	0	0	None	0
1950-1959	960/530	4/2	.4/.4	Stockton Creek (1950), Vega de Tera (1959), Malpasset (1959), Baldwin Hills (1963)	570(3)
Total (60 years)	2,700/1,650(4)	34/30	1.3/1.8	(23 earth and 11 concrete dams)	1,690 (18)(5)

NOTES: (1) Excluding Scandinavia
(2) No. of failures for which data are available
(3) Second figures apply to U.S.A. alone
(4) Among which 1,260/1,040 earth dams
(5) 410 deaths in 14 failures in U.S.A. alone

Later, Schnitter[2] listed the dam failures in the United States and Western Europe (with the exception of Scandinavia) for the period 1901-1960, and his results are shown in Table I.

From the current study of careful analyses of more than 300 dams from all over the world, it seems that roughly 35% of the disasters are due to the exceeding of the spillway design floods. This is a major cause for failures of earth and earth-rock dams, and embankments. Another 25% of the failures are due to foundation problems, i.e. piping, seepage, pore pressure, inadequate cut-off, fault movement, settlement, rock slide, etc. The remaining 40% are due to various causes, such as:

- Improper design and construction
- Improper operation and maintenance
- Use of inferior quality materials
- Ice pressure
- Enemy action
- Improper location and operation of gates
- Wave action
- Other causes, known and unknown.

Tables 2 and 3 show the estimated damages and loss of human lives due to a select few dam failures.

Table 2 – Some dam failures and estimated damages

Dam	River	Country	Year Failed	Damages in Million $U.S.
Mill River	Mill	U.S.A.	1874	1.0
Lynde Brook	Lynde Brook	U.S.A.	1876	1.0
Johnstown	Little Conemaugh	U.S.A.	1937	100.0
Brokaw 2	Wisconsin	U.S.A.	1938	0.7
Malpasset	Le Reyan	France	1959	68.0
Bab-i-yar	Dneiper	U.S.S.R.	1961	4.0
Baldwin Hills	Owens	U.S.A.	1963	50.0
Mayfield	Cowhitz	U.S.A.	1965	2.5
Wyoming	Sybille Creek	U.S.A.	1969	1.5
Pardo	Seco de Frias	Argentina	1969	20.0

Table 3–Death casualties in some major dam failures

Dam	Country	Date of Disaster	Loss of Lives
Vaiont	Italy	October 9, 1963	3,000
South Fork (Johnstown)	Pennsylvania	May 31, 1889	2,200
Oros	Brazil	March 25, 1960	1,000
Puentes	Spain	April 30, 1802	600
Saint Francis	California	March 13, 1929	450
Malpasset	France	December, 1959	421
Hyokiri	Korea	July, 1961	250
Quebrada la Chapa	Colombia	April, 1963	250
Bab-i-yar	U.S.S.R.	March, 1961	145
Veg de Tera	Spain	January 10, 1959	144
Pardo	Argentina	January 6, 1970	25
Baldwin Hills	California	December 14, 1963	3

Some Case Studies

The failures of some major dams and reservoirs will be discussed herein.

a. *Sheffield Dam*

The Sheffield dam, near Santa Barbara, California, was an earth-fill dam. Its upstream slope was protected by a facing of concrete slabs, on a 4-ft thick clay blanket that was carried 10 ft into the foundation to form a cut-off. The dam failed in June, 1925, due to a moderate earthquake[7] having an intensity of IX RF. At the time of the failure, the dam was subjected only to a head of 20 ft of water. The earthquake was responsible for moving a 300-ft long embankment from the central portion of the dam, thus releasing 45 million gallons of water.

Different opinions have been expressed regarding the mechanism of failure. Andrews[7] attributed the failure to the opening of joints between concrete slabs of the upstream lining and the resultant cracking of the clay blanket. This created uplift in the central fractured section which culminated in the sliding of the central part of the embankment. According to Nunn,[8] the earthquake opened vertical fissures which caused a section of the dam to be washed away. The U.S. Corps of Engineers, however, suggested that the failure occurred along a shear surface because of the instability caused by the horizontal earthquake acceleration.[9]

A recent comprehensive study of the Sheffield dam failure, by Seed et al,[10] based on the data available from the Corps of Engineers, concluded that:

a. The sliding occurred due to the liquefaction failure of the loose saturated silty sand near the base of the embankment. Similar opinion has also been expressed by Sherard et al.[11]

b. The dam would not have failed if the maximum ground acceleration due to the earthquake was 0.1g. The most probable value of ground acceleration at the time of failure was about 0.15g.

c. A reasonable compaction of the foundation or the embankment soil to about 90% on the standard AASHO compaction test would have prevented the occurrence of the failure.

d. Ground accelerations due to earthquakes of the order of 0.5g can be expected depending on the active characteristics of an area. Analysis of the performance of embankments during past earthquakes and evaluation of the ability of the analytical procedures to predict this performance would provide the necessary tools to examine the seismic behavior of dams and will be useful in designing dams that are likely to be subjected to major earthquakes.

From this analysis, it is evident that significant knowledge and understanding of the behavior of dams can be obtained from the study of dam failures.

b. *Malpasset Dam*

The Malpasset dam, built in 1954 on the Reyran River in the French Riviera, was one of the thinnest arch dams ever built for its height of 200 ft. It failed on December 2, 1959, at 9:10 p.m., releasing some 40,000 acre-ft of water. When the actual collapse occurred, the dam was subjected to a record head of water, which was about a foot below the highest water level, due to five days of unprecedented rainfall. According to the Inquiry Commission instituted by the French Ministry of Agriculture, the causes for the failure[12] were:

a. the arch ruptured as the left abutment gave way;

b. the left abutment moved about 208 cms in the tangential direction with a small radial component, by sliding along well-defined lines of fissuration;

c. the mechanical strength of certain rocks under-

neath the left abutment was less than expected;
d. the rock foundation was more deformable near the higher upstream rock fissure:
The Commission, after careful considerations, ruled out earth tremors, microseismic earth vibration, sabotage, etc., as possible reasons for the failure.

Various authorities like Terzaghi, Cambefort, Serafim and Bellier, have put forward different hypotheses regarding the actual mechanism of the failure. According to Terzaghi,[12] the failure occurred by sliding along a continuous seam of weak material covering a large area. He felt that a conventional site exploration would have indicated that the site of the dam was a potentially dangerous one, but it would have been impossible to predict accurately the surface of least resistance in the rock along which the actual failure occurred. Cambefort,[12] however, suggested that the buckling of the slender arch dam under axial loading was the primary cause of failure, and it resulted in the destruction of the abutment rocks and the eventual rotation of the dam. It has not been possible to justify the hypothesis by model studies made so far. The failure according to Serafim,[10] was caused by the high tensile stresses developed in the concrete, in a direction parallel to the foundation, near localized weak rocks, resulting in multiple fissuration of the dam. Bellier[13] pointed out that the dam rested on a rock dihedron, formed by the downstream fault plane dipping 45° and the upstream potential shear surfaces which were undetected by drilling. The weight of the dam and the arch thrust tended to compress and stabilize the dihedron. The high compression in the gneiss created an impervious cut-off in the foundation, against which seepage pressure built up gradually. Finally, the dihedron was subjected to a hydrostatic head of the reservoir level, which exceeded the weight of the foundation, and, thus caused the bank to fail.

Bellier's hypothesis, when viewed along with that of Terzaghi, seems to indicate the most plausible explanation of the failure mechanism. Unfortunately, both the left rock abutment and the foundation were washed away, and this made it extremely difficult to arrive at definite conclusions.

The Malpasset disaster clearly indicates that there is an urgent need for more intensive research in the field of safety of dams. The legal charges of homicides and injuries, caused due to negligence, brought against the chief engineer for Rural Engineering in the French Court of Law, indicate an increasing public concern about safety of dams. With the population growth and consequent encroachment of the flood plains, dam failures are likely to cause increasing loss of lives and property damages. Thus, in all probability, the public concern on dam-failures is likely to increase.

c. *Khadakwasla Dam*

The Khadakwasla, built in 1864 on the Mutha River near Poona, India, was a rubble masonry dam having a maximum height of 100 ft. It was not designed for uplift forces or foundation drainage. As a result of some 70 in. of rainfall in 23 days and the consequent failure of the Panshet dam upstream, the Khadakwasla was overtopped by 9 ft of water which created severe vibration problems. The 95-yr old dam withstood such severe conditions for about 4 hours, and then failed in two stages. The waste weir section sheared off within three hours and then a triangular section of the dam broke open "like a door" near a step in the foundation. The failure occurred when the receding flood was 6 ft above the top of the dam.

A two-dimensional stability analysis[15] was carried out to determine the causes of failure after the mishap. The results are quite revealing. The maximum tension at the upstream heel of the deepest section of the dam, with full reservoir level and uplift, was found to be 5.60 psi, and such conditions existed for about three months every year. With 9 ft of water over the top of the dam, the calculated tension was found as 105 psi. But, still the failure did not occur at the deepest section, even though the dam was subjected to a stress of 75% of the ultimate tensile strength of the masonry for a few hours. Under the same conditions of overtopping, the horizontal forces were found to be 1.1 times the total vertical forces, and the resultant force fell outside the base (beyond the toe) by 5 ft for 3 to 4 hours. Still, it is surprising to note that the dam neither failed by sliding nor by overturning. The downstream backfill was scoured away by the overflowing water.

A three-dimensional photo-elastic model was made of the portion of the dam where failure occurred due to a step in the foundation. The cantelever elements were subjected to twisting action due to variable heights, and the actual tensile stresses were found to be 140 psi. Obviously, the results indicate that the conventional analysis does not apply to such situations. Hence, there is an urgent need to develop a suitable methodology to analyse such stresses.

There are several lessons to be learned from the failure of the Khadakwasla dam.
a. There is a pressing need for conducting more intensive research on the existing design techniques and analyses of stability and strength of dams. It is also necessary to develop proper methodology for the evaluation of aging effects on the strength and stability of dams.
b. Design which cannot be treated by conventional analyses should be tested by model studies.
c. The old dams should be strengthened, if needed, for additional safety.
d. Suitable means of outflow like fuse plugs should be provided in the downstream dams to protect them from the failure of dams upstream.
e. There is still much to learn about the mechanics of sliding and overturning of dams.
f. It seems that it is possible to design masonry dams from failures due to overtopping. Obviously, this would provide greater safety of the dams from unpredictable hydro-meteorologic conditions.

d. *Panshet Dam*

The Panshet dam on the River Ambi at Panshet, India, is a 168 ft high earth dam having a side-channel spillway with a design capacity of 17,200 cusecs. Due to a heavy rainfall of 70 in. in 23 days, the newly created reservoir was subjected to a high runoff, resulting in the failure of the Panshet dam, and the Khadakwasla dam downstream, causing unprecedented havoc and misery to the city of Poona. Nearly 95,000 people were directly affected by the flood, and about 5,000 houses were either damaged or destroyed.[16]

The construction of the dam was started in 1957 and was scheduled for completion in 1962. Subsequently, the completion date was put forward to early 1961. Thus, when the filling of the reservoir was started, the construction of the dam was not complete. The unfortunate situation was a direct result of improper planning and management.

As the first outlet gates were delivered late, and the headstock gears did not arrive, the gates were installed in their guides and hung on chains with an opening of 2 ft. The gate tower access bridge was also not delivered in time. Extensive model studies made by Rao[14] indicated that dynamic flow of water through the partially opened gates caused severe vibrations due to air entrainment and cavitation in the outlet culvert. The rough, unfinished, and uneven culvert invert was subjected to high pulsating flows causing periodic breaking of the water column which resulted in water-hammer effects. These adverse vibratory forces led to progressive disintegration of the arch voussoirs of the outlet culvert, causing subsidence. The earth embankment sank 4½ ft in only 2½ hours.[15]

It is highly surprising that no model test was performed to evaluate the performance of the designed gates under high heads. Obviously, the designers did not take seriously a similar accident in the Bhakra Dam in India,[17] in 1959, when the gate tower failed due to heavy vibrations caused by the use of the tunnel gates to regulate flows under high heads.

e. *Vaiont Dam*

On the night of October 9, 1963, the Vaiont dam in Italy was overtopped by a 330-ft flood wave which caused a loss of 3,000 lives, the heaviest loss due to a dam failure ever known to history. The Vaiont is a 875-ft high arch dam, and is the second highest dam in the world. The flood was caused by an extremely heavy landslide having an approximate volume of 312 metric cu yds which filled up 1.25 miles of the reservoir with slide materials up to a height of 575 ft above the reservoir level. The dam can no longer be used for generation of hydro power as the cost of clearing the reservoir seems to be prohibitive. A by-pass tunnel under the right bank of the reservoir allows the water behind the "slide-dam" to be drained out into the river.

A technical board appointed by the Italian Government found "bureaucratic inefficiency, muddling, withholding of alarming information, lack of judgement and evaluation and lack of serious individual and collective consultation" as the real causes of the disaster. The report was accepted by the Italian Government, and resulted in the suspension and prosecution of those found responsible for the disaster. Fourteen engineers were prosecuted for manslaughter.

The causes that led to the gigantic Monte Toc slide into the reservoir have been investigated by Kiersch[17] and Müller[18]. Müller's conclusion "that the sliding could not possibly be foreseen by anybody in the form in which it actually took place and, in fact, nobody had foreseen nor predicted it," is in contradiction with the findings of the Italian Government. However, it was based on a thorough scientific investigation of pre- and post-disaster conditions and analyses. Jaeger[19,20] has considered Müller's work to be a major contribution to the mechanics of rock-slides.

The Vaiont disaster, however, indicated the extent of the static reserves of shells of the arch dams. In the Malpasset disaster, the failure of the rock abutments resulted in the complete destruction of the arch. It was, therefore, felt essential to strengthen the rock abutments against possible failure. Tie-rods were provided in the abutments of the Vaiont dam, which resisted the tremendous forces of the rock-slide and the consequent overtopping, and did not fail in spite of the cracks in the abutments. It clearly suggests that it is necessary to strengthen the rock abutments of arch dams. A proper warning system might have saved many lives in the case of the Vaiont disaster.

f. *Baldwin Hill Dam*

The dam, built in 1951, consisted of a main earthen embankment at the north end of the reservoir, and five minor ones to block the low-lying areas along the perimeter. The reservoir and the embankments had sandwich-type lining with pea-gravel drains to prevent seepage and to drain away all leakages. Such an expensive lining was necessary since the dam was built over a foundation having two fault zones running perpendicular to the northern embankment. During the site investigation, it was found that the faults were neither active nor potentially dangerous for the construction of a reservoir–unless seriously undermined by seepage.

On December 14, 1963, the northern embankment of the dam, adjacent to the spillway, failed at a section over one of the fault lines, forming a V-shaped breach 90 ft deep and 75 ft wide. It caused substantial property damage, but fortunately the loss of life was less because of the timely detection of the symptoms of the failure, and efficient warning, evacuation and rescue operations.[20]

An Engineering Board of Inquiry set up to investigate the failure reported that it was due to the gradual and progressive deterioration of the foundation which occurred because of subsidence along the fault zone, erosion under the undamaged blanket, and partially blocked drains (due to subsidence).[22] Eventually, it led to the final rupture of the impervious blanket. Thus, the full reservoir water pressure, acting on the pervious and erodible fault zone, created an opening through the abutment which made the overlying embankment collapse.

The leaking water attracted the attention of the caretaker, and his warning obviously saved many lives. The earth movement that caused the land subsidence was partly due to tectonic disturbances (about 0.03 ft per year) and partly from oil field activities. The total subsidence was believed to be about 0.2 ft per year. The Board expressed the need for a more comprehensive study to determine with reasonable accuracy, the contribution of the two factors to the total subsidence.[22]

There are many lessons to learn from this failure. The dam was designed to store water from the Owens River and the Colorado River aquaducts for distribution to the southwest Los Angeles area. The inflow could be regulated by a valve in the inlet tunnel. Thus, the reservoir and the dam were designed not to be overtopped by floods.

It may be noted that the dam was built on defective foundation. The earth movements and the weak and the erodible nature of the foundation were considered when the dam was designed and the geological investigations were thorough. The designers did consider the erodible nature of the foundation when subjected to water pressure. This resulted in the creation of the impervious blanket. But, the possibility of shearing of the membrane on account of fault movement was not thought likely,

The City of Los Angeles, and its Department of Water and Power sued the oil companies operating in the Inglewood Oil field on the west side of the reservoir.[23] The oil field activities were known to the designers of the Baldwin Hills, and could perhaps been projected into the future with the assistance of the oil companies.

The reservoir was kept under strict surveillance and the maintenance operations were good.[22] The last annual maintenance inspection of the dam by the State Supervision of Dam-Safety Office was made on April 3, 1963, about nine months before the failure, and it was found to be satisfactory.

Conclusion

Comprehensive studies of dam failures, for some unknown reason, have so far been few and far between. This is somewhat difficult to understand, especially when one considers the tremendous pay-off that is bound to result from such mission-oriented research investigations. Studies in this field have been carried out by Biswas[1,3,4,23], Gruner[5,24,25,26] and Schnitter[2,27].

From the failures of the dams discussed in this paper, and from numerous others investigated by the authors, many lessons are to be learned. Large dams and reservoirs create a complex new environment, and very little is known on the mutual interactions of the component forces, on a long-term basis, to keep the newly-created man-imposed systems and nature in a proper equilibrium. Recent investigations by Rothe,[28] for example, indicate the distinct possibility that construction of huge dams and reservoirs places a severe burden on the earth's crust which can result in earthquakes in zones that were previously free from them. Recent observations from Kariba, Monteyard and Koyna dams tend to confirm such a supposition.

The dam designers and hydrologists will have to accept the probabilistic nature of floods. The deterministic concept of the probable maximum flood has not provided a theoretical upper limit of floods in the past, and will not provide one in the future. The concept has severe shortcomings, and sooner they are realized the better. To give some examples, the Pardo dam, in Argentina, failed in 1969, because nearly a quarter of the average annual rainfall fell in its drainage basin in about two hours. Subsequent damages were estimated at $20 million. The Rincon de Bonette hydroelectric scheme on the Rio Negro had a similar fate. Later, the flood was estimated to have a return period of 500,000 years.

Failure of the Khadakwasla dam and the later analyses clearly indicate the present deficiency of knowledge on the true behavior of dams. The conventional analysis suggests that the dam should have failed by sliding or by overturning or by the tension generated at the heel. Since no such failure occurred, it is obvious that there is an urgent need for further research to modify and improve the existing practices and analyses.

The failures of the Moyie River dam in Idaho in 1926, and the Malpasset dam were due to defective rock foundations. The abutments of the Vaiont dam, therefore, were strengthened with tie rods, and this, undoubtedly, was one of the major causes which enabled the dam to withstand the tremendous forces generated by the landslide and the resultant overtopping, with very little damage to the structure itself. However, a serious drawback of the Vaiont project was the lack of a proper disaster warning system. Had there been one, it would have drastically reduced the number of lives lost.

Some of the dam failures indicate the need for decision-making at the upper echelons at short notice.[29] Bureaucratic delays and excessive red tape have contributed to dam failures in the past. The Sempor dam in Java failed in 1967 due to a flash flood,[30] since the structure was weakened due to construction delays resulting from lack of funds and late cement deliveries. Panshet dam, discussed before, is another example.

It has been suggested that extreme atmospheric conditions may act as a triggering mechanism for dam failures.[31] A recent study by Takase[32] suggests that the structural factor of safety of an earth dam will increase with time, if the structure does not encounter severe external forces in its early stages of life.

The failure of the St. Francis dam in California, in 1928, initiated a full-scale state supervision of dams in the following year. Their continuous and comprehensive evaluation of the safety of the old dams has not only proved to be effective in preventing disasters but has also made significant contributions to the overall field of dam engineering.[33] The need for proper and constant supervision and maintenance of old dams can never be overemphasized. This will not completely eliminate dam failures (the Wyoming dam failed in 1969 only 9 hours after the formal inspection and caused damages of about $1.5 million[34]), but it will reduce the number of failures to a great extent.

It seems that as long as we have dams, we will have to face risks and uncertainties. The best we can do as planners and designers is to reduce the risk to a level that is acceptable by the society as a whole.

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References

1. Biswas, Asit K., "The Philosophy of Estimating the Spillway Design Flood," *Engineering Journal,* Vol. 52, No. 1, January, 1969, pp. 20-30.
2. Schnitter, N.J., "A Short History of Dam Engineering," *Water Power,* Vol. 19, No. 4, April, 1967, pp. 2-8.
3. Biswas, Asit K., "History of Hydrology," Elesvier-North-Holland Publishing Co., Amsterdam, 1970.
4. Biswas, Asit K., "Hydrologic Engineering prior to 600 B.C.," *Journal of the Hydraulics Division, ASCE,* Vol. 93, No. HY5, September, 1967, pp. 115-135.
5. Gruner, E.C., "Catalogue of Dam Disasters," Gruner Brothers, Basle, Switzerland.
6. Babb, A.O., and Mermel, T.W., "Catalog of Dam Disasters, Failures and Accidents," PB179243, Bureau of Reclamation, Washington, D.C., 1968.
7. Ambraseys, N.N., "On the Seismic Behaviour of Earth Dams," Proceedings, 2nd World Conference on Earthquake Engineering, Tokyo and Kyoto, Japan, Science Council of Japan, Vol. 1, 1960, pp. 331-354.
8. Nunn, H., "Municipal Problems of Santa Barbara," *Bulletin, Seismological Society of America,* Vol. 15, 1925, pp. 308-319.
9. U.S. Army Corps of Engineers, "Report on Investigation of Failure of Sheffield Dam, Santa Barbara," June, 1949.
10. Seed, H.B., Lee, K.L., and Idriss, I.M., "Analysis of Sheffield Dam Failure," *Journal of Soil Mechanics and Foundation Division ASCE,* Vol. 95, No. SM6, November, 1969, pp. 1453-1490.
11. Sherard, J.L., Woodward, R.J., Gizienski, S.S., and Clevenger, W.A., "Earth and Earth—Rock Dams," John Wiley & Sons, Inc., New York, April, 1967, pp. 113-199.
12. Jaeger, C., "The Malpasset Report," *Water Power,* Vol. 15, No. 2, February, 1963, pp. 55-61.
13. Bellier, J., "The Malpasset Accident," *Water Power,* Vol. 22, No. 1, January, 1970, pp. 33.
14. Murti, N.G.K., "Khadakwasla, The Oldest Masonry Dam in India," Ninth Congress, International Commission on Large Dams Istambul, 1967, Q. 34, R. 53, pp. 895-915.
15. Hunter, J.K., "Failure of the Panshet and Khadakwasla Dams, Bombay," *Water Power,* Vol. 16, No. 6, June, 1964, pp. 251-252.
16. Rao, N.S.G., "Failure of the Khadakwasla and Panshet Dams", *Journal, Institution of Engineers* (India), Vol. 47, No. 11, Pt. C16, July, 1967, pp. 1123-1144.
17. Kiersch, G.A., "Vaiont Reservoir Disaster," *Civil Engineering—ASCE,* Vol. 34, No. 3, March, 1964, pp. 32-39.
18. Müller, L., "The Rock Slide in the Vajont Valley," *Journal of International Society of Rock Mechanics,* Vol. 2, No. 3-4, 1964, pp. 148-212.
19. Jaeger, C., "The Vaiont Rock Slide: Part 1," *Water Power,* Vol. 17, No. 3, March, 1965, pp. 110-111.
20. Jaeger, C., "The Vaiont Rock Slide: Part Two," *Water Power,* Vol. 17, No. 4, April, 1965, pp. 142-144.
21. Jessup, W.E., "Baldwin Hills Dam Failure," *Civil Engineering—ASCE,* Vol. 34, No. 2, February, 1964, pp. 62-64.
22. Jansen, R.B., et al, "Investigation of Failure, Baldwin Hills Reservoir," The Resources Agency, Department of Water Resources, State of California, Sacramento, April, 1964.
23. Biswas, Asit K., "Risk Criteria and Flood Estimation," Dept. of Civil Engineering, Queen's University, Kingston, Canada, 1967.
24. Gruner, E., "Dam Disasters," Proceedings, Institution of Civil Engineers, London, Vol. 24, Paper No. 6648, January, 1963, pp. 47-60.
25. Gruner, E., "The Safety of Reservoirs," in "World Dams Today," Japan Dam Association, Tokyo, 1967, pp. 104-109.
26. Gruner, E., "Vigilance over Reservoirs," *Water and Water Engineering,* September, 1969, pp. 369-373.
27. Schnitter, N.J., Personal Communication, 1968.
28. Rothe, J.P., "Fill a Lake, Start an Earthquake," *New Scientist,* July 11, 1968, pp. 75-78.
29. Biswas, Asit K., and Chatterjee, S., "Human Dimensions of Dam Safety," Policy Research and Coordination Branch, Water and Renewable Sector, Department of Fisheries and Forestry, Ottawa, Canada, January, 1971, 45 pp.
30. Anon., "Javaneese Dam Collapse During Monsoon Rains," *Engineering News-Record,* December 7, 1967, p. 16.
31. Gruner, E., "The Mechanism of Dam Failure," Ninth Congress, International Commission on Large Dams, Istambul, 1967, Q. 34, R. 12, pp. 197-206.
32. Takase, K., "Statistic Study on Failure Damage and Deterioration of Earth Dams in Japan," Ninth Congress, International Commission on Large Dams, Istambul, 1967, Q. 34, R. 1, pp. 1-19.
33. Cortright, O.C.J., "Re-evaluation and reconstruction of California Dams," *Journal of the Power Division, ASCE,* Vol. 96, No. PO1, January, 1970, pp. 55-72.
34. Anon., "Wyoming Dam Fails," *Engineering News-Record,* July, 17, 1969, p. 16.

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