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# Disasters as a Necessary Part of Benefit-Cost Analyses

Water-project costs should include the possibility of events such as dam failures.

R. K. Mark and D. E. Stuart-Alexander

Although it is well known that some low-probability events can be very costly, benefit-cost analyses for water projects generally have not included the probable value of these costs. The significance of expected costs is reflected in the growing difficulty of obtaining liability insurance against dam failure, even at highly inflated prices (*1*). This article is intended to stimulate discussion of the need to include events such as dam failures, impoundment-induced earthquakes, and landslides in the benefit-cost analyses of reservoir projects. It is not concerned with actual methods of estimation (*2*).

## Dam Failures

Dam failures are not uncommon. Gruner (*3*) reported that 33 dams failed in the United States between 1918 and 1958; five of these were major disasters involving the loss of 1680 lives. He stated that these 33 were part of a list of 1764 dams built prior to 1959. Other references list about 1000 more dams completed by 1959 (*4, 5*), so that we are assuming an average of 1600 dams over this 40-year period (*5*). These data suggest a failure rate of approximately $5 \times 10^{-4}$ per dam-year and a major disaster rate of approximately $0.8 \times 10^{-4}$ per dam-year. Kiersch (*6*) reported that from 1959 to 1965 "nine major dams of the world have failed in some manner." In 1962 there were 7833 major dams (*7*), indicating a worldwide failure rate of about $2 \times 10^{-4}$ per dam-year for that period. In 1976 there were six dam failures, four of which are considered major disasters, resulting in significant property damage and a total of more than 700 deaths. Dam failures have generally resulted from design, construction, or site inadequacies, or from natural phenomena, primarily storms or earthquakes.

Generalized estimates of dam failure probabilities can be based on historical frequency observations, either aggregated (as above) or, if sample size permits, disaggregated into categories and time periods (*5*). Historical trends may result from the balance between improving technology and the need to use more difficult dam sites. For instance, calculations based on data compiled by the Committee on Failures and Accidents to Large Dams (*5*) indicate that the U.S. major failure rate did decline by about an order of magnitude during the first four decades of this century, but has since fluctuated between about $1 \times 10^{-4}$ and $2 \times 10^{-4}$ per dam-year.

The number of failures in small populations of dams are generally insufficient to give precise estimates of failure rates, nevertheless it can be instructive to consider restricted populations. For example, the U.S. Bureau of Reclamation had accumulated approximately 4500 dam-years' experience on earth-filled dams for reservoirs in excess of 1000 acre-feet storage capacity (*8*), when its Teton Dam in Idaho failed on 5 June 1976. Terminating the sample at this first disastrous failure (*9*) (that is, an inverse binomial sample, with ~4500 dam-years to first failure), we obtain a median-unbiased estimate of the failure rate (*10*) as approximately

$$\frac{2}{3} \times \frac{1}{4500} = 1.5 \times 10^{-4} \text{ per dam-year}$$

Such an estimate, based on a single failure, has a very wide confidence interval; however, it is generally consistent with the other worldwide estimates.

Project-specific probabilities of failure as well as generalized probabilities of failure can be estimated by "fault tree" analysis of the probabilities of casual

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events such as major earthquakes, floods, and other failure mechanisms (*11*). In considering the earthquake hazards to embankment dams, Sherard (*12*) reported a consensus that some of the dams in any seismic region would fail if shaken by the maximum possible earthquake for that area. A few dams have failed from earthquake shaking, such as Sheffield Dam, California, in 1925 and a dam near Augusta, Georgia, in 1886 as a result of the Charleston, South Carolina, earthquake (*12*) more than 150 kilometers away. Other dams have very nearly failed from earthquakes, such as Hebgen Dam, Montana, during an earthquake of Richter magnitude 7.1 in 1959 and the lower Van Norman Reservoir Dam, California, during the San Fernando earthquake of magnitude 6.4 in 1971 (*12, 13*). The East Bay Municipal Utility District (*14*) has concluded that the San Pablo Dam, California (43,100 acre-foot capacity; 1 acre-foot = 1233.5 cubic meters) ". . . is not sufficiently stable to withstand a major earthquake on the San Andreas fault," which is 34 kilometers away. These examples suggest that the failure probability for some dams may approach the probability of severe local earthquakes. On the basis of both historic records and design flood probabilities, Gast (*15*) concluded that dam failure rates are on the order of $10^{-4}$ per dam-year. The probability of failure of a particular dam is difficult to estimate, but may depend strongly on many factors, including project-specific engineering and construction, geologic setting, surface faulting and seismicity, type and age of dam, and flood frequency (*12*).


## Summary

Benefit-cost analyses for water projects generally have not included the expected costs (residual risk) of low-probability disasters such as dam failures, impoundment-induced earthquakes, and landslides. Analysis of the history of these types of events demonstrates that dam failures are not uncommon and that the probability of a reservoir-triggered earthquake increases with increasing reservoir depth. Because the expected costs from such events can be significant and risk is project-specific, estimates should be made for each project. The cost of expected damage from a "high-risk" project in an urban area could be comparable to project benefits.


### Expected Cost of Failures

In addition to failure probabilities, expected costs must also include estimates of the failure-related damage. Methods of calculation for such estimates are related to the routinely calculated flood control benefits. Damage will depend on such factors as storage volume, topography, cause and mode of failure, and location, density, and type of existing and projected development. In the case of Teton Dam (288,000 acre-foot reservoir), damages have been estimated at between \$400 million and \$1 billlion, excluding the 11 deaths (*16*), or about \$1400 to \$3500 per acre-foot capacity (*17*). In an urban area, damages and loss of life would have been greater. For example, in the 1963 failure of the Baldwin Hills Reservoir in metropolitan Los Angeles, California, sudden release of approximately 250 million gallons of water (about 750 acre-feet) caused \$12 million property damage (and five fatalities) (*18*). In 1976 dollars, this is about \$28,000 per acre-foot. Rough estimates (based upon hypothetical flooding calculations) of the potential property damage to residential structures and loss of life due to complete and instantaneous failure of specific dams in urban areas of California have been given by Ayyaswamy and others (*19*), in a report for the U.S. Atomic Energy Commission. Their estimated values of residential property damage, normalized to storage capacity, range from about \$1500 to \$178,000 per acre-foot storage, with loss of life (without evacuation) from about 0.4 to 45 deaths per acre-foot. In the Buffalo Creek 'dam' failure (West Virginia, 26 February 1972), 135 million gallons (about 400 acre-feet) of water caused 125 deaths and damages of more than \$50 million (*20*), or about \$121,000 per acre-foot (*21*).

The expected cost of an event is its probability of occurrence times the cost of the damage. To calculate an expected annual cost of dam failure for a specific project, it is necessary to multiply the probability of each important failure mode by the estimated associated damage and then sum over the failure modes. For Teton Dam, if we assume an overall failure probability of $1.5 \times 10^{-4}$ per year and total damage of $\$7 \times 10^{8}$, the expected cost of failure is about \$105,000 per year or \$0.36 per acre-foot per year.

The benefit-cost analysis for the Lower Teton Division of the Teton Basin Project recalculated by the Bureau of Reclamation in 1969 was based on total annual benefits of \$2.9 million and annual equivalent costs of \$1.9 million (discount rate equal to 3¼ percent) for a benefit-cost ratio of 1.59 (*22*). A reduction in estimated annual flood-control benefits of \$355,000 by \$70,000 (*23*) for the expected cost of failure-caused flooding would have decreased the benefit-cost ratio to 1.51. If pre-project analysis had indicated that this was a high-risk site or design (*16, 24*), and that, for example, the estimated probability of failure was ten times as high, net flood-control benefits would have become zero and annual costs of the project would have increased to about \$2.2 million (with a net increase in flood-damage risk) for a benefit-cost ratio of about 1.15, a 26 percent reduction (*25*).

### Impoundment-Induced Earthquakes

A second example of events with low probability and potentially high costs is the now well-documented problem of impoundment-induced seismicity that has occurred in both seismically active and inactive regions (*26–29*). Earthquakes triggered by the impoundment of water have damaged two dams and caused damage to many other structures as well as loss of life. No dams are known to have failed from impoundment-induced seismicity, but such earthquakes contribute to the probability of dam failures.

More than 40 reservoirs reportedly have triggered earthquakes ranging from microseisms to about magnitude 6.4 (*27, 28, 30*). Many of these cases are well documented, but others are inconclusive or questionable (*30, 31*). The four or five reservoirs that have triggered damaging earthquakes (magnitudes greater than 5.5) have water depths in excess of 90 meters (*31*). In fact, there is a positive correlation between water depth and the observed frequency of reservoirs associated with earthquakes for all cases of significant (magnitude $\geq 3$) induced seismicity (*31*). Less than 0.2 percent of the reservoirs behind the world's approximately 11,000 large dams (greater than 10 to 15 meters) (*4*) are reported to have induced significant seismicity, but the number increases to 10 percent (13 well-documented cases out of 126) for reservoirs > 90 meters deep and water capacity $\geq 10^{3}$ cubic meters. The correlations with water depth become more dramatic when the reservoirs are separated into 30-meter intervals; however, the total number of reservoirs and the cases of induced seismicity are small in the deeper categories (4 out of 19 reservoirs more than 150 meters deep, for instance) so that probability estimates have wide confidence limits. Although the a priori probabilities of impoundment-induced seismicity are significant for deep reservoirs, for a specific site the probabilities depend strongly on geologic and tectonic setting [for example (*29, 30, 32*)].

In addition to the damage associated with dam failure, consideration must be given to direct seismic damage to manmade structures. This damage depends on density and type of development, as well as the geologic setting and earthquake magnitude. For example, the magnitude 6+ earthquake of 10 December 1967, associated with the impounding of Koyna Reservoir, India, killed more than 175 people, injured more than 1500 people, left thousands homeless, damaged the dam, and disabled the hydroelectric plant (*28*). Monetary estimates of the damage are not available, and would not be directly applicable to damage in the United States. However, there are many estimates of earthquake damage in the United States that should be directly applicable to induced earthquakes. For example, earthquakes up to magnitude 6.5 have produced damages of as much as half a billion dollars (*33*).

## Landslides

Other low-probability events can also cause disasters. A landslide-induced flood associated with the Vaiont Dam, Italy, killed more than 2000 people in 1963. The landslide, of massive proportions, generated a giant wave that overtopped the dam and flooded the valley below, obliterating several villages (*27*). The dam did not fail.

## Conclusions

When projects are designed, tradeoffs (either implicit or explicit) are made between project cost and residual risk. The examples given here demonstrate that the expected costs of low-probability disasters (the residual risks) associated with water projects can be significant and should be specifically estimated for each project. Evidence suggests that mean probabilities of dam failures are greater than or of the order of $10^{-4}$ per dam-year and that "high risk" projects could have appreciably higher failure rates. We have made no attempt to place value on loss of life. Even so, the total expected damage due to a dam failure, particularly in urbanized areas, can be so great that it may exceed the project benefits. Hazards such as impoundment-induced earthquakes and landslides also add to expected project costs. Even though it may be difficult to make specific estimates, failure to include these costs of residual risk in benefit-cost analyses clearly produces an upward bias that may result in projects that are not economically justifiable.

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