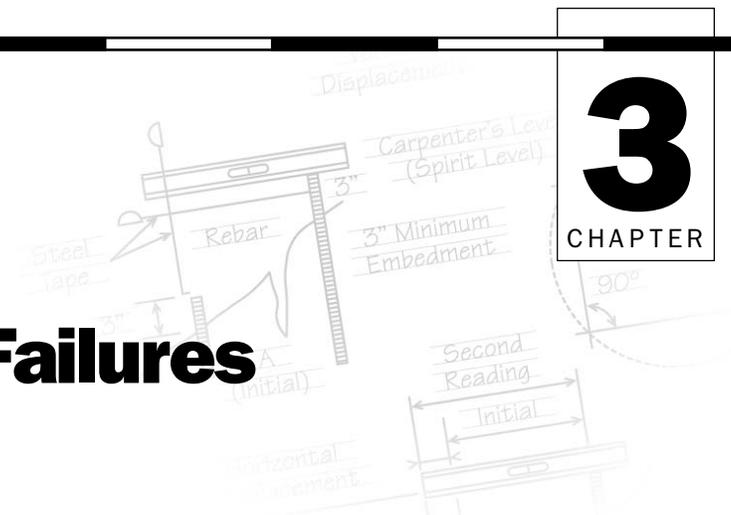


Chapter 3: Hazards, Risks, Failures



3.0 General

Dam failures are severe threats to life and property and are now being recorded and documented much more thoroughly than in the past. Recorded losses have been high. Statistics on losses of life and property fully justify the need for dam owners to better understand the risks to the public posed by dams, the kinds of hazards that promote those risks and owner liabilities associated with them, and, generally, the reasons that dams fail. Improving a dam owner's understanding of realistic risks and possible reasons for failure is an essential first step in any overall effort to improve dam safety and preserve the benefits of dam ownership.

3.1 Hazards as Sources of Risk

The dam structure itself can be a source of risk due to possible construction flaws and weaknesses that develop because of aging. The site immediately surrounding the structure may also increase the structural risk if the dam is not positioned or anchored properly or if excessive reservoir seepage erodes the foundation or abutments.

The physical hazards that can cause dam failure are translated into high risks when people or property are threatened, and where the high risks to which Americans are exposed are exacerbated by a number of important factors. For instance, in most states, people are allowed to settle below dams in potential inundation zones, thereby compounding risk.

Natural hazards such as floods, earthquakes, and landslides are also important contributors to risk. These natural phenomena existed long before humanity established patterns of settlement and are considered hazards because development has placed people and property in their way. Failure to adjust to these events has been costly both to dam owners and to the public in general.

Human behavior is another element of dam failure risk; simple mistakes, operational mismanagement, negligence, unnecessary oversights, or destructive intent can interact with other hazards to compound the possibility of failure. Thus, a broad range of natural and human hazards, taken separately or in combination, increase the probability of dam failure and injury to people and property.

The following discussion of some of the most significant hazards that lead to public risk illustrates the interrelationships among events that can lead to dam failure.

3.1.1 Natural Hazards That Threaten Dams

The most important natural hazards threatening dams include:

- flooding from high precipitation
- flooding from dam failure
- earthquakes
- landslides

Flooding from high precipitation. Of the natural events that can impact dams, floods are the most significant. A floodplain map of the U.S. (Figure 3.1) gives

some idea of the major flood prone areas. Flash floods can happen anywhere--even on small drainage areas but especially in the west. Floods are the most frequent and costly natural events that lead to disaster in the U.S. Therefore, flood potentials must be included in risk analyses for dam failure. Hurricanes and tropical storms can stall over an area, creating a significant precipitation event that can result in flooding. See Table 3.1 for extreme precipitation events in Texas.

Texas has design flood criteria derived from a percentage of the probable maximum flood (PMF) based on the dam's hazard potential and size classification. A PMF is the flood that may be expected from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the region. This assumed event becomes the basis for the design of structural and hydraulic elements of the dam.

Flooding from dam failure. When a dam fails as a result of a flood, more people and property are generally placed in jeopardy than during natural floods. The Rapid City, South Dakota, flood of 1970, which killed 242 people, caused a dam failure which added significantly to the loss of life. When a natural flood occurs near a dam, the probability of failure and loss of life almost always increases.

The sudden surge of water generated by a dam failure usually exceeds the maximum flood expected naturally; dam-failure inundation zones and 100-year

Table 3.1
Extreme Precipitation in Texas

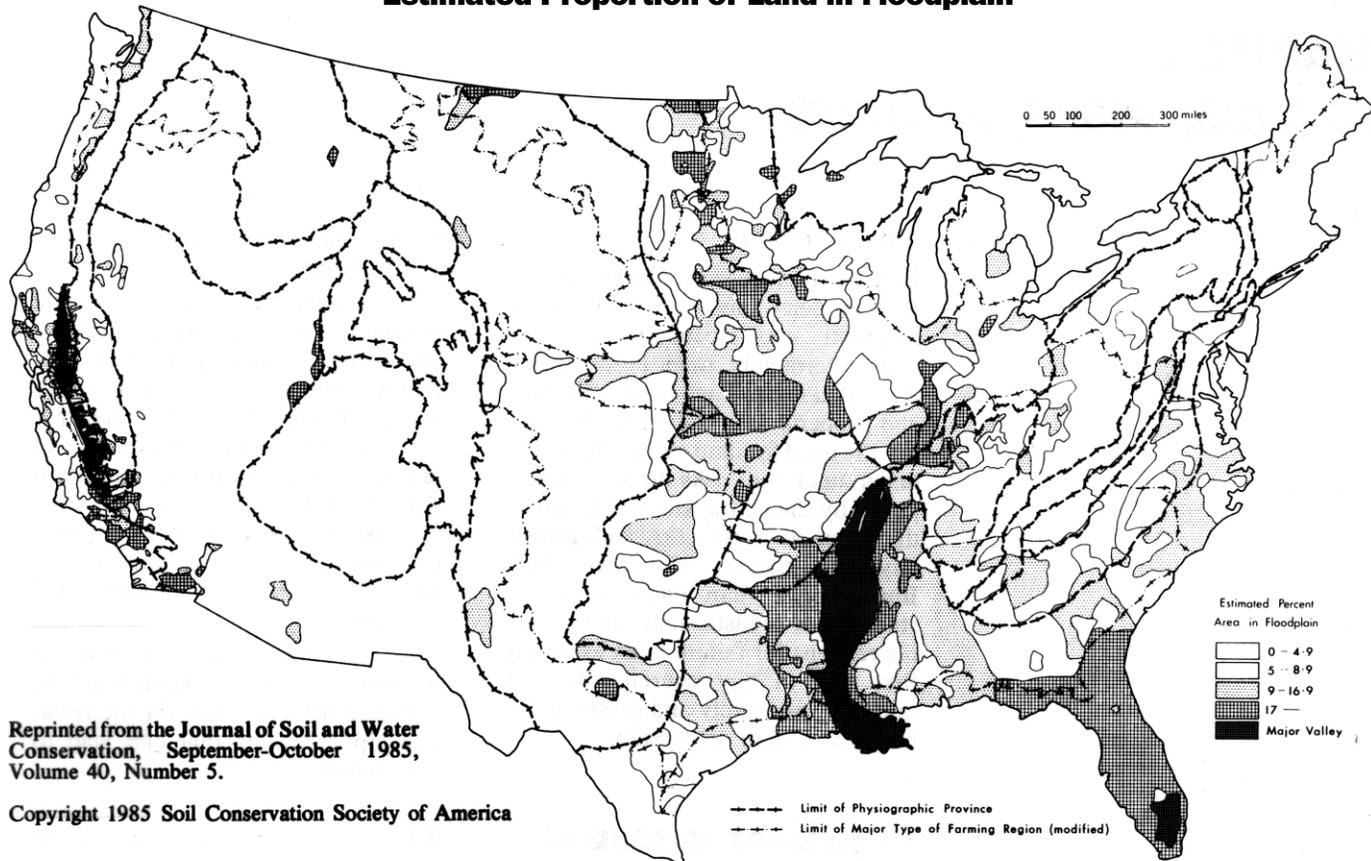
Location	Dates	Inches	Duration (hr)	Comments
Thrall	Sept. 9-10, 1921	38.2	24	36.4" in 18 hr
D'Hannis	May 31, 1935	22	3	
New Braunfels	May 11, 1972	16	4	
Taylor Ranch (San Saba Co.)	July 3, 1976	17.83	24	
Albany	August 4, 1978	29.05	24	23" in 8 hr
Medina	August 4, 1978	48	52	
Alvin	July 26, 1979	25.75	24	NWS reported 42" in 19 hr
Odem	Oct. 19, 1984	26	4	
Comanche	May 31, 1988	18	5	
Pearland	Oct. 17, 1994	28.2	48	
Lake Conroe	Oct. 16-19, 1994	27.76	96	

Sources: Bomar (1983); National Weather Service, San Antonio; NWS, Houston-Galveston; U.S. Geological Survey (2003).

floodplains are seldom congruent. The upper portion of an inundation zone almost always exceeds the 100-year floodplain considerably; therefore, residences and businesses that would escape natural flooding can be at extreme risk from dam failure flooding. Hence, it is important to inform residents and business personnel of the full risk to which they are exposed so that they can respond accordingly.

When one dam fails, the sudden surge of water may well be powerful enough to destroy another dam downstream, compounding the disaster. The potential for such a snowball effect is great, but the problem may seem remote to a dam owner who has not studied the potential impacts of upstream dams on his or her own structure. Upstream dams may seem too

Figure 3.1
Estimated Proportion of Land in Floodplain



far away to be a real threat, but inundation zones and surge crests can extend many miles downstream, especially if the reservoir behind the collapsed dam held a large quantity of water.

Earthquakes. Earthquakes are also significant threats to dam safety. Both earthen and concrete dams can be damaged by ground motions caused by seismic activity. Cracks or seepage can develop, leading to immediate or delayed failure. Dams such as those in California—located near relatively young, active faults—are of particular concern, but dams (especially older concrete and earthen structures) located where relatively low-scale seismic events may occur are also at risk. Areas of the U.S. where significant seismic risks exist are indicated in Figure 3.2. However, recent detailed seismic analyses have indicated a much broader area of seismic activity sufficient to damage dams than previously considered; the seismic risk is essentially nationwide. Dam owners should be aware of the

history of seismic activity in their locality and should develop their emergency procedures accordingly.

Landslides. Rock slides and landslides may affect dams directly by blocking a spillway or by eroding and weakening abutments. Indirectly, a large landslide into a reservoir behind a dam can cause an overflow wave that will exceed the capacity of the spillway and lead to failure. A landslide (or mudslide) can form a natural dam across a stream which can then be overtopped and fail. In turn, failure of such a natural dam could then cause the overtopping of a downstream dam or by itself cause damage equivalent to the failure of a human-built dam. In addition, large increases in sediment caused by such events can materially reduce storage capacity in reservoirs and thus increase a downstream dam’s vulnerability to flooding. Sedimentation can also damage low-level gates and water outlets; damage to gates and outlets can lead to failure.

3.1.2 Hazards From Human Activity

Human activity must also be considered when analyzing the risks posed by dams. In Texas, the hazard classification of dams is based on the potential for loss of life and economic loss in the area downstream of the dam, not on its structural safety. Thus, dams that may be of very sound construction are labeled “high hazard” if failure could result in catastrophic loss of life—in other words, if people have settled in the potential inundation zone. The “high hazard” designation does not imply structural weakness or an unsafe dam. See 30 Texas Administrative Code Chapter 299 for the Texas criteria for classifying dams in the three hazard potential categories.

Risk may well increase through time because few governmental entities have found the means to limit settlement below dams. The hazard level of more dams is rising to “high” or “significant” as develop-

Figure 3.2
Seismic Map of the United States

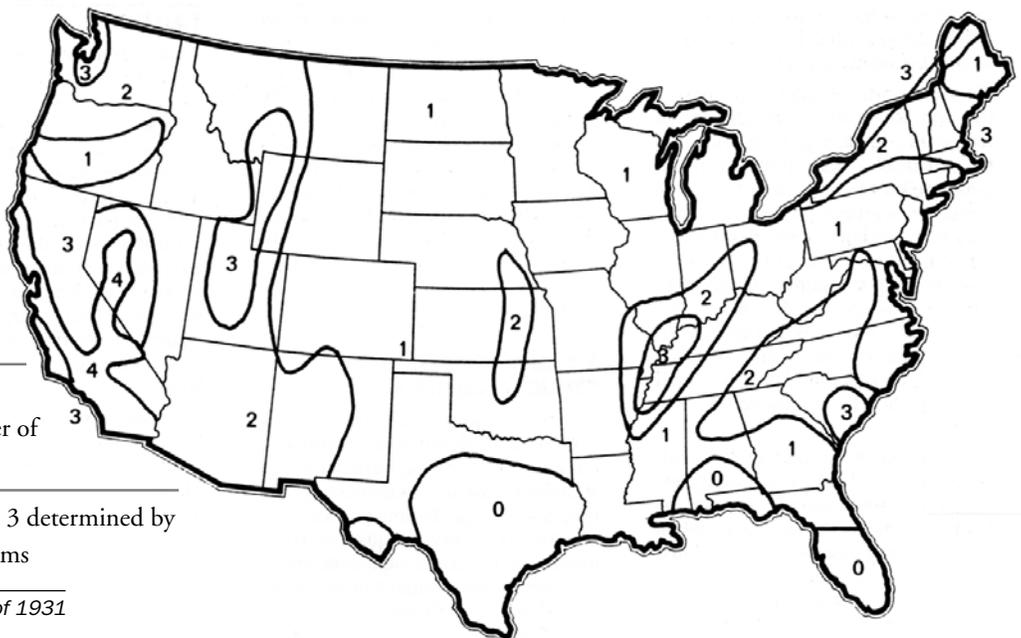
ZONE 0 No damage.

ZONE 1 Minor damage, distant earthquakes may cause damage to structures with fundamental periods greater than 10 seconds, corresponds to intensities V and VI of the M.M.* Scale.

ZONE 2 Moderate damage, corresponds to intensity VII of the M.M.* Scale.

ZONE 3 Major damage, corresponds to intensity VIII and higher of the MM* Scale.

ZONE 4 Those areas within Zone 3 determined by the proximity to certain fault systems



*Modified Mercatal Intensity Scale of 1931

Source: U.S. Army Corps of Engineers (1985).

ment occurs in potential inundation zones below dams previously rated “low hazard.”

Many other complex aspects of settlement and development must be considered in assessing dam risks. Because of short-term revenue needs or other pressures, governments often permit development in hazardous areas despite long-term danger and the risk of high future disaster costs. Diversion of development away from potential inundation zones is a sure means of reducing risk, but is not always a policy suitable to the immediate needs of local government. Perhaps the ultimate irony for a dam owner is to have developed and implemented a safety program and then to have development permitted in the potential inundation zone so that the hazard rating and owner’s liability increase.

Two extremes of human purpose, the will to destroy through war or terrorism and the urge to develop and to build, can both result in public risks. Dams have proven to be attractive wartime targets, and they may be tempting to terrorists. On the other hand, a terrorist’s advantage from holding the public at risk may well be illusory; the deliberate destruction of a dam is not at all easy to bring about. Yet the possibility exists that such an act could take place, and it should not be discounted by the dam owner.

All sorts of other human behavior should be included in risk analyses; vandalism, for example, cannot be excluded and is in fact a problem faced by many dam owners. Vegetated surfaces of a dam embankment, mechanical equipment, manhole covers and rock riprap are particularly susceptible to damage by people. Every precaution should be taken to limit access to a dam by unauthorized persons and vehicles. Dirt bikes (motorcycles) and off-road vehicles, in particular, can severely degrade the vegetation on embankments. Worn areas lead to erosion and more serious problems.

Mechanical equipment and associated control mechanisms should be protected from tampering, whether purposeful or inadvertent. Buildings housing mechanical equipment should be sturdy, have protected windows, and heavy-duty doors, and be secured with padlocks. Detachable controls, such as handles and wheels, should be removed when not in use and stored inside the padlocked building. Other controls should be secured with locks and heavy chains where possible. Manhole covers are often removed and sometimes thrown into reservoirs or spillways by vandals.

Rock used as riprap around dams is sometimes thrown into the reservoirs, spillways, stilling basins, pipe-spillway risers, and elsewhere. Riprap is often displaced by fishermen to form benches. The best way to prevent this abuse is to use rock too large and heavy to move easily, or to slush-grout the riprap. Otherwise, the rock must be regularly replenished and other damages repaired. Regular visual inspection can easily detect such human impacts.

Owners should be aware of their responsibility for the safety of people using their facility even though their entry may not be authorized. “No Trespassing” signs should be posted, and fences and warning signs erected around dangerous areas. As discussed in Chapter 10, liability insurance can be purchased for protection in the event of accidents.

3.2 Site-Specific Structural Risk

Developing site-specific risk analyses involves consideration of a number of hazards. Such analyses are helpful in stimulating better awareness, planning, and design. In some cases dam-structure analyses are quantitative and precise conclusions about engineering and design can be made. Probabilistic analyses can

also be important and useful. Still, exact quantitative and probabilistic tools are not yet applicable in many situations and do not fully supplement or replace qualitative analyses—informed perception and judgment of the risks. Judgment and engineering experience should play an important role in reaching useful conclusions in any site-specific analysis of structural risk.

As mentioned in Chapter 2, structural risks tend to result from design and construction problems related to the dam materials, construction practice, and hydrology. The complexity of the hazard is such that structural design and causes of dam failure are significant areas of research in engineering. Indeed, better design criteria have been developed and safer dams are being built, but there is no basis for complacency. Dams continue to age, people continue to move into inundation zones, and enough hazards exist that the net risk to the public will remain high.

3.3 Sources of Dam Failure

There are many complex reasons—both structural and non-structural—for dam failure. Many sources of failure can be traced to decisions made during the design and construction process and to inadequate maintenance or operational mismanagement. Failures have also resulted from the natural hazards already mentioned—large-scale flooding and earthquake movement. However, from your perspective as owner, the structure of a dam is the starting point for thorough understanding of the potentials for failure.

3.3.1 Three Categories of Structural Failure

Three categories of structural failure alluded to in Chapter 2 are:

- overtopping by flood

- foundation defects
- piping and seepage

Overtopping may develop from many sources, but often evolves from inadequate spillway design. Alternatively, even an adequate spillway may become clogged with debris. In either situation, water pours over other parts of the dam, such as abutments or the toe, and erosion and failure follow.

Concrete dams are more susceptible to foundation failure than overtopping, whereas earthen dams suffer from seepage and piping.

Overall, these three events have about the same incidence. A more specific analysis of the potential sources of failure has to take into account types of dams. Similarly, the characteristics of the type of dam being monitored will point to problems requiring more careful attention by the owner when developing a safety program.

3.3.2 Failures by Dam Type

Embankment or Earthen Dams. The major reason for failure of fill or embankment dams is piping or seepage, though other hydrologic failures are significant, including overtopping and erosion from water flows. All earthen dams exhibit some seepage; however, as discussed earlier, this seepage can and must be controlled in velocity and amount. Seepage occurs through the structure and, if uncontrolled, can erode material from the downstream slope or foundation backward toward the upstream slope. This “piping” phenomenon can lead to a complete failure of the structure. Piping action can be recognized by an increased seepage flow rate, the discharge of muddy or discolored water below the dam, sinkholes on or near the embankment, and a whirlpool in the reservoir.

Earthen dams are particularly susceptible to hydrologic failure since most

Box 3.1 Examples of Earthen-Dam Failures

SOUTHFORK, PENNSYLVANIA

The famous Johnstown disaster, caused by the failure of the South Fork Dam in 1889, in which 2,209 people were killed, is an example of the overtopping of an earthen dam. Heavy rainfall in the upper drainage basin of the dam filled the reservoir and caused overtopping. It was later calculated that, if a spillway had been built according to specifications and if the original outlet pipes had been available for full capacity discharge, there would have been no overtopping.

TETON DAM, IDAHO

The Teton Dam failure in 1976 was attributed to (1) internal erosion (piping) of the core of the dam deep in the right foundation key trench, with the eroded soil particles finding exits through channels in and along the interface of the dam with the highly pervious abutment rock and talus to points at the right groin of the dam; (2) destruction of the exit avenues and their removal by the outrush of reservoir water; (3) the existence of openings through inadequately sealed rock joints which may have developed through cracks in the core zone in the key trench; (4) the development of piping through the main body of the dam that quickly led to complete failure; and (5) the design of the dam did not adequately take into account the foundation conditions and the characteristics of the soil used for filling the key trench.

BALDWIN HILLS AND ST. FRANCIS DAMS, CALIFORNIA

The Baldwin Hills Dam failed in 1963 following displacement of its foundation. Foundation problems were ultimately traced to seismic activity along nearby faults. The failure of the large St. Francis Dam (part of the water supply system for Los Angeles) in 1928 was also attributed to a variety of problems related to foundation pressures, seepage around the foundation, and faulty operation.

Source: Jansen, 1980.

Box 3.2 Examples of Concrete-Dam Failures

AUSTIN, PENNSYLVANIA

An example of a foundation problem can be found in the failure of the Austin, Pennsylvania Dam in September, 1911. Evidently, the reservoir was filled before the concrete had set sufficiently. Eventual failure near the base occurred because of weakness in the foundation or in the bond between the foundation and the concrete.

WALNUT GROVE, ARIZONA

In 1890, the Walnut Grove dam on the Hassayompa River failed due to overtopping, killing about 150 people. The failure was blamed on inadequate capacity of the spillway and poor construction and workmanship. A spillway 6 x 26 feet had been blasted out of rock on one abutment, but, with a drainage area above the dam site of about 500 square miles, the spillway did not have nearly enough discharge capacity.

Source: Jansen, 1980.

sediments erode at relatively low waterflow velocities. Hydrologic failures result from the uncontrolled flow of water over the dam, around it, and adjacent to it, and the erosive action of water on the dam's foundation. Once erosion has begun during overtopping, it is almost impossible to stop. In a very special case, a well-vegetated earthen embankment may withstand limited overtopping if water flows over the top and down the face as an evenly distributed sheet and does not become concentrated in a single channel. Box 3.1 lists examples of earthen-dam failures caused by some of these conditions.

Concrete Dams. Failure of concrete dams is primarily associated with foundation problems. Overtopping is also a significant cause again primarily when spillways are built with inadequate capacity. Other causes include failure to let concrete set properly and earthquakes. The examples summarized in Box 3.2 illustrate typical foundation problems leading to dam failure.

3.3.3 Age and Its Relation to Failure

Foundation failures occur relatively early in the life of a dam, whereas other causes generally take much longer to materialize. Thus, it is not surprising that a very large percentage of all dam failures occur during initial filling, since that is when design or construction flaws, or latent site defects, appear.

As dams age, maintenance becomes more critical. Lack of maintenance will result in deterioration and eventually, failure.

Texas dams are aging as shown in Table 3.2, and problems as described above are slowly becoming apparent.

Table 3.2
Ages of Dams in Texas

Dates	Percentage of Dams
Prior to 1950	15.3
1950–59	15.3
1960–70	42.2
1971–80	18.7
1981–present	8.5

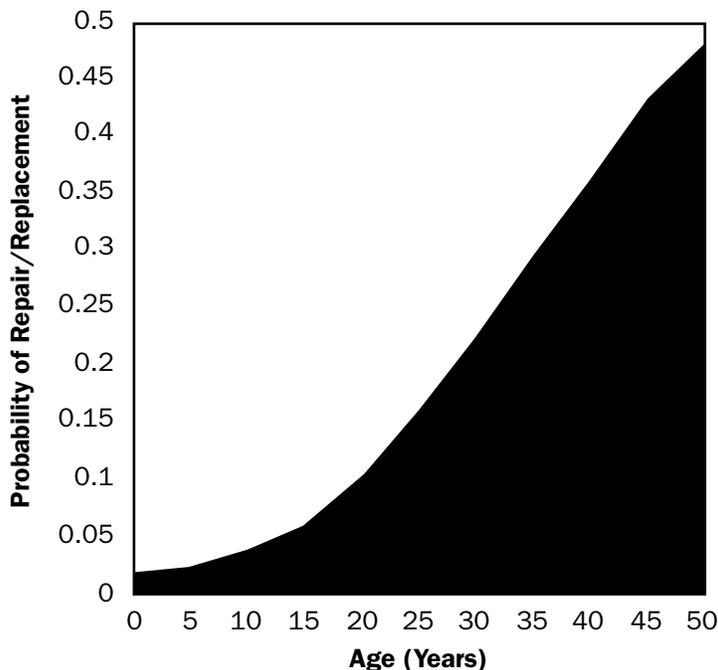
3.3.4 Condition Rating of Dam Conduits

As part of research work supported by the National Dam Safety Program, the National Performance of Dams Program

has developed an approach to predicting the condition of metal conduits in embankment dams. Utilizing the results of dam safety inspections from New Jersey, Washington, Virginia, Ohio, Kansas, and Oklahoma, a rating system was used to characterize the condition of metal conduits. Using these data, along with the age of the dam, a statistical model was developed to predict the condition of metal conduits as a function of age. The results of this assessment, combined with the recommendations of the dam inspectors, allow us to predict, as a function of age, the likelihood that a conduit will require repair or replacement (Figure 3.3).

Knowledge of the hazards, risks, and failures associated with dams is critical for owners. Consider each aspect of a safety program in relation to the most probable sources of failure for your dam in particular.

Figure 3.3
Prediction of the Likelihood of Metal Conduits Requiring Repair or Replacement as a Function of Age



Source: National Performance of Dams Program, Stanford University (e-mail Communication, March 26, 2004).