# Dams and Earthquake Safety

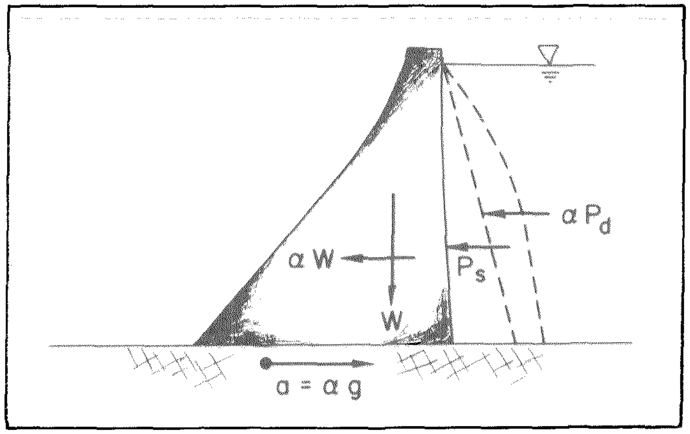
by John F. Hall

WILL DAMS SURVIVE severe earthquake shaking? Finding an answer to this question is one of the important goals for many engineers today. How are they going about including earthquake shaking as an element in dam design and in the evaluation of existing dams? In the past, earthquake effects may have been treated too lightly in dam design. Are such dams safe, and how have they fared in previous earthquakes? There are three major types of dams — embankment and concrete gravity and concrete arch — but this discussion will be limited to some of the findings about the two concrete types.

Concrete gravity dam design was, and still is, based on two-dimensional idealizations (as illustrated in the figure at the right) because gravity dams, which are generally located in wide river valleys, are long and nearly uniform in cross section. Water loading from the reservoir behind the dam seeks to overturn or slide the dam downstream; and the dam's own weight resists this action. A proper choice of dam cross section provides stability. In addition, since concrete is weak in tension and since no steel reinforcing is employed, engineers equated the presence of tensile stresses with failure. If their computations showed tensile stress at any point, they redesigned the cross section. Stress analysis was performed by treating the dam cross section as a beam of variable thickness cantilevering from the valley floor.

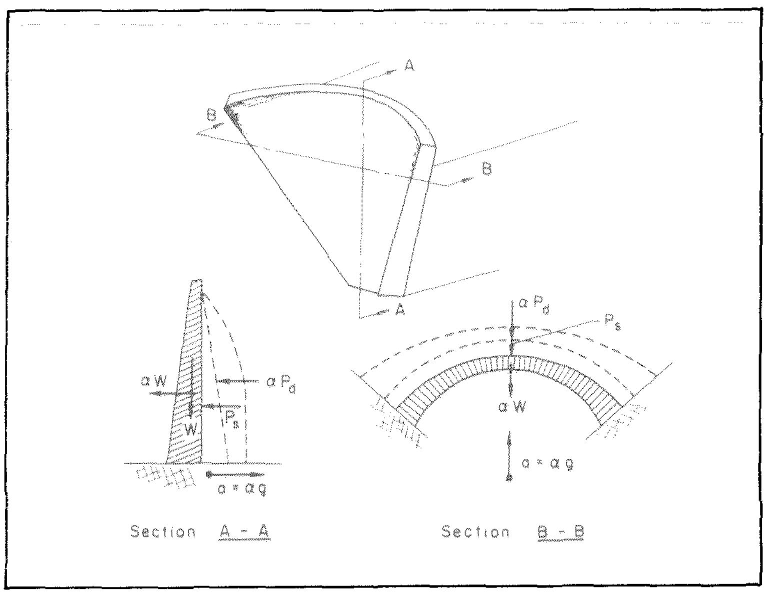
Arch dams are built in narrow canyons, and they are true three-dimensional structures. They resist the water load by combining cantilever bending from the canyon floor with arch thrusting to the abutments (lower right). Usually their proportions are much thinner than those of concrete gravity dams. Tensile stress was again avoided in the design, but engineers found stress analysis much more complicated. An iterative relaxation method applied to independent arch and cantilever sections was developed, which produced many rooms full of engineers grinding out stress calculations.

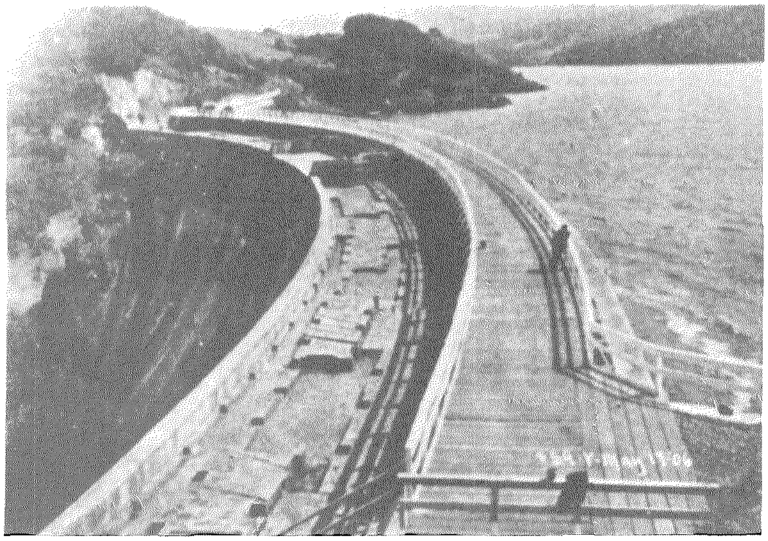
Engineers recognized early in this century that earthquake shaking introduced additional forces into their analyses. A horizontal acceleration in the upstream direction seemed most critical because it increased the overturning forces. The assumption was that the dam, which appeared to be a stiff structure, would move rigidly with the ground. Thus, if the ground accelerates at a fraction, designated α (alpha), of gravity, an inertial force of magnitude α times the dam weight is created and acts on the dam in the downstream direction. Moreover, additional water pressure is generated, proportional to the acceleration of the dam into the reservoir if water incompressibility is assumed. This feature was recognized in 1933, and it has been included in dam design ever since. Typical values of α were 0.05 to 0.15, and inclusion of earthquake effects still allowed



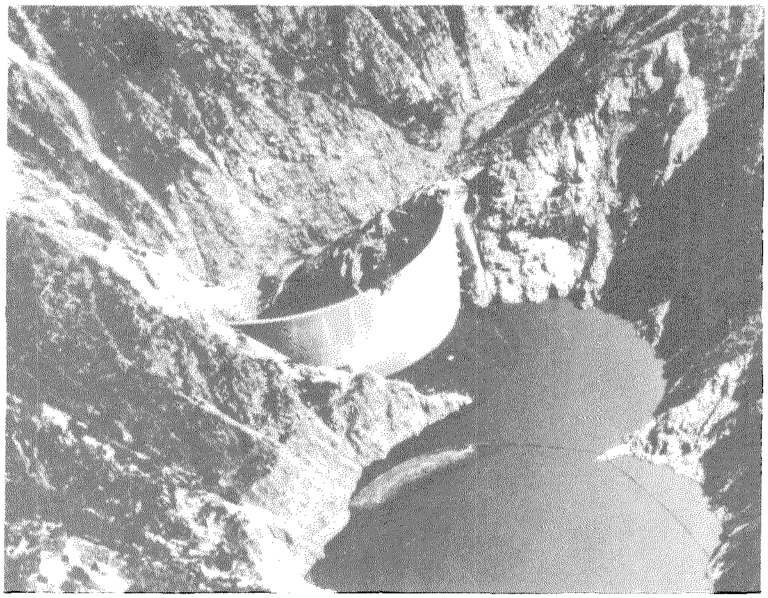

*Design of a concrete gravity dam (above) is based on a two-dimensional idealization. The design loads include the dam weight W, the static water force $P_s$ and the ground acceleration α (given as a fraction α of the gravitational acceleration g). The ground acceleration produces an inertia force αW on the dam and an additional water force $\alpha P_d$ (where $P_d$ is the water force caused by a unit acceleration of the water into the reservoir).*

*Design of a concrete arch dam (below) must take into account the three-dimensional structural action.*

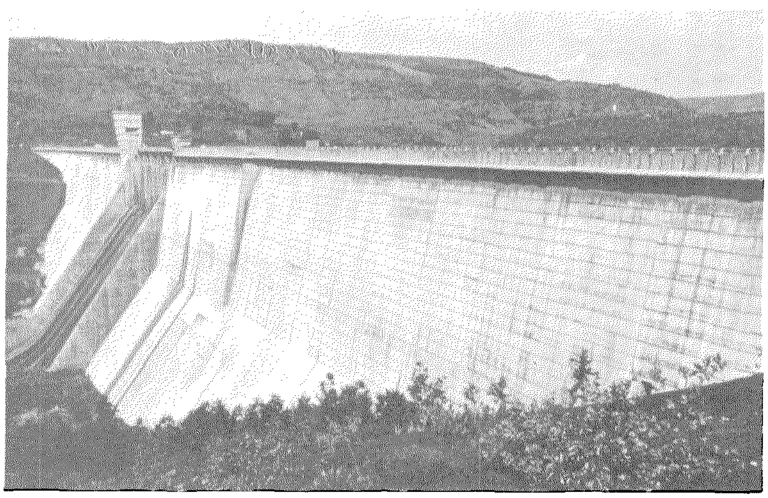




*Crystal Springs Dam (a curved gravity type shown above) was undamaged by the 1906 San Francisco earthquake. Furthermore, earthquake accelerations in the range of 1.0 g during the 1971 San Fernando earthquake failed to damage . . .*



*. . . Pacoima Dam (above), a 370-foot-high arch dam. The upper portion of Koyna Dam (a gravity dam pictured below) cracked through from upstream face to downstream face during an earthquake in 1967. No failure resulted.*

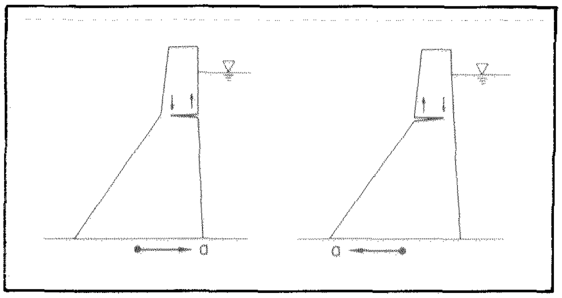


the no-tension criterion to be observed in the design.

Early design procedures were obviously great simplifications of reality. Dams are not really rigid; they are flexible structures that vibrate on their own when excited by ground motion. Stress analysis methods were approximate, and the maximum ground accelerations used were only fractions of what could occur. Vertical and cross-stream components of ground motion were neglected. But the pertinent question is, of course: How have dams designed by the methods described performed during past earthquakes? And the answer is: Fairly well, although there have been a few surprises.

The first significant event occurred in 1906 during the San Francisco earthquake. Crystal Springs Dam, a 145-foot-high curved gravity dam (pictured at the left), was located adjacent to the fault break, and it survived undamaged even though earthquake loading was not considered in its design. This good performance was attributed to a high reserve strength; the cross section was designed as a gravity section, but the curved plan also enabled arch action to carry a portion of the load. Another dam, Pacoima, performed well during the magnitude 6.4 San Fernando earthquake in 1971. Pacoima Dam (shown at the left) is an arch dam 370 feet high, 10 feet thick at the top, and 99 feet thick at the base. Earthquake accelerations measured above one abutment peaked at the remarkable value of 1.25 g. Yet the dam survived undamaged, possibly because of a low water level in the reservoir.

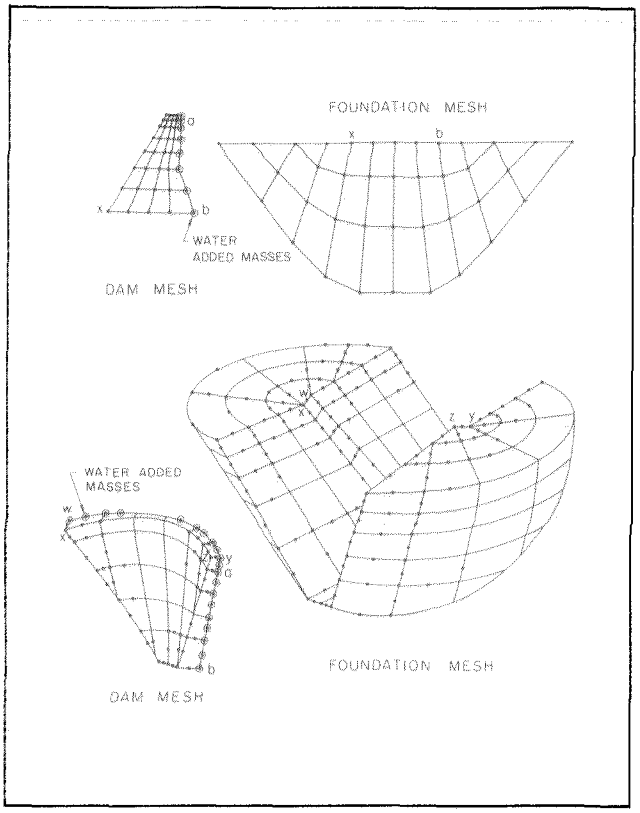
In 1962 Hsinfengkiang Dam, a 344-foot-high concrete dam near Canton, China, was shaken by a magnitude 6.1 earthquake. Considerable longitudinal cracking occurred in the upper portion of the dam, but no failure resulted. This event had a twofold significance. First, it showed that concrete tensile stress could be present (which cast doubt on the accepted methods of dam design). Second, it showed that considerable cracking does not necessarily imply failure. These two lessons were reinforced in 1967 during a magnitude 6.5 earthquake near Poona, India, which shook the 338-foot-high concrete gravity Koyna Dam (lower left). Maximum ground acceleration at the site measured 0.63 g. Again, extensive longitudinal cracking appeared in the upper portion of the dam, and again, failure did not occur. Researchers believe that the dam cross section cracked completely through from upstream face to downstream face, and the block above the crack rocked back and forth during the earthquake (as



shown in the figure above). Fortunately, this post-cracking stability is a real phenomenon, and there has come to be general agreement that arch dams, because of their combined cantilever and arch actions, possess a considerable amount of it.

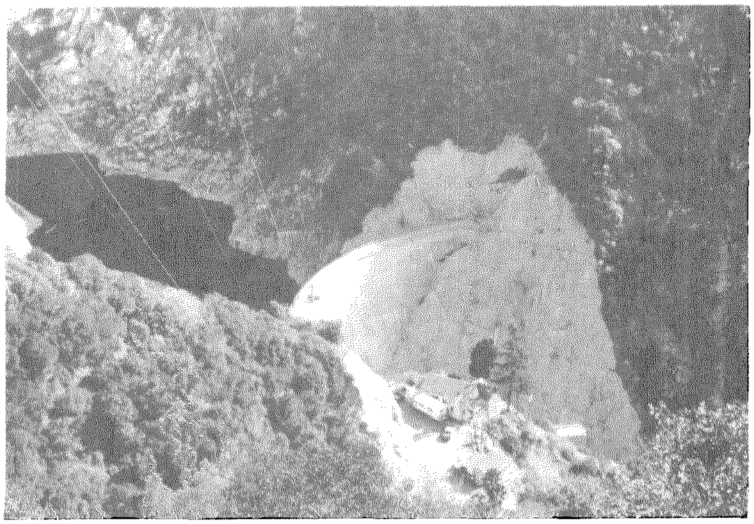
Although no earthquake-related failure of a concrete dam has occurred to date, no large concrete dam with a full reservoir has ever been subjected to really severe ground shaking. Such a possibility has many groups concerned, including the Division of Safety of Dams, a California state agency responsible for assuring the safety of California dams. The DSD has the power to order an updated seismic check of a dam if new information rises or if better analysis techniques are developed by researchers. In the early 1970s, two events led the DSD to initiate a program to perform seismic checks on all major dams under its jurisdiction. The first event was the near collapse of Lower San Fernando Dam, a large earthen dam, during the 1971 earthquake; and the second was the development of the finite element method, a tool for computerized stress analysis.

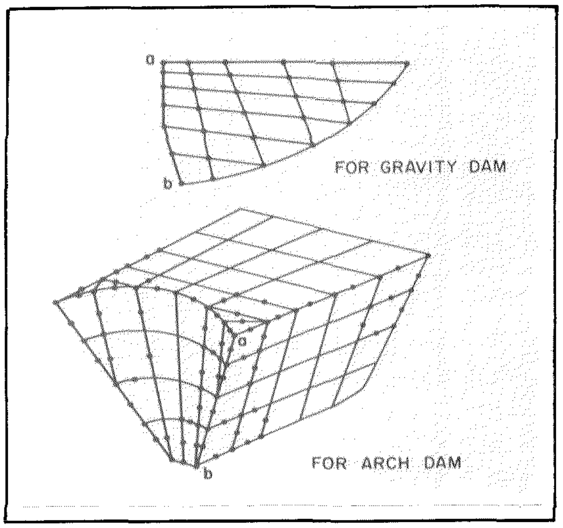
The finite element method transforms the governing differential equations (the equations of solid mechanics in the case of a dam) to a matrix equation that is solved on the computer. The structure to be analyzed is meshed into elements (see figure above right), which are connected at nodal points. Associated with these nodes are displacement degrees of freedom, which become the unknowns of the matrix equation. Solution of the matrix equation yields the structure displacements, from which the stresses are easily computed. As long as the governing differential equations are linear, the finite element method produces remarkable solutions. Nonlinearities, however, are much more difficult to handle. An example of nonlinearity in dam behavior is the formation of cracks or opening of built-in joints due to the presence of tensile stresses. Even today, finite element techniques have not progressed to the point where this type of nonlinearity can be handled.




*The top block of Koyna Dam (far left above) rocked back and forth but did not overturn. Above, an illustration of how improved earthquake safety evaluations of dams have been made possible through use of finite element analyses. A common procedure employs a dam mesh, a mesh of a finite region of the foundation, and added masses on the upstream dam face to represent the water.*

As a part of the DSD program, a standard procedure using the finite element method was developed for computing the (linear) response of concrete dams. The drawing above illustrates this procedure. A finite element model is constructed of the dam and of a portion of the foundation region that extends out to an artificial boundary where earthquake motions are applied. The motion specified by the engineer is actually the free-field motion (that is, the motion that would occur at the dam-foundation interface if the dam were not present), and the engineer must back-calculate what motion to apply at the foundation boundary. Since the foundation boundary produces wave reflections that contaminate the computed dam response after a short time, the foundation mesh is usually assumed to be massless. The alternative is to place the foundation boundary far away from the dam, but this results in a large, expensive-to-solve matrix equation. The water is included in the analysis by an added-mass approach. An appropriate volume of water is assigned to move with each horizontal, nodal degree of freedom at the upstream dam face. Treating the water in this manner neglects water compressibility (which can be important for deep reservoirs) and ignores the additional pressures generated by the vertical and cross-stream components of earthquake ground motion along the reservoir boundary.






*Finite element analysis revealed that Santa Anita Dam (above), a 230-foot-high arch dam, would have difficulty surviving severe ground shaking if its reservoir were full. Above right, finite element models of the water in the reservoir accurately represent its effect on the dam response to earthquake shaking. These models include water compressibility and the additional pressures generated by vertical and cross-stream motions of the reservoir boundaries.*

Nevertheless, this procedure has found wide application, because it can be readily implemented by a number of available structural analysis computer programs. Unfortunately, the assumption of linear behavior (no cracking) has been shown to be usually invalid. Consider, for example, the DSD-required check of Santa Anita Dam (pictured above left). It is a 230-foot-high arch dam, 7 feet thick at the top, and 62 feet thick at the base, located in a canyon above Monrovia, California. The purpose of the check was to determine if the dam could survive a hypothetical magnitude 7.0 earthquake on the nearby Sierra Madre fault. The free-field ground motion employed contained peak accelerations of 0.7 g and 0.45 g in the horizontal and vertical directions, respectively. Results of the linear, finite element analysis showed peak tensile stresses in the upper portion of the dam of 1400 psi, which is more than twice the tensile strength of concrete. Recognizing that Santa Anita Dam could take a reasonable amount of cracking and remain stable, the engineers faced the difficult task of judging the safety of the dam using an analysis that assumed no cracking — but that clearly showed significant cracking would occur. This remains the major dilemma today. The final decision on Santa Anita Dam was to lower the water level to a safe point until the dam could be strengthened.

Obviously, the most pressing research need is for computational techniques that accurately model the cracking behavior, but little progress has been made to date. Recently, however, some headway has been reported on improved modeling of the dam foundation and of the water in the reservoir. The artificial foundation boundary can be replaced by mathematical transmitting boundaries, which reflect only a small fraction of an incident wave. For the water, I have developed finite element models (shown above) that include water compressibility and the additional pressures generated by vertical and cross-stream motions of the reservoir boundaries. Both of these effects have been shown to influence the earthquake response of concrete dams significantly.

In order to provide guidance in the development of future mathematical models, the civil engineering group at Caltech has recently received a two-year grant for experimental research from the National Science Foundation. We plan to conduct an extensive series of shaking tests on actual dams using our 5000-pound shaking machines. Measurements will be made to define each dam's resonance and damping characteristics, the additional water pressure generated by the dam motions, and the stiffness characteristics of the foundations. Small-scale model tests will also be performed. Because calculations have shown that water pressures near the dam can reduce to water's vapor pressure during the shaking, we plan to study at reduced scale the mechanism by which this cavitation takes place. An interesting series of small-scale, shaking-table tests on precracked dam models will provide insight into the post-cracking stability of concrete dams. Future mathematical models should greatly benefit from these next two years of experimental research.

What will happen to dams during severe earthquake shaking? It is obvious that at present engineers cannot answer this question with any certainty. But we are very much aware of the threat of disastrous losses of life and damage to property if dams should fail, and we are making great effort to increase our understanding of this complex topic. □