

Earthquake analysis, design, and safety evaluation of concrete arch dams

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ABSTRACT: Summarized is the current state of knowledge about earthquake response analysis of concrete arch dams, and the application of this information to the earthquake-resistant design of new dams and to the seismic safety evaluation of existing dams. The limitations of the traditional design procedures are identified, the factors that should be considered in dynamic analysis are discussed, and procedures for earthquake response history analysis are summarized. The application of these linear analysis procedures to seismic design and safety evaluation of dams is discussed, followed by a brief mention of the limitations of the presently available nonlinear analysis procedures.

1 INTRODUCTION

The consequences of a large dam failing can be disastrous, so the seismic design of dams is an important part of earthquake engineering. Although no concrete dams have failed because of earthquakes, it is important to recognize that these structures have not been seriously tested--in the sense that very rarely has a large earthquake occurred close to a major concrete dam with a full reservoir. However, M6.5 earthquakes did occur close to Koyna Dam--a large concrete gravity dam--in India in 1967 and Hsinfengkiang Dam--a strengthened concrete buttress dam--in the People's Republic of China in 1962. A M7.6 earthquake occurred in 1990 near Sefidrud Dam--a large concrete buttrees--in Iran (Ahmadi and Khoshrang, 1992). All three dams were overstressed by the earthquake motions and were damaged to an alarming degree. Pacoima Dam, a concrete arch structure, sustained damage to one abutment during the 1971 San Fernando earthquake; its reservoir was only partly full at the time. The experience with the earthquake performance of these dams indicates that concrete dams are not immune to earthquake damage as had commonly been presumed. Thus, it is essential that increasing attention be given to the earthquake safety of these structures.

The ability to evaluate the effects of earthquake ground motion on concrete dams is essential to assess the safety of existing dams, to determine the adequacy of modifications planned to improve old

dams, and to evaluate proposed designs for new dams to be constructed. The prediction of the performance of concrete dams during earthquakes is one of the more complex and challenging problems in structural dynamics. The following factors contribute to this complexity:

- Dams and reservoirs are of complicated shapes, as dictated by the natural topography of the site.
- The response of dams may be influenced significantly by variations in the intensity and characteristics of the ground motion over the width and height of the canyon. However, for lack of appropriate instrumental records, the spatial variations of the ground motion cannot be defined with confidence at this time.
- The response of a dam is influenced, generally to a significant degree, by the earthquake-induced motion of the impounded water; by the deformability of the foundation rock; and by the interaction of the motions of the water, foundation rock, and the dam itself.
- During intense earthquake motions, vertical construction joints may slip or open; concrete may crack; and the stored water may locally separate from the upstream face of the dam, resulting in cavitation. These phenomena are nonlinear and extremely difficult to model and account for reliably.

Realistic analyses of the seismic response of dams were not possible until the development of the finite element method, recent advances in dynamic analysis procedures, and the availability of large-capacity, high-speed computers. Thus, much of the research did not start until the mid-1960's. Initially,

all nonlinear effects, including those associated with construction-joint opening, concrete cracking and water cavitation, were ignored, and the interaction effects of the impounded water and foundation rock were either neglected or grossly simplified. Subsequently, special techniques were developed for incorporating the interaction effects in linear analyses.

The objective of this paper is to summarize the current state of knowledge about linear earthquake response analysis of concrete arch dams and how this information can be applied to the earthquake-resistant design of new dams and to the seismic safety evaluation of existing dams.

The problem of earthquake response analysis of concrete dams has been the subject of numerous research investigations in the past twenty-five years. However, no attempt is made to establish the interrelationship of the material presented in this paper to the work of other researchers. This paper is based almost exclusively on the results of studies carried out at the University of California at Berkeley during the past ten years.

2 EVALUATION OF TRADITIONAL ANALYSIS AND DESIGN PROCEDURES

2.1 Traditional analysis and design procedures

Traditionally, the dynamic response of the system has not been considered in defining the earthquake forces in the design of arch dams. For example, in a 1965 publication of the U.S. Bureau of Reclamation, it is stated:

"The occurrence of vibratory response of the earthquake, dam and water is not considered, since it is believed to be a remote possibility."

Thus, the forces associated with the inertia of the dam were expressed as the product of a seismic coefficient--which is constant over the surface of the dam with a typical value of 0.10--and the weight of the dam. Water pressures, in addition to the hydrodynamic pressure, are specified in terms of the seismic coefficient and a pressure coefficient which is based on assumptions of rigid dam, incompressible water, and a straight dam. Finally, the effects of foundation rock flexibility are not considered in computing the aforementioned earthquake forces.

The traditional design criteria require that the compressive stress should not exceed one-fourth of the compressive strength or 1000 psi, and the tensile stress should remain below 150 psi.

2.2 Limitations of traditional procedures

The seismic coefficient of 0.1 is much smaller than the ordinates of the acceleration response spectra for intense earthquakes (Figure 1). Thus, the

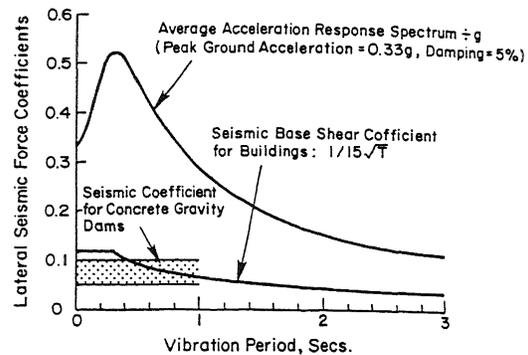


Figure 1. Comparison of earthquake response spectrum and design coefficients.

earthquake forces for arch dams are grossly underestimated in the traditional analysis procedures. It is of interest to note in Figure 1 that the seismic base shear coefficient values for dams are similar to those specified for buildings. However, building code design provisions (International Conference of Building Officials 1988) are based on the premise that buildings should be able to:

1. Resist minor earthquakes without damage;
2. Resist moderate earthquakes without structural damage, but with some nonstructural damage;
3. Resist major earthquakes . . . without collapse but with some structural . . . damage."

Whereas these may be appropriate design objectives for buildings, major dams should be designed more conservatively and this is reflected in the aforementioned design criteria used in traditional methods for design of dams. What these traditional methods fail to recognize, however, is that in order to achieve these criteria, dams should be designed for the larger seismic coefficients corresponding to pseudoacceleration response spectra for elastic structures (Figure 1).

The effective earthquake forces on a dam due to horizontal ground motion may be expressed as the product of a seismic coefficient, which varies over the dam surface, and the weight of the dam per unit surface area. The seismic coefficient associated with earthquake forces in the first two modes of vibration of the dam (fundamental symmetric and antisymmetric modes of a symmetric dam) varies as shown in Figure 2. In contrast, traditional design procedures ignore the vibration properties of the dam and adopt a uniform distribution for the seismic coefficient, resulting in erroneous distribution of lateral forces and hence of stresses in the dam.

The traditional design loadings for concrete dams include water pressures in addition to the hydrostatic

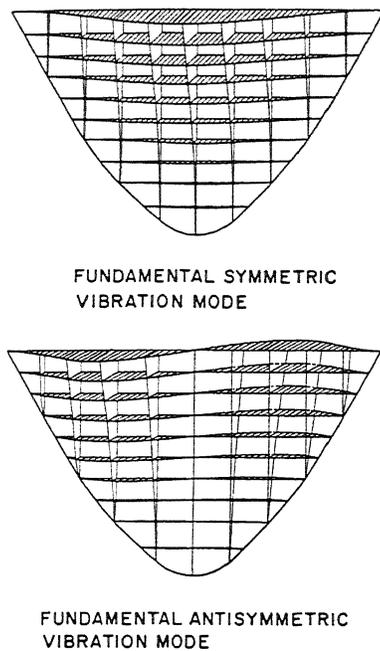


Figure 2. Distribution of seismic coefficients over the dam surface in the first two vibration modes of an arch dam (U.S. Bureau of Reclamation 1977).

pressures. A number of formulas, differing somewhat in detail and numerical values but not in the underlying assumptions, are in use (U.S. Army Corps of Engineers 1958 and U.S. Bureau of Reclamation 1966). One of these specifies the additional water pressure $p_e = C_p C_s w H$, where C_p is a pressure coefficient which varies from zero at the water surface to about 0.7 at the reservoir bottom, C_s is the seismic coefficient, w is the unit weight of water, and H is the total depth of water. For a seismic coefficient of 0.1, the additional water pressure at the base of the dam is 7 percent of the hydrostatic pressure; pressure values at higher elevations are similarly small. These small additional water pressures have little influence on the computed stresses and hence on the geometry of the dam section that satisfies the standard design criteria. However, it will be shown later that hydrodynamic effects are generally important in the response of arch dams.

Recognizing the aforementioned limitations of traditional analysis procedures, dam designers started using dynamic analysis procedures. For example, a dynamic finite-element analysis procedure, including an added mass representation of hydrodynamic effects, is described in Section 4-56 of

a 1977 USBR publication. While this procedure overcomes many of the deficiencies of the traditional procedure, it does not properly consider the hydrodynamic effects or dam-foundation rock interaction effects. In particular, the added mass is computed from the analysis of hydrodynamic pressures due to upstream-downstream vibration of a straight rigid dam, neglecting water compressibility (Westergaard, 1933). The resulting added mass is taken to be valid for both "symmetric" and "antisymmetric" vibration modes of the dam, which is obviously inappropriate. It will also be shown in the next section that water compressibility effects are generally significant. Furthermore, in particular, the foundation rock is invariably idealized as massless, an assumption that ignores the important effects of foundation material and radiation damping mechanism in dam-foundation rock interaction.

3 FACTORS TO BE CONSIDERED IN DYNAMIC ANALYSIS

The dynamic analysis of arch dams is especially complicated because they must be treated as three-dimensional systems. Utilizing recently developed dynamic analysis procedures, it is demonstrated that, in analyzing the earthquake response of concrete arch dams, the following factors should be considered: dam-water interaction, reservoir boundary absorption, water compressibility, and dam-foundation rock interaction. In addition, spatial variations in ground motion are expected to affect the dam response, but this factor has so far not been satisfactorily incorporated into the analysis.

3.1 Dam-water interaction

When dam-water interaction and water compressibility effects are properly considered in the analysis, the hydrodynamic effects are generally important in the response of arch dams, more so than for gravity dams. This is apparent from Figure 3 wherein the envelope values of the stresses on the upstream face

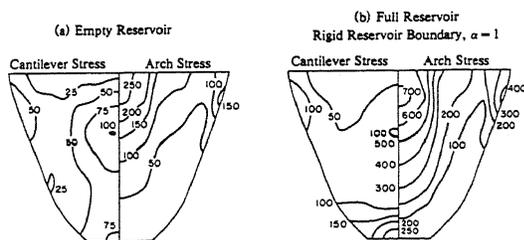


Figure 3. Hydrodynamic effects in response of Morrow Point Dam (Fok and Chopra 1986b).

of Morrow Point Dam due to the upstream component of Taft ground motion are presented for two conditions; hydrodynamic effects were included in one and neglected in the other. It is apparent that the tensile stresses in the dam due to upstream ground motion are more than doubled when hydrodynamic effects are included; even larger increases occur in the stresses caused by the other two components of ground motion. Therefore, it is obvious that the hydrodynamic effects are grossly underestimated in the traditional design loadings.

3.2 Reservoir boundary absorption

Commonly used finite-element analysis techniques do not recognize the partial absorption of hydrodynamic pressure waves by the sediments invariably deposited at the reservoir bottom and sides, or even by the rock underlying the reservoir. These effects are demonstrated in Figure 4 where

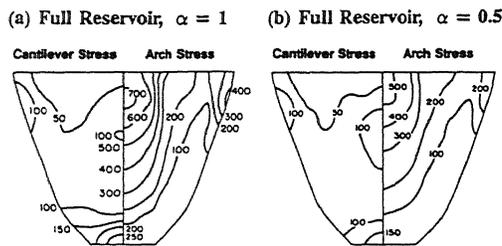


Figure 4. Reservoir boundary absorption effects in response of Morrow Point Dam (Fok and Chopra, 1986b).

envelope values of the stresses on the upstream face of Morrow Point Dam due to the upstream component of Taft ground motion are presented in for two conditions: rigid (fully reflective) reservoir boundary, $\alpha = 1$, and partially absorptive reservoir boundary, $\alpha = 0.5$, where α is the wave reflection coefficient. It is apparent that some of the stresses in the dam due to the upstream ground motion are reduced significantly because of reservoir boundary absorption; even larger decreases occur in the stresses caused by the other two components of ground motion (Fok and Chopra, 1986b). In general, assuming a non-absorptive (rigid) reservoir boundary leads to an unrealistically large response for dams with impounded water, particularly due to vertical and cross-stream ground motions.

3.3 Water compressibility

Westergaard's classical formula for the added hydrodynamic mass, commonly employed in dynam-

ic analysis of dams, is based on three assumptions that are usually not satisfied: (1) the dam is rigid, (2) it is straight in plan and has a vertical upstream face, and (3) the water is incompressible. Although this concept has long been used in practical dam analysis, the range of conditions for which it is valid was not well understood, and during the past two decades extensive research has been devoted to this question. These studies have demonstrated that dam-water interaction arising from dam flexibility should be considered in analyzing dam response. The assumption of a straight dam with vertical upstream face obviously ignores the curvature of an arch dam which can significantly influence hydrodynamic pressures. Therefore, numerical methods considering arbitrary geometry of the upstream dam face and the reservoir were developed to determine an added hydrodynamic mass matrix to be used in conjunction with finite-element analysis of dams (Kuo, 1982). Whereas this may be an improvement over Westergaard's formula for added hydrodynamic mass, water compressibility effects were still neglected in this procedure. Although studies conducted as early as 1968 and 1970 (Chopra, 1968; Chopra, 1970) demonstrated that water compressibility effects are significant in the response of concrete gravity dams, there continues to be much interest in research (Hall, 1986) and in practical applications (Tarbox et al., 1979) to neglect water compressibility in earthquake analysis of concrete dams, primarily because such an assumption leads to considerable simplification in the analysis. However, recent research has reconfirmed earlier results and further demonstrated that water compressibility effects would be significant in the earthquake response of most concrete dams.

The key parameter that determines the significance of water compressibility in the earthquake response of dams is the frequency ratio f_{res}/f_{dam} where f_{res} is the fundamental natural frequency of the impounded water and f_{dam} is the fundamental natural frequency of the dam alone. If this ratio is large enough (e.g. greater than 2 for gravity dams), the impounded water affects the dam response essentially as an incompressible fluid (Chopra, 1968). Water compressibility effects are significant in the earthquake response of arch dams with realistic values of E_s , the elastic modulus for concrete, but negligible if E_s is small enough. This is demonstrated in Figures 5 and 6 wherein is presented the earthquake response of Morrow Point Dam, assuming its elastic modulus E_s to be 4.0 million psi--a typical value--and 0.5 million psi--an unrealistically small value--respectively. It is apparent that neglecting water compressibility would be inappropriate in the first case but would be reasonable in the latter case in determining the response of the

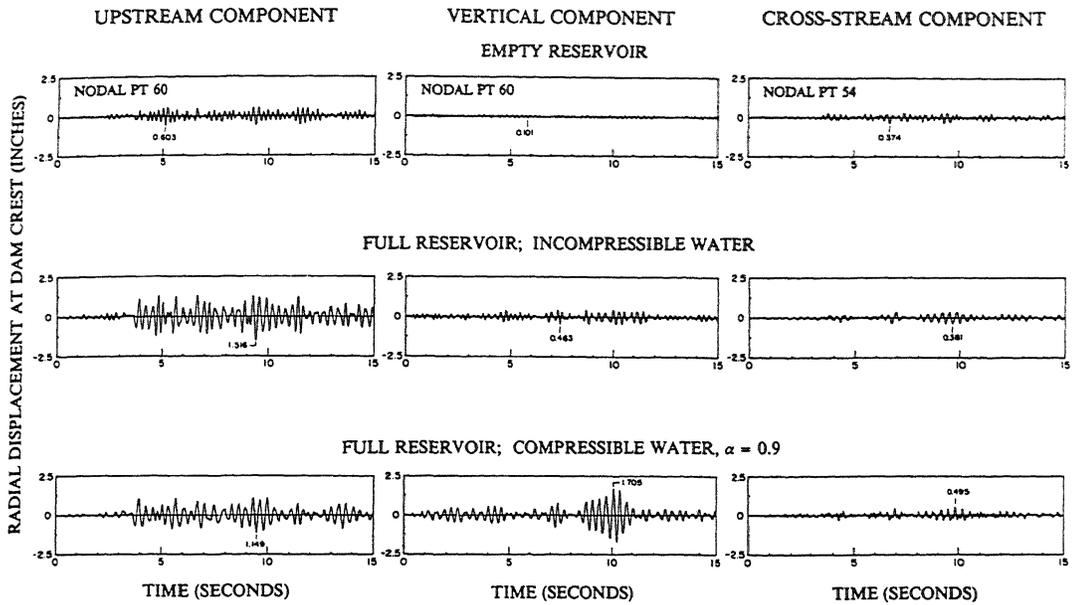


Figure 5. Displacement response of Morrow Point Dam ($E_s = 4$ million psi) due to upstream, vertical and cross-stream components, separately, of Taft ground motion (Fok and Chopra 1987).

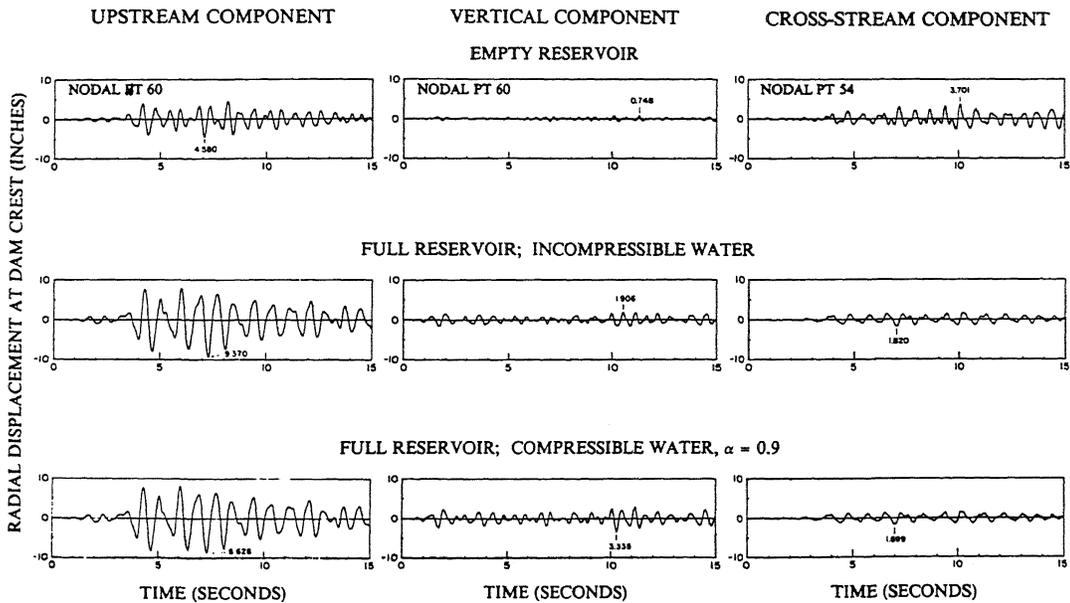


Figure 6. Displacement response of Morrow Point Dam ($E_s = 0.5$ million psi) due to upstream, vertical and cross-stream components, separately, of Taft ground motion (Fok and Chopra 1987).

dam to upstream or cross-stream ground motions. However, even for this unrealistically small E_s value, water compressibility has a significant influence on the response of the dam to vertical ground motion.

Water compressibility would be significant in the response of most concrete dams because E_s is generally much higher and f_{res}/f_{dam} is correspondingly smaller. Thus, the added mass representation of hydrodynamic effects, which is based on the assumption of incompressible water and is typically used in analysis of concrete dams, would generally lead to inaccurate results whether the added mass is determined from Westergaard's classical result for a straight dam, as is commonly done, or from a three-dimensional analysis of the fluid domain (Kuo, 1982).

3.4 Dam-foundation rock interaction

In standard finite element analyses the foundation rock is assumed to be massless and a portion is included in the finite element idealization of the system. This extremely simple idealization of the foundation rock, in which only its flexibility is considered but inertial and damping effects are ignored, is popular because the foundation impedance matrix (or frequency-dependent stiffness matrix) is very difficult to determine without resorting to these assumptions. Computation of this foundation impedance matrix for analysis of arch dams requires solution of a series of mixed boundary value problems governing the steady-state response of the canyon cut in a three-dimensional half-space. Such solutions have only recently been achieved (Zhang and Chopra, 1991) and have been incorporated in a substructure method for analysis of dam-water-foundation rock systems (Chopra and Tan, 1992). These very recent developments enable evaluation of the commonly used simplifications mentioned above.

Figures 7 and 8 show the envelope values of maximum tensile stresses in Morrow Point Dam with empty reservoir due to the upstream component of Taft ground motion for two conditions: only foundation flexibility effects were included in one and full dam-foundation rock effects were included in the other. Results are presented for two values of the ratio E_f/E_s , where E_f and E_s are Young's moduli of foundation rock and dam concrete, respectively: $E_f/E_s = 1$ and $1/4$, with $E_s = 4$ million psi. Full consideration of dam-foundation rock interaction reduces the maximum dynamic stresses by 12 to 18 percent, depending on the stress component and dam face if $E_f/E_s = 1$, and by 35 to 44 percent if $E_f/E_s = 1/4$. The stresses due to cross-stream ground motion are

reduced by similar amounts and the responses due to vertical ground are reduced by up to 62 percent. Thus, it is clear that the significant reduction in dam response arising from foundation material and radiation damping is not recognized in the "standard" analyses.

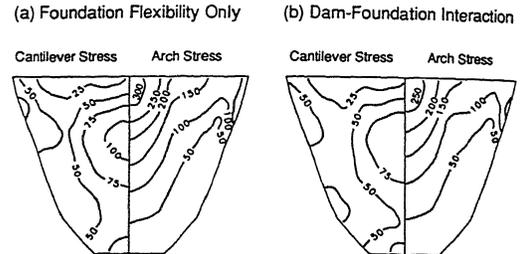


Figure 7. Dam-foundation interaction effects in response of Morrow Point Dam, $E_f/E_s = 1$.

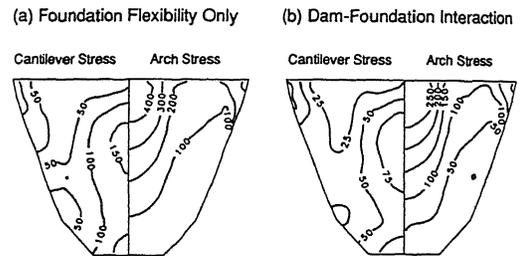


Figure 8. Dam-foundation interaction effects in response of Morrow Point Dam, $E_f/E_s = 1/4$.

4 ANALYSIS PROCEDURES AND COMPUTER PROGRAMS

A few years ago a procedure was developed to analyze the earthquake response of arch dams (Fok and Chopra, 1986a). Based on the substructure method, this procedure and the implementing computer program EACD-3D (Fok, Hall, and Chopra, 1986) included the effects of dam-water interaction, water compressibility, and reservoir boundary absorption. Recently, the procedure and computer program have been extended to include dam-foundation rock interaction without introducing the common assumption that the foundation rock is massless (Chopra and Tan, 1992). Thus, all the factors known to be significant in the earthquake response of arch dams can now be considered.

By this procedure, it is possible to perform a three-dimensional analysis of a concrete arch dam

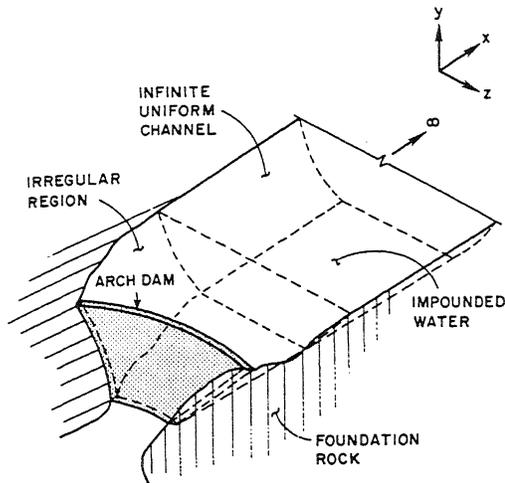


Figure 9. Arch dam-water-foundation rock system (Fok and Chopra 1985).

supported by flexible foundation rock in a canyon and impounding a reservoir of water (Figure 9). The system is analyzed under the assumption of linear behavior for the concrete dam, impounded water, and foundation rock. Thus, the possibility of water cavitation, concrete cracking, or opening of the vertical contraction joints of the dam during vibration is not considered.

In earthquake response analysis of dams by the substructure method, the earthquake input is specified as the free-field ground motion at the dam-foundation rock interface. Usually, the same motion is specified over the entire dam-foundation rock interface, an assumption that is inappropriate for arch dams because the dam boundary in contact with the foundation rock extends through the height of the dam and the free-field motion can vary significantly over the height and between the two sides of the canyon. Nonuniform boundary motions can be included in finite-element analysis of structures. The principal difficulty, however, is in rationally defining the variations in motions over the dam-foundation rock interface because few measurements of actual ground motion variations have been obtained at arch dam sites.

5 SEISMIC DESIGN AND SAFETY EVALUATION

The seismic evaluation of an existing dam involves the following phases: (1) selection of earthquake ground motions expected at the site; (2) analysis of the dynamic response of the dam; and (3) evaluation of the results of dynamic response analysis to predict the expected earthquake performance of the dam.

The current practice in the seismic analysis of concrete dams is to assume that the structure is linearly elastic. If the compressive and tensile stresses in the dam predicted by linear analysis procedures summarized in the preceding section do not exceed the compressive and tensile strengths, respectively, of concrete, the dam can be expected to remain undamaged during the selected earthquake ground motions. The concrete strength requirements will be controlled by the tensile stresses because they will be similar in magnitude to the compressive stresses, whereas the tensile strength of concrete is an order of magnitude less than its compressive strength.

Thus, the key property which determines the capacity of concrete dams to withstand earthquakes is the tensile strength of concrete. Among the various types of tests available, the splitting tension test is easiest to accomplish and provides the most reliable estimates of concrete strength. These strength values should be multiplied by about 4/3 to account for the nonlinear behavior of concrete near failure before using it to interpret results of linear finite-element analysis (Raphael, 1984).

Because the tensile strength of concrete depends on the rate of loading, the aforementioned tests should be conducted at loading rates the concrete may experience during earthquake motions of the dam. Lacking the facility to perform dynamic tests, it is recommended that the tensile strength of concrete for judging the seismic safety of a concrete dam should be the static value augmented by a multiplier of about 1.5.

The tensile strength should obviously be determined from appropriate tests on specimens of concrete for the particular dam. However, a preliminary estimate of the tensile strength can be obtained from Figure 10 which presents four plots of tensile strength as a function of compressive strength, to be used depending on need. The lowest two plots, $f_t = 1.7f_c^{2/3}$ and $f_t = 2.3f_c^{2/3}$, are for long-time or static loading. The lowest plot represents actual tensile strength, whereas the second plot takes into account the nonlinearity of concrete and is to be used to interpret the stresses computed by linear finite-element analysis. The third and fourth plots, $f_t = 2.6f_c^{2/3}$ and $f_t = 3.4f_c^{2/3}$, are the actual and "apparent" tensile strengths under seismic loading.

Permitting significant tensile stresses, up to the tensile strength of concrete, is of course a major departure from the standard design criteria wherein little tension is permitted. However, evidence is available to support the recommended design criteria that significant dynamic stresses in tension can be carried by sound concrete. In addition to the data from laboratory tests mentioned earlier, evidence of the dynamic tensile strength of concrete

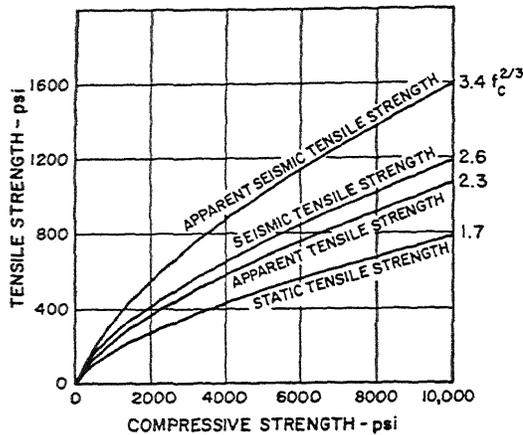


Figure 10. Design chart for tensile strength (Raphael 1984).

was provided by the performance of dams during earthquakes. Dynamic analyses indicated that Pacoima Dam should have developed maximum tensile stresses in the order of 750 psi during the San Fernando earthquake of 1971, yet no evidence of cracking could be found on either face of the dam (Swanson and Sharma, 1979). Elastic analyses of Koyna Dam indicated tensile stresses almost three times the tensile strength of concrete, resulting in significant cracking of the dam. However, the dam survived the earthquake without any sudden release of water (Chopra and Chakrabarti, 1973). Perhaps most interesting is the lack of damage to Crystal Springs Dam—a curved concrete gravity dam located approximately 1,000 ft from the San Andreas fault—during the great San Francisco earthquake of 1906 (Wulff and Van Orden, 1979).

Linear analyses of arch dams subjected to the very intense ground motions expected in highly seismic areas may indicate that the computed tensile stresses exceed the available tensile strength of concrete. While linear analyses can usually predict locations in the dam where cracking will be initiated, they may not reliably predict the extent of cracking or the true nonlinear behavior of dams during intense earthquake motions.

For these reasons nonlinear response of concrete dams has been a subject of increased research activity during recent years, and progress has been made in developing nonlinear analysis procedures (Dowling and Hall, 1989). However, the predictions of the extent of the damage obtained from these analyses are quite sensitive to the assumed nonlinear properties of mass concrete. Thus, the mechanical properties of mass concrete need to be better defined before the extent of damage, and its implications to dam safety can be determined with

confidence. Comprehensive testing programs are therefore necessary to determine the constitutive and strength properties of multiaxially loaded mass concrete under dynamic, reversible, cyclic strains and stresses representative of earthquake conditions.

Linear analyses of an arch dam, treated as a monolithic structure, for intense ground shaking may show that dynamic tensile stresses in the arch direction exceed the compressive arch stresses that exist prior to the earthquake. However, arch dams are typically constructed as cantilever monoliths separated by contraction joints which cannot develop tensile stresses. Thus, net tensile arch stresses predicted by linear analysis imply cyclic opening and closing of the vertical contraction joints during an earthquake. This joint-opening mechanism has been included in recently developed nonlinear analysis procedures (Fenves, Mojtahedi, and Reimer, 1992). However, so far it has not been possible to consider effects of water compressibility, reservoir boundary absorption, and dam-foundation rock interaction which are known to be significant in the earthquake response of arch dams.

6 APPLICATIONS TO ENGINEERING PRACTICE

Dam regulatory agencies have revised their design standards and engineering companies have updated their procedures to acknowledge the research accomplishments of the past decade, some of which have been summarized in this paper. Static force methods involving seismic coefficients have given way to dynamic analysis procedures. As shown in this paper, these procedures should consider the following factors: dam-water interaction, reservoir boundary absorption, water compressibility, and dam-foundation rock interaction. In order to produce safe and economical designs of concrete dams, the most reliable techniques considering the above-mentioned factors should be used to evaluate existing dams and proposed design of new dams. The EACD-3D computer program mentioned in this paper was used in recent seismic safety evaluations of Englebright and Pardee dams in California, and Valdecanas dam in Spain.

Since most existing dams were designed by methods that are now considered oversimplified, there is considerable interest in reevaluating the original designs using current procedures. As a result of such safety evaluations, structural modifications have been made to some dams, and restrictions on reservoir water levels have been imposed in some cases. Since the economic impact of such modifications and restrictions is generally substantial, it is important to improve the reliability of present methods of safety evaluation.

Although considerable progress has been made in the last decade, much additional research needs to be done to improve the reliability of present methods for the seismic analysis, design, and safety evaluation of concrete dams. In particular, spatial variability of ground motion around an arch dam canyon needs to be considered in linear analyses, and efficient and reliable procedures need to be developed to predict the damage expected in arch dams during intense ground motions.

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