DESIGN OF DAMS FOR EARTHQUAKE RESISTANCE

By Jerome M. Raphael[*]

INTRODUCTION

In many respects, earthquake resistant design of dams differs from that of other engineering structures. The external force of the reservoir not only remains during an earthquake, but increases due to hydrodynamic effects. In usual engineering structures, we are concerned with preventing local damage to the structure. In dams, the impounded waters present an additional threat. Any failure of the dam would have far-reaching consequences as the released waters would batter down anything in their path. M. C. Hinderlider, State Engineer of Colorado, writing in an ASCE Symposium on the Public Supervision of Dams, has said, "Probably in no field of endeavor are the responsibilities to the public so great or exacting as in that of the design, construction, or supervision of structures for the impounding of large bodies of water. It is well, therefore, that those charged with such obligations, should proceed with caution, be guided by a high degree of conservatism, and withal be imbued by an exalted sense of their responsibility."

The design of a dam is usually predicated on many considerations, of which earthquake resistance is only one. Economic and hydrologic considerations determine the size of the reservoir. Geologic and topographic considerations determine a suitable site, and consequently, the height of the dam. Reconsideration of the foregoing for a particular site then brings into consideration several major types of dams that will satisfy the physical requirements satisfactorily. One type, however, will emerge as the most economical for the site, and that will be chosen for analysis.

When the engineer first begins to consider the effect of earthquake on the dam, the location has been narrowed down to one or more sites in a close neighborhood, and one or two types of dams are under active consideration. The question of the effect of earthquake on each of these types is actually not one, but three questions:

1) What is the maximum earthquake to be expected in this locality?
2) What forces will be generated by this earthquake? and
3) What will be the effect of these forces on the stability and stresses in the dam?

MAXIMUM EARTHQUAKE

Dams are among the largest of engineering structures, but large as they are, they are dwarfed by the size of the reservoir that they impound. For this reason, major dams are generally located where land is cheap and

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the topography is suitable, often in remote mountain valleys in which there is no previous engineering construction to guide design. There is no general code to govern the design of dams, which are individually proportioned to fit into each individual site. For these reasons, the designing engineer must go back to fundamentals in order to arrive at a conclusion as to the magnitude of the earthquake that should be considered appropriate for the particular locality. Consideration must be given to the general seismicity of the region, and to its regional geology.

The general seismicity of the region is important, because, according to the elastic rebound theory, massive movements in the earth that have caused earthquakes in the past will persist for some time and cause earthquakes in the future. It is generally agreed that the actual kinetic energy sent out by an earthquake is the suddenly-released potential strain-energy that accumulates across a major fault, as strain accumulates from slow opposing land movements on each side of the fault. Evidence is plentiful of the land movements that have taken place with violence in recent earthquakes, and examination of topography and geologic strata show evidences of tremendous land movements of the past. There is considerably less agreement on the actual cause of the slow tectonic movements by which strain is accumulated across a fault. A partial list of those discussed by Byerly[1] include:

1. Thermal contraction of the earth
2. Isostasy
3. Drifting continents
4. Radioactivity and convection currents.

None of these theories are completely satisfactory in explaining the slow accumulation of strain in the earth's crust, yet they all agree in one respect that is important from the engineering point of view. The differential strains tend to be focused along certain regions or belts, where the incidence of earthquakes is much greater than in other parts of the earth. The majority of the major earthquakes originate in the belts where young and growing mountain masses are closely allied with deep ocean troughs.

The principal earthquake belts considered by Gutenberg and Richter[2] are:

1. The Circum-Pacific belt: This extends around the entire rim of the Pacific Ocean.
2. The Alpide belt: This extends from the Azores, across the Alpine structures of Mediterranean Europe, and across Asia to Burma, along the front of the Himalayas.
3. Minor active areas, including narrow belts in the Arctic, Atlantic, and Indian Oceans, rift zones internal to the stable masses, and active areas marginal to the continental stable masses.

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*Numbers in text refer to corresponding references listed at the end of the paper.

4. Stable masses: The continental nuclei of old rocks. Small shocks occur even here, and seem to take place occasionally almost anywhere.

Gutenberg and Richter's "Seismicity of the Earth" lists the major earthquakes of record, and plots them on regional maps which describe the principal geographical division in detail. By reference to these maps, it can be determined quickly whether or not the projected site for a dam is close to an active seismic belt. Assuming that it is, the next question is: what are the chances of a major earthquake at the site? Gutenberg and Richter[2] and Housner[3] have discussed statistical analyses of the shocks originating in a seismic region in a manner which is strongly reminiscent of the analyses for flood probability, with which every dam designer is familiar.

To make an analysis of the probability of an earthquake of a given magnitude occurring along a seismic belt, following Housner's method, a list is first prepared for that geographical division, tabulating all recorded earthquakes, their magnitudes, and date of occurrence. These can then be rearranged in order of increasing magnitude and plotted using cumulative number of earthquakes per 0.10 magnitude as ordinates, and earthquake magnitude as abscissa. From this plot it can be seen how many earthquakes of a given magnitude or better have occurred in the period of record. Conversely, the average number of years between earthquakes of a given magnitude, or the relative frequency of occurrence may be computed, so that one may refer to say a 10-year shock of low magnitude, or a 500-year shock of tremendous magnitude. The inference is that whatever movement has occurred in the past which has resulted in earthquakes, will continue at the same rate into the future. This movement will be relieved at irregular intervals, either by a succession of shocks of low magnitude, or a very few shocks of great magnitude.

Analyses of this type show that an earthquake magnitude 8.2 (Richter scale), (San Francisco, 1906) may be expected in California once every 200 years, while shocks of magnitude 6.25 (Long Beach, 1933) can be expected somewhere in California about every 18 months. A similar calculation made for the Himalayan arc showed that the expected frequency of occurrence of the Assam earthquake of August 15, 1940 of magnitude 8.4 was once every 500 years, while the expected frequency of occurrence of an earthquake of magnitude 8.3, such as was computed for the Bihar-Nepal earthquake of January 15, 1934 is once each 320 years. Despite statistics, these two earthquakes occurred within 16 years of each other. An important consideration in estimating the expected magnitude of the earthquake accelerations at a particular site, is its proximity to the earthquake source. If the shocks are associated with a well-defined source, such as the San Andreas fault, then it may be expected that energy of the shock will be diminished, as distance from the fault increases. While there is much contradictory evidence showing that some structures very close to actual faults that have moved during an earthquake have been relatively undamaged, while others at some remote location have been extensively damaged, the general rule is that energy attenuates with distance from the earthquake source. The farther the site of the structure from the earthquake belt, the less the energy that may be expected.

Another major factor which enters into the selection of the characteristic earthquake acceleration for a particular project is closely tied in with the design of the dam itself. Experience shows that structures founded on rock in general suffer less damage during earthquake than similar structures founded on alluvial materials. Gravity dams and arch dams are usually founded directly on sound rock, buttress dams and rockfill dams on intermediate materials and earth dams on the weakest of foundations. The Architectural Institute of Japan has recommended revisions to the Japanese National Building Code which recognize differences in behavior of rigid and flexible structures founded on rigid or flexible materials, and varies the recommended earthquake design factors accordingly. On soft foundations, flexible construction is designed for a higher seismic coefficient than is stiff construction, whereas on stiff foundations, the reverse is true. Similar considerations could be considered for stiff gravity and arch dams as opposed to the more flexible types.

In considering the probability of earthquake hazard, the services of a consulting engineering geologist will be invaluable in deducing, from the evidences of regional geology, the land movements that have most recently taken place, and how they can be expected to continue into the future. Geologically young regions, regions of recent uplift, particularly where associated with ocean deeps or alluvial planes on geosynclines, may be expected to be earthquake sources. Evidence should be gathered on the location of major faults, and study made to determine any recent activity along these faults. This information may already be available in connection with other studies. For instance, much of the published information on surface structural geology in the United States has been collected and correlated on the Tectonic Map of the United States.[5]

It should not be overlooked that the enormous load suddenly placed on the crust of the earth by a major reservoir as it fills is enough to cause tectonic movements. For instance, the 41-1/2 billion tons of water stored behind Hoover Dam was sufficient to cause a depression of the earth's surface of seven inches over a period of fifteen years.[6] Whether this disturbance would be enough to trigger off an earthquake has been the subject of much speculation. There have been many minor shocks in the Lake Mead area, but there is no evidence that such activity was not present before the lake filled.

The history of many major earthquakes occurring in a region where none were recorded before imposes caution on the design engineer. One method of providing for the contingency of an unexpected shock in a previously quiet region is to adopt a minimum design earthquake of 0.10g anywhere when considering the safety of a major dam. This follows the recommendations Westergaard[4] made after considering the characteristic vibrations of earthquakes, and the normal response of massive gravity dams. His recommendation of an earthquake acceleration of 0.10g has been accepted in the vast majority of dam designs, except where close proximity to a zone of high-magnitude earthquakes has warranted an increase. In designing Bhakra Dam, for instance, which is located to

the north of New Delhi, India, designers used a horizontal earthquake acceleration of 0.15g. Similarly, in the design of a dam proposed for a location 30 miles from the track of the Himalayan arc, accelerations of 0.20g horizontally, and 0.10g vertically were considered.

EARTHQUAKE FORCES

For a given earthquake acceleration, the earthquake forces in the dam and reservoir can be computed. Mass forces in the dam are found as a horizontal force which is the product of the earthquake factor and the weight of the mass. It can be seen that the smaller the mass, the smaller will be the horizontal body forces from earthquake. Hence, arch dams and buttress dams should be quite efficient in resisting earthquake forces, other things being equal.

The effect of earthquake on the interaction of dam, foundation and reservoir is not simple. In the critical case, the dam and foundation move upstream against the reservoir. If the movement is slow enough, the water simply flows away from the dam, with practically no increase in pressure. During earthquakes, however, the movement is so rapid that the water cannot escape completely, but builds up an instantaneous pressure at depth. The buildup of pressure depends on the depth of the water, and on the shape of the upstream face of the dam and of the reservoir itself.

Westergaard's classical paper[4] on the subject has long influenced dam designers. He analyzed the case of an infinitely long dam which has a straight plan, and vertical upstream face. From his analysis, the increase in pressure p at any depth y can be expressed as the parabola

$$p = C\alpha\sqrt{hy}$$

whence

$$p_0 = C\alpha h$$

where α is the ratio of the earthquake acceleration to g

h is the depth of reservoir

p_0 is the pressure at the bottom of the reservoir

and C is defined by the expression

$$C = \frac{51}{\sqrt{1 - 0.72\left(\frac{h}{1000t_e}\right)^2}}$$

in which t_e is the earthquake period in seconds, and h is measured in feet. The parabolic variation of pressure with depth, which was a simplified solution of Westergaard's general solution, is easily handled mathematically in computing total forces on the dam.

In discussing Westergaard's paper, Brahtz and Heilbron[6] considered the effect of the length of the reservoir on the water pressure. It was shown that for very short reservoirs the pressures were affected considerably, but that the error was negligible in a reservoir for which the length exceeded three times the height of the dam.

For many dams, the upstream face is not vertical, but inclined, either continuously, as in the case of a buttress dam, or with a discontinuous inclination as in the case of many gravity dams. A detailed study has been made by Zangar[8] to determine the hydrodynamic effect of horizontal earthquake action on dams having upstream faces with either constant or compound slopes. Assuming that the fluid was incompressible, flow nets could be constructed which would be directly related to the hydrodynamic effects of horizontal earthquake on the sides of vessels of any shape. However, instead of constructing flow nets, Zangar used an electric analogy tray apparatus to trace out equipotential lines. From this he computed the pressures at various depths for many shapes of dams. He concluded that, except for a vertical face, the maximum pressure coefficient occurs at some distance above the base of the dam, but that the distribution of pressure on any constant slope could be represented approximately by a parabola:

$$p = KC\alpha\sqrt{hy} \text{ , using previous notation.}$$

K was determined experimentally to vary almost directly with the angle of inclination of the upstream face, from maximum for a vertical face to 0 for a horizontal surface. It was further concluded that dams having upstream faces which are vertical for half or more of their height will have hydrodynamic pressures practically equal to those on dams having vertical upstream faces for the full height.

Very little is known about the effect of variation in plan from the straight line assumed by Westergaard in his analysis. If any horizontal slice is considered, the total force developed at its boundary as the dam moves upstream against the reservoir may be considered to be the force developed on a straight line external to the dam and normal to the direction of movement. Consider any prism of water between two vertical and two horizontal surfaces, parallel to the dam movement, the surface of the dam and the straight line. Water cannot escape laterally, as it is entrapped. It can escape vertically, which is the cause of the variation in pressure with depth. Thus, the unit pressure on any part of the face of the dam will be the force projected from the straight boundary, and should be the appropriate pressure from the Westergaard relation multiplied by the cosine of the angle of the angle of deviation, as proposed by Creager, Justin and Hinds.[7]

DESIGN OF DAMS

So far in this discussion, no attempt has been made to differentiate among types of dams. However, structural action varies greatly according to type, and dams will be discussed in four broad, general types, although in each type there are many subdivisions. Let us consider then the following:

1. Gravity dams

2. Arch dams

3. Buttress dams

4. Earth dams

Gravity Dams

Gravity dams are massive masonry dams of triangular cross-section, with the upstream face approximately vertical, and the downstream face on a slope generally around 50° to the horizontal. They may be straight, or curved in plan, as they are adapted to the topography of the site. They rely on their sheer weight to resist the imposed forces. Although stresses sometimes reach fairly high values in major dams, the critical problem is that of stability, to develop enough frictional force at the base to resist the static and dynamic shearing force of the reservoir. Overturning due to earthquake forces need not be considered, as the ground movement will change direction before the dam will move appreciably. Other criteria are the maintenance of a minimum compression at the upstream face so that the entire cross section is available to resist shearing. As a corollary to this, the resultant of all forces is usually made to lie within the middle third of the dam.

Small gravity dams are usually analyzed by considering a number of two-dimensional vertical elements of unit width taken at various sections depending on the topography. Each element is considered to act independently. For more important gravity dams, the interaction among elements is recognized, and a three-dimensional analysis is used. This recognizes that elements near the abutments, having different heights, deflect differently under load. If this relative deflection is prevented, as by keying and grouting joints, an added element of resistance to water load is given by the torsional or twist resistance of the elements. Hence a solution based essentially on the trial-load method of analysis developed by the Bureau of Reclamation[10] is available for this case.

Normal loads on a gravity dam include the weight of the concrete, hydrostatic pressure of reservoir and tailwater, uplift under the dam and in its pores, and sometimes ice thrust or silt loads. In addition, during an earthquake, which is generally critical upstream, there will be horizontal body forces, increased hydrodynamic forces from the

reservoir, and lessened hydrodynamic tailwater forces, both of which decrease stability. If vertical earthquake forces are considered as well, critical conditions will be attained with downward movement of the ground, which acts to decrease the effective weight of the dam, again decreasing stability.

For the gravity analysis, the forces determined as outlined previously are applied as static forces to each element of the dam, with some consideration being given to probable combinations of loads. Stability of the dam is measured by the shear-friction factor, expressed as:

$$SF = \frac{CA + Nf}{H}$$

where
C is the cohesion
A is the area of the base considered
N is the summation of normal forces (weight minus uplift)
f is the coefficient of internal friction
H is the summation of shear forces

The dam is proportioned to give a shear-friction factor of not less than 4. Although a factor of safety against overturning may also be computed, it is not necessary, as any dangerous moments will be manifested as excessively high stresses. Principal stresses are computed at the faces, and, for important structures, completely across the cross-section. Maximum compressive stress will be limited by the strength of the concrete with a suitable factor of safety; minimum compressive stress at the upstream face may be zero, or more conservatively, as a percentage of the reservoir pressure. The actual methods of analysis vary from the simple analysis for combined bending and direct compression, to complex analyses involving the dam and foundation together, either by models, or by a mathematical analogy of the action of a model.[11]

In addition to distributing the mass of a gravity dam to resist earthquake forces best, some gravity dams have been provided with a slip joint over a suspect fault, to allow free relative movement if necessary.

Arch Dams

Arch dams are thin masonry dams, curved in plan, which resist the action of the forces imposed on them by a combination of gravity and arch action. Arch dams are highly indeterminate structures, and it is only in the past few years that analyses have been developed that correctly interpret the actual resistance of arch dams to their imposed forces. The weight of the dam itself travels vertically downward to the foundations as each element of the dam is built. Once the joints are grouted, however, the arch dam presents many paths of stress for loads.

Correct distribution of stresses in an arch dam can be found easily by a model study, or by the trial-load analysis, which has been demonstrated to give equivalent results. In the trial-load analysis[10], the dam is considered to be divided into an intersecting network of vertical cantilever elements and horizontal arch elements. The analysis consists of finding by trial that division of loads among horizontal and vertical elements that will cause the deflected elementary structures to be congruent at all intersecting points. Each element will continue to fit with its neighbors, and boundary conditions will be satisfied. This means that radial deflections, tangential deflections, and horizontal and vertical twisting deflections for both sets of elements are equal at all points of intersection. When this division of loads has been found, stress analyses can be made separately for the cantilevers, as in the gravity analysis described previously, and for the arches, as is described in any work on applied mechanics. In assigning the loads, the cantilevers take the dead weight of the dam, vertical water and silt loads, uplift, vertical earthquake and any live load from the roadway on top of the dam. Tangential earthquake loads, and temperature loads are assigned to the arches. Loads that are divided among the arch and cantilever systems are the radial horizontal water load, radial horizontal wind load, and radial earthquake load.

In beginning the trial load analysis of an arch dam, the structure is first divided into systems of vertical cantilever elements and horizontal arch elements, the number depending on the configuration of the dam, and the stage of design. For preliminary design, a single cantilever is chosen at the center of the dam, with three or four arches. For final analysis the number of arches is doubled, and more cantilevers are chosen at each side of the maximum cantilever. Loads are then applied to the two systems, assigning loads whenever possible to arch or cantilever. Those loads that are to be divided between the two systems, are first assigned completely to one system. The radial deflection is then computed for each element at each point of intersection, using published tables of deflections for unit loads wherever possible to aid computations. In general, there will be considerable discrepancy in the radial position of the arch and cantilever at each point. Equal and opposite radial loads are then applied to the two systems to bring the elements into line radially. It will then be found that there will be discrepancies in tangential position of the elements which can be corrected by adding equal and opposite tangential loads to the structure. There still will be discrepancies in angular position of the elements, which are then corrected by adding moments and forces. All these adjustments will have changed the radial adjustment, so the process must be repeated until satisfactory agreement is reached.

This system of successive corrections sounds tedious, and it is. For preliminary design, only the radial adjustment is made on the crown cantilever, since that is the most important step in the trial load analysis. Much of the tedium can be taken out of the computation by committing as much of it as possible to modern high speed computers. In one such computation, involving fifty points of intersection, fifty equations were written for equality of the radial deflection of arch

and cantilever elements, containing fifty unknowns. A Univac solved
this problem in about a half hour. With these data, principal stresses
were computed quickly, modifications made on the dimensions of the dam,
with corresponding changes in the constants of the fifty deflection
equations, and new results obtained the same day. This reduced con-
siderably the time needed for analysis of the arch dam.

Arch dams with their relatively slender dimensions might be thought
to be so much more flexible than gravity dams that there might be
possibility of resonance with the frequencies of the ground during major
earthquakes. However, such is not the case. This doubly curved shell,
free along one edge only, is quite stiff. Its natural frequency, which
depends of course on its dimensions and configuration, is of the order
of four to eight cycles per second, which is far from any danger of
resonance with ground vibrations having a natural period of over a second.
Arch dams possess the unique property among the various types that, in
general, as loads increase, so too does stability, as the increased
forces are manifested as increased thrusts at the abutments. Coupled
with the generally smaller body forces due to smaller concrete volume,
the arch dam is a very efficient structure.

Buttress Dams

Buttress dams are composed of an inclined continuous water barrier
supported at intervals by buttress walls. The water barrier may be a
series of reinforced concrete slabs, a series of arches, or a series of
massive concrete enlargements to the buttress. Being articulated, they
can accomodate themselves to slight ground movements, which makes them
particularly attractive when a fault runs through the dam site. Buttress
dams have been built on sites over known faults. In one such application,
it was reasoned that if the fault moved enough to cause failure in one
span, the reservoir would be emptied at a controlled rate through the
gap, rather than all at once, as in the case of complete collapse of a
gravity or arch dam. In the design of another buttress dam over a fault,
one buttress, which was to be located directly on the fault, was sup-
ported on a horizontal arch which completely bridged the fault.

Buttress dams resist the horizontal forces from the reservoir by
friction with the foundation. Since buttress dams are much lighter
than gravity dams, they utilize weight from the reservoir itself to
increase friction. Thus the upstream face of the dam is generally
inclined, often at an angle of about 45°. The buttresses themselves,
being solid or hollow triangular walls, fixed at the base and at the
deck, and free at their downstream edge, must be investigated care-
fully for the effect of earthquake forces parallel to the dam. In
general, the flattened upstream slope, and the small body forces in the
thin concrete sections of a buttress dam reduce the earthquake problem
to that of adequately supporting the buttresses laterally, by the use of
struts or bracing walls.

Earth Dams

Since earth dams are constructed of materials readily available in the vicinity, designs are varied to fit the properties and quantities of materials on hand. However, there are definite points of similarity among all earth dams, and the following discussion will be of a typical earth dam.

In general, earth dams are characterized by flattened upstream and downstream slopes. Resistance to the passage of water is given by a core of relatively impervious material, buttressed up and downstream by one or two zones of successively more pervious material, which give stability to the structure. The actual material of the impervious zone is a mixture of solid mineral particles, water and air, the strength of which is a function of the internal friction of the mass, cohesion between particles, and pressure.

Hydrodynamic forces from the reservoir are much reduced in the case of the earth dam because of the flattened slopes. Mass forces in the embankment are tremendous, because of the large volume of materials. The actual values of the mass forces to be used in analyzing a particular cross-section for stability is under discussion, at present. Most designers use a seismic coefficient for finding horizontal earthquake forces, which is constant anywhere in the dam.[12] Others, taking into account the dynamic action of the embankment itself, advocate the use of seismic coefficients that increase in some manner from base to crest of dam[13], much like the increase in seismic coefficients in framed structures from lower to upper floors.

The most common method for evaluating the stability of the slopes is by the Swedish slip-circle method. Failure is assumed to occur along the arc of a circle, and forces that cause a mass of earth above the failure arc to move are evaluated against the forces along the arc that resist the movement. The safety factor is expressed as:

$$SF = \frac{C + \tan \phi \, (N - P)}{T}$$

where

C is cohesion
$\tan \phi$ is tangent of the angle of internal friction
P is pore pressure
N is summation of the normal forces
T is summation of the tangential forces

The factors in the numerator of the above equation express the shearing resistance of a soil. It has been found that shearing resistance of soil is greater under dynamic loadings than under static loadings. Casagrande and Shannon[14] found that the dynamic shearing resistance of clays increased 40 to 160%, sands increased 20%, and soft rock increased 80%, over the static resistance. Seed and Lundgren[15] found a 10% increase in shearing resistance of dry sand, and even greater

increases in saturated sand. Thus, as in many other cases of engineering
structures under transient loadings, the increased earthquake forces on
an earth dam are to some extent balanced by increased resistance to stress
and deformation.

Special provisions in aseismic design of earth dams include:

1. Carrying cutoff trench deep into foundation to intercept water
   flowing through foundation cracks.

2. Making the impervious section wider than any possible offset.

3. Prevention of slumping by weighting down impervious section
   with coarse pervious material.

4. Providing extra heavy outer slopes to close any tension fissures
   developed by stretching the dam.

Two earth dams in California successfully withstood the 1906 earth-
quake. Crystal Springs Upper Dam, which had water on both faces, was
actually offset by fault movement in the foundation, but did not slump
under the action. San Andreas Dam, 95 feet high above stream bed, al-
though cracked, developed no leaks and is still used. On the other hand,
a 25-foot high dam in Southern California slid out on its foundation
during an earthquake. With proper engineering design, earth dams can
resist seismic forces as well as any other structure.

SUMMARY

Earthquake resistant design of dams differs greatly from the design
of the usual type of engineering structures, since earthquake vibration
not only generates forces within the structure itself, but also increases
the magnitude of the external forces which are at all times acting on the
structure. Under the action of earthquake, the impounded water behind a
dam exerts hydrodynamic as well as the ever-present hydrostatic forces on
the dam. If failure of the dam were to occur, maximum damage would not
be confined to the dam, but would be widespread due to the battering-
ram effect of the suddenly released waters. As a consequence, earthquake
design for dams tends to be conservative. By their very nature, dams are
generally constructed in remote regions where very little engineering
experience is recorded. Determination of proper earthquake design factors
is the major problem in earthquake resistant design of dams. This is made
for a given locality after considering the recorded seismicity of the
region, and the relative activity of regional geologic processes causing
major tectonic movements, such as mountain building. Because of the
history of sudden major earthquakes in previously inactive regions,
major dams are usually designed for a minimum earthquake acceleration of
0.10g, ranging up to 0.20g in regions of maximum seismicity. For a given
earthquake acceleration, the hydrodynamic force on the face of the dam
depends on the size and configuration of the dam and reservoir. In some
cases, choice of type of dam is dictated by consideration of earthquake
action. General methods of stress analysis are described for major
types of dams.

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