DAMS, EMBANKMENTS, AND RESERVOIRS

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This paper on the performance of dams, reservoirs, levees, and other embankments during earthquakes covers current methods of analysis, improvement of existing structures, design of new structures, and needs for developing new knowledge in these areas. The emphasis is on dams because of the relative availability of technical literature and because the author's experience is primarily related to earth dams. Significant differences in earthquake performance of earth dams and other structures are explained.

INTRODUCTION

The usual design practice for dams prior to 1970 was to consider earthquake effects by incorporating in the stability or stress analysis, a static lateral force intended to represent the inertia force induced by the earthquake (National Research Council, 1984). This force usually was expressed as the product of a lateral force coefficient and the force of gravity. The coefficient generally varied between 0.05 and 0.15g depending on the seismicity of the area in which the dam was located and the judgment of the engineer involved. The method was called a pseudo-static analysis in recognition of the fact that static lateral forces were only intended to represent the effects of the actual dynamic earthquake forces that were known to be different.

The pseudo-static analysis was similar to that used for building design in seismically active areas. Hydrodynamic forces were applied to concrete dams according to the procedure developed by Westergaard in the 1920s. Results of studies by Zangar led to the conclusion that consideration of hydrodynamic forces was not necessary for flatter embankment dam slopes. The pseudo-static analysis combined with engineering judgment produced many excellent dams.

A series of events in the 1960s and early 1970s caused engineers to re-evaluate the adequacy of the pseudo-static approach:

1. Many slope failures occurred in the 1964 Alaska earthquake that would not have been predicted by the analysis.

2. Hsingfengkiang Dam, a concrete buttress dam in China, cracked

in 1962 under earthquake loading as did Koyna Dam, a concrete gravity dam in India, in 1967.

3. Lower San Fernando (Van Norman) Dam nearly failed and significant sliding occurred at Upper San Fernando (Van Norman) Dam in a 1971 Los Angeles area earthquake.

4. Accelerograms recorded during actual earthquakes exceeded 0.3g, more than double the highest pseudo-static coefficient commonly used.

One of the first reactions to unsatisfactory performance of Lower and Upper San Fernando Dams was an extensive study of the dams to determine if a dynamic finite analysis recently developed by Seed, Lee, and Idriss could have predicted the performance of the two hydraulic fills (Seed et al., 1975). In late 1971, the California Division of Safety of Dams was convinced it could have and ordered the owners of 29 other hydraulic fill dams analyzed by the new technique (Jansen et al., 1976). Subsequently, more than 50 additional embankment dams in California have been analyzed using variations of the technique. The results of these studies will be discussed later.

Pacoima Dam, a 365-foot-high concrete arch, was severely shaken during the 1971 earthquake. The dam was not damaged although the abutments closed 0.94 inches, the right end of the dam dropped 0.68 inches, and rock on a portion of one of the abutments cracked and slumped. Since 1971, Pacoima and several other concrete dams in California have been re-analyzed using dynamic analysis techniques.

These initial ventures into dynamic analysis of dams joined with similar efforts in the rest of the United States and the world have evolved so that today, most major governmental agencies, private owners, and consulting firms are using the techniques on moderate to large dams and other important structures (National Research Council, 1984). Nuclear power plant foundation and structure dynamic analysis paralleled the dam developments and often were done by the same consulting firms.

DYNAMIC ANALYSES

Dynamic analyses are currently used to:

1. Determine liquefaction potential or strain potential of embankments and foundations of soil that might lose strength during earthquake shaking.

2. Estimate settlements of embankments during earthquakes.

3. Determine stresses and cracking potential in concrete dams and dam appurtenances.

A full dynamic analysis consists of subjecting a finite element computer model of a dam to a series of accelerations that simulate an earthquake. The time increment between accelerations is 0.01 to 0.02 seconds and the earthquakes are 10 to 40 seconds long. The series of accelerations, called accelerograms, are obtained by adjusting actual earthquake records to fit site conditions or by computer generating accelerograms to match existing records. Site foundation conditions and proximity to faults must be well defined in order to develop meaningful accelerograms.

Stresses and strains are determined throughout the system for each acceleration by inputting strain-dependent modulus and damping curves and iterating to a reasonable level of accuracy. A combination of field shear wave velocity measurements, laboratory tests, and data from other projects is used to select modulus and damping values. The analyses are run in the elastic range. The strain-dependent modulus is incorporated to adjust for the known nonlinear behavior of the materials being analyzed.

Comparisons are made between the stresses developed and dynamic strengths of the soil or concrete. Laboratory shear tests and, more recently, Standard Penetration or Cone Penetrometer Test (SPT and CPT) correlations are used to determine dynamic strength or liquefaction resistance of soils. Results of stress-strength comparisons for soils usually are expressed in strain potentials. Dynamic strengths of concrete are determined by laboratory rapid-loading tests. The stress-strength comparisons identify overstressed areas of concrete or foundation rock. Highly judgmental evaluation processes follow.

In concrete dams, overstressed areas indicate cracking should occur; however, the analysis results frequently show that the overstress would occur only for a fraction of a second one or two times. Judgments are made on the possible extent of crack propagation. In soil systems, overstraining can indicate severe strength loss (liquefaction) or undesirable settlements and/or lateral movements. A next step in the process often is to run conventional stability analyses with cracks or liquefied zones assigned very low strengths and increased uplift or pore pressures as appropriate. There are also computer programs that make further computations on the output from the dynamic finite element analysis to aid in predicting settlement and deflections. Makdisi, Seed, and Idriss (1978) describe a full dynamic analysis of an embankment dam.

Examples of less complex dynamic analyses are:

1. Use of response spectra and mode shapes to determine stresses in concrete dams.

2. Estimating deformation of slopes by computing yield accelerations by limit equilibrium methods (Newmark approach).

3. Abbreviated analyses that utilize generalized results of several full dynamic analyses.

They are applicable to many problems and are significantly less time consuming and require much less computer time.

The cost of dynamic analyses for dams are high. One of the less complex analyses mentioned above could cost as little as $25,000. The cost of a few analyses have exceeded $1,000,000. A large part of the cost of the latter was in exploration to characterize the dam foundation system rather than in computer time.

WHICH DAMS AND STRUCTURES NEED DYNAMIC ANALYSES?

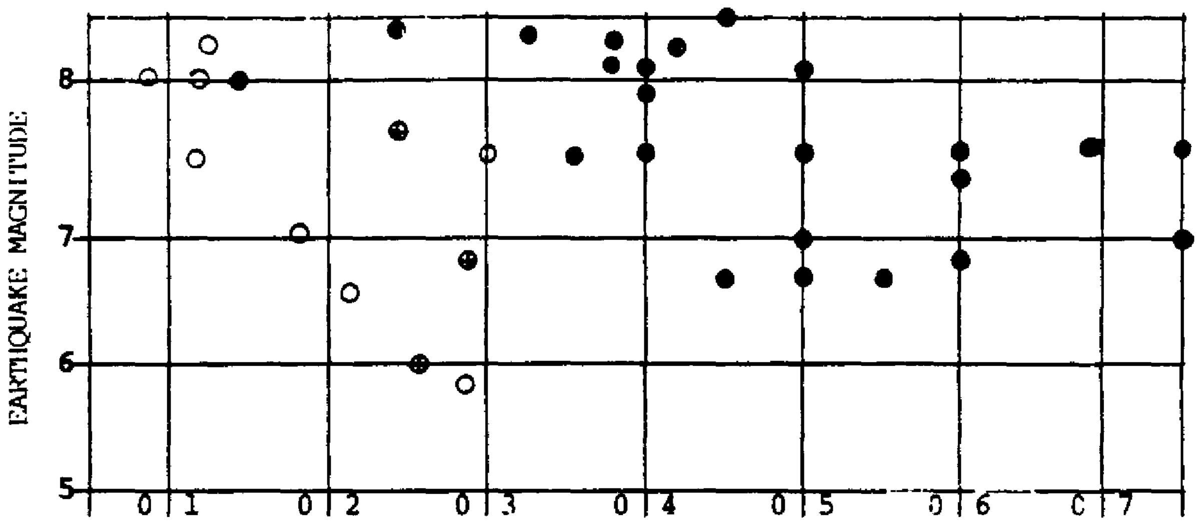
The high cost of dynamic analyses may not be justified for all dams. There are some records of dams experiencing significant earthquake shaking and, as discussed above, a number of dams have been analyzed. The following is intended to provide some guidance on the need for dynamic analyses by citing performance records and analysis results. The information was developed primarily from California dams. It should, however, have direct application to dams and embankments in other locations.

These guidelines must be used with caution. Dams must be treated conservatively because of the potential widespread damage that would be caused by the release of the reservoirs they impound. The consequences of damage to other lifeline facilities should likewise be considered in the choice to do a dynamic analysis.

Cohesionless Embankments

Both actual performance and analysis indicate that poorly compacted cohesionless embankments of sand, silty sand, gravelly sand, or sandy gravels suffer significant strength loss during earthquakes. The Upper and Lower San Fernando Dams' hydraulic fills already have been discussed. Two more hydraulic fills, Dry Canyon and South Haiwee Dams, suffered damage during the 1952 Kern County earthquake (Jansen et al., 1976). Sheffield Dam, a 25-foot-high, low-density, silty-sand embankment failed during an earthquake in Santa Barbara, California, in 1925 (Seed and Lee, 1969). There are numerous mentions in the technical literature of liquefaction of sand deposits and landslides in tailing embankments during or immediately after earthquakes. The results of the analyses of the hydraulic fill dams are summarized on Figure 1 (Babbitt et al., 1983). Generally, poor performance is predicted and it is important to note that Figure 1 would not have predicted the damage that occurred to South Haiwee Dam during the 1952 earthquake. The analysis procedure would have predicted an average peak ground acceleration of 0.04g.

Cohesionless soils are prone to strength loss because they tend to settle during shaking, thereby generating excess pore pressures. Liquefaction is the extreme of this condition. Everyone does not agree with the Seed-Lee-Idriss approach to analyzing this strength loss. Its critics believe there are flaws in the analysis that make the results too conservative. However, there is no disagreement that saturated poorly compacted cohesionless soils must be considered potentially troublesome during earthquakes.



PEAK GROUND ACCELERATION

- O **SATISFACTORY**
- ⊕ **MARGINALLY SAFE**
- ● **ALTERATIONS NEEDED, DAM ABANDONED OR STORAGE SEVERELY RESTRICTED**

FIGURE 1 Performance predicted by analysis of hydraulic fill dams. Peak ground accelerations were obtained from the Seed-Schnabel or later attenuation curves and represent an "engineered average" peak ground acceleration expected at the dam. The ground accelerations and duration of shaking increase with magnitude. Both are significant in determining soil performance.

Clayey Embankments

Clayey dams have performed very well during earthquakes (Seed et al., 1978). Thirty such dams were not severely damaged by the 1906 San Francisco magnitude 8+ earthquake. Several of these dams were within a few hundred feet of the fault. Hebgen Dam, a 90-foot-high embankment built in 1910 near West Yellowstone, Montana, was severely damaged but survived a local magnitude 7.6 earthquake in 1959 (Sherard, 1966). None of these dams were as well compacted as modern dams. Details of their performance are limited. However, the crest of Hebgen Dam settled a maximum of 6 feet upstream of its corewall. The slopes bulged and there was spreading of the base, indicating shearing strains may have been responsible for a major share of the crest settlement.

Strength losses that have occurred in cohesionless soil dams are not expected to occur in most clayey dams, even the older ones. However, potential for settlement like Hebgen must be considered. Very low density clays such as some lakebed deposits in embankment foundations and possibly "puddled clay" zones in dams could be overstressed during earthquakes and lose essentially all their strength.

Modern Dams

Dense to very dense modern embankments are expected to perform well under even the most severe earthquake shakings. Problems are only expected to develop where:

1. They have been constructed on natural cohesionless deposits that are not as dense as the embankment,

2. The slopes of embankment are unusually steep, or

3. The freeboard is inadequate.

Figure 2 summarizes the results of 43 analyses on dams located near active faults, several of which were selected for analysis because they were on questionable foundations or were not as well compacted as modern dams. Significantly better performance than for the hydraulic fills is indicated. These studies were all based on the Seed-Lee-Idriss procedure and, hence, would be considered by some to indicate a higher relative compaction for seismic stability than is really necessary. Actual performance of dams under severe earthquake loadings is too limited to prove which school of thought is correct; however, there is consensus that well built dams will resist the largest predicted earthquakes.

Dynamic analyses are considered unnecessary for well built dams on stable foundations where average peak ground accelerations do not exceed 0.2g. Analyses are required to estimate potential settlement of such dams where higher accelerations are expected (National Research Council, 1984). The need for settlement estimates has been substantiated by the occurrence of earthquake-induced settlements up to 12.6 inches at La Villita Dam in Mexico since 1968 (Bureau and Campos-Pina, 1986). La Villita Dam is a 197-foot-high earth and rockfill dam completed in 1967. The measured peak ground acceleration in the 1985 earthquake, which caused the 12.6 inches of settlement, was only 0.13g; however, the duration of shaking was an unusually long 50 seconds.

Seed and co-workers (1985) have proposed flatter slopes than the 1.3 to 1.5:1 slopes that currently are being used for concrete-faced rockfill dams if such structures are to be constructed in highly seismic areas. Their recommendations are based on the results of analytical studies. They recognize the lack of performance data and that adjustments will be made in their recommendations as data become available. The concern is distortions of the steep slopes rather than slides due to strength loss because these embankments are maintained dry by their concrete slabs and high embankment material permeabilities.

Concrete Dams

The information on seismic performance and analysis of concrete dams is much more limited than for earth dams. Also, concrete dams tend to be very unique structures. For these reasons, generalizations on the need for dynamic analyses of them are not possible at this time.

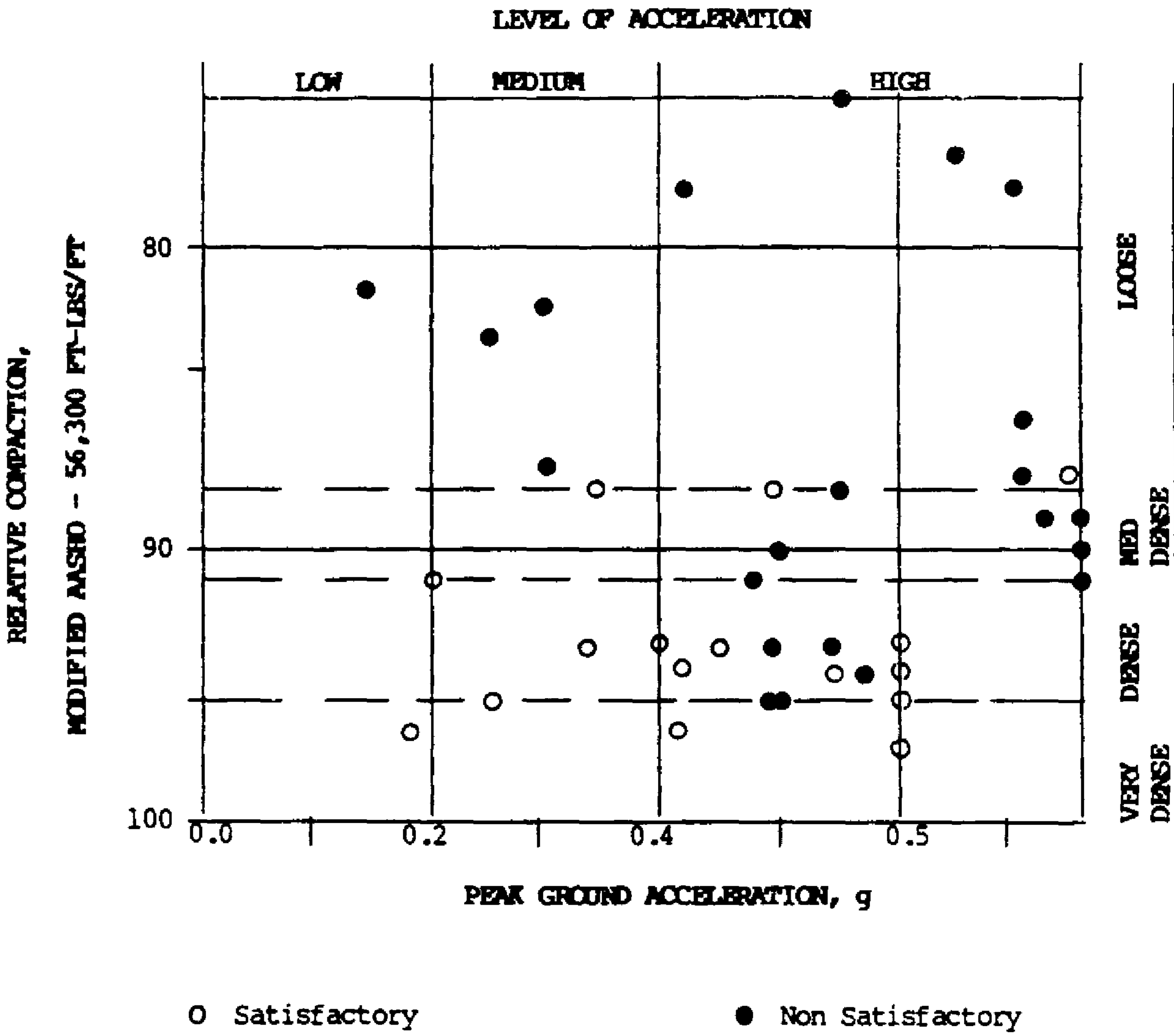


FIGURE 2 Performance predicted by analysis of nonhydraulic fill dams. Peak ground accelerations were obtained from the Seed-Schnabel or later attenuation curves and represent an "engineered average" peak ground acceleration expected at the dam. As previously noted, duration of shaking is also an important factor in determining soil performance.

Other Earth Structures

There are some important factors to be considered in applying the technology described above to structures other than dams.

Saturation, a necessary ingredient for severe strength loss, is usually present at dams. It is less common at other structures. Reservoirs with linings and subdrains are good examples of unsaturated embankments. University Mound North Basin Reservoir in San Francisco, in part a sand embankment on a sand foundation, survived the 1906 earthquake even though it was within 5 miles of the San Andreas fault (Seed et al., 1978).

Some levees and flood control dams with ungated outlets may only have water behind them and, hence, be subject to saturation and potential strength losses during earthquakes for a few hours each year. The probability of earthquake damage in this condition is obviously much less than where saturation is continuous.

The computations for earthquake-caused settlement are estimates at best. These estimates are acceptable for dams because they have ample freeboard for other conditions such as passing floods. Other embankments, particularly those supporting rigid structures or containing pipelines, may be less able to tolerate imprecise settlement estimates.

Dams usually are built in thoroughly explored canyons from which most soils have been removed. Levees, water treatment plants, and sewage holding ponds, for example, are necessarily built on alluvial or other soil foundations that may be weak. Knowledge of foundation conditions is never as complete as for dams, resulting in a lower level of confidence in the structures.

METHODS OF STABILIZATION

To date, the stabilizing of dams and other embankments to resist earthquake shaking has been by buttressing, draining, reduction in reservoir storage, and combinations of all three.

Buttresses usually have been designed by classic stability analysis techniques. Strengths of vulnerable soils have been reduced to the levels indicated by the dynamic analyses. The buttresses have been either free draining or contained drain zones so as not to trap pore pressures. Drainage has been provided to lower steady state phreatic lines with drain zones, thereby increasing the overall stability and in some cases, reducing the amount of potentially liquefiable soil. Buttresses generally have proven ineffective where significant foundation strength loss has been predicted.

Drainage also can be provided to accommodate earthquake-induced pore pressures by introducing wick drains into the suspect material. The wicks can either carry the excess pore water away or, if maintained partially dry, provide storage space for it. The Metropolitan Water District of Southern California is employing the latter technique to stabilize a slope at its Joseph Jensen treatment plant.

Reducing reservoir storage levels has, in addition to lowering phreatic lines, provided additional freeboard where slumping of the dams was considered possible. Additional freeboard also has been provided by adding fill to the dam crests.

Potentially liquefiable soils have been densified by blasting, vibratory probing, vibro-compaction (includes adding backfill), driving compaction piles, and heavy tamping (weight dropping) (Ledbetter, 1985). These techniques have been used at many building and plant sites and at a few new dam sites, but the Bureau of Reclamation's use of heavy tamping at Jackson Lake Dam will be the first densification at an existing dam known to the author.

Grouting of dam foundations of soil is considered possible but is as yet untried for improving earthquake resistance.

Concrete dams have been stabilized most often by reducing reservoir storage. The hydrodynamic load, a major factor, is greatly reduced. Improved knowledge of earthquake performance of concrete dams may allow lifting these storage restrictions in the future. A roller-compacted concrete buttress currently is being designed to improve the seismic stability of an existing 169-foot-high arch dam in a highly seismic area. An increase in dam height is being considered as part of the project to offset storage lost to reservoir siltation.

DESIGN OF NEW DAMS, EMBANKMENTS, AND RESERVOIRS

Earth Dams

Current practice in designing earth dams subject to earthquake shaking is to shape the structure by performing conventional static or pseudo-static analyses, avoiding such pitfalls as loose cohesionless soils, and providing conservative zoning and crest details. Dynamic analyses are conducted on high or complex dams to check the design. Smaller conventional dams are compacted to densities that experience shows (Figure 2 is an example) will prevent the material from losing strength during shaking. A few cyclic triaxial shear tests are sometimes run for confirmation. More often, the static shear test results are reviewed to assure that the soils have a strong tendency to dilate during shear.

Conservative crest details include adequate freeboard for estimated settlement and an allowance for cracking associated with it, transition and shell zones extended to the crest to control any seepage that develops through cracks, and camber for static and dynamic settlement. Conservative zoning consists of confined clay cores, wide cohesionless transitions, and free draining shells. Some of these details are admittedly redundant. The higher the dam and the greater the expected shaking, the more conservative the design should be.

Concrete-faced rockfill dams and concrete-lined reservoirs also need conservative crest details. Embedded, reinforced concrete parapet walls might be important elements in these details.

Almost all aspects of earth dam design in earthquake areas are more difficult and require more conservatism. Two examples are: (1) earthquake loading is another unknown in assessing the landslide into reservoir problems, and (2) transverse cracking of a dam due to a differential settlement could be rapidly triggered by an earthquake.

The conservative embankment details are considered very important for dams constructed near faults where there is possibility of fault movement in the foundation, regional tilting, or other near field effects. Otherwise inactive faults in foundations need to be considered because they may move in sympathy with active faults during earthquakes.

Concrete Dams

Concrete dam designs are developed in the same manner as earth dams although some less complex dynamic analyses may be used in the shaping process. The expensive full dynamic analyses are used primarily as a check. Conservative design practices such as thorough foundation exploration and treatment, good geometrical configuration, and effective quality control are used. The dynamic tensile strength of the concrete is often the controlling parameter in seismic design. Testing early in the final design stage is usually prudent.

Earth Structures

The earthquake resistant design concepts of dams apply, in theory, to all earth structures. The differences between dams and other earth structures, discussed in the "Dynamic Analyses" section above, apply to design too. Lack of saturation may greatly reduce the possibility of damage. The level of exploration, testing, and design for dams is achieved for few other structures which yield less predictable or reliable reactions to earthquakes. There is another major factor--cost. Clearly, levees and canal embankments cannot have the expensive details discussed above. These limitations need to be recognized in assessing the reliability and safety of earth structures other than dams.

Cost

The incremental cost of constructing new dams on good foundations to resist light to moderate shaking is not high, with the possible exception of outlet towers and mechanical equipment. Building dams to resist strong earthquake shaking can add to compaction and concrete costs and to dam volumes, both earth and concrete, if flatter slopes are necessary. Reinforced concrete structure costs are usually higher too. Designing for foundation fault displacement can be very expensive if zoned embankment materials are not locally available. The cost of improving the earthquake resistance of water retention structures varies widely because of site conditions.

Construction of dams across faults that might move is very rare. Retrofitting after such faults are discovered is more common. There are about 10 dams across active or potentially active faults in California, most of them small.

Building earthquake resistance into any massive structure on poor foundations is costly. In addition to extra structure costs, the foundation improvement techniques mentioned previously cost from $5 to $20 per cubic yard.

MAINTENANCE

Dams and reservoirs should suffer less damage than other components of lifeline systems because their potential hazard has justified conservative design and construction practices. They must be properly maintained to assure the better performance. Valves must be exercised regularly and emergency power sources tested so that the valves can shut off flow to damaged distribution lines or be opened to lower a reservoir if a dam has been damaged. Drain systems in and under dams and embankments must be maintained to assure stability and, in some installations, prevent liquefaction.

INUNDATION AND EVACUATION PLANS

Inundation maps and downstream evacuation plans for dams above inhabited areas have been required in California since 1974 and more recently in many other states. Several currently available dam-break computer programs are suitable for determining the potential inundation. Dam owners are responsible for having the maps prepared. In California, the State Office of Emergency Services has the maps reviewed and works with local law enforcement agencies to develop evacuation plans. Well known geographical boundaries bordering the inundation area are designated the evacuation limits in the plans.

There have been at least two successful uses of such plans. Both of the plans were prepared by a prudent owner prior to enactment of laws requiring them. Evacuation plans should be available for all dams of significant potential hazard. However, they cannot be substitutes for safe dams, particularly when the seismic safety is at question.

Alarm systems have been installed below dams with inadequate spillways or other defects to provide an improvement in safety. Earthquakes occur too quickly and without warning for alarm systems and evacuation plans to be practical.

ONGOING DEVELOPMENT OF NEW KNOWLEDGE

The high cost of providing earthquake resistance to structures justifies ongoing development of new knowledge in both analysis and construction techniques.

Sponsors and Workers

Design and construction of the California Water Project in the 1960s focused the need for information on earthquakes and seismic design criteria because the project parallels and crosses the San Andreas fault. The project funded studies by universities and individuals on a wide spectrum of problems from fault creep to the beginning of the Seed-Lee-Idriss analysis. This research has continued and expanded with federal funding by the National Science Foundation, the Corps of Engineers, the Bureau of Reclamation, and many other organizations and firms.

As mentioned above, the analysis development paralleled work on nuclear power plants. Private and public utilities developing plans for proposed plants hired consultants to map faults, evaluate sites, and do much of the dynamic-analysis work. A considerable amount of this information was directly transferable to dams and other structures.

Universities, the Corps, the Bureau, and several consulting firms currently are doing most of the development of analysis and testing procedures. Federal agency dam safety efforts are coordinated through the Interagency Committee on Dam Safety (ICODS), which is an emerging source of publications (ICODS, 1985). The U.S. Committee on Large Dams (1983) has published a bibliography on performance of dams during earthquakes and a set of guidelines for inspecting dams after earthquakes and has other projects under way.

The U.S. Geological Survey and its state and local counterparts are continuing sources of information on faults and the earthquake parameters needed for dynamic analyses. Additional sources are other governmental agencies and the private developers and their consultants who are designing or re-evaluating specific projects.

The state of California has a strong-motion instrumentation program designed to collect accelerograms near faults, on structures, and at free-field sites. The information is used to develop fault-to-site attenuation relationships and to check results of dynamic analyses. Approximately 400 instrumented sites currently are maintained at an annual cost of more than $1.5 million, which is derived from a tax on building permits. More structures need to be instrumented in California so an increase in the program is being planned. There are also a similar number of strong-motion sites in California maintained by others. Attenuation relationships and structure responses vary with the geology and fault tectonics so similar programs are needed throughout the country in areas where earthquakes are expected to occur with some regularity.

Analysis

Almost every aspect of a dynamic analysis can have a significant impact on its results. Because of this, all input and procedures need essentially the same attention. This situation makes identification of needs for development of new knowledge difficult.

The current efforts to identify active (capable) faults and improve the knowledge of fault-to-site attenuation of earthquake shaking should be continued at the present level or increased. The level of earthquake shaking expected at a site determines if seismic design is a nominal problem or the dominate design consideration. This aspect of the earthquake problem is particularly challenging east of the Rocky Mountains where few earthquakes can be associated with mapped faults (National Research Council, 1984). The level of shaking to be expected in that area is critical to the nuclear power industry as well as to dam owners. The limited knowledge of where earthquakes may occur causes nearly worst-case assumptions to be used on important structures.

Geotechnical and dam journals have been filled with articles on dynamic analyses and laboratory testing for the past 15 years. There has been healthy competition between universities and others to develop knowledge of such important effects as how soils generate and dissipate pore pressures during and after earthquakes. These efforts should be continued.

At the same time more field work is necessary to refine or redirect the analysis procedures and input data now being used. Back-figuring performance of structures during actual earthquakes is vital to this effort. Another evaluation of Lower San Fernando Dam commenced in 1985. It should aid in resolving the previously mentioned conflicts with the Seed-Lee-Idriss analysis. An analysis of recent tailing dam failures in Chile was started in 1986. Ten such studies by universities, costing $200,000 to $500,000 each, would answer many pressing questions.

The Standard Penetration Test should be standardized or replaced. It is, in reality, rarely a standard test; yet, it has a significant effect on the results of dynamic analyses. Previous attempts to standardize have not been effective. Some other exploration techniques are nearly as crude and need to be improved to approach the level of accuracy of the computers used to make the computations. Practicing professionals who make critical decisions based on the results of these tests, need to take the lead and direct research to standardize or replace the SPT and should individually insist that only the best (and usually most expensive) exploration and geophysical tests are always used on their projects. These actions should start an evolution toward better field testing. The initial SPT testing should cost $250,000 to $500,000 and could be done by the Corps' Waterways Experiment Station, the Bureau's Engineering and Research Center, or a similar installation. The cost of using better tests is so much smaller than the cost of misleading analysis results that it should not be computed.

Pooling the results of dynamic analyses might show that there are dependable correlations between static and dynamic analyses, particularly where there is no serious loss of soil strength or cracking of concrete during earthquake shaking. Correlation studies expanding on Figures 1 and 2 and costing about $200,000 should test the concept and, if successful, provide extremely useful data. Graduate students could do the necessary researching of dam owner and control agency files.

Construction

Most techniques for improving earthquake resistance utilize conventional construction practices and will continue to evolve with that industry in general. The exception is densifying potentially liquefiable soils, particularly those under existing structures. The current techniques available, discussed above under "Methods of Stabilization," are very expensive and sensitive to soil types being treated. Densification is difficult at an open site; doing it without damaging existing structures is a real challenge. The government should be encouraged to try the techniques as learning experiences on projects it is considering abandoning. Several million dollars would be required.

Other Considerations

Guidelines on abatement of seismic hazards to lifelines should:

1. Advocate ample reservoir emergency reservoir drawdown capacity,

2. Stress the need for good maintenance, and

3. Recommend that inundation maps and evacuation plans be prepared for all impoundments that are potential hazards to life and/or property.

Dam safety has been regulated in California since 1929 and is currently regulated in most states. Preparation for earthquakes is a major consideration in dam safety. Regulation experience for dams may be transferable to other lifelines. The Association of State Dam Safety Officials is currently the best resource for information on dam safety regulation.

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