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FEASIBILITY OF USING CONTAINED-EXPLOSION TECHNIQUE FOR EARTH DAM TESTING

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INTRODUCTION

Studies on the performance of earth dams in past earthquakes (Ambrasseys 1960, Seed et al. 1978) show very few failures, suggesting that the designs of most existing earth dams are quite conservative. Conservatism is provide mainly by using gentle slopes, which may not be economical and may be impractical under the limitations of some new site conditions. Such an approach to the design of larger dams at seismically active sites, which are unsatisfactory in terms of foundation and abutment rock conditions, goemetry of the valley, and distance from borrow sites for fill material, will make their construction costs prohibitive. Clearly, the need for rational and economical design of earth dams is greater now than ever before.

Studies of the few earth dams that have failed in the past suggest that failure was caused by phenomena involving the dam and reservoir system during earthquakes not considered in their design and not by defective design or stability in the conventional sense. Dams constructed of saturated cohesionless soils (Seed et al. 1978) suffer greater damage than those constructed of unsaturated cohesive soils. Buildup of pore-water pressure in the embankment and possible loss of strength and reduction in yield acceleration may be the cause for this behavior. Since the physics of the phenomena causing failure is not clearly understood, the problem cannot be studied entirely analytically. Therefore, a technique is needed for testing earth dams to collect response data under dynamic conditions.

This paper explores the feasibility of using the contained-explosion technique for earth dam testing. Computations are presented to illustrate how the technique could be used to simulate a real accelerogram and its response spectra. Examination of the physical phenomena important in dynamic dam response and the criteria for simulating earthquake motion as relevant to dam response lead to the design of an

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array of contained-explosion sources and a plan for a program of earth dam testing.

REVIEW OF DAM TESTING TECHNIQUES

Shake table tests have found very limited application to dam testing because of serious limitations in providing simulation conditions important to dam response and development of porewater pressures. These limitations include small model size and hence improper gravity forces, limited topography surrounding the dam model, inability to shake the dam through its abutments in addition to the foundation, and difficulty in reproducing drainage and saturation conditions in the region around the dam.

Dynamic testing on centrifuges has been under development in recent years to more properly reproduce gravity forces. However, the models must be very small, the interaction with foundation, abutements, and surrounding topography cannot be simulated, and representative relative timing of hydrodynamic forces with respect to other forces may be difficult to obtain.

The use of buried explosions to simulate earthquake ground motion for field testing of small prototype structures and models of larger structures at several response levels, including failure, shows great potential. A straightforward way of doing this is to detonate explosives in drill holes and underground cavities constructed directly in the earth materials (Higgins et al. 1978). Another method, specially conceived for field tests on structures, is to contain the explosions so that cratering is avoided and the desired ground motion characteristics are simulated over a small controlled area (Bruce et al. 1981). Some of the relevant features and capabilities of the direct and contained explosion techniques are compared here.

Direct Explosions	Contained Explosions
Initial tests with little or no developmental work on the technique could produce sizable excitation because of earlier experience and available data for explosives in other applications.	Initial tests can be done with moderate ground excitations, but further development is needed to obtain ground motions to cause structural damage.
Use of planar arrays (series of line sources in a plane) to produce	Use of planar arrays has been demonstrated. The charge, size

a plane wave front has been recommended. The amount of explosive in each drill hole and the length of the hole are used to control amplitudes.	and number of the sources control amplitudes and also the size of test area.
Huge quantities of explosive must be used because of the large separation between shot point and test structure needed to provide attenuation to earthquake motion. Leads to uniform motion in a large area.	Much smaller quantities of explosive are used because the containment provides attenuation so that the array can be placed much closer to the test structure. Excitation is limited to a smaller area.
Technique depends on natural attenuation through earth materials 1) to limit the energy per unit volume within the elastic limit of earth materials and 2) to control the frequency of ground motion. Some frequency control is provided by the detonation sequence (up to about four detonations).	The contained source controls the stress level in the surrounding earth materials. Frequency is controlled through the rate of release of explosive pressure from contained source and by the firing sequence (projected capability of a 4–array facility is 12 firings at high levels, and twice this number at lower levels).
Restoration of site for repeat use involves large efforts for each test. Reproduction of same ground motion may be difficult even after restoration.	No restoration of the site is required. Repeat tests can be performed with the same explosive containers with excellent reproducibility of ground motion.
Simulation of response spectra in limited frequency range is considered practical.	Simulation of various ground motion parameters seems possible and will result in simulation of the response spectra in range of usual interest (1 to 20 Hz) for structures.

The comparison shows that the contained-explosion technique is better suited to systematic testing of structures over a range of amplitudes, frequencies, and durations. The technique is particularly well suited to dam testing if model dams are specially constructed at a field test site developed for the purpose. For this application, the contained-explosion technique is superior because only small quantities of explosive are required, no restoration of the site is necessary, and repeated use of the site will allow more tests at lower costs than the uncontained technique.

Comparison of Contained-Explosion and Shake Table Tests:—In the absence of suitable field techniques for dynamic excitation, limited tests have been conducted on shake tables (Clough & Pirtz 1956, Seed & Clough, 1963). However, researchers have not pursued such tests in depth because they can serve only very limited purposes. Some of the advantages of the contained-explosion technique over shake table tests are summarized below:

Shake Table Tests	Contained–Explosion Tests
Very small models (0.6 m tall), resulting in problems of scaling material properties, forces, and ground motion to meet simulation requirements.	Test dams 2 to 6 m can be used to limit scale ratios and even treat them as small prototype dams.
A dam model on a shake table does not represent actual field conditions with respect to the foundation and its contact with earth dam material.	Test dam can be sited on specially prepared uniform condition that is very representative of the foundation condition of an actual dam.
Participation of abutments in shaking of dam and influence of surrounding topography cannot be simulated.	Shaking of dam along with the abutments and surrounding topography can be achieved.
Low strain levels; application to higher strain levels corresponding to an earthquake condition is questionable.	Proposed strain levels are much higher and more representative of actual conditions.
The influence of different overburden pressures on possible dilatation of sand under shear deformation cannot be investigated (Seed & Clough 1963).	Testing three distinctly different size prototype dams with different overburden pressures would enable study of this effect.
Similitude requirements presume undrained condition without knowing to what extent this is true.	No assumptions about the drainage conditions are required, and the actual phenomena are monitored.

No efforts are made to evaluate quantitatively the capacity of a dam to undergo permissible inelastic deformations.	The capacity of a dam subjected to inelastic deformation can be evaluated.
The role of model and foundation interaction, if any, is not typical of actual conditions.	The interaction of the dam and its foundation under representative conditions can be studied.
Actual field conditions cannot be simulated for development of pore-water pressure and saturation conditions.	The study of development of pore-water pressure under representative saturation condition for static and dynamic conditions is possible.

Contained-explosion tests are therefore expected to add substantially to the current understanding of the response of earth dams when subjected to dynamic excitation.

Contained-Explosion Technique:—The contained-explosion technique for dynamic field testing of moderate size prototype structures, or models of very large structures, has been under development at SRI International for the past several years (Bruce et al. 1981). The technique produces earthquake-like ground motion by simultaneous firing of a planar array of vertical line sources placed in the soil near the test structure. The key feature of each line source is a cylindrical steel canister in which the charge is fired. Controlling the release of the heigh-pressure explosion products from this canister allows controlled pressurization of the surrounding soil. In this way, both the amplitude and frequency content are controlled at levels suitable for testing with the arrays of contained-explosion sources placed close to the test structure.

This technique opens the possibility of in-situ testing at high levels of earth motion with a minimum amount of explosive and with little disturbance to the surroundings. The frequency and duration of the simulated earthquake motion can be controlled by delayed multiple firings within each line source and between groups of line sources.

Cylindrical line sources with 10 and 30 cm diameters and 4.5 and 11.1 m lengths, respectively have been designed, developed, and successfully tested individually and in a group of ten and eight, respectively, to form planar arrays (Bruce et al. 1981). A 9-m-long array of ten of the smaller (10 cm diameter) sources with a total explosive charge of 2.8 kg (6.2 pounds) produces ground motion with a dominant frequency of 8 Hz and peak values of 2 g acceleration, 30 cm/sec velocity and 1 cm displacement. Preparations for testing of a 30-m-long array of 30-cm-diameter, 11.1-m-long sources are in progress. This array is expected to use 55 kg (120 pounds) of explosive to produce ground motion with 1.0 g acceleration, 3 Hz frequency, 30 cm/s velocity, and 2 cm displacement. Structures with plan dimensions of about 10 by 10 m could be tested with this facility. Development of sources with a three pulse capability is also planned for the near future.

A quasi static analytical method has been developed to permit design of arrays to provide ground motion with the desired characteristics. The stress, strain, and displacement around the array can be computed by straight-forward elastic-plastic theory (Bruce et al. 1981). The designs so obtained are within conventional construction capabilities, even for arrays required to test structures with plan dimensions of about 40×40 m. The analytical method developed shows that displacements are inversely proporional to the soil modulus of elasticity. Therefore, obtaining large displacement on hard rock sites may be difficult. Thus, initial testing of dams at high ground motion levels is proposed to be limited to dams on soil foundations. Nevertheless, some of the most important questions of dam response can be answered by tests with soil foundations. For example, development of porewater pressure is most serious in a dam founded on soil.Testing at a soil site also allows the topography surrounding the dam to be made in any desired shape by inexpensive earth movement.

COMPARISON OF ACTUAL EARTHQUAKE MOTION WITH MOTION FROM CONTAINED-EXPLOSION LINE SOURCE ARRAYS

A series of pulses with selected amplitudes, frequencies, and delays can be produced by use of contained-explosion line source arrays. The ground motion thus generated has many of the important features of earthquake ground motion. The following computations give a simple test case illustrating these features for a selected earthquake ground motion.

The selected ground motion (because of ready availability of data) is that recorded at Castaic (N69w) during the San Fernando, California, earthquake of February 9, 1971, shown in Figure 1. Twelve pulses to be used in a simulation were selected with periods and amplitudes based on their importance in the recorded ground acceleration over a 15-second period. These are to be obtained with four arrays, each with three charges fired sequentially. These appear to be the minimum needed for simulating the ground motion for 15 seconds.

The wave form (shape) for each individual pulse was taken as that actually recorded from a contained-explosion line source array (10 sources 0.10-m-diameter by 5-m-deep, in 10-m-long array). Amplitudes and

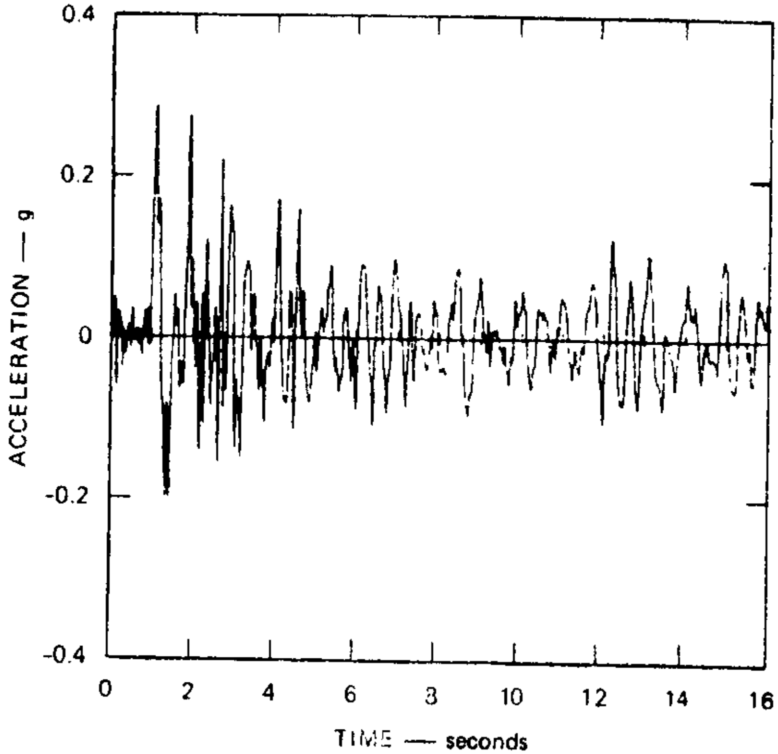

Fig. 1. Accelerogram for San Fernando, California Earthquake (February 9, 1971, Castaic N 69 W)

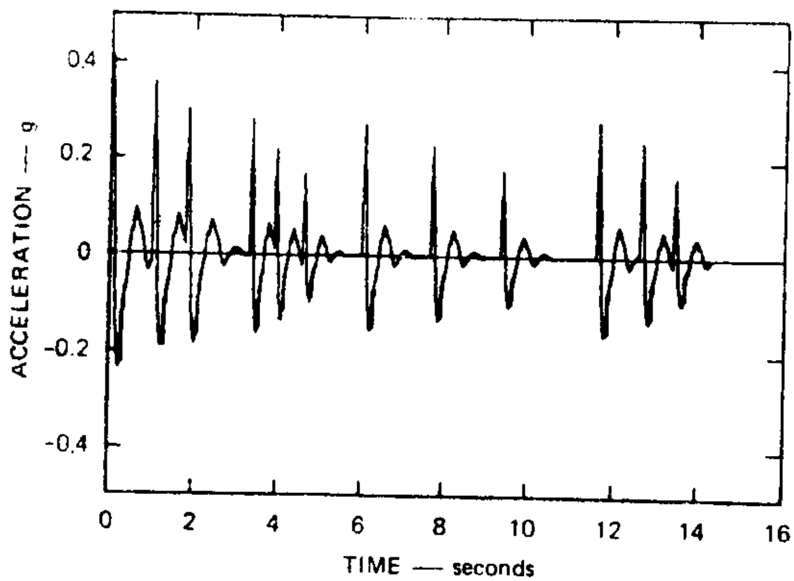

Fig. 2. The History of Ground Acceleration, Simulating the San Fernando, California, Earthquake with 12 Array Pulses

durations of each pulse were selected to approximetely match those of the large pulses in the earthquake accelerogram. These are shown in Figure 2. Ground velocity and displacement (Figures 3 and 4) were computed by integrating these pulses. Velocity and displacement found in the same way, but from the actual San Fernando earthquake accelerogam, are given

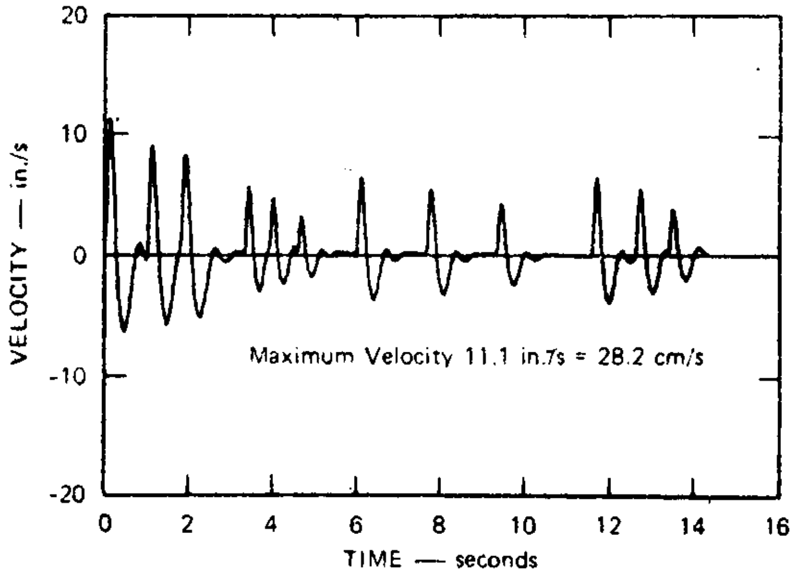

Fig. 3. Velocity-Time History for Test Earthquake

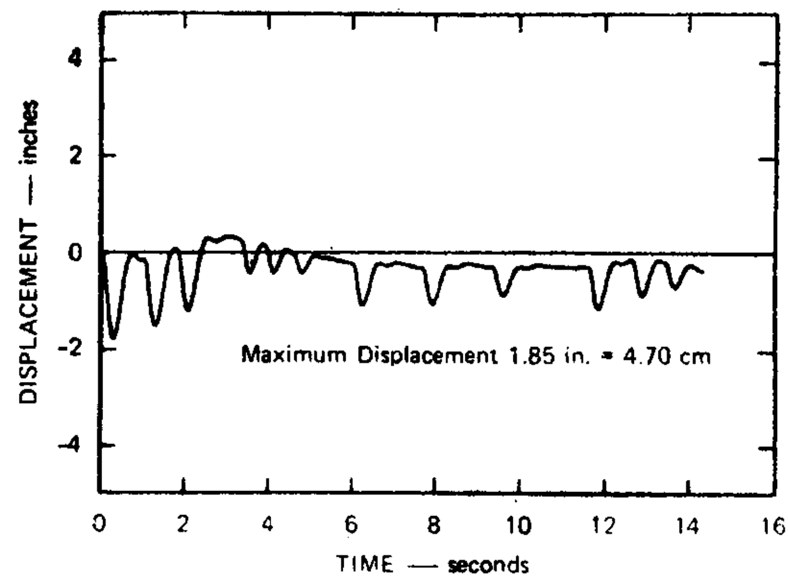

Fig. 4. Displacement-Time History for Test Earthquake

in Figures 5 and 6. The general trends of all three simulated quantities (acceleration, velocitiy, disglacement) follow surprisingly well the corresponding trends in the earthquake quantities.

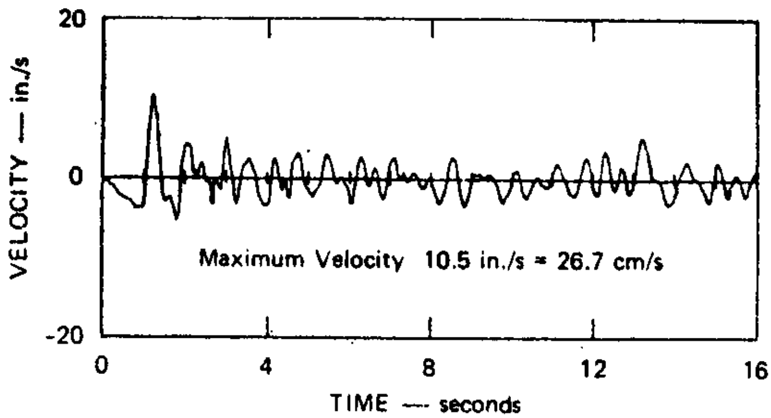

Fig. 5. Velocity-Time history, San Fernando, California Earthquake (February 9, 1971, Castaic N69W). Segmentally Adjusted Record. From Reference 6.

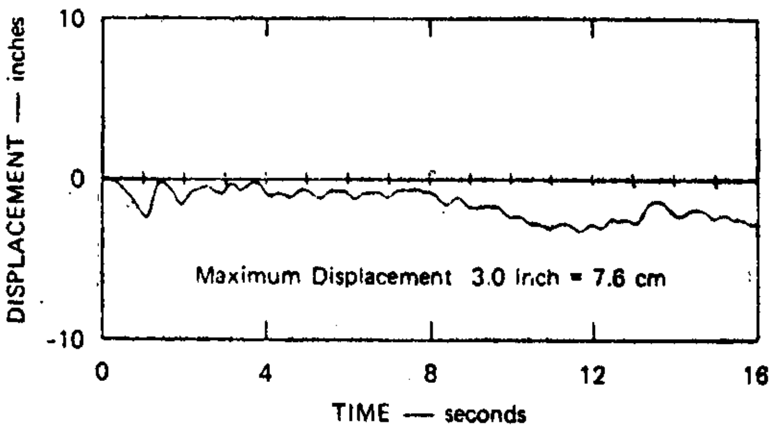

Fig. 6. Displacement-time History, San Fernando, California Earthquake (February 9, 1971, Castaic N69W). Segmentally Adjusted Record. From Reference 6.

Further comparison was made by calculating the response spectrum for 5% damping. The actual and simulated spectra are compared in Figure 7. The general forms of the two spectra are quite similar, but the response spectrum for the test earthquake is lower. When the test spectrum is scaled up by a factor of 2, which can be achieved by suitable enhancement in selected pulses, it yields an exceptionally good match. The simulation would further improve for higher damping. Note that this simulation match was made with first choice of pulses. A few further trials could result in an improved match, if needed.

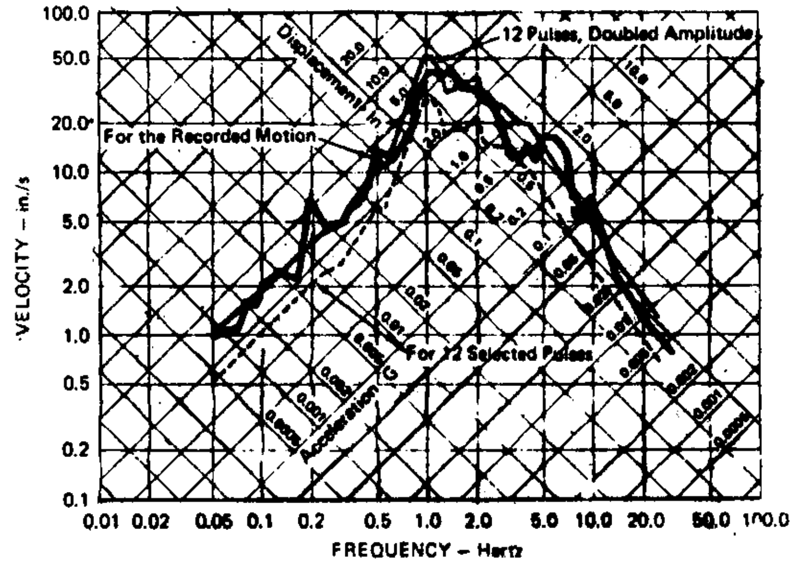

Fig. 7. Response spectra for San Fernando Earthquake (from reference 6) and test Earthquakes

RELEVANT EARTH DAM RESPONSE CHARACTERISTICS

A good plan for testing earth dams should allow study of those physical phenomena that are not well understood and are not fully accounted for in design. Such phenomena are discussed in the following paragraphs.

Development of Porewater Pressure—Porewater pressure plays an important role in the response of earth dams under dynamic loads. Some of the more important factors in the development of prowater pressure are: the siting of a dam in a particular topography; actual saturation, and drainage conditions of the whole system; the frequency, duration, and level of dynamic excitation (very rapid loading may not allow drainage); and the nature of the foundation and dam material.

Interaction of Dam with Foundation and Abutments.—Dam response is likely to be very defferent if tested on a shake table where the dam is excited primarily at the base (foundation) without abutments as compared with natural conditions where shaking through abutments may also be significant. The dam's height, base length, and spread along the valley are imprtant in the relative importance of shaking through abutments and foundation.

Influence of Surronding Topography—The dimensions of earth dams tend to be comparable to the elevations of surrounding topography and the wave lengths of ground motion. Thus, the dynamic response of earth dams and the host topogrphy are interdependent. If the earth materials surrounding the dam are similar to those from which the earth dam is constructed (i.e., the site is soil), such an intercoupling of response may be more pronounced.

Permissible Level of Inelastic Deformation—After an earth dam has undergone inelastic deformation, e.g., slip or displacement has occurred on a failure surface within some limited range, the slip surface can usually still carry substantial loading during subsequent shaking. With an extended period of time between earthquakes, these surfaces can also heal themselves. This forgiving and self-healing character of earth dams, unlike brittle structures, needs to be evaluated. The amount of slip that can be sustained before the dam becomes nonfunctional should be explored as a possible safety margin in the economical design of earth dams. The tests should therefore be conducted to cover moderate to large deformations and eventual failure of the test dams.

Effects of Dam Construction Materials—The materials with which earth dams are constructed are far more complex than other construction materials. As a consequence, construction of meaningful scaled models for dynamic testing is a very difficult task, at least with the present state of knowledge. Usually, simplifying assumptions are made to enable limited representation for a specific study. Because the phenomena important in the dynamic response of earth dams are not understood, neither the gravitational nor constitutive effects of these materials can be ignored in preparing scaled models. However, once the physics of the phenomena involved has been understood through the initial tests, it may be possible to adjust construction materials to allow limited scaling of large prototypes in future testing.

Effect of Dam Size on Response—To determine the effect of dam size on response as a result of changed overburden pressures and associated change in material properties, at least three sizes of test dams should be tested, The test results could be interpreted by first treating the test dams as prototype small dams, and then, with some reasonable engineering judgment, as geometrically similar models of a large dam

EARTHQUAKE MOTION SIMULATION CRITERIA

The overall dynamic response of an earth dam cannot be well represented by elastic analysis using the response spectrum technique because response is very sensitive to plastic deformations, which may be allowable in the design to the extent that the dam remains functional. It is therefore necessary to emphasize the simulation of those characteristics of ground motion that may be important in determining the extent of deformation and displacements rather than to simply simulate the linear response spectrum.

The interrelationship between the predominant ground motion frequency and the natural frequency of earth dams will be important in dynamic response buildup. Also, the duration of ground motion (or, for simplicity of application here, the number of significant pulses in the ground motion) has great importance in determining the inelastic response because displacements produced by successive pulses will be additive, resulting in larger deformations than those resulting from fewer pulses. Thus, the test earthquakes should simulate the frequency, duration, and displacements of prototype earthquake motion. Moreover, they must be of great enough intensity to lead to failure of some of the test dams.

The choice of a prototype earthquake is determined by the dynamic characteristics of the earth dam, which in turn, is dictated mainly by the dam size, distances of seismogenic features, and the maximum expected size of the earthquake. Two distinct situations where failure may occur are as follows :

(1) A moderate earthquake (6.5 Richter magnitude) close (25 km) to an earth dam will cause failure of a small dam only, since larger dams will have a natural frequency that is significantly different from the ground motion frequency.

(2) A major earthquake (8.0 Richter magnitude) could be relatively far (40 km) from any size dam and still cause failure.

The focal depth would be only about 25 km in these two cases. The various dynamic characteristics of ground motion, namely, acceleration, displacement, frequency, and duration, for the two situations can be taken from the averaged data from past earthquakes (Mathiesen et al. 1973 and Trifunac & Brady, 1975) if no accelerograms are available for the site under reference in tests. The selected ground motion is then simulated by contained-explosion source arrays.

CONTAINED-EXPLOSION LINE SOURCE ARRAYS FOR EARTH DAM TESTS

The general level of ground excitation required for earth dam tests will be 0.5 to 1.0 g acceleration, 1.5 to 5 Hz frequency, and about 15 s duration. Twelve ground motion pulses are considered the minimum to simulate this duration. This can be done by using four contained explosion arrays, each with sources having a three-pulse capability, as described in discussing Figures 1 through 7. The extrapolation of existing data gives the following dimensions for each of the four arrays : 12 sources, each 60 cm in diameter and 27 m long, spaced on about 5.5-m centers to obtain a 60-m-long array (Agrawal & Bruce, 1980). The amount of explosive needed for simulation of motion from the San

Fernando, California earthquake, as given in Figure 2, is about 5000 kg. Considerable development of the contained-explosion technique at an appropriate size will be needed before such large arrays can be built. However, because of the time required, the dam tests need to be planned while the technique is being further developed for this application.

OUTLINE OF EARTH DAM TEST PLAN

Data on high response levels including structural failure is initially needed for understanding nonlinear earth dam behavior. It is not practical to conduct tests on existing earth dams with this objective because of the risk. Thus the most practical approach seems to be to construct test dams that could be tested to failure. A logical sequence for a long-range earth dam test program, with growing confidence in the application of this testing technique, would be as follows :

Structure	Location	Response Level
Earth dams constructed for testing	Test site independent of dam site	Failure
	Test site near dam	Failure
	Future dam site	Minor settlements
Diversion dikes	Close to future dam	As practical
Existing dams (nonfunctional)	Consequence of failure to be controlled	As practical
Existing dams (functional)	Active seismic regions	Elastic range

The test site for initial earth dam tests would be one where it is easily possible to simulate porewater pressure, saturation, and drainage and to dig the desired topography to provide a natural dam setting. A good choice would be a sandy soil site with a shallow water table. Such a site is also ideally suited for generation of larger ground displacements using the contained-explosion technique. The test plan would generally involve the following steps :

1. Selection of a suitable test site of about 2 × 2 km.
2. Detailed site investigations.
3. Construction of the desired river channel and topography.
4. Construction of a test dam with conservative sections following the usual construction sequence.
5. Arrangements for water filling and allowing for the buildup of representative saturation conditions.

6. Arrangements for control of the consequences of test dam failure, including plans for flushing the reservoir water without causing flooding.
7. Test on a safe dam section with increasing intensity of ground motion until settlement or slumping occurs.
8. Modification of the dam section to make it weak by removal of material from dam toes and relaying the top section of dam.
9. Test with successively increasing intensity of ground motion until the dam section has been shaken by the motion that caused slumping in earlier tests of a safe section.
10. If the test dam does not completely fail, further modification of section to make it weaker and repetition of tests.

The initial tests will provide an understanding of the physics of earth dam failure. The data should be interpreted by treating test dams as prototypes of small dams. The test dams may be chosen in three different sizes so that the effect of changed confining conditions for material inside the dam and their role in overall response can also be studied. Tests on 2 th 6 m tall test dams may be a good starting point. It may also be useful to design the test dam geomctrically similar to large dams and to examine the possibility of extrapolating the observed behavior. Once the physics of the nonlinear earth dam behavior has been understood, hybrid scaling could be used to test models of large dams.

CONCLUSIONS

The contained-explosion line source arrays hold a better prospect for earth dam testing than any other technique, including conventional direct-explosive line arrays. However, development of large size contained-explosion line sources to give desired frequencies and multiple pulses must preceed their application for earth dam testing.

Extrapolation of experimental results from contained-explosion line source arrays so far completed shows that ground motion can be produced with the amplitudes, frequencies, and duration of motion required for simulation of strong-motion earthquakes. This enables reasonable simulation of oscillatory motion parameters for nonlinear response (that produce soil liquifaction or cumulative plastic deformation), and also the elastic response spectrum for linear systems over a wide frequency band. The simulation therefore satisfies the requirements for dam testing and also for testing of other structures that can be added to the tests with a fractional increase in cost. These could include tests of soil-structure interaction and response of nuclear reactor buildings, bridge foundations, liquid storage tanks, intake and other submerged structures, and phenomena of ground liquefaction in general.

A sandy soil site with a shallow water table is recommended for a dam test facility. The objective of initial dam testing should be to understand the physics of phenomena accompanying dam failure. Once the physics of failure is understood, hybrid scaling could be used for testing models of large dams.

Dynamic tests on earth dams are not restricted to an academic research need, but are directly linked to efficient design and execution of numerous major engineering projects of great importance to countries all over the world, especially in active seismic regions. Test data are necessary for improving earth dam designs and for reducing the cost of overly conservative construction. Although the costs of earth dam tests are estimated to be high (millions of dollars), they must be viewed in relation to the cost of constructing earth dams. Improved design and construction with only about 1% savings in the cost of a single dam like the Tehri Dam in India could pay for the tests in addition to ensuring an improved performance of the dam during earthquakes.

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