NSF/RA-800421

PB81-174006

SIMULATION OF STRONG EARTHQUAKE MOTION WITH CONTAINED-EXPLOSION LINE SOURCE ARRAYS

Report on Task 6
Feasibility of Earth Dam Testing

September 1980

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Prepared for:

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Grant No. PFR-7920722

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PREFACE

This study of the feasibility of earth dam testing was Task 6 of an overall grant from the National Science Foundation to study the simulation of strong earthquake motion with contained-explosion line source arrays. The possibility of constructing and dynamically testing earth dams in India was suggested by the Indo-U.S. Workshop on Natural Disaster Hazards Mitigation Research, held in New Delhi in December 1978, as an area of mutual interest for collaborative research between India and the United States.

As a result of this suggestion, Professor P. N. Agrawal of the University of Roorkee, India, accepted an invitation to come to SRI International as a postdoctoral fellow to conduct this study with Dr. H. E. Lindberg of SRI. John R. Bruce provided assistance throughout the study, and Kitta Reeds contributed greatly in preparing the final manuscript of the report.

The work is intended as a feasibility study of explosive testing of earth dams in general, and not necessarily a recommendation that such tests be performed at any particular location. We chose testing in India in our cost analysis because of the mutual interest expressed at the Indo-U.S. workshop, and because Prof. Agrawal's participation gave a unique and timely opportunity to use his intimate familiarity with the geology and construction costs at possible sites in India. Decisions on funding for dam testing and selection of favorable test site locations must, of course, be made in consultation with a broader community within the dam and earthquake engineering profession.

Planning decisions must also take into account that, while performing dam tests as described herein, a large area would be available for testing other structures on the opposite side of the explosive arrays. These might include building or bridge foundations, nuclear reactor building models, liquid storage tanks, pipelines, tunnels, or other structures whose response is strongly influenced by soil-structure interaction or soil liquefaction.

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INTRODUCTION

The objective of this study was to explore the feasibility, scope, and cost of dynamic testing of earth and rock-filled dams using explosives to generate the required earthquake-like ground motions. The Indo-U.S. Workshop on Natural Disaster Hazards Mitigation Research, held in New Delhi in December 1978, suggested constructing and testing earth dams in India to achieve cost savings to both countries. A detailed work plan was to be prepared containing the scope of the dynamic tests, the design of test dams and explosive arrays, instrumentation and data analysis, as well as the cost of implementing the plan.

Most of the favorable sites for construction of earth dams are being exhausted. Therefore, new dams may have to be constructed at sites that, in addition to being seismically active, may also be unsatisfactory in terms of foundation and abutment rock conditions, geometry of the valley (leading to taller and larger dams), and distance from borrow sites for the required fill material. Our knowledge of dam response must therefore grow to meet these more challenging dam design requirements.

The performance of existing earth dams during moderate and major earthquakes suggests that existing dams are constructed with great conservatism and hence with unnecessarily flat slopes and high construction costs. Such a conservative approach to the design of larger dams at more difficult sites will make their construction costs prohibitive. It is, therefore, evident that the need for rational and economical design of earth dams is greater now than even before.

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CONCLUSIONS AND RECOMMENDATIONS

From the study here, we conclude that response of dams to high level, sustained earth shaking representative of actual earthquakes can be investigated with explosive array techniques. The dams would have to be of small to moderate size (less than about 10 m in height and about 25 m in plan dimensions) and are recommended to be constructed in a special field test site with moderately strong native soil (not rock). Earth shaking would be provided by contained-explosion arrays that can produce the high level, sustained motion in repeated tests without replacement.

We also explored the use of arrays to test existing dams or specially constructed test dams at actual future dam sites. For these in-situ dams, we conclude that application of strong motion from explosive arrays is not practical because of the risk of damage to the dam or its surroundings. These dams can be tested for low-level linear response, but for testing at high levels with earthquake-like motion, and hence to investigate damage mechanisms and more efficient dam design, test dams should be constructed at a site where damage can be tolerated and contained.

With dams constructed at a dedicated test site, site parameters are open to specification by the investigator. We recommend that the selected site be in soil, rather than in rock as in many dams. To produce strong motion in rock would require use of a direct-explosion technique, and even with this technique production of damaging-level motion in rock may not be practical. In this technique, tens to hundreds of <u>tons</u> of explosive are detonated in buried, sequentially detonated arrays, with the explosive contained only by the burial medium. This produces motion over a large area, and attenuation with distance is used to adjust amplitude. In soil, strong motion can be produced with either the direct or contained-explosion technique. In the contained-explosion technique, hundreds to thousands of <u>pounds</u> of explosive are exploded in buried, sequentially fired arrays, but with the explosion gases contained within steel canisters.

These gases are released against the soil at a controlled rate to produce the desired amplitude of motion over a limited region near the array. The same arrays can be used repeatedly with no need for major earth moving to fill in the craters created by directly emplaced explosions. After comprehensive testing with contained-explosions, it may be desirable to perform some tests with direct explosions for comparison.

A soil site gives the further advantage that it can be easily excavated to reproduce any desired topography for dam construction. Dams would then be made of real construction materials with the actual three-dimensional features of typical slopes and abutments. Then, with high-level sustained shaking from the contained-explosion array, complex three-dimensional and nonlinear behavior of the dam could be observed, including porewater pressure buildup with successive cycles of ground motion, yielding and flow of the rock- and soil-fill dam materials, and ultimately failure in various designs to test the degree of conservatism in conventional designs.

We recommend that, initially, twenty tests be performed on dams of three sizes: nine on 2-m dams, six on 4-m dams, and five on 6-m dams. The dams would be designed as full-scale prototypes of small dams, to test current design procedures and to explore more efficient designs. Dam features could be made geometrically similar to large dams, such as the proposed Tehri dam in India, to give some information on the effect of specific geometry on response and failure modes.

The explosive array should be designed to simulate ground motions from both a moderate earthquake (6.5 Richter magnitude, 25 km from the epicenter) and a major earthquake (8.0 Richter magnitude, 40 km from the epicenter), each at a focal depth of 25 km. Ground motion characteristics for these earthquakes should be taken from records of previous earthquakes. Duration of the simulated motion should be representative of actual earthquakes so that resonance, porewater pressure buildup, and nonlinear response can be properly investigated.

The estimated cost of designing, constructing, performing, and analyzing these twenty tests over a 5-year period is about $12.5 million (about $3 million in the United States and $9.5 million in India). Much of the cost and research would be associated with developing and building an array test facility of the size needed for dam testing. During this development, use of the arrays can and should be made for testing other soil-structure interaction systems, as found in building and bridge foundations, nuclear reactor building models, liquid storage tanks, and other structures whose response is strongly influenced by soil-structure interaction and soil liquefaction. Site selection should therefore be determined as much or more by these test requirements as by the requirements for dam testing. A crucial consideration for site selection is therefore that a broad earthquake engineering community have convenient access to the test site for fielding their experiments. The cost of the array facility development is much more reasonably justified by these multiple uses; dam testing is simply an example (although one of the most challenging) of how such a facility can be used. The array facility will become a permanent earthquake soil-structure testing center unique in the world.

Finally, we must emphasize that it is a large extrapolation from existing contained-explosion experience (0.3 m-diameter sources in a single array operating at 3 to 10 Hz frequencies for about one second) to the arrays needed for dam testing (0.6 m-diameter sources in four parallel arrays operating at 1.5 to 5 Hz frequencies for about 15 seconds). Array technology development is a prerequisite for and a large part of the program described here. The large extrapolation also implies a large risk. This risk is greatly reduced when the purpose of the facility is general soil-structure interaction testing rather than simply dam testing. Then the extrapolation can be made in smaller steps in cost and technology with useful structure response information obtained at each step. The range of shaking levels of interest (amplitudes, frequencies, and durations) is much wider for these wider applications. More modest permanent facilities for these applications in two 10 by 10 m test areas range in cost from a few hundred thousand to about one million dollars, depending on the desired amplitudes and durations of motion.

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DAM TESTING TECHNIQUES

Need for Dam Testing

Studies on the performance of earth dams in past earthquakes (Ambrasseys, 1960; Seed et al., 1978) report very few failures, suggesting that the design of most existing earth dams is quite conservative, with associated higher costs. However, the phenomena suspected of causing possible dam failures in earthquakes are not well understood. Conservatism in present dams is provided mainly by using flat slopes, which may not be economical and may be impractical under the limitation of some of site conditions. More data from dynamic tests are needed to provide a sound basis for more economical but still safe designs.

Studies of the few dams that have failed in past earthquakes suggest that failure was caused by phenomena occurring within the dam and reservoir system during earthquakes, and not by defective design or stability in the conventional sense. Dams constructed of saturated cohesionless soils suffer greater damage than those constructed of unsaturated cohesive soils (Seed et al., 1978). Buildup of porewater pressure in the embankment and possible loss of strength and reduction in the yield acceleration due to porewater pressure may be the cause of this behavior. The development of porewater pressure in embankments, even under static conditions, is not well understood, and it becomes even more complicated under dynamic (earthquake) excitation.

The problem cannot be solved analytically, and the need for dam testing and collection of data on the response of prototypes under dynamic conditions is well recognized. Several techniques for testing dams are available, but all have limitations, as discussed below.

Review of 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 and the technique includes the other limitations of shake table testing.

Clearly, a new technique is needed to enable field testing of dams. 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 for such field testing. A straightforward way of doing this is to detonate explosives in drill holes and underground cavities constructed <u>directly</u> in the earth materials. Another way of doing this, specially conceived for field tests on structures, is to <u>contain</u> the explosions so that cratering is avoided and the desired ground motion characteristics are simulated over a smaller controlled area. Some of the contrasting developments 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 excitations, but further development work is needed to extend the method to larger sizes.
Use of planar arrays (series of line sources in a plane) to produce a plane wave front has been recommended. The amount of explosive in each source and its length are used to control amplitudes.	Use of planar arrays (a series of line sources in a plane) has been demonstrated. The charge sizes and the number and length of the sources control amplitudes.

Direct Explosions	Contained Explosions
Huge qualities of explosive must be used because of the large separation between shot point and test structure needed to provide attenuation to earthquake motion levels. Leads to more uniform motion in a larger 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 over a smaller area with no debris or disturbance to the surroundings.
Depends on natural attenuation through earth materials (1) to keep 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 4 detonations).	The contained source itself keeps the energy level within the elastic range of 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 even after restoration may be difficult.	No restoration of the site is required after each test. Any desired number of repeat tests can be performed with the same explosive containers with excellent reproducibility of ground motion.

The comparison clearly 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 site is necessary, and repeated use of the site will allow more tests at lower costs than for the direct-explosive technique.

The contained-explosion technique in its present form, as described in the following section, can be deployed for excitation of earth dams to the desired response levels if the dams are located in soil (not rock). Although this precludes testing of soil-rock interaction, a site entirely in soil accentuates porewater pressure development, which is a crucial problem in dam dynamic response, and also allows the topography to be easily adjusted by straightforward excavation and earth movement.

Features of 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, Lindberg, and Schwer, 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 high-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 array 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 firing within each line source and between groups of line sources.

Status of Contained-Explosion Technique

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 to form a planar array. The unique features of these planar arrays are that they can be used repeatedly, need only small charge sizes, and produce controlled amplitude and frequency vibration. Only the limited area under test is vibrated and affected.

A 9-m-long array of ten of the smaller sources produces ground motion with peak values of 2 g acceleration, 8 Hz frequency, and 1 cm displacement with a total explosive charge of 2.8 kg (6.2 pounds). An assembly drawing of the developmental line source is given in Figure 1.

Work on testing of a 30-m-long array of 30-cm-diameter, 11.1-m-long sources is 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, 38 cm/s velocity, and 3 cm displacement. Structures with plan dimensions of about 10 by 10 m could be tested with this facility.

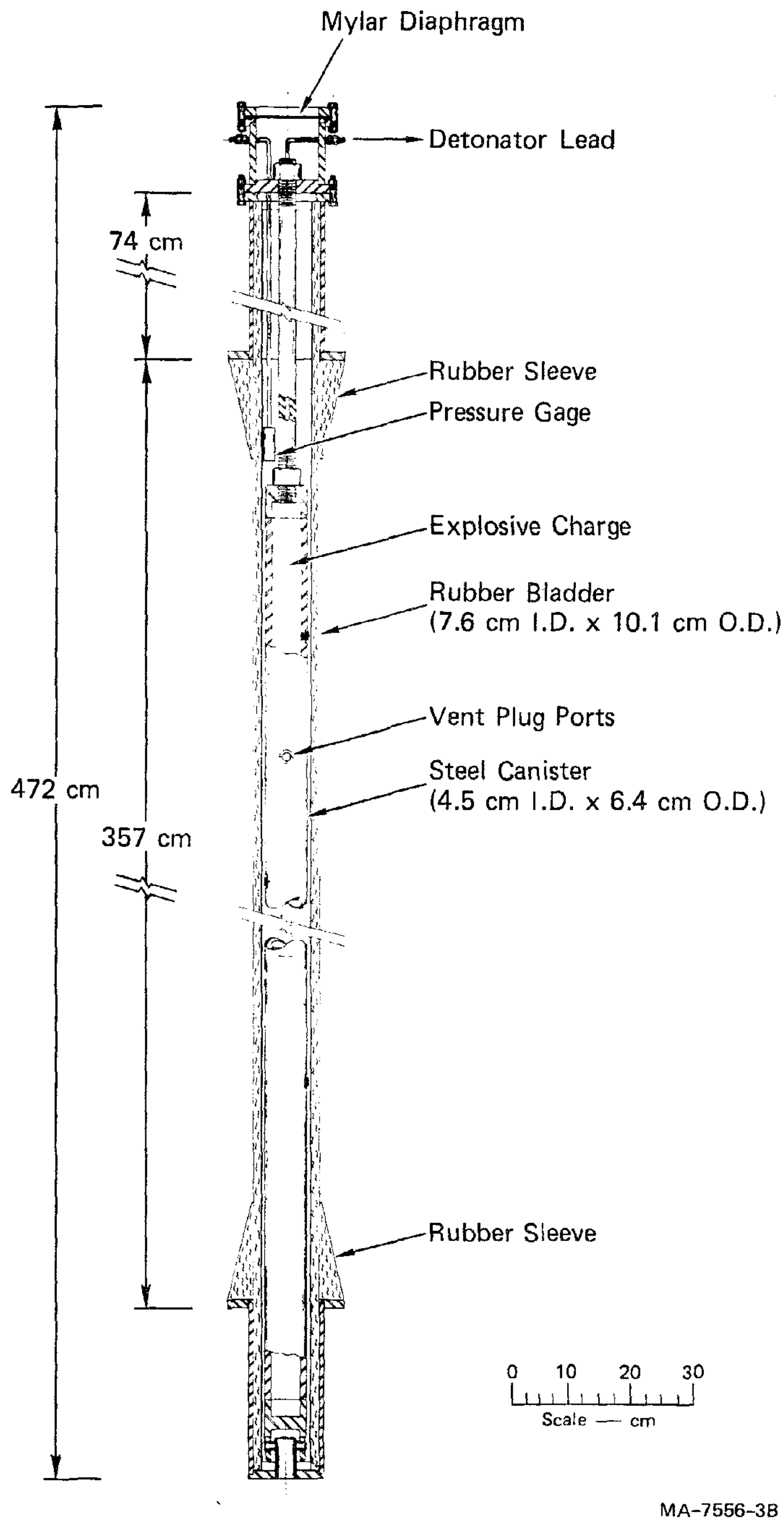

FIGURE 1 ASSEMBLY DRAWING OF DEVELOPMENTAL LINE SOURCE

An 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 (Bruce, Lindberg, and Schwer, 1981) by straightforward elastic-plastic theory. The designs so obtained are within conventional construction capabilities, even for arrays three to four times larger than those tested so far.

The contained-explosion technique in its present form is not applicable to destructive testing of structures on hard rock (attainable displacements are inversely proportional to the soil modulus of elasticity). This imposes a severe restriction on its adoption for testing of dams sited in various geologic conditions. Testing in rock sites may be possible with the direct-explosion technique, but environment damage costs would be very high as already mentioned.

Comparison with Shake Table Tests

In the absence of suitable field techniques for dynamic excitation, limited tests have been conducted on shake tables (Clough and Pritz, 1956; Seed and 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.	Prototype dams 2 to 6 m tall can be used to avoid scaling altogether for small dams and limit scale ratios for larger 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 with a reasonable size model.	Shaking of dam along with the abutments and surrounding topography can be achieved.

Shake Table Tests	Contained-Explosion Tests
Low strain levels because of large model weights; 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 and Clough, 1963).	Testing three distinctly different size prototype dams with different overburden pressures would enable study of this problem.
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 porewater pressures and saturation conditions.	The study of development of porewater pressures 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.

Recommended Technique

The contained-explosion technique seems to be the most suitable technique available for testing dams founded on soils. Attention should be focused on response from many successive cycles of ground motion generated by contained explosions in a suitably designed array. Figure 2 shows a typical test dam, its abutments, and the planes in which the sources would be placed in four planar arrays. In a second phase of work, the direct and contained-explosion techniques could be combined to overcome limitations of each technique and extend the dynamic testing capability.

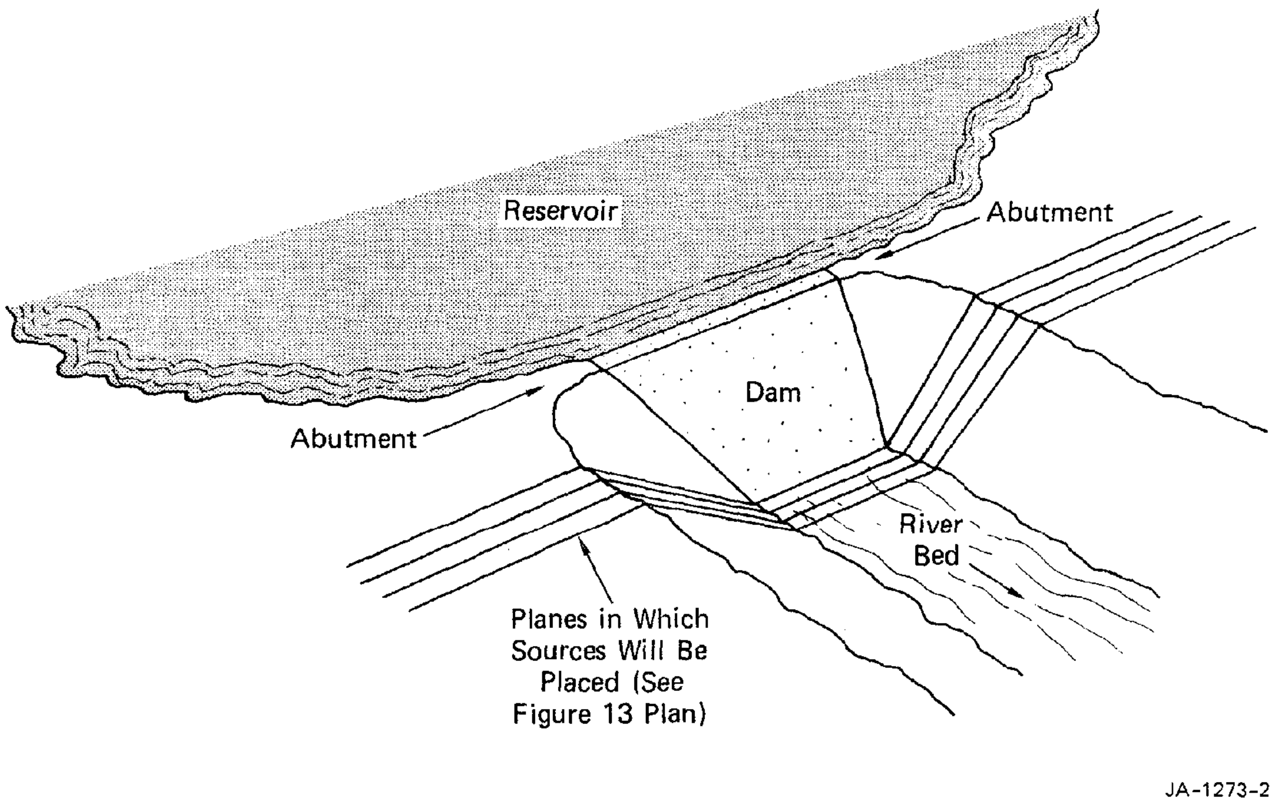

FIGURE 2 SKETCH OF A TEST DAM, ITS ABUTMENTS, AND EXPLOSIVE ARRAY PLANES

SCOPE OF EARTH DAM TESTING

To determine the appropriate scope of earth dam testing, we needed to consider the following questions:

- What characteristics of the response of earth dams during earthquakes should be investigated?
- What characteristics of earthquake ground motion should be simulated for dam testing?
- Under what seismic conditions are earth dams likely to fail?
- How successfully can the contained-explosion arrays simulate the selected accelerograms?

This section discusses these questions and gives recommendations on the scope of initial testing required to provide the data needed for a better understanding of earth dam response. The details of the test plan developed from these considerations are given in the following section.

Dam Response Characteristics

The plan for testing earth dams should be designed to allow study of those physical phenomena that are not well understood and are not fully accounted for in the current designs of earth dams. Such phenomena include:

- Development of porewater pressure under both static and dynamic conditions.
- Interaction of a dam with its foundation and abutments.
- Influence of the surrounding topography on the dynamic response of a dam.
- The permissible level of inelastic deformations.
- The gravitational and constitutive effects of dam construction materials.
- Effect of dam size on response.

A better understanding of these phenomena should allow us to design safe dams with less conservatism and at lower cost.

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 porewater 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.

It is, therefore, crucial that tests of earth dams be conducted on a suitably selected alluvial or sandy soil where adverse conditions of porewater pressure development can be conveniently reproduced.

Interaction of Dam with Foundation and Abutments. Dam response is likely to be very different 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 important in the relative importance of shaking through abutments and foundation.

Influence of Surrounding Topography. The dimensions of earth dams tend to be comparable to the elevations of surrounding topography and the wavelengths of ground motion. Thus, the dynamic response of earth dams and the host topography 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 in soil), such an intercoupling of response may be more pronounced.

Permissible Level of Inelastic Deformation. After an earth dam has undergone inelastic deformations, e.g., slip or displacement has occurred on a failure surface within some limited range, the slip surface can still carry substantial loading during subsequent shaking. This forgiving 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 scaled models for dynamic testing is an impossible task, at least with the present state of knowledge. 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 suggested test plan, it may be possible to adjust construction materials to allow limited scaling of larger prototypes.

Effect of Dam Size. To determine the effect of dam size on response as a result of changed overburden pressures, and to evaluate any other effects of scaling, we recommend that three sizes of test dams be used. Tests of 2, 4, and 6-m dams would allow the test dams to be treated both as small prototype dams and as geometrically similar models of large dams such as the Tehri Dam in India.

Seismic Considerations

The scope of earth dam testing also depends on seismic considerations that have direct bearing on earth dam response. Such considerations are:

- Earthquake motion simulation criteria
- Selection of earthquakes for simulation
- Success of simulation.

The utility of dam testing will hinge greatly on careful consideration of these factors.

Earthquake Motion Simulation Criteria. The overall dynamic response of an earth dam cannot be well represented by elastic analysis using response spectrum techniques 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.

Selection of Earthquakes for Simulation. The prototype earthquake selected for simulation must generate the ground motion characteristics whose simulation is important for inelastic dam response. In addition, some combinations of selected earthquakes and dam design must lead to the failure of the test dam.

The choice of a prototype earthquake is determined primarily by the dynamic character of the earth dam which, in turn, is dictated mainly by its size, the 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; Trifunac and Brady, 1975), as shown in Table 1.

Table 1

EARTHQUAKES PARAMETERS FOR SIMULATION

	Moderate Earthquake	Major Earthquake
Magnitude (Richter)	6.5	8.0
Epicentral distance (km)	25	40
Focal depth (km)	25	25
Acceleration (g)	0.3-0.4	0.8-1.0
Displacement (cm)	10	25
Duration (s)	15	25*
Dominant frequency (Hz)	2	2

*Simulations would be limited to 15 seconds unless more than four contained-explosion line source arrays were used.

Suggested Accelerograms and Their Simulation Procedure. Numerous actual accelerograms are available that could be modified to match the chosen ground motion characteristics. The accelerogram obtained at San Fernando, California (Castaic N69W), on February 7, 1971, is suggested for simulation of a moderate earthquake because the data are readily available, the accelerogram would match the chosen ground motion characteristics without modification, and the earthquake was associated with an earth dam failure. This accelerogram is given in Figure 3.

For interpretation in terms of dams scheduled for construction in India, it is suggested that the accelerogram recorded for the Koyna earthquake of December 11, 1967 (component along dam axis) be modified to match the specifications for simulation of a major earthquake. This accelerogram is given in Figure 4.

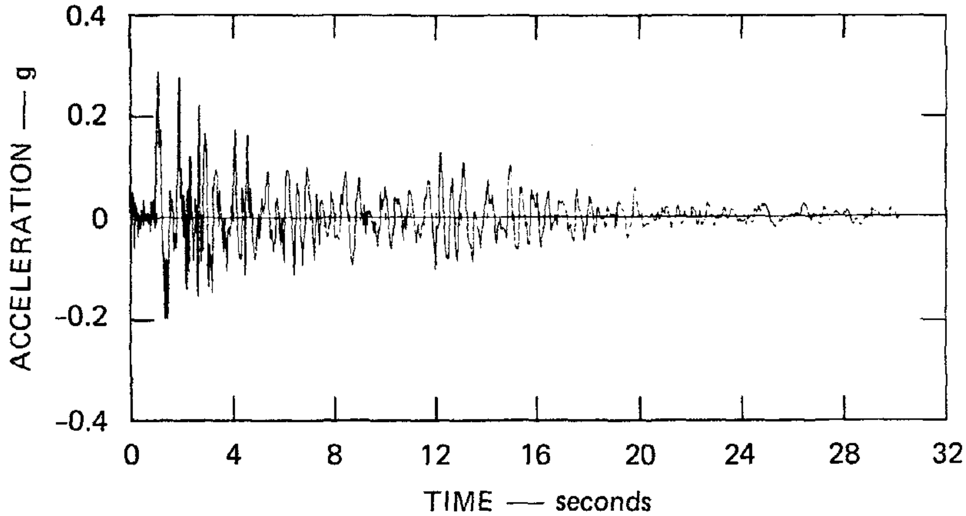

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FIGURE 3 ACCELEROGRAM FOR SAN FERNANDO, CALIFORNIA, EARTHQUAKE (February 9, 1971, Castaic N69W)

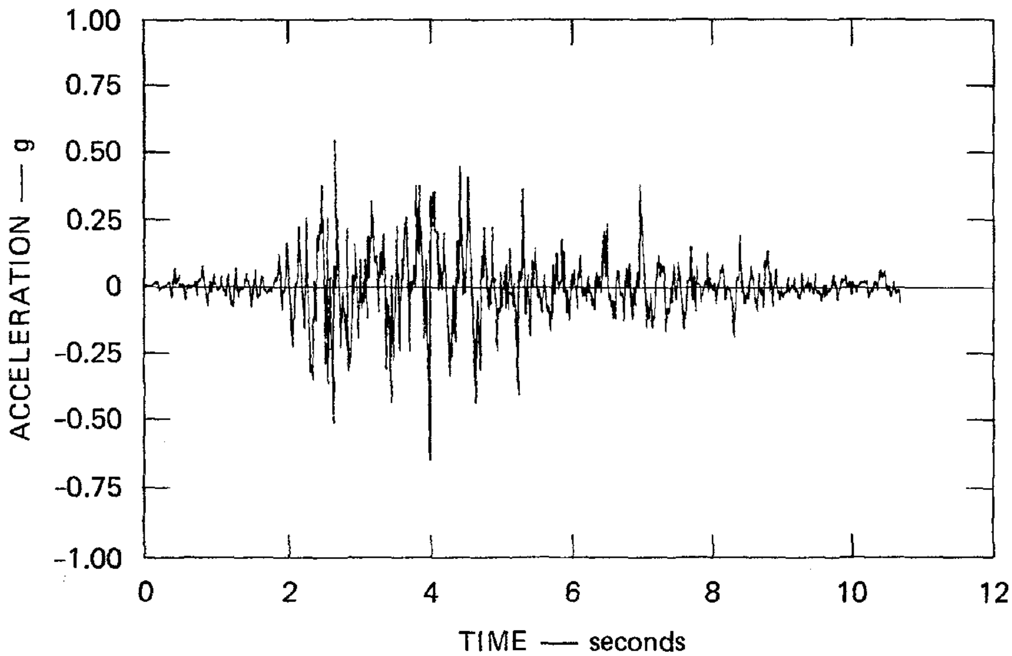

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FIGURE 4 ACCELEROGRAM FOR KOYNA, INDIA, EARTHQUAKE (December 10, 1967, Component along Dam Axis)

To simulate these selected accelerograms, twelve pulses with different amplitudes, periods, and times of occurrence were selected on the basis of their importance in the respective accelerograms. These pulses are shown in Figures 5 and 6 for the two earthquakes. The pulses for the San Fernando (Castaic) accelerograms do not require any modification and represent well a 6.5 magnitude earthquake at 25 km distance. The amplitude and time scales of the pulses for the Koyna accelerogram need multiplication by factors of 1.5 and 3.0, respectively, to provide a match with parameters of an 8.0 magnitude earthquake at 40 km as listed in Table 1. The data on the pulses thus obtained for the San Fernando (Castaic) and Koyna earthquakes are given in Tables 2 and 3. The pulse accelerations in Tables 2 and 3 are not exactly those corresponding to Figures 5 and 6 because they have been selected to obtain a best simulation with actual array pulse shapes as described in the next paragraph.

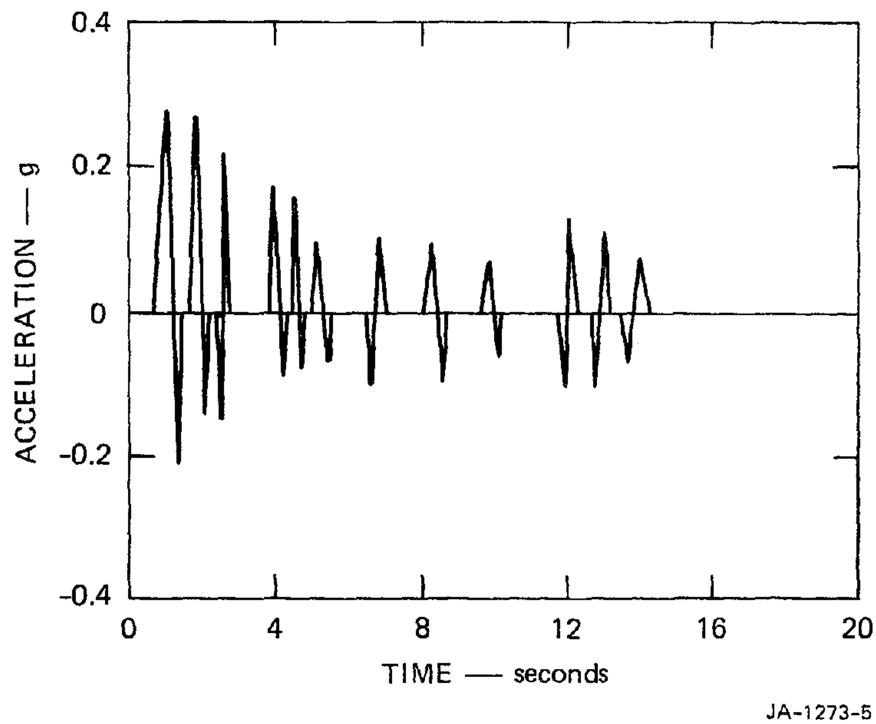

FIGURE 5 MAIN PULSES OF ACCELEROGRAM FOR SAN FERNANDO, CALIFORNIA, EARTHQUAKE (February 9, 1971, Castaic N69W)

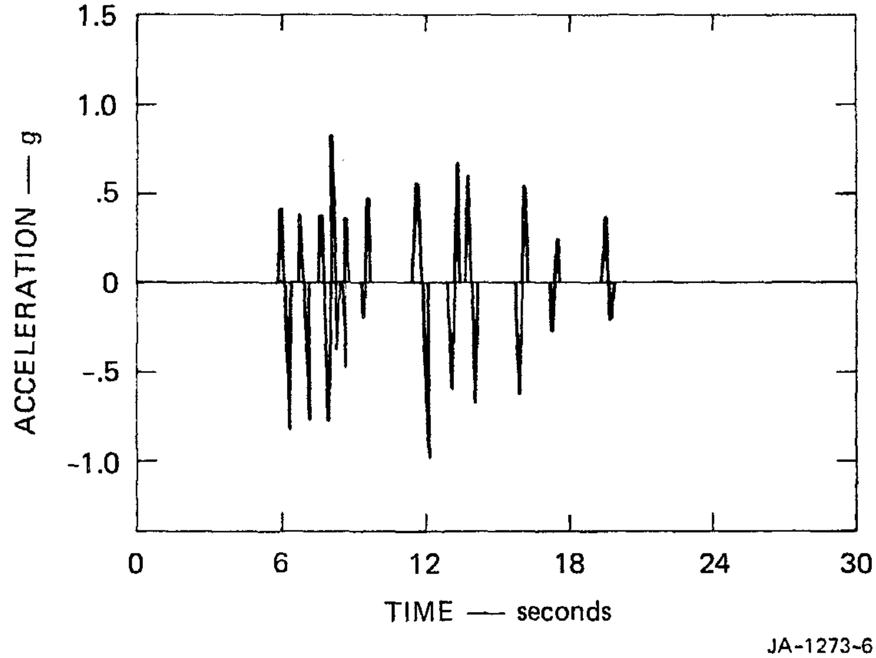

FIGURE 6 MAIN PULSES OF MODIFIED (Acceleration x 1.5, Time x 3) ACCELEROGRAM FOR KOYNA, INDIA, EARTHQUAKE (Component along Dam Axis)

Success of Simulation. Computations were made for the San Fernando (Castaic) accelerogram to check the feasibility of using twelve selected pulses with varying amplitudes, frequencies, and delays to simulate ground motions by pulses produced by the contained-explosion arrays. In the absence of data from arrays large enough to produce the desired pulses, recorded data from 10-cm-diameter sources in a 4.5-cm-long array were scaled in amplitude and frequency to represent response from the proposed arrays. This was done with the theory of Bruce, Lindberg, and Schwer (1981), which agrees well with the experimental data.

By replacing the pulses shown in Figure 5 with scaled pulses having a waveform matching that measured in the 30-foot explosive array, we generated the test earthquake accelerogram shown in Figure 7. The general trends in ground velocity and displacement computed for the actual and test earthquake accelerograms (Figures 8 through 11) compare well.

Table 2

CHARACTERISTICS OF PULSES SIMULATING THE SAN FERNANDO, CALIFORNIA, EARTHQUAKE (February 9, 1971, Castaic N69W) AND CALCULATED CHARGE WEIGHT REQUIRED*

Pulse No.	Time (s)	Accln. (g)	Period (s)	Velocity (cm/s)	Disp. (cm)	Charge Wt./Pulse (kg)
1	0	0.32	0.7	27.44	5.53	624
2	1.00	0.28	0.7	24.01	4.84	564
3	1.80	0.24	0.7	20.58	4.15	504
4	3.34	0.22	0.5	13.48	1.94	312
5	3.92	0.18	0.5	11.03	1.59	276
6	4.59	0.14	0.5	8.58	1.23	240
7	6.00	0.22	0.6	16.17	2.79	384
8	7.67	0.18	0.6	13.23	2.29	336
9	9.34	0.14	0.6	10.29	1.78	288
10	11.60	0.22	0.6	16.17	2.79	384
11	12.64	0.18	0.6	13.23	2.29	336
12	13.42	0.14	0.6	10.29	1.78	288
Total Explosive Required						4536

*Values in this table are calculated by extrapolating existing data over a factor of about 6 in source and array sizes. Motion estimates can therefore easily be in error by a factor of two, and explosive estimates could be in error by a factor of three or more. Shortfall can probably be overcome by development of improved array techniques, which must precede the dam testing program described here.

Table 3

CHARACTERISTICS OF PULSES SIMULATING THE MODIFIED KOYNA, INDIA, EARTHQUAKE (December 10, 1967, Component Along Dam Axis) AND CALCULATED CHARGE WEIGHT REQUIRED*

Pulse No.	Time (s)	Accln. (g)	Period (s)	Velocity (cm/s)	Disp. (cm)	Charge Wt./Pulse (kg)
1	0	0.83	0.5	50.84	7.32	762
2	0.82	0.77	0.5	47.16	6.79	732
3	1.64	0.75	0.5	45.94	6.62	720
4	2.09	0.85	0.5	52.06	7.50	798
5	2.55	0.50	0.5	30.63	4.41	510
6	3.33	0.47	0.5	28.79	4.15	498
7	5.45	1.00	0.5	61.25	8.82	900
8	6.82	0.67	0.5	41.04	5.91	660
9	7.64	0.65	0.5	39.81	5.73	642
10	9.64	0.62	0.5	37.98	5.47	618
11	11.09	0.37	0.5	22.66	3.26	420
12	13.27	0.30	0.5	18.38	2.65	246
Total Explosive Required						7506

*See comment on Table 2.

Comparison of the response spectra for 5% damping for the two accelerograms is shown in Figure 12. The general forms of the two spectra are quite similar except that the response spectrum for the test earthquake is a bit lower. When the test earthquake spectrum is increased in amplitude by a factor of 2, as shown in Figure 12, it yields an exceptionally good match. The simulation for higher dampings, which would correspond to those for earth dams, is expected to be even closer. This simulation match was made with the first choice of pulses. A few trials could result in an improved match, if needed.

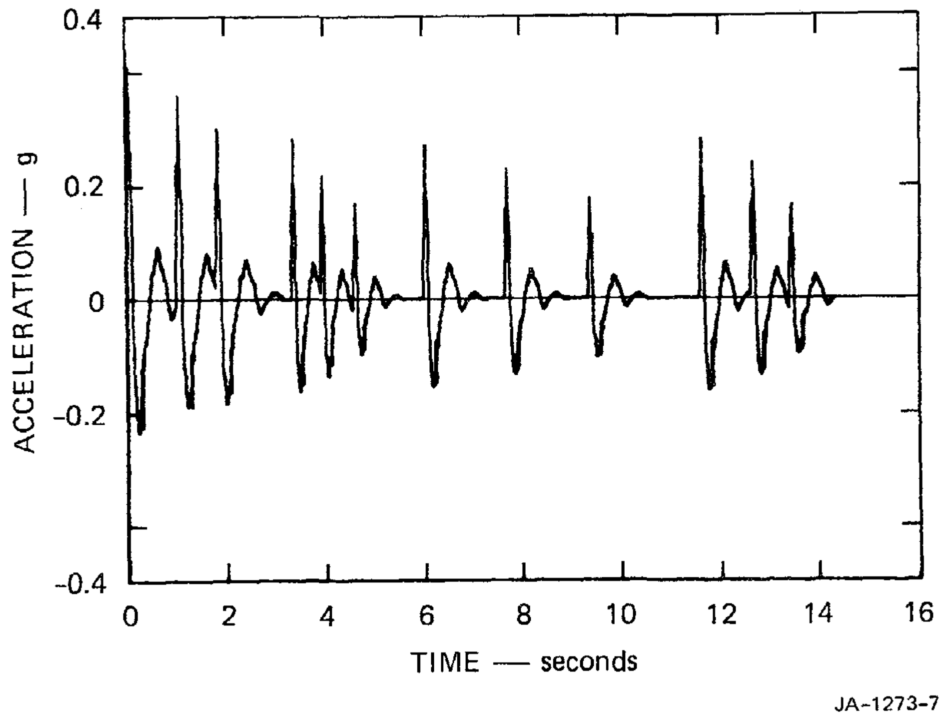

FIGURE 7 TIME HISTORY OF GROUND ACCELERATION, SIMULATING THE SAN FERNANDO, CALIFORNIA, EARTHQUAKE WITH 12 ARRAY PULSES

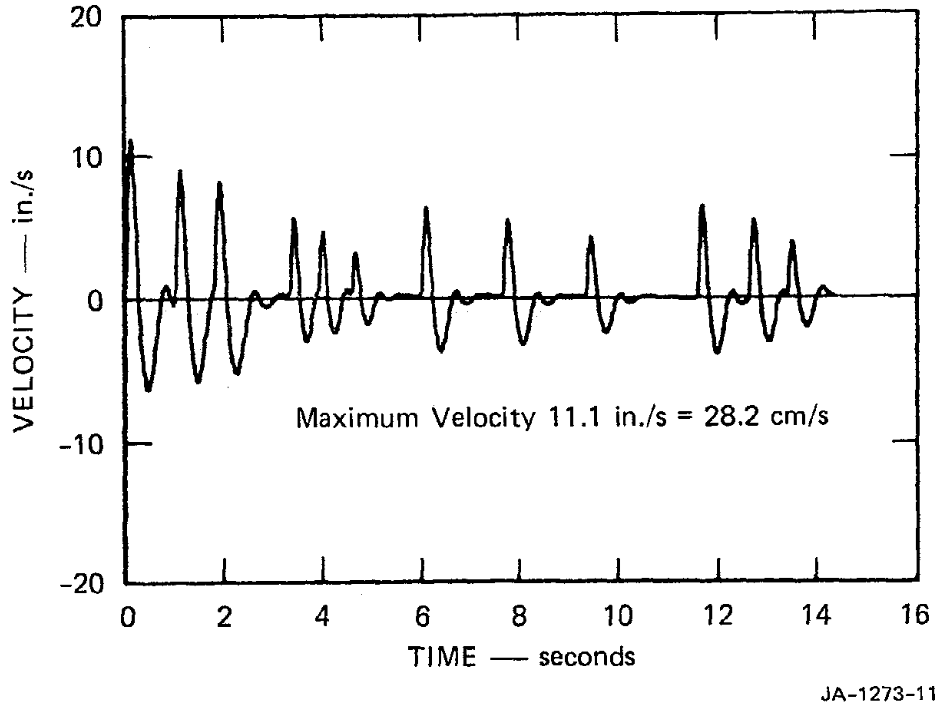

FIGURE 8 VELOCITY-TIME HISTORY FOR TEST EARTHQUAKE

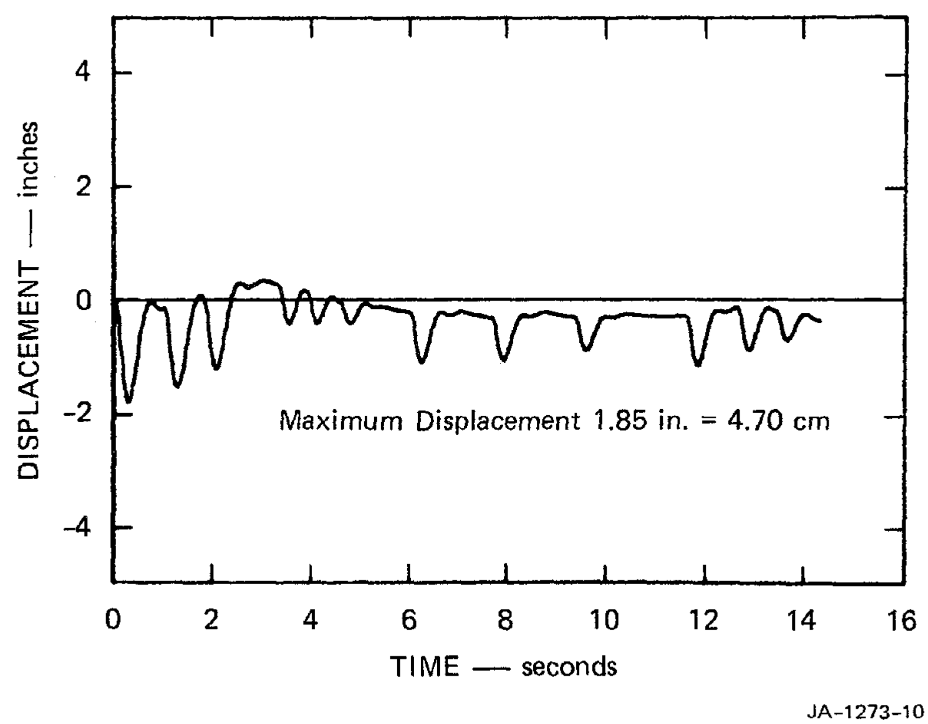

FIGURE 9 DISPLACEMENT-TIME HISTORY FOR TEST EARTHQUAKE

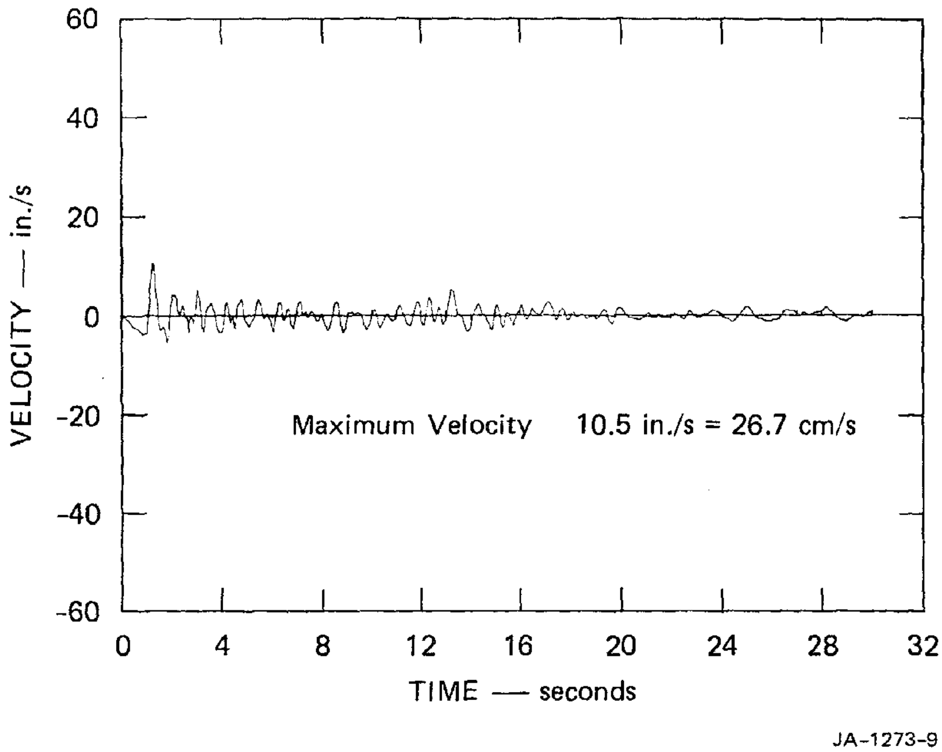

FIGURE 10 VELOCITY-TIME HISTORY, SAN FERNANDO, CALIFORNIA
(February 9, 1971, Castaic N69W)
Segmentally Adjusted Record. From Newmark, 1973.

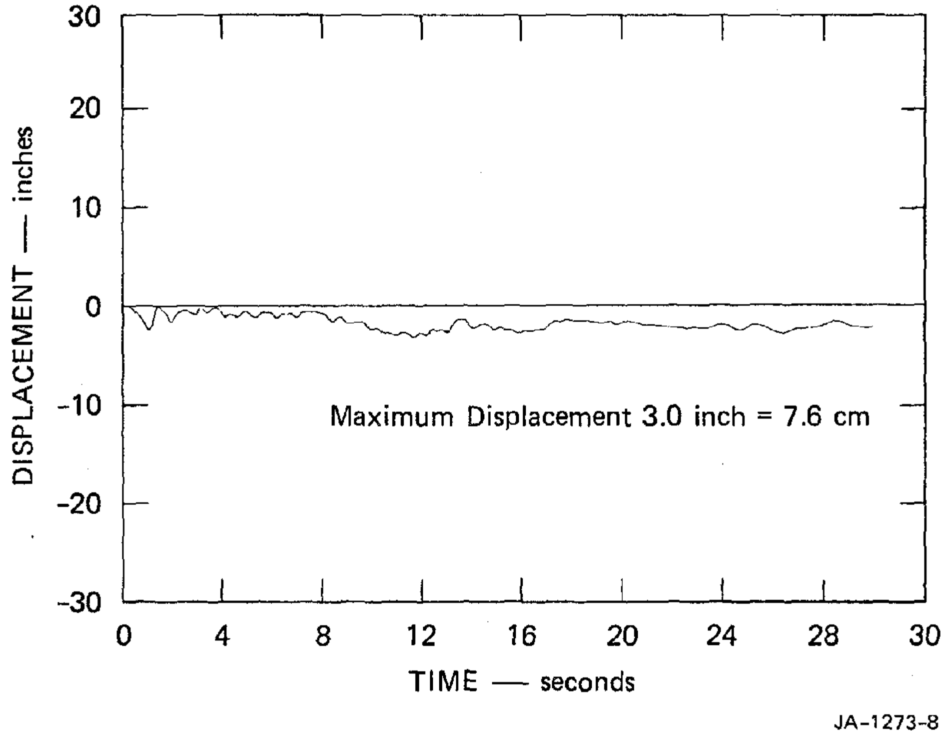

FIGURE 11 DISPLACEMENT-TIME HISTORY, SAN FERNANDO, CALIFORNIA
(February 9, 1971, Castaic N69W)
Segmentally Adjusted Record. From Newmark, 1973.

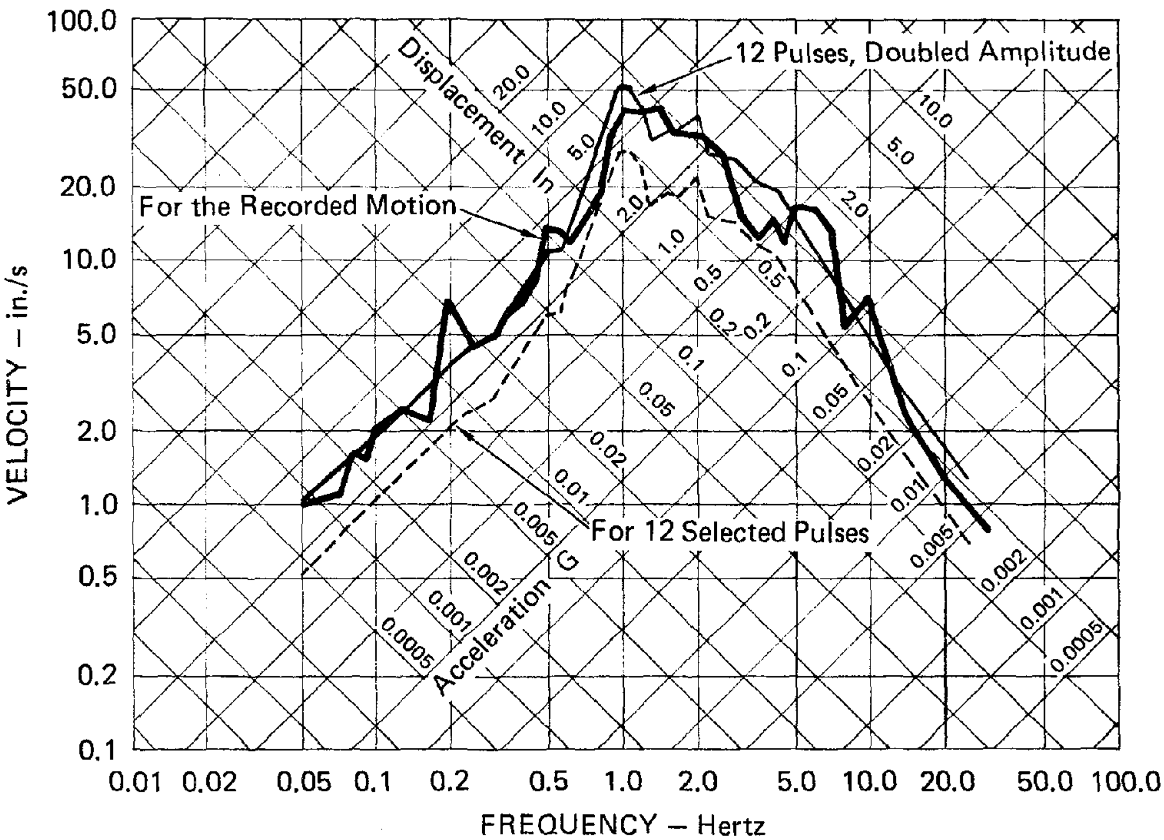

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FIGURE 12 RESPONSE SPECTRA FOR SAN FERNANDO EARTHQUAKE (FROM NEWMARK, 1973) AND TEST EARTHQUAKES

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RECOMMENDED TEST PLAN

It is recommended that the contained-explosion technique be used in a five-year program to study the performance of earth dams during earthquakes. Approximately twenty tests with three size dams are proposed: about nine tests on 2-m-dams, six tests on 4-m dams, and five tests on 6-m dams. Tests of the 2-m dams will include at least two repeat experiments at the same level to check the reproducibility of the results. Tests will begin with dams of gentle slopes, gradually moving to dams with steeper (less conservative) slopes. The number of dams to be constructed will be about half the number of tests, since on some dams repeat testing at increasing levels will be performed. Design, testing, and data interpretation will be done by treating the test dams both as prototype small dams and as geometrically similar models of large dams. In relation to the Tehri Dam in India, the test dams would represent scale ratios of 1/130, 1/65, and 1/43.

Contained-explosion line source arrays will be designed to produce the number of pulses and level of ground displacement required to achieve response levels up to failure. It is estimated that ground motion similar to earthquakes of 6.5 and 8.0 Richter magnitudes at 25 and 40 km, respectively, can be produced by four arrays, each consisting of twelve 0.6-m-diameter, 27-m-long sources. The sources are reusable indefinitely. Details of the array design are given later in this section.

For each test, the representative surrounding topography will be created, and the dam will be constructed following typical construction procedures. It is crucial that the tests be conducted on a suitable alluvial or sandy soil so that the adverse conditions of porewater pressure development can be reproduced and large displacements achieved. A site with uniform conditions, a shallow water table, and a 3 by 3 km area will be developed for the tests. The reservoir will be filled gradually so that buildup of porewater pressure can be monitored during filling.

Enough time will be allowed for development of a stable saturation condition before testing begins.

Arrangements for draining the reservoir water after dam failure have been considered, but the details cannot be included in this report because they will depend heavily on the test site conditions. A site with a shallow water table as is proposed to be used for the tests will not allow digging of deeper channels downstream for draining. However, if a natural dip in the ground water table in the appropriate direction is available, it would facilitate the arrangements. In fact, drainage and other ideas that emerge during the detailed planning will contribute to site selection in addition to the parameters discussed in this report. These arrangements become critical if simultaneous tests on other structures placed downstream of the dams are visualized.

The major items of work involved in this test plan are given in Table 4, which also gives a schedule for completing these tasks in a five-year program. Completion in five years would require a very high activity level in both India and in the U.S.(for the prerequisite technique development at smaller scale).

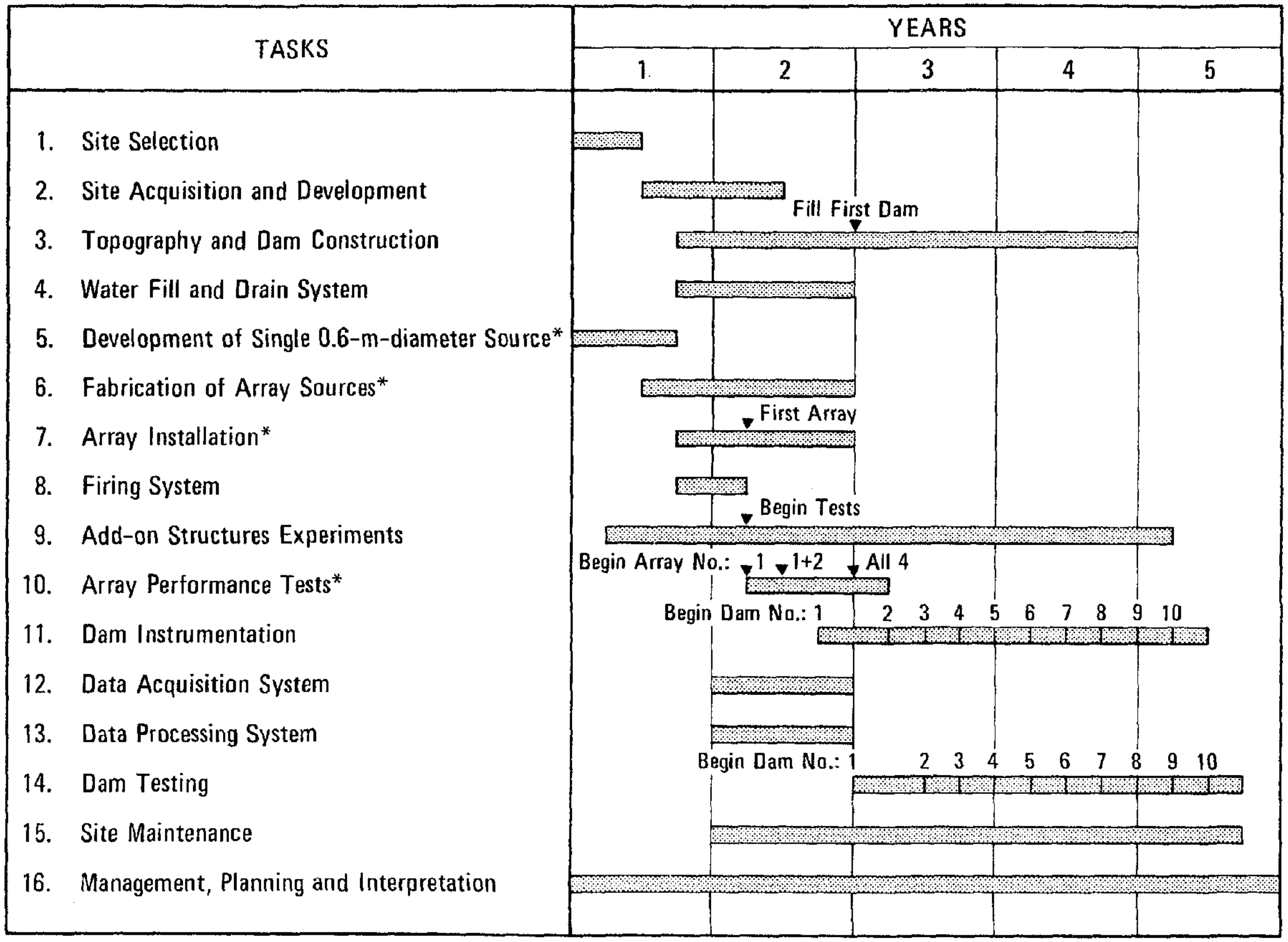
Array Design

The following design rules are based on the experience already gained by use of contained-explosion sources of 10- and 30-cm diameter at SRI International.

The array length should be about two to three times the general plan dimensions of the test structure. Therefore, for the largest plan dimensions of the proposed test structure, 14 by 28 m, an array of 60 m is considered suitable. A corresponding depth is about 27 m. The ratio of the source diameter to the intersource spacing should be about 1:9. Accordingly, twelve 60-cm-diameter sources spaced 5 m apart are proposed for use in these tests.

To achieve the desired duration of ground motion, 12 pulses with suitably selected delays are considered the bare minimum to simulate about 15 seconds of ground motion. Each source in a single array will

Table 4
SCHEDULE



*Schedules for the array tasks (5, 6, 7 and 10) assume that similar work has been completed on arrays half this size (0.3-m-diameter sources) before this program is begun. This smaller-scale development would take about two years to complete in the U.S. at a high activity level.

provide three successive pulses of gradually decreasing amplitude (three large pulses is the expected limit for a single source). Thus, four such arrays are expected to provide the desired simulation.

The source and array dimensions given here should provide the maximum displacement (10 cm) and frequency (1.5 to 5 Hz) requirements for an individual pulse to simulate the important characteristics of earthquake ground motion given in Table 1.

Table 5 compares the dimensions of the sources and arrays already tested (1/3-scale) and being tested (full-scale) at SRI with those proposed for dam testing. Development work will be required before construction of the proposed sources and their field use in arrays since these are substantially larger than the sources already developed.

Table 5

COMPARISON OF DIMENSIONS FOR ALREADY TESTED AND PROPOSED SOURCES AND ARRAYS

Dimensions	First Array (1/3-scale)	Second Array (Full-Scale)	Proposed Array (For Dam Tests)
Radius of source (cm)	5.0	15.0	30.0
Length of source (m)	4.5	11.1	27.0
Length of array (m)	9.0	24.0	60.0
Intersource distance (m)	0.9	2.4	5.0

Estimate of Array Explosive Weight

Table 6 gives ground motion data obtained with different explosive weights for 5-cm-radius sources in a 9 by 4.5 m array (Bruce, Lindberg, Abrahamson, 1980) as well as the scaled values for identical source pressures and source ground coupling conditions in 30-cm-radius sources forming a 60 by 27 m array. The explosive weight required increases in the ratio of volume, i.e., 216 times. The displacement increases sixfold, which is the ratio of increase in area of source-soil contact for unit length.

These data have been extrapolated to obtain the explosive weight required in the proposed array to generate various size pulses as selected for simulation of the two earthquakes. These charge weights were given earlier in Tables 2 and 3 for the San Fernando and Koyna earthquakes, respectively. Thus, the explosive required to generate the 12 pulses simulating the San Fernando and Koyna earthquakes is 4536 kg and 7506 kg, respectively. Table 7 summarizes the amount of explosive required for twenty tests involving thirteen simulations of the San Fernando earthquake at two levels and seven simulations of the Koyna earthquake. The total weight required for the twenty tests is about 100,000 kg.

Table 6

DEPENDENCE OF GROUND MOTION ON EXPLOSIVE WEIGHT FOR SMALL ARRAY AND SCALED VALUES FOR PROPOSED ARRAY

	Small Array			Proposed Array		
Explosive weight per source (kg)	0.11	0.17	0.28	25.00	36.30	61.00
Bladder pressure (kg/cm^2)	6.47	7.67	8.33	6.47	7.67	8.33
Soil stress (kg/cm^2)	0.20	0.37	0.77	0.20	0.37	0.77
Displacement (cm)	0.28	0.53	1.00	1.88	3.53	6.70
Velocity (cm/s)	9.50	16.25	29.50	9.50	16.25	29.50
Acceleration (g)	0.95	1.20	2.00	0.14	0.18	0.30
Period (s)	0.10	0.11	0.12	0.67	0.74	0.80

The plan of the largest dam proposed to be tested is shown in Figure 13 along with the plan position of the sources in the four arrays. The positions of the arrays and the dam axis will remain the same for tests at all dam sizes.

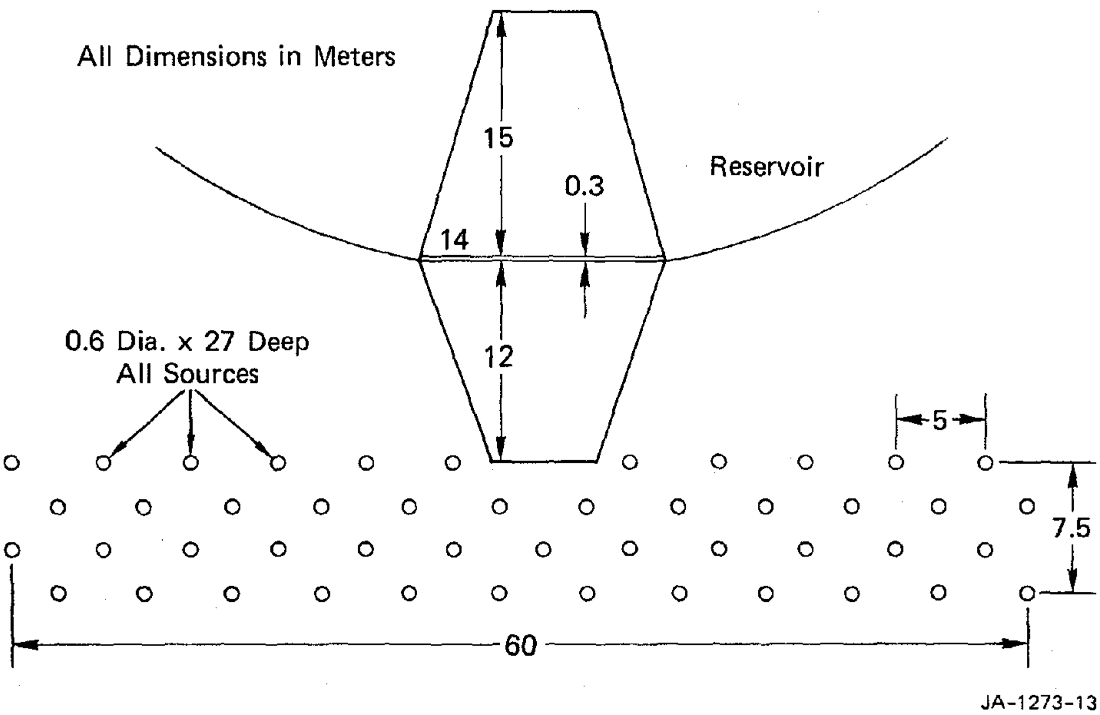


FIGURE 13 IDEALIZED PLAN OF 6-m-TALL TEST DAM SHOWING THE POSITIONS OF LINE SOURCES IN FOUR ARRAYS

Table 7

EXPLOSIVE ESTIMATES FOR TWENTY EARTH DAM TESTS

Test No.	Dam Height (m)	Dam Slope	Charge Weight* (kg) San Fernando-Type Simulation	Koyna-Type Simulation
1	2	Gentle	3,000	
2	2	Gentle	4,536	
3	2	Moderate	3,000	
4	2	Moderate	3,000	
5	2	Moderate	4,536	
6	2	Moderate		7,506
7	2	Steep	3,000	
8	2	Steep	4,536	
9	2	Steep		7,506
10	4	Gentle		7,506
11	4	Moderate	3,000	
12	4	Moderate	4,536	
13	4	Moderate		7,506
14	4	Steep	3,000	
15	4	Steep	4,536	
16	6	Gentle		7,506
17	6	Moderate	4,536	
18	6	Moderate		7,506
19	6	Steep	4,536	
20	6	Steep		7,506
		Totals	49,752	52,542

*Each entry is the total weight of charge for 12 array explosions.

The normalized displacement field for a shot in an individual array has been computed and is shown in Figure 14. The computed time history of ground motion at the midpoint of the dam for simulation of the San Fernando earthquake was shown earlier in Figure 7. The objective is to simulate ground displacement characteristics over a representative duration rather than the response spectra. However, response spectra are also well matched, as shown in Figure 12.

Choice of Earth Dam Sections

The Tehri Dam in India is considered an appropriate choice for specifying the geometry of the test dams. It is one of the largest earth- and rock-filled dams under design and construction in India and provides a good chance for the results of these tests to be used in its construction.

Figure 15 shows the sections of the Tehri dam proposed to be tested (simplified to some extent). The surrounding topography (Lavania, 1975) in the appropriate scale (shown in Figure 16) will be constructed at the test site before the dams are built. The topography will be simplified as shown in Figure 17 to allow more general application of the test data. In each series of tests, the final test dams will have steeper slopes (also shown in Figure 17) than provided for the Tehri dam.

An analysis to determine whether the proposed sections of the test dams would fail under the ground motion produced by the test earthquakes will precede the construction of the test dams, taking into account actual data on characteristics of the foundation and dam material. The proposed sections may then need revision.

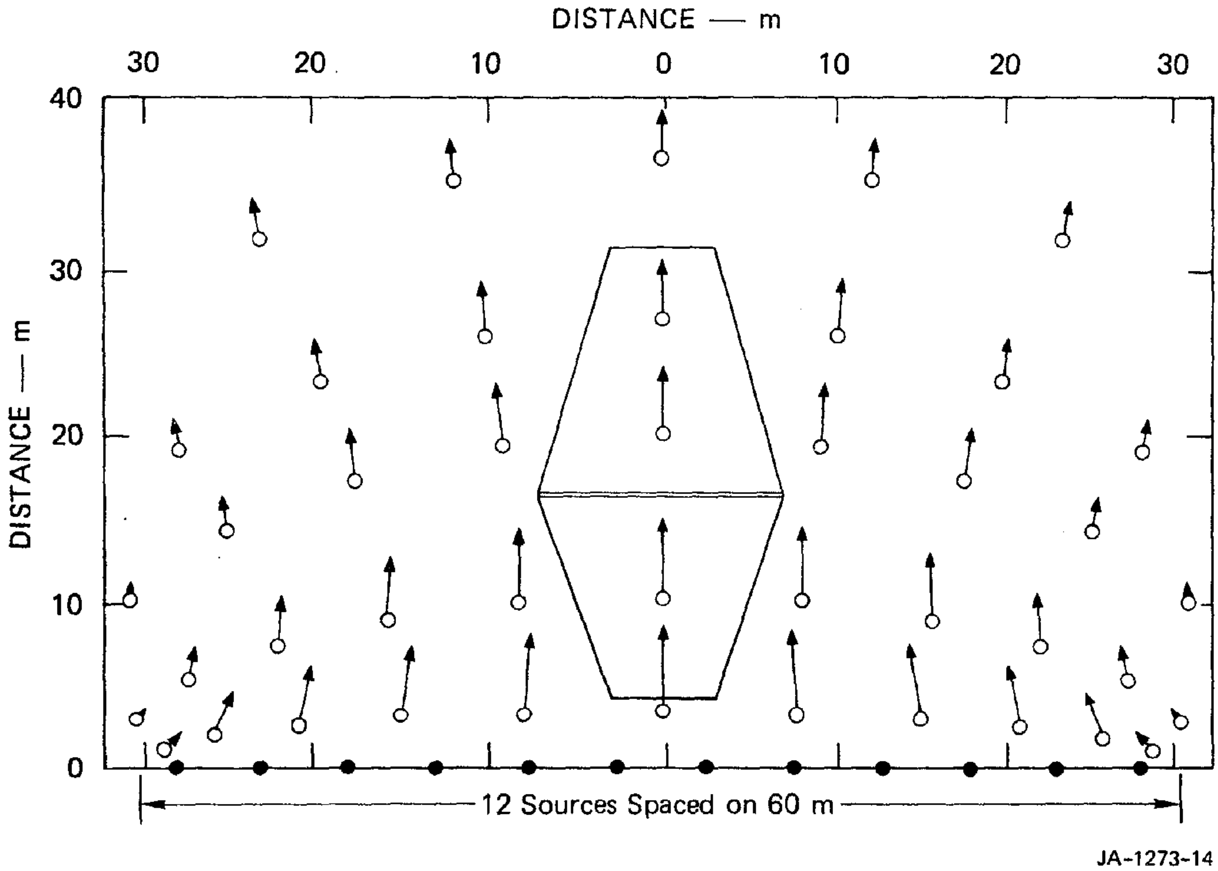


FIGURE 14 DISPLACEMENT FIELD AROUND ARRAY AND RELATIONSHIP TO TEST DAM

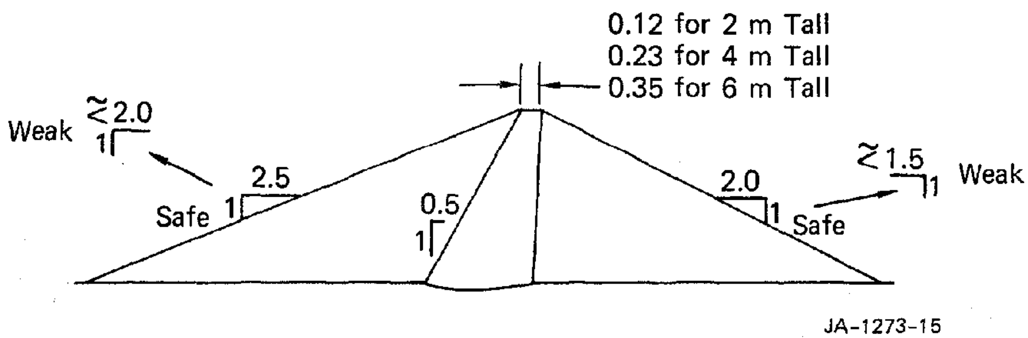


FIGURE 15 POSSIBLE TEST DAM SECTIONS

Contours (meters)	Values for Dam Height (m) 6	4	2
a	9.00	6.00	3.00
b	6.69	4.47	2.23
c	4.38	2.93	1.46
d	2.07	1.39	0.69
River Bed Level	0	0	0

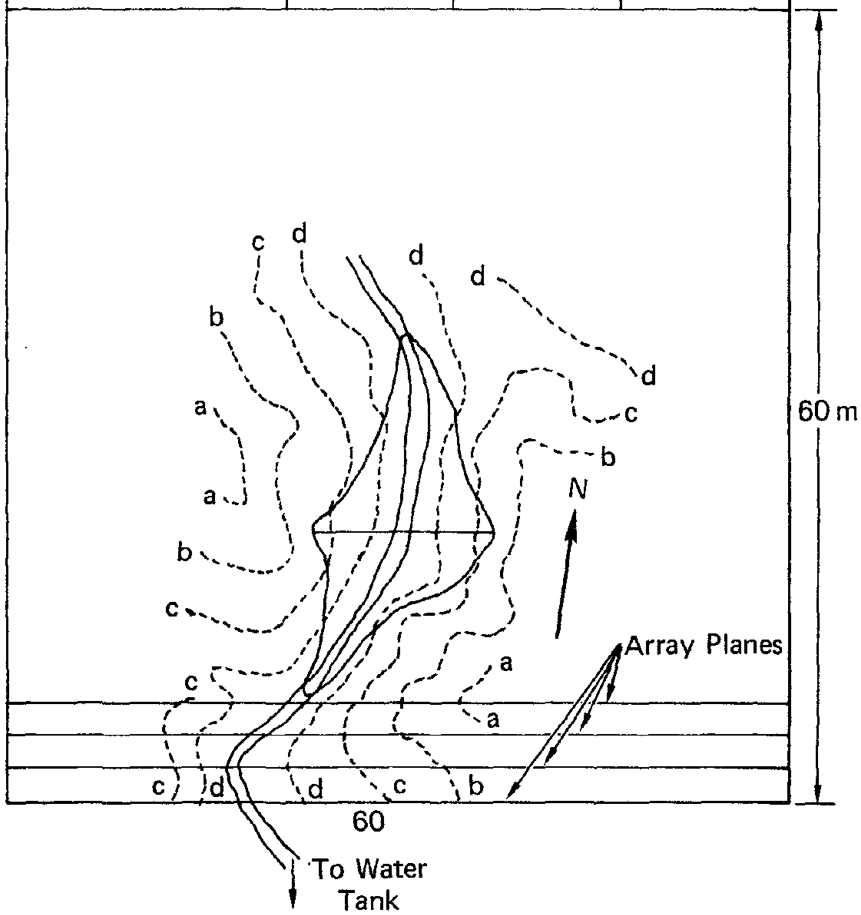


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FIGURE 16 CONTOURS SHOWING TOPOGRAPHY AROUND TEHRI DAM AT TEST DAM SCALES

Dam Height	6 m	4 m	2 m
Contour (meters)			
b	6.69	4.47	2.23
c	4.38	2.93	1.46
d	2.07	1.39	0.69
River Bed Level	0	0	0

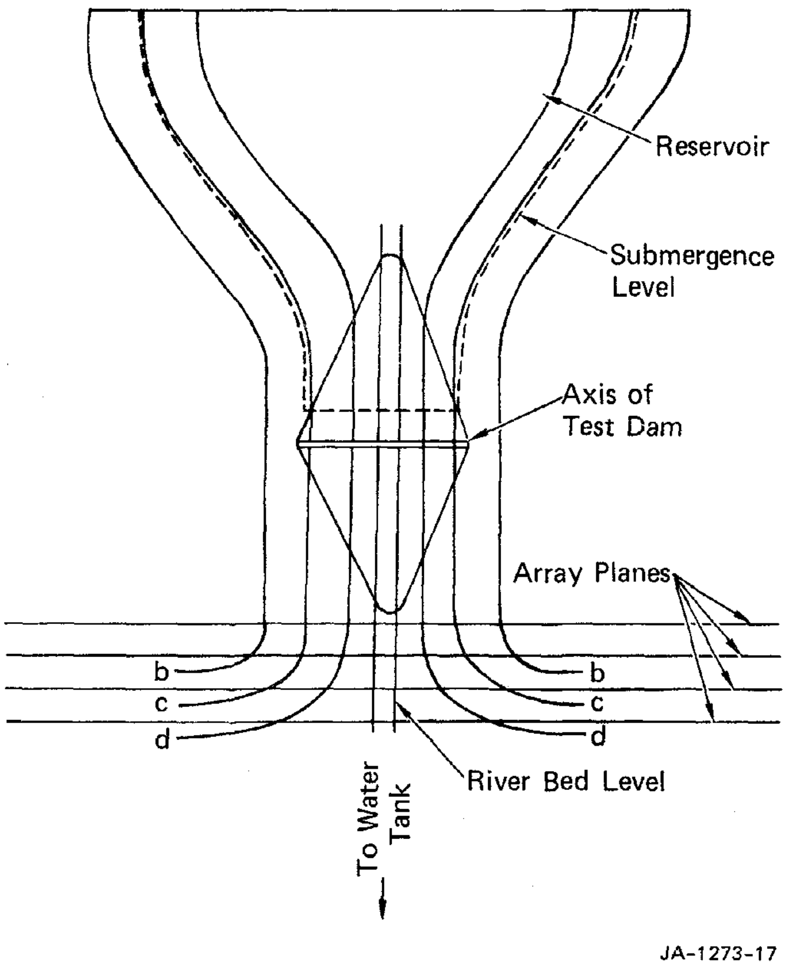

FIGURE 17 SIMPLIFIED TOPOGRAPHY TO BE EXCAVATED FOR TEST DAM CONSTRUCTION

COST ANALYSIS

Table 8 gives the estimated costs for the schedule of tasks given in Table 4. Table 8 also describes the tasks in more detail so that program changes and improved cost estimates can be made during program review. A cost summary without this detail is given in Table 9. Because so much new technology is involved, the estimates can be in error by about ±40%. The total cost is $12.5 million, of which $9.6 million is in India and $2.9 million is in the United States.

The largest costs are for the array test facility, which would be a permanent installation that can be used on a wide variety of soil and soil-structure testing both during this program and for years to come. The total cost for development, fabrication, installation, and calibration of the arrays themselves (Tasks 5, 6, 7, 8, and 10) is $7.9 million. Cost for the data acquisition and processing systems (Tasks 12 and 13) is $480 thousand, and for site development is $200 thousand. Thus, of the $12.5 million total cost, $8.6 million is for the permanent facility and $3.9 million is for construction of the dams and topology, dam instrumentation, planning and performing the dam tests, and interpretation of the results.

Another pertinent cost grouping is the instrumentation and data handling systems (Tasks 11, 12, and 13) of which $830 thousand is for equipment that will be available at the facility for future work.

Table 8

COST ESTIMATE

TASK	ESTIMATED COSTS, $K (1980)		DESCRIPTION
	India (PL 480 Funds)	U. S. (Interagency Funds)	
1. Site Selection	50	20	Exploratory, seismic, and soil test surveys; 3-week visit of U.S. geologist and engineer.
2. Site Acquisition and Development	200		Property lease (5 years); detailed seismic and soil property testing; construction of fences and buildings for offices, maintenance, and staff housing; lines for water, electrical power, and communication; purchase of transportation vehicles.
3. Earth Movement for Topography and Construction of Dams	700		Topography for 3 dam sizes (dam heights of 2, 4, and 6 m). Construction of 10 dams (4 at 2 m, 3 at 4 m, and 3 at 6 m).
4. Water Fill and Drain System	400		Construction of upstream and downstream reservoirs, piping, pumps, water-saturation acceleration system, drainage around add-on structures experiments on downstream side of array.
5. Design, Development, and Test of Single 0.6-m Source*		350	Design and construction of 0.6-m-diameter by 27-m long source; field tests and development in single-pulse mode; addition of multi-pulse capability, field tests and development to prototype condition.
6. Fabrication of Array Sources*	4,500	1,000	Materials, machining, and assembly to field-ready condition. (U.S. costs are for items possibly unobtainable in India.)
7. Array Installation	1,500		Drilling 48 cased holes 0.8-m-diameter by 30-m deep, assembly and emplacement of sources and removal of casings as each source is set in place.
8. Firing System	20	100	Design, fabrication, and emplacement of one 12-shot sequencer, six 5000-volt charging units, 48 detonator units (each unit fires 3 or 4 detonators), 5000 detonators (3000 for 20 dam tests plus 2000 for array development testing and spares, all made in India).
9. Add-on Structures Experiments	open	open	Design, fabrication, installation, instrumentation and recording system, test planning and results interpretation, etc. These can take advantage of ground motions generated in the 8 to 10 tests to develop and calibrate array performance (Task 10) as well as in dam testing (Task 14).
10. Array Performance Tests*	400	30	Ground motion check-out and calibration tests as each of the four 12-source planar arrays is installed (minimum of 3 tests with array 1, 2 tests with arrays 1 and 2, and 3 tests with all four arrays).
11. Dam Instrumentation	200	400	Purchase and installation (during dam construction) of gages for soil stress, soil strain, porewater pressure, acceleration, displacement: 100 gages per dam x 10 dams with 2/3 survival rate from dam to dam, at $800 per gage plus $200 per gage for cabling (U.S. parts, India install).
12. Data Acquisition System	40	330	120 channels: signal conditioning at $800/channel, multiplexer at $600/channel, 3 tape recorders at $30,000, 2 quick-look playback recorders at $11,000 each, instrumentation trailer at $50,000 (U.S. parts at above cost, plus India labor to install and check-out).
13. Data Processing System	10	100	Analog-to-digital converter (tape drive plus digital scope), processor computer, hard-copy plotter.
14. Dam Testing	1,000		20 tests over a 3-year period. Includes filling and draining dam reservoir, explosive cost, charge preparation, firing system maintenance, instrumentation hook-up and check-out for each test series, backfilling and maintenance of sources after each test, data reduction, rehabilitation of dams between tests as needed.
15. Site Maintenance	300		Staff of 5 over a 4-year period for general maintenance of power, communication, roads, pumping and water control system, housing and kitchen operation, security, safety, instrumentation system.
16. Management, Test Planning and Interpretation	300	500	Average professional staff for 5 years: India, principal investigator plus 4 assistants; U.S., principal investigator plus 2 assistants (all 1/4 time with full overhead at home bases).

*Ability to perform Tasks 5, 6 and 10 assumes that similar developments have been made on arrays about half this size (0.3-m-diameter sources). Such development requires at least two years and would cost about $1500 to perform in the U.S. This would result in a 48-source permanent array facility for research with test areas half the size of those described in this report.

Table 9
COST SUMMARY

TASK	$ K (1980) INDIA	U.S.
1. Site Selection	50	20
2. Site Development	200	
3. Topography and Dams	700	
4. Water System	400	
5. Single-Source Development		350
6. Array Sources	4,500	1,000
7. Array Installation	1,500	
8. Firing System	20	100
9. Add-on Structures	open	open
10. Array Performance Tests	400	30
11. Dam Instrumentation	200	400
12. Data Acquisition System	40	330
13. Data Processing System	10	100
14. Dam Testing	1,000	
15. Site Maintenance	300	
16. Management, Test Planning and Interpretation	300	500
TOTALS:	9,620	2,830
GRAND TOTAL	$12,450,000	

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