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DYNAMIC INTERACTION EFFECTS IN ARCH DAMS

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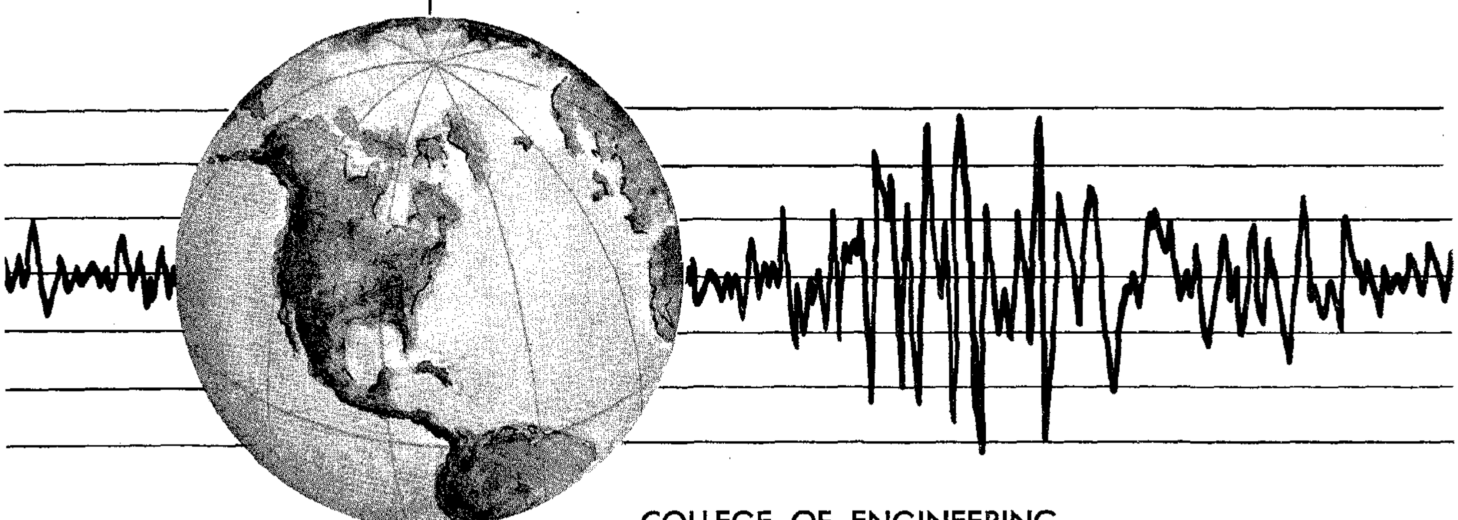
Report to the National Science Foundation on Research conducted under the U.S.-China Protocol for Scientific and Technical Cooperation in Earthquake Studies



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A Report on Research Conducted under the
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Earthquake Engineering Research Center
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ABSTRACT

This report summarizes the results obtained and the conclusions drawn from a four year cooperative research project on "Interaction Effects in the Seismic Response of Arch Dams". The work has been done under the U.S.-China Protocol for Scientific and Technical Cooperation in Earthquake Studies, by the Scientific Research Institute for Water Conservancy and Hydroelectric Power and Tsinghua University, both of Beijing, China, collaborating with the Earthquake Engineering Research Center of the University of California, Berkeley. The central feature of the research was correlation of field measurements of the forced vibration response of two arch dams in China, Xiang Hong Dian and Quan Shui, with corresponding results predicted by computer analyses; the principal emphasis of the work was on the effects induced by dynamic interaction of the foundation rock and the reservoir water with the response of the dams.

The results demonstrated that the foundation rock does participate significantly with the forced vibrations of the dams, but that this type of interaction can be represented adequately by including a block of foundation rock with the dam in forming the finite element mathematical model. Using a block with dimensions equal to the height of the dam in directions upstream, downstream, and radially outward from the dam base is adequate if a rock modulus consistent with the static test data is applied.

Similarly these results clearly show the important influence of the reservoir water interacting with the dam, and demonstrate that complicated reservoir geometries can be modelled effectively using liquid finite elements. However, the very important question of whether the reservoir water should be treated as compressible or incompressible in the mathematical model has not been answered by these analyses, which assumed

incompressibility. Discrepancies between measured and calculated hyrdodynamic pressures, especially for Quan Shui dam, suggest that the water should be treated as compressible, but further research is needed to explain the differences in the correlation obtained for the two dams and also to demonstrate the significance that compressibility has on response to earthquake motions (as compared with harmonic excitation).

Preliminary studies performed during this project demonstrated that the interacting foundation rock also plays an important part in the earthquake response behavior of arch dams, and that further study is needed on seismic input aspects of the foundation interaction mechanism. Continuing research by the cooperating institutions is proposed to obtain final answers to the remaining questions about reservoir and foundation interaction.

PUBLICATION NOTE

This report is being published simultaneously by the Scientific Research Institute for Water Conservancy and Hydroelectric Power of Beijing and by the Earthquake Engineering Research Center of the University of California, Berkeley. The report produced by each organization is provided with the standard cover for that organization.

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CHAPTER 1

INTRODUCTION

1.1 Background

A four year cooperative research program directed toward evaluation of interaction effects in the dynamic behavior of arch dams was initiated in September 1981 under the U.S.-China Protocol for Scientific and Technical Cooperation in Earthquake Studies. The cooperating institutions were the Earthquake Engineering Research Center (EERC) of the University of California, Berkeley, and the Scientific Research Institute for Water Conservancy and Hydroelectric Power (SRIWCHP) together with Tsinghua University, both of Beijing, China. The Principal Investigators were Professors K. T. Chang of Tsinghua University and Professor R. W. Clough of the University of California. Financial support for the U.S. part of the effort was provided by the U.S. National Science Foundation; the Chinese activities were supported by the Ministry of Water Conservancy and Electric Power. The principal objectives of the research were to obtain improved understanding of the dynamic interaction mechanisms between an arch dam and its foundation rock, as well as between the dam and its reservoir water; and also to develop dynamic response analysis procedures that would represent the interaction mechanisms more realistically and conveniently.

The research effort involved performing harmonic forced vibration tests of two arch dams in China, using the SRIWCHP vibration test system and data acquisition system supplemented by specialized EERC transducers and recorders. Then the corresponding analytical results were evaluated at the EERC, using University of California computer systems and programs. The first dam to be studied was Xiang Hong Dian, a single curvature gravity arch located in Anhui Province. The field test was done in August 1982, and the analytical correlations were carried out during the following year. The experimental techniques and analysis procedures are described and the results of the correlation studies are summarized in a report published in English by EERC in April 1984[1]; the report subsequently was translated into Chinese and published by SRIWCHP. The second dam tested was Quan Shui, a thin shell double curvature arch located in Guangdong Province. The field work was done in July 1983 and the analytical correlations were carried out in California during the following year. The report describing these experiments and analytical correlations was published in English by EERC in November 1984[2]; followed by publication of the Chinese language version by SRIWCHP.

1.2 Organization of this Report

This present document is the third and final report describing the work done on this cooperative research project. Its first objective is to summarize the knowledge about interaction mechanisms gained in the studies of the two dams, thus it reviews the results presented in the first two reports (1,2) and draws conclusions from these results. The second purpose of this report is to identify various aspects of the foundation and reservoir interaction mechanisms that still are not adequately understood or formulated for analyses, and then to outline additional research aimed at further improvements in analytical procedures intended to account for each type of interaction mechanism. Each of the topics mentioned above is discussed in a separate chapter of this report, starting with summaries of the results and conclusions obtained for foundation interaction and for reservoir interaction, presented in Chapters 2 and 3, respectively. The additional research proposed to be done with regard to reservoir and to foundation interaction mechanisms, respectively, are described in Chapter 4 and 5. Finally, Chapter 6 provides a summary of the benefits derived from this cooperative project, including reference to work done in consultation on the design of Er-Tan Dam.

1.3 Proposals for Further Research

It must be emphasized, that the additional work mentioned in Chapters 4 and 5 will not be part of the present cooperative research project, which will terminate with the publication of this report. Instead, a separate proposal already has been submitted for the additional studies on reservoir interaction[3], and plans are being made for further studies of foundation interaction and seismic input for arch dams. It is possible that analytical studies on these foundation interaction and input topics will be carried out independently by the cooperating institutions in Beijing and by the EERC in Berkeley, with informal collaboration by correspondence, but no formal research project in this area is planned.

CHAPTER 2

CONCLUSIONS ABOUT FOUNDATION INTERACTION

2.1 Foundation Modelling

The importance of foundation interaction on the displacements and stresses resulting from loading an arch dam has long been recognized, for static as well as dynamic loads. However, the amount of flexibility that actually is contributed by the foundation rock has been only a matter of conjecture and the appropriate mathematical model to provide the desired amount has been even more uncertain. Foundation flexibility has been incorporated into typical "trial-load" method analyses by means of Vogt coefficients[4], but these are merely the equivalent of springs supporting the ends of the arch and cantilever members forming the "trial-load" model as indicated in Fig. 2-1a. This type of foundation model may be able to simulate the effect of the foundation rock so far as stresses and deformations within the body of the dam are concerned; however, it is evident that it provides no equivalent of the stress concentration mechanism that must exist where the concrete abuts on the rock continuum, as shown in Fig. 2-1b.

With the introduction of the finite element method, the validity of the foundation interaction model was greatly improved; it was possible to simulate the three-dimensional elastic behavior of the foundation rock, and thus to represent the stress concentration effect at the concrete-rock interface. With this type of model, it is evident that the concrete stresses indicated in the abutment region will be greater than those predicted by the trial-load model because the latter ignores the stress concentration mechanism at the interface. However, it must be emphasized that the tensile stresses given by the finite element model also tend to deviate from reality because this analysis assumes that both concrete and foundation rock are linearly elastic -- in tension as well as compression. In actual fact, the foundation rock generally is jointed to a significant degree, and cannot develop effective tensile stress. For this reason it is evident that any tensile stresses indicated in the concrete adjacent to the foundation rock are largely fictitious; they cannot exist if the rock is incapable of resisting tension.

In summary, a finite element foundation model is capable of representing the stress concentration that must develop adjacent to the concrete-rock interface, but judgement is needed in interpreting any tensile component of the indicated concrete stresses. However, an additional problem must be considered in formulating the finite element model: the Vogt coefficients are intended to approximate the flexibility of a semi-infinite elastic rock body, but clearly it is impractical to model a semi-infinite body by ordinary 3D solid elements. For computational convenience it is desirable to include as few nodal points as possible in the foundation model, thus Mesh 1 shown in Fig. 2.2 is often used for practical analyses with the ADAP program[1,2]. The effective modulus of elasticity of this relatively limited volume of rock then is chosen such that it will approximate the flexibility of a semi-infinite rock mass.

2.2 Experimental Study

In previous experimental studies of the dynamic behavior of arch dams, no specific effort was made to evaluate the contribution to the vibration behavior that is made by the foundation interaction. In general an arbitrary foundation model was adopted, and then the modulus of elasticity of rock and concrete was adjusted to provide the best possible correlation between calculated frequencies of vibration and the measured values. In this cooperative project, however, it was decided to investigate whether the foundation contribution could be identified quantitatively by measuring vibratory motions of the foundation rock during the harmonic testing of the dam.

The first conclusion to be drawn from this effort is that measurable motions are indeed induced in the foundation rock by the vibration exciters mounted on the dam, and that the attenuation of the rock motion with distance from the dam base also can be observed to distances significantly greater than the dam height. Thus, it is evident that the relatively small ADAP Mesh 1 foundation model cannot fully represent the actual foundation interaction mechanism; however, by appropriate selection of the rock modulus, this model still may lead to adequate predictions of the stresses developed in the concrete.

By measuring the rock motions at the abutments of the dam in addition to the resonant frequencies, a basis was obtained for determining the relative modulus of elasticity of the foundation rock as compared with that of the concrete. Of course the limited volume of rock included in the foundation model means that the relative rock stiffness actually is represented by an effective modulus defined specifically for this model. The results of this experiment were not very conclusive -- the correlation between measured and calculated mode shapes at the interface varied considerably from one mode to another, and it is difficult to conclude that any one assumed ratio of rock to concrete modulus gave the most consistent results. This question deserves further study to determine whether more extensive and refined measurements of the harmonic rock motions can lead to a more realistic model of the foundation rock.

A very important factor to be considered in this regard is that the foundation rock used in the ADAP correlation studies was assumed to be massless, and of course this assumption may have had a major influence on the calculated motions at the base of the dam. In the study of Xiang Hong Dian dam, a comparative analysis including the foundation mass showed no significant difference for the lower mode frequencies, but a gradually increasing effect was observed for the higher modes. In other cases the rock mass may influence the apparent rock: concrete modulus ratio or the selection of the concrete modulus. The choice of a massless foundation material was made for two reasons: (1) to avoid wave propagation effects in the foundation which may artificially amplify the earthquake signal used to excite the structures in earthquake response analyses, and (2) to obtain vibration properties that are representative of the dam, and are not dominated by the inertial effects of the foundation block the volume of which is chosen arbitrarily by the analyst. The wave propagation effect is not important in a dam vibration test, so it is possible that the foundation mass should have been considered in these correlation analyses. However, the size of the foundation model, i.e., the volume of rock to be considered with the dam, still would be a question requiring further consideration. Moreover, the question of how best to model the foundation and the seismic input mechanism for an earthquake response analysis requires extensive additional study, as described in Chapter 5 of this report.

CHAPTER 3

CONCLUSIONS ABOUT RESERVOIR INTERACTION

3.1 Reservoir Modelling

The important influence of the reservoir water on the dynamic behavior of concrete dams was first demonstrated by Westergaard, who formulated the analysis of hydrodynamic pressures at the vertical face of a rigid gravity dam subjected to harmonic motion[5]. He included the compressibility of water in this analysis, but pointed out that the reservoir effect could be represented by an "added mass" attached to the face of the dam if compressibility were neglected. The incompressible added mass concept has become the standard method of representing reservoir interaction for gravity dams, and various modifications have been made to apply the equivalent concept to arch dams. However, finite element reservoir modelling techniques permit much better treatment of the complicated geometric form of an arch dam reservoir, therefore this type of reservoir interaction model has been used in the correlation analyses carried out in this project.

3.2 Experimental Study

As was noted by Westergaard, the added mass effect of the reservoir is frequency independent if the water compressibility is neglected, and an incompressible liquid finite element model was employed in the analytical correlation studies carried out during this investigation. One of the major purposes of the research was to determine by direct measurement whether the compressibility of the reservoir water has any significant effect on the dynamic response of the dam or on the hydrodynamic pressures resulting from dam-reservoir interaction.

An important conclusion from this experimental research program was that it is indeed feasible to measure the hydrodynamic pressures developed in the reservoir during a forced vibration dam test. The pressure sensing and recording system proved to be sensitive enough to determine the pressures developed over a wide frequency range, and to define the distribution of pressures at the dam face as well as into the reservoir. In the test of Xiang Hong Dian dam, the technique of waterproofing the pressure gages proved to be inadequate, and only a small fraction of the desired measurements were obtained. However, before the test of Quan Shui dam the waterproofing procedure was greatly improved, and no difficulties were encountered during the pressure measurement program on that structure. So it may be concluded that hydrodynamic pressure measurements now can be included routinely as part of a forced vibration dam test.

3.3 Analytical Correlation with Experiments

Based on the predicted harmonic forced vibration motion of the dam, it was possible to calculate the corresponding hydrodynamic pressures in the reservoir, using the incompressible finite element model. As was noted in the Xiang Hong Dian dam report[1], the correlation between the analytically predicted and the measured pressures was quite good. The analytical predictions underestimated the experimental values slightly, but it was concluded that the incompressible liquid model gave satisfactory results for that case. It is worth noting that this is the first experiment in which field measured hydrodynamic pressures were compared with calculated results.

However, when the same modelling concept and analysis procedure was applied to Quan Shui dam[2], the results were far from satisfactory. The analysis greatly underestimated the measured pressure at nearly all measurement points; in fact, it appears that the measured pressures must have been subjected to some form of resonant amplification which is not contained in the incompressible liquid model. Of course, the resonance effects are typical of spring-mass systems and tend to imply a compressibility (spring) effect in the reservoir water. Further analyses and experiments will be required to verify this conjecture, as described in Chapter 4 of this report, but there is good reason to believe that compressibility of the reservoir water might have had a significant influence on the experimental results obtained at Quan Shui dam. The reason why this effect is so much more prominent at Quan Shui as compared with Xiang Hong Dian, however, will require considerably more detailed study.

Another conclusion that can be drawn from the analytical results is that the geometric form of both the dam face and the reservoir topography can influence the reservoir interaction mechanism. The finite element reservoir model has proven to be effective in representing these geometric forms, and can demonstrate differences in the hydrodynamic pressures resulting from changes in the assumed reservoir or dam geometry. Of course, the extent to which compressibility affects the interaction mechanism also is expected to depend on the size and geometry of the dam-reservoir system.

CHAPTER 4

FURTHER RESEARCH ON RESERVOIR INTERACTION

4.1 Preliminary Comments

The contrasting performance demonstrated by the incompressible reservoir model in correlation with experimental results from the two dam tests clearly demonstrates the need for further research on the reservoir interaction mechanism. Although the reason is not yet known for the relatively large discrepancy exhibited in the analytical results for Quan Shui dam, as noted above, it seems most likely that it is associated with compressibility of the reservoir water. Such flexibility effects in the liquid can lead to harmonic resonances in the reservoir and associated hydrodynamic amplification, and this could explain why the measured pressures are significantly greater than those predicted by the incompressible reservoir model (which does not permit reservoir resonances).

Further study of this problem is proposed to be undertaken by both analytical and experimental means. The analytical development will involve inclusion of the liquid compressibility in the finite element reservoir model. The procedure for doing this is well-known[6], but the compressibility formulation has not been implemented in the ADAP-II reservoir model previously because it makes the added mass property of the reservoir frequency dependent--therefore the earthquake response analysis considering compressible reservoir interaction must be carried out in the frequency domain and the resulting calculations are rather expensive. However, the compressible reservoir effect for any frequency considered during harmonic testing can be studied quite easily, so this will be the first objective of the analytical study. Correlation of calculated hydrodynamic pressures with the measured results for the two dams will be carried out both neglecting and including compressibility; this should quickly demonstrate whether compressibility is the cause of the discrepancies exhibited by the correlations for Quan Shui dam.

It is also proposed to do further research on reservoir compressibility by experimental procedures during a forced vibration test on Monticello dam, a doubly curved thin shell structure in California[7]. These tests will make use of rotating mass shakers mounted at the crest of the dam, and the principal emphasis of the study will be to measure possible resonances in the reservoir as the shakers are operated through their full frequency range. Of course, analyses will be made of the hydrodynamic pressures expected in the reservoir during the harmonic tests, so the experimental data will give a direct indication of whether or not the compressible reservoir model gives improved correlation with harmonic test results.

After the tests have been completed analyses will be made of the earthquake response of Monticello Dam, both including and neglecting the reservoir compressibility. The objective of these studies will be to determine the importance of compressibility on the earthquake response behavior of arch dams. By variation of the frequency properties of the earthquake as well as of the geometric scale of the dam-reservoir system it is hoped to establish a range of conditions for which an incompressible reservoir model can be expected to give satisfactory results; outside of this range, the use of the compressible reservoir model will be recommended.

As was mentioned earlier, a proposal for carrying out this program of additional research on reservoir interaction already has been submitted to the National Science Foundation[3], with a proposed starting date of 1 October 1985. If funding is provided at that date, it is expected that the field test will be done in May-June 1986 and the research program will be completed by 31 March 1987. A preliminary discussion of the proposed analytical and experimental research is presented in the following sections of this Chapter.

4.2 Analytical Development

4.2.1 Incompressible Liquid Finite Element Model

The formulation of the finite element model of an incompressible liquid reservoir has been presented in Reference 1, but the essential features of that development will be repeated here for convenience in discussing the extension to the compressible liquid case. The equation of equilibrum of an incompressible liquid may be expressed in Cartesian coordinates in terms of the pressure, p, as follows:

$$\nabla^2 p \equiv \frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = 0 \tag{4.1}$$

Boundary conditions to be considered for a dam-reservoir system are established as follows:

(a) at the dam-reservoir interface $\frac{\partial p}{\partial n} = - \rho \ddot{v}_n^{\,t}$

(b) at the fixed reservoir boundaries (reservoir floor, canyon walls, upstream face) $\ddot{v}_n^{\,t} = 0$, i.e., $\frac{\partial p}{\partial n} = 0$

(c) at the reservoir free surface (neglecting surface waves) $p = 0$

where "n" is the outward normal direction from the reservoir boundary, $\ddot{v}_n^{\,t}$ is the normal component of total acceleration of the reservoir boundary, and ρ is the mass density of the water.

The Galerkin weighted residual method was used to discretize the reservoir domain, using the finite element pressure interpolation functions as the Galerkin weighting functions. The result of this discretization procedure is the finite element equivalent of the pressure equilibrium equation (Eq. 4.1) incorporating the reservoir boundary conditions; this may be expressed as follows:

$$\begin{bmatrix} \underline{g}_{rr} & \underline{g}_{rs} \\ \underline{g}_{sr} & \underline{g}_{ss} \end{bmatrix} \begin{Bmatrix} \underline{p}_r \\ \underline{p}_s \end{Bmatrix} = \begin{Bmatrix} 0 \\ \underline{b}_s \ddot{\underline{v}}_{sn}^{\,t} \end{Bmatrix} \tag{4.2}$$

in which $\underline{p}_r$ and $\underline{p}_s$ are the pressures at nodes within the reservoir and at nodes on the dam-reservoir interface, respectively. The matrices $\underline{g}$ and $\underline{b}_s$ are assembled from the corresponding quantities evaluated using Gaussian Quadrature on an element by element basis as follows:

$$g_{ij}^{(e)} = \sum_k \sum_m \sum_n f_{ij}^{(e)} (r_k, s_m, t_n) \left| J_{kmn}^{(e)} \right| W_k W_m W_n \tag{4.3}$$

$$b_{s_i}^{(e)} = \rho \sum_m \sum_n \eta^{(i)} (r_m, s_n) \left| J_{mn}^{(i)} \right| W_m W_n \tag{4.4}$$

in which: $W_j (j = k,m,n)$ = Gaussian Quadrature weighting factor

(r_j, s_j, t_j) = integration points in natural coordinates r,s,t.

Also:

$$f_{ij}^{(e)} (r_k, s_m, t_n) = \left(\frac{\partial N_i^{(e)}}{\partial x} \cdot \frac{\partial N_j^{(e)}}{\partial x} + \frac{\partial N_i^{(e)}}{\partial y} \cdot \frac{\partial N_j^{(e)}}{\partial y} + \frac{\partial N_i^{(e)}}{\partial z} \cdot \frac{\partial N_j^{(e)}}{\partial z} \right) \tag{4.5}$$

and

$$\eta^{(i)} (r_m, s_n) = \underline{N}_s^{(i)T} \, \underline{\lambda}_{mn}^{(i)} \, \underline{\phi}_s^{(i)} \tag{4.6}$$

in which

$$\lambda_{mn}^{(i)} = < \lambda_x^{(i)} \quad \lambda_y^{(i)} \quad \lambda_z^{(i)} >_{mn} \tag{4.7}$$

are the normal direction cosines. The interpolation functions used to express pressure variations in the 3D liquid elements are designated $N^{(e)}$ and the corresponding interpolation functions used to express pressure variations on the 2D dam-liquid interface are denoted $\underline{N}_s^{(i)}$. The determinants of the Jacobean matrices associated with the 3D and the 2D interpolations are designated $|J_{kmn}^{(e)}|$ and $|J_{mn}^{(i)}|$, respectively.

4.2.2 Extension to Include Compressibility

When compressibility of the liquid is considered the equation of pressure equilibrium takes the form

$$\nabla^2 p = \frac{1}{C^2}\, \ddot{p} \tag{4.8}$$

where $C = \sqrt{E/\rho}$ is the speed of sound in the liquid, E is the bulk modulus, and ρ is the mass density. The boundary conditions are the same for the compressible liquid as for incompressible. The only change from Eq. 4.2 in this finite element discretization of the compressible liquid field is the addition of terms associated with the second time derivative of the pressure, thus the pressure equilibrium equation now takes the form

$$\begin{bmatrix} \underline{g}_{rr} & \underline{g}_{rs} \\ \underline{g}_{sr} & \underline{g}_{ss} \end{bmatrix} \begin{Bmatrix} \underline{p}_r \\ \underline{p}_s \end{Bmatrix} + \begin{bmatrix} \underline{q}_{rr} & \underline{q}_{rs} \\ \underline{q}_{sr} & \underline{q}_{ss} \end{bmatrix} \begin{Bmatrix} \ddot{\underline{p}}_r \\ \ddot{\underline{p}}_s \end{Bmatrix} = \begin{Bmatrix} 0 \\ \underline{b}_s \ddot{V}^t_{sn} \end{Bmatrix} \tag{4.9}$$

The elements of the matrix $\underline{q}$ are assembled from the corresponding quantities evaluated element by element, using Gaussian Quadrature as follows:

$$\underline{q}^{(e)}_{ij} = \frac{1}{C^2} \sum_k \sum_m \sum_n F^{(e)}_{ij} (r_k, s_m, t_n) \left| J^{(e)}_{kmn} \right| W_k W_m W_n \tag{4.10}$$

where

$$F^{(e)}_{ij} (r_k, s_m, t_n) = N^{(e)}_i \cdot N^{(e)}_j$$

and the other quantities are as defined earlier.

For pure harmonic excitation at frequency $\bar{\omega}$, $\ddot{\underline{p}} = -\omega^2 \underline{p}$ so Eq. 4.9 can be written in the form

$$\begin{bmatrix} \bar{\underline{g}}_{rr} & \bar{\underline{g}}_{rs} \\ \bar{\underline{g}}_{sr} & \bar{\underline{g}}_{ss} \end{bmatrix} \begin{Bmatrix} \underline{p}_r \\ \underline{p}_s \end{Bmatrix} = \begin{Bmatrix} 0 \\ \underline{b}_s \ddot{V}^t_{sn} \end{Bmatrix} \tag{4.11}$$

in which $\bar{\underline{g}}_{rr} = \underline{g}_{rr} - \bar{\omega}^2 \underline{q}_{rr}$, etc.

This equation has the same form as the incompressible reservoir expression, Eq. 4.2, so it is evident that the evaluation of the added mass effect of the compressible reservoir can be carried out by the same procedures described earlier[1] for the incompressible reservoir. The only difference is that the coefficients in Eq. 4.11 are frequency dependent, so the added mass determined from this expression also is frequency dependent and must be evaluated for each frequency considered. The program RESVOR developed previously[1] for analysis of incompressible reservoirs has now been extended to include the frequency dependent terms, so it can be used in analysis of the reservoir interaction at any specified excitation frequency, $\bar{\omega}$.

4.3 Preliminary Analyses

4.3.1 Effect of Compressibility with Rigid Dam

To obtain a first indication of the significance of liquid compressibility on dam-reservoir interaction, the frequency dependent liquid finite element model described in the previous section was used to evaluate hydrodynamic pressures generated in a reservoir by harmonic motions of a rigid dam. Flexibility of the dam was not included so that the dynamic behavior of the reservoir alone could be evaluated. Three different reservoir geometries were studied: (1) a rectangular box canyon with a plane rigid dam at one end and a plane rigid upstream boundary at a distance of three times the water depth, (2) the Xiang Hong Dian reservoir model that is described in Reference 1, and (3) the Quan Shui reservoir as described in Reference 2.

Figure 4.1 shows the dimensions of the rectangular box canyon reservoir, and the variation of hydrodynamic pressure at the base of the dam as the frequency of the rigid dam harmonic motion is changed while its acceleration amplitude remains constant. For an incompressible liquid, the pressure response is independent of frequency, as indicated by the horizontal dashed line, but including the compressibility permits dynamic amplification to take place as shown by the solid curve. It will be noted that these pressure values including effects of compressibility have been normalized by dividing by the incompressible liquid pressure, so the curve directly indicates the amplification factor due to compressibility.

The frequency axis of the figure shows the ratio of the existing frequency to the first natural frequency of the reservoir, $\omega_1^r = \frac{\pi C}{2H}$, where C is the velocity of sound in water and H is the reservoir depth. Thus, the curve shows that the compressible water pressure becomes infinite as the excitation frequency approaches resonance ($\bar{\omega}_1 = \omega_1^r$). Additional vibration frequencies of an infinite reservoir with rectangular section are associated with higher vertical vibration modes and are given by $\omega_n^r = (2n-1)\omega_1^r$, so the next resonance with a frequency for an infinite reservoir is shown in the figure at the frequency ratio $\bar{\omega}/\omega_1^r = 3$. The three other resonances shown at frequency ratios between 1 and 3 are believed to be associated with vibration waves propagating along the canyon, reflecting between the dam face and the rigid boundary at the opposite end, but further study would be required to identify these precisely. It should be noted that there are no reflections from the side walls because of the two-dimensional behavior produced by this model.

Figure 4.2 similarly shows the pressures produced by a rigid dam with the geometric form of Xiang Hong Dian applying harmonic excitation to the Xiang Hong Dian reservoir. The pressure at the base of the dam is normalized with respect to the incompressible reservoir pressure, and the excitation frequency is normalized with respect to the fundamental frequency of an infinite box canyon reservoir with the same depth as the Xiang Hong Dian reservoir (71.5m). In general, this frequency response curve is similar to that of Fig. 4.1, except that the first resonance occurs at a frequency ratio of 1.3. Thus, it is clear that the effective depth of this reservoir is only about 77% of its 71.5m maximum depth due to the influence of its actual topography. Although the other resonances in Figure 4.2 have not been studied in detail, it is probable that they are associated with wave reflections from the assumed rigid, vertical upstream boundary located 300m upstream from the dam face, as well as from the side boundaries of the reservoir.

The corresponding results obtained by harmonic motion of a rigid Quan Shui dam are shown in Figure 4.3, in which the pressure at the base of the dam is normalized against the incompressible reservoir pressure and the frequencies are normalized with respect to the fundamental frequency of an infinitely long box canyon reservoir of the Quan Shui depth (74.5m). The frequency response curve is more complicated in this case because of the double curvature form of the dam face and due to the sharp curve in the reservoir plan form immediately upstream of the dam. The effective depth of the reservoir in this case is only about 67% of its 74.5m maximum depth, which demonstrates the very narrow aspect ratio of the Quan Shui canyon, especially in its base region.

It is important to note that the resonance peaks calculated for all of these dams are unbounded, i.e., the pressure approaches infinity at resonance. This is because the reservoir boundaries in the mathematical model are rigid and at finite distances. In a real system, energy would be lost by radiation in the upstream direction and also into the deformable bottom and sides of the reservoir; consequently the pressure amplitude at resonance in the actual dam would be bounded.

The variation of pressure with depth also is influenced by the compressibility effect, as may be seen in Fig. 4.4 for the case of the 80 ft deep box canyon reservoir with plane rigid dam. The figure shows the ratio of the pressure at any level on the face of the dam with respect to the pressure at the base, for various excitation frequencies; the zero frequency result applies to the incompressible reservoir at all frequencies. The pressure distributions shown for frequencies of 14.75 and 44.25 Hz depict the vertical wave resonance effects; at other frequencies, longitudinal waves have significant effects on the distribution of pressure at the dam face.

4.3.2 Effect of Uncoupled Compressible Reservoir on Flexible Dam Response

Analysis of harmonic excitation pressures at the face of a flexible dam was described in Reference 1 for the case of an incompressible reservoir. To reduce the computational effort, the dynamic behavior of the flexible dam was expressed in its vibration mode coordinates, where these were calculated for the combined incompressible reservoir-dam system. Modal coordinate masses and harmonic exciting forces were then evaluated, using the combined mass of the concrete plus the added mass of the incompressible reservoir, and the harmonic modal response was determined at each frequency, using the specially derived subroutine FORCEVB[1]. Finally the mode shape was used together with the calculated modal acceleration value to express the accelerations at each node on the face of the dam, and these were then converted to nodal pressures using the hydrodynamic pressure coefficients provided by the RESVOR program.

In general, the same procedure can be employed to calculate the pressures obtained at any given frequency for the compressible reservoir; but in this case obviously it is necessary to use the extended RESVOR program to express the pressures in the compressible reservoir at any specified frequency. In addition, however, it must be noted that the modal mass matrix obtained for the compressible reservoir is not of diagonal form because the frequency dependent added mass of the compressible liquid does not satisfy modal orthogonality conditions for the incompressible reservoir mode shapes. Thus, the frequency response curve must be evaluated by solving the coupled modal transfer function which expresses modal response in terms of several modal excitations for each desired frequency.

However, as a first step in estimating the influence of compressibility on the forced vibration pressures, it was decided to ignore the modal coupling induced by the frequency dependent added mass. In fact, in this initial effort, the compressibility component of the added mass was neglected completely in the transfer function evaluation. Thus, the modal transfer function was the same as was evaluated for the incompressible reservoir study[1], and the only difference in the present pressure analysis is that the compressible reservoir pressure coefficients (derived by the extended RESVOR program) were used to convert the nodal accelerations to nodal pressures.

Pressures at the face of Xiang Hong Dian dam calculated in this way for the first four vibration frequencies are compared in Figs. 4.5 to 4.8 with the corresponding analytical results from Reference 1. Clearly the compressible reservoir coefficients give slightly, but consistently, higher pressures than the incompressible values; this increase is to be expected on the basis of the rigid dam pressure response curves shown in Fig. 4.2. Note that the first four dam frequencies with incompressible reservoir (expressed as a ratio to the first frequency of a box canyon reservoir of the same depth) have been marked on this graph; for all four modes, the pressures of the compressible reservoir are greater than for the incompressible case. Also shown in Figs. 4.5 to 4.8 are the hydrodynamic pressures measured at each modal frequency. In general these test data agree better with results obtained from the compressible reservoir pressure coefficients, so compressibility appears to have a beneficial influence on the predicted reservoir interaction of Xiang Hong Dian dam, even though it was concluded in Reference 1 that the incompressible reservoir model gave satisfactory correlation with the experiments. However, it must be remembered that these new results do not represent the full effect of the compressibility because the modal frequency response was determined using the incompressible reservoir added mass.

Corresponding results calculated for Quan Shui dam are shown in Figs. 4.9 to 4.13; from Figs. 4.9 and 4.10 it is clear that the pressure coefficients derived for the compressible reservoir do not give any significant improvement in the pressure produced by excitation at the frequencies of the first two incompressible modes. However, the hydrodynamic pressures determined from the compressible reservoir coefficients at the third, fourth, and fifth mode frequencies (Figs. 4.11 to 4.13) are significantly greater than the incompressible results, and correspondingly are in better agreement with the experimental data. These results also are generally consistent with the Quan Shui reservoir frequency response curve, Fig. 4.3, in which the frequencies of the dam with incompressible reservoir have been marked.

4.3.3 Compressibility Effects Considering Modal Coupling

It was noted in the preceding section that the frequency dependent added mass of the compressible reservoir will lead to modal coupling if the mode shapes derived with the incompressible added mass are used. Moreover, it is essential to take account of this coupling if the full effect of compressibility on the dam-reservoir interaction is to be considered. Thus, a procedure for dealing with the coupled equations in analyzing the response to harmonic excitations is described here.

The finite element equations of motion of the dam and compressible reservoir may be expressed as follows:

$$[\underline{m} + \underline{m}_a + \underline{m}_{ac}\ (\bar{\omega})]\ \ \ddot{\underline{v}} + \underline{c}\ \dot{\underline{v}} + \underline{k}\ \underline{v} = \underline{P}_o e^{i\bar{\omega}t} \tag{4.12}$$

where $\underline{m}$, $\underline{c}$, and $\underline{k}$ are the mass, damping and stiffness matrices of the dam structure; $\underline{m}_a$ is the added mass of the incompressible reservoir, $\underline{m}_{ac}(\bar{\omega})$ is the additional frequency dependent mass of the compressible reservoir, and $\underline{P}_o e^{i\bar{\omega}t}$ is the excitation vector due to the rotating mass shakers attached to the crest of the dam. Note that both $\underline{m}_a$ and $\underline{m}_{ac}(\bar{\omega})$ are calculated using the extended RESVOR program.

The vibration mode shapes $\underline{\phi}$ of the incompressible reservoir-dam system were calculated in References 1 and 2 by solving the eigenproblem

$$[\underline{k} - \omega^2\ \bar{\underline{m}}]\ \hat{\underline{v}} = \underline{0} \tag{4.13}$$

in which $\bar{\underline{m}} = \underline{m} + \underline{m}_a$ is the combined mass of the dam reservoir system, excluding the frequency dependent added mass. These incompressible reservoir system mode shapes can now be used to approximate the response of the structure, using the superposition expression:

$$\underline{v} = \underline{\Phi}\ \underline{Z} \doteq \sum_{n=1}^{M} \underline{\phi}_n\ \ Z_n \tag{4.14}$$

where $\underline{\phi}_n$ is the shape of mode "n" and Z_n is the amplitude of the n^{th} modal coordinate. The approximation indicated in Eq. 4.14 is due to the truncation of the series to only M modes; the response of the dam-compressible reservoir system could be expressed exactly in terms of these incompressible reservoir mode shapes if all N modes were used.

Transforming Eq. 4.12 to the truncated set of modal coordinates of

Eq. 4.14 leads to a set of "M" equations that may be expressed

$$[\underline{\bar{M}}^* + \underline{M}_{ac}^* (\bar{\omega})] \; \ddot{\underline{Z}} + \underline{C}^* \; \dot{\underline{Z}} + \underline{K}^* \; \underline{Z} = \underline{P}_o^* e^{i\bar{\omega}t} \tag{4.15}$$

where the modal coordinate properties are denoted by

$$\left.\begin{aligned} \underline{\bar{M}}^* &= \underline{\phi}_M^T \; \underline{\bar{m}} \; \underline{\phi}_M \quad ; \quad \underline{M}_{ac}^*(\bar{\omega}) = \underline{\phi}_M^T \; \underline{m}_{ac}(\bar{\omega}) \; \underline{\phi}_M \\ \underline{C}^* &= \underline{\phi}_M^T \; \underline{C} \; \underline{\phi}_M \quad ; \quad \underline{K}^* = \underline{\phi}_M^T \; \underline{k} \; \underline{\phi}_M \end{aligned}\right\} \tag{4.16}$$

and the modal load vector is given by

$$\underline{P}_o^* = \underline{\phi}_M^T \; \underline{P}_o \quad \text{in which} \tag{4.17}$$

$\underline{\phi}_M$ is the set of M mode shapes, and $\underline{\phi}_M^T$ is the transposed mode shape matrix. Assuming a proportional viscous damping mechanism, all of the generalized property matrices except the frequency dependent added mass, $\underline{M}_{ac}^*(\bar{\omega})$, are of diagonal form because of the orthogonality properties of the mode shapes for the dam and incompressible reservoir, hence the equation set (Eq. 4.15) is coupled only by the frequency dependent modal added mass coefficients.

The coupled harmonically varying modal response vector, $\underline{Z}$, in general is complex as well as frequency dependent, and can be expressed in terms of its real and imaginary components, $\underline{\bar{Z}}_1$ and $\underline{\bar{Z}}_2$ respectively, as follows:

$$\underline{Z}(i\bar{\omega}) = \underline{\bar{Z}} \; e^{i\bar{\omega}t} \equiv (\underline{\bar{Z}}_1 + i\underline{\bar{Z}}_2) \; e^{i\bar{\omega}t} \tag{4.18}$$

Substituting Eq. 4.18 into Eq. 4.15 leads to the following pair of frequency response equations:

$$\left.\begin{aligned} [\underline{K}^* - \bar{\omega}^2 \; [\underline{\bar{M}}^* + \underline{M}_{ac}^* \; (\bar{\omega})]] \; \underline{\bar{Z}}_1 - \underline{C}^*\bar{\omega}\underline{\bar{Z}}_2 &= \underline{P}_o^* \\ \underline{C}^*\bar{\omega} \; \underline{\bar{Z}}_1 + [\underline{K}^* - \bar{\omega}^2 \; [\underline{\bar{M}}^* + \underline{M}_{ac}^* \; (\bar{\omega})]] \; \underline{\bar{Z}}_2 &= 0 \end{aligned}\right\} \tag{4.19}$$

However, noting that the ADAP program normalizes the mode shapes so that the generalized mass involved in the eigenproblem is unity (i.e., $\underline{\bar{M}}^* = \underline{I}$), these equations are reduced to the following convenient forms,

$$[\underline{\Omega}^2 - \bar{\omega}^2 \ [\underline{I} + \underline{M}^*_{ac}(\bar{\omega})]] \ \bar{\underline{Z}}_1 - 2 \ \xi \ \underline{\Omega} \ \bar{\omega} \ \bar{\underline{Z}}_2 = \underline{P}^*_o$$

$$2 \ \xi \ \underline{\Omega} \ \underline{\bar{\omega}} \ \bar{\underline{Z}}_1 + [\underline{\Omega}^2 - \bar{\omega}^2 \ [\underline{I} + \underline{M}^*_{ac} (\bar{\omega})]] \ \bar{\underline{Z}}_2 = 0 \qquad (4.20)$$

This coupled set of 2M equations now can be solved for the M frequency dependent real and imaginary parts of the modal response amplitudes $\bar{\underline{Z}}_1(\bar{\omega})$ and $\bar{\underline{Z}}_2(\bar{\omega})$.

Following the general approach applied previously to the solution of the incompressible reservoir response to harmonic excitation, it was assumed that at most only three modes would contribute to the response at any given frequency of excitation -- the mode with frequency closest to the excitation frequency and the modes with the next closest frequencies above and below the excitation frequency. Thus, solving the frequency response equations (Eq. 4.20) expressed for three adjacent modes led to the real and imaginary parts of the three modal responses at the specified frequency, and the program FORCEVB was used to calculate the dam response amplitude at this frequency. Applying this procedure for a range of frequencies above and below the frequency of the system with incompressible reservoir, it was possible to identify the frequency at which the maximum response was observed. This then was assumed to be the natural frequency of the dam-compressible reservoir system, and the pressure distribution at this frequency was evaluated by superposing the response contributions from the three adjacent modes used in the analysis near that frequency.

Using this method, the peak response frequencies were determined for the first five modes of Quan Shui dam with a compressible reservoir. Results are listed in Table 4.1, where it will be noted that compressibility had no effect on the frequency of the first two modes. For mode 3, the compressibility led to a slight reduction of frequency, and a corresponding improvement in agreement with the experimental results. Changes of frequency for the fourth and fifth modes are seen to be negligible. Pressure distributions corresponding to these analytical frequencies have not yet been evaluated.

4.3.4 Experimental Study of Reservoir Compressibility

Although the analytical results described above indicate that compressibility of the liquid may be the reason for the poor correlation obtained between the analytical predictions and the observed hydrodynamic pressures for the Quan Shui Dam test, it will be necessary to carry out another test program on a dam-reservoir system to demonstrate conclusively the manner in which compressibility affects the hydrodynamic pressures during harmonic excitation of an arch dam. For this reason, as noted earlier, a new research program has been proposed to the National Science Foundation to carry out the necessary additional field tests and analytical studies for another thin shell doubly curved arch dam[3]. The structure to be studied in this case is Monticello Dam, a dam built by the U.S. Bureau of Reclamation about 50 miles from Berkeley, California. This dam was selected both because of its proximity to the Earthquake Engineering Research Center and also because it has been tested previously[7,8] so a great deal already is known about its vibration mode shapes and frequencies.

In the proposed new test program only limited measurements will be made of the Monticello dam vibration properties; these new measurements will serve to verify the results obtained previously, and also will permit validation of a new mathematical model of the dam-reservoir system. The main emphasis in this experimental study will be on measurement of pressure frequency response functions for various points in the reservoir; the measurement points will be at selected depths both at the face of the dam and also at varying distances up to 10 meters from the dam face. It is hoped that these frequency response curves will identify a number of resonances in the reservoir that are independent of any dam frequency and thus that they will relate directly to the compressibility effect of the reservoir water. Of course efforts will be made to correlate these observed hydrodynamic pressure effects with analytical predictions based on the compressible reservoir model formulation described above. In addition, the influence of a silt layer at the bottom of the reservoir, which is expected to absorb some vibration energy, will be considered in some analyses.

4.3.5 Study of Compressibility Effects on Earthquake Response

Although it is well known that liquid compressibility can have a very important influence on the response of a dam-reservoir system during harmonic excitation, especially when there is no energy absorbed into the reservoir boundaries, it is not clear that the compressibility effect on the response of a dam to earthquake excitation will be very great. This is because the earthquake response is associated with a wide range of input frequencies each of which acts with significant energy only for limited time spans. For this reason it is intended to study the earthquake response history of Monticello Dam when it is subjected to several different earthquake motion records and for each case to compare the response obtained with a compressible reservoir with the incompressible reservoir interaction response. By these studies it is hoped that it will be possible to identify the range of dam and earthquake parameters for which the effects of compressibility on the earthquake response can be neglected; correspondingly, an attempt will be made to determine the circumstances under which the compressibility mechanism is of significance and must be considered in the analysis.

CHAPTER 5

PRELIMINARY STUDY OF EARTHQUAKE INPUT MODELS

5.1 Preliminary Comments

Although measurement of the interactive response of the foundation rock was a major objective of the experimental research program proposed for this project, it is apparent that the foundation performs differently during harmonic excitation applied to the dam crest as compared with its contribution to the earthquake response of the dam. In the former case, the foundation merely contributes to the flexibility of the responding system, but in the latter the foundation also must transmit the earthquake excitation to the base of the dam. For this reason, a mathematical model of the foundation that is appropriate for simulating the response to crest excitation may not be very effective for an earthquake response analysis.

Because modelling the earthquake input mechanism has received relatively little attention during the development of dynamic response analysis procedures for arch dams, and because the earthquake input is associated with the foundation model, it is useful to include a study of procedures for applying the earthquake to an arch dam as part of this project's research on the foundation interaction mechanism.

In this chapter, first will be presented brief formulations of four different earthquake input procedures that might be employed in the earthquake response analysis of arch dams. Then a comparative study is described of the dynamic response of a simplified two-dimensional dam model to an earthquake applied by these four procedures. This investigation was carried out under the supervision of Professor R. W. Clough by Mr. Hao-wu Liu of Chengdu University of Science and Technology while he was a Visiting Scholar at the Earthquake Engineering Research Center; typical results of his study are presented and conclusions are summarized here. Finally, a procedure is proposed for applying the recommended free-field earthquake input mechanism to three-dimensional arch dam-canyon rock systems.

5.2 Formulation of Earthquake Input Mechanisms

5.2.1 Standard Base Input Model (Case A)

The finite element system depicted in Fig. 5.1 is intended to represent a three-dimensional model of an arch dam constructed in a rock canyon. Note that appropriate supports are employed at all vertical boundaries of the model to approximate its response to each specified component of earthquake motion. For example, response to a cross-canyon earthquake motion would be modelled by rollers at the two sides that would permit horizontal displacements but no vertical motion. In the standard earthquake input mechanism assumed for such models, the specified earthquake acceleration history is applied to the rigid base rock; thus it is assumed that the same motions act at all points at the base of the deformable foundation. Recent measurements of the spatial distribution of earthquake motions show that this uniform base motion is reasonable for an earthquake which has its focus directly beneath the local base rock. However, it also has been seen that significant horizontal wave propagation effects result if the focus is not directly below, and this type of earthquake mechanism is not modelled by the system of Fig. 5.1. For the case shown in Fig. 5.1 base motions are propagated vertically through the deformable foundation rock by elastic wave mechanisms. Thus, the earthquake reaches the interface between the foundation rock and the dam concrete with changes in frequency content and in intensity as compared with the rigid base motions.

Considering only a single horizontal earthquake component, for simplicity, the equation of motion for the finite element model subjected to this earthquake excitation may be written

$$\underline{m}\,\ddot{\underline{v}} + \underline{c}\,\dot{\underline{v}} + \underline{k}\,\underline{v} = -\,\underline{m}\,\underline{r}\,\ddot{v}_g(t) \tag{5.1}$$

in which m, c, and k are the finite element mass, damping and stiffness matrices for the combined foundation-dam system, $\underline{v}$ is the nodal point displacement vector, $\ddot{v}_g(t)$ is the specified earthquake acceleration history and $\underline{r}$ is the displacement transformation vector expressing the nodal displacements resulting from a unit value of the base rock displacement, $v_g = 1$.

A major deficiency of this standard input mechanism is that the earthquake applied at the base rock level usually is an acceleration history actually recorded at the ground surface; typically the recorder was in a free-field location where it was not influenced by the response of any structures. When this free-field motion is applied at the base rock level as indicated in the sketch, it is modified by propagation through the deformable foundation rock as mentioned above and it generally would have a quite different character when it reached the ground surface even if there were no dam or canyon to influence it.

5.2.2 Massless Foundation Rock Model (Case B)

A modification of the base rock input mechanism described above was proposed in the late 1970's[10] and has been used extensively for arch dam analyses since then. The only difference in this case is that the deformable foundation rock is assumed to be massless, thus it functions only as a spring in the foundation interaction mechanism. Obviously, the absence of mass makes no difference in a static analysis, but in an earthquake response analysis the earthquake forces applied at the rigid base rock are transmitted instantaneously through the foundation rock to the base of the dam, without any wave propagation effects. It is appropriate to apply a free-field surface motion as the earthquake input at the base rock in this case, because the same free-field motions would be observed at the surface of the foundation rock if there were no canyon-dam interaction effects, while the dam-foundation interface motions would be modified by interaction effects as expected. Another effect of the massless foundation is that the dam vibrations are not affected by the foundation mass; thus, vibration modes of the foundation do not tend to dominate the dynamic behavior of the dam, as will happen if a large volume of foundation rock with mass is included in the model. However, it is not certain that the system frequencies given by the massless foundation are valid.

5.2.3 Deconvolution Base Rock Input (Case C)

A more direct means to avoid the amplification problem resulting from applying a free-field motion at the base rock of the mathematical model is to first apply a deconvolution analysis to the measured free-field accelerogram[11] and thus to define a more appropriate base rock motion. Typically it is assumed that the free-field motion was recorded at the surface of a horizontally stratified deformable foundation rock of infinite extent in the horizontal direction, as indicated in Fig. 5.2. Then a base rock input that might have produced the free-field motion at the surface of this layered rock is determined by inverse application of the one-dimensional wave propagation equations -- a process called deconvolution, as described in Reference 11.

Finally it is assumed that this same deconvolved base rock motion is applied at the base of the three-dimensional foundation rock-dam system of Fig. 5.1, in which the foundation rock is assumed to have its normal mass as well as stiffness properties. In this case, wave propagation mechanisms take place in the foundation rock, and if only the original layered rock were present (i.e., if there were no dam-canyon system) the original free-field motions would be observed at the surface as expected. With the presence of the dam and canyon in the mathematical model, however, the motions are modified by reflection and refraction at the canyon and dam interface, as they would be in reality. Moreover, any desired geological features could be included in the three-dimensional foundation rock model employed in this analysis; there is no need to employ the same layered system that was used in the deconvolution analysis. The basic assumptions in this case are that the earthquake is applied at a rigid base beneath the deformable foundation rock, and that the motions so applied are those given by a one-dimensional deconvolution analysis of a specified free-field earthquake motion.

5.2.4 Free Field Arch Dam Input (Case D)

The deconvolved base rock motion applied in Case C, above, is a rational representation of the earthquake input, and should lead to valid results. However, the analysis would be rather expensive because the 3D foundation rock model is so extensive. A more efficient procedure would be to use a two-dimensional model to evaluate the free-field motions at the canyon walls (without the dam in place) as shown in Fig. 5.3, and then to apply these canyon free-field motions at the dam-rock interface of a three-dimensional dam-canyon model. In this case it would be appropriate to employ only the relatively small volume of foundation rock typically used in the ADAP dam-foundation models[1,2], as indicated in Fig. 5.4, but to include the rock mass. A description of how this type of analysis might be carried out is presented in Section 5.4 of this chapter.

5.3 Simplified Two-Dimensional Study (9)

As was noted above, a preliminary study of the seismic input mechanism was carried out by Visiting Scholar Hao-wu Liu to determine how sensitive the structural response might be to the input assumptions. In order to minimize the computational costs, this study was carried out on a two-dimensional model of a dam-canyon system, as shown in Fig. 5.5. This model was subjected only to a single component earthquake, applying a horizontal excitation in the plane of the model. Obviously, this response mechanism does not include the true three-dimensional arch dam behavior; however, it does permit a comparative evaluation of the effects of the different input assumptions at minimal cost. The earthquake used in this study was the N-S component of the May 18, 1940 earthquake recorded at El Centro, California.

The four different input assumptions described in the preceding section of this report, denoted Cases A, B, C and D, were considered in this study. The finite element model employed in the analyses (Fig. 5.5) crudely represents the profile of Xiang Hong Dian dam, with a crest length of 361m, a maximum dam height of 87.5m, and with canyon walls extending about 40m above the dam crest. The model consists of 30 plane stress elements and has 56 degrees of freedom; nodes at the sides were supported by rollers that permitted only horizontal motions. The modulus of elasticity of the rock layers varied between 0.7 and 2.4 kg/cm^2 (increasing downward) while the modulus of the concrete was 4.0 kg/cm^2.

Only a small part of the results of these analyses are discussed here, but these demonstrate how the input assumptions can lead to dramatic differences in the dynamic response of the system. Figure 5.6 presents plots of the total displacement of Point "X" located at the left end of the dam crest, as shown in Fig. 5.5; results were calculated for Cases A, B, and D. Only a short time interval of the response is shown, but this includes the maximum total motion. As expected, the surface record applied at the base of the model including the rock mass (Case A) gives the greatest total response; and as shown in Fig. 5.7, the amplification resulting from the Case A input is even more significant in terms of the relative motion; that is, it produces by far the greatest model distortion. Figure 5.8 shows that the greatest horizontal normal stress at Point "Z" also is produced by the Case A assumptions, but for reasons that are not evident the greatest shear stress at this point (shown in Fig. 5.9) is given by the free-field input assumption of Case D.

Because the two-dimensional model studied here is not at all equivalent to an arch dam, it is not useful to try to draw conclusions as to which of the assumed input models is "best". The significant fact is that the different assumptions lead to widely varying results, thus, it is clear that detailed studies must be made of complete three-dimensional arch dam-foundation models to determine how to model the earthquake input. Obviously, it is not sensible to put a great deal of effort into defining the intensity and frequency properties of a design earthquake if the way it is applied can lead to such drastic differences in the response results.

5.4 Proposed Procedure for Seismic Input to Arch Dams

Based on the investigation described above, it is believed that the "Case D" type of seismic input should give the most reliable indication of the earthquake response behavior of an arch dam. The first step in this free-field input method is to determine the base rock motions by one-dimensional deconvolution analysis, as in Case C. Then this deconvolved base motion must be used as the input to the two-dimensional canyon system shown in Fig. 5.3 to obtain the free-field motion at the canyon walls. Actually, three analyses would have to be done; two separate 2D plane stress analyses should be performed with appropriate symmetric and antisymmetric roller boundary conditions to evaluate the response to the vertical and to the in-plane horizontal base motions, respectively, plus a 2D shear distortion analysis to evaluate response to the out-of-plane (upstream-downstream) horizontal motion. The two-dimensional models are justified, of course, if it is assumed that the canyon is of prismatic form extending to infinity.

When the three separate free-field motions of the infinite canyon have been determined, these are then applied as free-field input to the concrete-rock interface. As noted above, the mathematical model of the foundation rock in this case would be the relatively limited ADAP system shown in Fig. 5.4.

The derivation of the dynamic response to the free-field input is well-known[12] and need not be repeated here; however, the final result is presented for convenience:

$$\underline{m}\,\ddot{\underline{v}} + \underline{c}\,\dot{\underline{v}} + \underline{k}\,\underline{v} = -\left[\,\underline{m}\,\bar{\underline{r}} + \bar{\underline{m}}\,\right]\,\ddot{\tilde{\underline{v}}}_g \qquad (5.2)$$

in which $\bar{\underline{m}}$ is the mass of the dam which has been added to the mass of the free-field canyon system, $\ddot{\tilde{\underline{v}}}_g$ is the acceleration vector of the free-field canyon wall nodes that are associated with the dam, and $\bar{\underline{r}}$ is the influence coefficient matrix expressing displacements of the complete model resulting from unit displacements of the interface nodes $\tilde{\underline{v}}_g$. The dynamic response $\underline{v}$ in this case is the motion developed in addition to the free-field motion; for the dam itself, this is the entire motion because it was not part of the free-field response.

It is worth noting that modification would have to be made to the ADAP program to permit use of this free-field input mechanism because it presently assumes that the earthquake is applied through the rigid boundary of the foundation rock model. In general, the free-field motions at the dam-rock interface are not the same at all nodes, so the program would have to be modified to permit multiple interface node excitation. However, it is believed that a further improvement could be made to the analysis procedure if the dynamic response calculations are carried out using Lanczos coordinates[13] instead of the normal modal coordinates. These coordinates should be well adapted to defining the added motion response to the free-field input, and are expected to require very few Lanczos shapes to obtain reliable results. To obtain the greatest benefits from the use of Lanczos coordinates, it is proposed to solve for the response of the dam separately for each of the three components of earthquake motion, and then to combine the dynamic component effects with the static load response as the final step in the analysis. It is hoped that an analysis of the earthquake response of Monticello dam based on this free-field approach can be carried out as part of the proposed Monticello dam project[3].

CHAPTER 6

CONCLUDING REMARKS

6.1 Benefits from Cooperation

This cooperative research project has benefitted the participants from both countries in many ways, and has contributed significantly to the art of designing earthquake resistant arch dams. Possibly the most significant benefit to the participants was bringing together the widely separated groups of researchers, and thus creating a research team with capabilities much greater than the sum of the component parts. The manpower that was provided by the Chinese institutions made it possible to complete the extensive field measurement programs very expeditiously. But additionally the prior experience and special instrumentation provided by the EERC participants made unique contributions to evaluation of the interaction mechanisms that were the basic subject of the research. There is no question that the results of these cooperative experimental studies were much more significant than could have been obtained by any single one of the participating institutions.

6.2 Future Cooperation on Analytical Methods

With regard to the analytical part of the research, it is evident that the computer analysis capabilities of the Chinese participants have been greatly enhanced by this cooperative effort. Also, their experience with analysis of complex interacting arch dam systems has been greatly increased so that by the end of the project both Chinese institutions (SRIWCHP and Tsinghua University) were carrying out very sophisticated earthquake response analyses of dam-foundation-reservoir systems. It is hoped that the participants from both countries will maintain communication with regard to their work in this field, and will continue to share their experience in analytical study of the earthquake performance of arch dams. It is important that parametric studies be carried out to determine the range of influence of reservoir interaction effects and of foundation interaction-input mechanisms; and it would be very appropriate that such studies be arranged by informal cooperation between the institutions. Specific opportunities for initiating such continued collaboration will be provided by the proposed research project on Monticello dam in California.

6.3 Questions Needing Further Study

Summarizing the knowledge gained about reservoir interaction during this investigation, it may be concluded that finite element modelling is a practical and effective means of representing the reservoir effect; there is little reason to continue trying to adapt the Westergaard type of added mass model to the analysis of arch dams. The critical question that remains in this matter is whether or not the compressibility of the reservoir water must be recognized. It had been hoped that the research which Professor A. K. Chopra had under way could be applied to the dams studied in this project in order to obtain a definitive answer to this question. Unfortunately, the thesis written by his student Dr. K. L. Fok[14], was not completed in time to be used in connection with this research, but it is hoped that it can be applied in the proposed study of Monticello dam together with the modifications of ADAP discussed above, and that this will contribute to drawing final conclusions on reservoir interaction.

With regard to the foundation interaction mechanism, it has become evident that the most critical question is how to apply the earthquake input to an arch dam; the most stringent requirements imposed on the foundation model relate to this input problem. Thus, although the results obtained in this project suggest that the ADAP type of foundation model may be adequate for use in correlation of forced vibration response of arch dams, it will be necessary to make extensive analytical studies in order to establish the most effective foundation interaction model for seismic input. It is hoped that this question may be explored to a limited extent in the proposed study of Monticello dam; however, much more extensive parametric studies will be needed to draw final conclusions. As mentioned earlier, such additional analytical studies could be the subject of continued informal collaboration between the cooperating institutions of this project.

6.4 *Dynamic Analysis of Er-Tan Dam*

A final topic to be mentioned here is the design of Er-Tan Dam. This 240m high doubly curved arch dam proposed to be built near Doukuo in Sichuan Province has been a subject of continuing discussion between the project participants during the entire course of the project. Meetings between Professor R. W. Clough and the dam designers from Chengdu were held in 1982 and 1983 during which factors involved in the dynamic earthquake response analysis of the dam were discussed. Then at a 1985 meeting in Chengdu, involving project participants from SRIWCHP and Tsinghua University as well as Professor Clough and the dam design team, extensive discussions were held on the results of dynamic response analyses performed by both SRIWCHP and Tsinghua University. There is no doubt that the cooperative research done on this project has made an important contribution to understanding and evaluating the earthquake resistance of Er-Tan Dam; the continuing influence on arch dam design in the future will be equally significant.

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TABLE 4.1

Comparison of Measured and Calculated Frequencies
QUAN SHUI DAM

Mode #	No Reservoir	Incompressible Reservoir	Compressible Reservoir	Measured
1	4.25	3.85	3.85	3.85
2	5.05	4.00	4.00	4.10
3	8.34	7.03	6.86	6.80
4	9.43	8.03	8.00	7.60
5	10.05	9.86	9.86	8.80
6	10.89	10.24	--	9.05
7	11.87	11.27	--	--
8	13.06	11.47	--	--

$E_f/E_c = 0.5$

$E_c = 3.788 \times 10^6 \ T/m^2$

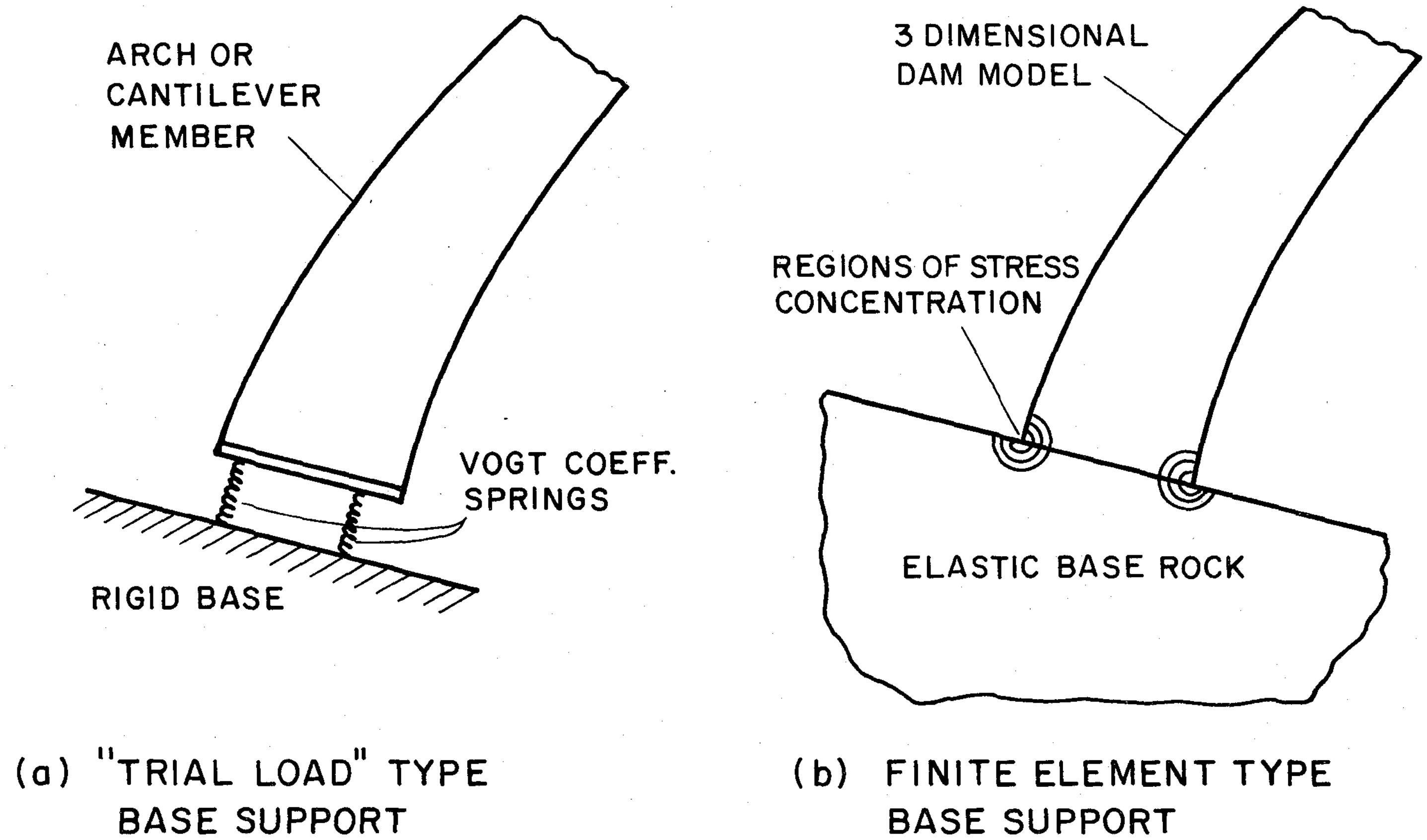
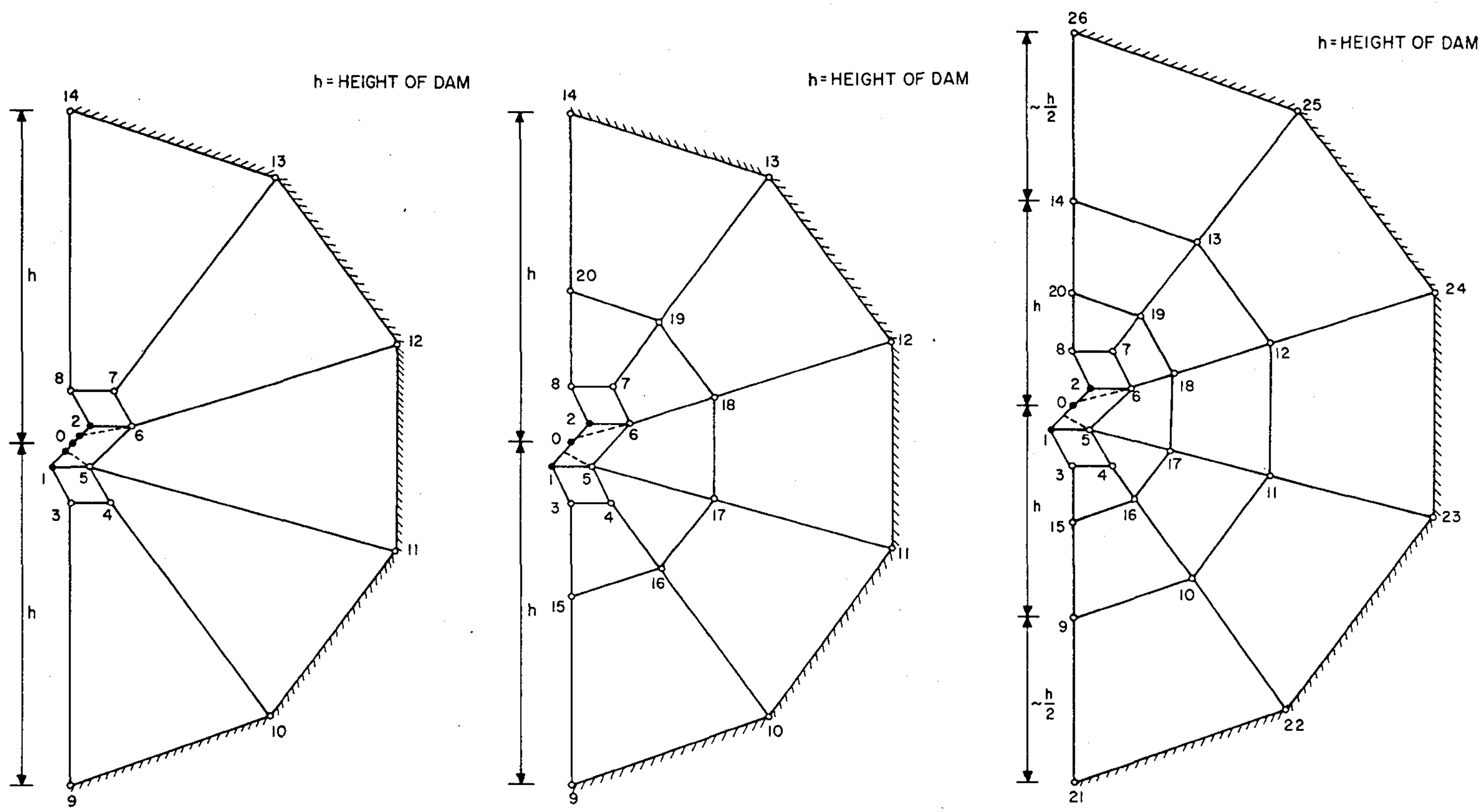


Fig. 2.1 Modelling of Foundation Flexibility



MESH 1, NODAL POINTS ON INCLINED PLANE   MESH 2, NODAL POINTS ON INCLINED PLANE   MESH 3, NODAL POINTS ON INCLINED PLANE

Fig. 2.2 ADAP Foundation Models on Sections Normal to Dam-Rock Interface

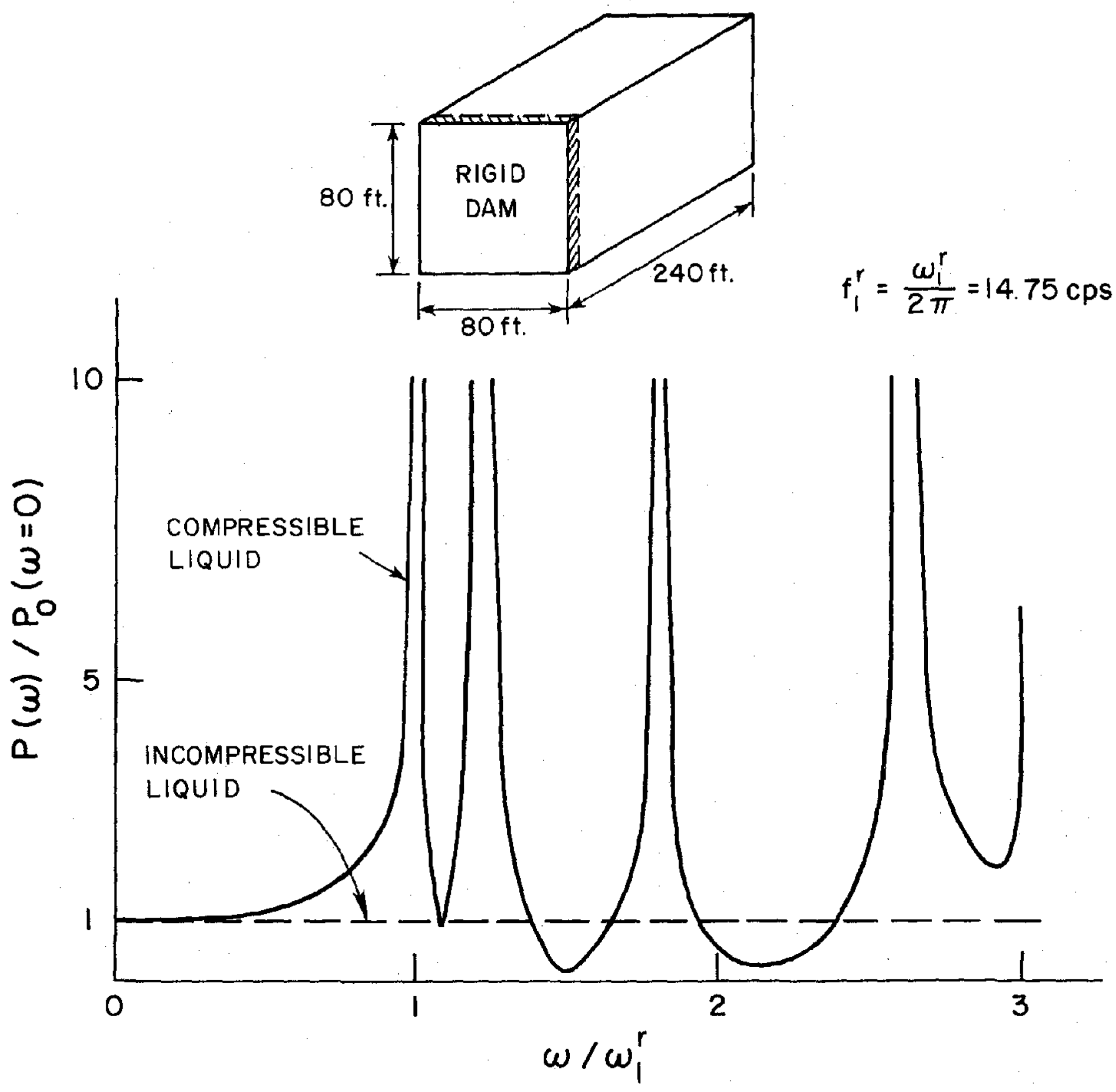


Fig. 4.1 Frequency Response Curve, Pressure at Base of Rigid Rectangular Dam

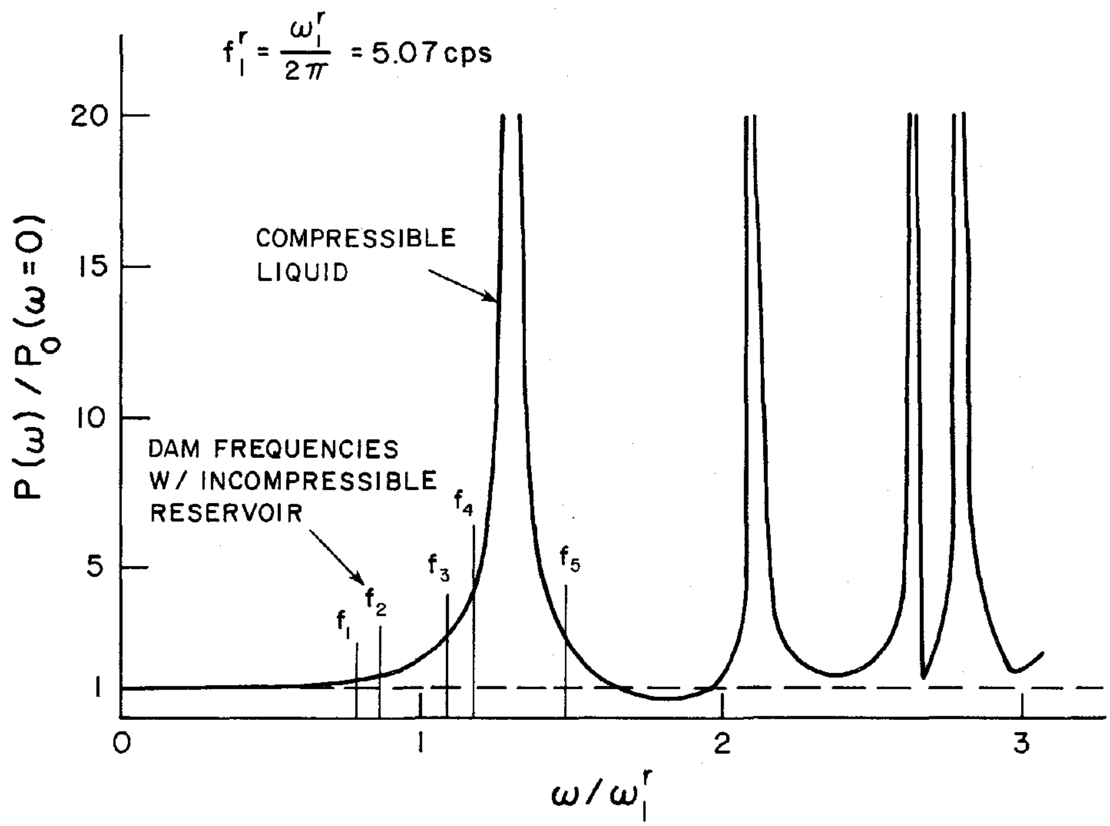


Fig. 4.2 Frequency Response Curve, Pressure at Base of Rigid XHD Dam (with Natural Reservoir Topography)

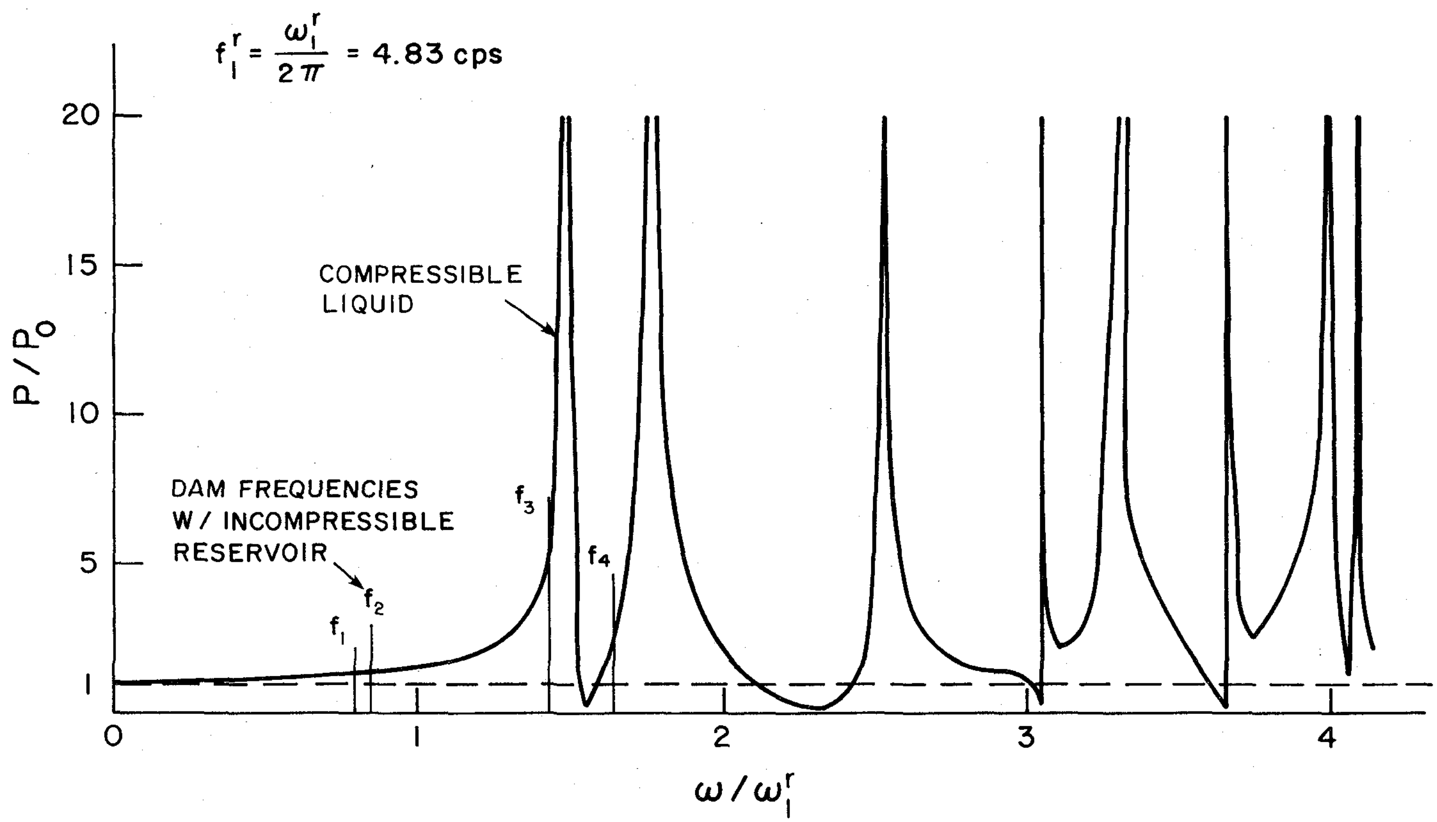


Fig. 4.3 Frequency Response Curve, Pressure at Base of Rigid QS Dam (with Natural Reservoir Topography)

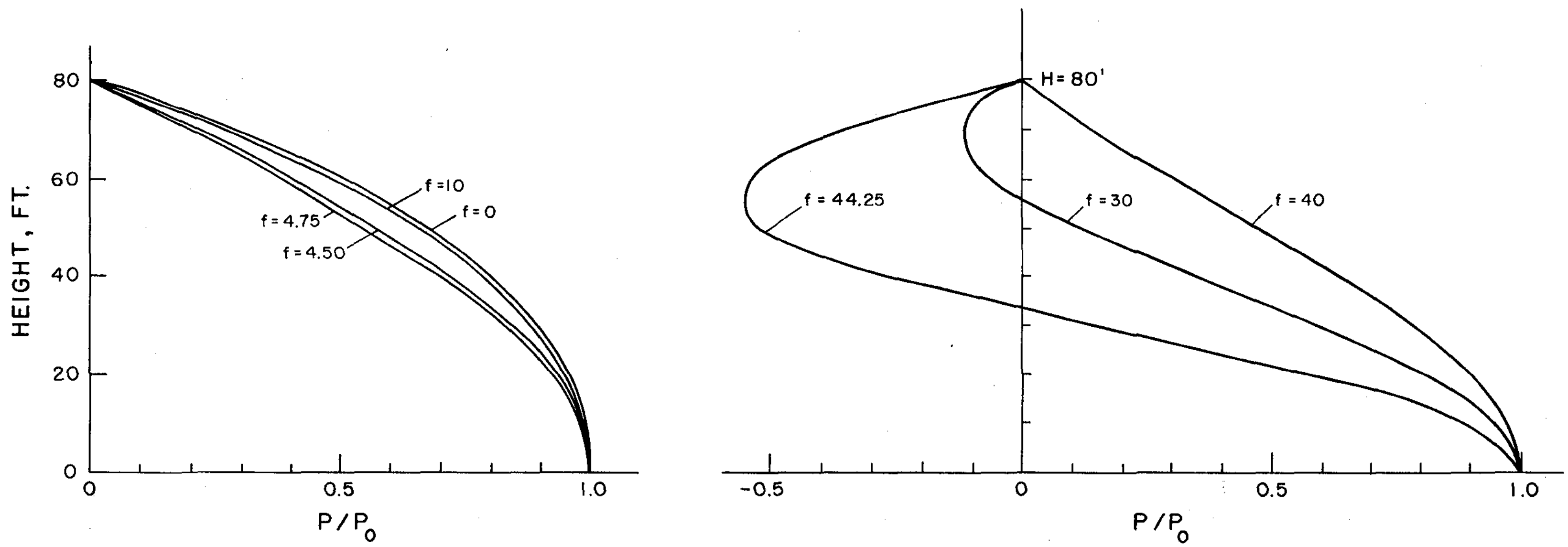


Fig. 4.4 Pressure Variation with Depth at Various Excitation Frequencies (Rigid Rectangular Dam)

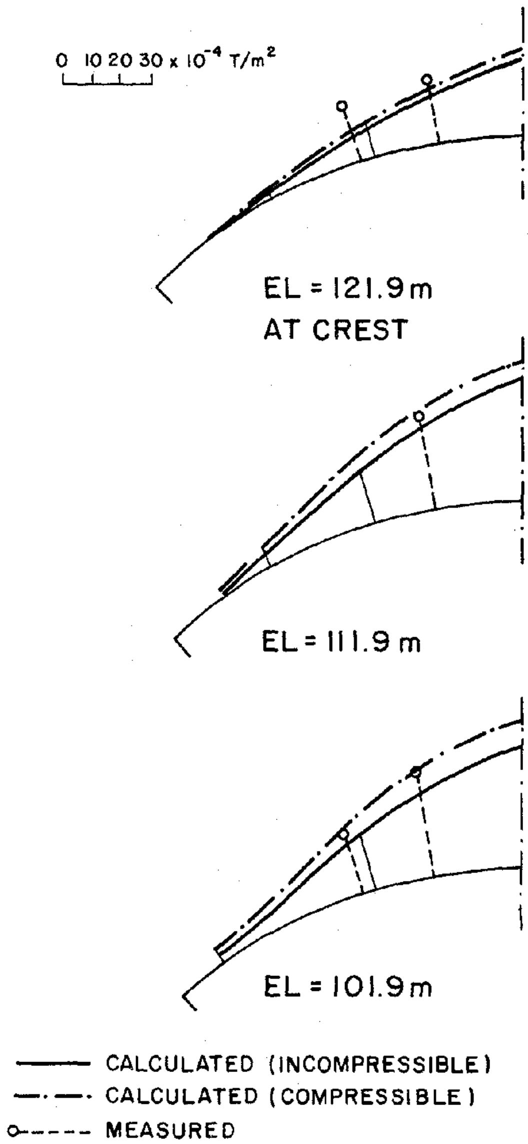


Fig. 4.5 $f_1 = 4.1$ Hz

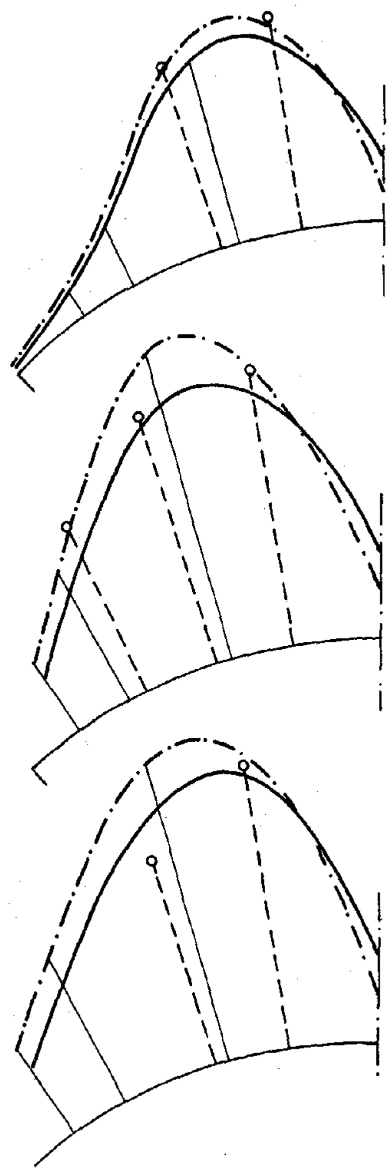


Fig. 4.6 $f_2 = 4.3$ Hz

Forced Vibration Hydrodynamic Pressures for Xiang Hong Dian Dam

Forced Vibration Hydrodynamic Pressures for Xiang Hong Dian Dam

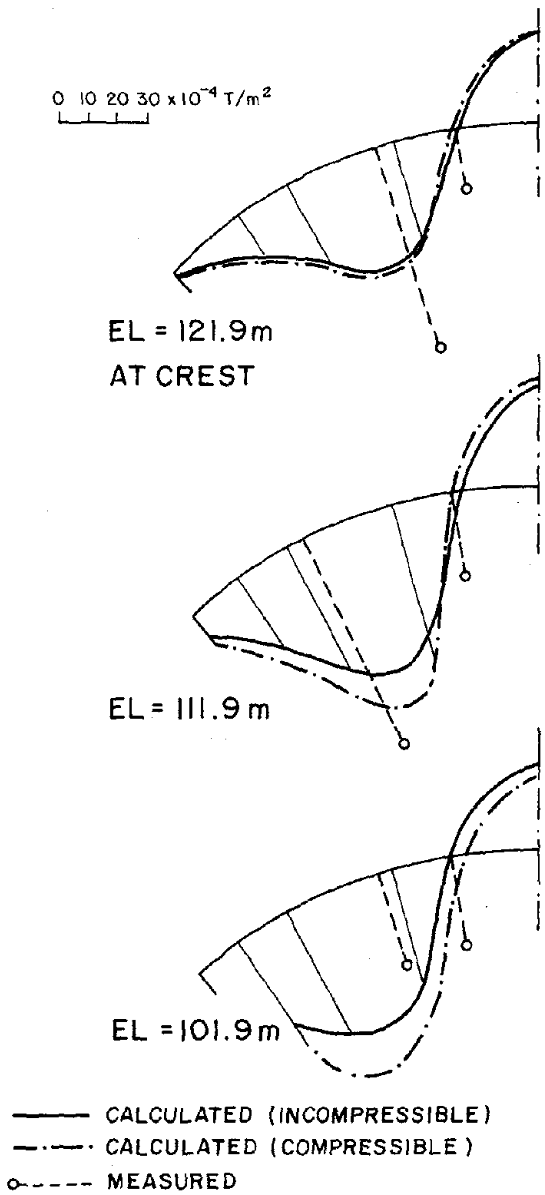


Fig. 4.7 f_3 = 5.1 Hz

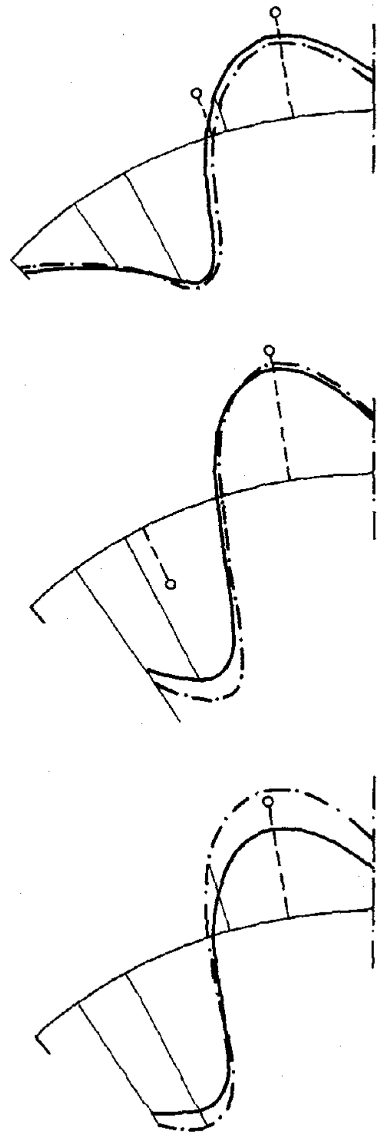


Fig. 4.8 f_4 = 6.0 Hz

Forced Vibration Hydrodynamic Pressures for Quan Shui Dam

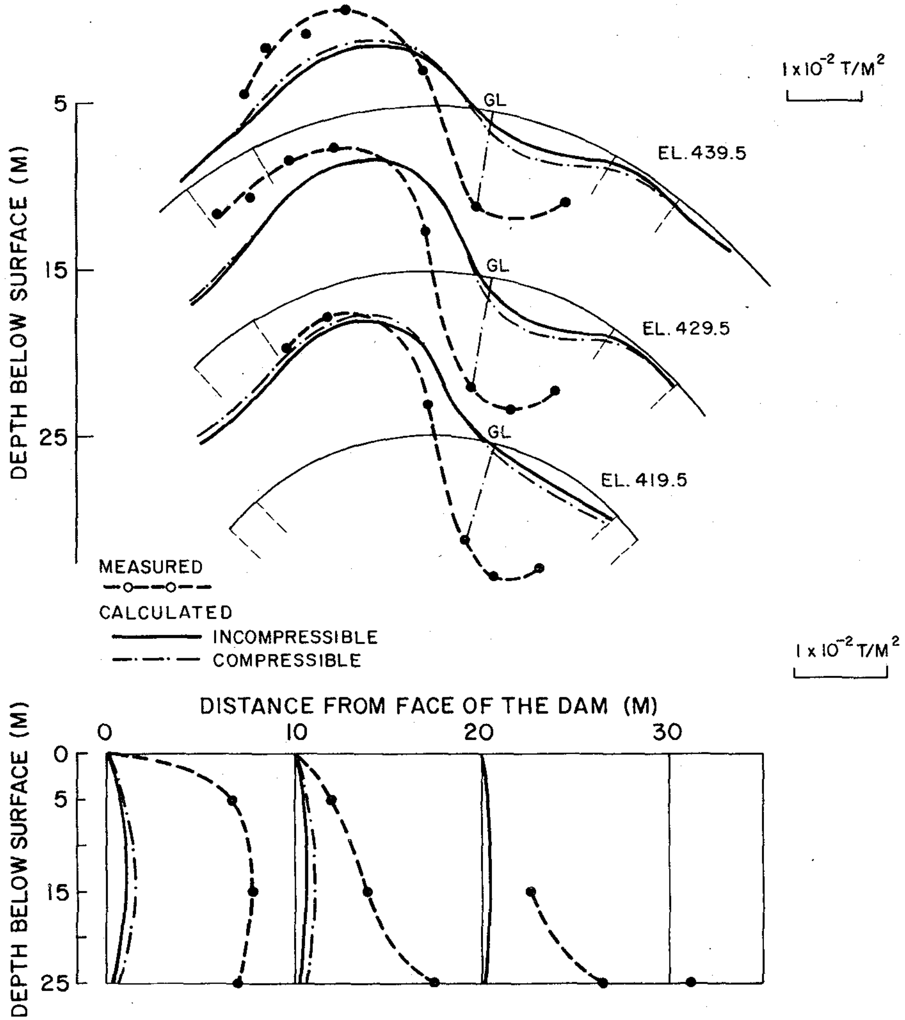


Fig. 4.9 $f_1 = 3.96$ Hz

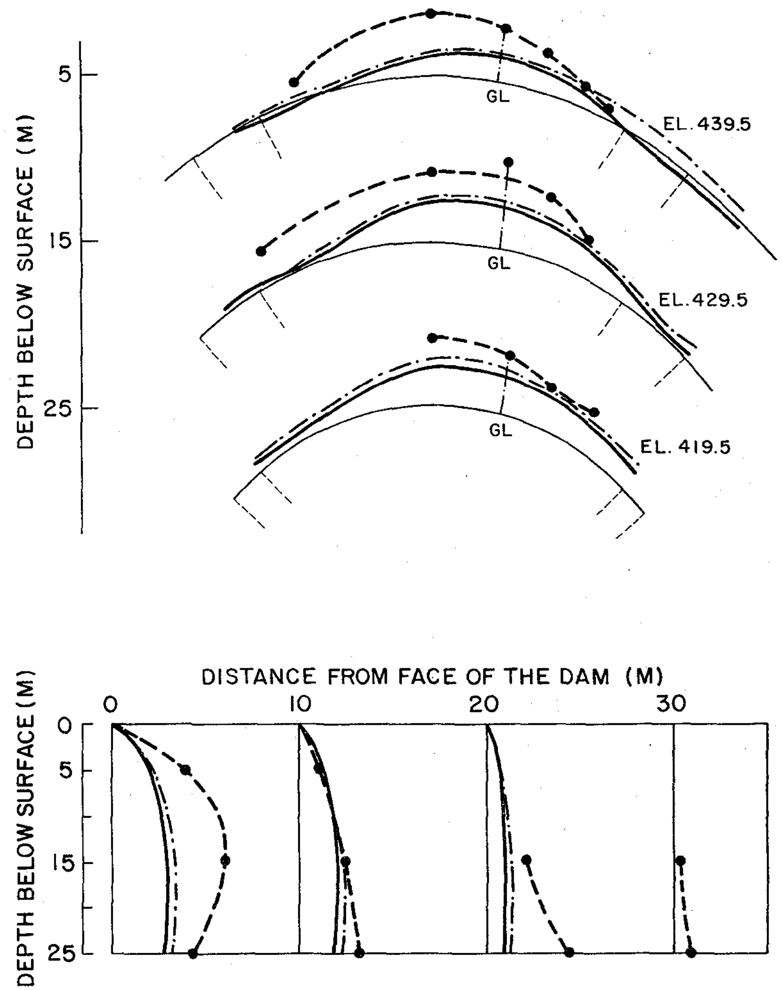


Fig. 4.10 $f_2 = 4.30$ Hz

Forced Vibration Hydrodynamic Pressures for Quan Shui Dam

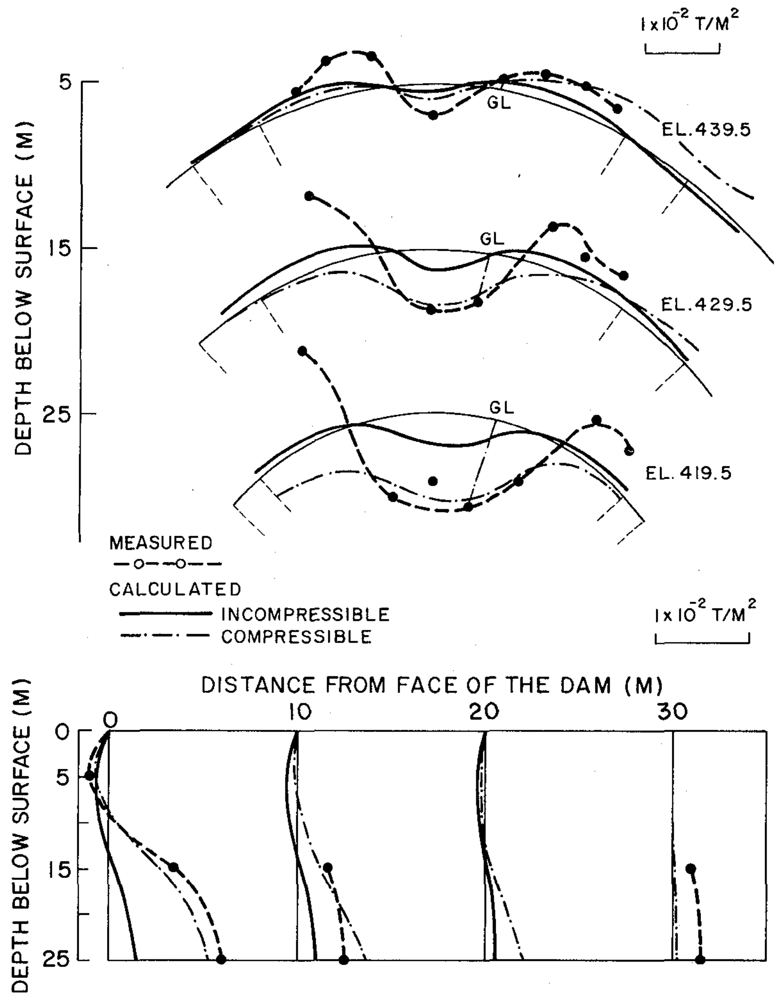


Fig. 4.11 f_3 = 6.85 Hz

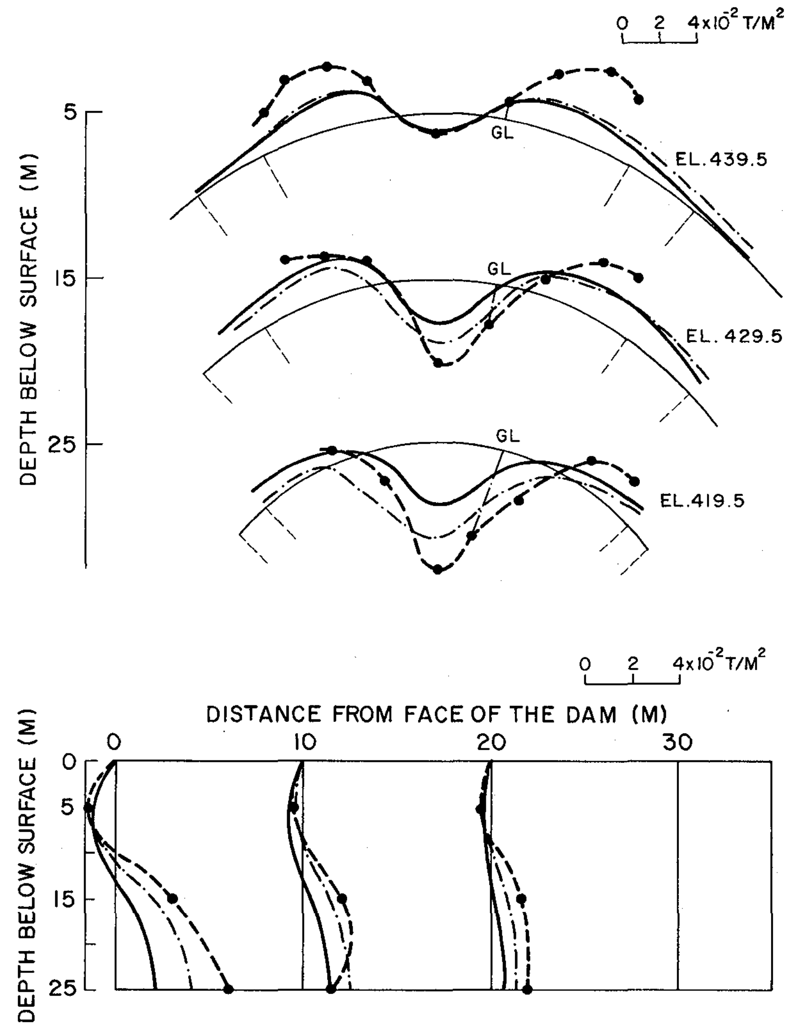


Fig. 4.12 f_4 = 7.75 Hz

Forced Vibration Hydrodynamic Pressures for Quan Shui Dam

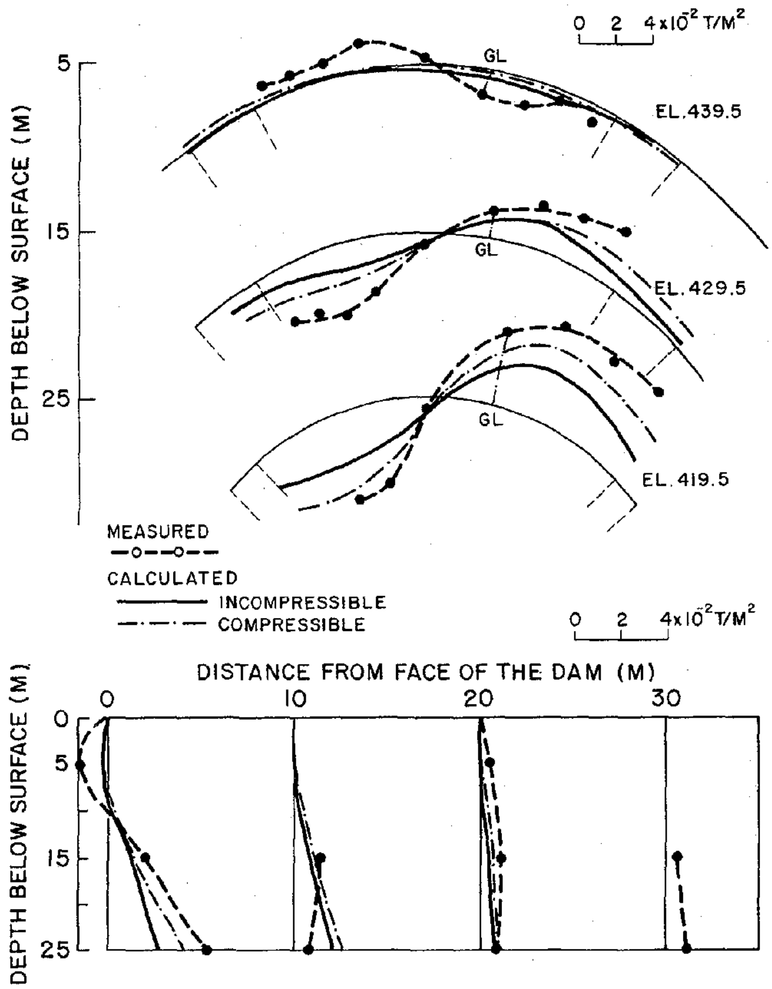


Fig. 4.13 f_5 = 8.83 Hz

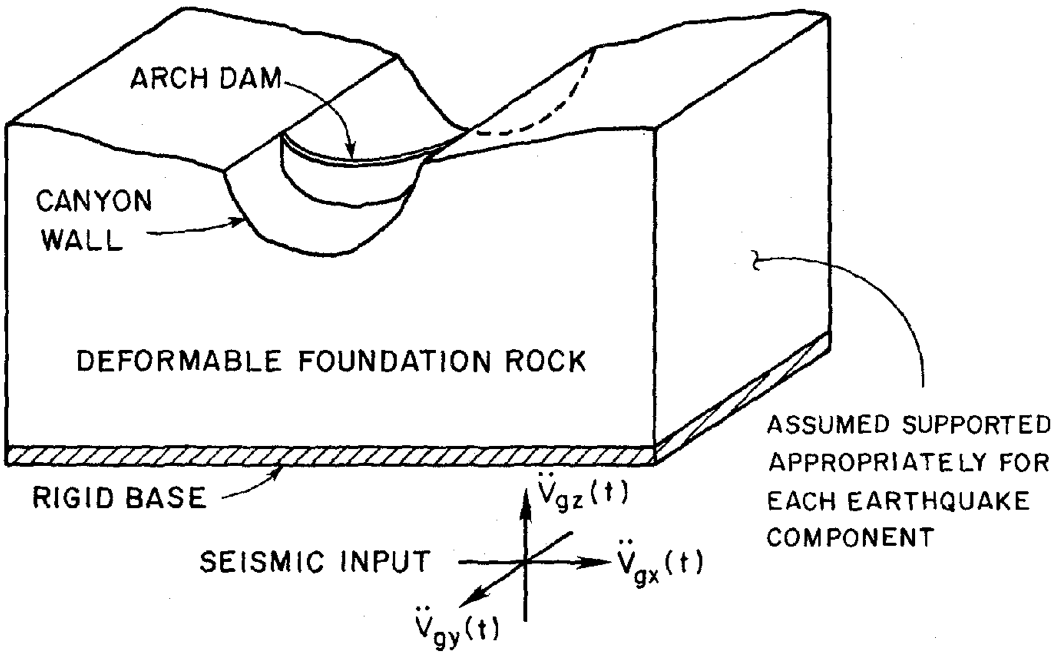


Fig. 5.1 Seismic Input Mechanisms for Arch Dam and Canyon Model

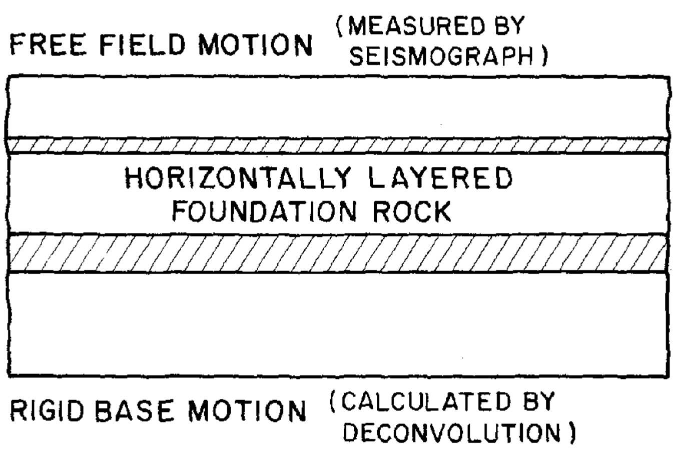


Fig. 5.2 One-Dimensional Deconvolution Model

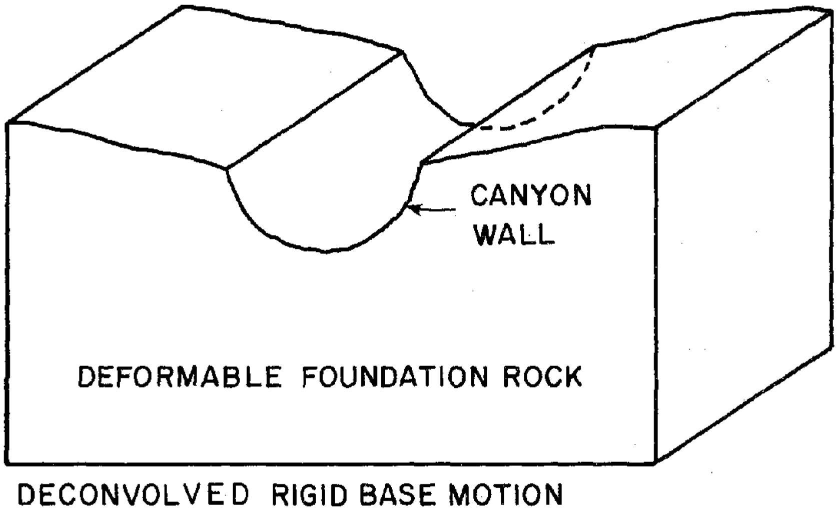


Fig. 5.3 Two-Dimensional Canyon "Scattering" Model

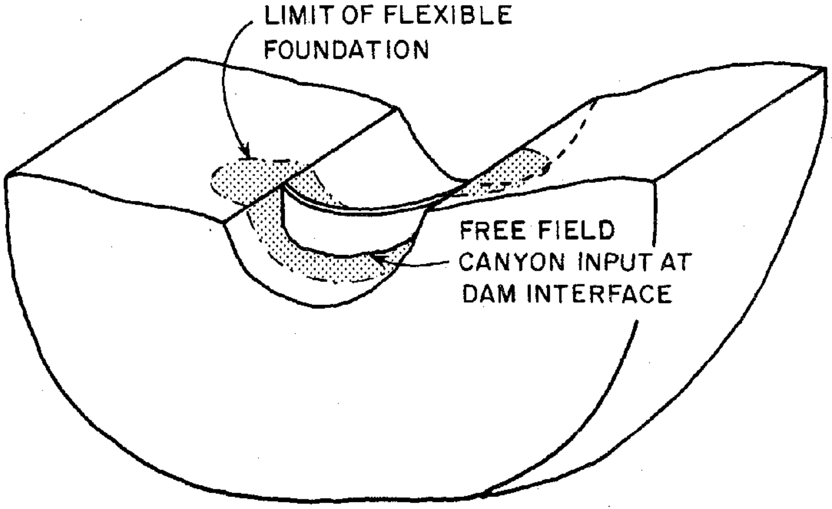
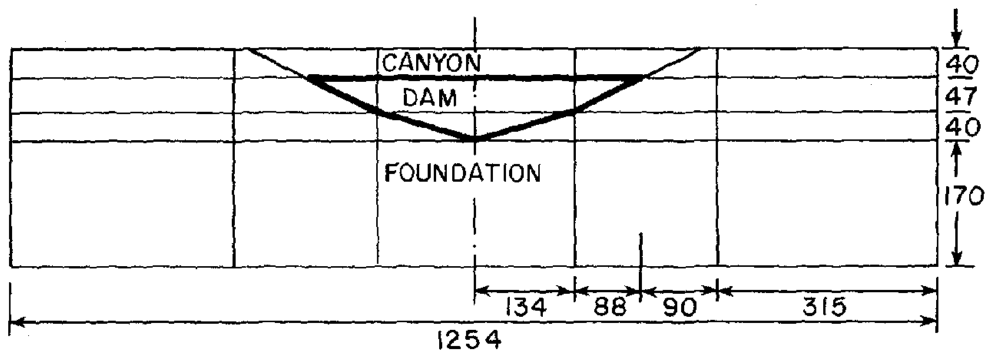
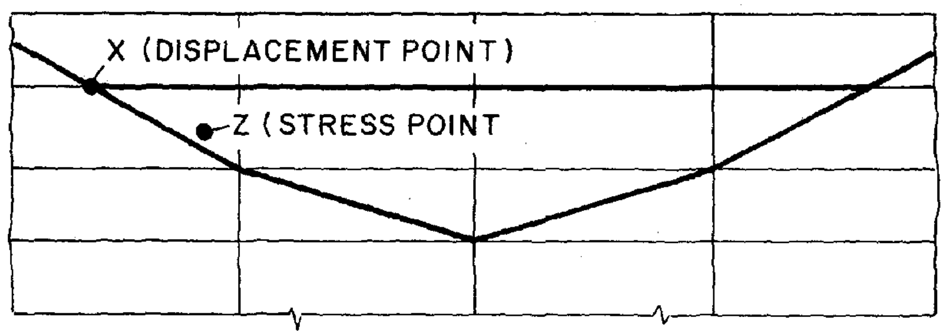


Fig. 5.4 "ADAP" Foundation Rock for Free-Field Input



(a) FINITE ELEMENT MESH OF DAM-CANYON-FOUNDATION



(b) LOCATION OF DISPLACEMENT AND STRESS POINTS IN DAM

Fig. 5.5 Plane Stress Model of Dam and Canyon

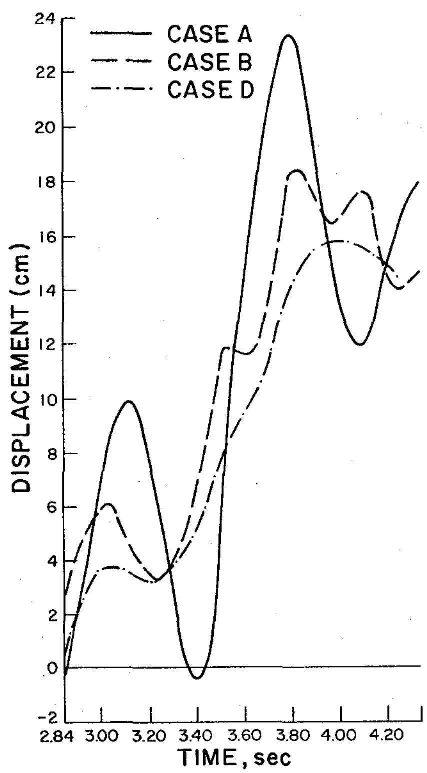


Fig. 5.6 Total Displacement History of Point "X"

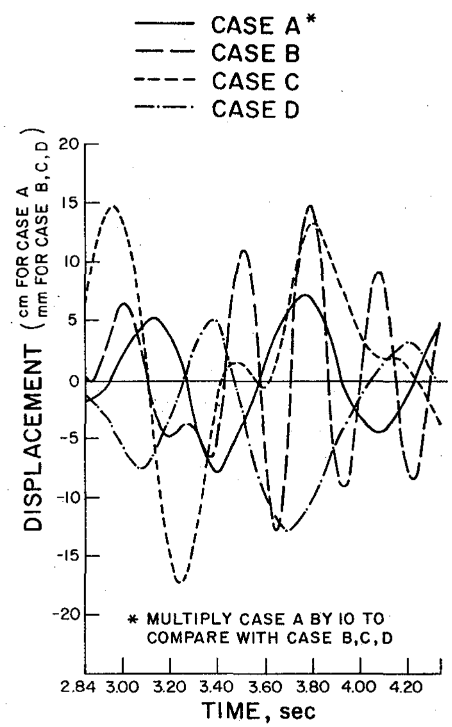


Fig. 5.7 Relative Displacement History of Point "X"

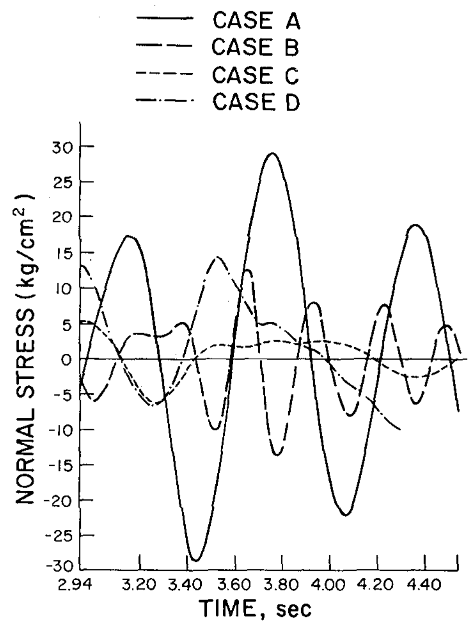


Fig. 5.8 Horizontal Normal Stress History at Point "Z"

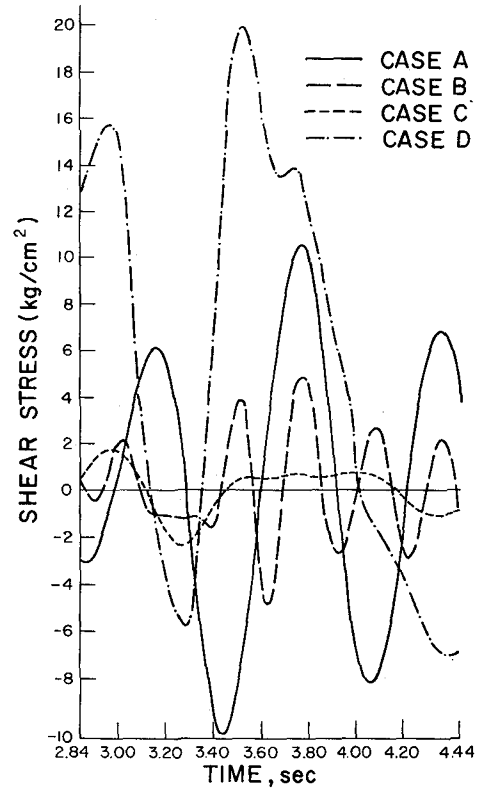


Fig. 5.9 Shear Stress History at Point at Point "Z"

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NOTE: Numbers in parentheses are Accession Numbers assigned by the National Technical Information Service; these are followed by a price code. Copies of the reports may be ordered from the National Technical Information Service, 5285 Port Royal Road, Springfield, Virginia, 22161. Accession Numbers should be quoted on orders for reports (PB --- ---) and remittance must accompany each order. Reports without this information were not available at time of printing. The complete list of EERC reports (from EERC 67-1) is available upon request from the Earthquake Engineering Research Center, University of California, Berkeley, 47th Street and Hoffman Boulevard, Richmond, California 94804.

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UCB/EERC-79/02 "The Development of a Mathematical Model to Predict the Flexural Response of Reinforced Concrete Beams to Cyclic Loads, Using System Identification," by J. Stanton & H. McNiven - Jan. 1979(PB 295 875)A10

UCB/EERC-79/03 "Linear and Nonlinear Earthquake Response of Simple Torsionally Coupled Systems," by C.L. Kan and A.K. Chopra - Feb. 1979(PB 298 262)A06

UCB/EERC-79/04 "A Mathematical Model of Masonry for Predicting its Linear Seismic Response Characteristics," by Y. Mengi and H.D. McNiven - Feb. 1979(PB 298 266)A06

UCB/EERC-79/05 "Mechanical Behavior of Lightweight Concrete Confined by Different Types of Lateral Reinforcement," by M.A. Manrique, V.V. Bertero and E.P. Popov - May 1979(PB 301 114)A06

UCB/EERC-79/06 "Static Tilt Tests of a Tall Cylindrical Liquid Storage Tank," by R.W. Clough and A. Niwa - Feb. 1979 (PB 301 167)A06

UCB/EERC-79/07 "The Design of Steel Energy Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety: Volume 1 - Summary Report," by P.N. Spencer, V.F. Zackay, and E.R. Parker - Feb. 1979(UCB/EERC-79/07)A09

UCB/EERC-79/08 "The Design of Steel Energy Absorbing Restrainers and Their Incorporation into Nuclear Power Plants for Enhanced Safety: Volume 2 - The Development of Analyses for Reactor System Piping,""Simple Systems" by M.C. Lee, J. Penzien, A.K. Chopra and K, Suzuki "Complex Systems" by G.H. Powell, E.L. Wilson, R.W. Clough and D.G. Row - Feb. 1979(UCB/EERC-79/08)A10

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