Title

EACD-3D-96: a computer program for three-dimensional earthquake analysis of concrete dams

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Publication Date

1996-10-01

REPORT NO.
UCB/SEMM-96/06

STRUCTURAL ENGINEERING
MECHANICS AND MATERIALS

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A COMPUTER PROGRAM FOR THREE-DIMENSIONAL EARTHQUAKE ANALYSIS OF CONCRETE DAMS

BY

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AUGUST 1997

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UNIVERSITY OF CALIFORNIA, BERKELEY

Structural Engineering Mechanics and Materials

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Report Number UCB/SEMM-96/06
October 1996
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ACKNOWLEDGMENTS

This research investigation was supported by the National Science Foundation under Grant BCS-9121943. The authors are grateful for this support.

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1. INTRODUCTION

The computer program EACD-3D, originally developed in 1986 [1], implements the analytical procedure for three-dimensional analysis of earthquake response of concrete dams [2-5] including the effects of dam-water interaction, water compressibility, reservoir boundary absorption due to alluvium and sediments at the bottom and possibly at sides of actual reservoirs. The flexibility of the foundation rock is included in the computer analysis but its inertia and damping effects were ignored.

The response analysis procedure has recently been extended to include the inertia and damping effects of the foundation rock [6,7]. Thus, the various effects of dam-foundation rock interaction — including the effects of foundation flexibility, inertia, material damping, and radiation damping arising from the interaction — are included in the analysis. The computer program EACD-3D has been modified and extended to EACD-3D-96 to implement this new procedure. As before, the dam and fluid domain substructures are modeled by three-dimensional finite elements; however, the foundation rock region is modeled by boundary elements on the surface of the canyon along the dam-foundation rock interface. The number of boundary elements needed is considerably smaller than the number of finite elements required in EACD-3D to model the huge foundation rock region [1]. Furthermore, these surface boundary elements are much easier to generate than three-dimensional finite elements.

The analytical procedure underlying the computer program EACD-3D-96 assumes linear behavior for concrete dam, impounded water and foundation rock. Thus the possibilities of concrete cracking, construction joints of the dam opening during vibration, and water cavitation are not considered.

The computer program EACD-3D-96 has been developed to perform three dimensional analysis of concrete dams. Thus the earthquake response of arch dams, which must be treated as three-dimensional systems, can be analyzed. Concrete gravity dams are traditionally built as a series of monoliths, usually with straight contraction joints, either grouted or ungrouted. Such joints would slip and the monoliths tend to vibrate independently, as evidenced by the spalled concrete and increased water leakage at the joints of Koyna Dam during the Koyna Earthquake of December 11, 1967 [8]. For such dams, a two-dimensional, plane stress idealization of the individual monoliths appears to be appropriate for predicting their earthquake response. On the other hand, three-dimensional idealizations would be usually necessary for concrete gravity dams with keyed contraction joints. For rollcrete dams which are built without joints, two-dimensional, plane-strain idealization may be appropriate if the dam is located in a wide valley; otherwise a three-dimensional idealization may be necessary. Three-dimensional analyses of gravity dams can be implemented by this computer program. For two-dimensional earthquake analyses of concrete or rollcrete gravity dams, a computer program EAGD-84 is available [9], in which a viscoelastic half-plane idealization is used for the foundation-rock region, considering the inertial, flexibility, and material as well as radiation damping effects of the foundation rock.

This report is intended as a user's guide for EACD-3D-96. Selected features of the computer program, which would facilitate its use, are described; idealization of the system is discussed; the required input data are described; the output is explained; and the response results from an example analysis are presented.

2. SYSTEM AND GROUND MOTION

2.1 System Geometry and Assumptions

The system consists of a concrete arch dam supported by flexible foundation rock in a canyon and impounding a reservoir of water in the upstream direction (Figure 2.1). Although the arch dam is usually built in a narrow part of the canyon, in this computer analysis the canyon is assumed to be infinitely long with an arbitrary but uniform cross-section cut in a homogeneous viscoelastic half-space (Figure 2.2). The cross-section of the uniform canyon is uniquely defined by the projection of the mid-surface of the dam on the y-z plane (Figures 2.2). The finite element models of the dam and fluid domain substructures and the boundary element model of the foundation rock substructure are shown in Figure 2.3. The assumption of uniform canyon may introduce incompatibility between the geometries of the dam, foundation rock, and fluid domain [Figure 2.3(d)]. Special methods have been developed to deal with the resulting displacement incompatibility between the dam abutment, the dam-foundation rock interface Γ_i, and the dam-water interface (Section 3.4 of Reference [7]). However, if the special treatment is not applied or is not available, the errors resulting from the displacement incompatibility are small, as shown in Appendix A. The system is analyzed under the assumption of linear behavior for the concrete dam, impounded water, and foundation rock. Note that the x, y, z axes are a right-handed set with x horizontal and pointing upstream, y vertical (up) and z cross-stream.

2.2 Concrete Dam

The concrete arch dam is idealized as an assemblage of finite elements [Figure 2.3(a)]. Thick-shell finite elements [10] are normally used in the major part of the dam and transition elements [10,11] along its junction with foundation rock. The transition elements are designed to connect the thick-shell finite elements in the dam to the surface boundary elements idealizing the foundation rock [Figure 2.3(b)]. Three-dimensional solid elements can also be employed in a three-dimensional

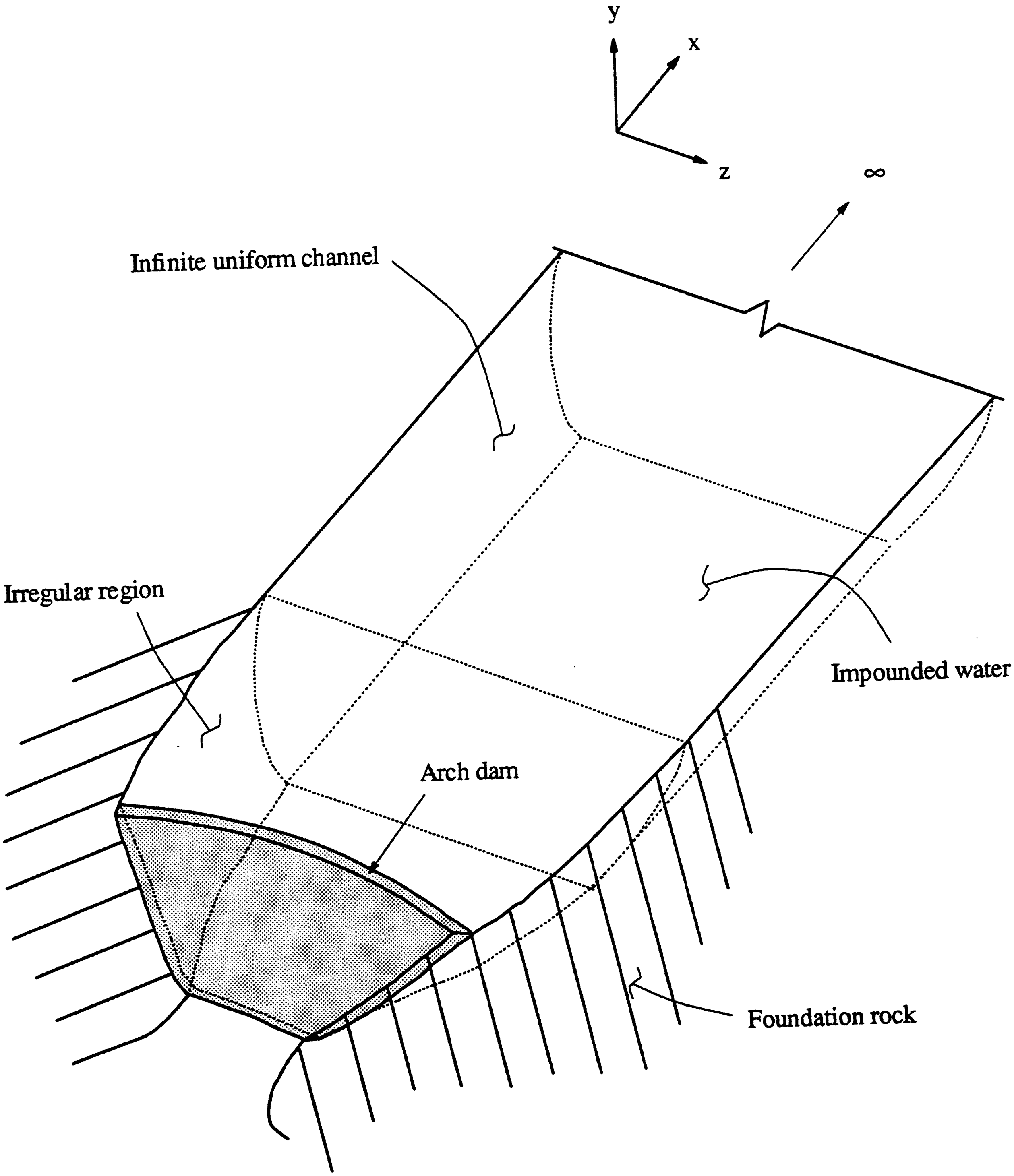


Figure 2.1 Arch dam-water-foundation rock system.

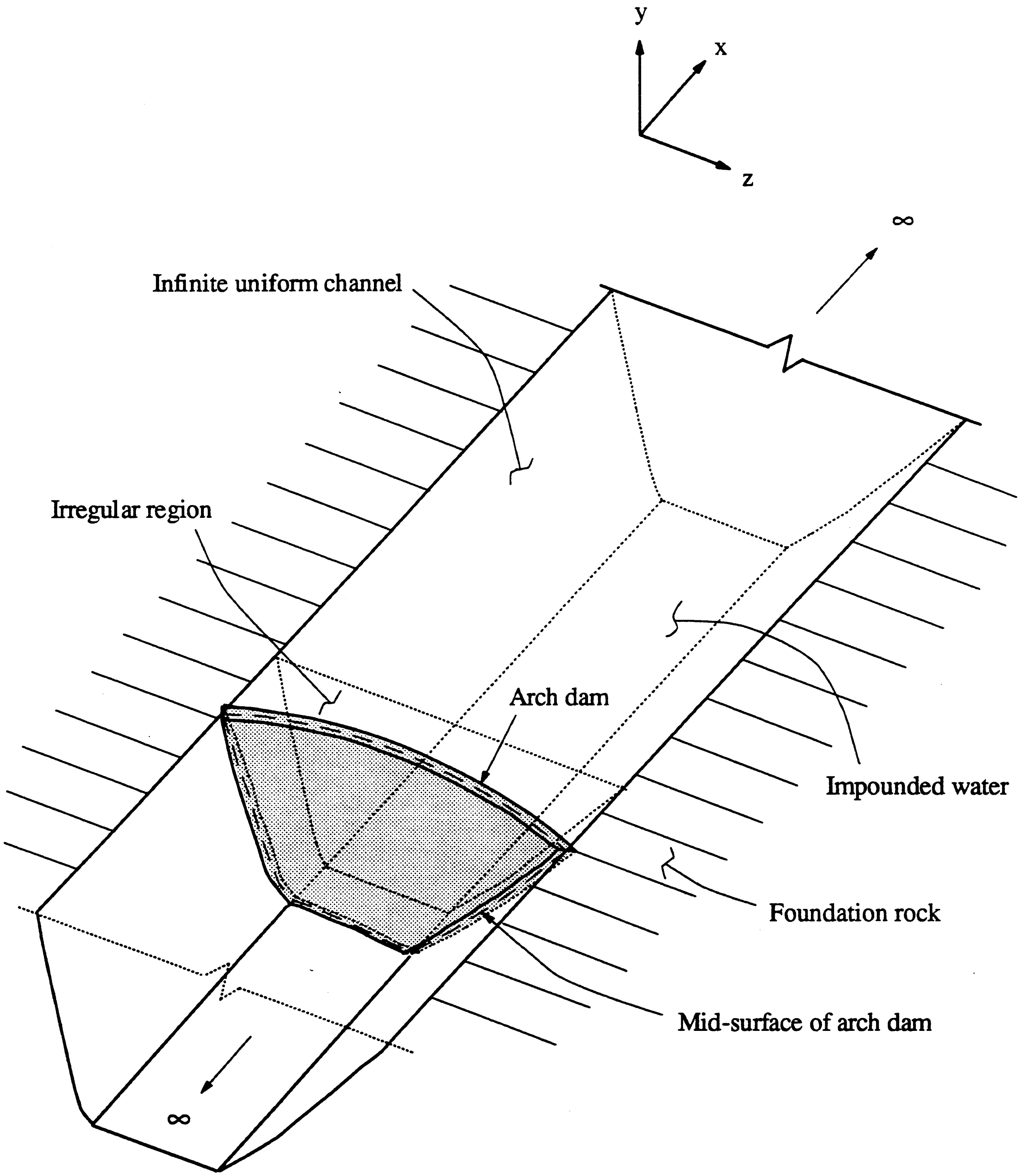
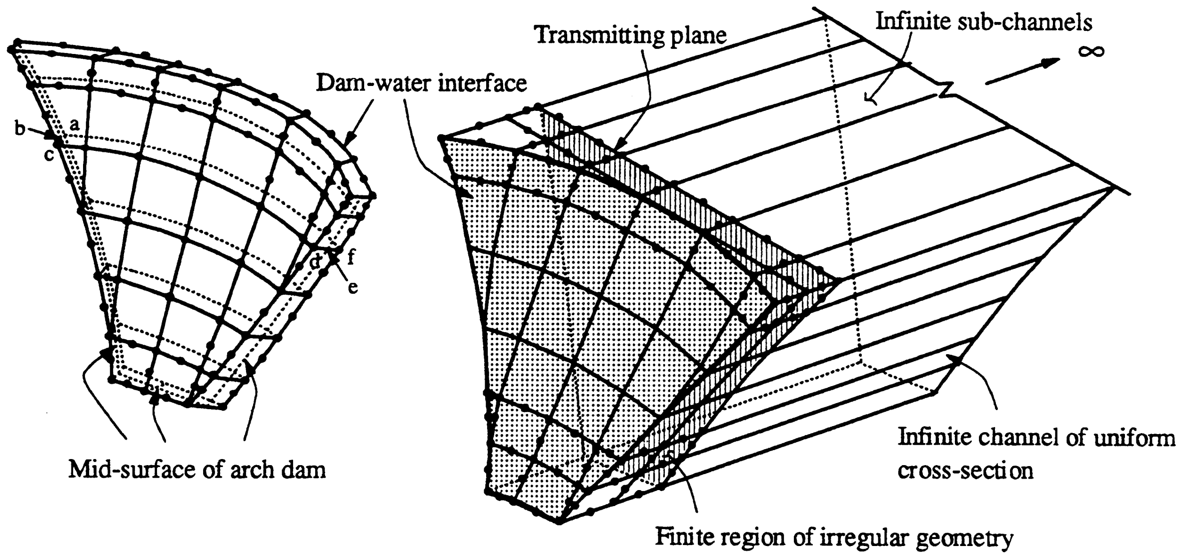
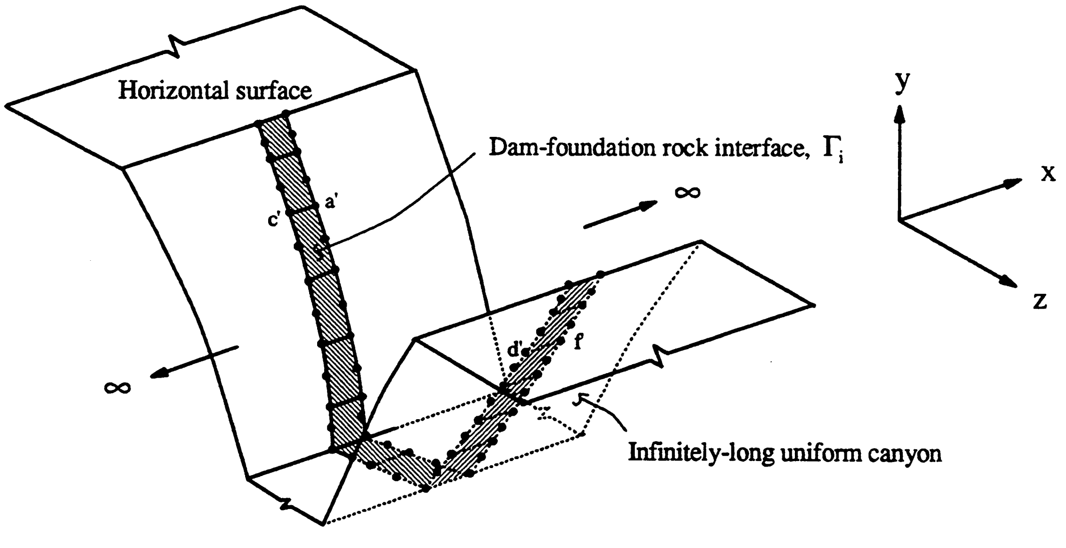


Figure 2.2 Idealized arch dam-water-foundation rock system in an infinitely-long uniform canyon.

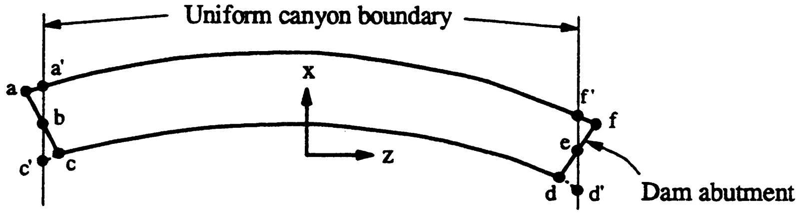


(a) Arch Dam Substructure

(c) Fluid Domain Substructure



(b) Foundation Rock Substructure



(d) Section a-b-c-d-e-f-a of the Arch Dam and its Intersection with the Uniform Canyon

Figure 2.3 (a)-(c) Finite element models of dam and fluid domain substructures and boundary element model of foundation rock [parts (a) and (c) adapted from Reference [4]; (d) Incompatibility between the dam abutment and canyon.

idealization of a gravity dam or a thick arch dam. The properties of each finite element are characterized by the Young's modulus E_s, Poisson's ratio ν_s; and unit weight w_s of the concrete.

The vibrational energy dissipation properties of the dam are characterized by the constant hysteretic damping factor η_s. A viscous damping ratio ξ, the same for all the natural vibration modes of dam on rigid foundation rock with an empty reservoir, corresponds to a constant hysteretic damping factor of $\eta_s = 2\xi$. Forced vibration field tests on dams indicate that the viscous damping ratio is in the range of 1 to 3 percent, fairly independent of the vibration mode number. A constant hysteretic damping factor of $\eta_s = 0.1$, which corresponds to a 5 percent viscous damping ratio in all vibration modes of the dam, is a reasonable value for much larger, but essentially linear, response to earthquake ground motion.

2.3 Foundation Rock

Required in the substructure method for analysis of earthquake response of dams is the complex-valued frequency-dependent impedance (or dynamic stiffness) matrix $\mathbf{S}_f(\omega)$ for the foundation rock, defined at the nodal points on the dam-foundation rock interface Γ_i, relating the interaction forces at the dam-foundation rock interface to the corresponding displacements relative to the earthquake-induced displacements in the absence of the dam [Figure 2.3(b)]. Evaluation of these forces requires solution of a series of mixed boundary value problems (BVPs) with displacements prescribed at the interface Γ_i and tractions prescribed as zero outside Γ_i — on the canyon wall and the half-space surface. Instead of directly solving this mixed BVP, it is more convenient to solve a stress BVP in which non-zero tractions are specified at the interface Γ_i and the resulting displacement at Γ_i are determined. Assembled from these displacements, the dynamic flexibility influence matrix is inverted to determine the impedance matrix $\mathbf{S}_f(\omega)$.

A direct boundary element procedure has been developed to determine the impedance matrix assuming the canyon to be infinitely-long with uniform cross-section [12,13]. Such assumption permits analytical integration along the canyon axis of the three-dimensional boundary integral equation. Thus, the original three-dimensional problem is reduced to an infinite series of two-dimensional problems, each of which corresponds to a particular wave number and involves Fourier transforms of full-space Green's functions. Appropriate superposition of the solutions of these two dimensional boundary value problems leads to a dynamic flexibility influence matrix which is inverted to determine the impedance matrix. This procedure is shown to be more accurate and efficient than the general three-dimensional boundary element method [12,13].

For this direct boundary element procedure, the dam-foundation rock interface is discretized into a set of boundary elements with their nodal points matching the finite element idealization of the dam [Figure 2.3(b)]. The properties of the foundation rock are characterized by its Young's modulus E_f, Poisson's ratio ν_f, and unit weight w_f. The vibrational energy dissipation properties of the foundation rock are characterized by the constant hysteretic damping factor η_f.

2.4 Impounded Water

The reservoir behind a dam is of complicated shape, as dictated by the natural topography of the site. Typically the impounded water extends to great distances, up to a few tens of miles, in the upstream direction. Finite element idealizations are necessary to properly represent the complicated geometry of the impounded water. But such an idealization should be exorbitantly expensive, to the point of becoming impractical, if the standard finite element idealization was employed to large distances in the upstream direction.

The fluid domain, bounded by the upstream face of the dam and the uniform canyon surface, is idealized as a finite region of irregular geometry adjacent to the dam connected to an infinite uniform channel — a region that extends to infinity along the upstream direction (x axis) with uniform y-z cross section (Figure 2.2). With this restriction, it is possible to efficiently recognize the infinite extent of the reservoir in the upstream direction.

For computer analysis, the finite region of irregular geometry is idealized as an assemblage of three-dimensional finite elements as shown in Figure 2.3(c). Each nodal point of the irregular fluid region on the upstream dam face boundary must correspond with a dam node at the dam-water interface. Therefore the finite element mesh for dam should be selected to be compatible with the design water level in the reservoir. For the infinite channel of uniform cross section, a finite element discretization of the cross section, compatible with the discretization of the irregular region over the common cross-section — the transmitting plane in Figure 2.3(c) — combined with a continuum representation in the infinite direction provides for the proper transmission of pressure waves. Physically this treatment can be interpreted as a discretization of the fluid domain into sub-channels of infinite length [Figure 2.3(c)]. The properties of the impounded water are characterized by the unit mass ρ and the velocity of pressure waves in water C.

The computer program can also handle impounded water extending to a finite distance. In this case, the entire fluid domain is idealized as an assemblage of finite elements.

2.5 Absorptive Reservoir Bottom and Sides

The absorptiveness of the alluvium, silt and other sedimentary materials at the bottom and possibly sides of the reservoir is characterized by the wave reflection coefficient α, which is the ratio of the amplitude of the reflected hydrodynamic pressure wave to the amplitude of a propagating pressure wave incident normally at the reservoir boundary. The value $\alpha = 1$ indicates that pressure waves are completely reflected; and $\alpha = 0$ indicates that the waves are fully absorbed into the reservoir bottom materials without reflection. The materials at the bottom and sides of the reservoir determine the value of the wave reflection coefficient α according to the following equation:

$$\alpha = \frac{1-k}{1+k}$$

where $k = \rho C / \rho_r C_r$, $C_r = \sqrt{E_r / \rho_r}$, and ρ_r are the elastic modulus and unit mass of the reservoir bottom-sides materials.

Because for narrow and steep canyons, the sediments may be essentially confined to the reservoir bottom, the computer program permits the option that only a portion of the reservoir boundary is absorptive. Thus non-absorptive reservoir sides with an absorptive reservoir bottom can be modeled by the program.

No field data are presently available for the wave reflection coefficient at actual reservoirs behind dams. In the absence of such data $\alpha = 0.90$ to 1 is recommended for proposed new dams or recent dams where sediment deposits are meager, and $\alpha = 0.75$ to 0.90 is recommended for older dams with substantial sediment deposits.

2.6 Ground Motion

In earthquake response analysis of dams by the substructure method, the earthquake input is specified as the free-field ground motion at the dam-foundation rock interface [2]. In the 1996 version of this computer program, the free-field motion is assumed to be uniform along the dam-foundation rock interface and over the reservoir sides and bottom and in the upstream direction (water-foundation rock interface), except as controlled by the parameter NYZ in the program. With this parameter it is possible to specify that the ground motion is limited to a finite distance in the upstream direction (see Chapter 9 — Subprogram 6). The ground acceleration is defined by its three components: $a_g^x(t)$ in the upstream direction, $a_g^z(t)$ in the cross-stream direction, and $a_g^y(t)$ in the vertical direction.

3. OUTLINE OF ANALYTICAL PROCEDURE

The computer program EACD-3D-96 implements the analytical procedure developed [6,7] for three-dimensional analysis of the dam-water-foundation rock system, idealized in accordance with the preceding section, to determine the earthquake response of concrete dams. This procedure is an extension of the earlier analysis procedure [2-5] to consider inertia and damping — material and radiation — effects of the foundation rock supporting the dam. The effects of water-foundation rock interaction are not included because they are small [7]. The static analysis considers only the effects of the weight of the dam and hydrostatic pressures on the upstream face of the dam. Thermal effects in the concrete or construction sequence of the dam are not included.

The overall efficiency of the dynamic analysis procedure lies in representing the dam, the impounded water, and the foundation rock as three substructures of the complete system, with appropriate idealizations for each; and in a dramatic reduction in the degrees of freedom (DOFs) by transforming the displacements of the dam to generalized coordinates. For computational efficiency the computer program incorporates several features: (1) efficient analytical formulations and computational procedures for evaluating the hydrodynamic terms [4,5], (2) use of rational expressions as interpolating functions for the frequency response functions for the modal coordinates of a structure to reduce the number of frequency points at which a response function must be computed exactly [4,5], and (3) use of a cubic interpolation scheme to reduce the number of frequency values for which the complex-valued frequency-dependent foundation impedance matrix is computed [6,7].

Thus the resulting analytical procedure and computer program provides an effective tool for computing the earthquake response of proposed designs for new arch dams and in evaluating the seismic safety of existing dams.

4. PROGRAM FEATURES

4.1 Subprograms, Problem Symmetry, and Storage

The computer program is divided into a main section and seven subsections. In the main section, a group of input variables is read. Included in this group are variables that control which of the seven subsections are called. A subsection is called only by the main section, and all information besides the input data needed by the subsections is passed via COMMON statements and disk files (see Table 8.1). The main section and seven subsections will be referred to as the Main Program and Subprograms 1,2, ···, 7 in the remainder of this report.

Subprograms 1, 2 and 3 deal with the dam-foundation rock system. The boundary element mesh of the dam-foundation rock interface is input in Subprogram 1 where the foundation impedance matrix is computed at selected frequencies. The dam mesh is input in Subprogram 2 where element stiffness, mass and stress transformation matrices are computed. The dam stiffness and mass matrices are assembled in Subprogram 3; included is the foundation stiffness matrix (i.e., the foundation impedance matrix at the frequency of zero) computed from Subprogram 1. Following the assembly, the eigenproblem of the dam-foundation rock system is solved for the natural frequencies and mode shapes (the generalized coordinates) in dynamic analysis; while the self-weight load vector of the dam is computed for static analysis. Subprograms 4 and 5 deal with the fluid domain, defining Meshes 1 and 2 as well as the three boundary meshes (Meshes 3, 4 and 5); these are described in detail in Section 5.1. The Mesh 1 and 2 matrices are assembled and the Mesh 2 eigenproblem (used to construct the transmitting plane matrix) is solved at an excitation frequency of zero in dynamic analysis. The computations which are performed with the matrices from the boundary meshes are related to the fluid domain load vectors and dam-fluid connectivity. In static analysis, the hydrostatic pressure load vector on the dam is computed. In Subprogram 6, the frequency responses of the dam and fluid domain are computed. Included in this computation are Mesh 2 eigensolutions at non-zero excitation frequencies, solution of the Mesh 1 equations, and solution of the dam equations in terms of the generalized coordinates. Under the static solution option, the static response of the dam is computed in Subprogram 6. Time history responses of the dam are computed in Subprogram 7.

The program can analyze dam-water-foundation rock systems symmetric or non-symmetric about the x-y plane. For symmetric systems, the program permits use of a mesh which extends only to one side of the plane of symmetry. The procedure of running the program for symmetric systems is described in Chapter 8.

The program makes efficient use of matrix storage. All matrices are stored in a blank common array by the method of dynamic storage allocation. The array dimension is set at 400000, but this value can be increased if more storage is desired. In each of the seven subprograms, the actual storage used is printed, or, if current storage is insufficient, the required storage is printed. The program automatically blocks the matrices of the dam-foundation rock system (Subprograms 2 and 3) and the matrices which contain the frequency responses and time history responses of the dam (Subprogram 7). Therefore, no storage limitations are present in these areas of the program. However, blocking is not used for matrices of the foundation impedance matrix and the fluid domain, and this may be a limiting factor when either the boundary element mesh of the dam-foundation rock interface Γ_i, or Mesh 1 of the fluid domain is large. For virtual memory storage computer machines, this storage limitation is usually not a problem because of the large amount of available memory; but it can be a problem if the available amount of memory is limited. In this case, an estimate of the total storage S_1 required for the full complex-valued foundation impedance matrix is

$$S_1 = 2(\mathrm{NNODE} \times 3)^2$$

where NNODE is the total number of nodes on Γ_i. Also a lower bound estimate S_2 of the total storage required by the Mesh 1 matrices, which are stored by the skyline method, is

$$S_2 = 3\sum_{i=1}^{\mathrm{NEQ}} (i - i_{\min} + 1)$$

where NEQ = number of equations in the fluid domain mesh and i_{min} is the minimum equation number connected to equation i (Equation numbers are similar to node numbers except zero pressure nodes are not counted). All equations on the transmitting plane [Figure 2.3(c)] should be considered coupled to each other because of the transmitting plane matrix [2].

4.2 Implementation on Other Computers

The program has now been written for VAX computer and workstations with UNIX operating system. It contains features which facilitate implementation on other computers. One of these features is the use of standard, basic FORTRAN throughout. Other features are discussed below.

1. Integer variables of the form MTi are used as unit numbers in READ and WRITE statements. These unit numbers are assigned in the Main Program.
2. Preceding each READ (MT5, format statement number) statement are free format READ (MT5, *) statements which appear as comment lines (C in column one). To change to free format, switch the C in column one from the fixed READ to the free READ.

The program is in double precision which is usually required on VAX computers. Implementation on other computers, such as CDC and CRAY machines, may require only single precision. Implementation on another computer may also require addition of the PROGRAM record in the Main Program and possibly introducing an overlay structure. Because of the way the program is written and the information is transferred between the Main Program and the subprograms, an overlay structure is possible to save much storage for computer machines with limited available amount of memory [1].

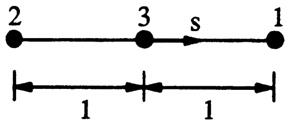
The CPU time for each subprogram run is printed by calling subroutine getime, which in turn calls subroutine dtime from the VAX FORTRAN library to calculate the CPU time. For machines without such function, the user should remove the entire subroutine getime and all FORTRAN statements calling it in the main program. Consequently, no CPU time is output (see Chapter 10).

5. DESCRIPTION OF FINITE AND BOUNDARY ELEMENTS

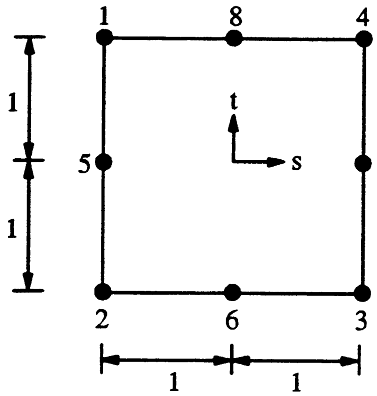
5.1 Fluid Elements

Finite elements used to discretize the impounded water are derived in the appendices of Reference [2]. They result from solution of the pressure wave equation and thus have only one unknown, the hydrodynamic pressure at each node. The following element types are employed: line, triangular, rectangular, triangular prism, and rectangular prism. The elements are shown in Figures 5.1(a) to 5.1(e) in their undistorted or parent form. They are isoparametric and can be mapped into distorted shapes. The local element axes s, t, r are also shown; these are area coordinates [19] in the triangular domains. The nodal numbering indicated is the order in which the actual node numbers must be input in an element's LM array (see Chapter 9 – Subprogram 4). Quadratic shape functions are employed; they default to linear shape functions where non-corner nodes are omitted. Element types are denoted by the input value of NELTY (see Chapter 9 – Subprogram 4).

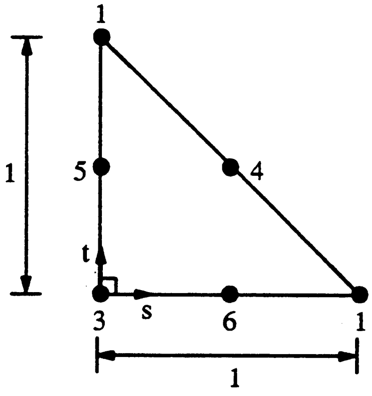
The above-mentioned types of finite elements are used in different portions of the finite element discretization for the impounded water. In the finite element model for an infinite reservoir consisting of an irregular region next to the dam and an infinite channel of uniform cross-section, it is convenient to identify five meshes, or sub-meshes (Figure 5.2): Mesh 1 discretizes the entire irregular region of the reservoir; Mesh 2 spans the transmitting plane — the plane connecting the irregular region with the infinite uniform channel; Mesh 3 discretizes the dam-water interface of the reservoir; Mesh 4 spans the reservoir bottom and sides of the irregular region; and Mesh 5 discretizes the bottom and sides of the transmitting plane. It is similarly convenient to identify two types of nodal points in the finite element model of the irregular region of an infinite reservoir (Figure 5.2): Type 1 includes all nodal points not on the transmitting plane, and Type 2 includes all nodal points on the transmitting plane. The finite element model for a finite reservoir, consisting of only an irregular region, does not contain Type 2 nodal points nor Meshes 2 and 5. Some comments on the use of the various types of finite elements in the five meshes are as follows.



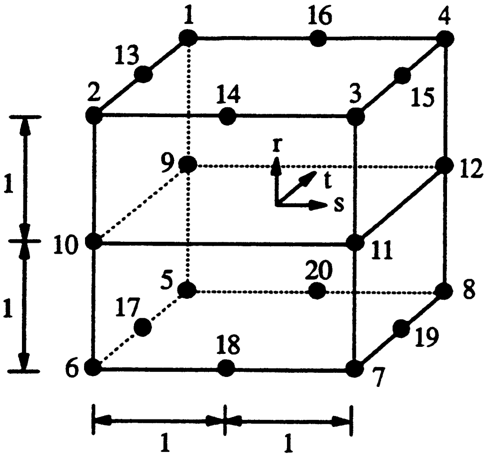
(a) Line element; NELTY = 1



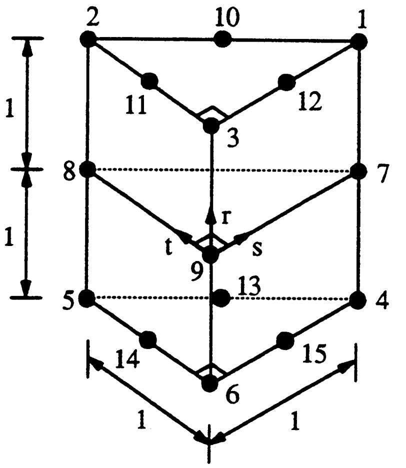
(b) Rectangular element; NELTY = 2



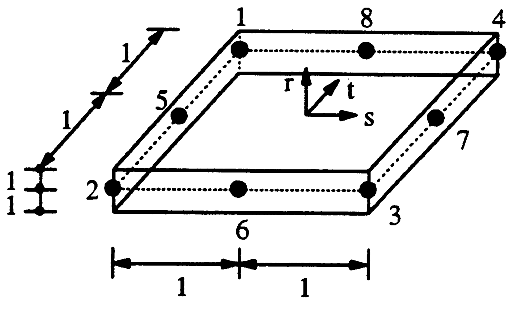
(c) Triangular element; NELTY = 3



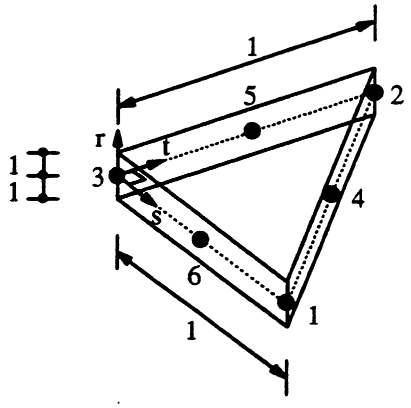
(d) Rectangular prism element; NELTY = 4



(e) Triangular prism element; NELTY = 5



(f) Rectangular shell element; NELTY = 6



(g) Triangular shell element; NELTY = 7

Figure 5.1 Finite and boundary element type. Elements are shown in undistorted or parent form.

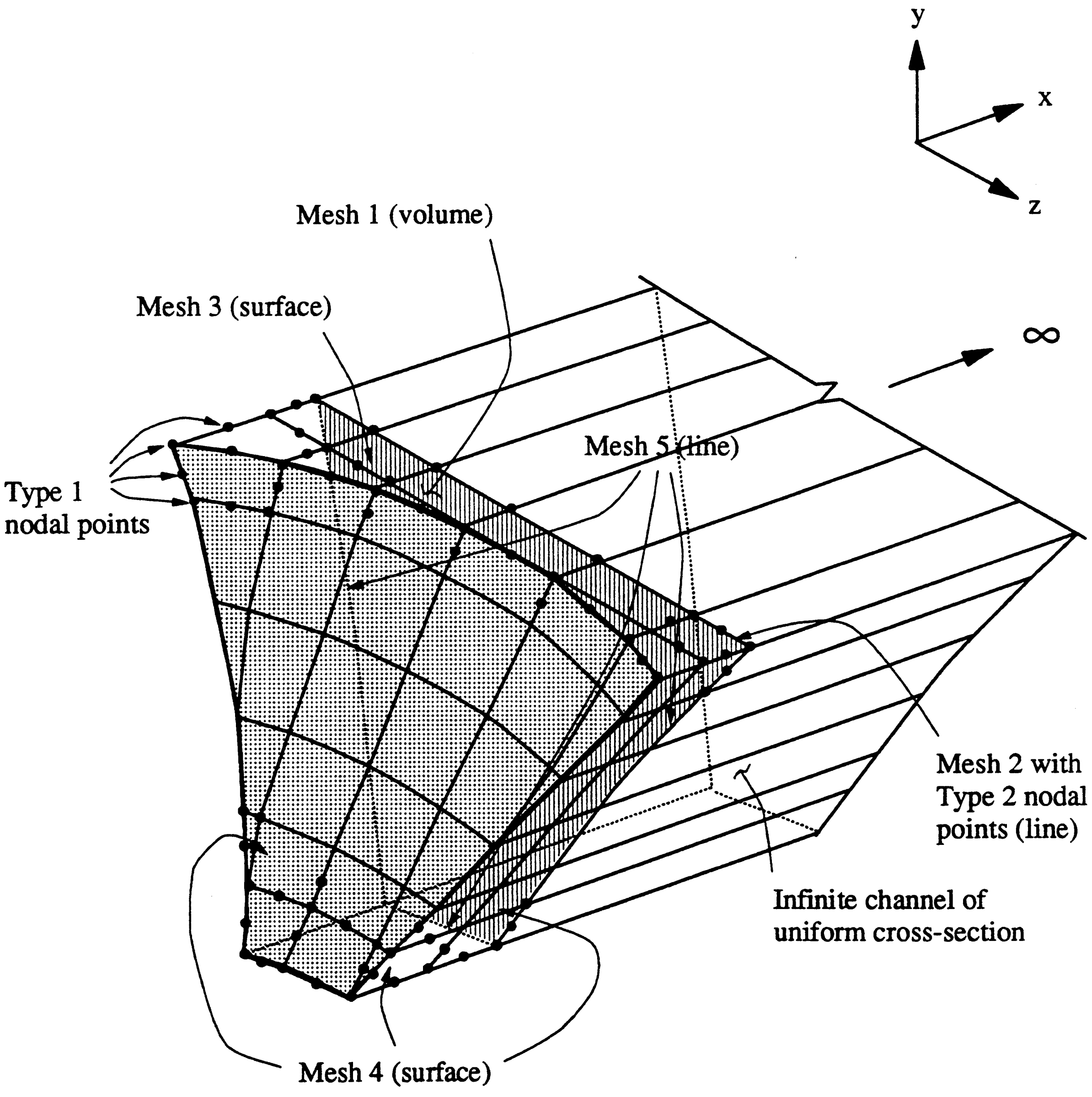


Figure 5.2 Infinite reservoir domain illustrating Type 1 and Type 2 nodal points and the Meshes 1, 2, 3, 4, and 5.

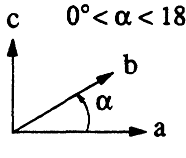
The line element (NELTY = 1) is a variable 2 to 3 node element. Node 3 can be omitted. When used in Mesh 5 (Figure 5.2), the element is mapped onto a y-z plane, and $s \times x$ should point inside the finite element mesh.[†] Thus, to an observer located downstream of the transmitting plane, each element's s axis should be directed along a counter-clockwise path around the transmitting plane [Figure 5.3(a)].

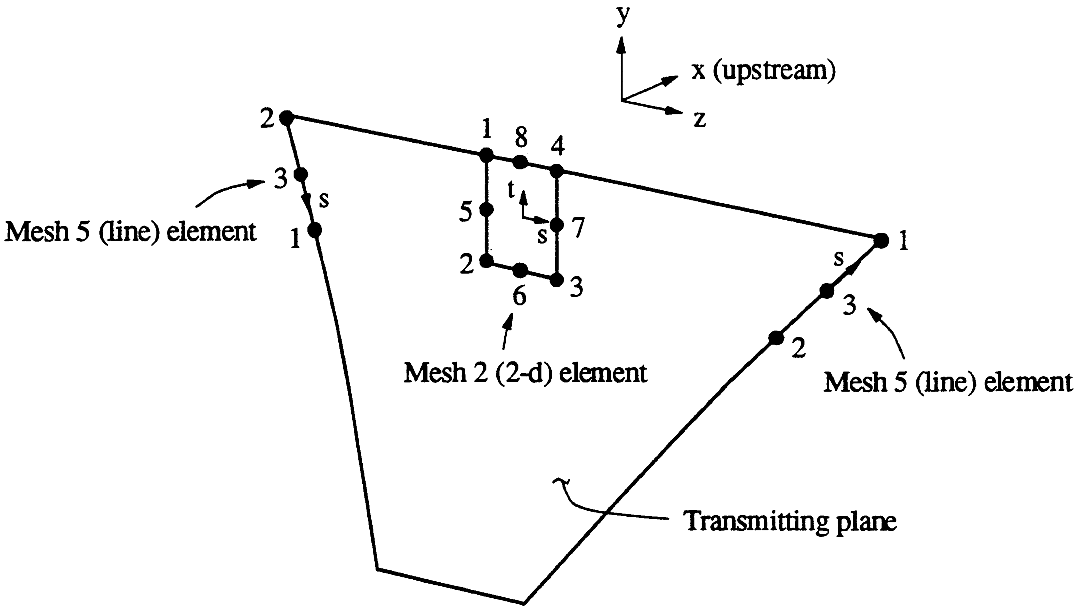
Two-dimensional elements can be triangular or rectangular. The rectangular element (NELTY = 2) is a variable 4 to 8 node element. Any or all of nodes 5, 6, 7, 8 can be omitted. The triangular element (NELTY = 3) is a variable 3 to 6 node element. Any or all of nodes 4, 5, 6 can be omitted. When used in Mesh 2 (Figure 5.2), the elements are mapped onto a y-z plane, and $s \times t$ should point in the negative x direction [Figure 5.3(a)]. When used in Mesh 3 or Mesh 4 (Figure 5.2), the elements are mapped into x, y, z space, and $s \times t$ should point outside the finite element mesh. Thus, to an observer located outside the finite element mesh, the nodes should be numbered counter-clockwise [Figure 5.3(b)].

Three-dimensional elements can be triangular prism or rectangular prism (Figure 5.1). The rectangular prism element (NELTY = 4) is a variable 8 to 20 node element. Any or all of nodes 9, 10, 11, ···, 19, 20 can be omitted. The triangular prism element (NELTY = 5) is a variable 6 to 15 node element. Any or all of nodes 7, 8, 9, ···, 14, 15 can be omitted. These elements are used in Mesh 1 (Figure 5.2) and are mapped into x, y, z space in any orientation.

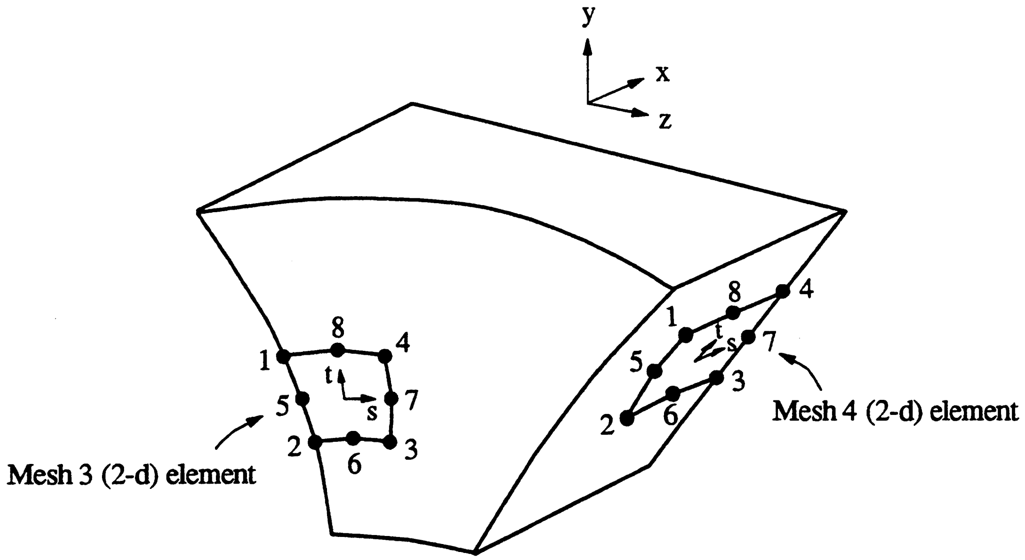
Other element shapes can be constructed by superimposing 2 or more corner nodes. This entails repeating the actual node numbers in an element's LM array. Before superimposing corner nodes, the in-between mid-side nodes should be omitted. An example is shown in Figure 5.4. Table 5.1 contains a summary of the usage of the different fluid elements and the restriction on their orientation.

[†] This and the subsequent discussion makes use of a vector cross product $c = a \times b$ to define the orientation of a new vector c in terms of two existing vectors a and b. The new vector c is perpendicular to the plane containing the vectors a and b and points in the direction given by the right hand rule.



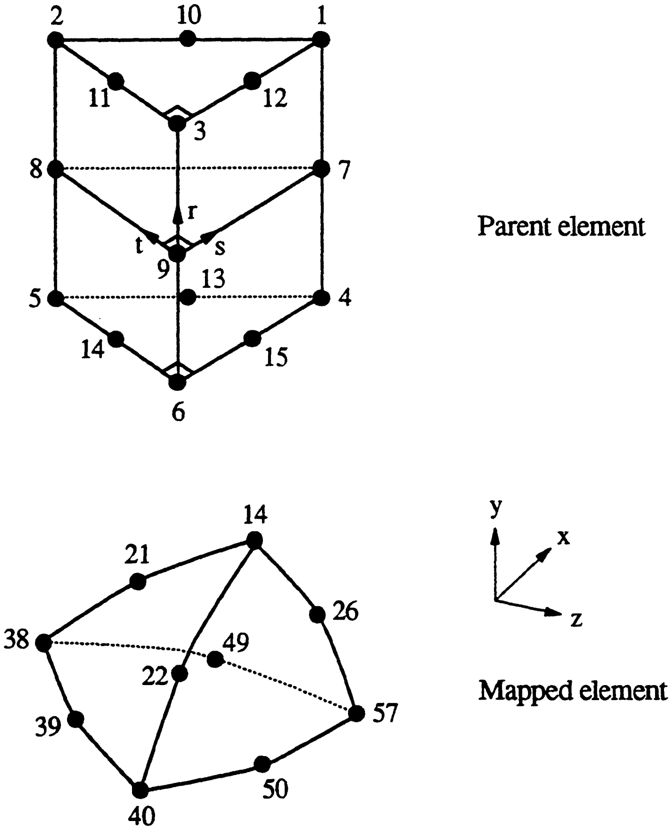


(a) Proper numbering direction of nodes for Mesh 5 (line) element and Mesh 2 (2-d) element



(b) Proper numbering direction of nodes for Mesh 3 (2-d) and Mesh 4 (2-d) elements

Figure 5.3 Example of proper numbering direction of fluid Meshes 2, 3, 4, and 5 elements.



LM = <14 14 14 57 38 40 26 21 22 0 0 0 49 39 50>

Figure 5.4 Formation of tetrahedral element from triangular prism.

Table 5.1 Usage and restriction on orientation of the finite element type

Element	**Usage**	**Restriction on Orientation**
Line	Fluid Mesh 5	s × x points inside the finite element mesh
Plane, Triangular and Rectangular	Fluid Mesh 2 Fluid Mesh 3 Fluid Mesh 4 Foundation rock	s × t points in –x direction s × t points outside the finite element mesh s × t points outside the finite element mesh No restriction
3-d Triangular Prism and Rectangular Prism	Fluid Mesh 1 Dam	No restriction s × t has a component in +x direction
3-d Triangular and Rectangular Shell	Dam	s × t has a component in +x direction

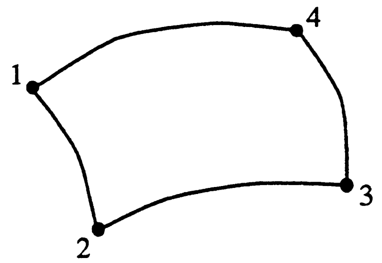
5.2 Foundation Elements

The dam-foundation rock interface is discretized by surface boundary elements derived in References [12] and [13]. Each node in the surface boundary element has three DOFs — the x, y, and z translations. The elements in their undistorted or parent form are shown in Figure 5.1(b) and 5.1(c). They are isoparametric and can be mapped into distorted shapes. The local element axes s and t are also shown. No specific direction for these two axes is required; however, the nodal numbering indicated is the order in which the actual node numbers must be input in an element's LM array (see Chapter 9 – Subprogram 1). Quadratic shape functions are employed; they default to linear shape functions where non-corner nodes are omitted. Only 4, 6, and 8 node quadrilateral elements and 6 node triangular element are available (Figure 5.5). An example of proper numbering of nodes for these elements is shown in Figure 5.6. Element types are denoted by the input value of NELTY (see Chapter 9 – Subprogram 1). Table 5.1 contains a summary of the usage of the different foundation elements and the restriction on their orientation.

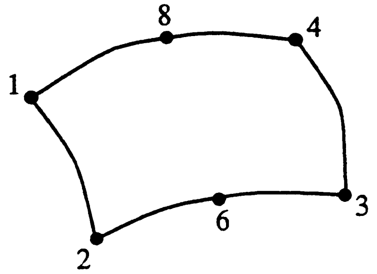
5.3 Dam Elements

Finite elements used to discretize the dam are standard elements derived in Reference [19]. The following element types are employed: solid elements [Figures 5.1(d) and 5.1(e)] and shell elements [Figures 5.1(f) and 5.1(g)]. The elements are shown in their undistorted or parent form. They are isoparametric and can be mapped into distorted shapes. The local element axes s, t, r are also shown; these are area coordinates [19] in the triangular domains. The nodal numbering indicated is the order in which the actual node numbers must be input in an element's LM array (see Chapter 9 – Subprogram 2). Quadratic shape functions are employed; they default to linear shape functions where non-corner nodes are omitted. Nodes can be superimposed as described in the previous section. Element types are denoted by the input value of NELTY (see Chapter 9 – Subprogram 2).

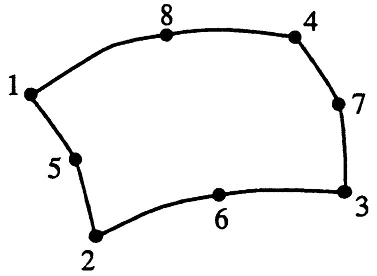
The solid elements (Chapters 6, 7 and 8, Reference [19]) are used for discretizing a three-dimensional dam. Each node in the solid element has three DOFs — the x, y and z translations. The



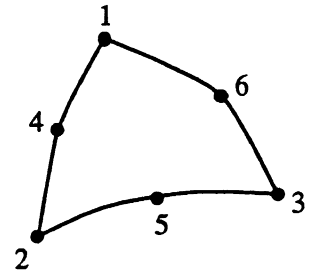
(a) Numbering of 4 node quadrilateral element (NELTY = 2)



(b) Numbering of 6 node quadrilateral element (NELTY = 2)



(c) Numbering of 8 node quadrilateral element (NELTY = 2)



(d) Numbering of 6 node triangular element (NELTY = 3)

Figure 5.5 Proper numbering of nodes for different foundation elements.

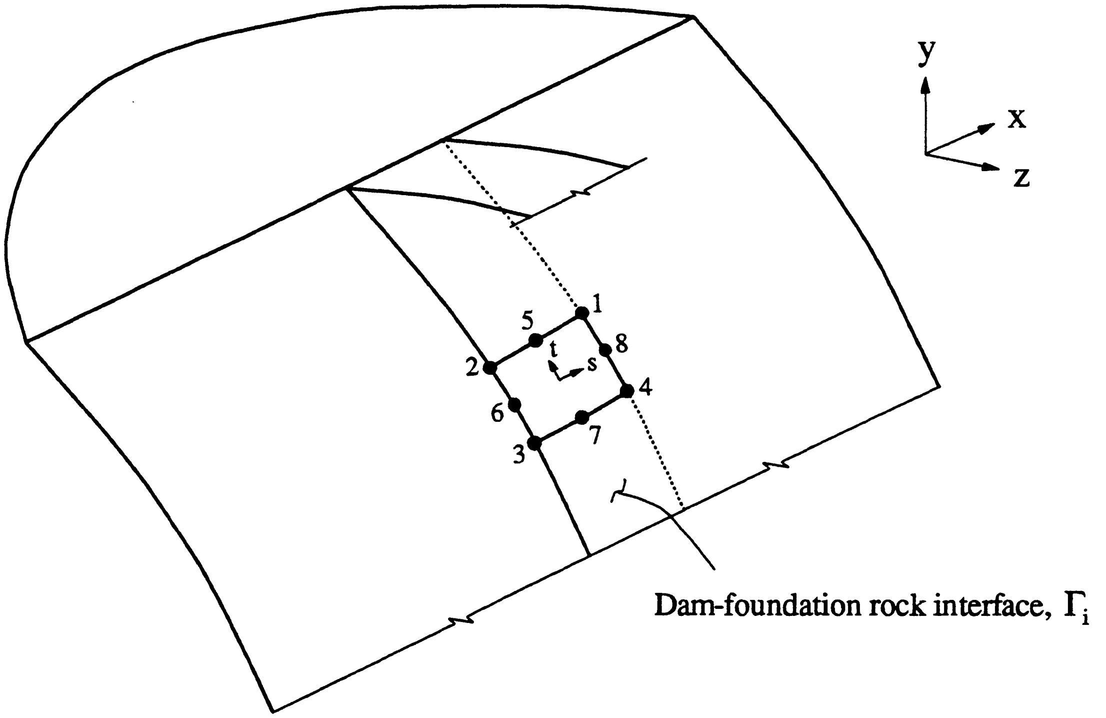
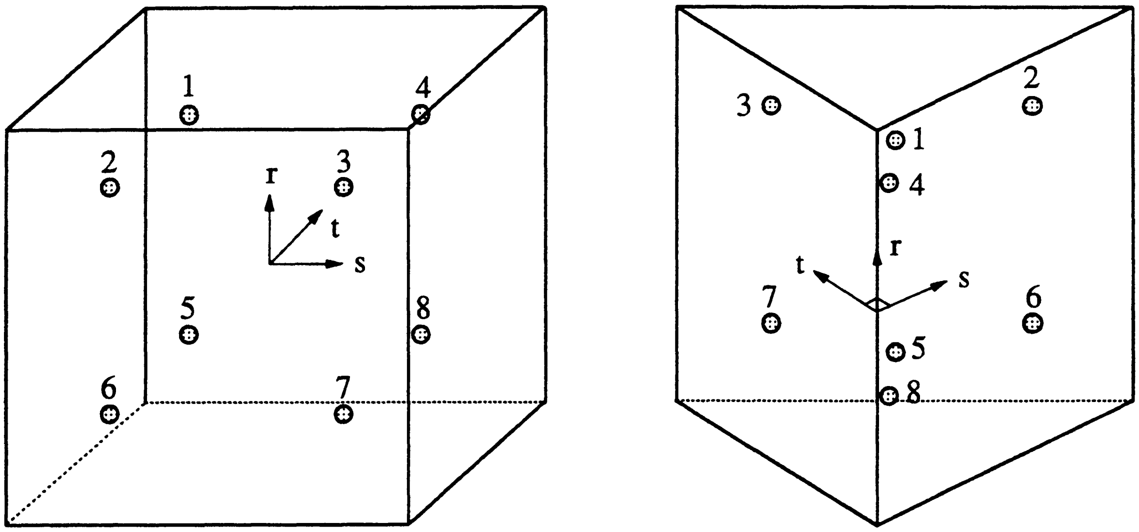


Figure 5.6 Example of proper numbering direction of nodes for the surface boundary elements on the dam-foundation rockr interface.

rectangular prism form (NELTY = 4) is a variable 8 to 20 node element. Any or all of nodes 9, 10, 11, ···, 19, 20 can be omitted. The triangular prism form (NELTY = 5) is a variable 6 to 15 node element. Any or all of nodes 7, 8, 9, ···, 14, 15 can be omitted. Element integrations are performed by Gauss quadrature [Figure 5.7(a), Table 5.2(a)]. Solid elements are mapped into x, y, z space with the requirement that s × t has a component in the positive x direction. Thus, to an observer located upstream of the dam, the nodes should be numbered counter-clockwise [Figure 5.8(a)].

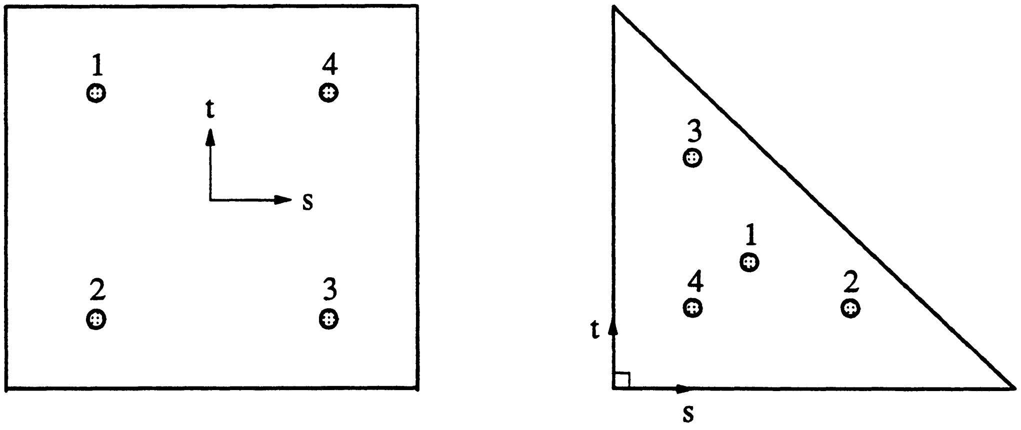
The shell element (Chapter 16, Reference [19]) is used for discretizing an arch dam. A shell element mesh employs one element in the thickness direction of the dam. Nodes are located at the mid-surface. Each mid-surface node is associated with two auxiliary "nodes" — one on the upstream face and one on the downstream face of the dam. It is the auxiliary nodes whose numbers and locations are actually input by the user. Upstream auxiliary nodes are numbered first followed by the downstream auxiliary nodes in the same order. Mid-surface node numbers are the same as those of the corresponding upstream auxiliary nodes. The coordinates of the mid-surface nodes are computed as the average of the coordinates of the corresponding upstream and downstream auxiliary nodes. The DOFs in a shell element mesh are associated with the mid-surface nodes. Each mid-surface node has five DOFs: x, y and z translations and two rotations of the "normal" which connects the upstream and downstream auxiliary nodes. Note that this normal is in the mapped direction of the local element coordinate r. The two rotational DOFs of the normal are about an axis a = y × r and an axis b = r × a. The rectangular form (NELTY = 6) is a variable 4- to 8- (mid-surface) node element. Any or all of nodes 5, 6, 7, 8 can be omitted. The triangular form (NELTY = 7) is a variable 3 to 6 (mid-surface) node element. Any or all of nodes 4, 5, 6 can be omitted. Element integrations are performed by Gauss quadrature in s and t [Figure 5.7(b), Table 5.2(b)], and are exact in r. Shell elements are mapped into x, y, z space with the requirement that s × t has a component in the positive x direction. Thus, to an observer located upstream of the dam, the nodes should be numbered counter-clockwise [Figure 5.8(b)]. Table 5.1 contains a summary of the usage of the different dam elements and the restriction on their orientation.



rectangular prism

triangular prism

(a) 3-d solid element



rectangular

triangular

(b) 3-D shell element

(for clarity, thickness of element is not shown)

Figure 5.7 Numbering scheme for element Gauss quadrature and stress output locations. For 3-d solid element, the stress locations are at the face of the element if that face lies on the upstream face or downstream face of the dam (see Figure 5.8).

Table 5.2 Local coordinates of the Gauss quadrature and stress output locations for finite elements

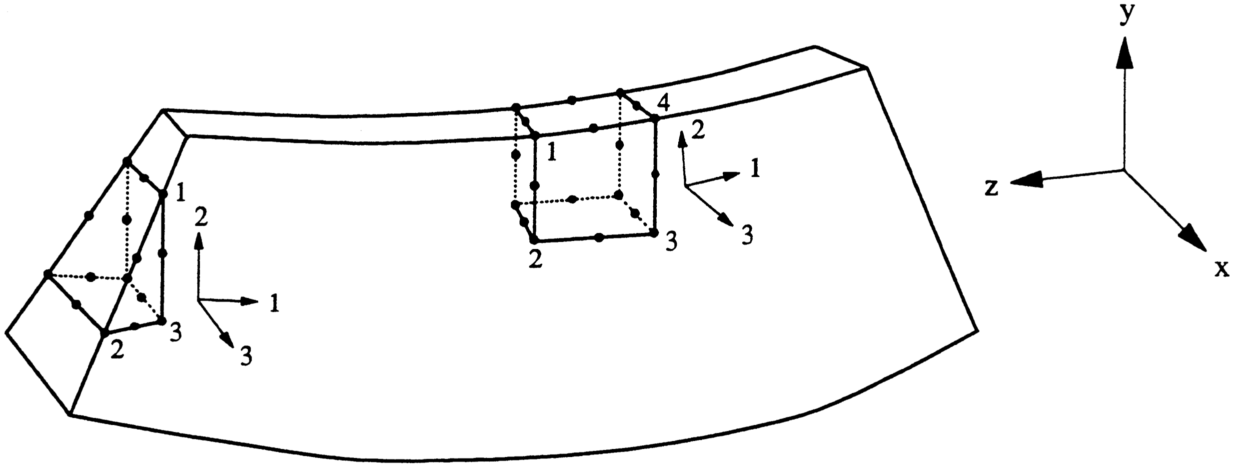
(a) 3-d solid element

Gauss Quadrature/ Stress Location Number	Rectangular Prism			Triangular Prism		
	s coordinate	t coordinate	r† coordinate	s coordinate	t coordinate	r† coordinate
1	– 0.5774	0.5774	0.5774	0.3333	0.3333	0.5774
2	– 0.5774	– 0.5774	0.5774	0.6000	0.2000	0.5774
3	0.5774	– 0.5774	0.5774	0.2000	0.6000	0.5774
4	0.5774	0.5774	0.5774	0.2000	0.2000	0.5774
5	– 0.5774	0.5774	– 0.5774	0.3333	0.3333	– 0.5774
6	– 0.5774	– 0.5774	– 0.5774	0.6000	0.2000	– 0.5774
7	0.5774	– 0.5774	– 0.5774	0.2000	0.6000	– 0.5774
8	0.5774	0.5774	– 0.5774	0.2000	0.2000	– 0.5774

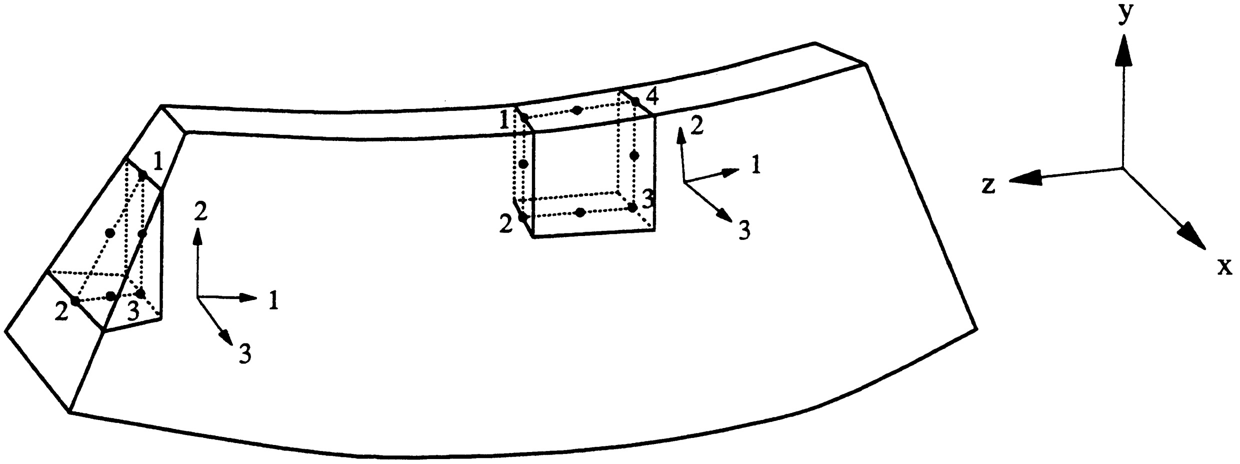
(b) 3-d shell element

Gauss Quadrature/ Stress Location Number	Rectangular Prism		Triangular Prism	
	s coordinate	t coordinate	s coordinate	t coordinate
1	– 0.5774	0.5774	0.3333	0.3333
2	– 0.5774	– 0.5774	0.6000	0.2000
3	0.5774	– 0.5774	0.2000	0.6000
4	0.5774	0.5774	0.2000	0.2000

† For 3-d solid element, $r = 1.0$ for stress locations 1, 2, 3 and 4 if the surface represented by $r = 1.0$ lies on the upstream face of the dam; and $r = -1.0$ for stress locations 5, 6, 7 and 8 if the surface represented by $r = -1.0$ lies on the downstream face of the dam (see also Figure 5.9).



(a) Solid element mesh



(b) Shell element mesh

Figure 5.8 Example of proper direction of node numbering; also shown are the directions of local stress axes.

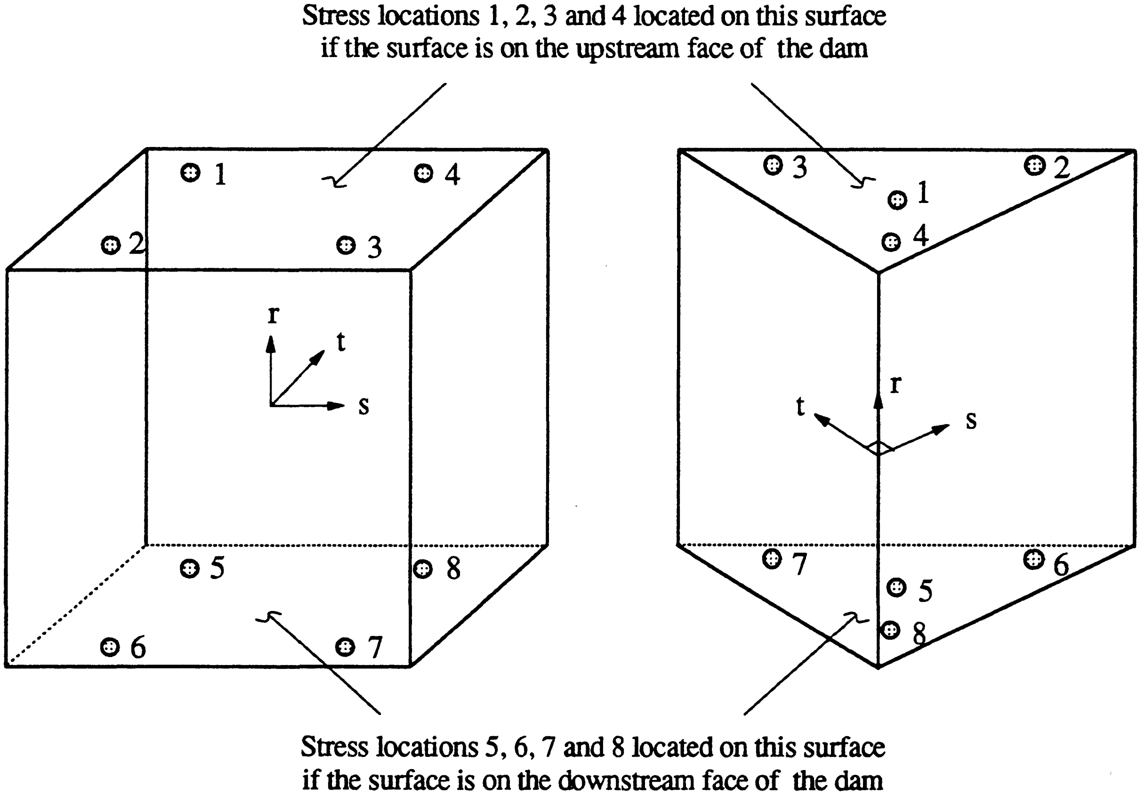
A connection cannot be made directly between a dam shell element and a surface foundation element because, as mentioned earlier, each node in the shell element has five DOFs (three translational and two rotational), and each node in the foundation element has three translational DOFs. This problem can be resolved by transforming the shell element into a transition element by linearly transforming the five DOFs for each shell mid-surface node on the dam abutment to the six DOFs at the corresponding two auxiliary nodes [1]. The first three of these six DOFs are x, y and z translations of the upstream auxiliary node and the other three are x, y and z translations of the downstream auxiliary node. This concept is explained by examining the horizontal cross-section a-b-c-d-e-f-a of the dam [Figure 2.3(d)]. The 5 DOFs (3 translational and 2 rotational) of node b, the middle point of the dam abutment a-c, are linearly transformed to the 6 translational DOFs of the auxiliary nodes a and c [Figure 2.3(d)]. Similarly, the 5 DOFs of node e, the middle point of the dam abutment d-f, are linearly transformed to the 6 translational DOFs of auxiliary nodes d and f. This transformation is possible because the displacements vary linearly through the thickness of the shell element.

However, it may not be possible to connect directly a dam shell element adjacent to a surface foundation element with a surface foundation element because of the geometric incompatibility between the dam abutment and the uniform canyon (Section 2.1). In order to make this connection, the shell element can be transformed to a transition element with a special treatment: the five DOFs for each shell mid-surface node on the dam abutment are linearly transformed to the six DOFs at the two nodes on the dam-foundation rock interface of the uniform canyon, instead of the two auxiliary nodes defining the mid-surface node as described in the previous paragraph. For example, as shown in Figure 2.3(d), the 5 DOFs of node b are linearly transformed to the 6 translational DOFs of nodes a' and c' on the dam-foundation rock interface Γ_i, instead of the 6 translational DOFs of the auxiliary nodes a and c. Similarly, the 5 DOFs of node e are linearly transformed to the 6 translational DOFs of nodes d' and f'. Test results have shown the validity of using the transition elements with this approximate special treatment in the arch dam with a uniform canyon (Section 3.4 of Reference [7]).

Furthermore, displacement compatibility between the dam abutment and dam-foundation rock interface on the uniform canyon is ensured by this special treatment. The transition elements without the special treatment are automatically formed from shell elements by the program where needed. An option is also provided in the program for users to apply the special treatment. As demonstrated for one example in Appendix A, errors in the dam response due to ignoring the special treatment are small. However, applying the special treatment will ensure compatibility between the dam and foundation rock, and between the dam and the fluid domain. Therefore, it is highly recommended that the special treatment be applied for shell elements where needed.

An output for the finite elements of the dam mesh is stresses at element locations which are the Gauss quadrature locations shown in Figure 5.7 and Table 5.2. However, for solid elements, the stress locations are on the face of the element if the face is on the upstream or downstream face of the dam (Figure 5.9). Two types of stress components are computed. First are principal stress components, the orientations of which are output with respect to a local set of axes 1, 2, 3 which are defined at each stress location in terms of the mapped s, t, r axes. Second are local stress components referred to these same 1, 2, 3 axes. A stress table is output in Subprogram 2 which contains the x, y, z coordinates of each stress location and the x, y, z direction cosines of the 1, 2, 3 axes at each stress location in each dam element.

For solid elements, $3 = s \times t$; $1 = y \times 3$ or $= -z$ if 3 is in the y direction; and $2 = 3 \times 1$. Six local stress components are available: normal along 1, 2 and 3 and shear in the 1-2, 2-3 and 1-3 planes. In this order, the components are numbered 1 to 6 for use in array ISTYPE (see Chapter 9 – Subprogram 7). When computing the principal stress components and directions, only the normal stresses along the 1, 2 and the shear in the 1-2 plane are considered as in a plane stress situation. Discretizing an arch dam with proper ordering of element node numbering as shown in Figure 5.8(a) orients 1, 2 and 3 in the arch, cantilever and normal directions, respectively, and the principal stress components will be in a plane parallel to the surface of the dam. The element stress locations are shown in Figures 5.7(a), 5.9, and Table 5.2(a). They are numbered 1 to 8 for use in array INS2 (see



Rectangular prism

Triangular prism

3-D Solid Element

Figure 5.9 Stress locations of 3-d solid element when the r = 1.0 face of the element lies on the upstream face of the dam or when the r = –1.0 face of the element lies on the downstream face of the dam.

Chapter 9 – Subprogram 7). As mentioned above, the stress locations are on the face of the element if the face is on the upstream or downstream face of the dam (Figure 5.9). In this case, the stress components are first computed at the Gauss quadrature locations in the global x, y, and z axes; then the stress components at the face of the element in the global x, y, and z axes are obtained by linearly extrapolating their values at the Gauss quadrature locations, and a stress transformation is made to obtain the stress components in the local 1, 2 and 3 axes.

For shell elements, $3 = s \times t$ and is in the true normal direction; $1 = y \times 3$ or $= -z$ if 3 is in the y direction; and $2 = 3 \times 1$. Ten local stress components are available: normal along 1 and 2 and shear in the 1-2, 2-3 and 1-3 planes at the upstream face followed by the same five at the downstream face. In this order, the components are numbered 1 to 10 for use in array ISTYPE (see Chapter 9 – Subprogram 7). The normal stress along 3 is set to zero in the element formulation. Similar to solid elements, when computing principal stresses, only the normal stresses along 1 and 2 and the shear in the 1-2 plane are considered. Proper ordering of element node numbering as shown in Figure 5.8(b) orients 1, 2 and 3 in the arch, cantilever and normal directions, respectively. The element stress locations are shown in Figure 5.7(b) and Table 5.2(b). They are numbered 1 to 4 for use in array INS2 (see Chapter 9 – Subprogram 7).

As mentioned earlier, either the solid or shell element can be used for discretizing an arch dam, and no mixing of element types is permitted within the body of the dam. Unless the arch dam is unusually thick, the shell element will suffice and is recommended. A further recommendation is the use of shell elements employing quadratic shape functions (8-node rectangle, 6-node triangle). Such elements are more economical than elements interpolated linearly.

The analyst should be aware of two sources of error, although usually minor, encountered when using the shell element. First is the approximate representation of shear deformations. While plane sections originally normal to the mid-surface are allowed to rotate with respect to the mid-surface, they are constrained to remain plane. Since most arch dams are thick (relative to the spans involved) at their bases, some error will be present in this region due to the plane-sections-remain-plane constraint. Second is the plane stress behavior of the shell element; i.e., no normal stress is developed perpendicular to the plane of the shell. Some error will occur at the foundation interface where the restraint provided by the foundation rock produces stress normal to the plane of the shell. This effect dies out rapidly away from the interface.

If an arch dam is unusually thick, then the use of solid elements throughout should be considered. Over large portions of these dams, shearing action causes significant departure from plane-sections-remain-plane behavior. The through-thickness discretization should be a single solid element with quadratic interpolation. Of course, as the dam thickness approaches that of a gravity dam, then a multiple element discretization of the thickness will be needed. For reasons of economy, quadratic interpolation in the plane of an arch dam is appropriate. Thus, it is recommended that unusually thick arch dams be discretized with 20 node solid elements, with a single element in the thickness direction. Use of solid elements with linear interpolation in the through-thickness direction (no interior nodes) is not advised.

Although the 20 node solid element avoids the two sources of error mentioned earlier with the shell element, use of the 20 node solid element for arch dams is limited by three factors. First is the additional expense over the shell element because the interior nodal points in the through-thickness direction require more DOFs resulting in a more expensive solution. Second is the possible ill-conditioning of the stiffness matrix at thin sections of the dam when the 20 node solid element is employed due to the close proximity of the three nodes along a through-thickness line. Third is the slight error when using solid elements for arch dams due to the incompatibility between the dam and the uniform canyon, and between the dam and the fluid domain because the special treatment in the shell elements to ensure the compatibility between the dam and the uniform canyon is not applicable to the solid elements (Appendix A).

6. COMPUTATION OF FOUNDATION IMPEDANCE MATRIX

The modified direct boundary element procedure [12,13] is implemented in the EACD-3D-96 program to determine the foundation impedance matrix (see Section 2.3). In this procedure, the dam-foundation rock interface Γ_i is discretized into a surface boundary element mesh, and the curve $\Gamma_c \cup \Gamma_h$, defined by the intersection of the canyon surface with the y-z plane at x = 0 (Figure 6.1), should be discretized into a one-dimensional mesh [13]. In particular, two types of the dam-foundation rock system can be analyzed:

a. Symmetric system about the x-y plane.

b. Non-symmetric system about the x-y plane.

The input data for computing the foundation impedance matrix consist of two groups: (1) the general control data, and (2) the mesh/geometry information data (see Chapter 9 – Subprogram 1). In the first group, frequency, material properties, and the general information about the discretized system should be provided. In the second group, the nodal coordinates, the element connectivity information and the geometry at non-smooth boundary points should be specified.

6.1 Program Restrictions

The EACD-3D-96 program will compute the foundation impedance matrix for the whole foundation rock system whether or not the system is symmetric about the x-y plane. However, for a symmetric system about the x-y plane, the computed foundation impedance matrix for the whole system will be transformed into two matrices for symmetric and antisymmetric analyses, respectively (see also Section 8.2).

The first restriction requires that the number of nodes for the one-dimensional mesh system on Γ_c (Figure 6.1) should not be less than the number of nodes in each row of the boundary element mesh on Γ_i, and the spacing of the nodes along Γ_c should be roughly even. For example, there are two rows of nodes in the boundary element mesh in Figure 6.2(a) and nodes 1 to 7 form one row of nodes

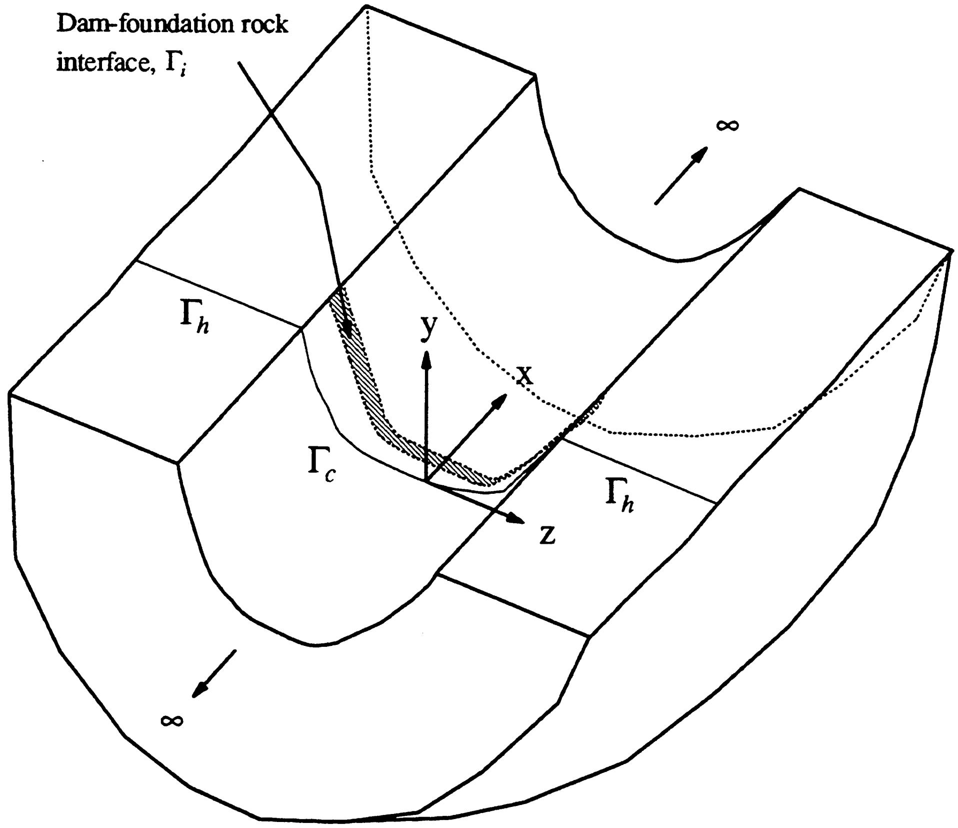
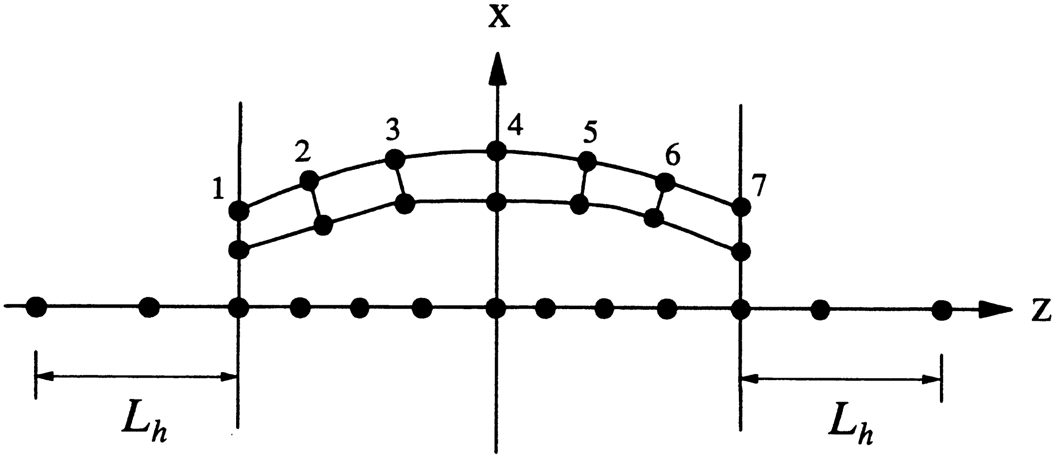
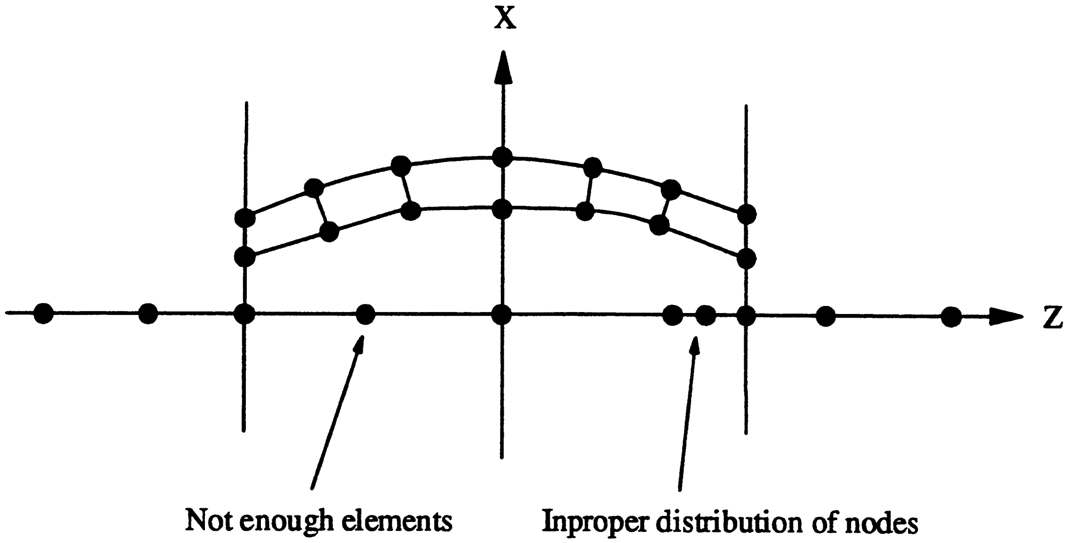


Figure 6.1 Infinitely-long canyon of arbitrary but uniform cross-section cut in a homogeneous half-space.



(a) Acceptable distribution



(b) Unacceptable distribution

Figure 6.2 Illustration of acceptable and unacceptable distribution of nodes on the canyon boundary at $x = 0$.

and the other row also has 7 nodes. Figure 6.2(a) demonstrates an acceptable discretization of Γ_c with 9 (which is greater than 7, the maximum number of nodes in all rows) evenly-distributed nodes. Shown in Figure 6.2(b) is the same boundary mesh with Γ_c inappropriately discretized with only 5 (which is smaller than 7) unevenly-distributed nodes. This restriction is necessary not only for good accuracy but also for making the flexibility influence matrix non-singular [13].

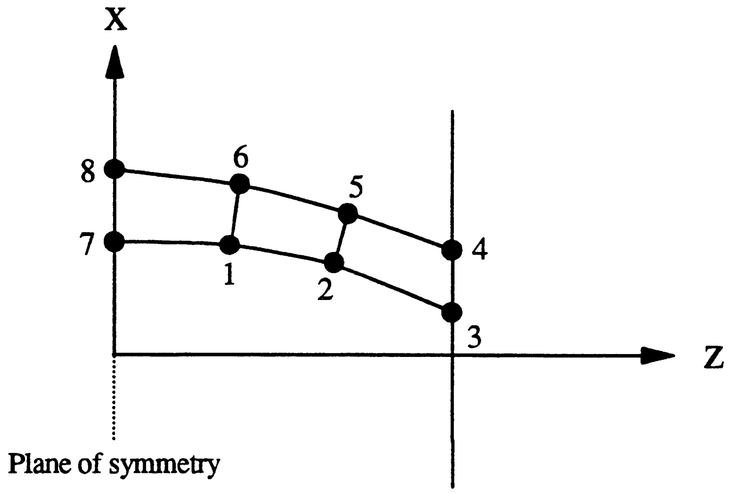
The second restriction is on the numbering of nodes on the dam-foundation rock interface when the system is symmetric about the x-y plane, in which case only half of the system needs to be discretized. This restriction requires that the nodes on the symmetric plane be numbered last, as illustrated in Figure 6.3. If the system is not symmetric about the x-y plane, the nodes can be numbered arbitrarily.

As mentioned in Section 5.2, only four types of surface boundary elements on the dam-foundation rock interface are currently included in the computer program: 4, 6, and 8 node quadrilateral and 6 node triangular elements (Figure 5.5). In providing element connectivity information for elements on the dam-foundation rock interface, it is required that the nodal numbers be supplied in a proper order as shown in Figure 5.5.

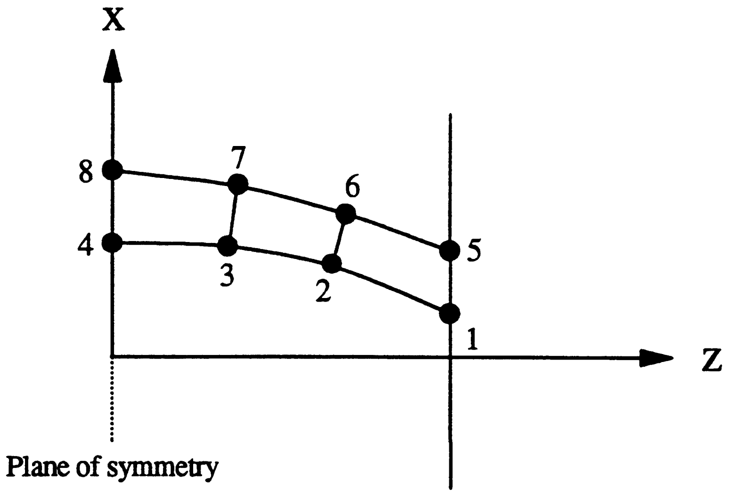
Figure 6.4 shows a banded foundation of width $0.2L$ supported on a semi-circular canyon of radius L cut in a half-space. Because the system is symmetric about the x-y plane, only half of the system is discretized according to the rules described above. However, for illustrative purpose, Figure 6.5 shows the whole banded foundation discretized as if it is non-symmetric about the x-y plane.

6.2 Selection of Controlling Parameters

For accurate results, the discretization on both the dam-foundation rock interface Γ_i and the boundaries $\Gamma_c \cup \Gamma_h$ should be fine enough to describe the actual variations of the displacements and tractions. Therefore, the element size on Γ_i should not exceed $\lambda_s/4$ for 4 node elements and $\lambda_s/2$ for 6 or 8 node elements; λ_s is the shear wavelength for the foundation rock. Similarly, the discretization of the boundary at $x = 0$ should be fine enough so that element size is smaller that $\lambda_s/4$.



(a) Acceptable numbering



(a) Unacceptable numbering

Figure 6.3 Illustration of acceptable and unacceptable numbering of nodal points for symmetric system.

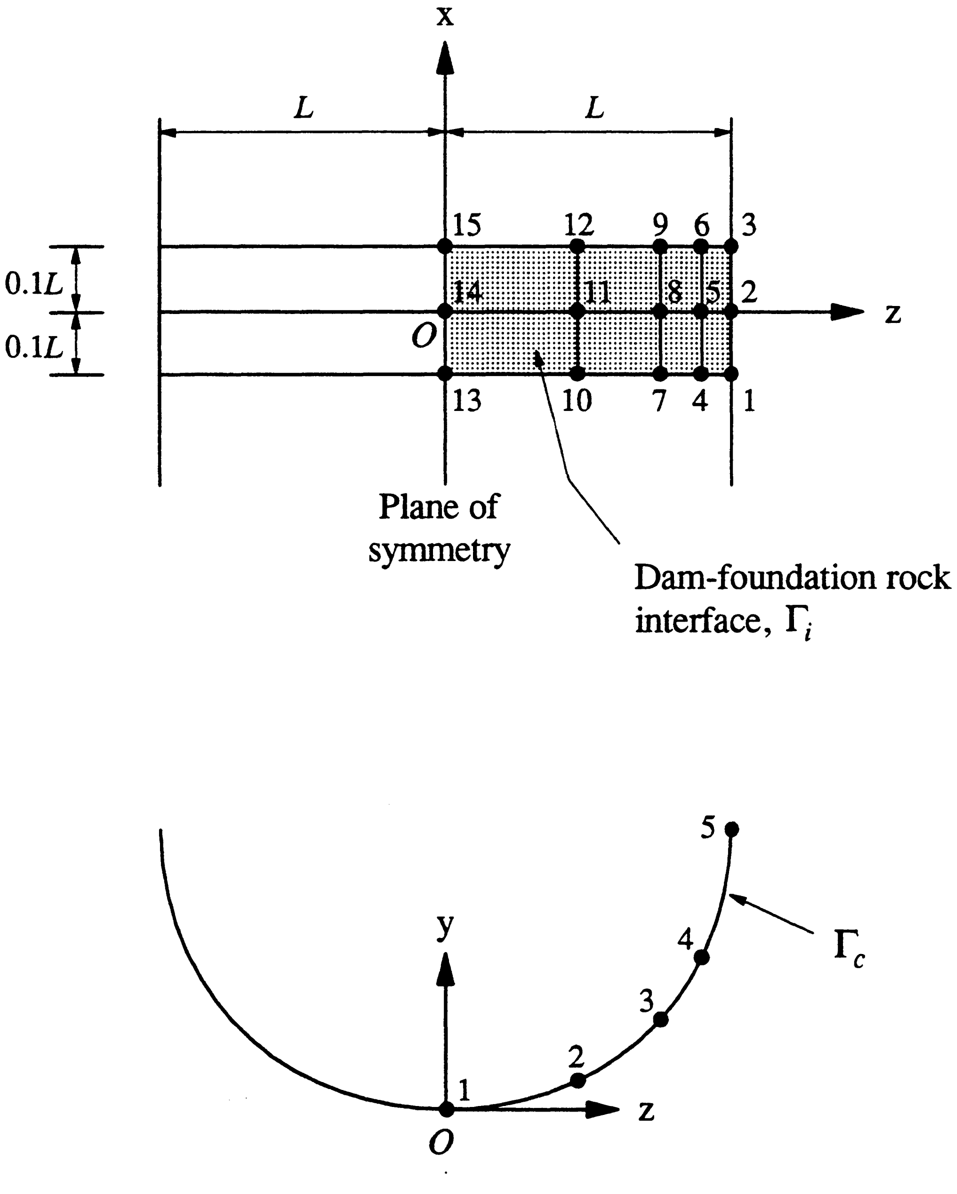


Figure 6.4 Example of a discretized system, treated as a symmetric system about the x-y plane.

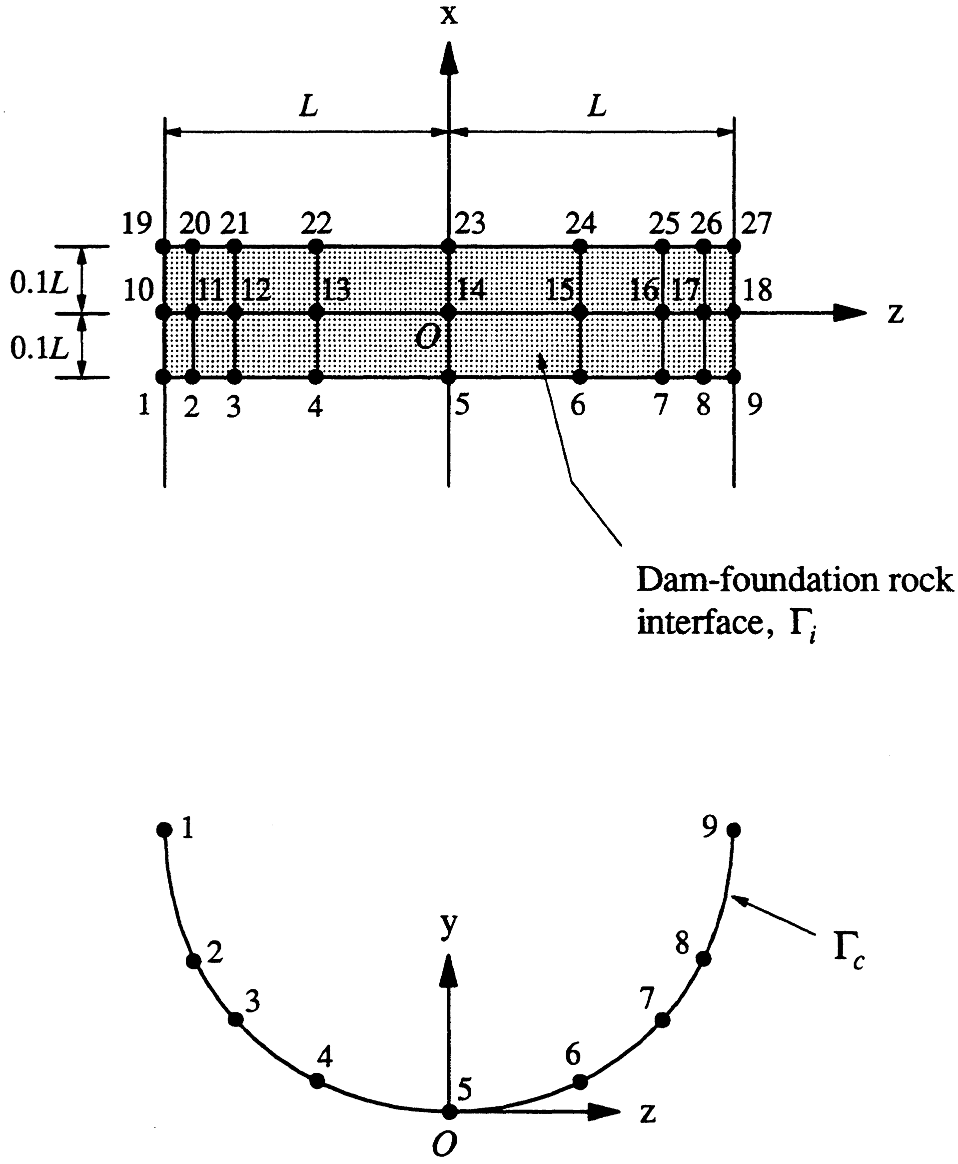


Figure 6.5 Example of a discretized system, treated as a non-symmetric system.

As mentioned earlier, the impedance coefficients are determined by integrating the solutions for a series of two-dimensional boundary value problems associated with a set of discrete wavenumbers, k_q, $q = 1, 2, ..., n_q$, over a finite range $(0, K)$. In the computer program, two different integration schemes are available to the user. The first scheme is piecewise four point Gauss integration where the integration domain $(0, K)$ is divided into three or four subdomains associated with different integration step size (Figure 6.6). For better accuracy and efficiency, the step size near the Rayleigh wavenumber k_r should be smaller than elsewhere. The actual values for the various parameters that define the sizes of the wavenumber domain and the corresponding integration step-size depend on the frequency, the size of the system and the fineness of the discretization. Default values for these parameters are calculated by the program if zero value is specified for an input parameter (see Chapter 9 – Subprogram 1).

The second scheme uses an adaptive procedure to determine the sampling points in the wavenumber domain based on the piecewise Simpson's rule and on a test function which characterizes the main features of the Fourier transforms of the displacement. Only an error tolerance parameter needs to be specified for this scheme (see Chapter 9 – Subprogram 1).

In order to control error, the discretization range, L_h [Figure 6.2(a)], on the half-space surface is recommended to be greater than twice of the canyon width or the shear wavelength, whichever is smaller. If zero value is specified in the input data for L_h, the default value will be calculated and used.

6.3 Efficient Evaluation of Foundation Impedance Terms

The computation of the frequency-dependent foundation impedance matrix requires an enormous amount of CPU time compared to other parts of the earthquake analysis of arch dams (Section 6.8 of Reference [7]). However, this computational effort can be reduced by recognizing that the foundation impedance matrix is a smooth function of frequency (Section 4.4.2 of Reference [7]). Therefore, the elements of the foundation impedance matrix are computed only at a few selected

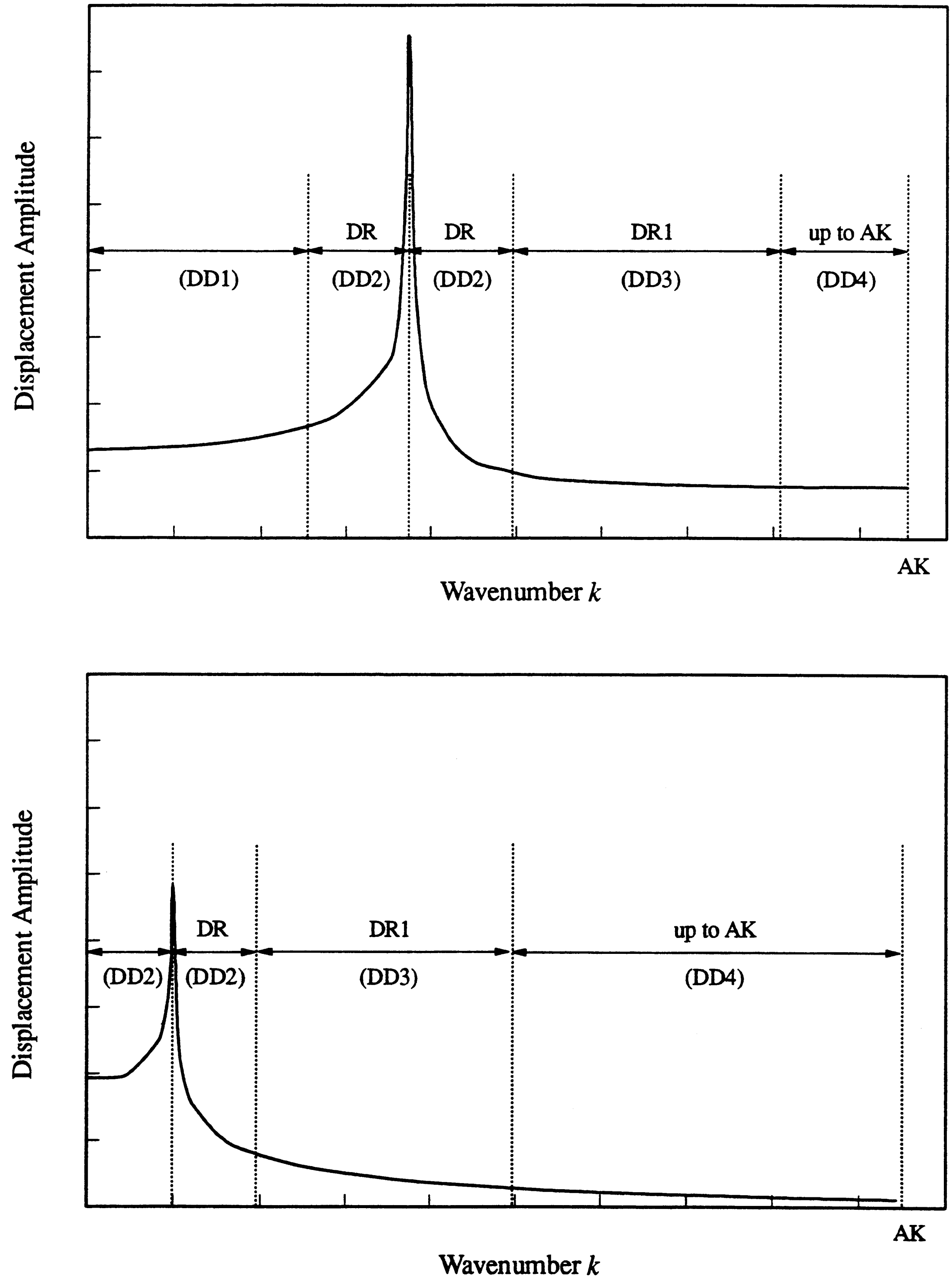


Figure 6.6 Division of wavenumber domain into 3 or 4 subdomains. DD1 to DD4 are the step-sizes used in the corresponding subdomains.

frequency values and their numerical values at other frequencies are determined by interpolating between their known values at these selected frequencies with a cubic interpolation scheme (Section 4.4.2 of Reference [7]). Therefore, the foundation impedance matrix should at least be computed at four different frequencies (including the zero frequency) for the dynamic analysis of the system. The program automatically sets the frequency values at which the foundation impedance matrix is computed to be equally spaced between zero and the maximum frequency (see Chapter 9 – Main Program).

If the impedance matrix for foundation rock with a certain Young's modulus (called the "base" foundation impedance matrix) is computed, the impedance matrix for foundation rock with a different Young's modulus can be obtained readily from the "base" matrix provided the Poisson's ratio and damping values are the same in the two cases (Section 4.43 of Reference [7]). Therefore, an option is available in the program for the user to reuse the "base" foundation impedance matrix if it has already been computed (see Chapter 9 – Subprogram 1). If the Young's modulus is to be varied to study its effect on the earthquake response of a dam, it is recommended to compute the "base" foundation impedance matrix for the foundation rock with the smallest Young's modulus (see Section 4.4.3 of Reference [7]).

7. SELECTION OF IMPORTANT PARAMETERS CONTROLLING COMPUTED RESPONSES

To ensure that the computer program gives accurate dynamic response of a dam, the parameters that govern the response computation must be carefully selected. This section gives guidelines to aid in the selection of the response parameters.

7.1 Fourier Transform Parameters

The FFT algorithm employed by the program is fully described in Reference [20]; only those topics of direct interest to the user are covered here. An illustration of the discrete Fourier transform procedure for response computation appears in Figure 7.1. The parameters used in an FFT analysis are T, Δt, N, f_{max} and Δf. These parameters are defined as follows:

T = the period of the computation. In Fourier analysis both the excitation and response are periodic; i.e., the values at times $\cdots$ t – 2T, t – T, t, t + T, t + 2T, $\cdots$ in both the excitation and response are the same.

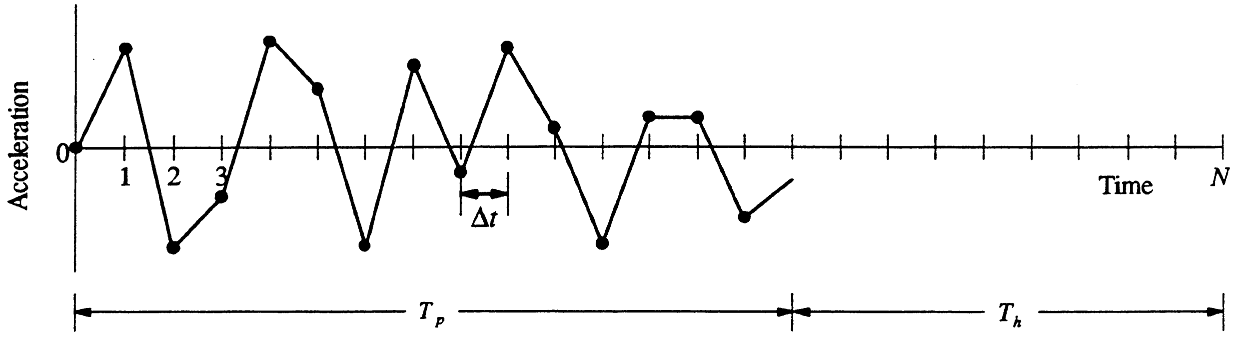
Δt = the time increment and is referred to in the program as TINC. The excitation and response are discrete functions defined at equal time increments Δt; i.e., at times 0, Δt, $2\Delta t$, $\cdots$, $T - \Delta t$.

N = $T/\Delta t$ = the number of discrete time instants in the computation period T.

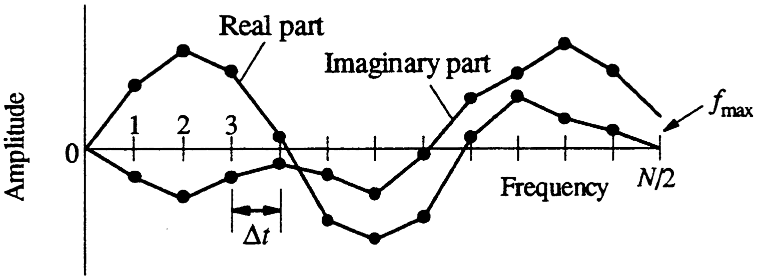
f_{max} = $N/2T = 1/2\Delta t$ = the maximum frequency in Hz that is included in the analysis and is referred to in the program as FMAX.

Δf = $1/T$ = the frequency increment in Hz. The frequencies included in the analysis are 0, Δf, $2\Delta f$, $\cdots$, f_{max} — a total of N/2 + 1 frequencies.

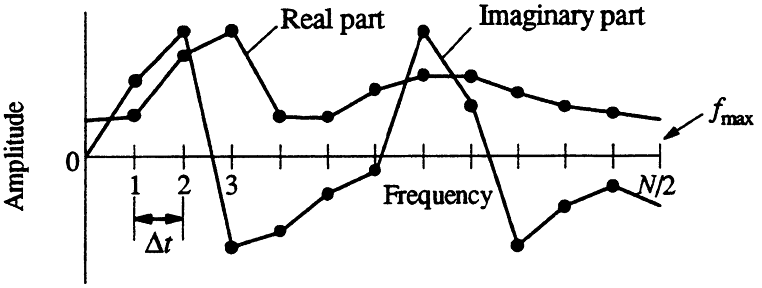
Note that selection of any two of the above five parameters determines the other three. The input section of the program (see Chapter 9 – Main Program and Subprogram 7) requires f_{max} and N. The selection of f_{max} is completely determined by the time interval Δt at which the given earthquake



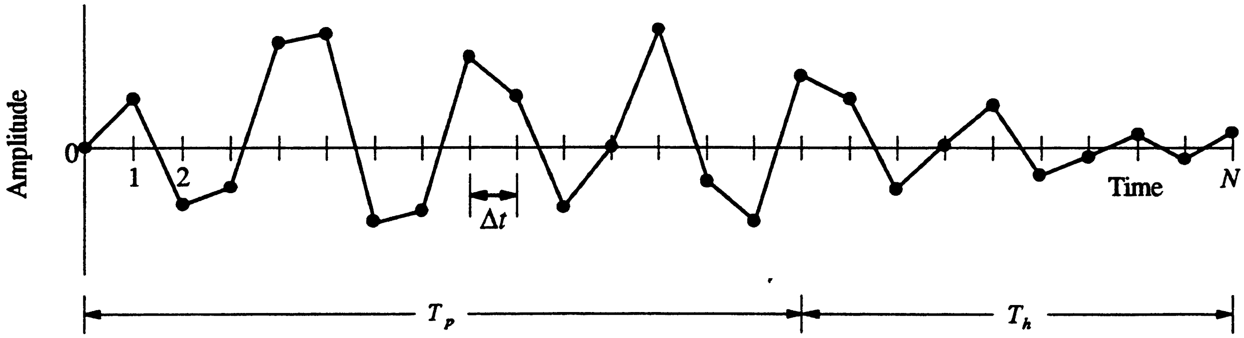
(a) Earthquake accelerogram



(b) Complex-valued Fourier transform of accelerogram



(c) Complex-valued frequency response function



(d) Time history response computed by inverse Fourier transform of the product of (b) and (c) above

Figure 7.1 Discrete Fourier transform procedure for response computation.

record and the resulting responses are defined. As given above, $f_{max} = 1/2\Delta t$. Earthquake accelerograms are processed at standard time intervals, usually .02 or .01 seconds, which result in the f_{max} values of 25Hz and 50Hz, respectively. Accurate computation of response at frequencies higher than these values cannot be made because they represent upper bounds on the frequency content information in the accelerograms. Fortunately, occurrence of significant dynamic response of a concrete dam is unlikely at frequencies above 25 Hz, and is especially unlikely above 50 Hz. Re-interpolation of standard processed accelerograms to a time interval different from the original one is not advised: thus, the choices for f_{max} are limited to the two values given above.

The choice of N is made so that T, computed from $T = N\Delta t$ is appropriate. The following formula is useful for selecting the minimum value of T:

$$T = T_p + T_h$$

where T_p = the duration of the earthquake record employed, and T_h = the time required for the dam response present at the end of the earthquake record to decay to a small relative value. The selection of T_h should be based on the period $\tilde{T}_1$ and damping ξ_1 associated with the fundamental resonant response of the dam-fluid-foundation rock system: $T_h = \beta\tilde{T}_1/\xi_1$, where β is a constant dependent on the percent decay in dam response over T_h desired. $\tilde{T}_1$ and ξ_1 can be obtained from the frequency response output of Subprogram 6. A plot of the frequency response function provides the fundamental resonant period $\tilde{T}_1$ and application of the half-power method [18] yields ξ_1. The value $\beta = .73$ yields a 99% decay in dam response over T_h and is recommended. As an example, $\beta = .73$, $\tilde{T}_1 = .3$ seconds and $\xi_1 = .05$ results in $T_h = 4.4$ seconds. In addition, the choice of T should give a small enough Δf (= $1/T$) for representing the frequency response functions for the generalized coordinates, especially near the fundamental resonant peak. For this purpose, it is recommended that $T \geq 50T_1$ where T_1 is the fundamental period of vibration of the dam-foundation rock system with no water.

The possible choices for N are $N = 2^{MM} \times LL$ where MM is a positive integer and LL = 2 or 3 (see Chapter 9 – Subprogram 7). Once T is selected, N is chosen as the minimum of the possible values which exceed $T/\Delta t$. A final check on whether T_h is long enough is that the computed time histories should begin with a small value at time zero and reach small values as t approaches T; i.e., not exceeding 1% of the maximum computed response when $\beta = .73$.

In order to limit the volume of time history output and reduce cost, the time increment of the computed time histories is increased to

$$\text{TINCK} = \text{TINC} \times 2^{\text{KK}}$$

where KK is input. No approximation in the computed values is involved. Additionally, only responses in the interval from zero second to the input value TEND are output and used for computation of the extreme stress responses.

7.2 Number of Vibration Modes of the Dam-Foundation Rock System

The number NFD (see Chapter 9 – Main Program) of vibration modes required to represent the earthquake response of a dam is much less than the number of DOFs in the finite element system. In general, all the vibration modes that significantly contribute to the earthquake response of the dam should be included. A few additional modes should also be included for accurate response results at the high-frequency end of the frequency range.

The number of vibration modes required depends on the particular dam-water-foundation rock system and earthquake ground motion. In many cases, 15 vibration modes may be sufficient if the foundation rock is assumed rigid, and 15 to 20 modes may be sufficient if the foundation-rook flexibility is included, with the larger number of modes required for increasingly flexible foundation rock. The user should check whether enough vibration modes were included by examining the change in the maximum stresses in the dam with an increase in the number NFD of modes included. If the stresses remain essentially unchanged, then the number NFD used in the previous analysis and the corresponding response results are satisfactory.

7.3 Frequencies at Which the Fluid Mesh 2 Eigenproblem Is Solved

If the impounded water is infinite consisting of an irregular region and an infinite channel of uniform cross-section, there is an eigenvalue problem of the fluid Mesh 2 at the transmitting plane that needs to be solved (Figure 5.2) [3,5]. When water compressibility is considered in the analysis (NWAT = 3; see Chapter 9 – Main Program), the eigenvalues and eigenvectors of the infinite uniform channel depend on excitation frequency and need to be defined at each excitation frequency at which the frequency response function is computed. However, it has been demonstrated that accurate frequency response functions can be efficiently obtained by exactly computing the eigenvalues and eigenvectors only at widely separated excitation frequencies and obtaining them at intermediate frequencies by linear interpolation [4,5].

The excitation frequencies at which the eigenproblem is exactly solved are determined automatically by the computer program with the frequencies separated over a constant frequency interval. This interval was chosen to be more conservative than the recommendation in Reference [4]. Occasionally, multiple eigenvalues may occur at any one excitation frequency, in which case the frequency interval is subdivided automatically by the computer program to eliminate this occurrence of multiple eigenvalues.

7.4 Interpolation of Frequency Response Functions

In order to reduce the computational effort required in analyzing arch dams, the frequency response functions for the modal coordinates are computed exactly at selected frequencies and their values at other frequencies are obtained by interpolation. The selection of the frequencies at which response is exactly computed should obviously depend on the rapidity with which the response varies with excitation frequency; i.e., these frequencies should be closely spaced in the frequency range where the response varies rapidly and widely spaced if the response varies slowly.

The interpolation procedure based on the concept of representing the dam response, over a sub-range of frequencies, by the response function considering only the two vibration modes contributing significantly. This procedure as well as the selection of frequencies at which the response is computed exactly is described in Reference [4] and has been incorporated into the computer program with more conservative values of the selection parameters.

8. PROCEDURE TO USE THE PROGRAM

Theoretically, the computer program can be executed in one continuous run for static analysis and for many cases of dynamic analysis. However, owing to the large size of the program, the many different disk files used, and for reasons of computational efficiency, one continuous run is not recommended, especially when the foundation rock is flexible. The guidelines in this chapter are intended to assist the user in selecting the best procedure to execute the program for a particular analysis problem. For convenience, the most direct procedure for execution of the program, although not necessarily the optimal choice, is outlined first followed by the recommended procedure which usually involves executing the program in parts. Frequent reference to Table 8.1 is made, as it shows the disk file usage of the various subprograms.

8.1 Static Analysis

In static analysis of a dam-water-foundation rock system, the Main Program can be executed with one continuous run of Subprograms 1, 2, 3, 4, and 6 (Subprograms 5 and 7 are skipped in static analysis; see Chapter 9 – Main Program). If the foundation rock is rigid, Subprogram 1 is skipped; if the reservoir is empty, Subprogram 4 is skipped. The static displacements and stresses for the dam due to its dead weight and the hydrostatic pressure are computed and output in Subprogram 6. If the static stresses are to be added to the earthquake dynamic stresses computed in a separate dynamic analysis, the static stresses which are written onto file 7 (see Table 8.1) should be saved after the execution of Subprogram 6 (see also Section 8.3).

If the flexibility of the foundation rock is included in the static analysis of the system, Subprogram 1 for the foundation rock can be first run separately. The stiffness matrix with reference to the DOFs at the dam-foundation rock interface (i.e., the foundation impedance matrix at zero frequency) will be computed and saved in file 2 (Table 8.1). File 2 also stores information about mapping of nodes between the dam and foundation rock at the interface. Therefore, file 2 saved by

Subprogram 1 can be used in the subsequent subprograms to compute the static dam response, regardless of the water level in the reservoir (Table 8.1).

8.2 Dynamic Analysis

The frequency-dependent foundation impedance matrix is generated in Subprogram 1 and stored in file 21 if the dam-water-foundation rock system is non-symmetric about the x-y plane and in files 21 (for antisymmetric case) and 22 (for symmetric case) if the system is symmetric about the x-y plane (Table 8.1). For a system symmetric about the x-y plane, the foundation impedance matrix for the whole system will be generated and transformed into two matrices, one for symmetric analyses and the other for antisymmetric analyses. In Subprogram 3, files 21 and/or 22 will be converted into files 23 and/or 24, which will subsequently be used in Subprogram 6 (Table 8.1). As mentioned in Section 6.3, the foundation impedance matrix should at least be evaluated at four different frequencies, including the zero frequency. Therefore, It is recommended to run Subprogram 1 in dynamic analysis to generate the foundation impedance matrix before performing the static analysis. The zero-frequency value of the matrix is stored in file 2 to evaluate the vibration frequencies and corresponding Ritz vectors of the dam-foundation rock system [7].

In the earthquake analysis of a dam-water-foundation rock system non-symmetric about the x-y plane, the Main Program can be executed with only one continuous run of Subprograms 1 to 7, with Subprogram 1 skipped for a rigid foundation rock and Subprograms 4 and 5 skipped for an empty reservoir (see Chapter 9 – Main Program). The earthquake time-history displacement and stress responses and the extreme stress values are computed and output in Subprogram 7.

In the earthquake analysis of a dam-water-foundation rock system symmetric about the x-y plane, only one-half of the entire system needs to be analyzed. Upstream (x) and vertical (y) components of ground motion cause responses symmetric about the plane of symmetry (x-y plane), and symmetric boundary conditions are therefore imposed on this plane. Cross-stream (z) ground

Table 8.1 Input and output disk files of the different subprograms

Section	Input/Output Files	Static Analysis	Dynamic Analysis
Main Program	Input files from previous subprograms	-	-
	Output files needed by subsequent subprograms	-	-
Subprogram 1	Input files from previous subprograms	-[*]	-[*]
	Output files needed by subsequent subprograms	file 2	file 2 If NSYM = 3, file 21 If NSYM ≠ 3, files 21 and 22
Subprogram 2	Input files from previous subprograms	If IFRIG ≠ 2, file 2	If IFRIG ≠ 2, file 2
	Output files needed by subsequent subprograms	file 99	file 99 If NSYM ≠ 2, file 12 If NSYM = 2, file 13
Subprogram 3	Input files from previous subprograms	file 99 (from Subprogram 2) file 2 (from Subprogram 1)	file 99 (from Subprogram 2) file 2 (from Subprogram 1) If NSYM ≠ 2, file 12 (from Subprogram 2) If NSYM = 2, file 13 (from Subprogram 2) If NSYM ≠ 2, file 21 (from Subprogram 1) If NSYM = 2, file 22 (from Subprogram 1)
	Output files needed by subsequent subprograms	file 8	file 8 If NSYM ≠ 2, files 12 and 23 If NSYM = 2, files 13 and 24
Subprogram 4	Input files from previous subprograms	-	-
	Output files needed by subsequent subprograms	file 3	file 99
Subprogram 5	Input files from previous subprograms	-	file 99 (from Subprogram 4) file 2 (from Subprogram 3)
	Output files needed by subsequent subprograms	-	file 3
Subprogram 6	Input files from previous subprograms	file 3 (from Subprogram 4) file 8 (from Subprogram 3)	file 3 (from Subprogram 5) file 8 (from Subprogram 3) If NSYM ≠ 2, files 12 and 23 (from Subprogram 3) If NSYM = 2, files 13 and 24 (from Subprogram 3)
	Output files needed by subsequent subprograms	file 7	file 4
Subprogram 7	Input files from previous subprograms	-	file 7 (from Subprogram 6, static analysis)[†] If NSYM = 3, file 8 (from Subprogram 3) and file 4 (from Subprogram 6) If NSYM = 2, file 8 (from Subprogram 3, symmetric analysis) and file 4 (from Subprogram 6, symmetric analysis) if x or y ground motion is considered; and file 1 (file 8 from Subprogram 3, antisymmetric analysis) and file 10 (file 4 from Subprogram 6, antisymmetric analysis) if z ground motion is considered. If NSYM = 3, file 12 (from Subprogram 3) If NSYM = 2, files 12 and 13 (from Subprogram 3)
	Output files for post-processing	-	files 15, 98 and 99

[*] Assuming foundation impedance matrix is not available from previous run.

[†] File 7 needed only if static stresses due to dead weight of the dam and hydrostatic pressure are to be included in the principal stresses and extreme values of stresses output in Subprogram 7; or if the static forces due to dead weight of the dam and hydrostatic pressure are to be included in computing the forces imposed by the dam on the foundation rock in Subprogram 7.

motion causes responses antisymmetric about the plane of symmetry, and antisymmetric boundary conditions are therefore imposed on this plane. When only upstream (x) and/or vertical (y) ground motions are considered as the excitation, the Main Program is executed with one continuous run of Subprograms 1 to 7 (again, Subprogram 1 is skipped if the foundation rock is rigid and Subprograms 4 and 5 are skipped if the reservoir is empty) to obtain the earthquake time-history responses. However, when the cross-stream (z) component of ground motion is considered as the excitation or as one of the components of the excitation, Subprogram 7 has to be run separately from Subprograms 1 to 6 in the following situations:

1. When the responses to symmetric — upstream (x) and/or vertical (y) — components of ground motion and the responses to antisymmetric — cross-stream (z) — component of ground motion are to be combined together in Subprogram 7 or computed separately in the same run of Subprogram 7, the complex-valued frequency response functions for the three excitation components should be obtained first from two separate executions of Subprograms 1 to 6 (NSYM = 2 for x and y ground motion components and NSYM = 1 for the z component; see Chapter 9 – Main Program), and saving file 8 and file 4 after the execution of Subprogram 6 in each of two separate runs (see Table 8.1). Subsequently Subprogram 7 can be executed using file 8 and file 4 from the symmetric (NSYM = 2) run of Subprograms 1 to 6, which are now also referred to as file 8 and file 4, respectively, in Subprogram 7; and using file 8 and file 4 from the antisymmetric (NSYM = 1) run of Subprograms 1 to 6, which are now referred to as file 1 and file 10, respectively, in Subprogram 7 (see Table 8.1).

2. When only the response to the antisymmetric — cross-stream (z) — component of ground motion is to be computed in Subprogram 7, Subprograms 1 to 6 should be executed first (NSYM = 1; see Chapter 9 – Main Program), and file 8 and file 4 should be saved. Subsequently, Subprogram 7 is run (NSYM = 2; see Chapter 9 – Main Program) using the saved file 8 and file 4 which are now referred to as file 1 and file 10, respectively, in Subprogram 7 (see Table 8.1).

The computer program can also be run in parts, for reasons mentioned in the beginning of this chapter, to obtain the earthquake response of a dam-water-foundation rock system, irrespective of its symmetry. By saving the necessary files for the subsequent execution of the corresponding subprograms, Subprogram 1 can be executed first for the foundation rock (if it is not assumed rigid), and then Subprograms 2 and 3 can be executed for the dam to obtain the vibration frequencies of the dam-foundation rock system. Then Subprograms 4 and 5 can be executed separately for the reservoir water (if it is not empty), followed by the execution of Subprogram 6 for the frequency response, and finally the execution of Subprogram 7 for the earthquake response. Running Subprogram 1 separately makes it possible to make efficient use of files 2, 21 and/or 22, as discussed earlier in this section. Running other subprograms in parts will also be computationally efficient if the earthquake responses of the same dam-foundation rock system under different cases and conditions are desired. For example, changing the reservoir conditions requires running only Subprograms 4, 5, 6 and 7; changing the earthquake ground excitation requires running only Subprogram 7; changing the wave reflection coefficient α requires running only Subprograms 4, 5, 6 and 7 or, in some special cases, just Subprograms 6 and 7; and changing the maximum excitation frequency FMAX in the Fourier Transform requires running only Subprograms 5, 6 and 7 if the foundation impedance matrix generated in Subprogram 1 still covers the new FMAX.

Consider the following example to demonstrate the economy of running the program in parts. A non-symmetric system is to be analyzed for an empty, half-full, and full reservoir under two earthquake excitations. Subprograms 1, 2 and 3 are run first followed by three runs of Subprograms 4, 5 and 6, one run for each of the three reservoir conditions. Finally, six runs of Subprogram 7 are made to obtain the dam responses for each of the three reservoir conditions under the two earthquake excitations. Additional runs of Subprogram 7 could be made if additional response output, not obtained previously, is desired.

8.3 Combined Static and Dynamic Analysis

If static stresses are to be added to the dynamic stresses, and the static forces are to be added to the equivalent static forces imposed by the dam on the foundation rock computed in Subprogram 7 (for the load cases when NCOMB(4) ≠ 0, see Chapter 9 – Subprogram 7), Subprogram 7 has to be executed separately from Subprograms 1 to 6 under all conditions. First, the dynamic response of the dam-water-foundation rock system is analyzed by one execution of Subprograms 1 to 6 for a non-symmetric system (NSYM = 3), or by one or two (symmetric and/or antisymmetric) executions of Subprograms 1 to 6 for a symmetric system (see Section 8.2 above), with file(s) 8 and file(s) 4 saved in either case. Subsequently, static analysis of the system by executing Subprograms 1 to 6 is carried out and file 7 containing the static stresses due to the dead weight of the dam and the hydrostatic pressure is saved. Finally, Subprogram 7 is executed, using file 7 (which is now also referred to as file 7), file(s) 8 (referred to as file 8 and/or file 1 in Subprogram 7; see Section 8.2 above) and file(s) 4 (referred to as file 4 and/or file 10 in Subprogram 7; see Section 8.2 above).

In addition to a separate execution of Subprogram 7 in which the static responses are combined with the dynamic responses of the dam as described above, the execution of Subprograms 1 to 6 in the static or dynamic analysis can be carried out in parts. In the static analysis, Subprogram 1 can be executed first separately if the foundation rock is flexible as described in Section 8.1 above. In the dynamic analysis, Subprogram 1, Subprograms 2 and 3, Subprograms 4 and 5, and Subprogram 6 can be executed separately as described in Section 8.2 above.

9. INPUT DATA DESCRIPTION

The computer program can analysis three-dimensional dams with different assumptions for the dam, foundation rock, and reservoir. With the specification of the input data, the following cases of dam, foundation rock, and reservoir conditions can be analyzed:

1. Dam-water-foundation rock system
   a. symmetric about the x-y plane
   b. non-symmetric about the x-y plane
2. Foundation rock supporting the dam
   a. rigid
   b. flexible
3. Reservoir domain
   a. extent of reservoir
      i. infinite extent
      ii. finite reservoir
   b. compressibility of water
      i. compressibility included
      ii. compressibility neglected
   c. reservoir boundary (bottom and sides)
      i. absorptive (when compressibility is also included)
      ii. non-absorptive (or rigid)
   d. water level
      i. any water level provided the finite element mesh for the dam is defined to include nodal points at the water surface
      ii. empty reservoir

The computer program consists of one main program and seven subprograms. Parameters input to the main program direct and control the execution of the seven subprograms. The primary functions of each of the seven subprograms are listed below:

Subprogram 1 —The complex-valued frequency-dependent foundation impedance matrix of the flexible foundation rock for DOFs along the dam-foundation rock interface is computed.

Subprogram 2 —The element stiffness, mass, and stress matrices of the dam are computed.

Subprogram 3 —The dam stiffness and mass matrices are assembled with the foundation stiffness matrix (foundation impedance matrix at zero frequency) from Subprogram 1 included for a flexible foundation rock. In dynamic analysis, the natural frequencies and mode shapes of the dam-foundation rock are computed. In static analysis, the self-weight load vector of the dam is computed.

Subprogram 4 —The five fluid meshes are defined, and in dynamic analysis, the element "stiffness", "mass", and "damping" matrices of Meshes 1 and 2 are computed. In static analysis, the hydrostatic pressure load vector on the dam is computed.

Subprogram 5 —The element matrices of fluid Meshes 1 and 2 from Subprogram 4 are assembled and the Mesh 2 eigenproblem of an infinite uniform channel is solved at an excitation frequency of zero in dynamic analysis. The load vectors of the fluid domain are also computed.

Subprogram 6 —The complex-valued frequency responses of the dam modal coordinates are computed in dynamic analysis. In static analysis, the static displacements and stresses of the dam are computed.

Subprogram 7 —The earthquake time-history responses of the dam are computed.

The input data for the different subprograms are described in this chapter. A line of input will be referred to as a record. The format of each line is described by fields which are denoted by Iw (integer), Fw (floating point) or Ew (exponential), where w is the field width. Inclusive record columns for each input variable are also given. Integer values must be right justified in the Iw field and in the optional exponent portion of the Ew field.

The weight and the length dimensions in the input data can be in any unit system (e.g., lb, ft or N, m), and the output displacements and stresses will also be in the same unit system (e.g., ft, lb/ft^2 or m, N/m^2).

MAIN PROGRAM: MASTER CONTROL RECORDS

A maximum of five records are input in the main program.

Record A — Control record for subprogram execution (7I4)

1 – 4	NOPT1	= 0, rigid foundation rock or if Subprogram 1 is skipped. ≠ 0, flexible foundation rock with execution of Subprogram 1.
5 – 8	NOPT2	= 0, if Subprogram 2 is skipped. ≠ 0, dam considered with execution of Subprogram 2.
9 – 12	NOPT3	= 0, if Subprogram 3 is skipped. ≠ 0, dam considered with execution of Subprogram 3.
13 – 16	NOPT4	= 0, empty reservoir of if Subprogram 4 is skipped. ≠ 0, reservoir water considered with execution of Subprogram 4.
17 – 20	NOPT5	= 0, empty reservoir or if static analysis is performed or if Subprogram 5 is skipped. ≠ 0, reservoir water considered in dynamic analysis with execution of Subprogram 5.
21 – 24	NOPT6	= 0, no computation of frequency responses in dynamic analysis or static responses in static analysis; Subprogram 6 is skipped. ≠ 0, frequency responses (dynamic analysis) or static responses (static analysis) are computed with execution of Subprogram 6.
25 – 28	NOPT7	= 0, static analysis or no computation of earthquake responses; Subprogram 6 is skipped. ≠ 0, earthquake responses are computed with execution of Subprogram 6.

Record B — General Control record (I8, 4I4, 2E12)

1 – 8	MTOT	Maximum size of the blank common storage to be used (≤ current dimension of array A, which is set at 200,000 but can be changed by the user).
9 – 12	NSYM	When running Subprograms 1 to 6, NSYM identifies the symmetry of the dam-water-foundation rock system and the components of ground motion considered. = 1 for analysis of one-half of a symmetric system with antisymmetric boundary conditions to cross-stream (z) ground motion. = 2 for analysis of one-half of a symmetric system with symmetric boundary conditions to upstream (x) and vertical (y) ground motions, or to static loading (NSD = 0; see later part of this record). = 3 for a non-symmetric system. When running Subprogram 7, NSYM also identifies the symmetry of the dam-water-foundation rock system. = 2 for a symmetric system. = 3 for a non-symmetric system.

13 – 16	IFRIG	$= 0$, for rigid foundation rock. $\neq 0$, for flexible foundation rock.
17 – 20	NWAT	For dynamic analysis (NSD $\neq 0$; see next entry), $= 0$, empty reservoir. $= 1$, impounded water is assumed incompressible† (α does not apply). $= 2$, impounded water is compressible and the reservoir bottom-sides are rigid ($\alpha = 1$; α is the value REF input in Record A of Subprogram 6). $= 3$, impounded water is compressible and some parts of the reservoir bottom-sides are absorptive ($\alpha < 1$). For static analysis (NSD $= 0$; see next entry), $= 0$, empty reservoir. $\neq 0$, the solutions due to the dead weight of the dam along, the water pressure along, and both dead weight and water pressure are computed.
21 – 24	NSD	$= 0$, perform static analysis (final results appear in Subprogram 6). $\neq 0$, perform dynamic or earthquake analysis, whether the static stresses are combined with the dynamic stresses or not.
25 – 36	FMAX	Maximum excitation frequency, in Hz, considered in the frequency response and earthquake response computations (refer to Section 7.1) for selection of FMAX); not needed in static analysis.
37 – 48	DFR	Frequency increment, in Hz, considered in the computation of the foundation impedance matrix; not needed in static analysis.

In dynamic analysis (NSD = 1), the number of frequencies at which foundation impedance matrix is computed will be determined by FMAX and DFR automatically. As mentioned in Section 6.3, this number should be larger than 4 for the cubic interpolation scheme to properly determine the numerical values of the foundation impedance matrix by interpolating between their known values at these selected frequencies. It is recommended that this number be around 10 to provide accurate analysis results. In static analysis (NSD = 0) only the foundation stiffness matrix (at zero frequency) is computed regardless of the values of FMAX and DFR.

Record C — Parameters for the finite element idealization of the dam (4I4)

1 – 4	NDTP	Parameter identifying the type of finite element used to idealize the dam; all elements are of the same type. = 1 for 3-d shell dam element (including transition element). = 2 for 3-d solid dam element.
5 – 8	NFD	Number of vibration modes of the dam-foundation rock system including in dynamic or earthquake analysis ($2 \times$ NFD and NFD + 8 must not exceed the

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† For incompressible water and infinite reservoir, the velocity of pressure waves is assigned a value of 4720 ft/sec (as if water is compressible) in the program when determining the number of infinite channel eigenvectors to include; because this results in the same number of eigenvectors as for compressible water for a given FMAX. This value should be changed if other unit system is used (by changing the first executable statement in subroutines sub5 and sub6).

		total number of DOFs in the dam mesh; refer to Section 7.2 for selection of NFD); not needed in static analysis.
9 – 12	NNPD	Number of nodal points in the dam mesh.
13 – 16	NELD	Number of finite elements in the dam mesh.

If the 3-d shell dam element is used (NDTP = 1), NNPD is the number of mid-surface nodal points in the dam mesh (see Record A of Subprogram 2 in this chapter for numbering the nodal points for shell element).

Record D — Parameters for the boundary element idealization of the foundation rock (2I4, E12)

Omit this record if the foundation rock is rigid (IFRIG = 0 in Record B of this subprogram).

1 – 4	NNPRF	Number of nodal points in the foundation mesh for the dam-foundation rock interface.
5 – 8	NELRF	Number of boundary elements in the foundation mesh for the dam-foundation rock interface.
9 – 20	HMAX	y coordinate of the free surface level of the reservoir; needed only if the reservoir is not empty and if static analysis is performed.

Record E — Parameters for the finite element idealization and the property of the impounded water and reservoir boundary (7I4, E12)

Omit this record if the reservoir is empty (NWAT = 0 in Record B of this main program).

1 – 4	NNP1	Number of Type 1 nodal points in the fluid mesh (a Type 1 node is any node not a Type 2; see next entry).
5 – 8	NNP2	Number of Type 2 nodal points in the fluid mesh (a Type 2 node is a node on the transmitting plane); = 0 if the impounded water is idealized to extend to finite length in the upstream direction.
9 – 12	NEL1	Number of finite elements in Mesh 1 (Mesh 1 spans the entire irregular region of the impounded water. Legal elements are triangular prism and rectangular prism elements).
13 – 16	NEL2	Number of finite elements in Mesh 2 (Mesh 2 spans the transmitting plane. Legal elements are triangular and rectangular plane elements); = 0 if the impounded water is idealized to extend to finite length in the upstream direction.
17 – 20	NEL3	Number of finite elements in Mesh 3 (Mesh 3 spans the boundary of the impounded water in contact with the dam. Legal elements are triangular and rectangular plane elements).
21 – 24	NEL4	Number of finite elements in Mesh 4 (Mesh 4 spans the reservoir bottom and sides. Legal elements are triangular and rectangular plane elements).

25 – 28	NEL5	Number of finite elements in Mesh 5 (Mesh 5 spans the bottom and sides of the transmitting plane. Legal elements are triangular and rectangular plane elements); = 0 if the impounded water is idealized to extend to finite length in the upstream direction.
29 – 40	C	Velocity of pressure waves in water; needed only in dynamic or earthquake analysis when the impounded water is compressible ($\text{NWAT} \geq 2$ in Record B of this main program).
41 – 52	REFB	Wave reflection coefficient α of the reservoir bottom; needed only in dynamic or earthquake analysis when wave absorption is considered in some or all parts of the reservoir bottom-sides ($\text{NWAT} = 3$ in Record B of this main program).
53 – 64	REFS	Wave reflection coefficient α of the reservoir sides; needed only in dynamic or earthquake analysis when wave absorption is considered in some or all parts of the reservoir bottom-sides are absorptive ($\text{NWAT} = 3$ in Record B of this main program).

Note that REFB and REFS are used to compute the normalized damping matrix at the reservoir boundary. The real wave reflection coefficient at the reservoir bottom is input in Subprogram 6 (REF in Record A of Subprogram 6) to obtain the real damping matrix. It is required that $0 \leq \text{REFB} < 1$, and $\text{REFB} \leq \text{REFS} \leq 1$. The wave reflection coefficient REF should be equal to REFB if $\text{REFS} \neq \text{REFB}$. However, if $\text{REFS} = \text{REFB}$ (equally absorptive at the reservoir bottom and sides) or $\text{REFS} = 1$ (rigid reservoir sides), REF can be different from REFB (see also Record A of Subprogram 6). This feature is useful in parametric study on the effects of reservoir boundary absorption: Subprograms 4 and 5 need to be run once whereas Subprograms 6 and 7 can be run separately for each specified REF value.

Figure 5.2 illustrates Type 1 and 2 nodal points and the meshes 1, 2, 3, 4 and 5 for an infinite reservoir domain. When only static analysis is performed ($\text{NSD} = 0$ in Record B of this main program), a complete fluid mesh or only a mesh 3 at the dam face may be input. For the latter case, $\text{NEL1} = 0$, $\text{NEL2} = 0$, $\text{NEL3} > 0$, $\text{NEL4} = 0$, $\text{NEL5} = 0$; and the mesh 3 nodal points can be classified as all Type 1 or Type 2.

SUBPROGRAM 1: FOUNDATION ROCK

No records are required if the foundation rock is rigid, in which case NOPT1 = 0 (Record A of Main Program). If NOPT1 ≠ 0, the following records should be supplied:

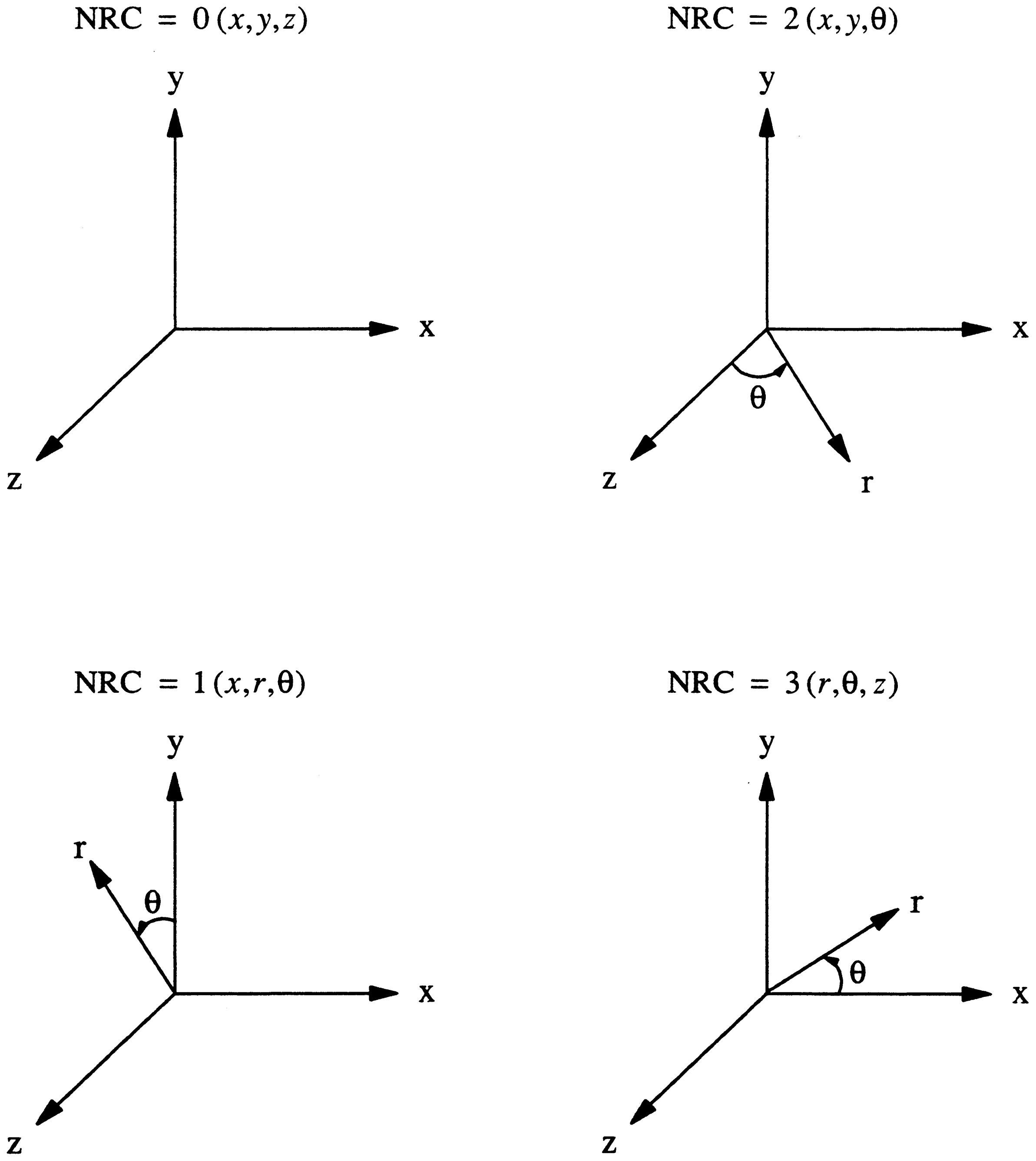
Record A — Control record for computing foundation impedance matrix (2I4)

1 – 4	NIMP	= 0 if foundation impedance matrix is already computed and available. = 1 if foundation impedance matrix is to be computed.
5 – 6	NCONT	= 0 if the program should stop after generating the foundation impedance matrix; no effect if NIMP = 0. = 1 if the program should continue to execute after generating the foundation impedance matrix; no effect if NIMP = 0.

NCONT has no effect if NIMP = 0.

Record B — Nodal point coordinates (I4, I2, 3F10, I2, I4, 3F10)

1 – 4	N	Nodal point number.
5 – 6	NRC	= 0 if the input values are in rectangular coordinates (x, y, z). = 1 if polar coordinates are used in the y-z plane (x, r, θ) = 2 if polar coordinates are used in the z-x plane (r, y, θ) = 3 if polar coordinates are used in the x-y plane (r, θ, z) Figure 9.1 shows the coordinates axes for NRC = 0, 1, 2 and 3.
7 – 16	COOR1	= x coordinate of nodal point N (NRC = 0 or 1). = r coordinate of nodal point N (NRC = 2 or 3).
17 – 26	COOR2	= y coordinate of nodal point N (NRC = 0 or 2). = r coordinate of nodal point N (NRC = 1). = θ coordinate, in degrees, of nodal point N (NRC = 3).
27 – 36	COOR3	= z coordinate of nodal point N (NRC = 0 or 3). = θ coordinate, in degrees, of nodal point N (NRC = 1 or 2).
37 – 38	NFW	Number of following nodes for which coordinates are to be automatically generated by this record. The nodal point numbers of these NFW nodes are incremented successively by NINC, and the coordinates by CINC1, CINC2, and CINC3 (see next four entries).
39 – 42	NINC	Nodal point number increment for generated nodal points (can be < 0).
43 – 52	CINC1	COOR1 coordinate increment for generated nodal points.
53 – 62	CINC2	COOR2 coordinate increment for generated nodal points.
63 – 72	CINC3	COOR3 coordinate increment for generated nodal points.



NRC = $0\,(x,y,z)$

NRC = $2\,(x,y,\theta)$

NRC = $1\,(x,r,\theta)$

NRC = $3\,(r,\theta,z)$

Figure 9.1 Coordinate axes for NRC = 0, 1, 2, 3 for defining the nodal point coordinates.

The nodal points are numbered 1 to NNPRF (input in Record D of Main Program) and can be input in any sequence. The above record needs to be repeated until all the NNPRF nodal point coordinates are defined.

Record C — Nodal points on plane of symmetry (20I4)

1 – 80	JSYM(I)	Vector of nodal point numbers of foundation rock nodes located on the plane of symmetry of the dam-water-foundation rock system (the x-y plane). Fixed nodes need not be included.

The nodal point numbers (in any order) are read in 20 at a time, and the sequence must be terminated by a zero (or blank). Enough records should be supplied to read in all the nodal points located on the plane of symmetry. A blank record should be supplied even if there is no plane of symmetry in a non-symmetric system.

Record D — Mapping of foundation nodal points to dam nodal points (20I4)

1 – 80	JRCK(I), JDAM(I)	JRCK(I) is the Ith element if the vector of nodal point numbers of the foundation rock nodes. JDAM(I) is the Ith element of the vector of nodal point numbers of the dam nodes that correspond to the foundation nodes. Thus, JRCK(I) and JDAM(I) for any single I correspond to the same node on the interface. The nodal point number pairs should be input in the order such that the nodal point number of the dam, JDAM(I), is monotonically increasing.

When shell elements are used in the dam (NDTP = 1 in Record C of Main Program) to connect with surface boundary elements in the foundation rock, each mid-surface node of the dam is associated with two nodes of the foundation rock, one on the upstream face and the other on the downstream face (see Section 5.2). In this case, JRCK(I) and JDAM(I) for each nodal connection on the interface should be of the form: NFOUP, NDAM. NFODN, NDAM where NFOUP and NFODN are the nodal point numbers of the upstream and downstream foundation nodes, respectively, and NDAM is the nodal point number of the corresponding dam mid-surface node. Fixed nodes need not be included.

The nodal point numbers (2 in one pair) are read in 20 (10 pairs) at a time, and the sequence must be terminated by a zero (or blank). Enough records should be supplied to read in all the nodal points located on the dam-foundation rock interface.

Record E — Material properties sets of the foundation elements

Record E.1 — Number of different material properties sets (I4)

1 – 4	NUMMAT	The number of different material properties sets used in the boundary element idealization of the foundation rock.

Record E.2 — Material properties sets records (I4, 4E12)

1 – 4	N	Material properties set number.

5 – 16	EEF	Young's modulus of elasticity in this material properties set.
17 – 28	PRF	Poisson's ratio in this material properties set.
29 – 40	RHOF	Unit mass in this material properties set.
41 – 52	DRF	Constant hysteretic damping ratio in this material properties set.

In the current version of the computer program, NUMMAT must be set to 1 because the foundation rock is assumed to be homogeneous. If future version allows multiple material property sets, the material properties sets are numbered 1 to NUMMAT (input in Record E.1 of this subprogram above) and can be input in any order, and a total of NUMMAT records should therefore be supplied here to specify all the material properties sets.

The "base" foundation impedance matrix, from which the impedance matrix for foundation rock with a different Young's modulus can be readily obtained, can be computed for the foundation rock with this set of material properties (see also Record L of this subprogram below). It is recommended to chose the foundation rock with the smallest Young's modulus to compute the "base" foundation impedance matrix (Section 6.3).

Record F — Element properties and definition records

Two records are required for each of the NELRF (input in Record D of Main Program) foundation elements. The elements are numbered 1 to NELRF and can be input in any sequence.

Record F.1 — Element data and properties (4I4)

1 – 4	N	Element number.
5 – 8	NELTY	Element type identifier. = 2 for rectangular surface element. = 3 for triangular surface element.
9 – 12	NMAT	Material properties set number defining the properties of this element (a number between 1 and NUMMAT; see Record E.1 of this subprogram above).

Record F.2 — Element connectivity (20I4)

1 – 80	LM(I)	Vector (I = 1, NENI) of nodal point numbers of the element nodes. Refer to Figure 5.1 for proper ordering of nodes. NENI is the maximum number of nodal points per element. NENI = 8 and 6, respectively, for NELTY = 2 and 3.

If the Ith element nodal point is to be omitted (allowed only for non-corner nodes), LM(I) = 0. To combine nodes, omit in-between nodes and repeat the corner node in the LM vector (see Section 5.1).

Record G — Parameters for discretizing the dam-foundation rock interface

Record G.1 — Along the x axis (I4)

1 – 4	NTK	Maximum number of elements on dam-foundation rock interface intersected by a line parallel to the x axis.

Record G.2 — At x = 0 (F10, 4I4)

1 – 10	AL	Discretization range on the half-space surface Γ_h.
11 – 14	NL	Number of elements on Γ_h.
15 – 18	ME	Number of elements on the canyon boundary Γ_c; for symmetric system, number of elements on half of Γ_c.
19 – 22	NCORN	Number of non-smooth points on Γ_c; for symmetric system, number of non-smooth points on half of Γ_c.
23 – 26	NGS	Number of Gauss integration points in each element on $\Gamma_c \cup \Gamma_h$, between 2 and 6).

Record H — Parameters for the integration scheme

Record H.1 — Integration scheme identifier (I4)

1 – 4	INSP	= 1 to specify integration subdomains (Figure 6.4) and use piecewise Gauss integration scheme. = 2 to use adaptive procedure based on a test function.

Record H.2 — Integration control parameters

If INSP = 1, the following parameters about the sizes of the subdomains and the corresponding integration step-sizes should be supplied (7E11):

1 – 11	AK	Maximum integration range in wavenumber domain.
12 – 22	DR	Half-width of the wavenumber subdomain containing the Rayleigh wavenumber.
12 – 33	DR1	Size of a wavenumber subdomain.
34 – 44	DD1	Piecewise integration step size in the first wavenumber subdomain.
45 – 55	DD2	Piecewise integration step size in the second wavenumber subdomain.
56 – 66	DD3	Piecewise integration step size in the third wavenumber subdomain.
67 – 77	DD4	Piecewise integration step size in the fourth wavenumber subdomain.

The meanings of the parameters, from AK to DD4, are illustrated in Figure 6.4. If any of these parameters is specified as zero, default value will be used for that parameter.

If INSP = 2, the tolerance for the adaptive procedure should be supplied (E11):

1 – 11	TOL	Tolerance for the adaptive procedure based on a test function.

The adaptive procedure (INSP = 2) is recommended and TOL = 0.001 is sufficient for most cases.

Record I — Geometry parameter of the coordinate system (F10)

1 – 10	YZERO	Vertical distance from the origin of the x-y-z coordinate system to the horizontal surface of the canyon. YZERO is defined positive if the origin is below the horizontal surface of the canyon.

Record J — Coordinates for the reference nodal points on the canyon boundary at $x = 0$

Each line consists of two real numbers defining a reference nodal point (2F10):

1 – 10	Y2	y-coordinate of the nodal point.
11 –20	Z2	z-coordinate of the nodal point.

Enough lines should be supplied until coordinates for all the ME + 1 nodes (refer to Record G.2 of this subprogram for ME), from left to right, on Γ_c are specified. For symmetric system, nodal coordinates are required only for half of the system.

Record K — Geometry of non-smooth boundary points

Each line consists of three numbers (I4, 2F10):

1 – 4	J	Nodal number of the non-smooth node on Γ_c; or on half of Γ_c if the system is symmetric.
5 – 14	ϕ_1	Angle of the tangent line in radius for the non-smooth node defined in Figure 9.2.
15 – 24	ϕ_2	Angle of the tangent line in radius for the non-smooth node defined in Figure 9.2.

It should be noticed that $\phi_1 - \phi_2 > 0$. Enough lines should be supplied until the geometry for all the NCORN non-smooth nodes are defined.

Record L — Utilizing previously-computed foundation impedance matrix (F10)

1 – 4	EFR	Young's moduli of the foundation rock in the current analysis divided by its value for which the "base" foundation impedance matrix is already available.

Note that the Poisson's ratio and damping values of the foundation rock must be the same as the foundation rock for which the "base" foundation impedance matrix is computed (Section 6.3). It is recommended that EFR $\geq$ 1.

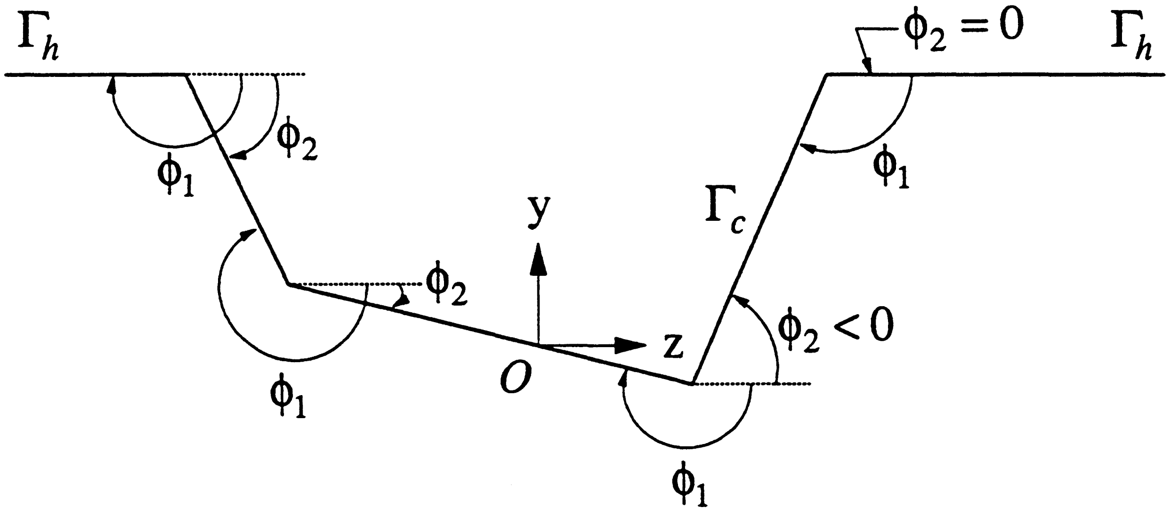


Figure 9.2 Definition of angles of tangents for the non-smooth boundary points.

SUBPROGRAM 2: DAM

If NOPT2 ≠ 0 (Record A of Main Program), the following records should be supplied:

Record A — Nodal point coordinates (I4, I2, 3F10, I2, I4, 3F10)

1 – 4	N	Nodal point number.
5 – 6	NRC	= 0 if the input values are in rectangular coordinates (x, y, z). = 1 if polar coordinates are used in the y-z plane (x, r, θ) = 2 if polar coordinates are used in the z-x plane (r, y, θ) = 3 if polar coordinates are used in the x-y plane (r, θ, z) Figure 9.1 shows the coordinates axes for NRC = 0, 1, 2 and 3.
7 – 16	COOR1	= x coordinate of nodal point N (NRC = 0 or 1). = r coordinate of nodal point N (NRC = 2 or 3).
17 – 26	COOR2	= y coordinate of nodal point N (NRC = 0 or 2). = r coordinate of nodal point N (NRC = 1). = θ coordinate, in degrees, of nodal point N (NRC = 3).
27 – 36	COOR3	= z coordinate of nodal point N (NRC = 0 or 3). = θ coordinate, in degrees, of nodal point N (NRC = 1 or 2).
37 – 38	NFW	Number of following nodes for which coordinates are to be automatically generated by this record. The nodal point numbers of these NFW nodes are incremented successively by NINC, and the coordinates by CINC1, CINC2, and CINC3 (see next four entries).
39 – 42	NINC	Nodal point number increment for generated nodal points (can be < 0).
43 – 52	CINC1	COOR1 coordinate increment for generated nodal points.
53 – 62	CINC2	COOR2 coordinate increment for generated nodal points.
63 – 72	CINC3	COOR3 coordinate increment for generated nodal points.

For a 3-d solid element mesh (NDTP = 2 in Record C of Main Program), the nodal points are numbered 1 to NNPD (input in Record C of Main Program) and can be input in any order. The above record is repeated until all the NNPD nodal point coordinates are defined.

For a 3-d shell element mesh (NDTP = 1 in Record C of Main Program), It is the coordinates of the 2 × NNPD auxiliary nodes on the dam's upstream and downstream faces which are input (in any order). These nodes are numbered 1 to NNPD on the upstream face and are numbered NNPD + 1 to 2 × NNPD on the downstream face in the same order. (Number of downstream node = NNPD + number of corresponding upstream node.) The above record is repeated until all the 2 × NNPD auxiliary nodal point coordinates are defined. Node number of the mid-surface nodes are those of the upstream auxiliary nodes, and coordinates of the mid-surface nodes are computed by the program as the averages of the coordinates of the upstream and downstream auxiliary nodes.

Record B — Fixed nodal points (20I4)

1 – 80	JFIX(I)	Vector of nodal point numbers of dam nodes on dam base (if foundation rock is rigid) with fixed boundary conditions.

The nodal point numbers (in any order) are read in 20 at a time, and the sequence must be terminated by a zero (or blank). Enough records should be supplied to read in all fixed nodal points. If shell elements are used, only the numbers of the mid-surface nodal points [the numbers 1 to NNPD (input in Record C of Main Program) corresponding to the upstream auxiliary nodes] should be used. A blank record should be supplied even if there are no fixed dam nodal points.

Record C — Nodal points on plane of symmetry (20I4)

1 – 80	JSYM(I)	Vector of nodal point numbers of dam nodes located on the plane of symmetry of the dam-water-foundation rock system (the x-y plane). Fixed nodes need not be included.

The nodal point numbers (in any order) are read in 20 at a time, and the sequence must be terminated by a zero (or blank). Enough records should be supplied to read in all the nodal points located on the plane of symmetry. If shell elements are used, only the numbers of the mid-surface nodal points [the numbers 1 to NNPD (input in Record C of Main Program) corresponding to the upstream auxiliary nodes] should be used. A blank record should be supplied even if there is no plane of symmetry in a non-symmetric system.

Record D — Nodal points on dam-foundation rock interface (20I4)

1 – 80	JINT(I)	Vector of nodal point numbers of dam nodes located on the dam-foundation rock interface of the dam-water-foundation rock system. Fixed nodes and nodes on the plane of symmetry for a symmetric system should also be included.

The nodal point numbers (in any order) are read in 20 at a time, and the sequence must be terminated by a zero (or blank). Enough records should be supplied to read in all the nodal points located on the plane of symmetry. If shell elements are used, only the numbers of the mid-surface nodal points [the numbers 1 to NNPD (input in Record C of Main Program) corresponding to the upstream auxiliary nodes] should be used.

Record E — Nodal point coordinates for the special treatment in transition elements (I5, 3F10)

Omit this record for a 3-d solid element mesh (NDTP = 2 in Record C of Main Program).

1 – 5	N	Nodal point number.
6 – 15	COOR1	= x coordinate of nodal point N.
16 – 25	COOR2	= y coordinate of nodal point N.
26 – 35	COOR3	= z coordinate of nodal point N.

The above record is repeated until the coordinates for all dam nodes along the abutment that need modification are defined (see Section 5.3). A blank record should be supplied even if there is no nodal point modified.

Record F — Material properties sets of the dam elements

Record F.1 — Number of different material properties sets (I4)

1 – 4	NUMMAT	The number of different material properties sets used in the finite element idealization of the dam.

Record F.2 — Material properties sets records (I4, 3E12)

1 – 4	N	Material properties set number.
5 – 16	EE	Young's modulus of elasticity in this material properties set.
17 – 28	PR	Poisson's ratio in this material properties set.
29 – 40	RHO	Unit mass in this material properties set.

The material properties sets are numbered 1 to NUMMAT (input in Record F.1 of this subprogram above) and can be input in any order. A total of NUMMAT records should therefore be supplied here to specify all the material properties sets.

Record G — Element properties and definition records

Two records are required for each of the NELD (input in Record C of Main Program) dam elements. The elements are numbered 1 to NELD and can be input in any sequence.

Record G.1 — Element data and properties (6I4)

1 – 4	N	Element number.
5 – 8	NELTY	Element type identifier. = 4 for 3-d rectangular prism element. = 5 for 3-d triangular prism element. = 6 for 3-d rectangular shell element. = 7 for 3-d triangular shell element.
9 – 12	NMAT	Material properties set number defining the properties of this element (a number between 1 and NUMMAT; see Record F.1 of this subprogram above).
13 – 16	NUPSM	Needed only for 3-d solid element (NDTP = 2 in Record C of Main Program); = 1 if a face of the element is on the upstream face of the dam. This face must be that at r = +1 (Figure 5.9). = 0 if none of the faces of the element is on the upstream face of the dam.
17 – 20	NDNSM	Needed only for 3-d solid element (NDTP = 2 in Record C of Main Program);

= 1 if a face of the element is on the downstream face of the dam. This face must be that at $r = -1$ (Figure 5.9).
= 0 if none of the faces of the element is on the downstream face of the dam.

Record G.2 — Element connectivity (20I4)

1 – 80	LM(I)	Vector (I = 1, NENI) of nodal point numbers of the element nodes. Refer to Figure 5.1, Figure 5.8 and Table 5.1 for proper ordering of nodes. NENI is the maximum number of nodal points per element. NENI = 20, 15, 8 and 6, for NELTY = 4, 5, 6 and 7, respectively.

If the I-th element nodal point is to be omitted (allowed only for non-corner nodes), LM(I) = 0. To combine nodes, omit in-between nodes and repeat the corner node in the LM vector (see Section 5.1).

SUBPROGRAM 3: DAM

If NOPT3 ≠ 0 (Record A of Main Program), the following records should be supplied:

Record A — Boundary condition modification records

Record A.1 — Number of nodal points to be changed (I4)

1 – 4	ICH	Number of dam nodal points whose fixity conditions are to be altered.

Record A.2 — Boundary condition records (7I4)

If ICH > 0, ICH records should be supplied after record A.1 with the format and input data for each record as follows:

1 – 4	N	Nodal point number (between 1 and NNPD) of the dam node whose fixity conditions is to be altered.
5 – 28	IDCH(I)	Vector (I = 1, NDPN) of the fixity conditions of the NDPN DOFs of the nodal point with number N. IDCH(I) = 0 if the I-th DOF is fixed. ≠ 0, if the I-th DOF is free. NDPN = 3 for a 3-d solid element node with DOF ordered as x, y, and z; = 5 for a 3-d shell element node not on the dam-foundation rock interface with DOF ordered as x, y, z, rotation about axis a, rotation about axis b (see Section 5.2); = 6 for a 3-d shell element node on the dam-foundation rock interface with DOF ordered as x, y, z at upstream auxiliary node, and x, y, z at downstream auxiliary node.

SUBPROGRAM 4: WATER

No records are required if the reservoir is empty, in which case NOPT4 = NOPT5 = 0 (Record A of Main Program), If NOPT4 ≠ 0, the following records should be supplied:

Record A — Type 1 and 2 nodal point coordinates (I4, I2, 3F10, I2, I4, 3F10)

1 – 4	N	Nodal point number.
5 – 6	NRC	= 0 if the input values are in rectangular coordinates (x, y, z). = 1 if polar coordinates are used in the y-z plane (x, r, θ) = 2 if polar coordinates are used in the z-x plane (r, y, θ) = 3 if polar coordinates are used in the x-y plane (r, θ , z) Figure 9.1 shows the coordinates axes for NRC = 0, 1, 2 and 3.
7 – 16	COOR1	= x coordinate of nodal point N (NRC = 0 or 1). = r coordinate of nodal point N (NRC = 2 or 3).
17 – 26	COOR2	= y coordinate of nodal point N (NRC = 0 or 2). = r coordinate of nodal point N (NRC = 1). = θ coordinate, in degrees, of nodal point N (NRC = 3).
27 – 36	COOR3	= z coordinate of nodal point N (NRC = 0 or 3). = θ coordinate, in degrees, of nodal point N (NRC = 1 or 2).
37 – 38	NFW	Number of following nodes for which coordinates are to be automatically generated by this record. The nodal point numbers of these NFW nodes are incremented successively by NINC, and the coordinates by CINC1, CINC2, and CINC3 (see next four entries).
39 – 42	NINC	Nodal point number increment for generated nodal points (can be < 0).
43 – 52	CINC1	COOR1 coordinate increment for generated nodal points.
53 – 62	CINC2	COOR2 coordinate increment for generated nodal points.
63 – 72	CINC3	COOR3 coordinate increment for generated nodal points.

The Type 1 nodal points should be numbered first from 1 to NNP1 (input in Record E of Main Program) and the type 2 nodal points should be numbered from NNP1 + 1 to NNP1 + NNP2 (input in Record E of Main Program). The nodal points can be input in any sequence. The above record needs to be repeated until all NNP1 + NNP2 nodal point coordinates are defined.

Record B — Free surface nodal points (20I4)

1 – 80	JFIX(I)	Vector of nodal point numbers of free surface nodes.

The nodal point numbers (in any order) are read in 20 at a time, and the sequence must be terminated by a zero (or blank). Enough records should be supplied to read in all fixed nodal points.

Record C — Nodal points on plane of symmetry (20I4)

1 – 80	JSYM(I)	Vector of nodal point numbers of fluid nodes located on the plane of symmetry of the dam-water-foundation rock system (the x-y plane). Free surface nodes need not be included.

The nodal point numbers (in any order) are read in 20 at a time, and the sequence must be terminated by a zero (or blank). Enough records should be supplied to read in all the nodal points located on the plane of symmetry. A blank record should be supplied even if there is no plane of symmetry in a non-symmetric system.

Record D — Nodal points on dam-water interface (20I4)

1 – 80	JF3(I), JDAM(I)	JF3(I) is the I-th element if the vector of nodal point numbers of the fluid mesh 3 nodes (Figure 5.2). JDAM(I) is the I-th element of the vector of nodal point numbers of the dam upstream face nodes that correspond to the fluid mesh 3 nodes. Thus, JF3(I) and JDAM(I) for any single I correspond to the same node on the interface.

The nodal point numbers (2 in one pair) are read in 20 (10 pairs) at a time, and the sequence must be terminated by a zero (or blank). Enough records should be supplied to read in all dam-water interface nodal points.

Record E — Nodal points on the bottom and sides of the irregular fluid region (20I4)

1 – 80	JF4(I)	Vector of nodal point numbers of Mesh 4 (Figure 5.2) nodes.

The nodal point numbers (in any order) are read in 20 at a time, and the sequence must be terminated by a zero (or blank). Enough records should be supplied to read in all nodal points located on the reservoir bottom and sides.

Record F — Nodal points on the bottom and sides of the transmitting plane (20I4)

1 – 80	JF5(I)	Vector of nodal point numbers of Mesh 5 (Figure 5.2) nodes.

The nodal point numbers (in any order) are read in 20 at a time, and the sequence must be terminated by a zero (or blank). Enough records should be supplied to read in all nodal points located on the bottom and sides of the transmitting plane.

Record G — Mesh 1 element records

No records are required if static analysis is performed (NSD = 0 in Record B of Main Program). Otherwise, two records for each of the NEL1 (input in Record E of Main Program) Mesh 1 elements (Figure 5.2) need be supplied. The elements are numbered 1 to NEL1 and can be input in any sequence.

Record G.1 — Element data (2I4)

1 – 4	N	Element number.
5 – 8	NELTY	Element type identifier. = 4 for 3-d rectangular prism element. = 5 for 3-d triangular prism element.

Record G.2 — Element connectivity (20I4)

1 – 80	LM(I)	Vector (I = 1, NENI) of nodal point numbers of the element nodes. Refer to Figure 5.1 for proper ordering of nodes. NENI is the maximum number of nodal points per element. NENI = 20 and 15, respectively, for NELTY = 4 and 5.

If the I-th element nodal point is to be omitted (allowed only for non-corner nodes), LM(I) = 0. To combine nodes, omit in-between nodes and repeat the corner node in the LM vector (see Section 5.1).

Record H — Mesh 2 element records

No records are required if there are no Mesh 2 elements (NEL2 = 0 in Record E of Main Program) for an impounded water idealized to extend to finite length in the upstream direction, or if static analysis is performed (NSD = 0 in Record B of Main Program). Otherwise, two records for each of the NEL2 Mesh 2 elements (Figure 5.2) need be supplied. The elements are numbered 1 to NEL2 and can be input in any sequence.

Record H.1 — Element data (2I4)

1 – 4	N	Element number.
5 – 8	NELTY	Element type identifier. = 2 for 2-d rectangular plane element. = 3 for 2-d triangular plane element.

Record H.2 — Element connectivity (20I4)

1 – 80	LM(I)	Vector (I = 1, NENI) of nodal point numbers of the element nodes. Refer to Figure 5.1, Figure 5.3(a) and Table 5.1 for proper ordering of nodes. NENI is the maximum number of nodal points per element. NENI = 8 and 6, respectively, for NELTY = 2 and 3.

If the I-th element nodal point is to be omitted (allowed only for non-corner nodes), LM(I) = 0.

Record I — Mesh 3 element records

Two records are supplied for each of the NEL3 (input in Record E of Main Program) Mesh 3 elements (Figure 5.2). The elements are numbered 1 to NEL3 and can be input in any sequence.

Record I.1 — Element data (2I4)

1 – 4	N	Element number.
5 – 8	NELTY	Element type identifier. = 2 for 2-d rectangular plane element. = 3 for 2-d triangular plane element.

Record I.2 — Element connectivity (20I4)

1 – 80	LM(I)	Vector (I = 1, NENI) of nodal point numbers of the element nodes. Refer to Figure 5.1, Figure 5.3(b) and Table 5.1 for proper ordering of nodes. NENI is the maximum number of nodal points per element. NENI = 8 and 6, respectively, for NELTY = 2 and 3.

If the I-th element nodal point is to be omitted (allowed only for non-corner nodes), LM(I) = 0.

Record J — Mesh 4 element records

No records are required if static analysis is performed (NSD = 0 in Record B of Main Program). Otherwise, the Mesh 4 elements (Figure 5.2) are numbered 1 to NEL4 (input in Record E of Main Program) and the following records should be supplied.

Record J.1 — Less Absorptive sides Mesh 4 elements (20I4)

1 – 80	JSIDE4(I)	Vector of element numbers of Mesh 4 elements at which less wave absorption takes place, that is, the wave reflection coefficient at the reservoir sides, REFS, is larger than the wave reflection coefficient at the reservoir bottom, REFB (see also Record E of Main Program).

The element numbers (in any order) are read in 20 at a time, and the sequence must be terminated by a zero (or blank). Enough records should be supplied to read in all Mesh 4 elements at which a less absorptive condition for wave reflection is assumed. A blank record should be supplied even if there are no less absorptive Mesh 4 elements. For an infinite reservoir, Mesh 4 intersects the transmitting plane at Mesh 5 (Figure 5.2); therefore the specification of less absorptive Mesh 4 elements here has to be consistent with the specification of less absorptive Mesh 5 elements (see Record K.1 of this subprogram below) at the reservoir bottom-side boundary of the transmitting plane. This input has meaning only when wave absorption is considered in some parts of the reservoir bottom-sides (NWAT = 3 in Record B of Main Program) in dynamic analysis. When the entire reservoir bottom-sides is assumed rigid (NWAT = 2) or when the impounded water is assumed incompressible (NWAT = 1), this input is ignored and a blank record is all that is needed here.

Record J.2 — Element records

Two records are required for each of the NEL4 Mesh 4 elements. The elements can be input in any sequence.

Record J.2.1 — Element data (2I4)

1 – 4	N	Element number.
5 – 8	NELTY	Element type identifier. = 2 for 2-d rectangular plane element. = 3 for 2-d triangular plane element.

Record J.2.2 — Element connectivity (20I4)

1 – 80	LM(I)	Vector (I = 1, NENI) of nodal point numbers of the element nodes. Refer to Figure 5.1, Figure 5.3(b) and Table 5.1 for proper ordering of nodes. NENI is the maximum number of nodal points per element. NENI = 8 and 6, respectively, for NELTY = 2 and 3.

If the I-th element nodal point is to be omitted (allowed only for non-corner nodes), LM(I) = 0.

Record K — Mesh 5 element records

No records are required if there are no Mesh 5 elements (NEL5 = 0 in Record E of Main Program) for an impounded water idealized to extend to finite length in the upstream direction, or if static analysis is performed (NSD = 0 in Record B of Main Program). Otherwise, the Mesh 5 elements (Figure 5.2) are numbered 1 to NEL5 and the following records should be supplied.

Record K.1 — Less Absorptive sides Mesh 5 elements (20I4)

1 – 80	JSIDE5(I)	Vector of element numbers of Mesh 5 elements at which less absorptive wave absorption takes place, that is, the wave reflection coefficient at the reservoir sides, REFS, is larger than the wave reflection coefficient at the reservoir bottom, REFB (see Record E of Main Program).

The element numbers (in any order) are read in 20 at a time, and the sequence must be terminated by a zero (or blank). Enough records should be supplied to read in all Mesh 4 elements at which a less absorptive condition for wave reflection is assumed. A blank record should be supplied even if there are no less absorptive Mesh 5 elements. For an infinite reservoir, Mesh 5 intersects Mesh 4 at the transmitting plane (Figure 5.2); therefore the specification of rigid Mesh 5 elements here has to be consistent with the specification of less absorptive Mesh 4 elements (see Record J.1 of this subprogram above) at the reservoir bottom-side boundary of the transmitting plane. This input has meaning only when wave absorption is considered in some parts of the reservoir bottom-sides (NWAT = 3 in Record B of Main Program) in dynamic analysis. When the entire reservoir bottom-sides is assumed rigid (NWAT = 2) or when the impounded water is assumed incompressible (NWAT = 1), this input is ignored and a blank record is all that is needed here.

Record K.2 — Element records

Two records are required for each of the NEL5 Mesh 5 elements. The elements can be input in any sequence.

Record K.2.1 — Element data (2I4)

1 – 4	N	Element number.

5 – 8	NELTY	Element type identifier. = 1 for line element.

Record K.2.2 — Element connectivity (20I4)

1 – 80	LM(I)	Vector (I = 1, NENI) of nodal point numbers of the element nodes. Refer to Figure 5.1, Figure 5.3(a) and Table 5.1 for proper ordering of nodes. NENI is the maximum number of nodal points per element. NENI = 3 for NELTY = 1.

If the 3rd element nodal point is to be omitted , LM(3) = 0.

SUBPROGRAM 5: WATER

No records are required in this subprogram whether NOPT5 = 0 or ≠ 0 (Record A of Main Program).

SUBPROGRAM 6: FREQUENCY RESPONSES OF DAM MODAL COORDINATES

If NOPT6 ≠ 0 (Record A of Main Program), the following records should be supplied.

Record A — Some system parameters and properties

Record A.1 — System properties (2E12)

Supply this record if static analysis is performed (NSD = 0 in Record B of Main Program).

1 – 12	RHOF	Unit mass of the impounded water; needed only if the reservoir is not empty (NWAT ≠ 0 in Record B of Main Program).
12– 24	AG	The acceleration due to gravity.

Record A.2 — System parameters and properties (3E12, 2I4)

Supply this record if dynamic analysis is performed (NSD ≠ 0 in Record B of Main Program).

1– 12	DR	Constant hysteretic damping factor for the dam.
12– 24	RHOF	Unit mass of the impounded water; needed only if the reservoir is not empty (NWAT ≠ 0 in Record B of Main Program).
25– 36	REF	Wave reflection coefficient α of the absorptive parts of the reservoir bottom-sides; needed only if wave absorption is considered in some parts of the reservoir bottom-sides (NWAT = 3 in Record B of Main Program). It is required that REF = REFB, the wave reflection coefficient at the reservoir bottom, if REFB ≠ REFS, the wave reflection coefficient at the reservoir sides (Record E of Main Program). However, REF can be different from REFB if REFB = REFS or REFS = 1 (see also Record E of Main Program and Records J.1 and K.1 of Subprogram 4).
37– 40	NANAL	> 0, to print the absolute values of the frequency responses. < 0, to print the real and imaginary components of the frequency responses.
41– 44	NYZ	Needed only for infinite fluid domains. = 0, if full vertical or cross-stream ground motion is considered along the entire reservoir bottom and sides. = 1, if the vertical or cross-stream ground motion is considered only along the reservoir bottom and sides of the irregular region, i.e., between the dam and the transmitting plane, but not beyond the transmitting plane.

SUBPROGRAM 7: EARTHQUAKE RESPONSES

If NOPT7 ≠ 0 (Record A of Main Program), the following records should be supplied.

Record A — Control parameters (7I4)

1 – 4	NCASE	Number of load cases (ground motion combinations and static contribution) to be included (see Record B of this subprogram below).
5 – 8	NQD	Number of time histories of dam nodal dynamic relative displacement components (NDA = 0; see later part of this record) or absolute acceleration components (NDA ≠ 0) for each load cases; ≤ NNPD (input in Record C of Main Program) × 5 (x, y, z, radial and tangential components). The static displacements are not included in these time histories.
9 – 12	NQS	Number of time histories of dynamic local stress components of the dam for each load case; ≤ NELD (input in Record C of Main Program) × number of stress locations per element (= 4 for 3-d shell element; = 8 for 3-d solid element) × number of stress components per stress location (= 10 for 3-d shell element; = 6 for 3-d solid element). The static stresses are not included in these time histories.
13 – 16	NEXS	≠ 0, compute and print the extreme values of local stress components and principal stresses and their times of occurrence at each of the stress locations in each dam element for each load case. = 0, no extreme stress computation.
17 – 20	NOUT	= 1, print time history responses only. = 2, write time history responses onto files 98 and 99 only. = 3, print and write time history responses. NOUT applies only to the NQD + NQS time history responses described above.
21 – 24	NDA	= 0, dam dynamic relative displacements are computed. ≠ 0, dam absolute accelerations are computed (no stresses of any kind will be computed in this case even if asked for).
25 – 28	NTS	> 0, equals the number of time instants at which the principal stresses at each of the stress locations in each dam element for each load case are computed and printed (see Record C of this subprogram below). = 0, no principal stresses at particular time instants are printed. < 0, time histories of the local stress components and principal stresses at each of the stress locations in each dam element for each load case are computed and the results written onto files 98 and 99. This output occurs in this case regardless of the value of NOUT.
29 – 32	NFO	= 0, equivalent static forces imposed by the dam on the foundation rock are not computed. > 0, equivalent static forces imposed by the dam on the foundation rock are computed.

Record B — Ground motion combination and static contribution (4I4)

1 – 16 (NCOMB(I), I = 1, 4) NCOMB(1), NCOMB(2), NCOMB(3) correspond relatively to the upstream (x), vertical (y) and cross-stream (z) ground motion components. For each of these three parameters, = 1, add ground motion component contribution to the total responses; = 0, omit contribution; = – 1, subtract contribution.

NCOMB(4) controls the static contribution to the stresses and forces; = 0, no static contribution; ≠ 0, add static stresses and forces due to dead weight and hydrostatic pressure resulting from a previous separate static analysis (file 7; see Table 8.1) to the extreme values of stresses (NEXS ≠ 0 in Record A of this subprogram above), to the stress results computed under the NTS < 0 or NTS > 0 option (see Record A of this subprogram above), and to the force results computed under the NFO > 0 option (see Record A of this subprogram above).

A total of NCASE (input in Record A of this subprogram above) records should be supplied here to read in all NCASE load cases.

Record C — Time instants for principal stresses (10F8)

Required only if NTS > 0 (see Record A of this subprogram above).

1 – 80 TIMS(I) Vector (I = 1, NTS) of time instants, in seconds, at which the principal stresses at each of the stress locations in each dam element for each load case are computed. The time instants should be multiples of $\text{TINCK} = \text{TINC} \times 2^{KK}$ and less than or equal to the ending time instant determined by TEND (see Record F of this subprogram below), and the time instants should be input in the order such that they are monotonically increasing.

Enough records should be supplied to read in all NTS time instants.

Record D — Dam displacement or acceleration responses (4(2I4, E12))

Required only if NQD > 0 (see Record A of this subprogram above).

1 – 80 (IND1(I), IND2(I), ANG(I), I = 1, NQD)

IND1(I) = nodal point number of the dam node at which the I-th displacement or acceleration time history is desired.

IND2(I) = 1 for x component of response
= 2 for y component of response
= 3 for z component of response
= 4 for the component of response at the angle defined by ANG(I) (see the next entry)

ANG(I) = angle, in degrees, defining the direction of the component of response desired; needed only if IND2(I) = 4 (see the previous entry). It is measured clockwise starting from the + x axis (pointing in the upstream direction) to the direction of the component in the z-x plane. This input data can be used to define, e.g., the radial and tangential components.

Enough records should be supplied to read in data for specification of all NQD responses.

Record E — Dam stress responses (20I4)

Required only if NQS > 0 (see Record A of this subprogram above).

1 – 80 (INS1(I), INS2(I), ISTYPE(I), I = 1, NQS)

INS1(I) = dam element number in which the I-th stress quantity time history is desired.

INS2(I) = stress location number within the dam element at which the I-th stress quantity time history is desired.

ISTYPE(I) = local stress component number of the I-th stress quantity time history in element INS1(I) at location INS2(I); = 1 to 6 for 3-d solid element, 1 to 10 for 3-d shell element (refer to Section 5.2 for description of the local stress components and the stress locations of the dam elements).

Enough records should be supplied to read in data for specification of all NQS responses.

Record F — FFT and time histories output parameters (E12, 3I4)

1 – 12	TEND	Determines the ending time instant, in seconds, of the time interval for which the earthquake motion is output and for which the time history responses and extreme stress values are computed and output. Ending time instant = the smallest multiple of TINCK (see later part of this record) which is ≥ TEND. TEND has to be ≤ N/(2×FMAX); N is related to MM and LL as described below in this record while FMAX is input in Record B of Main Program.
13 – 16	MM	Positive integer to determine the number of discrete time instants in the FFT computation, N, from the equation $N = 2^{MM} \times LL$.
17 – 20	LL	LL = 2 or 3.
21 – 24	KK	Integer ≥ 0 such that all the responses are output at time increments of $TINCK = TINC \times 2^{KK}$, where TINC = 1/(2×FMAX).

Record G — Earthquake ground motion records

For each of the three components of ground motion (x, y, and z), the following records are supplied in the order upstream (x) component, vertical (y) component and cross-stream (z) component. The first record is supplied even though a certain component of ground motion does not contribute in any of the NCASE (input in Record A of this subprogram above) load cases.

Record G.1 — Control parameters (2I4)

1 – 4	NPTEQ	Number of points (time instants) to define the component of ground motion, ≤ N (see Record F of this subprogram above).

= 0, if the component is not included in any of the NCASE load cases according to NCOMB (input in Record B of this subprogram above).

5 – 8 NOUTE = 0, no output of the earthquake component.
= 1, print the time function of the earthquake component only.
= 2, write the time function of the earthquake component onto files 98 and 99 only.
otherwise, print and write the time function.

Record G.2 — Earthquake acceleration records (10F8)

Required only if NPTEQ > 0 (see Record G.1 of this subprogram above).

1 – 80 EQ(I) Vector (I = 1, NPTEQ) of earthquake accelerations of the component at equally spaced time intervals of TINC [= 1/(2×FMAX)].

Enough records should be supplied so that all NPTEQ values are read in.

10. OUTPUT DESCRIPTION

Printed Output

All input data to the main program and subprograms described in Chapter 9 are printed in the corresponding main program or subprograms including the names of the variables and the values read in by the program. Thus the user of the program can verify the correctness of the input data. In addition to the input data, the printed output includes the following information in the different subprograms. Some output in Subprograms 6 and 7 for the frequency and time history responses is controlled by the input data.

As mentioned in Chapter 9, the output displacements and stresses are in the same unit system as the input data.

Main Program

No other information is printed in addition to the input data.

Subprogram 1

1. Nodal point coordinates of the foundation rock.
2. Global equation numbers of the DOFs of each nodal point in the foundation rock.
3. Half-bandwidth of the foundation impedance matrix, and blocking and number of equations information.
4. Actual Young's modulus of the foundation rock used for the analysis.
5. Actual blank common storage used in Subprogram 1.
6. CPU time in seconds for this subprogram and accumulative CPU time in this run.

Subprogram 2

1. Nodal point coordinates of the dam.

2. Nodal point coordinates of the dam abutment for the special treatment in transition elements if the dam is modeled by 3-d shell elements.
3. In the case of dam transition elements, the number of pairs of nodal points connected to the foundation rock in each transition element is printed.
4. A stress table listing the direction cosines of the local stress directions and the global coordinates of each stress location in each element of the dam.
5. Actual blank common storage used in Subprogram 2.
6. CPU time in seconds for this subprogram and accumulative CPU time in this run.

Subprogram 3

1. Global equation numbers of the DOFs of each nodal point in the dam.
2. Half-bandwidth of the dam stiffness and mass matrices, and number of equations per block and the number of blocks.
3. For dynamic analysis, there is output from the subspace iteration algorithm to obtain the dam mode shapes and frequencies. The mode shapes are printed in the x, y, and z components. The modal inertial forces due to the ground motion components and the natural frequencies are also printed.
4. Actual blank common storage used in Subprogram 3.
5. CPU time in seconds for this subprogram and accumulative CPU time in this run.

Subprogram 4

1. Nodal point coordinates of the impounded water.
2. Fluid domain loads over Mesh 3, Mesh 4, and Mesh 5 due to unit rigid accelerations in the x, y, and z directions for dynamic analysis. For static analysis, the x, y, and z components of dam loads over Mesh 3 due to static pressure of unit weight fluid are printed.

3. Actual blank common storage used in Subprogram 4.
4. CPU time in seconds for this subprogram and accumulative CPU time in this run.

Subprogram 5

No output is printed in this subprogram if static analysis is performed. For dynamic analysis, the following information is printed:

1. Global equation numbers of the pressure nodal points in the fluid.
2. Information on the fluid matrices stored in active columns.
3. Output from the secant iteration algorithm to obtain the eigenvectors and eigenvalues of the infinite uniform channel cross section at zero excitation frequency. The eigenvectors, eigenvalues and the square roots of the eigenvalues are printed.
4. Actual blank common storage used in Subprogram 5.
5. CPU time in seconds for this subprogram and accumulative CPU time in this run.

Subprogram 6

1. For static analysis, the static displacements of all nodal points are printed, following by the static local stress components and principal stresses at each stress location in each element of the dam.
2. For dynamic analysis, the actual number of the infinite channel eigenvectors included is printed. The square roots of the Mesh 2 eigenvalues at different excitation frequencies for an infinite reservoir of compressible water with absorptive reservoir boundary are printed. Then the frequency responses of the dam generalized coordinates due to the unit harmonic ground accelerations in the appropriate directions at each excitation frequency are printed.
3. Actual blank common storage used in Subprogram 6.
4. CPU time in seconds for this subprogram and accumulative CPU time in this run.

Subprogram 7

1. Blocking information, time increments, and time interval of all printed output.
2. Time histories of the different components of the earthquake acceleration record included in the analysis.
3. Time histories of the specified components of dynamic relative displacements or absolute accelerations at specified nodal points.
4. Time histories of the specified dynamic local stress components at specified stress locations.
5. The principal stresses at the specified time instants and the extreme values of principal stresses and local stress components and their times of occurrence at the stress locations in each dam element are printed. For the extreme values of the principal stresses, for each stress location in each dam element, the maximum of the maximum principal stress and the minimum of the minimum principal stress and the two time instants of occurrence are printed. However, the minimum of the maximum principal stress and the maximum of the minimum principal stress which are also printed have not much meaning physically because usually they are not the extreme values of stress in the principal direction. Hence, the value printed as the minimum of the maximum principal stress actually corresponds to the minimum principal stress at the instant when the maximum of the maximum principal stress occurs. Likewise, the maximum of the minimum principal stress actually corresponds to the maximum principal stress at the instant when the minimum of the minimum principal stress occurs. The values printed as the maximum and minimum of the angle correspond respectively to the angles of the maximum principal stress direction at these two instants when the maximum of the maximum principal stress and the minimum of the minimum principal stress occur.
6. The maximum and minimum values and their times of occurrence of the equivalent static forces imposed by the dam on the foundation rock at all DOFs of the dam-foundation rock interface. If the static responses are to be added to the earthquake dynamic responses in at least one of the NCASE load cases, the static forces imposed by the dam on the foundation rock at all DOFs of the

dam-foundation rock due to the dead weight of the dam and the hydrostatic pressure on the upstream face of the dam are also printed.

7. Actual blank common storage used in Subprogram 7.
8. CPU time in seconds for this subprogram and accumulative CPU time in this run.

Output 3. to 5. above is printed for each load case of the analysis.

Output on file 11, from Subprogram 1

File 11 after execution of Subprogram 1 contains the nodal point coordinates and the element connectivity vectors of the finite element model of the foundation rock, and element connectivity vectors of the surface elements in contact with water. This information, if file 11 is saved after executing the program, can be used for plotting or other post-analysis processing. File 11 is an unformatted FORTRAN file with the following logical records; some variables in the records are part of the input data described in Chapter 9, others are defined here below:

1. RECORD 1: NNPRF, NELRF
2. Nodal point coordinate records.

Next NNPRF records: Each record is of the form: I, COOR(I, 1), COOR(I, 2), COOR(I, 3) where I is the nodal point number, COOR(I, k) denotes the x, y, and z coordinates of nodal point I for k = 1, 2, 3. I increases form 1 to NNPRF.

3. Connectivity records for foundation elements.

Next NELRF records: Each record is of the form: I, NENI, (LM(J), J = 1, NENI) where I is the number between 1 and NELRF.

Output on file 11, from Subprogram 2

File 11 after execution of Subprogram 2 contains the nodal point coordinates and the element connectivity vectors of the finite element model of the dam. If Subprograms 1 and 2 are run continuously in one run, the following logical records are written immediately after the previous records written in Subprogram 1. Otherwise, the first record written is the first logical record in file 11.

1. First record written in Subprogram 2: MNPD, NELD

MNPD is the total number of nodal points needed to define the dam mesh; it is equal to NNPD when 3-d solid elements (NDTP = 2) are used to discretize the dam, but is equal to NNPD × 2 when 3-d shell elements (NDTP = 1) are used.

2. Nodal point coordinate records.

Next MNPD records:	Each record is of the form: I, COOR(I, 1), COOR(I, 2), COOR(I, 3) where I is the nodal point number, COOR(I, k) denotes the x, y, and z coordinates of nodal point I for k = 1, 2, 3. I increases form 1 to MNPD.

3. Element connectivity records.

Next NELD records:	Each record is of the form: I, NENI, (LM(J), J = 1, NENI) where I is the dam element number between 1 and NELD.

Output on file 11, from Subprogram 3

File 11 after execution of Subprogram 3 contains the mode shapes of the dam-foundation rock system. If Subprograms 1 and/or 2 are run together with Subprogram 3 in one continuous run, the following logical records are written immediately after the previous records written in Subprograms 1 and/or 2. Otherwise, the first record written is the first logical record in file 11.

1. First record written in Subprogram 3: NNPD, NFD

2. x component of the mode shape.

Next record:	(AMODE(I, J), I = 1, NNPD), J = 1, NFD) where AMODE(I, J) is the x component of the J-th mode shape at nodal point I.

3. y component of the mode shape.

Next record:	(AMODE(I, J), I = 1, NNPD), J = 1, NFD) where AMODE(I, J) is the y component of the J-th mode shape at nodal point I.

4. z component of the mode shape.

Next record:	(AMODE(I, J), I = 1, NNPD), J = 1, NFD) where AMODE(I, J) is the z component of the J-th mode shape at nodal point I.

If 3-d shell elements are used to discretize the dam, the mode shapes are computed at the NNPD mid-surface nodal points; except if a nodal point is on the dam-foundation rock interface in a transition element, the mode shape values written in the above records are for the upstream auxiliary node.

Output on file 11, from Subprogram 4

File 11 after execution of Subprogram 4 contains the nodal point coordinates of the finite element model of the impounded water and the element connectivity vectors of Meshes 1, 2, 3, 4 and 5. If any of the Subprograms 1 to 3 is run together with Subprogram 4 in one continuous run, the following logical records are written immediately after the previous records. Otherwise, the first record written is the first logical record in file 11.

1. First record written in Subprogram 4:

NNPF, NEL1, NEL2, NEL3, NEL4, NEL5

where NNPF = NNP1 + NNP2 is the total number of nodal points in the finite element model of the impounded water.

2. Nodal point coordinate record.

Next NNPF records:	Each record is of the form: I, COOR(I, 1), COOR(I, 2), COOR(I, 3) where I is the nodal point number, COOR(I, k) denotes the x, y, and z coordinates of nodal point I for k = 1, 2, 3. I increases form 1 to NNPF.

3. Mesh 1 connectivity records.

Next NEL1 records: Each record is of the form: I, NENI, (LM(J), J = 1, NENI) where I is the Mesh 1 element number between 1 and NEL1.

4. Mesh 2 connectivity records: exist only if NEL2 > 0.

Next NEL2 records: Each record is of the form: I, NENI, (LM(J), J = 1, NENI) where I is the Mesh 2 element number between 1 and NEL2.

5. Mesh 3 connectivity records.

Next NEL3 records: Each record is of the form: I, NENI, (LM(J), J = 1, NENI) where I is the Mesh 3 element number between 1 and NEL3.

6. Mesh 4 connectivity records.

Next NEL4 records: Each record is of the form: I, NENI, (LM(J), J = 1, NENI) where I is the Mesh 4 element number between 1 and NEL4.

7. Mesh 5 connectivity records: exist only if NEL5 > 0.

Next NEL5 records: Each record is of the form: I, NENI, (LM(J), J = 1, NENI) where I is the Mesh 5 element number between 1 and NEL5.

Output on file 4, from Subprogram 6

File 4 after execution of Subprogram 6 contains the complex-valued frequency response functions for the generalized coordinates of the dam-foundation rock. If file 4 is saved after program execution, the frequency response functions can be plotted; and if the mode shapes, which are written on both file 11 and file 8, are saved after executing Subprogram 3, the frequency response functions of the displacement and acceleration at the dam nodal points can be computed. File 4 is an unformatted FORTRAN file with logical records that are controlled by the input data NFD and NSYM. There is one logical record corresponding to each excitation frequency at which the frequency responses are computed in Subprogram 6. Each of these records is of the form:

FREQ, (TVEC(I), I = 1, NLEN)

where FREQ is an excitation frequency at which the frequency responses are computed. TVEC is a complex-valued array of dimension NLEN containing the complex-valued frequency responses at that excitation frequency FREQ; and (see Chapter 9 – Main Program)

NLEN = NFD × NSYM

The first NFD elements of TVEC are the complex-valued frequency responses of the NFD generalized coordinates of the dam-foundation rock. These NFD elements of TVEC are repeated NSYM times for the different components of ground motion (NSYM = 1 for z ground motion, = 2 for x and y ground motions, = 3 for x, y, and z ground motions).

In addition to the above logical records, the last record in file 4 is a record of the same form corresponding to a fictitious excitation frequency of 999999. with the same frequency responses in TVEC as the frequency responses in the immediately preceding logical record (the record corresponding to the largest excitation frequency at which the frequency responses are computed). This fictitious frequency marks the end record of file 4.

Output on files 98 and 99, from Subprogram 7

Files 98 and 99 after execution of Subprogram 7 contain the time histories for the earthquake records, dynamic nodal displacements or accelerations, and dynamic local stress components; various variables and parameters are also written onto this file for purpose of identifying the earthquake records and time histories results. In addition, if NTS < 0, the time histories of all the local stress components and principal stresses at each stress location in each dam element are written onto files 98 and 99. These data may be used for plotting and other post-analysis processing if files 98 and 99 are saved after program execution. File 98 is a formatted FORTRAN file with text explaining the stored data, whereas file 99 is the corresponding unformatted FORTRAN file with data only. File 99 contains the following logical records; some variables in the records are part of the input data described in Chapter 9, others are defined here below:

1. RECORD 1 NL, TINCK, TBEG, TEND, NPTR, NQD, NQS, NOUT, NDA, NTS, NCASE, ((NCOMB(I, J), J = 1, 4), I = 1, NCASE), NSPL, NDTP

NL is the total number of stress locations in the whole dam = NELD × (number of stress locations per element, = 4 for 3-d shell element, = 8 for 3-d solid element).

TBEG = 0.

NPTR is the total number of values output for each of the time histories; these values correspond to time instants that are multiples of TINCK from TBEG to TEND.

NSPL is the number of local stress components per stress location in the dam; = 6 for 3-d solid element, and 10 for 3-d shell element (refer to Section 5.2 for further description).

2. Earthquake acceleration records that are written on file 99:

Next record:	NOUTE for x component
Next record:	upstream (x) component of earthquake acceleration if NCOMB(I, 1) $\neq$ 0 for some I from 1 to NCASE, and if NOUTE for x component $\neq$ 0 and $\neq$ 1.
Next record:	NOUTE for y component
Next record:	vertical (y) component of earthquake acceleration if NCOMB(I, 2) $\neq$ 0 for some I from 1 to NCASE, and if NOUTE for y component $\neq$ 0 and $\neq$ 1.
Next record:	NOUTE for z component
Next record:	cross-stream (z) component of earthquake acceleration if NCOMB(I, 3) $\neq$ 0 for some I from 1 to NCASE, and if NOUTE for z component $\neq$ 0 and $\neq$ 1.

Each of the records above is of the form: (EQ(I), I = 1, NPTR), where EQ is a one-dimensional array containing the NPTR values of earthquake accelerations. No records are written here if NOUTE = 0 or 1.

3. Displacement (or acceleration) and stress records.

Next record: (IND1(I), IND2(I), ANG(I), I = 1, NQD) if NQD > 0.

Next record: (INS1(I), INS2(I), ISTYPE(I), I = 1, NQS) if NQS > 0 and NDA = 0.

Next NQD record: Dynamic relative displacement (NDA = 0) or absolute acceleration (NDA ≠ 0) time history responses. Each record corresponds to each combination of node number and component defined by IND1(I), IND2(I), and ANG(I); and I increases from 1 to NQD.

Each of the above NQD records is of the form: (D(I), I = 1, NPTR) where D is a one-dimensional array containing the NPTR values of displacement or acceleration. No records are written here if NQD = 0 or NOUT = 1.

Next NQS record: Dynamic local stress component time history responses. Each record corresponds to each combination of dam element, stress location and component defined by INS1(I), INS2(I), and ISTYPE(I); and I increases from 1 to NQD.

Each of the above NQS records is of the form: (S(I), I = 1, NPTR) where S is a one-dimensional array containing the NPTR values of stress. No records are written here if NQS = 0 or NDA ≠ 0 or NOUT = 1.

Next NPTR × NL records: NPTR records of local stress components and principal stresses at on stress location; each record corresponds to a time instant which increases in increments of TINCK from TBEG to TEND.

NPTR records above are repeated NL times; each set of NPTR records corresponds to a global stress location number which increases from 1 to NL. A global stress location number in given by: (element number – 1) × NSPL + local stress location number in that element, where NSPL is defined above in the first record of file 99.

Each of the above NPTR × NL records is of the form:

(S(I), I = 1, NSPL), PS1, PS2, ANG for 3-d solid dam elements, or

(S(I), I = 1, NSPL), UPS1, UPS2, UANG, DPS1, DPS2, DANG for 3-d shell dam elements

where S is a one-dimensional array containing the NSPL local stress component values; PS1, PS2, and ANG are respectively the maximum principal stress, minimum principal stress, and the angle of the maximum principal stress direction (measured in a counter-clockwise direction, when looking downstream, from the local stress direction 1 axis in the 1-2 plane). For 3-d shell elements, UPS1, UPS2 and UANG are respectively the upstream face values of PS1, PS2 and ANG; while DPS1, DPS2 and DANG are the downstream face values. No records are written here if NTS ≥ 0 or NDA≠ 0.

This set of records described above for group 3, except the first two records, is repeated NCASE times; each set corresponds to a combination of ground excitation and static combination defined by (NCOMB(J), J = 1, 4) for the I-th load case (I increases from 1 to NCASE).

Output on file 15, from Subprogram 7

File 15 after execution of Subprogram 7 with NFO > 0 contains the time histories for the forces imposed by the dam on the foundation rock at all DOFs of the dam-foundation rock interface. These data may be used for plotting and other post-analysis processing if file 15 is saved after program execution. File 15 is an unformatted FORTRAN file with data only. It contains the following logical records; some variables in the records are part of the input data described in Chapter 9, others are defined here below:

1. RECORD 1 NCASE, ((NCOMB(II, JJ), JJ = 1, 4), II = 1, NCASE), IST, NPTR, NFF, TINCK

IST = 0 if static forces due to the dead weight of the dam and the hydrostatic pressure on the upstream face of the dam are not needed in all of the NCASE load cases; = 1 otherwise.

NPTR is the total number of values output for each of the time histories; these values correspond to time instants that are multiples of TINCK from 0 to TEND.

NFF is the total number of DOFs of the dam-foundation rock interface at which forces are computed and output. If the dam is modeled by 3-d solid elements (NDTP = 1; see Chapter 9 — Main Program), NFF = 3 × the number of nodal input in Record D of Subprogram 2; the DOFs are numbered as (I – 1) × 3 + J for the J-th (J = 1 for x, 2 for y, and 3 for z) translational DOFs of the I-th dam nodal input in the Record D (see Chapter 9 — Subprogram 2). If the dam is modeled by 3-d shell elements (NDTP = 2; see Chapter 9 — Main Program), NFF = 6 × the number of input in Record D of Subprogram 2; the DOFs are numbered as (I – 1) × 6 + J for the J-th translational DOFs of the upstream auxiliary node of the I-th dam nodal input in the Record D, and as (I – 1) × 6 + J + 3 for the J-translational DOFs of the downstream auxiliary node of the I-th dam nodal input in the Record D (see Chapter 9 — Subprogram 2).

2. RECORD 2: (FST(I), I = 1, NFF)

FST(I) is the static forces at DOF I due to the dead weight of the dam and the hydrostatic pressure on the upstream face of the dam. This record is written onto File 15 only if IST = 1.

3. Time histories of equivalent static force records:

Next NPTR records: (F(I), I = 1, NFF)

In the J-th record (J increases from 1 to NPTR), F(I) is the equivalent static force at DOF I at time = (J – 1) × TINCK.

This set of records is repeated NCASE times: each corresponds to a combination of ground excitation and static combination defined by (NCOMB(J), J = 1, 4) for the I-th load case (I increases from 1 to NCASE).

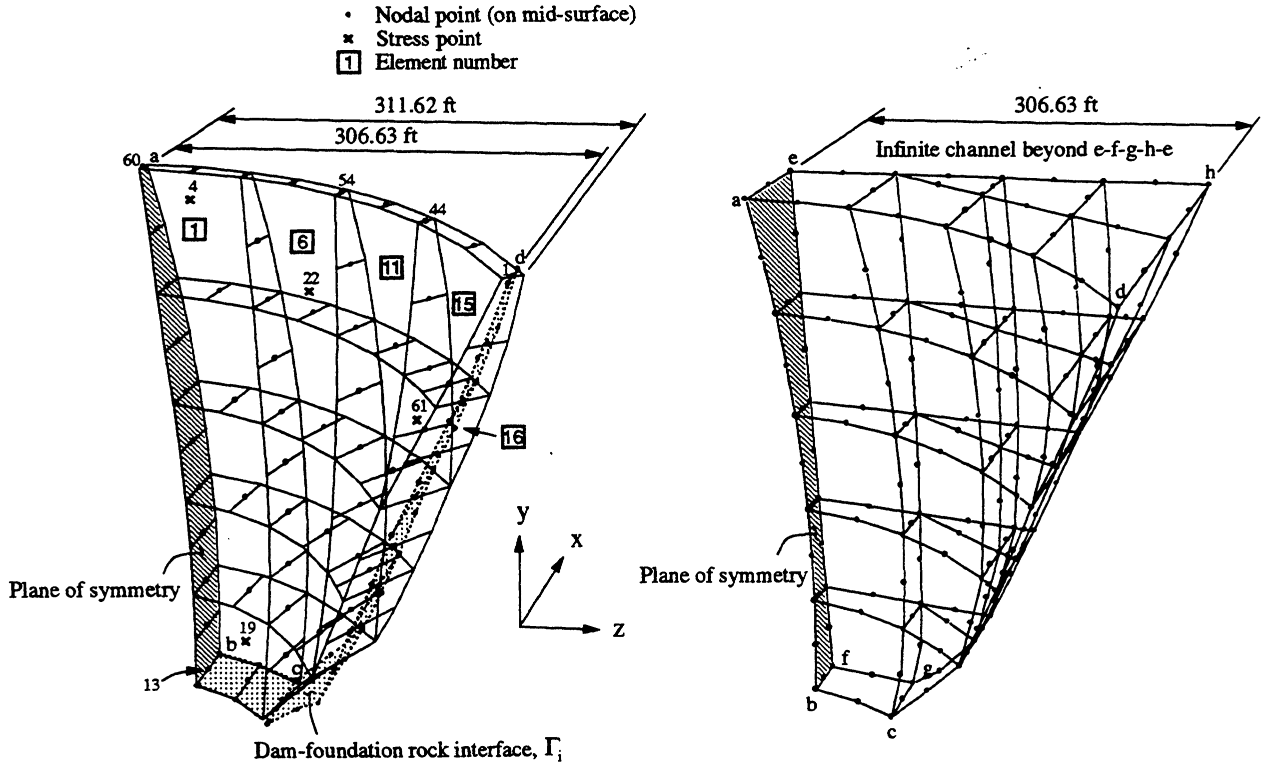
11. EXAMPLE EARTHQUAKE RESPONSE ANALYSIS OF MORROW POINT DAM

To demonstrate the use of the program EACD-3D-96, we present the analysis of the Morrow Point Dam due to Taft ground motion. The selection of the important response parameters, the input data, and some of the output response results are described and presented in this chapter.

11.1 Morrow Point Dam and Ground Motion

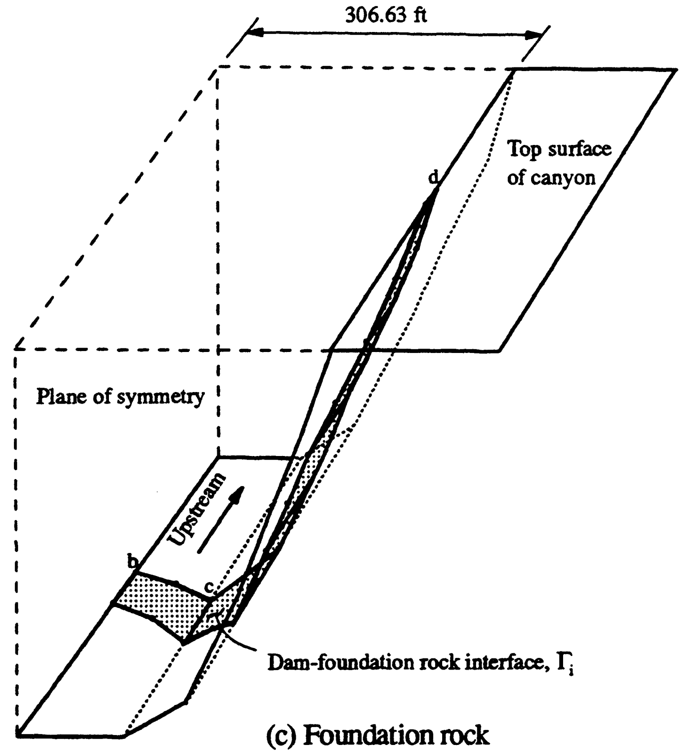
Morrow Point Dam, located on the Gunnison River in Colorado, is a 465 ft high, approximately symmetric, single centered arch dam. Detailed description of the geometry of this dam is available in References [4] and [5]. To simplify the dynamic analysis, the dam and its supporting canyon are assumed to be symmetric about the x-y plane. The fluid domain is also assumed symmetric about the x-y plane and extending to infinity in the upstream direction. As mentioned in Section 8.2, with the assumption of symmetry, only one-half of the dam-fluid-foundation rock system needs to be analyzed. The response to the upstream (x) or the vertical (y) component of ground motion, which are symmetric about the x-y plane, is determined by analyzing one-half of the system with symmetric boundary conditions on the x-y plane. The response to the cross-stream (z) component of ground motion, which is antisymmetric about the x-y plane, is determined by analyzing one-half of the system with antisymmetric boundary conditions on the x-y plane.

The finite element idealizations of the arch dam and the impounded water, and the boundary element idealization of the foundation rock are shown in Figure 11.1. The finite element idealization of one-half of the dam body [Figure 11.1(a)] consists of 8 thick-shell finite elements in the main part of the dam and 8 transition elements in the part of the dam near its junction with the foundation rock, with a total of 61 nodal points at the mid-surface of the dam. When the foundation rock is flexible, this idealization has a total of 296 DOFs for symmetric (x- and y-component) ground motion and for static analysis and 284 DOFs for antisymmetric (z-component) ground motion. Figure 11.2 shows detailed drawing of two 3-d thick-shell finite elements (numbered 6 and 11, respectively) and two



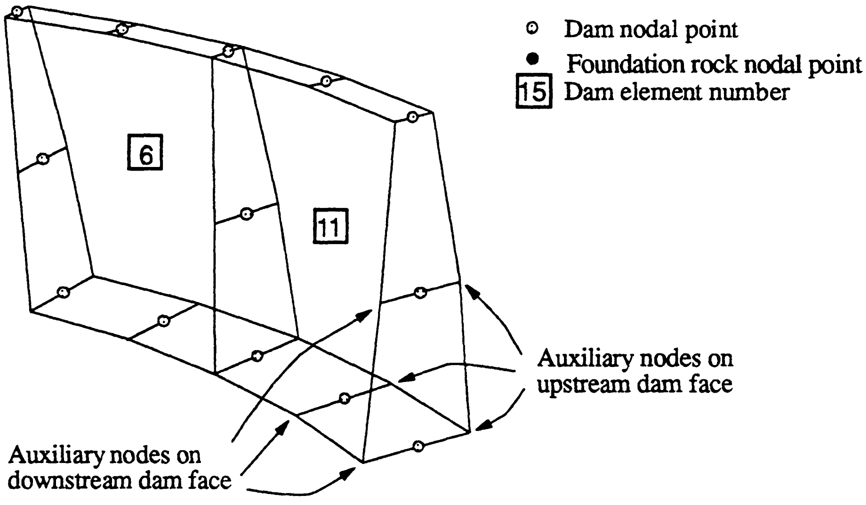
(a) Morrow Point Dam

(b) Fluid domain

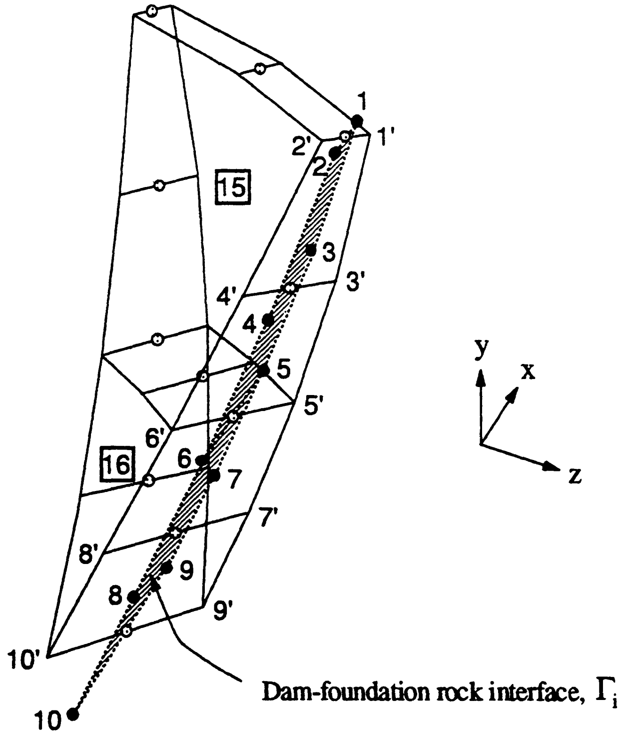


(c) Foundation rock

Figure 11.1 Finite element and boundary element meshes of one-half of the Morrow Point Dam-water-foundation rock system. (Parts (a) and (b) adapted from Reference [4])



(b) Typical Thick-Shell Elements



(b) Typical Transition Elements

Figure 11.2 Typical thick-shell finite elements and transition elements of the arch dam.

transition elements (numbered 15 and 16, respectively) of the arch dam. Note that in the transition elements, auxiliary nodes numbered with prime (e.g., 1' and 2') are on the dam abutment; whereas the nodes numbered without prime (e.g., 1 and 2) are on the dam-foundation rock interface Γ_i [Figure 11.2(b)]. As mentioned in Section 5.3, the stiffness matrix of the dam with reference to the nodal points on the dam abutment is modified by the linear transformation to overcome the incompatibility between the dam abutment and the canyon. The mass concrete in the dam is assumed to be homogeneous, isotropic and linear elastic with the following properties: Young's modulus E_s = 4.0 million psi, unit weight w_s = 155 pcf, and Poisson's ratio ν_s = 0.2. A constant hysteretic damping factor η_s = 0.10, which corresponds to 5% viscous damping in all natural vibration modes of the dam with empty reservoir on rigid foundation rock, is selected.

For computational convenience, the water level is assumed to be at the dam crest level in this example analysis. The combined finite element-continuum idealization of one-half of the fluid domain consists of 27 three-dimensional finite elements for the irregular fluid region with 189 nodal points [Figure 11.1(b)]. This idealization contains 157 pressure DOFs for symmetric (x- and y-component) ground motion and 132 pressure DOFs for antisymmetric (z-component) ground motion. The irregular fluid region is bounded by the upstream face of the dam, the uniform canyon, and the transmitting plane e-f-g-h-e [Figure 11.1(b)]. Special equilibrium and compatibility conditions are imposed on the transmitting plane connecting the irregular fluid region with the infinite channel to represent the upstream transmission of the hydrodynamic pressure waves. The following properties are assumed for the impounded water: velocity of pressure waves C = 4720 ft/sec and unit weight w_w = 62.4 pcf.

The cross-section of the infinitely-long uniform canyon shown in Figure 11.1(c) is uniquely defined by the projection of the mid-surface of the Morrow Point Dam on the y-z plane. Therefore, the half-width of the canyon, 306.63 ft, is smaller than the half-width of the upstream face of the dam, 311.62 ft [Figure 11.1(a)]. The boundary element idealization of one-half of the dam-foundation rock interface that lies completely on the surface of the infinitely-long uniform canyon is also shown in Figure 11.1(c); the top surface of the canyon is assumed to be horizontal. The projections of the boundary element mesh of the dam-foundation rock interface on the x-z plane (plan view) and y-z plane (vertical view) are shown as the solid lines in Figures 11.3(a) and 11.3(b), respectively. The mesh consists of 6 boundary elements with 26 nodes with three translational DOFs for each node; the node numbering is also shown in Figure 11.3. Consequently, there are 76 DOFs for symmetric (x- and y-component) ground motion or static analysis and 74 DOFs for antisymmetric (z-component) ground motion. The number of nodes and DOFs match those of the finite element mesh for the dam. The dotted lines in Figures 11.3(a) and 11.3(b) represent the projections of the finite element mesh of the dam at its interface with the foundation rock on the x-z plane and y-z plane, respectively. Note that the dotted lines do not coincide with the solid lines because of the difference in the geometry of the arch dam abutment and the uniform canyon. The foundation rock is assumed to be homogeneous, isotropic, and viscoelastic with the following properties: unit weight w_f = 165 pcf, and Poisson's ratio ν_f = 0.2, and the Young's modulus E_f = 4.0 million psi. Energy dissipation in the flexible foundation rock is represented by a constant hysteretic damping factor η_f = 0.10, which corresponds to viscous damping ratio of 5%.

There are no data available for the alluvium and sediments at the bottom and sides of the reservoir impounded by Morrow Point Dam. A wave reflection coefficient α = 0.5 is arbitrarily selected for both reservoir bottom and sides for this analysis.

The ground motion recorded at the Taft Lincoln School Tunnel during the Kern County, California earthquake of July 1, 1952 is selected as the excitation. The upstream, vertical, and cross-stream ground motion components; $a_g^x(t)$, $a_g^y(t)$, and $a_g^z(t)$; in the analysis are chosen as the S69E, vertical, and S21W components of the recorded motion, respectively (Figure 11.4).

11.2 Response Parameters

In the Fast Fourier Transform (FFT) computations, 2048 time steps of 0.02 sec. are used, i.e., $N = 2048$ (MM = 10, LL = 2), Δt (TINC) = 0.02 sec., $T = 40.96$ sec. (see Section 6.1). The duration of the ground motion (Figure 11.4) is T_p = (NPTEQ – 1) × TINC = (1001 – 1) × 0.02 = 20 sec.;

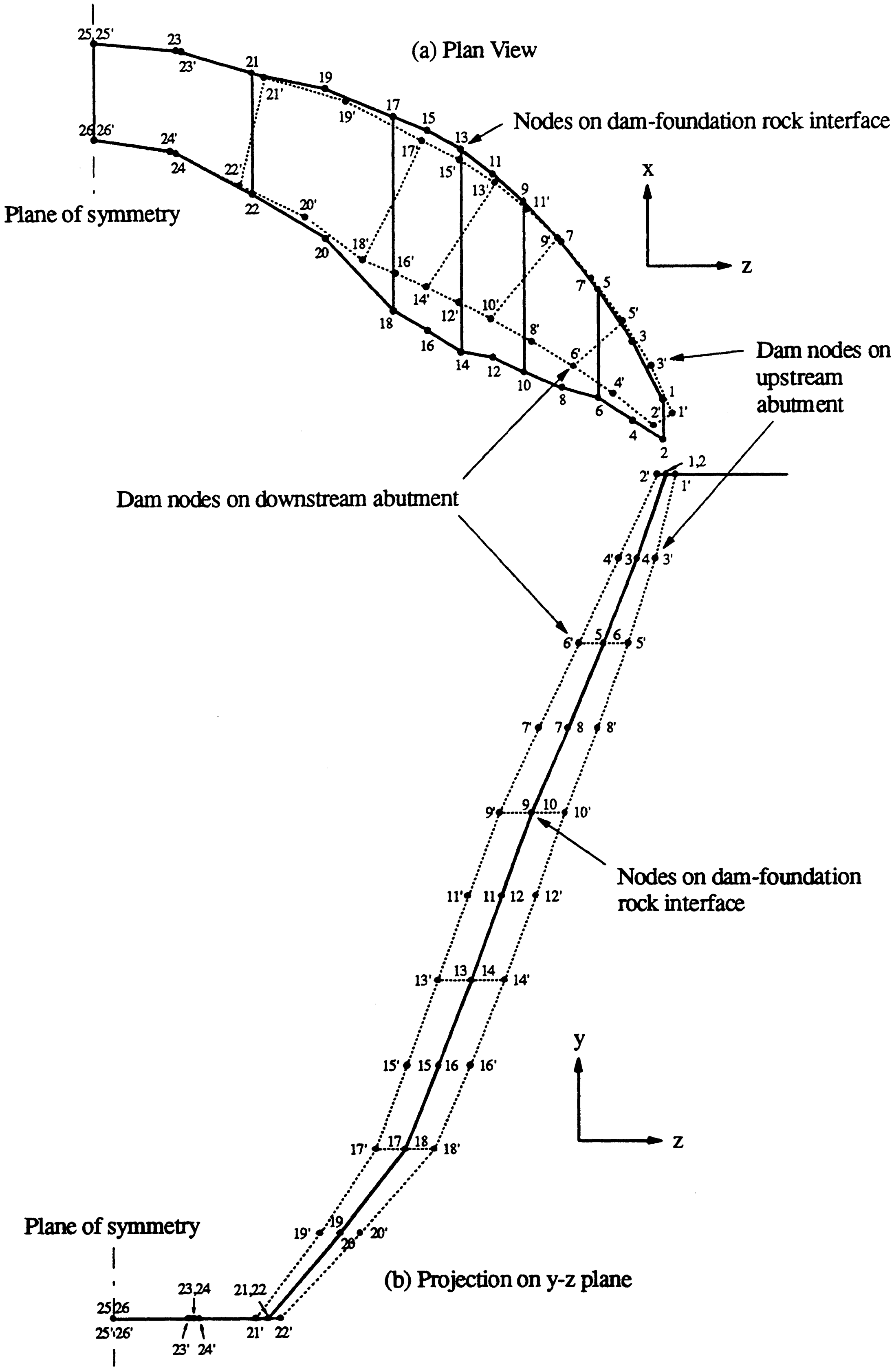


Figure 11.3 Boundary element mesh layout for one-half of the dam-foundation rock interface of the Morrow Point Dam on an infinitely-long uniform canyon.

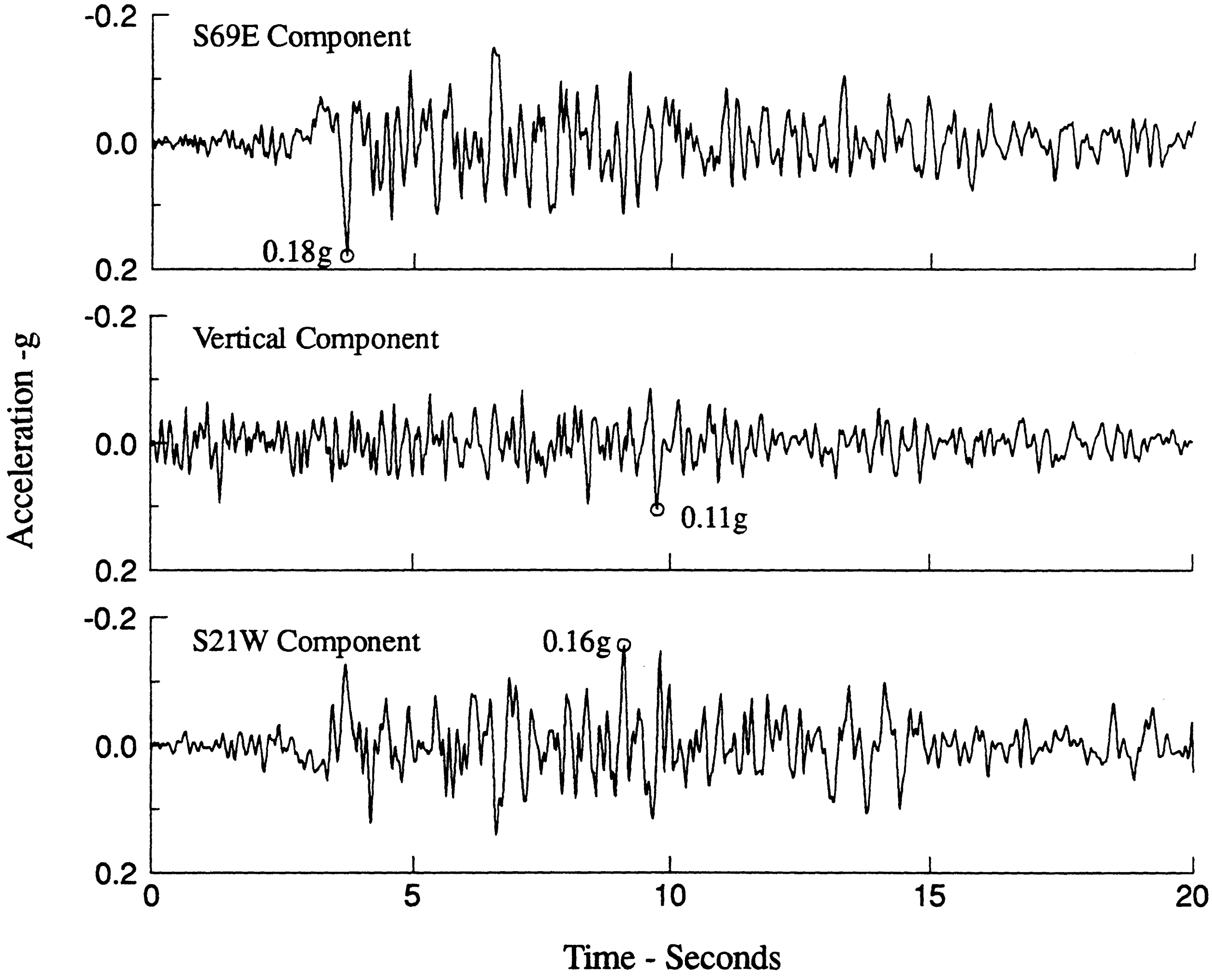


Figure 11.4 Ground motion at Taft Lincoln School Tunnel, Kern County, California, Earthquake, July 21, 1952.

therefore, approximately the second half of the 2048 time steps corresponding to a T_h = 40.96 – 20 = 20.96 sec. forms a grace band of zero excitation to reduce the aliasing error in the FFT calculations. For this dam-water-foundation rock system with the selected α value, $0.73\tilde{T}_1/\xi_1$ = 1.73, 1.78, and 4.25 sec. respectively for upstream, vertical, and cross-stream ground motions (Section 7.1). Therefore, T_h = 20.96 sec. is long enough for the dam response present at the end of the earthquake record to decay to a small relative value, based on the period and damping associated with the fundamental resonant response of the dam-water-foundation rock system (see Section 7.1). In Subprogram 6, the frequency responses are computed up to a maximum frequency FMAX = $1/2\Delta t$ = 25 Hz (see Section 7.1). For this example, 18 (the value of NFD) vibration modes of the dam-foundation rock system were found to be sufficient to obtain accurate responses (Section 7.2).

11.3 Procedure Used in Running the Program

A complete analysis of the response of the dam due to its weight, the hydrostatic pressure and the simultaneous action of the three components of Taft ground motion was carried out using the computer program EACD-3D-96.* The procedure used in running the program to obtain the response results is summarized next (see the corresponding input data records described in Chapter 9, and the input data files shown in Appendix B):

1. Subprograms 1 to 6 were run first, separately for symmetric and antisymmetric dynamic analyses, saving the results on file 8 and file 4. In the symmetric run, the foundation impedance matrices for the antisymmetric and symmetric cases were computed and saved on files 21 and 22, respectively; therefore, the foundation impedance matrix for the antisymmetric case did not need recomputing in the antisymmetric run (see Section 6.1 and Appendix B.1).
2. Using the stored file 22, Subprograms 1 to 6 were run for static analysis (NSD = 0), and the results were saved on file 7 (see Appendix B.2).

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* The hydrostatic pressure acting on the foundation rock at the water-foundation rock interface is not included in the static analysis, unlike the results presented in Reference [7].

3. Using the stored files 8 and files 4 from the symmetric and antisymmetric runs of Subprograms 1 to 6 and the stored file 7 from static analysis, Subprogram 7 was run, and the response results were saved on files 15 (unformatted), 98 (formatted) and 99 (unformatted) for post-processing (see Appendix B.3).

The detailed steps for running this example analysis are summarized in Table 11.1.

11.4 Response Results

Figure 11.5 shows the time history of radial, vertical, and tangential displacements at nodal points 44 and 60 located at the dam crest, and at nodal points 1 and 13 located at the dam-foundation rock interface [Figure 11.1(a)]. Figure 11.6 shows the time history of arch and cantilever stresses on the upstream face at global stress locations 4 and 9 and on the downstream face at global stress locations 22 and 61 [Figure 11.1(a)]. Figure 11.7 shows the distribution of envelope values of the maximum arch and cantilever stresses on the upstream and downstream faces of the dam (maximum tension is positive). Such stress results aid in identifying areas in the dam that may crack during an earthquake.

The CPU time required for a complete earthquake analysis is dominated by the computation of the foundation impedance matrix. In this example analysis, the CPU time on a DEC workstation for computing the foundation impedance matrix at selected excitation frequencies ranged from 3000 to 7000 sec. (Figure 11.8). The CPU time for all the entire remaining analysis is less than 2000 seconds. Therefore, significant saving in the overall computation time can be achieved by prudent selection of the number of frequency values at which foundation impedance matrix is computed and by reusing the computed foundation impedance matrices for other analysis cases (see Section 6.3).

Table 11.1 — Steps for Running EACD-3D-96 for the Example Analysis

Part	Steps*	Comments
Part 1: Generate foundation impedance matrix and run dynamic analysis for symmetric case	cp ex-dy.dat input.dat	select ex-dy.dat as the input data file (Appendix B.1)
	eacd-3d-96	execute eacd-3d-96 program
	mv output ex-out1	save output as ex-out1 for viewing and checking
	cp unit4.dat unit4s.dat	save unit4.dat as unit4s.dat for use in Part 4
	cp unit8.dat unit8s.dat	save unit8.dat as unit8s.dat for use in Part 4
	cp unit21.dat ex-fas.dat	save unit21.dat as ex-fas.dat for other analysis cases
	cp unit22.dat ex-fs.dat	save unit21.dat ad ex-fs.dat for other analysis cases
Part 2: Run dynamic analysis for antisymmetric case	vi input.dat	edit the same input.dat file such that NSYM = 1 and IMP = 0 (Appendix B.1)
	eacd-3d-96	execute eacd-3d-96 program
	mv output ex-out2	save output as ex-out2 for viewing and checking
	cp unit4.dat unit4a.dat	save unit4.dat as unit4a.dat for use in Part 4
	cp unit8.dat unit8a.dat	save unit4.dat as unit8a.dat for use in Part 4
Part 3: Run static analysis	cp ex-st.dat input.dat	select ex-st.dat as the input data file (Appendix B.2)
	eacd-3d-96	execute program
	mv output ex-out3	save output as ex-out3 for viewing and checking
	cp unit7.dat ex-7.dat	save unit7.dat as ex-7.dat for other example cases
Part 4: Run earthquake analysis	cp ex-eq.dat input.dat	select ex-eq.dat as the input data file (Appendix B.3)
	cp unit4s.dat unit4.dat	restore unit4.dat from unit4s.dat saved in Part 1
	cp unit8s.dat unit8.dat	restore unit8.dat from unit8s.dat saved in Part 1
	cp unit4a.dat unit10.dat	restore unit4.dat from unit4a.dat saved in Part 2, and rename it to unit10.dat
	cp unit8a.dat unit1.dat	restore unit8.dat from unit8a.dat saved in Part 2, and rename it to unit1.dat
	eacd-3d-96	execute eacd-3d-96 program
	mv output ex-out4	save output as ex-out4 for viewing and checking
	mv unit15.dat ex-15.dat	save unit15.dat as ex-15.dat for post-processing
	mv unit98.dat ex-98.dat	save unit98.dat as ex-98.dat for post-processing
	mv unit99.dat ex-99.dat	save unit99.dat as ex-99.dat for post-processing

* All commands are for machines with UNIX operation system: cp = copy, mv = move, and vi is a text editor.

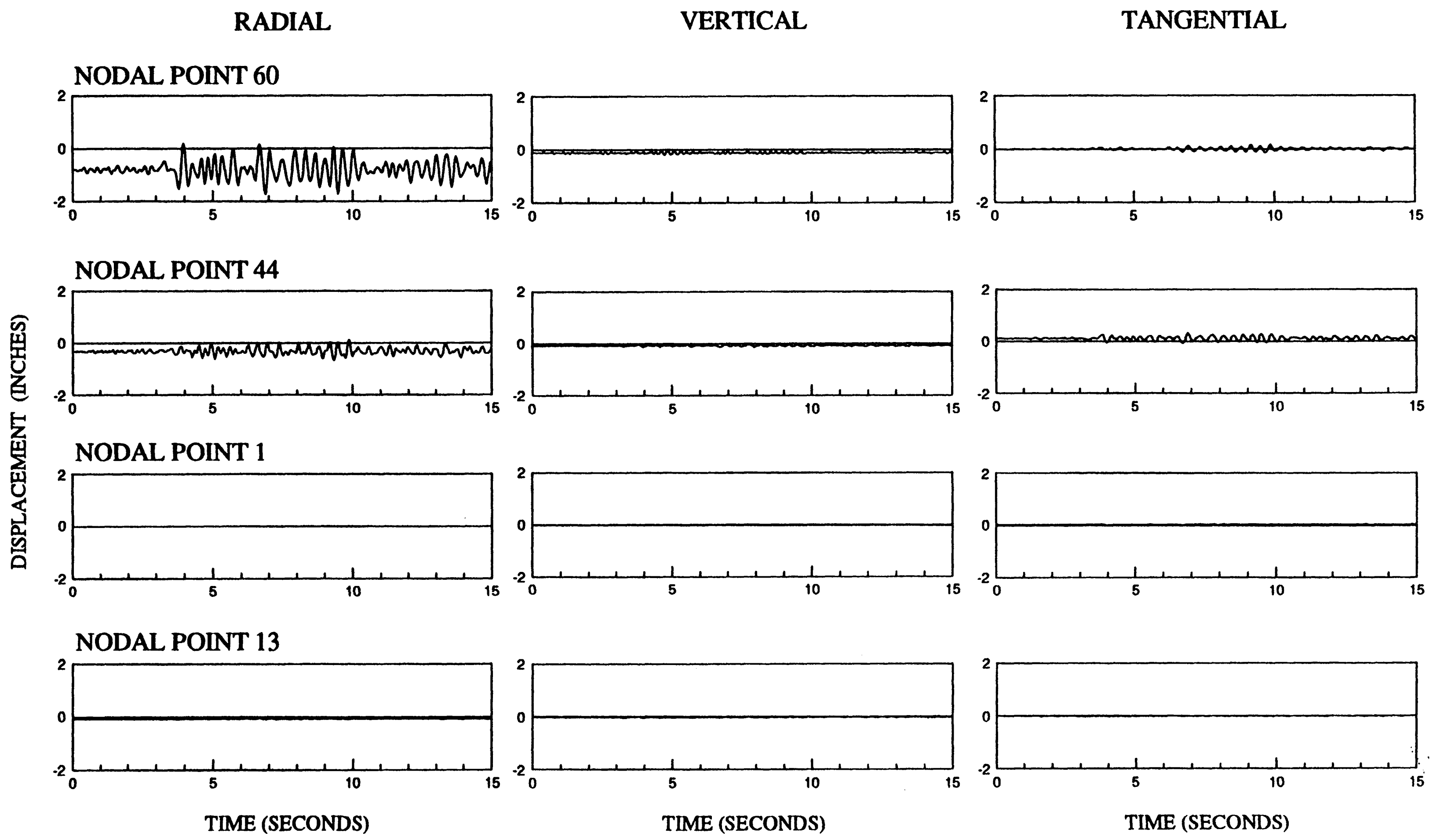


Figure 11.5 Displacement response of Morrow Point Dam with full reservoir and absorptive reservoir boundary ($\alpha = 0.5$), supported on flexible foundation rock with $E_f/E_s = 1$, due to upstream, vertical, and cross-stream components, simultaneously, of Taft ground motion.

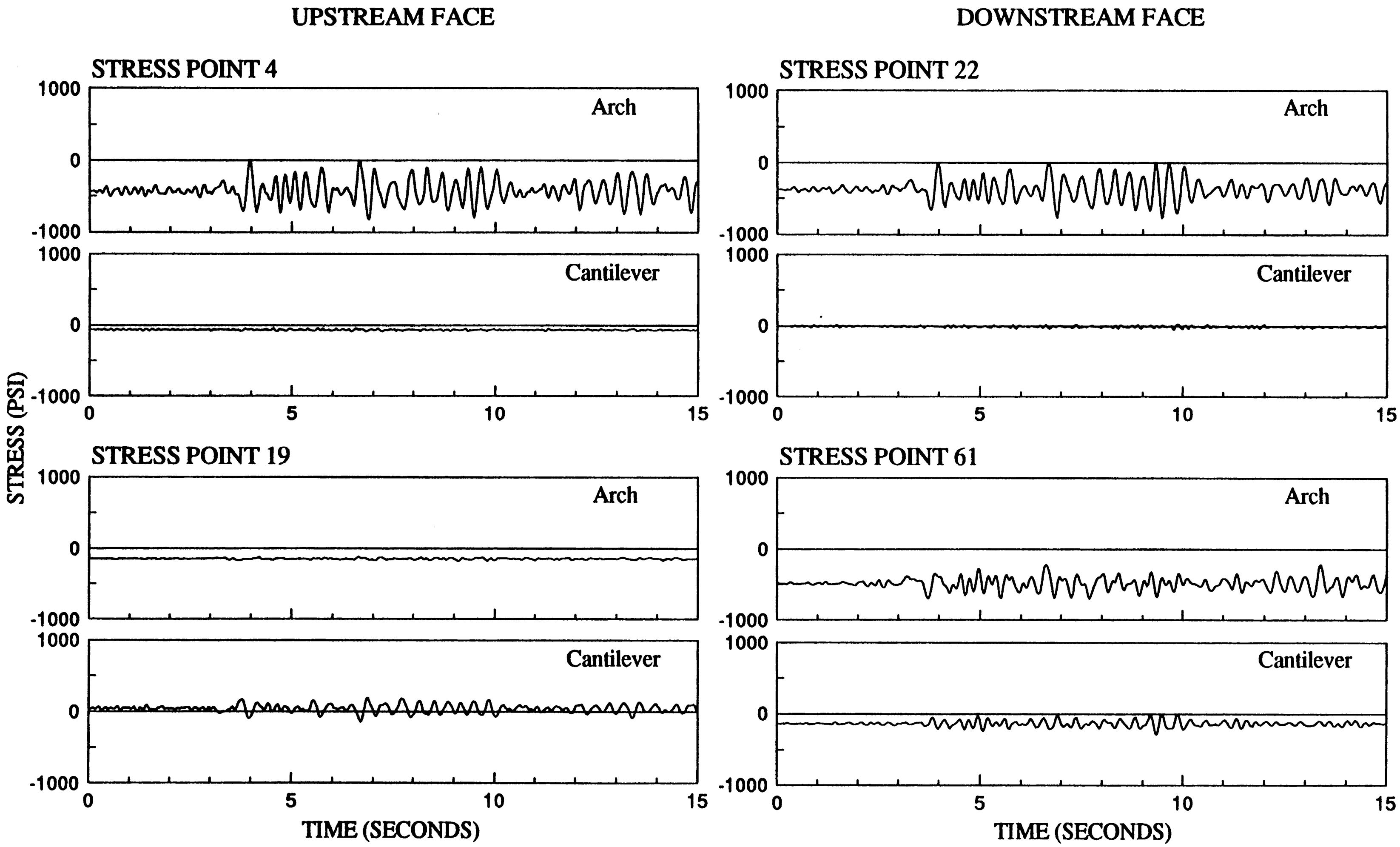
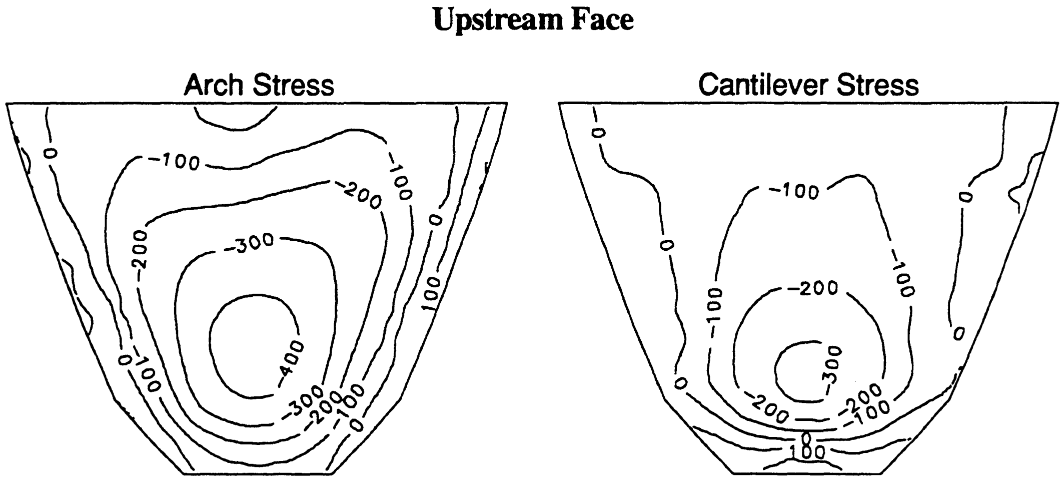
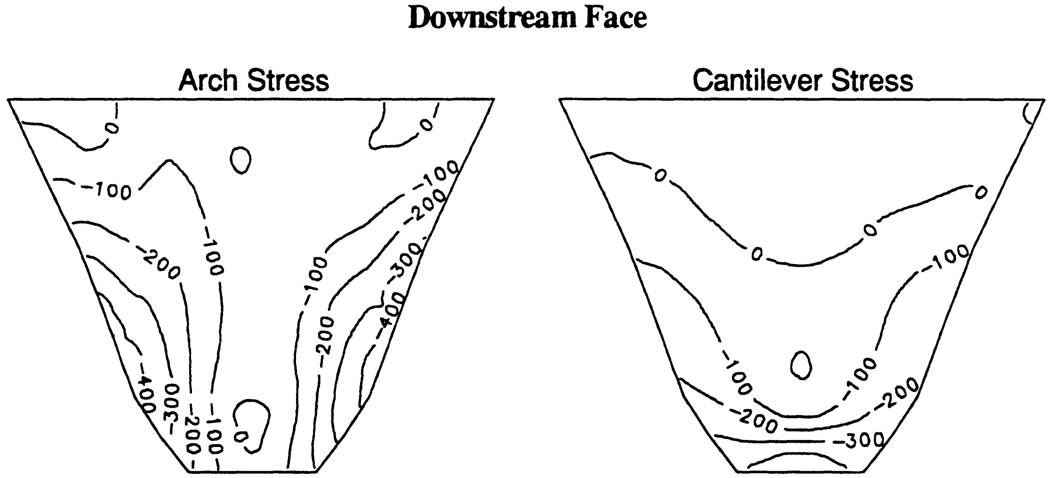


Figure 11.6 Stress response of Morrow Point Dam with full reservoir and absorptive reservoir boundary ($\alpha = 0.5$), supported on flexible foundation rock with $E_f/E_s = 1$, due to upstream, vertical, and cross-stream components, simultaneously, of Taft ground motion.


Upstream Face

Arch Stress

Cantilever Stress


Downstream Face

Arch Stress

Cantilever Stress

Figure 11.7 Envelope values of maximum arch and cantilever stresses (in psi) on the upstream and downstream faces of Morrow Point Dam with full reservoir and absorptive reservoir boundary ($\alpha = 0.5$), supported on flexible foundation rock with $E_f/E_s = 1$, due to the upstream, vertical, and cross-stream components, simultaneously, of Taft ground motion. Initial static stresses are included.

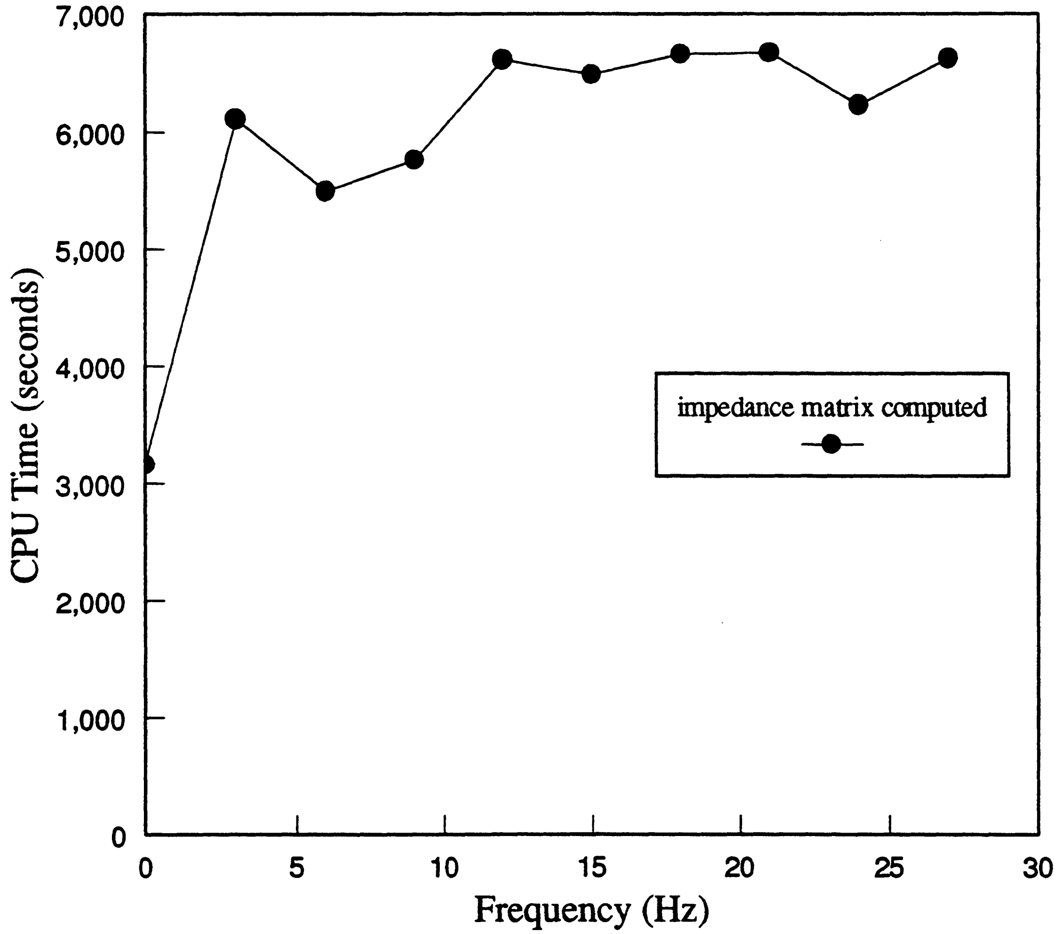


Figure 11.8 CPU time in seconds to compute the foundation impedance matrix at different excitation frequencies for the example analysis.

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APPENDIX A: GEOMETRIC INCOMPATIBILITY BETWEEN THE DAM AND THE FOUNDATION ROCK

The assumption of an infinitely-long uniform canyon introduces geometric incompatibility between the dam and the foundation rock, resulting in displacement incompatibility between these two substructures along the dam-foundation rock interface. If the dam is discretized by thick shell finite elements, a special treatment is available for dam elements along the dam abutment to deal approximately with the incompatibility between the dam abutment and the dam-foundation rock interface (Section 3.4 of Reference [7]). With this special treatment, two objectives are achieved: (1) the dam substructure retains its original geometry, and (2) the displacement compatibility between the dam abutment and the dam-foundation rock interface is ensured. This special treatment, available for thick shell elements, takes advantage of the unique way the element stiffness matrix is formulated [10]. However, such a treatment is not available for 3-d solid elements.

Therefore, it is of interest to examine the errors in the response of Morrow Point Dam [7], allowing the above-mentioned displacement incompatibility. The dam, discretized by thick shell finite elements, is analyzed with or without the special treatment in the elements along the dam abutment; the foundation rock is discretized by surface boundary elements. The values of the Young's moduli of the dam and foundation rock, E_s and E_f, respectively, are chosen so that $E_f/E_s = 1$ and 1/4; the reservoir is assumed empty. The response of the dam to upstream, vertical or cross-stream harmonic ground motion is plotted against the excitation frequency in Figures A.1 and A.2 for $E_f/E_s = 1$ and 1/4, respectively. Overall, the errors in the dam response introduced by allowing the geometric incompatibility between the dam and foundation rock appear to be slight.

If the special treatment in the shell element adjacent to the dam abutment is not used, incompatibility between the dam and the fluid substructure, bounded by the upstream face of the dam and the uniform canyon surface, also exists along the dam abutment. The frequency responses of the dam with full reservoir and $\alpha = 0.5$ are shown in Figures A3 and A4 for $E_f/E_s = 1$ and 1/4, respectively. As demonstrated in these figures, the errors due to the incompatibility between the dam

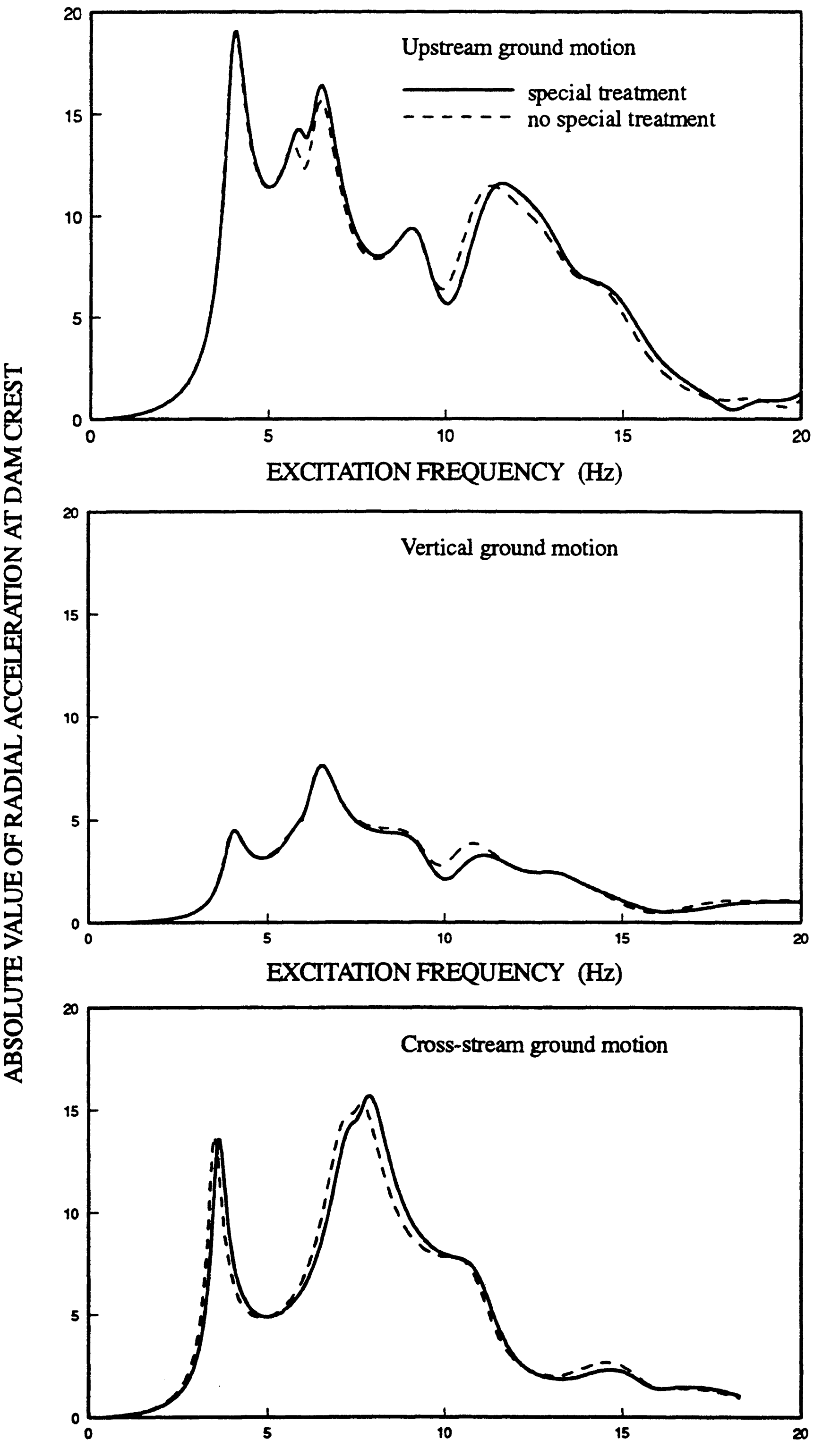

Figure A.1 Comparison of frequency response functions for Morrow Point Dam with empty reservoir obtained with or without the special treatment in the thick shell finite elements of the dam along the dam abutment; $E_f/E_s = 1$.

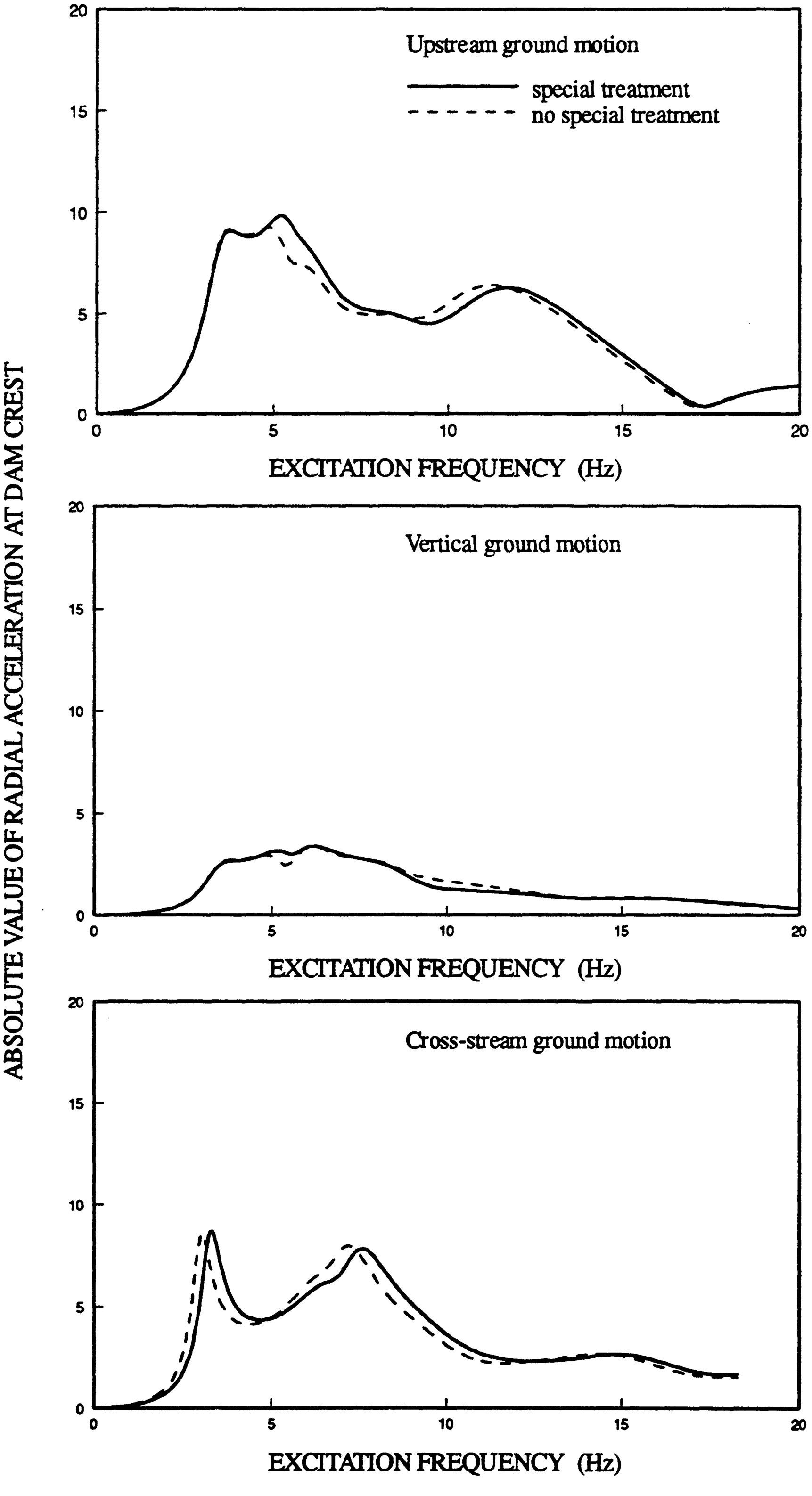

Figure A.2 Comparison of frequency response functions for Morrow Point Dam with empty reservoir obtained with or without the special treatment in the thick shell finite elements of the dam along the dam abutment; $E_f/E_s = 1/4$.

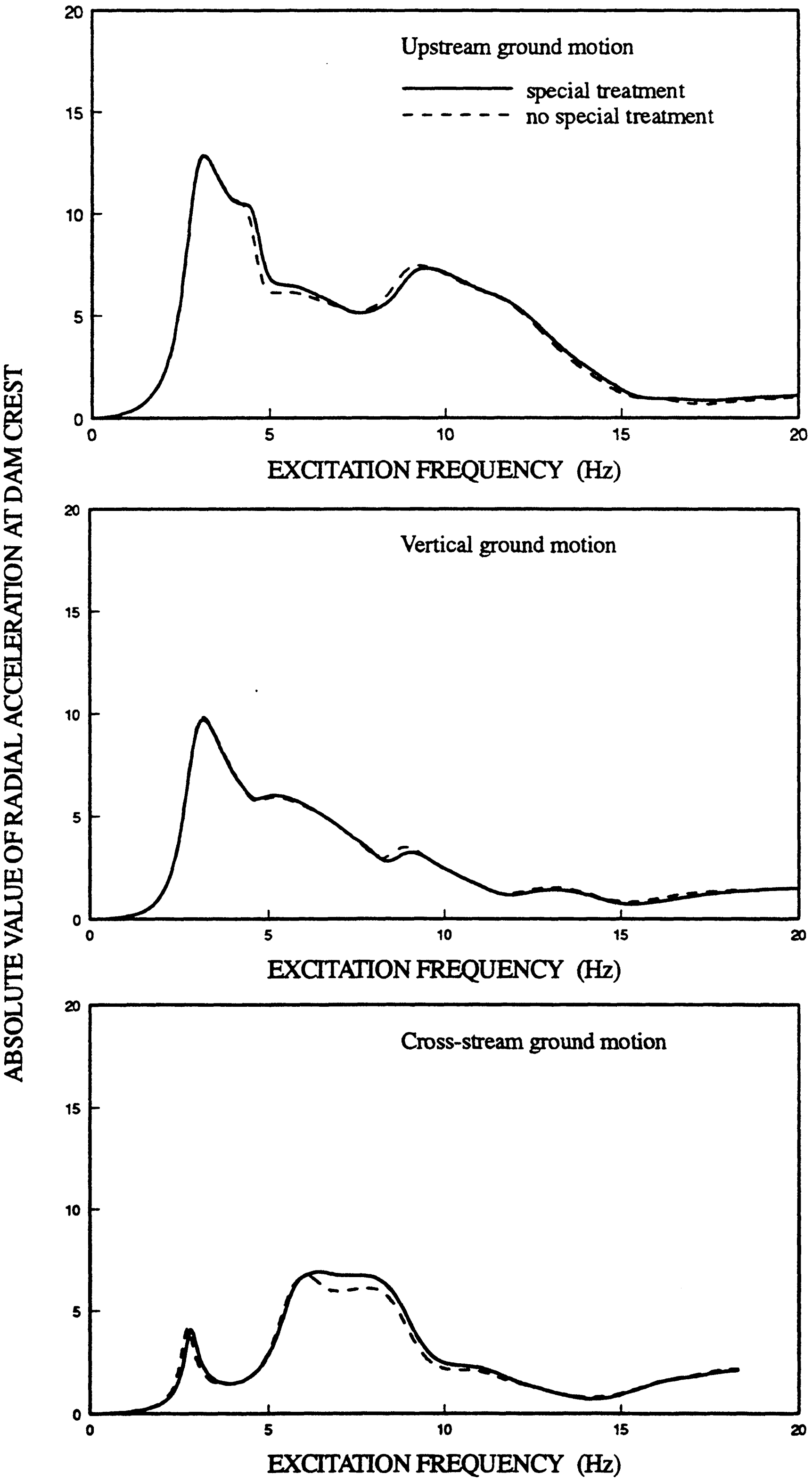

Figure A.3 Comparison of frequency response functions for Morrow Point Dam with full reservoir obtained without the special treatment in the thick shell finite elements of the dam along the dam abutment; $E_f/E_s = 1$ and $\alpha = 0.5$.

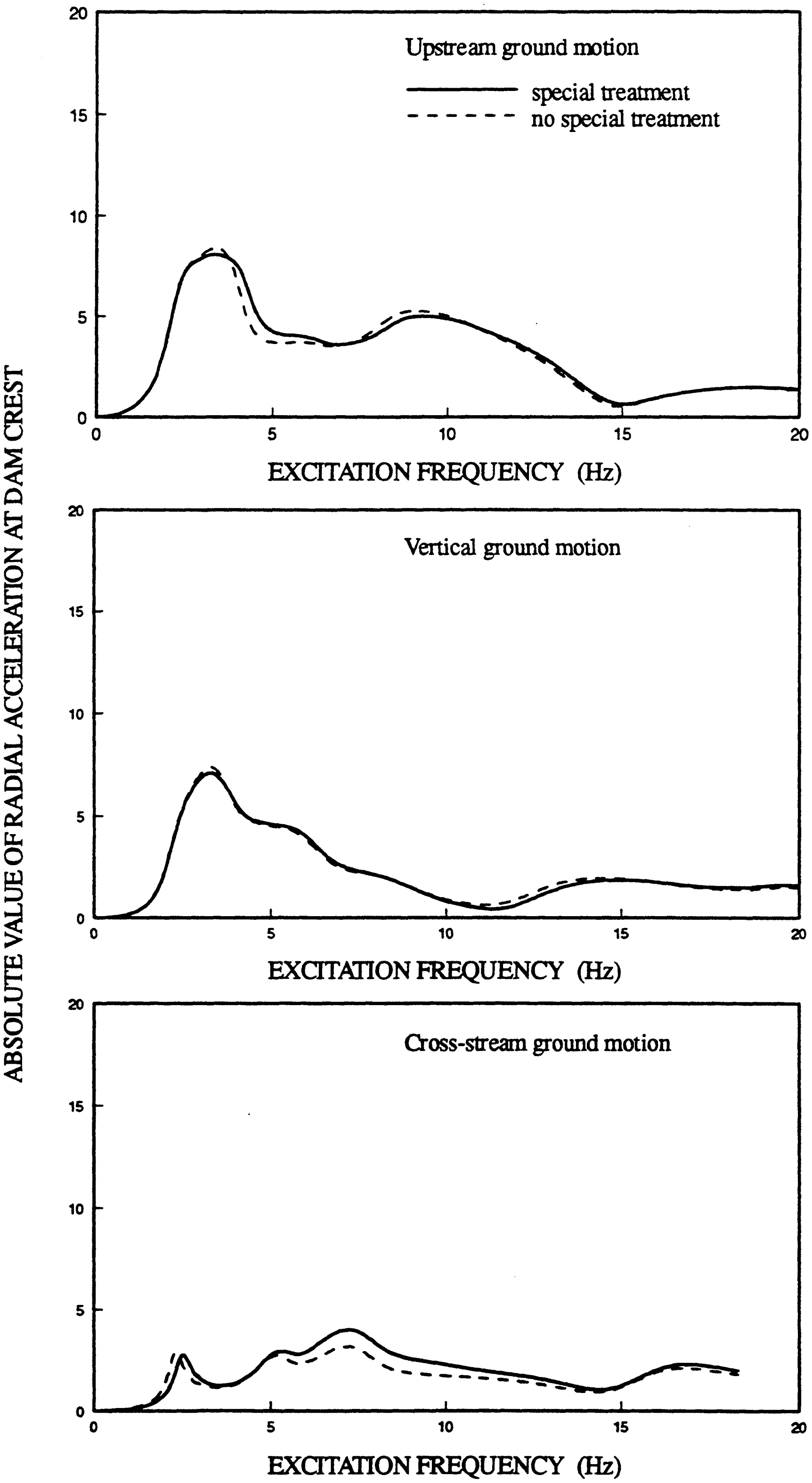

Figure A.4 Comparison of frequency response functions for Morrow Point Dam with full reservoir obtained without the special treatment in the thick shell finite elements of the dam along the dam abutment; $E_f/E_s = 1/4$ and $\alpha = 0.5$.

and water are also small.

Based on the above findings, it is not essential to implement the special treatment for the shell elements, thus allowing geometric incompatibility between the dam and foundation rock, and between the dam and water. More importantly, the preceding results suggest that an arch dam idealized by 3-d solid elements can also be analyzed without any special geometric treatment.

APPENDIX B:INPUT DATA FILES FOR EXAMPLE ANALYSIS

B.1 Symmetric Dynamic Analysis (Subprograms 1 to 6 run — ex-dy.dat)

```
  1   1   1   1   1   1   0
 400000   2   1   3   1   25.000      3.0         ← 400000   1   1   3   1   25.000     3.0
  1  18   61  16                                       (for antisymmetric dynamic analysis)
 26   6
128  61   27  16  16  11   64720.          0.5          0.5
  1   1                                                ← 0   1
  1 0   -159.227  465.       306.633                   (for antisymmetric dynamic analysis)
  2 0   -180.529  465.       306.633
  3 0   -127.420  418.5      290.442
  4 0   -170.201  418.5      290.442
  5 0   -99.320   372.       272.067
  6 0   -158.015  372.       272.067
  7 0   -73.929   325.5      252.522
  8 0   -152.615  325.5      252.522
  9 0   -51.464   279.       232.26
 10 0   -144.157  279.       232.26
 11 0   -36.355   232.5      215.535
 12 0   -136.085  232.5      215.535
 13 0   -23.114   186.       198.254
 14 0   -133.117  186.       198.254
 15 0   -12.91    139.5      180.249
 16 0   -121.569  139.5      180.249
 17 0   -5.538    93.        161.507
 18 0   -110.628  93.        161.507
 19 0     9.388   46.5       125.291
 20 0   -71.347   46.5       125.291
 21 0    18.363   0.         85.202
 22 0   -46.615   0.         85.202
 23 0    30.296   0.         43.915
 24 0   -24.529   0.         43.915
 25 0    34.427   0.         0.
 26 0   -17.227   0.         0.
 25   26
  1   1   2   1   3   2   4   2   5   3   6   3   7   4   8   4   9   5  10   5
 11   6  12   6  13   7  14   7  15   8  16   8  17   9  18   9  19  10  20  10
 21  11  22  11  23  12  24  12  25  13  26  13
  1
  1 144000000.  .2          5.1242236    0.1
  1   2   1
  5   6   2   1   0   4   0   3
  2   2   1
  9  10   6   5   0   8   0   7
  3   2   1
 13  14  10   9   0  12   0  11
  4   2   1
 17  18  14  13   0  16   0  15
  5   2   1
 21  22  18  17   0  20   0  19
  6   2   1
 25  26  22  21   0  24   0  23
  1
 500.       6  12   2   3
  2
    0.001
  465.
0.        0.
0.        43.915
0.        85.202
46.5      125.291
93.       161.507
139.5     180.249
186.      198.245
232.5     215.535
279.      232.26
325.5     252.522
372.      272.067
418.5     290.442
```

```
465.      306.633
 13  1.9059     0.
  3  3.1416    -0.8593
  4.0
  1 0  -166.389  465.      311.619
  2 0  -140.532  418.5     300.376
  3 0  -116.611  372.      285.464
  4 0  -93.501   325.5     268.771
  5 0  -71.401   279.      250.267
  6 0  -55.564   232.5     234.22
  7 0  -41.262   186.      216.732
  8 0  -28.85    139.5     197.841
  9 0  -18.749   93.       177.62
 10 0  2.7       46.5      136.539
  .
  .
  .
  .
  .
  .
  .
  .
113 0  -17.816   372.      84.106
114 0  -.84      279.      0.
115 0  -21.663   465.      83.2
116 0  -19.625   418.5     83.68
117 0  -9.287    372.      42.476
118 0  -3.63     325.5     0.
119 0  -14.424   465.      41.88
120 0  -6.42     372.      0.
121 0  -12.      465.      0.
122 0  -9.21     418.5     0.

 60  61  59  57  53  48  43  38  31  22  13
  1   2   3   4   5   6   7   8   9  10  11  12  13
  1  -159.227  465.      306.633
 62  -180.529  465.      306.633
  2  -127.420  418.5     290.442
 63  -170.201  418.5     290.442
  3  -99.320   372.      272.067
 64  -158.015  372.      272.067
  4  -73.929   325.5     252.522
 65  -152.615  325.5     252.522
  5  -51.464   279.      232.26
 66  -144.157  279.      232.26
  6  -36.355   232.5     215.535
 67  -136.085  232.5     215.535
  7  -23.114   186.      198.254
 68  -133.117  186.      198.254
  8  -12.91    139.5     180.249
 69  -121.569  139.5     180.249
  9  -5.538    93.       161.507
 70  -110.628  93.       161.507
 10    9.388   46.5      125.291
 71  -71.347   46.5      125.291
 11   18.363   0.        85.202
 72  -46.615   0.        85.202
 12   30.296   0.        43.915
 73  -24.529   0.        43.915
 13   34.427   0.        0.
 74  -17.227   0.        0.

  1
 1576000000.  .2          4.8159
  1   6   1
 54  52  59  60  55  56  61  58
  2   6   1
 52  47  53  59  49  50  57  56
  3   6   1
 47  36  43  53  41  42  48  50
  4   6   1
 36  29  31  43  37  30  38  42
  .
  .
  .
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   .
   .
   .
   .
   .
  13   6   1
   5   7  28  26   6  18  27  17
  14   7   1
   7   9  28   8  19  18
  15   6   1
   1   3  25  23   2  15  24  14
  16   7   1
   3   5  25   4  16  15
   0
   1      0.      465.0000     0.
   2     37.5000  465.0000     0.
   3     -2.5040  465.0000    43.2640
   4     -9.9830  465.0000    85.9500
   5     32.5090  465.0000    85.9500
   6    -22.3360  465.0000   127.4880
   7     53.1260  465.0000   127.4880
   8    -39.4000  465.0000   167.3240
   9     -3.6260  465.0000   167.3240
  10     32.1490  465.0000   167.3240
   .
   .
   .
   .
   .
   .
   .
   .
 180     75.0000   93.0000    48.7250
 181     75.0000   93.0000    95.6620
 182     75.0000   93.0000   128.5850
 183     75.0000   93.0000   161.5070
 184     75.0000   46.5000     0.
 185     75.0000   46.5000    94.1310
 186     75.0000   46.5000   125.2910
 187     75.0000    0.         0.
 188     75.0000    0.        42.6010
 189     75.0000    0.        85.2020
   1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
  21  22  23 129 130 131 132 133 134 135 136 137
  24  32  33  55  63  64  80  86  87 103 109 110 120 124 125 138 143 152 157 164
 168 175 179 184 187
   1  60   3  58   4  54   6  51   8  44  12  39  14  23  18  14  20   1  24  61
  25  55  26  45  28  24  30   2  32  59  34  56  35  52  37  46  39  33  43  32
  45  25  49  15  51   3  55  57  56  49  57  34  59  16  61   4  63  53  65  50
  66  47  68  40  70  26  74  17  76   5  80  48  81  41  82  27  84   6  86  43
  88  42  89  36  91  35  93  28  97  18  99   7 103  38 104  37 105  19 107   8
 109  31 111  30 112  29 114  20 116   9 120  22 121  21 122  10 124  13 126  12
 127  11
  20  21  22  23  30  31  51  52  53  54  61  62  76  77  78  79  84  85  99 100
 101 102 107 108 116 117 118 119 122 123 124 125 126 127 128 137 142 151 156 163
 167 174 178 183 186 187 188 189
 137 142 151 156 163 167 174 178 183 186 189 188 187
   1   4   1
 129   1   4 131 143  32  35 145 138  24  25 139   2   3   5 130  33  34  36 144
   2   4   1
 143  32  35 145 157  63  66 159 152  55  56 153  33  34  36 144  64  65  67 158
   3   4   1
 157  63  66 159 168  86  89 170 164  80  81 165  64  65  67 158  87  88  90 169
   4   4   1
 168  86  89 170 179 109 112 181 175 103 104 176  87  88  90 169 110 111 113 180
   .
   .
   .
   .
   .
   .
   .
   .
  14   4   1
 147  41  47 149 161  72  78 163 154  58  60 155  42  44  48 148  73  75  79 162
```

```
  15   4   1
 161  72  78 163 172  95 101 174 166  83  85 167  73  75  79 162  96  98 102 173
  16   4   1
  16  14  20  22  47  45  51  53  29  28  30  31  15  18  21  19  46  49  52  50
  17   4   1
 135  16  22 137 149  47  53 151 141  29  31 142  17  19  23 136  48  50  54 150
  18   5   1
 131  10 133 145  41 147 139  27 140   7  11 132  38  42 146
  19   5   1
 145  41 147 159  72 161 153  58 154  38  42 146  69  73 160
  20   5   1
 159  72 161 170  95 172 165  83 166  69  73 160  92  96 171
  21   5   1
 170  95 172 181 118 183 176 106 177  92  96 171 115 119 182
  22   5   1
  45  76  51  47  78  53  46  77  52  59  61  49  60  62  50
  23   5   1
  47  78  53 149 163 151  48  79  54  60  62  50 155 156 150
  24   5   1
  93 116  99  95 118 101  94 117 100 105 107  97 106 108  98
  25   5   1
  95 118 101 172 183 174  96 119 102 106 108  98 177 178 173
  26   5   1
 112 127 116 181 189 118 113 128 117 121 122 114 185 123 115
  27   5   1
 118 118 118 181 189 183 115 123 119   0   0   0 185 186 182
   1   2   1
 129 143 145 131 138 144 139 130
   2   2   1
 143 157 159 145 152 158 153 144
   3   2   1
 157 168 170 159 164 169 165 158
   4   2   1
 168 179 181 170 175 180 176 169
   5   2   1
 179 187 189 181 184 188 185 180
   6   2   1
 131 145 147 133 139 146 140 132
   7   2   1
 145 159 161 147 153 160 154 146
   8   2   1
 159 170 172 161 165 171 166 160
   9   2   1
 170 181 183 172 176 182 177 171
  10   2   1
 133 147 149 135 140 148 141 134
  11   2   1
 147 161 163 149 154 162 155 148
  12   2   1
 135 149 151 137 141 150 142 136
  13   2   1
 161 172 174 163 166 173 167 162
  14   3   1
 149 163 151 155 156 150
  15   3   1
 172 183 174 177 178 173
  16   3   1
 181 189 183 185 186 182
   1   2   1
   1  32  35   4  24  34  25   3
   2   2   1
  32  63  66  35  55  65  56  34
   3   2   1
  63  86  89  66  80  88  81  65
   4   2   1
  86 109 112  89 103 111 104  88
   5   2   1
 109 124 127 112 120 126 121 111
   6   2   1
   4  35  39   8  25  37  26   6
   7   2   1
  35  66  70  39  56  68  57  37
   8   2   1
  66  89  93  70  81  91  82  68
   9   2   1
```

```
  89 112 116  93 104 114 105  91
  10   3   1
 112 127 116 121 122 114
  11   2   1
   8  39  45  14  26  43  28  12
  12   2   1
  39  70  76  45  57  74  59  43
  13   2   1
  70  93  99  76  82  97  84  74
  14   3   1
  93 116  99 105 107  97
  15   2   1
  14  45  51  20  28  49  30  18
  16   3   1
  45  76  51  59  61  49

   1   2   1
  20  51  53  22  30  52  31  21
   2   2   1
  51  76  78  53  61  77  62  52
   3   2   1
  76  99 101  78  84 100  85  77
   4   2   1
  99 116 118 101 107 117 108 100
   5   2   1
 116 127 189 118 122 128 123 117
   6   2   1
  22  53 151 137  31  54 142  23
   7   2   1
  53  78 163 151  62  79 156  54
   8   2   1
  78 101 174 163  85 102 167  79
   9   2   1
 101 118 183 174 108 119 178 102
  10   3   1
 118 189 183 123 186 119
  11   2   1
 127 124 187 189 126 125 188 128

   1   1   1
 137 151 142
   2   1   1
 151 163 156
   3   1   0
 163 174 167
   4   1   0
 174 183 178
   5   1   1
 183 189 186
   6   1   1
 189 187 188
.1          1.9388      0.5           -1   0
```

B.2 Static Analysis (Subprograms 1 to 6 run — ex-st.dat)

```
  1   1   1   1   0   1   0
 400000   2   1   3   0
  1      61  16
 26   6   0 465.
128  61  27  16  16  11   6
  0   1
  1 0  -159.227  465.      306.633
  2 0  -180.529  465.      306.633
  3 0  -127.420  418.5     290.442
  4 0  -170.201  418.5     290.442
  5 0  -99.320   372.      272.067
  6 0  -158.015  372.      272.067
  7 0  -73.929   325.5     252.522
  8 0  -152.615  325.5     252.522
  9 0  -51.464   279.      232.26
 10 0  -144.157  279.      232.26
 11 0  -36.355   232.5     215.535
 12 0  -136.085  232.5     215.535
 13 0  -23.114   186.      198.254
 14 0  -133.117  186.      198.254
 15 0  -12.91    139.5     180.249
 16 0  -121.569  139.5     180.249
 17 0  -5.538    93.       161.507
 18 0  -110.628  93.       161.507
 19 0    9.388   46.5      125.291
 20 0  -71.347   46.5      125.291
 21 0    18.363  0.        85.202
 22 0  -46.615   0.        85.202
 23 0    30.296  0.        43.915
 24 0  -24.529   0.        43.915
 25 0    34.427  0.        0.
 26 0  -17.227   0.        0.
 25  26
  1   1   2   1   3   2   4   2   5   3   6   3   7   4   8   4   9   5  10   5
 11   6  12   6  13   7  14   7  15   8  16   8  17   9  18   9  19  10  20  10
 21  11  22  11  23  12  24  12  25  13  26  13
  1
  1 144000000.  .2          5.1242236    0.1
  1   2   1
  5   6   2   1   0   4   0   3
  2   2   1
  9  10   6   5   0   8   0   7
  3   2   1
 13  14  10   9   0  12   0  11
  4   2   1
 17  18  14  13   0  16   0  15
  5   2   1
 21  22  18  17   0  20   0  19
  6   2   1
 25  26  22  21   0  24   0  23
  1
 500.       6  12   2   3
  2
   0.001
  465.
0.        0.
0.        43.915
0.        85.202
46.5      125.291
93.       161.507
139.5     180.249
186.      198.245
232.5     215.535
279.      232.26
325.5     252.522
372.      272.067
418.5     290.442
465.      306.633
 13  1.9059     0.
  3 3.1416     -0.8593
  4.0
  1 0  -166.389  465.      311.619
```

```
  2 0  -140.532  418.5     300.376
  3 0  -116.611  372.      285.464
  4 0  -93.501   325.5     268.771
  5 0  -71.401   279.      250.267
  6 0  -55.564   232.5     234.22
  7 0  -41.262   186.      216.732
  8 0  -28.85    139.5     197.841
  9 0  -18.749   93.       177.62
 10 0  2.7       46.5      136.539
 11 0  15.655    0.        91.987
 12 0  29.674    0.        47.001
 13 0  34.427    0.        0.
 14 0  -123.347  465.      278.021
 15 0  -94.387   372.      267.926
 16 0  -65.646   325.5     244.000
 17 0  -38.288   279.      218.663
 18 0  -16.052   186.      190.1
 19 0  -6.297    139.5     172.1
 20 0    9.845   93.       139.122
  .
  .
  .
  .
  .
  .
  .
  .
103 0  -1.924    186.      43.331
104 0  2.578     186.      0.
105 0  -50.139   465.      161.97
106 0  -50.095   418.5     161.991
107 0  -31.791   372.      124.071
108 0  -15.15    279.      84.733
109 0  1.788     232.5     0.
110 0  -16.328   325.5     84.456
111 0  -4.455    279.      43.037
112 0  -33.622   465.      123.409
113 0  -17.816   372.      84.106
114 0  -.84      279.      0.
115 0  -21.663   465.      83.2
116 0  -19.625   418.5     83.68
117 0  -9.287    372.      42.476
118 0  -3.63     325.5     0.
119 0  -14.424   465.      41.88
120 0  -6.42     372.      0.
121 0  -12.      465.      0.
122 0  -9.21     418.5     0.

 60  61  59  57  53  48  43  38  31  22  13
  1   2   3   4   5   6   7   8   9  10  11  12  13
  1  -159.227  465.      306.633
 62  -180.529  465.      306.633
  2  -127.420  418.5     290.442
 63  -170.201  418.5     290.442
  3  -99.320   372.      272.067
 64  -158.015  372.      272.067
  4  -73.929   325.5     252.522
 65  -152.615  325.5     252.522
  5  -51.464   279.      232.26
 66  -144.157  279.      232.26
  6  -36.355   232.5     215.535
 67  -136.085  232.5     215.535
  7  -23.114   186.      198.254
 68  -133.117  186.      198.254
  8  -12.91    139.5     180.249
 69  -121.569  139.5     180.249
  9  -5.538    93.       161.507
 70  -110.628  93.       161.507
 10    9.388   46.5      125.291
 71  -71.347   46.5      125.291
 11   18.363   0.        85.202
 72  -46.615   0.        85.202
 12   30.296   0.        43.915
 73  -24.529   0.        43.915
 13   34.427   0.        0.
```

```
 74  -17.227   0.          0.

  1
  1576000000.  .2          4.8159
  1   6   1
 54  52  59  60  55  56  61  58
  2   6   1
 52  47  53  59  49  50  57  56
  3   6   1
 47  36  43  53  41  42  48  50
  4   6   1
 36  29  31  43  37  30  38  42
  5   6   1
 29  11  13  31  21  12  22  30
  6   6   1
 44  33  52  54  45  46  55  51
  7   6   1
 33  26  47  52  34  40  49  46
  8   6   1
 26  28  36  47  27  35  41  40
  9   6   1
 28   9  29  36  19  20  37  35
 10   7   1
  9  11  29  10  21  20
 11   6   1
 23  25  33  44  24  32  45  39
 12   6   1
 25   5  26  33  16  17  34  32
 13   6   1
  5   7  28  26   6  18  27  17
 14   7   1
  7   9  28   8  19  18
 15   6   1
  1   3  25  23   2  15  24  14
 16   7   1
  3   5  25   4  16  15
  0
  1       0.       465.0000    0.
  2      37.5000   465.0000    0.
  3      -2.5040   465.0000   43.2640
  4      -9.9830   465.0000   85.9500
  5      32.5090   465.0000   85.9500
  6     -22.3360   465.0000  127.4880
  7      53.1260   465.0000  127.4880
  8     -39.4000   465.0000  167.3240
  9      -3.6260   465.0000  167.3240
 10      32.1490   465.0000  167.3240
  .
  .
  .
  .
  .
  .
  .
  .
180      75.0000    93.0000   48.7250
181      75.0000    93.0000   95.6620
182      75.0000    93.0000  128.5850
183      75.0000    93.0000  161.5070
184      75.0000    46.5000    0.
185      75.0000    46.5000   94.1310
186      75.0000    46.5000  125.2910
187      75.0000     0.        0.
188      75.0000     0.        42.6010
189      75.0000     0.        85.2020
  1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16  17  18  19  20
 21  22  23 129 130 131 132 133 134 135 136 137
 24  32  33  55  63  64  80  86  87 103 109 110 120 124 125 138 143 152 157 164
168 175 179 184 187
  1  60   3  58   4  54   6  51   8  44  12  39  14  23  18  14  20   1  24  61
 25  55  26  45  28  24  30   2  32  59  34  56  35  52  37  46  39  33  43  32
 45  25  49  15  51   3  55  57  56  49  57  34  59  16  61   4  63  53  65  50
 66  47  68  40  70  26  74  17  76   5  80  48  81  41  82  27  84   6  86  43
 88  42  89  36  91  35  93  28  97  18  99   7 103  38 104  37 105  19 107   8
109  31 111  30 112  29 114  20 116   9 120  22 121  21 122  10 124  13 126  12
```

```
 127  11
  20  21  22  23  30  31  51  52  53  54  61  62  76  77  78  79  84  85  99 100
 101 102 107 108 116 117 118 119 122 123 124 125 126 127 128 137 142 151 156 163
 167 174 178 183 186 187 188 189
 137 142 151 156 163 167 174 178 183 186 187 188 189
   1   2
   1  32  35   4  24  34  25   3
   2   2
  32  63  66  35  55  65  56  34
   3   2
  63  86  89  66  80  88  81  65
   4   2
  86 109 112  89 103 111 104  88
   5   2
 109 124 127 112 120 126 121 111
   6   2
   4  35  39   8  25  37  26   6
   7   2
  35  66  70  39  56  68  57  37
   8   2
  66  89  93  70  81  91  82  68
   9   2
  89 112 116  93 104 114 105  91
  10   3
 112 127 116 121 122 114
  11   2
   8  39  45  14  26  43  28  12
  12   2
  39  70  76  45  57  74  59  43
  13   2
  70  93  99  76  82  97  84  74
  14   3
  93 116  99 105 107  97
  15   2
  14  45  51  20  28  49  30  18
  16   3
  45  76  51  59  61  49
1.9388      32.2
```

B.3 Earthquake Analysis (Subprogram 7 run — ex-eq.dat)

```
   0   0   0   0   0   0   1
  400000   2   1   3   1  25.000     3.0
   1  18  61  16
  26   6
 128  61  27  16  16  11  64720.         0.5         0.5
   1  12   8   1   3   0   0   1
   1   1   1   1
  60   1              60   2             60   4 90.          13   1
  13   2              13   4 90.         44   4 26.5         44   2
  44   4 116.5         1   4 56.2         1   2               1   4 146.2
   1   4   1   1   4   2   5   3   1   5   3   2   6   2   6   6   2   7  16   1
   6  16   1   7
15.           10   2   0
1001   1
  -.2034  -.0623   .1312   .3248   .1706  -.0098  -.1378  -.0919   .0394   .1739
   .1280  -.0984  -.2789  -.2789  -.1969  -.0262  -.0098  -.0066   .1312   .3445
   .3740   .2133   .1444   .0755   .0689   .0623  -.1280  -.2428  -.0361   .1903
   .0919  -.3346  -.3707  -.1542   .1608   .0328  -.1312  -.0820   .1903   .2362
  -.2133  -.3510   .1050   .5545   .3248  -.1575  -.2133   .1181   .1476  -.0919
   .
   .
   .
   .
   .
   .
   .
   .
  -.2100  -.7382  -.8661  -.8891  -.7382  -.4692   .0164   .5249  1.1024  1.2828
  1.0203   .8268   .7218   .5906   .3839   .1870   .1542   .2559   .2592   .1640
   .0820  -.0131  -.1608  -.3707  -.4298  -.2657  -.1608  -.0951   .0722   .3609
   .3412   .1444  -.0951  -.3510  -.5545  -.4560  -.2461  -.2067  -.5643  -.8497
 -1.0466
1001   1
   .8793  -.1608   .1083  -.0558  -.1115   .2165   .7152   .9318   .4396  -.1640
  -.9088 -1.1909  -.6791   .0098   .7480  1.0400   .6365   .0131  -.7283 -1.1352
  -.7612  -.1706   .4888  1.0499   .6234   .0558   .0328   .5020  1.0663  1.1942
  1.2894  1.2139   .2822  -.8924 -1.8143 -1.0335   .2625  1.5715  1.2992   .5741
   .4134   .1804  -.5741  -.6037  -.2264   .2362  -.3904 -1.0236  -.9547  -.8268
   .
   .
   .
   .
   .
   .
   .
   .
  -.2723  -.3281  -.2887  -.2231  -.2690  -.3445  -.4364  -.4692  -.4626  -.4364
  -.2920  -.0919   .0230   .0098  -.1542  -.3379  -.2756  -.0656  -.0295  -.3018
  -.5577  -.7087  -.5840  -.3051  -.0164   .0492   .0131   .1181   .3018   .5282
   .5118   .2559  -.0492  -.1444   .0984   .1772  -.0033  -.1148  -.1312  -.0656
  -.0755
1001   1
   .4035  -.0033   .0131  -.0984  -.1345  -.0689  -.0623  -.1181   .0525   .2001
   .0722  -.0820  -.1083   .0098  -.0066  -.0492  -.1148  -.0919  -.0459   .1870
   .3675   .4396   .3839   .2723   .0689  -.1870  -.1903  -.1509  -.1345  -.1542
  -.2198  -.4757  -.6299  -.6693  -.4790  -.1411   .2493   .4331   .2461   .0525
  -.1312  -.1542  -.0591   .0525   .2789   .2986   .1542  -.0230  -.1706  -.0656
   .1312   .1214   .0951   .1509   .1345   .0820   .0951   .2100   .3215   .2297
   .
   .
   .
   .
   .
   .
   .
   .
 -1.4895 -1.8701 -1.8176 -1.3648  -.8661  -.3445   .1903   .5676   .5971   .5741
   .5381   .4823   .2034  -.1608  -.4692  -.5709  -.4167  -.1214   .1903   .3740
   .4331   .4396   .4068   .3773   .3412   .3117   .2723   .2657   .3445   .4823
   .5709   .3970   .1050   .0328   .3281   .6594   .5151  -.0230  -.5774 -1.1483
  1.3484
```