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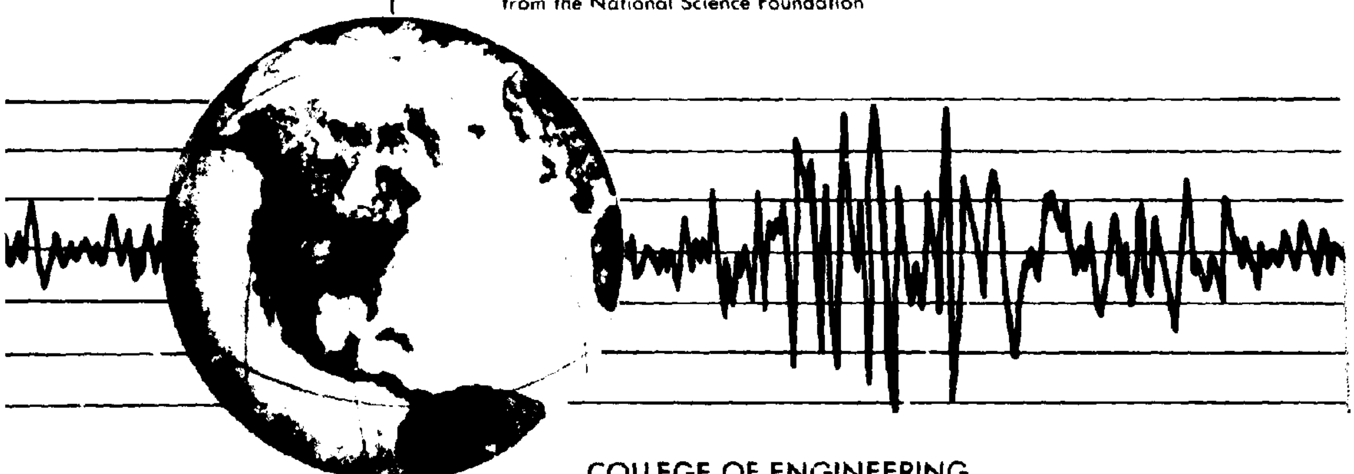
EACD-3D
A COMPUTER PROGRAM FOR THREE-DIMENSIONAL EARTHQUAKE ANALYSIS OF CONCRETE DAMS

by

KA-LUN FOK
JOHN F. HALL
ANIL K. CHOPRA

A Report on Research Conducted Under
Grants CEE-8120308 and CEE-8401439
from the National Science Foundation



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A procedure has been developed for three-dimensional analysis of earthquake response of concrete dams [1,2,3,4,]. The effects of dam-water interaction and of alluvium and sediments, usually present at the bottom and possibly at sides of actual reservoirs, are included in the analysis. As a first step towards considering the effects of dam-foundation rock interaction, the flexibility of the foundation rock is considered in the analysis but its inertial and damping effects are ignored. This report is concerned with the computer program EACD-3D that implements the analytical procedure.

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TABLE OF CONTENTS

1. INTRODUCTION

A procedure has been developed for three-dimensional analysis of earthquake response of concrete dams [1,2,3,4]. The effects of dam-water interaction and of alluvium and sediments, usually present at the bottom and possibly at sides of actual reservoirs, are included in the analysis. As a first step towards considering the effects of dam-foundation rock interaction, the flexibility of the foundation rock is considered in the analysis but its inertial and damping effects are ignored. This report is concerned with the computer program EACD-3D that implements the analytical procedure.

The analysis procedure underlying the computer program EACD-3D assumes linear behavior for the 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 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 [5]. 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 recently completed computer program EAGD-84 is available [6], in which a viscoelastic halfplane 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 the computer program EACD-3D. 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 a sample analysis are presented.

2. SYSTEM AND GROUND MOTION

2.1 Concrete Dam

The system considered consists of a concrete dam supported by flexible foundation rock in a canyon and impounding a reservoir of water (Figure 2.1). 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. The system is analyzed under the assumption of linear behavior for the concrete dam, impounded water and foundation rock.

The dam is idealized as an assemblage of finite elements. In a three-dimensional idealization of an arch dam, its main part is represented by thick shell finite elements [7], and the part of the dam near its junction with foundation rock represented by transition elements [7,8], designed to connect thick shell elements in the dam to three-dimensional solid elements employed in idealizing the foundation rock [Figure 2.2(a)]. Three-dimensional solid elements are employed in a three-dimensional 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.

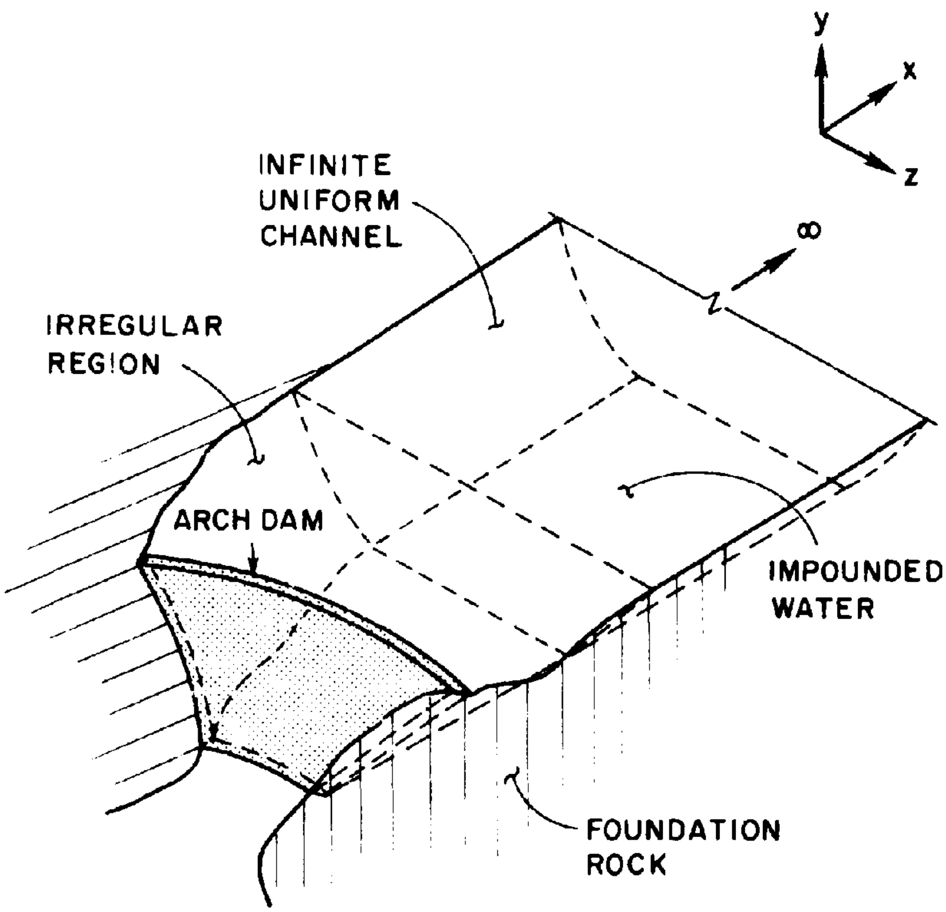


Figure 2.1 Arch dam-water-foundation rock system.

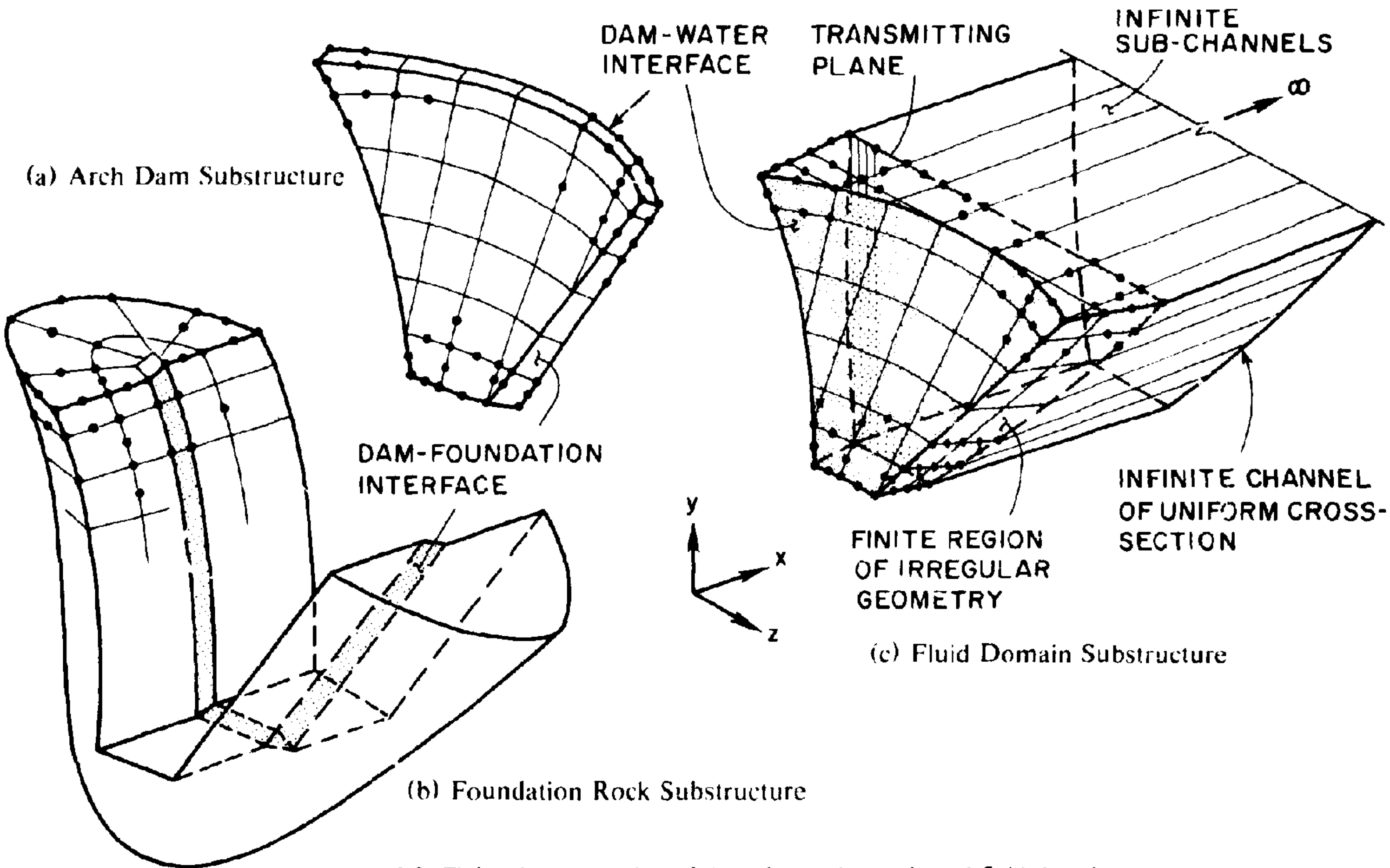


Figure 2.2 Finite element models of dam, foundation rock, and fluid domain substructures. (Parts (a) and (c) adapted from reference [1])

2.2 Foundation Rock

Required in the substructure method for analysis of earthquake response of dams is the frequency-dependent stiffness (or impedance) matrix for the foundation rock, defined at the nodal points on the dam-foundation rock interface. This matrix for a viscoelastic half plane was determined for two-dimensional analysis of concrete gravity dams supported on the horizontal surface of foundation rock [9], and is utilized in computer program EAGD-84 [6] for two-dimensional analysis of gravity dams. However, such a foundation model is inappropriate for analysis of arch dams or gravity dams built in narrow canyons with the dam boundary in contact with the foundation rock extending over the height of the dam.

An alternative approach is to idealize a portion of the foundation rock as a finite element system and to determine the impedance matrix for this idealization. The principal decision required in defining this idealization is the extent and boundary conditions of the foundation-rock region to be included in the analysis. For concrete dam sites where typically similar rocks extend to considerable distances, wave-transmitting boundaries are necessary if the finite sized foundation rock region is to represent the unbounded extent in the field. Such transmitting boundaries have been developed for two-dimensional analysis [10] with seemingly ad-hoc extensions proposed for three-dimensional analyses. The latter, if developed properly, would be computationally expensive perhaps to the point of being prohibitive for practical problems.

For these reasons and because it is virtually impossible to rationally specify the free-field earthquake motions at the dam-rock interface in narrow canyons, an extremely simple idealization for the foundation rock is used here [11]. Only the foundation rock flexibility is considered in this investigation; i.e. the inertial and damping effects of the foundation rock are ignored in considering dam-foundation interaction effects.

The shape of the foundation rock is idealized using a procedure that has been adopted in the computer program ADAP [8]. Basically, this procedure assumes that the dam canyon is prismatic in the upstream direction (x direction), and the volume of the foundation rock is described by a size parameter R_f. With this procedure to define the shape of the foundation-rock region, the size of the region depends entirely on R_f. This parameter should be chosen to be large enough to satisfactorily represent foundation flexibility effects in analysis of the dam, and it has been shown that the ratio of foundation modulus to dam modulus governs the selection of this parameter [3].

Theoretically, the shape of the foundation-rock region should be compatible with the geometry of the dam and impounded water in the finite element system to be analyzed. However, this may sometimes be difficult to achieve with the shape of the foundation rock region idealized using the aforementioned procedure. Since foundation rock flexibility is represented by the condensed stiffness matrix defined with reference to the degrees of freedom at the dam-foundation rock interface, compatibility must be satisfied at this interface but minor violations at the foundation-water interface may be acceptable.

As shown in Figure 2.2(b) for arch dams, an appropriate portion of the foundation-rock region is idealized as an assemblage of three-dimensional solid finite elements. The elastic modulus E_f and Poisson's ratio ν_f must be specified for each finite element in the foundation rock idealization.

2.3 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 would be exorbitantly expensive, to the point of becoming impractical, if the standard finite element idealization was employed to large distances in the upstream direction.

An effective approach employed in this computer program is to idealize the fluid domain as shown in Figure 2.1, with 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. 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 2.2(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 2.2(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 2.2(c)]. The properties of the impounded water are characterized by the mass density 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.

2.4 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. $\alpha = 1$ 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 $k = \rho C / \rho_r C_r$, $C_r = \sqrt{E_r / \rho_r}$, E_r and ρ_r are the elastic modulus and mass density of the reservoir bottom-sides materials.

Because for narrow, 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 modelled 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 α = 0.90 to 1 is recommended for proposed new dams or recent dams where sediment deposits are meagre; α = 0.75 to 0.90 is recommended for older dams with substantial sediment deposits.

2.5 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 [1]. This free-field ground motion was assumed to be uniform across the base in two-dimensional analyses of concrete gravity dams [12]. This approach of specifying the same motion over the entire dam-foundation rock interface is not appropriate in three-dimensional analysis of arch or gravity dams because the free-field motion may vary significantly across the width and over the height of the river canyon. Non-uniform boundary motions can be included in finite element analysis of structures [13]. The principal difficulty, however, is in rationally defining the variations in motions around the river canyon because very few, if any, records have been obtained of actual ground motion variations in arch dam locations. Another possible approach is to define the earthquake input as a rigid-body translation of the base of the combined finite element model of the dam and a portion of the foundation rock. However, very little is known about earthquake motion at depth because most of the available strong motion records are from accelerographs located at the ground surface or in basements of buildings.

From the preceding discussion it is clear that it is difficult to define a suitable earthquake input mechanism in three-dimensional analysis of arch or gravity dams. Neither of the two approaches can be justified rationally, thus a much simpler approximation is employed in this computer program. Specifically, a sufficient portion of the foundation rock is included to represent only the static foundation flexibility effects: the foundation rock is assumed to be massless for the dynamic analysis, and the earthquake input is specified as spatially-uniform motion of the basement rock [11]. Since there is no wave propagation mechanism in the massless foundation rock, the specified basement rock motion is transmitted without modification to the dam-foundation rock interface. In the context of the substructure method of analysis, the above mentioned approximation is equivalent to specifying the same free-field ground motion throughout the dam-foundation rock interface with the foundation rock assumed to be massless in computing the foundation impedance matrix. The free-field motion is also assumed to be uniform 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. The ground acceleration is defined by its three components: $a_g^x(t)$ in the upstream direction, $a_g^y(t)$ in the cross-stream direction, and $a_g^z(t)$ in the vertical direction.

3. OUTLINE OF ANALYTICAL PROCEDURE

The computer program EACD-3D implements the analytical procedure developed [3,4] 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 [1,2] to consider flexibility of the foundation rock supporting the dam and to include Fourier synthesis of harmonic responses to obtain the earthquake response of dams. In addition, the analytical procedure described in References [3] and [4] has been extended to include the effects of hydrostatic pressure at the foundation rock surface on the static response of the dam. The static analysis considers only the effects of the weight of the dam and hydrostatic pressures, not the thermal effects in the concrete or construction sequence of the dam.

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 by transforming the displacements of the dam to generalized coordinates. The earlier analytical procedure [1,2] has been improved by incorporating more efficient analytical formulations and computational procedures for evaluating the hydrodynamic terms. Additional efficiency is achieved by taking advantage of the idea that rational expressions can be used as interpolating functions for the frequency response functions for the modal coordinates of a structure, thus reducing the number of frequency points at which a response function must be computed exactly. As a result of these improvements it has been possible to reduce the computational costs for analyzing arch dams by an order of magnitude.

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 7.1). 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 system. In Subprogram 1, the mesh for the foundation of the dam is input, and the foundation stiffness matrix is computed and condensed to the degrees of freedom along the dam-foundation interface. In static analysis when the reservoir is not empty, the hydrostatic load vector on the foundation rock is computed and condensed to the degrees of freedom along the dam-foundation interface. The dam mesh is input in Subprogram 2 where element stiffness, mass and stress computation matrices are computed. The dam stiffness and mass matrices are assembled in Subprogram 3; included is the foundation stiffness matrix from Subprogram 1. Following the assembly, the eigenproblem of the dam-foundation 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 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 7.

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 45000, 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 system (Subprograms 1, 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 fluid domain, and this may be a limiting factor when 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, a lower bound estimate of the total storage required is the storage required by the Mesh 1 matrices. These matrices are stored by the skyline method, and the required storage S_1 is estimated by

$$S_1 = 3 \sum_{i=1}^{NEQ} (i - i_{\min} + 1)$$

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 2.2(c)] should be considered coupled to each other because of the transmitting plane matrix [1].

4.2 Implementation on Other Computers

The program was originally developed for a CDC computer but has now been rewritten for IBM mainframe computers. 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 IBM computers. Implementation on other computers, e.g. CDC machines, may require only single precision. Implementation on another computer may also require addition of the PROGRAM card 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. In this case, the Main Program should be changed to the main overlay and each of the seven subprograms should be changed to a suboverlay directly below the Main Overlay. The overlay-structure is produced by introducing the following statements.

a. The statement OVERLAY(XFILE,0,0) begins the Main Overlay.

b. The statements OVERLAY(XFILE,i,0) and PROGRAM SUBi begin the ith overlay, where i = 1,2, · · · ,7.

c. The ith overlay is called from the Main Overlay by the statement CALL OVERLAY(5HXFILE,i,0,0) .

4.3 Mesh Generation Program

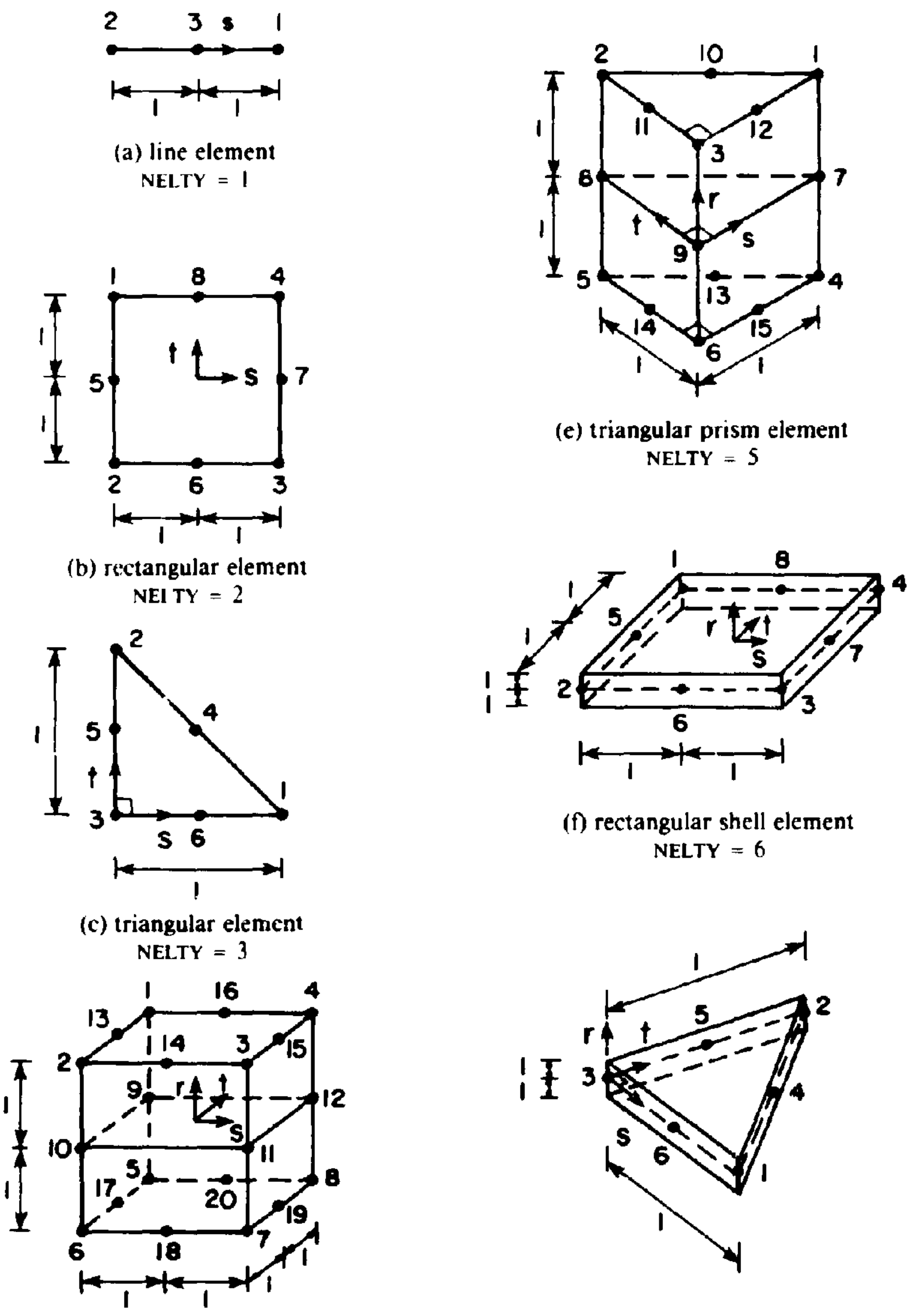
In order to facilitate the preparation of the input data for finite element meshes of the dam (see Chapter 8 - Subprogram 2), foundation rock (see Chapter 8 - Subprogram 1), and reservoir water (see Chapter 8 - Subprogram 4), a mesh-generation computer program is available. The input data to this mesh generation program is kept to a minimum and the output from this program consists of the nodal point coordinates and element connectivity of the finite element meshes. In this way, the user can minimize the laborious task of preparing the input data for the computer program. A detailed description of this mesh generation program and its users' guide is presented in Appendix A.

5. DESCRIPTION OF FINITE ELEMENTS

5.1 Fluid Elements

Finite elements used to discretize the impounded water are derived in the appendices of Reference [1]. 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 [14] 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 8 - 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 8 - 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 element types. Elements are shown in undistorted or parent form.

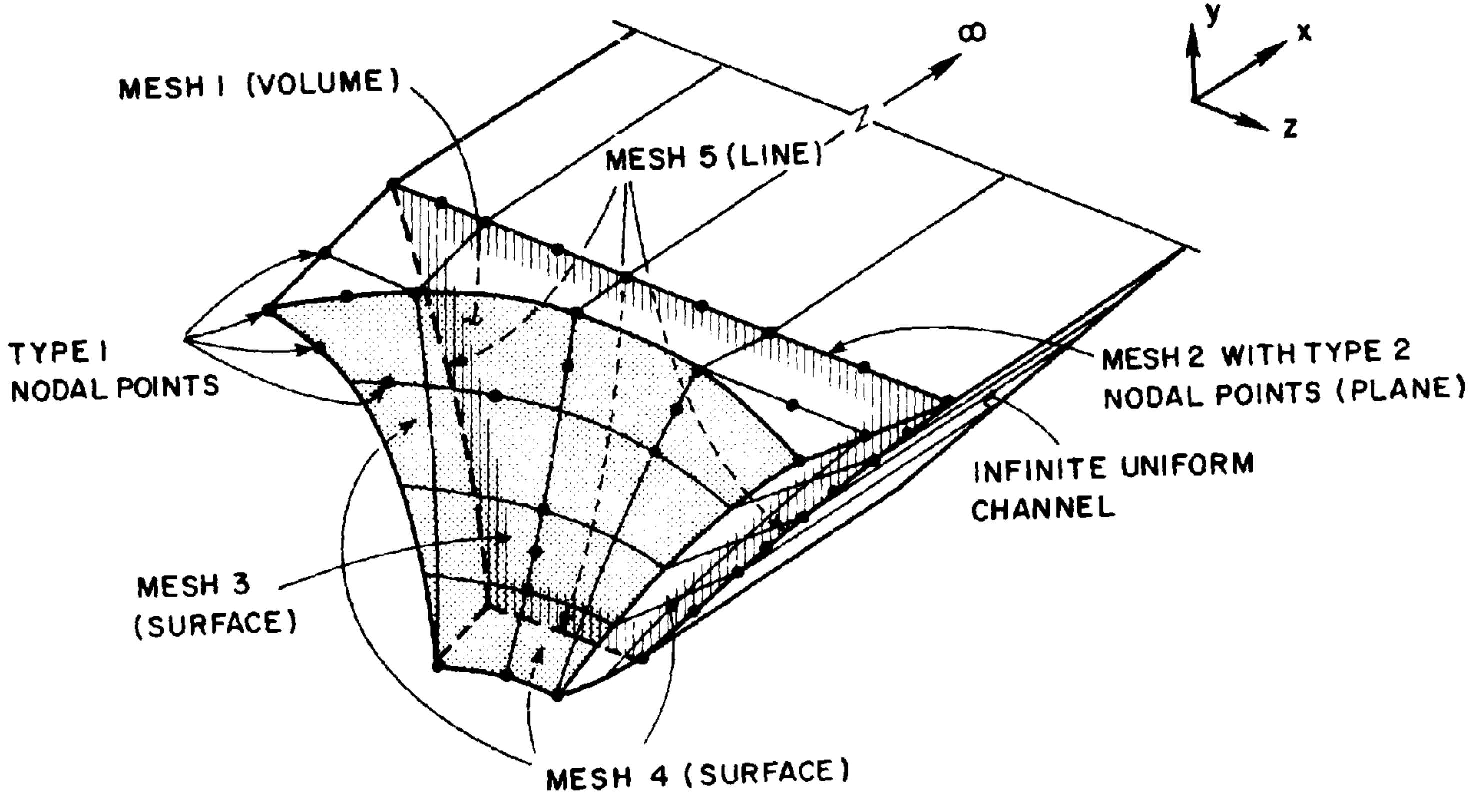


Figure 5.2 Infinite reservoir domain illustrating Type 1 and Type 2 nodal points and the Meshes 1, 2, 3, 4, and 5.

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 × 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 × 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 × 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.

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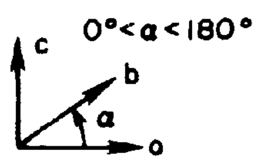
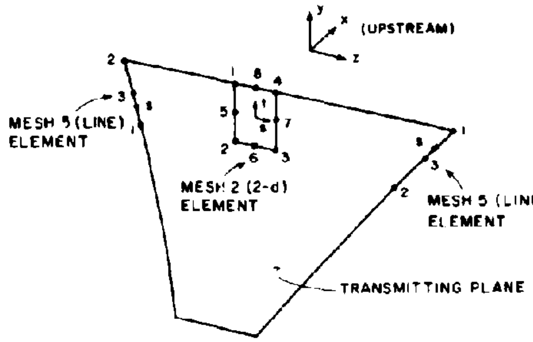
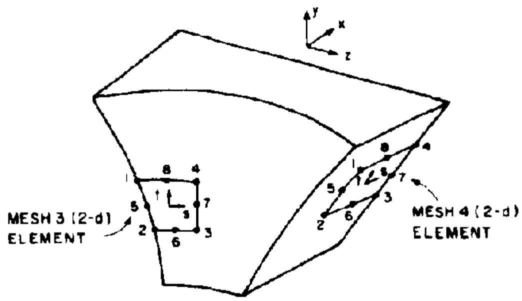
† This and the subsequent discussion makes use of a vector cross product c = a × b to define the orientation of a new vector c in terms of two existing vectors a and b. The new vector c is perpendicular to the plane containing the vectors a and b and points in the direction given by the right hand rule.

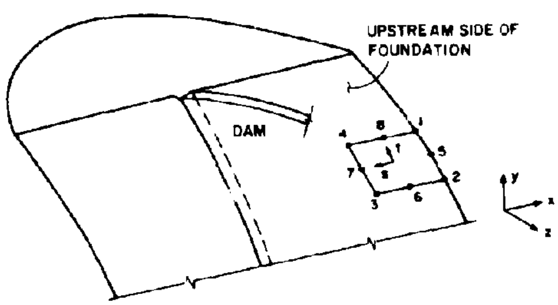




(a) Proper numbering direction of nodes for Mesh 5 (line) element and Mesh 2 (2-d) element

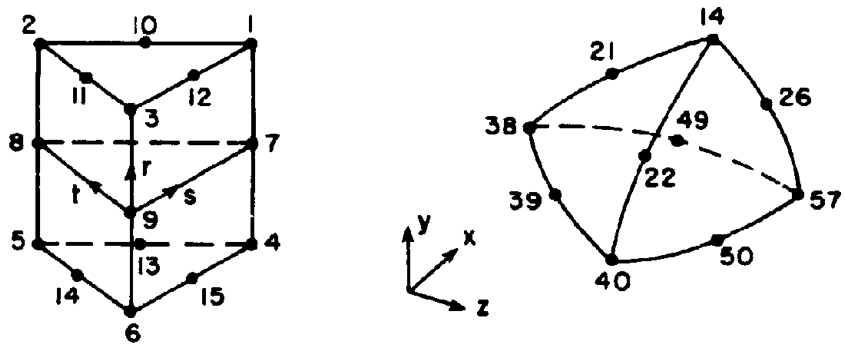


(b) Proper numbering direction of nodes for Mesh 3 and Mesh 4 2-d elements



(c) Proper numbering direction of nodes for foundation-water interface 2-d elements

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



Parent Element

Mapped Element

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.

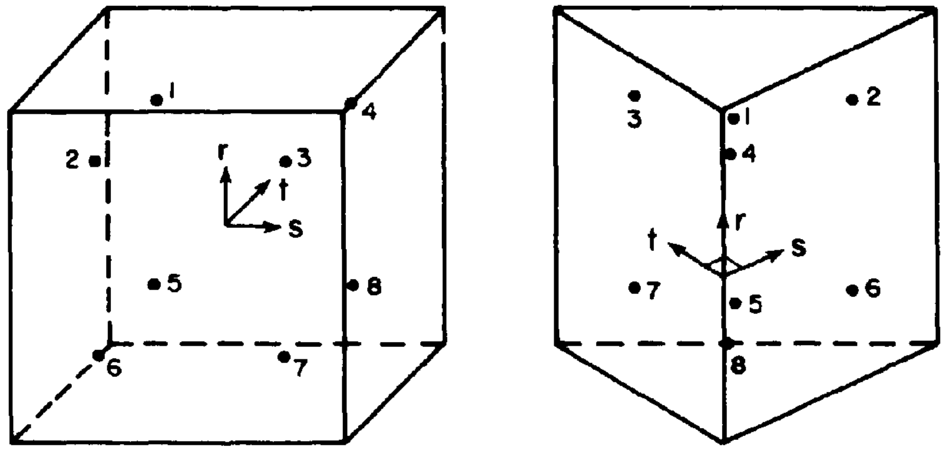
Table 5.1 -- Usage and restriction on orientation of the finite element types.

Element	Usage	Restriction on Orientation
Line	Fluid Mesh 5	$s \times x$ points inside the finite element mesh
Plane, Triangle and Rectangle	Fluid Mesh 2	$s \times t$ points in -x direction
	Fluid Mesh 3	$s \times t$ points outside the finite element mesh
	Fluid Mesh 4	$s \times t$ points outside the finite element mesh
	Water foundation interface	$s \times t$ points outside the fluid finite element mesh into the foundation mesh
3-d Triangular Prism and Rectangular Prism	Fluid Mesh 1	No restriction
	Dam	$s \times t$ has a component in +x direction
	Foundation	No restriction
3-d Triangular and Rectangular Shell	Dam	$s \times t$ has a component in +x direction

5.2 Dam and Foundation Elements

Finite elements used to discretize the dam and the dam foundation are standard elements derived in Reference [14]. 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)]. Two-dimensional elements [Figures 5.1(b) and 5.1(c)] are also employed to discretize the surface of the foundation rock at the water-foundation rock interface in static analysis. 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 [14] in the triangular domains. The nodal numbering indicated is the order in which the actual node numbers must be input in an element's IM array (see Chapter 8, Subprograms 1 and 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 8 - Subprograms 1 and 2).

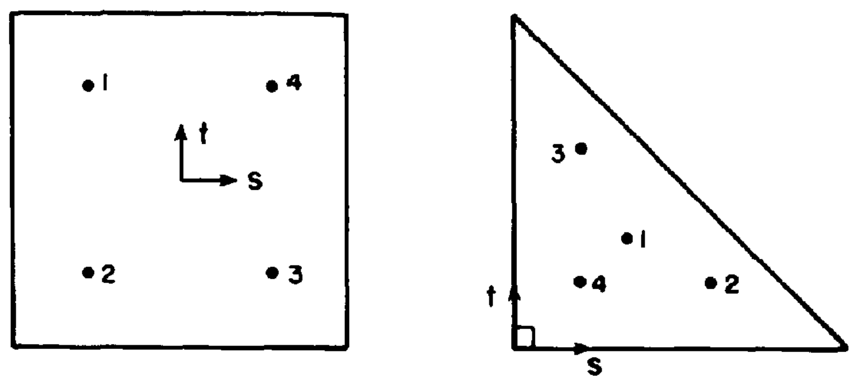
The solid elements (Chapters 6, 7 and 8, Reference [14]) are used for discretizing a three-dimensional dam-foundation system. It has three degrees of freedom per node - the x, y and z translations. The rectangular prism form (NELTY = 4) is a variable 8 to 20 node element. Any or all of nodes 9, 10, 11, ... 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 5.5, Table 5.2). 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 5.6(a)]. In static analysis when the reservoir is not empty, two-dimensional elements to discretize the surface of the foundation rock at the water-foundation rock interface are needed to compute the hydrostatic pressure on the top of the foundation rock (see Chapter 8 - Subprogram 1). This two-dimensional finite element mesh is naturally selected as the mesh at the water-foundation rock interface resulting from the three-dimensional discretization of the foundation rock. These two-dimensional elements (NELTY = 2 or 3) are mapped into x, y, z space, and s × t should point into the foundation rock.



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 5.5 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 5.6).

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

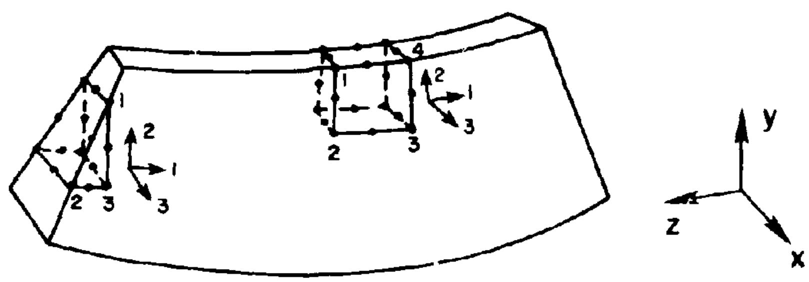
(a) 3-d solid element

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	0.6	0.2	0.5774
3	0.5774	-0.5774	0.5774	0.2	0.6	0.5774
4	0.5774	0.5774	0.5774	0.2	0.2	0.5774
5	-0.5774	0.5774	-0.5774	0.3333	0.3333	-0.5774
6	-0.5774	-0.5774	-0.5774	0.6	0.2	-0.5774
7	0.5774	-0.5774	-0.5774	0.2	0.6	-0.5774
8	0.5774	0.5774	-0.5774	0.2	0.2	-0.5774

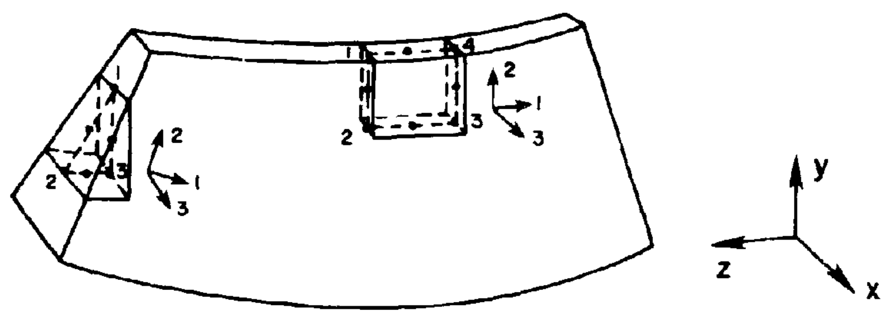
(b) 3-d shell element

Gauss Quadrature/ Stress Location Number	Rectangular		Triangular	
	s coordinate	t coordinate	s coordinate	t coordinate
1	-0.5774	0.5774	0.3333	0.3333
2	-0.5774	-0.5774	0.6	0.2
3	0.5774	-0.5774	0.2	0.6
4	0.5774	0.5774	0.2	0.2

† 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 5.7).



(a) Solid Element Mesh



(b) Shell Element Mesh

Figure 5.6 Example of proper direction of node numbering; also shown are the directions of local stress axes.

Thus, to an observer located outside the foundation rock finite element mesh, the nodes should be numbered clockwise [Figure 5.3(c)].

The shell element (Chapter 16, Reference [14]) is used for discretizing an arch dam. Any foundation region must be discretized with the solid element. 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 auxilliary "nodes" - one on the upstream face and one on the downstream face. It is the auxilliary nodes whose numbers and locations are actually input by the user. Upstream auxilliary nodes are numbered first followed by the downstream auxilliary nodes in the same order. Mid-surface node numbers are the same as those of the corresponding upstream auxilliary nodes. The coordinates of the mid-surface nodes are computed as the average of the coordinates of the corresponding upstream and downstream auxilliary nodes. Degrees of freedom in a shell element mesh are associated with the mid-surface nodes. Each mid-surface node has five degrees of freedom: x, y and z translations and two rotations of the "normal" which connects the upstream and downstream auxilliary nodes. Note that this normal is in the mapped direction of the local element coordinate r. The two rotational degrees of freedom of the normal are about an axis $a = y \times r$ and an axis $b = r \times a$. 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 5.5, Table 5.2), and are exact in r. Shell elements are mapped into x, y, z space with the requirement that $s \times t$ 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 5.6(b)]. Table 5.1 contains a summary of the usage of the different dam and foundation elements and the restriction on their orientation.

A connection cannot be made directly between a dam shell element and a solid foundation element because of the different types of degrees of freedom employed. In order to make this connection, a dam shell element adjacent to a solid foundation element is transformed to a transition element by transforming the five degrees of freedom for each shell mid-surface node on the dam-foundation interface to six degrees of freedom at the auxilliary nodes. The first three of these six degrees of freedom are x, y and z translations of the upstream auxilliary node and the last three are x, y and z translations of the downstream auxilliary node. This transformation is possible because the displacements vary linearly through the thickness of the shell element. The transition element is compatible with the adjacent solid foundation element if the interface side of the latter has its nodes at the mid-surface locations omitted. Transition elements are automatically formed from shell elements by the program 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 5.5 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 5.7). 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 × t; 1 = y × 3 or = - z if 3 is in the y direction; and 2 = 3 × 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 8 - 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 5.6(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 5.5(a), 5.7 and Table 5.2(a). They are numbered 1 to 8 for use in array INS2 (see Chapter 8 - 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 5.7). In this case, the stress

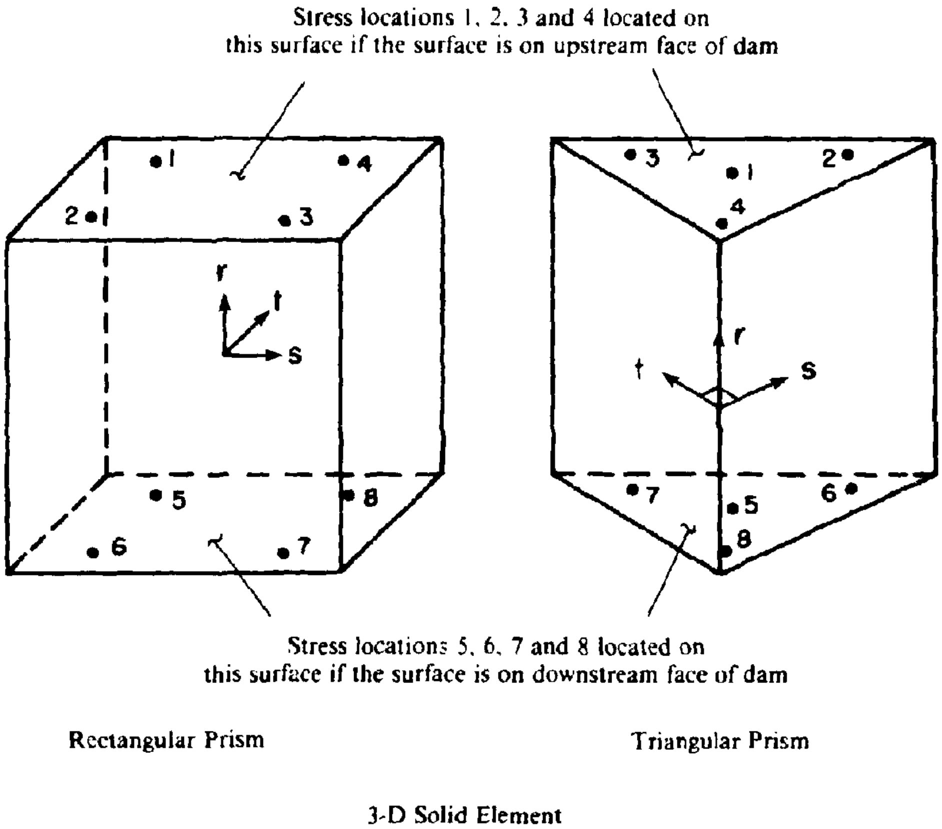


Figure 5.7 Stress locations of 3-d solid element when the $r = 1.0$ face of the element lies on the upstream face of the dam or when the $r = -1.0$ face of the element lies on the downstream face of the dam.

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 × t and is in the true normal direction; 1 = y × 3 or = - z if 3 is in the y direction; and 2 = 3 × 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 8 - 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 5.6(b) orients 1, 2 and 3 in the arch, cantilever and normal directions, respectively. The element stress locations are shown in Figure 5.5(b) and Table 5.2(b). They are numbered 1 to 4 for use in array INS2 (see Chapter 8 - 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 both sources of error mentioned earlier with the shell element, use of the 20-node solid element for arch dams is limited by two factors. First is the additional expense over the shell element because the interior nodal points in the through-thickness direction require more degrees of freedom resulting in a more expensive solution. Second, when the 20 node solid element is employed, ill-conditioning of the stiffness matrix will result at thin sections of the dam due to the close proximity of the three nodes along a through-thickness line.

6. 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.

6.1 Fourier Transform Parameters

The FFT algorithm employed by the program is fully described in Reference [15]; 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 6.1. 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.

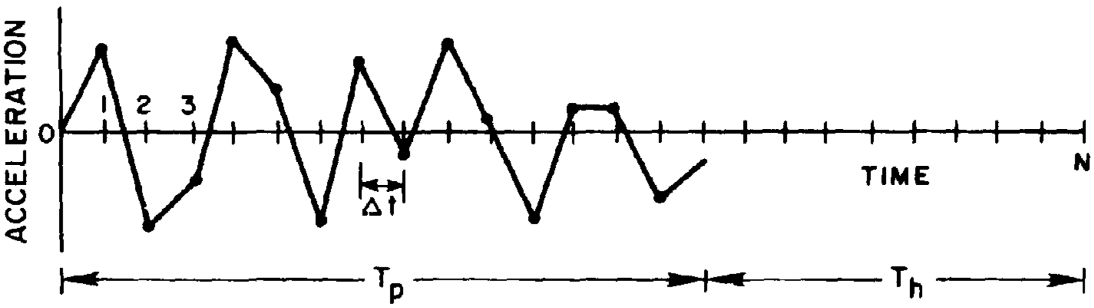
Δt = the time increment and is referred to in the program as TINC. The excitation and response are discrete functions defined at equal time increments Δt; i.e., at times $0, \Delta t, 2\Delta t, \cdots T-\Delta t$.

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

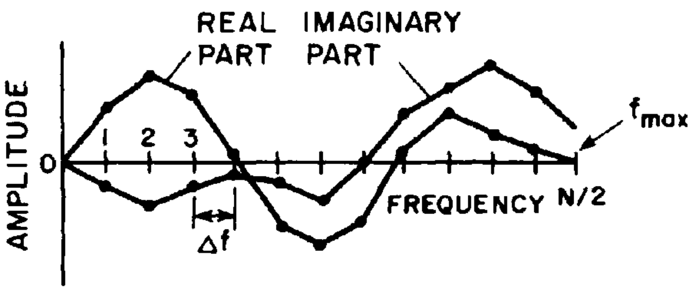
f_{max} = $N/2T$ = $1/2\Delta t$ = the maximum frequency in Hz that is included in the analysis and is referred to in the program as FMAX.

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

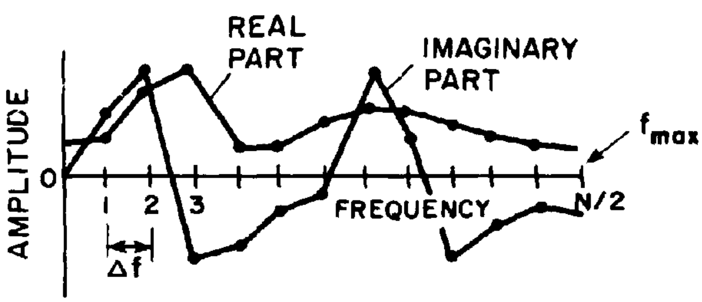
Note that selection of any two of the above five parameters determines the other three. The input section of the program (see Chapter 8 - Main Program and Subprogram 7) requires f_{max} and N. The selection of f_{max} is completely determined by the time interval Δt at which the given earthquake record 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}



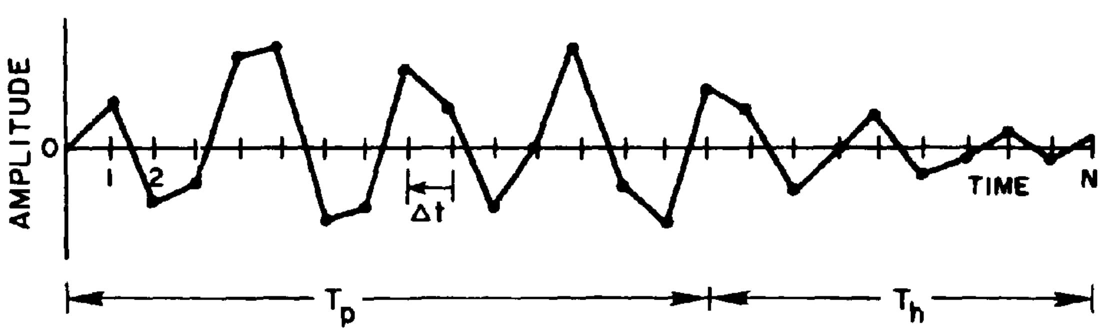
(a) Earthquake accelerogram



(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 6.1 Discrete Fourier transform procedure for response computation.

values of 25 Hz and 50 Hz, 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. Reinterpolation 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 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 [13] 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 system with no water.

The possible choices for N are $N = 2^{MM} * LL$ where MM is a positive integer and LL = 2 or 3 (see Chapter 8 - 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

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

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.

6.2 Number of Vibration Modes of the Dam-foundation System

The number NFD (see Chapter 8 - Main Program) of vibration modes required to represent the earthquake response of a dam is much less than the number of degrees-of-freedom 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 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-rock 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.

6.3 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) [2,4]. When water compressibility is considered in the analysis (NWAT = 3; see Chapter 8 - 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 [3,4].

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 [3]. 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.

6.4 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 is 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 [3] and has been incorporated into the computer program with more conservative values of the selection parameters.

7. 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 for dynamic analysis or for static analysis 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 7.1 is made, as it shows the disk file usage of the various subprograms.

7.1 Static Analysis

In static analysis of a dam-water-foundation 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 8 - Main Program). If the foundation rock is rigid, Subprogram 1 is skipped; if the reservoir is empty, Subprogram 4 is skipped (see Chapter 8 - Main Program). 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 7.1) should be saved after the execution of Subprogram 6 (see also Section 7.3).

If the foundation-rock flexibility is included in the static analysis, Subprogram 1 for the foundation can be run first separately, saving file 2 afterward (Table 7.1). Then, Subprograms 2, 3, 4 and 6 can be run, using the saved file 2 to compute the static dam response.

A note should be presented here concerning the efficient use of the file 2 after execution of Subprogram 1 for the foundation rock. For static analysis with empty reservoir, or for dynamic analysis (with empty or full reservoir), the only information needed from the foundation rock is the condensed stiffness matrix with reference to the degrees of freedom at the dam-foundation interface, and this

Table 7.1 -- 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
Subprogram 2	Input files from previous subprograms	-	-
	Output files needed by subsequent subprograms	file 99	file 99
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)
	Output files needed by subsequent subprograms	file 8	file 8
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 8 (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)
	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 motions are 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.
	Ouput files for post-processing	-	file 99

* 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.

information is stored in file 2. Therefore, the file 2, obtained after execution of Subprogram 1, is directly usable for dynamic analysis (with empty or full reservoir) and for static analysis with empty reservoir. Thus, the file 2 saved by Subprogram 1 for one of these three cases can also be used to run the subsequent subprograms under any of the other two cases.

However, execution of Subprogram 1 for static analysis with impounded water in the reservoir generates file 2 which contains, in addition to the condensed stiffness matrix, the condensed force vector (arising from hydrostatic forces on the water-foundation rock interface) with reference to the degrees of freedom at the dam-foundation interface. In this case, the force-vector portion of file 2 depends on the reservoir water level. Therefore it needs to be obtained from a separate run of Subprogram 1 with the appropriate water level, and cannot be substituted by the file 2 saved under one of the earlier three cases. In contrast, file 2 obtained from static analysis when the reservoir is not empty can also be used for running the subsequent subprograms under any of the earlier three cases, i.e. for dynamic analysis or for static analysis when the reservoir is empty.

7.2 Dynamic Analysis

In the earthquake analysis of a dam-water-foundation system non-symmetric about the x-y plane, the Main Program is executed with 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 8 - 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 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 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 antisymmeric -- 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 8 - Main Program), and saving file 8 and file 4 after the execution of Subprogram 6 in each of the separate runs (see Table 7.1). 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 7.1).

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 8 - Main Program), and file 8 and file 4 should be saved. Subsequently, Subprogram 7 is run (NSYM = 2; see Chapter 8 - 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 7.1).

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 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 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 file 2 as discussed earlier in Section 7.1. Running other subprograms in parts will also be computationally efficient if the earthquake responses of the same dam-foundation 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 6 and 7; and changing the maximum excitation frequency FMAX in the Fourier Transform requires running only Subprograms 5, 6 and 7.

Consider the following example to demonstrate the economy of running the program in parts. A nonsymmetric 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.

7.3 Combined Static and Dynamic Analysis

If static stresses are to be added to the dynamic stresses computed in Subprogram 7 (for the load cases when NCOMB(4) $\neq$ 0, see Chapter 8 - Subprogram 7), Subprogram 7 has to be executed separately from Subprograms 1 to 6 under all conditions. Static analysis of the dam-water-foundation rock system by executing Subprograms 1 to 6 is carried out first and file 7 containing the static stresses due to the dead weight of the dam and the hydrostatic pressure is saved for later use. Subsequently, the dynamic response of the system is analyzed by one execution of Subprograms 1 to 6 for a non-symmetric system (NSYM = 3), and by one or two (symmetric and/or antisymmetric) executions of Subprograms 1 to 6 for a symmetric system (see Section 7.2 above), with file(s) 8 and file(s) 4 saved in either case. 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 7.2 above) and file(s) 4 (referred to as file 4 and/or file 10 in Subprogram 7; see Section 7.2 above).

In addition to a separate execution of Subprogram 7 in which the static stresses are combined with the dynamic stresses 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 7.1 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 7.2 above.

8. INPUT DATA DESCRIPTION

The computer program can analyze 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-foundation-reservoir 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 stiffness matrix of the flexible foundation rock is computed and condensed to the degrees of freedom along the dam-foundation interface. In static analysis with a non-empty reservoir, the hydrostatic force vector on the surface of the foundation rock is computed and condensed to the degrees of freedom along the dam-foundation interface.

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 from Subprogram 1 included for a flexible foundation. In dynamic analysis, the natural frequencies and mode shapes of vibration of the dam-foundation 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 fluid 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 card in a card set. 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 card 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 CARDS

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

Card set 1. Control card for subprogram execution (7I4).

1 - 4	NOPT1	= 0, rigid foundation or if Subprogram 1 is skipped. ≠ 0, flexible foundation 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 or 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 7 is skipped. ≠ 0, earthquake responses are computed with execution of Subprogram 7.

Card set 2. General Control Data (I8, 4I4, E12).

1 - 8	MTOT	Maximum size of the blank common storage to be used (≤ current dimension of array A, which is set at 45,000 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 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 card set). = 3 for a non-symmetric system. When running Subprogram 7, NSYM also identifies the symmetry of the dam-water-foundation system. = 2 for a symmetric system. = 3 for a non-symmetric system.

13 - 16	IFRIG	= 0, for rigid foundation rock. ≠ 0 for flexible foundation rock.
17 - 20	NWAT	For dynamic analysis (NSD ≠ 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 is rigid (α = 1; α is the value REF input in Card set 1 of Subprogram 6). = 3, impounded water is compressible and some parts of the reservoir bottom-sides is absorptive ($\alpha < 1$). For static analysis (NSD = 0; see next entry), = 0, empty reservoir. ≠ 0, the solutions due to the dead weight of the dam alone, the water pressure alone, and both dead weight and water pressure are computed.
21 - 24	NSD	= 0, perform static analysis (final results appear in Subprogram 6). ≠ 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 6.1 for selection of FMAX); not needed in static analysis.

Card set 3. 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 system included in dynamic or earthquake analysis (2 x NFD and NFD + 8 must not exceed the total number of degrees of freedom in the dam mesh; refer to Section 6.2 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 Subprogram 2, Card set 1 in this chapter for numbering the nodal points for shell element).

Card set 4. Parameters for the finite element idealization of the foundation rock (3I4,E12).
Omit this card if the foundation rock is rigid (IFRIG = 0 in Card set 2 of this subprogram).

1 - 4	NNPRF	Number of nodal points in the foundation mesh.
5 - 8	NELRF	Number of finite elements in the foundation mesh.

† For incompressible water and infinite reservoir, the velocity of pressure waves in water 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).

9 - 12	NELW	Number of surface finite elements in the foundation mesh in contact with water on the upstream side; needed only if the reservoir is not empty (NWAT ≠ 0 in Card set 2 of this subprogram) and if static analysis is performed (NSD = 0 in Card set 2 of this subprogram).
13 - 24	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.

Card set 5. Parameters for the finite element idealization and the property of the impounded water (7I4, E12).
Omit this card if the reservoir is empty (NWAT = 0 in Card set 2 of this subprogram).

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 line 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 (NWAT ≥ 2 in Card set 2 of this subprogram).

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 (NSD = 0 in Card set 2 of this subprogram), a complete fluid mesh or only a mesh 3 at the dam face may be input. For the latter case, NEL1 = 0, NEL2 = 0, NEL3 > 0, NEL4 = 0, NEL5 = 0; and the mesh 3 nodal points can be classified as all Type 1 or Type 2.

SUBPROGRAM 1: FOUNDATION ROCK

No cards are required if the foundation rock is rigid, in which case NOPT1 = 0 (Card set 1, Main Program). If NOPT1 ≠ 0, the following cards should be supplied:

Card set 1. 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 8.1 shows the coordinate 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 card. 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 nodal points are numbered 1 to NNPRF (input in Card set 4 of Main Program) and can be input in any sequence. The above card needs to be repeated until all the NNPRF nodal point coordinates are defined. See Appendix A for using the available mesh generation program to prepare this card set.

Card set 2. Fixed nodal points (20I4).

1 - 80	JFIX(I)	Vector of nodal point numbers of foundation nodes on foundation rock base 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 cards should be supplied to read in all fixed nodal points.

Card set 3. Nodal points on plane of symmetry (20I4).

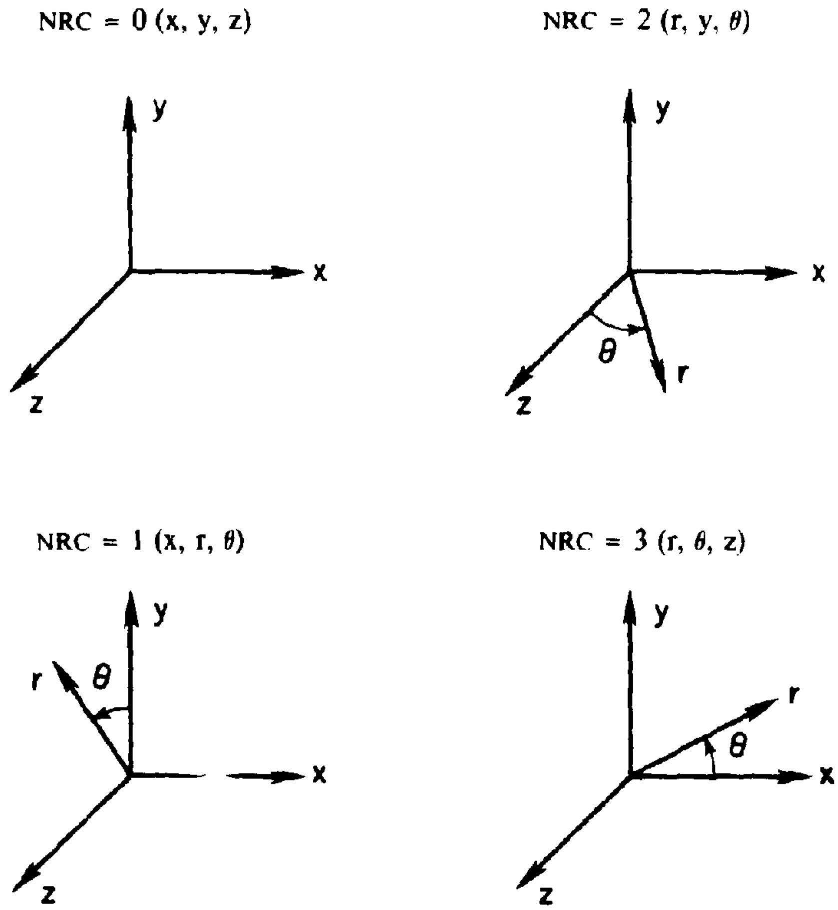


Figure 8.1 Coordinate axes for NRC = 0, 1, 2, 3 for defining the nodal point coordinates.

1 - 80	JSYM(I)	Vector of nodal point numbers of foundation nodes located on the plane of symmetry of the dam-water-foundation 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 cards should be supplied to read in all the nodal points located on the plane of symmetry. A blank card should be supplied even if there is no plane of symmetry in a nonsymmetric system.

Card set 4. Nodal points on dam-foundation interface (20I4).

1 - 80	JRCK(I), JDAM(I)	JRCK(I) is the Ith element of the vector of nodal point numbers of the foundation rock nodes on the dam-foundation interface. JDAM(I) is the Ith element of the vector of nodal point numbers of the dam nodes that correspond to the foundation nodes at the interface. Thus, JRCK(I) and JDAM(I) for any single I correspond to the same node on the interface. The nodal point numbers 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 Card set 3 of Main Program) to connect with 3-d solid elements in the foundation, each mid-surface node of the dam is associated with two nodes of the foundation, one on the upstream face and one 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 cards should be supplied to read in all the nodal points located on the dam-foundation interface.

Card set 5. Material properties sets of the foundation elements.

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 foundation.

2. Material properties sets cards (I4, 2E12).

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.

The material properties sets are numbered 1 to NUMMAT (input in the first card of this card set above) and can be input in any order. A total of NUMMAT cards should therefore be supplied here to specify all the material properties sets.

Card set 6. Element properties and definition cards.

Two cards are required for each of the NELRF (input in Card set 4 of Main Program) foundation elements. The elements are numbered 1 to NELRF and can be input in any sequence.

1. Element data and properties (4I4).

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.
9 - 12	NMAT	Material properties set number defining the properties of this element (a number between 1 and NUMMAT; see Card set 5 above).

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 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).

See Appendix A for using the available mesh generation program to prepare this card set.

Card set 7. Boundary condition modification cards.

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

1 - 4	ICH	Number of foundation nodal points whose fixity conditions are to be altered.

2. If ICH > 0, ICH cards should be supplied after card 1 with the format and input data for each card as follows:

Boundary condition cards (4I4).

1 - 4	N	Nodal point number (between 1 and NNPRF) of the foundation node whose fixity condition is to be altered.
5 - 16	(IDCH(I), I=1, 3)	Vector of the fixity conditions of the three degrees of freedom of the nodal point with number N. IDCH(I) = 0 if the Ith degree of freedom is fixed, ≠ 0 if the Ith degree of freedom is free. I = 1, 2, and 3 for the x, y, and z degrees of freedom, respectively.

Card set 8. Surface elements in contact with water.

Two cards are required for each of the NELW (input in Card set 4 of Main Program) surface foundation elements in contact with water; however, no cards should be input here if the reservoir is empty (NWAT = 0 in Card set 2 of Main Program) or if dynamic analysis is performed (NSD ≠ 0 in Card set 2 of Main Program). The elements are numbered 1 to NELW and can be input in any sequence.

1. Element data (3I4).

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.

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

SUBPROGRAM 2: DAM

If NOPT2 $\neq 0$ (Card set 1, Main Program), the following cards should be supplied:

Card set 1. 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 8.1 shows the coordinate 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 card. 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 Card set 3 of Main Program), the nodes are numbered 1 to NNPD (input in Card set 3 of Main Program) and can be input in any order. The above card is repeated until all the NNPD nodal point coordinates are defined.

For a 3-d shell element mesh (NDTP = 1 in Card set 3 of Main Program), it is the coordinates of the 2 × NNPD auxilliary 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 card is repeated until all the 2 × NNPD auxilliary nodal point coordinates are defined. Node numbers of the mid-surface nodes are those of the upstream auxilliary nodes, and coordinates of the mid-surface nodes are computed by the program as the averages of the coordinates of the upstream and downstream auxilliary nodes.

See Appendix A for using the available mesh generation program to prepare this card set.

Card set 2. 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 cards 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 Card set 3 of Main Program) corresponding to the upstream auxilliary nodes] should be used. A blank card should be supplied even if there are no fixed dam nodal points.

Card set 3. 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 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 cards 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 Card set 3 of Main Program) corresponding to the upstream auxilliary nodes] should be used. A blank card should be supplied even if there is no plane of symmetry in a nonsymmetric system.

Card set 4. Material properties sets of the dam elements.

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.

2. Material properties sets cards (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	Mass density in this material properties set.

The material properties sets are numbered 1 to NUMMAT (input in the first card of this card set above) and can be input in any order. A total of NUMMAT cards should therefore be supplied here to specify all the material properties sets.

Card set 5. Element properties and definition cards.

Two cards are required for each of the NELD (input in Card set 3 of Main Program) dam elements. The elements are numbered 1 to NELD and can be input in any sequence.

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 Card set 4 above).
13 - 16	NUPSM	Needed only for 3-d solid element (NDTP = 2 in Card set 3 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 5.7). = 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 Card set 3 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 5.7). = 0 if none of the faces of the element is on the downstream face of the dam.

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 5.6 and Table 5.1 for the proper ordering of nodes. NENI is the maximum number of nodal points per element. NENI = 20, 15, 8, 6 respectively for NELTY = 4, 5, 6, 7.

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).

See Appendix A for using the available mesh generation program to prepare most of the input data for this card set. The input data NUPSM and NDNSM cannot be generated by this mesh generation program and therefore have to be input manually.

SUBPROGRAM 3: DAM

If NOPT3 ≠ 0 (Card set 1, Main Program), the following cards should be supplied:

Card set 1. Boundary condition modification cards.

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

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

2. If ICH > 0, ICH cards should be supplied after card 1 with the format and input data for each card as follow:

Boundary condition cards (7I4).

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

SUBPROGRAM 4: WATER

No cards are required if the reservoir is empty, in which case NOPT4 = NOPT5 = 0 (Card set 1, Main Program). If NOPT4 ≠ 0, the following cards should be supplied:

Card set 1. 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 8.1 shows the coordinate 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 card. 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 Card set 5 of Main Program) and the Type 2 nodal points (if any) should be numbered from NNP1 + 1 to NNP1 + NNP2 (input in Card set 5 of Main Program). The nodal points can be input in any sequence. The above card needs to be repeated until all NNP1 + NNP2 nodal point coordinates are defined. See Appendix A for using the available mesh generation program to prepare this card set.

Card set 2. 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 cards should be supplied to read in all free surface nodal points.

Card set 3. 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 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 cards should be supplied to read in all nodal points located on the plane of symmetry. A blank card should be supplied even if there is no plane of symmetry in a nonsymmetric system.

Card set 4. Dam-water interface nodal points (20I4).

1 - 80	JF3(I), JDAM(I)	JF3(I) is the Ith element of the vector of nodal point numbers of the fluid mesh 3 nodes (Figure 5.2). JDAM(I) is the Ith 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 in any order, and the sequence must be terminated by a zero (or blank). Enough cards should be supplied to read in all dam-water interface nodal points.

Card set 5. 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 this sequence must be terminated by a zero (or blank). Enough cards should be supplied to read in all nodal points located on the reservoir bottom and sides.

Card set 6. 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 this sequence must be terminated by a zero (or blank). Enough cards should be supplied to read in all nodal points on the bottom and sides of the transmitting plane.

Card set 7. Mesh 1 element cards.

No cards are required if static analysis is performed (NSD = 0 in Card set 2 of Main Program). Otherwise, two cards for each of the NEL1 (input in Card set 5 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.

1. Element data (3I4).

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.

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 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 then repeat the corner node in the LM vector (see Section 5.1).

See Appendix A for using the available mesh generation program to prepare this card set.

Card set 8. Mesh 2 element cards.

No cards are required if there are no Mesh 2 elements (NEL2 = 0 in Card set 5 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 Card set 2 of Main Program). Otherwise, two cards 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.

1. Element data (3I4).

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.

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

Card set 9. Mesh 3 element cards.

Two cards are supplied for each of the NEL3 (input in Card set 5 of Main Program) Mesh 3 elements (Figure 5.2). The elements are numbered 1 to NEL3 and can be input in any sequence.

1. Element data (3I4).

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

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

Card set 10. Mesh 4 element cards.

No cards are required if static analysis is performed (NSD = 0 in Card set 2 of Main Program). Otherwise, the Mesh 4 elements (Figure 5.2) are numbered 1 to NEL4 (input in Card set 5 of Main Program) and the following cards should be supplied.

1. Rigid bottom and sides Mesh 4 elements (20I4).

1 - 80	JSIDE4(I)	Vector of element numbers of Mesh 4 elements at which no wave absorption takes place, that is, the wave reflection coefficient α equals to 1.0.

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 cards should be supplied to read in all Mesh 4 elements at which a rigid condition for wave reflection is assumed. A blank card should be supplied even if there are no rigid Mesh 4 elements. For an infinite reservoir, Mesh 4 intersects the transmitting plane at Mesh 5 (Figure 5.2); therefore the specification of rigid Mesh 4 elements here has to be consistent with the specification of rigid Mesh 5 elements (see first card in Card set 11 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 Card set 2 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 card is all that is needed here.

2. Element cards.

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

a. Element data (3I4).

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

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

Card set 11. Mesh 5 element cards.

No cards are required if there are no Mesh 5 elements (NEL5 = 0 in Card set 5 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 Card set 2 of Main Program). Otherwise, the Mesh 5 elements (Figure 5.2) are numbered 1 to NEL5 and the following cards should be supplied.

1. Rigid bottom and sides Mesh 5 elements (20I4).

1 - 80	JSIDE5(I)	Vector of element numbers of Mesh 5 elements at which no wave absorption takes place, that is, the wave reflection coefficient α equals to 1.0.

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 cards should be supplied to read in all Mesh 5 elements at which a rigid condition for wave reflection is assumed. A blank card should be supplied even if there are no rigid 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 rigid Mesh 4 elements (see first card in Card set 10 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 Card set 2 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 card is all that is needed here.

2. Element cards.

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

a. Element data (3I4).

1 - 4	N	Element number.
5 - 8	NELTY	Element type identifier. = 1 for line element.

b. 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 cards are required in this subprogram, whether NOPT5 = 0 or ≠ 0 (Card set 1, Main Program).

SUBPROGRAM 6: FREQUENCY RESPONSES OF DAM MODAL COORDINATES

If NOPT6 ≠ 0 (Card set 1, Main Program), the following cards should be supplied.

Card set 1. Some system parameters and properties.

1. If static analysis is performed (NSD = 0 in Card set 2 of Main Program), the following card is supplied:

System properties (2E12).

1 - 12	RHOF	Mass density of the impounded water; needed only if the reservoir is not empty (NWAT ≠ 0 in Card set 2 of Main Program).
13 - 24	AG	The acceleration due to gravity.

2. If dynamic analysis is performed (NSD ≠ 0 in Card set 2 of Main Program), the following card is supplied:

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

1 - 12	DR	Constant hysteretic damping factor for the dam.
13 - 24	RHOF	Mass density of the impounded water; needed only if the reservoir is not empty (NWAT ≠ 0 in Card set 2 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 Card set 2 of Main Program).
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 (Card set 1, Main Program), the following cards should be supplied.

Card set 1. Control parameters (7I4).

1 - 4	NCASE	Number of load cases (ground motion combinations and static contribution) to be included (see Card set 2 below).
5 - 8	NQD	Number of time histories of dam nodal dynamic relative displacement components (NDA = 0: see later part of this card set) or absolute acceleration components (NDA ≠ 0) for each load case; ≤ NNPD (input in Card set 3 of Main Program) x 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 Card set 3 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, computes and prints 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 file 99 only. otherwise, 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 Card set 3 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 file 99. This output occurs in this case regardless of the value of NOUT.

Card set 2. Ground motion combination and static contribution (4I4).

1 - 16	(NCOMB(I), I=1, 4)	NCOMB(1), NCOMB(2), NCOMB(3) correspond respectively 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; = 0, no static stress contribution; ≠ 0, add static stresses due to dead weight and hydrostatic pressure resulting from a previous separate static analysis (file 7; see Table 7.1) to the extreme values of stresses (NEXS ≠ 0 in Card set 1 above) and the stress results computed under the NTS < 0 or NTS > 0 option (see Card set 1 above).

A total of NCASE (input in Card set 1 above) cards should be supplied here to read in all NCASE load cases.

Card set 3. Time instants for principal stresses (10F8).

Required only if NTS > 0 (see Card set 1 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 TINCK = TINC x 2^{KK} and less than or equal to the ending time instant determined by TEND (see Card set 6 below), and the time instants should be input in the order such that they are monotonically increasing.

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

Card set 4. Dam displacement or acceleration responses (4(2I4, E12)).

Required only if NQD > 0 (see Card set 1 above).

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

IND1(I)	= nodal point number of the dam node at which the Ith 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 cards should be supplied to read in data for specification of all NQD responses.

Card set 5. Dam stress responses (20I4).

Required only if NQS > 0 (see Card set 1 above).

1 - 80	(INS1(I), INS2(I), ISTYPE(I), I=1, NQS)	INS1(I) = dam element number in which the Ith stress quantity time history is desired. INS2(I) = stress location number within the dam element at which the Ith stress quantity time history is desired. ISTYPE(I) = local stress component number of the Ith 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 cards should be supplied to read in data for specification of all NQS responses.

Card set 6. FFT and time histories output parameters (E12, 3I4).

Refer to Section 6.1 for criteria for selection of FFT parameters.

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 card set) which is ≥ TEND. TEND has to be ≤ N /(2×FMAX); N is related to MM and LL as described below in this card set while FMAX is input in Card set 2 of Main Program.
13 - 16	MM	Determines the number of discrete time instants in the FFT computation, N. N = 2^{MM} x LL.
17 - 20	LL	MM is a positive integer and LL = 2 or 3.
21 - 24	KK	Integer ≥ 0 such that all the responses are output at time increments of TINCK = TINC x 2^{KK}, where TINC = 1 /(2×FMAX).

Card set 7. Earthquake ground motion records.

For each of the three components of ground motion (x, y, and z), the following cards are supplied in the order upstream (x) component, vertical (y) component and cross-stream (z) component. The first card is supplied even though a certain component of ground motion does not contribute in any of the NCASE (input in Card set 1 above) load cases.

1. Control parameters (2I4).

1 - 4	NPTEQ	Number of points (time instants) to define the component of ground motion, ≤ N (see Card set 6 above). = 0 if the component is not included in any of the NCASE load cases according to NCOMB (input in Card set 2 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 file 99 only. otherwise, print and write the time function.

2. Earthquake acceleration record (10F8).

Required only if NPTEQ > 0 (see 1. 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 cards should be supplied so that all NPTEQ values are read in.

9. OUTPUT DESCRIPTION

Printed Output

All input data to the main program and subprograms described in Chapter 8 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 8, 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 degrees of freedom of each nodal point in the foundation rock.
3. Half-bandwidth of the foundation stiffness matrix, and blocking and number of equations information.
4. In static analysis with a non-empty reservoir, the hydrostatic pressure load vector with non-zero terms at the nodal points on the water-foundation rock interface is printed. The data is printed for water of unit weight.
5. Actual blank common storage used in Subprogram 1.
6. In static analysis with a non-empty reservoir, the hydrostatic pressure load vector condensed to the degrees of freedom along the dam-foundation interface is printed.

Subprogram 2

1. Actual blank common storage used in Subprogram 2.

2. Nodal point coordinates of the dam.

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.

Subprogram 3

1. Global equation numbers of the degrees of freedom of each nodal point in the dam.

2. Half-bandwidth of the dam stiffness and mass matrices, number of equations per block and the number of blocks.

3. Actual blank common storage used in Subprogram 3.

4. 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.

Subprogram 4

1. Nodal point coordinates of the impounded water.

2. Actual blank common storage used in Subprogram 4.

3. 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.

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.

Subprogram 6

1. Actual blank common storage used in Subprogram 6.
2. For static analysis, the static displacements of all nodal points are printed, followed by the static local stress components and principal stresses at each stress location in each element of the dam.
3. 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.

Subprogram 7

1. Blocking information, actual blank common storage used in Subprogram 7, and 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 value printed as 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 time instants when the maximum of the maximum principal stress and the minimum of the minimum principal stress occur.

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 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 8, others are defined here below:

1. RECORD 1: NNPRF, NELRF, NELW

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 from 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 element number between 1 and NELRF.

4. Connectivity records for surface elements in contact with water; exist only if NSD = 0 and NWAT $\neq$ 0.

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

Output on file 11, from Subprogram 2

File 11 after execution of Subprogram 2 contains the nodal point coordinates and 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 $\times$ 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 from 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 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 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 shapes.

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

3. y component of the mode shapes.

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

4. z component of the mode shapes.

Next record: ((AMODE(I, J), I = 1, NNPD), J = 1, NFD) where AMODE(I, J) is the z component of the Jth 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 interface in a transition element, the mode shape values written in the above records are for the upstream auxillary 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 one of Subprograms 1 to 3 is run together with Subprogram 4 in one continuous run, the following logical records are written immediately after the previously written 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 records.

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 from 1 to NNPF.

3. Mesh 1 element 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 element 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 element 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 element 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 element 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. 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 8 - 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. 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 ficticious 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 ficticious frequency marks the end record of file 4.

Output on file 99, from Subprogram 7.

File 99, as output from Subprogram 7, contains 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 file 99. These data may be used for plotting and other post-analysis processing if file 99 is saved after program execution. File 99 is an unformatted FORTRAN file with the following logical records; some variables in the records are part of the input data described in Chapter 8, 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, = 1 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) ≠ 0 for some I from 1 to NCASE, and if NOUTE for x component ≠ 0 and ≠ 1.

Next record: NOUTE for y component

Next record: vertical (y) component of earthquake acceleration if NCOMB(I, 2) ≠ 0 for some I from 1 to NCASE, and if NOUTE for y component ≠ 0 and ≠ 1.

Next record: NOUTE for z component

Next record: cross-stream (z) component of earthquake acceleration if NCOMB(I, 3) ≠ 0 for some I from 1 to NCASE, and if NOUTE for z component ≠ 0 and ≠ 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 records: 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 records: 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 NQS.

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 x NL records: NPTR records of local stress components and principal stresses at one 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 is given by: (element number - 1) $times$ 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 x 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, 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 is repeated NCASE times; each set corresponds to a combination of ground excitation and static contribution defined by (NCOMB(I, J), J=1, 4) and I increases from 1 to NCASE.

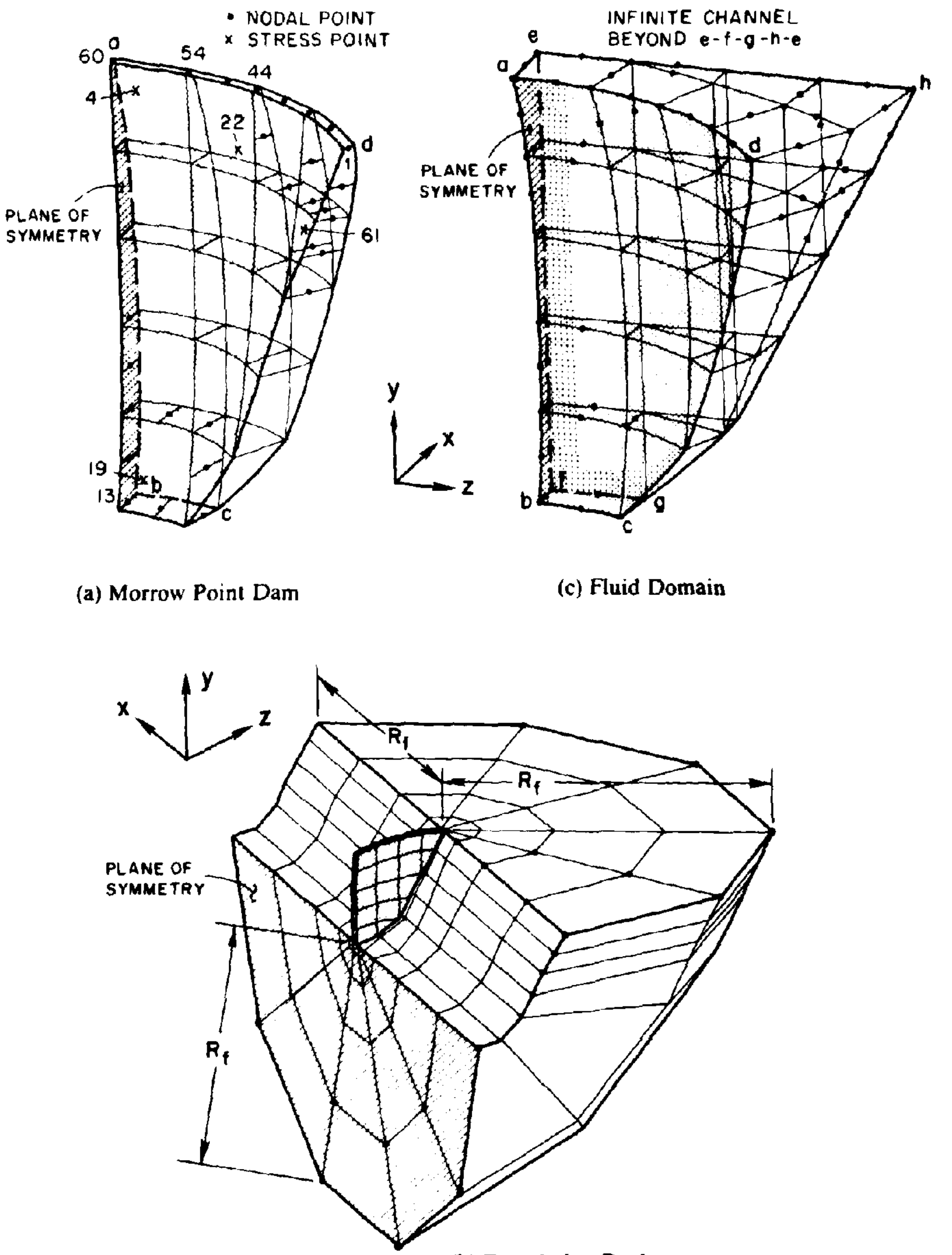
10. EXAMPLE EARTHQUAKE RESPONSE ANALYSIS OF MORROW POINT DAM

To demonstrate the use of the program EACD-3D, an earthquake response analysis of a 3-d arch dam, Morrow Point Dam, due to the Taft ground motion including static effects is presented here. The selection of the important response parameters, the input data card deck, and some of the output response results are described and presented in this chapter.

10.1 Morrow Point Dam and Ground Motion

Morrow Point Dam is a 465 ft high, approximately symmetric, single centered arch dam located on the Gunnison River in Colorado. A detailed description of the geometry of the dam is available in References [3] and [4]. For the purpose of dynamic analysis, the dam is assumed to be symmetric about the x-y plane with the dimensions averaged from the two halves. The foundation and fluid domains are also assumed symmetric about the x-y plane, with the fluid domain extending to infinity in the upstream direction.

Since the dam, fluid domain, and the foundation rock are assumed symmetric about the x-y plane, only one-half of the dam-fluid-foundation system needs be analyzed. The response to upstream (x) or vertical (y) components of ground motion, which is symmetric about the x-y plane, is determined by analyzing one-half the system with symmetric boundary conditions on the x-y plane. The response to cross-stream (z) ground motion, which is antisymmetric about the x-y plane, is determined by analyzing one-half the system with antisymmetric boundary conditions on the x-y plane. The finite element idealizations of one-half of the arch dam, foundation rock and the impounded water are shown in Figure 10.1. The finite element idealization of the dam, shown in Figure 10.1(a), consists of 8 thick shell finite elements in the major part of the dam and 8 transition elements in the part of the dam near its junction with foundation rock, with a total of 61 nodal points. When foundation-rock flexibility is considered, this idealization has 296 degrees of freedom for symmetric (x and y components) ground motion or static analysis and 284 degrees of freedom for antisymmetric (z component) ground motion. The mass concrete in the dam is assumed to be homogeneous, isotropic and linearly elastic with the following properties: Young's modulus = 4.0 million psi, unit weight



(a) Morrow Point Dam

(c) Fluid Domain

(b) Foundation Rock

Figure 10.1 Finite element meshes of one-half of the Morrow Point Dam-water-foundation rock system. (Parts (a) and (c) adapted from reference [1])

= 155 pcf and Poisson's ratio ν_s = 0.2. A constant hysteretic damping factor η_s = 0.10, which corresponds to five percent damping in all natural vibration modes of the dam, is selected.

The portion of the foundation rock included in the analysis to represent its static flexibility effects is shown in Figure 10.1(b) with its external boundaries assumed fixed. The shape of the foundation rock region is defined according to Reference [8], and its size is described by a radius parameter R_f, which is selected as 3 times the height H_s of the dam [3]. The three-dimensional finite element idealization consists of 138 solid finite elements with 236 nodal points; and has 556 degrees of freedom for symmetric (x and y components) ground motion or static analysis and 530 degrees of freedom for antisymmetric (z component) ground motion. The foundation rock is assumed to be homogeneous, isotropic, and linearly elastic with the following properties: Young's modulus = 4.0 million psi, and Poisson's ratio ν_f = 0.2.

For computational convenience, the water level is assumed to be at the crest level in this analysis. The finite element idealization of the fluid region [Figure 10.1(c)] consists of 27 three dimensional finite elements for the irregular fluid region with 189 nodal points; and has 157 pressure degrees of freedom for symmetric (x and y components) ground motion and 132 degrees of freedom for antisymmetric (z component) ground motion. Special equilibrium and compatibility conditions are imposed on the transmitting plane e-f-g-h-e [Figure 10.1(c)] connecting the irregular 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 = 62.4 pcf.

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

The ground motion recorded at the Taft Lincoln School Tunnel during the Kern County, California earthquake of 21 July 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 10.2).

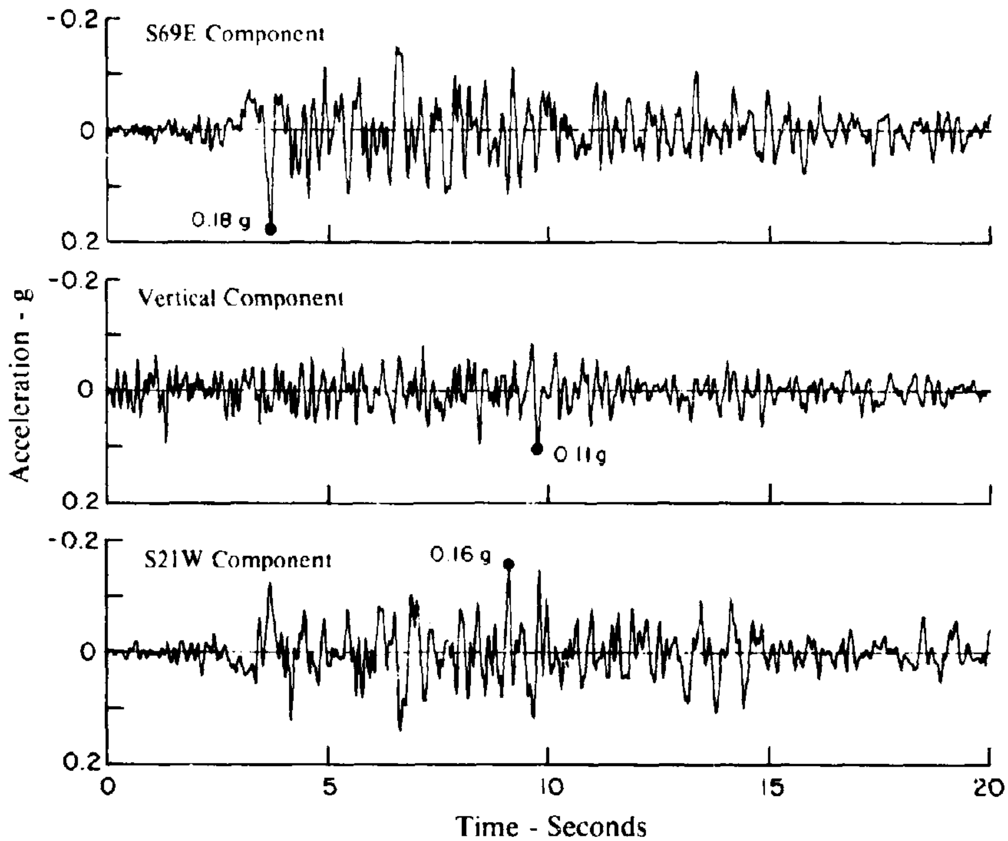


Figure 10.2 Ground motion at Taft Lincoln School Tunnel, Kern County, California, Earthquake, 21 July 1952.

10.2 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). In the input Taft ground motion, a duration of T_r = (NPTEQ - 1)*TINC = 20 sec. is employed for the earthquake record; therefore, approximately the last half-number of the 2048 time steps corresponding to a T_h = 20.96 sec. forms a grace band of zero excitation to reduce the aliasing error in the FFT calculations. For this dam-water-foundation system with the selected α value, $0.73\tilde{T}_1/\xi_1$ = 1.29, 1.27, and 5.45 sec. respectively for upstream, vertical, and cross-stream ground motions (Section 6.1). Therefore, this value of T_h 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 system (see Section 6.1). The maximum frequency at which the frequency responses are computed in Subprogram 6, FMAX, is 25 Hz in this analysis based on a Δt value of 0.02 sec. (see Section 6.1) For this example, 18 (the value of NFD) vibration modes of the dam-foundation system is found to be sufficient to obtain accurate responses (Section 6.2).

10.3 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. The hydrostatic pressure acting on the foundation rock at the water-foundation rock interface is included in the static analysis, unlike the results presented in References [3] and [4]. The procedure used in running the program to obtain the response results is summarized here below (see the corresponding input data card decks):

1. Subprogram 1 was run first, separately for symmetric static analysis and antisymmetric dynamic analysis, saving the results on file 2.

2. Using the stored file 2 from the symmetric static run of Subprogram 1, Subprograms 2 to 6 were run for static analysis (NSD = 0), saving the results on file 7.

3. Using the corresponding file 2 from the symmetric static and antisymmetric dynamic run of

Subprogram 1. Subprograms 2 to 6 were run, separately for symmetric and antisymmetric dynamic analysis, saving the results on file 8 and file 4.

4. Using the stored files 8 and files 4 from the symmetric and antisymmetric runs of Subprograms 2 to 6 and the stored file 7 from static analysis, Subprogram 7 was run, saving file 99 for plotting of the response results.

10.4 Response Results

Figure 10.3 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 10.1(a)]. Figure 10.4 shows the time history of arch and cantilever stresses on the upstream face at global stress locations 4 and 19 and on the downstream face at global stress locations 22 and 61 [Figure 10.1(a)]. Figure 10.5 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 computation time required for a complete earthquake analysis (excluding the time for static analysis) of this selected dam is shown as Case 6 in Table 10.1. Also included in Table 10.1 are the computation times required for response analyses of the dam under alternative assumptions for the effects of impounded water, foundation rock and the reservoir bottom-side materials. The computation times shown are for an earlier version of the program executed on the CDC 7600 computer. The additional computation time required to consider dam-water interaction is significant because of the complications associated with the evaluation of hydrodynamic terms for three-dimensional fluid domains. Also consideration of foundation rock flexibility in the analysis increases the computational time because of the additional effort required for computing the foundation-rock stiffness matrix, the additional degrees of freedom at the dam-foundation rock interface, and the larger number of generalized coordinates required. In earlier analyses [1], the computational effort increased by a factor of 7 to 8 to include wave absorption at reservoir bottom and sides. However, the efficient evaluation of

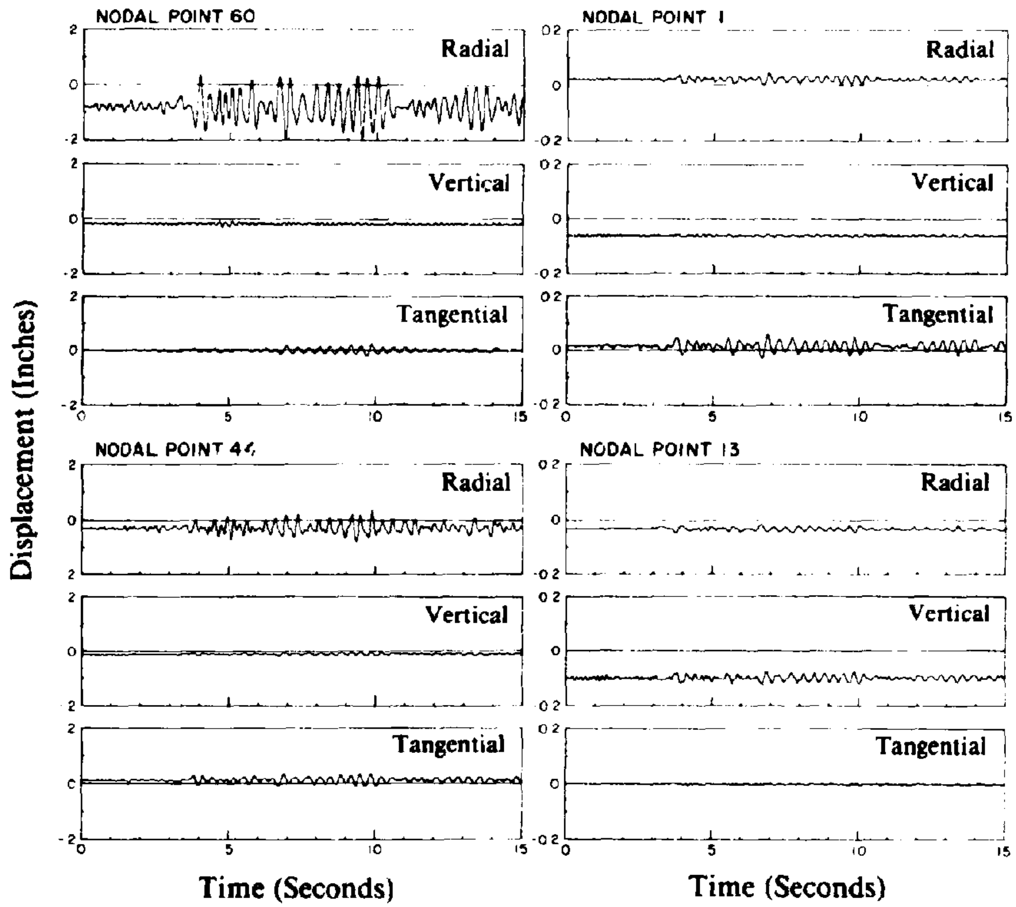


Figure 10.3 Displacement response of Morrow Point Dam on flexible foundation rock with full reservoir and absorptive reservoir boundary ($\alpha = 0.5$) due to upstream, vertical, and cross-stream components, simultaneously, of Taft ground motion.

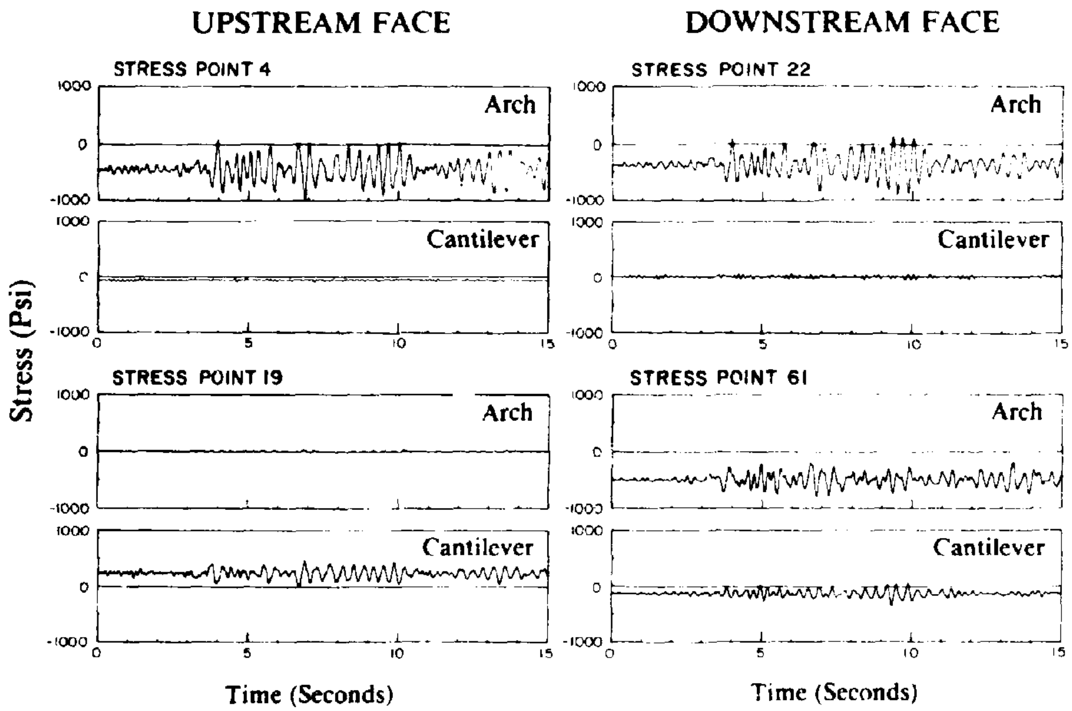


Figure 10.4 Stress response of Morrow Point Dam on flexible foundation rock with full reservoir and absorptive reservoir boundary (α = 0.5) due to upstream, vertical, and cross-stream components, simultaneously, of Taft ground motion.

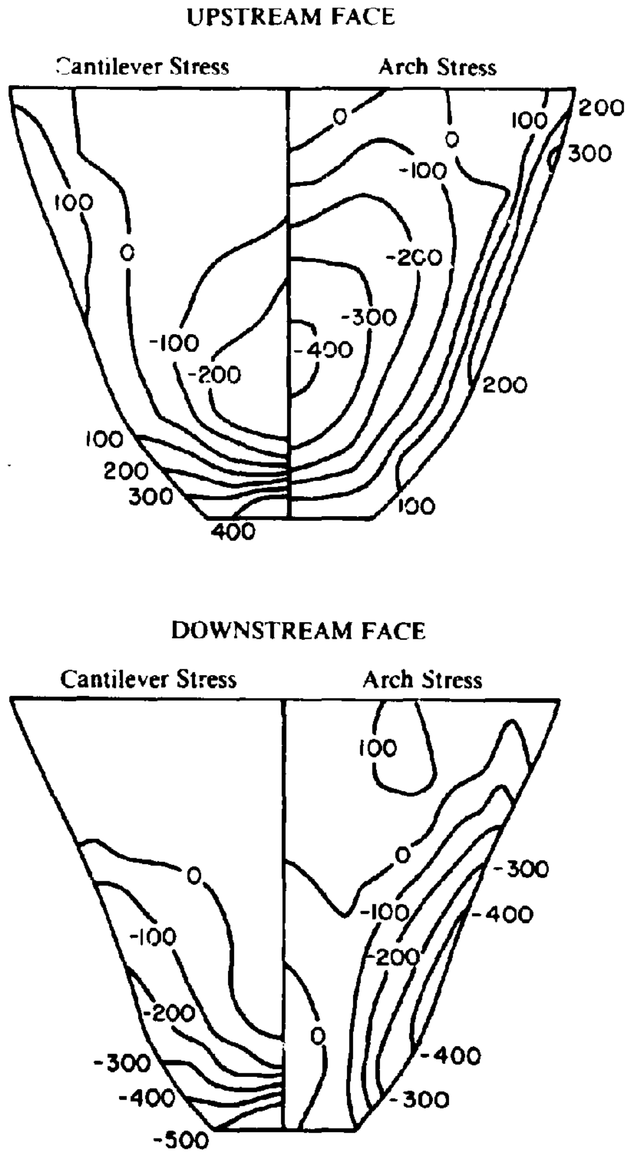


Figure 10.5 Envelope values of maximum arch and cantilever stresses (in psi) in Morrow Point Dam on flexible foundation rock with full reservoir and absorptive reservoir boundary (α = 0.5) due to upstream, vertical, and cross-stream components, simultaneously, of Taft ground motion. Initial static stresses are included.

Table 10.1 -- Computation Times for Complete Analysis of Morrow Point Dam to Upstream, Vertical and Cross-stream Components, Simultaneously, of Taft Ground Motion

Case	Foundation Rock	Water	Reservoir Boundary	No. of Generalized Coordinates	Central Processor Time* (sec)
1	rigid	empty	-	12	47
2	rigid	full	rigid	12	152
3	rigid	full	absorptive	12	113
4	flexible†	empty	-	18	113
5	flexible†	full	rigid	18	249
6	flexible†	full	absorptive	18	204

* CDC 7600 Computer

† Foundation rock region shown in Figure 10.1(b) with $R_f = H_s$

hydrodynamic terms developed in this work, the interpolation of the frequency response functions, and more efficient computer programming make it possible to include this effect without any increase in the computational effort, which actually decreases (Table 10.1; Section 3.5 in Reference [3]).

Input Data Card Decks for Example Analysis

1. Subprogram 1 run -- static analysis (symmetric)

```
  1     0     0     0     0     0     0
 45000     2     1     3     0
  1        61    16
236   138   30465.
128    61    27    16    16    11    6
```

← For antisymmetric dynamic analysis, the first 5 records should read:

```
  1     0     0     0     0     0     0
 45000     1     1     3     1
  1    18    61    16
236   138
128    61    27    16    16    11    64720.
```

```
  1   -173.06500 465.00000 301.64700
  2   -166.38900 465.00000 311.61900
  3   -179.74100 465.00000 306.63300
  4   -179.74100 462.67411 312.89073
  5   -173.06500 464.41113 308.21704
  6   -166.38900 460.93701 317.56435
  7   -159.71300 462.67411 312.89073
  8   -159.71300 465.00000 306.63300
  9   -231.40300 465.00000 306.63300
 10   -300.52563 431.89167 395.70985
 11   -219.58763 411.42959 450.76237
 12   -119.76637 411.42959 450.76237
 13    -38.92837 431.89167 395.70985
 14     -8.05100 465.00000 306.63300
 15   -634.72700 465.00000 306.63300
 16   -545.91990 369.77638 562.82894
 17   -213.41990 310.92494 721.16674
 18    -26.03410 310.92494 721.16674
 19    206.46590 369.77638 562.82894
 20    295.27300 465.00000 306.63300
  .
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  .
217    175.78660-121.46817     0.
218    215.25400    0.         0.
219   -456.40000    0.         0.
220   -367.59290-273.32014     0.
221   -135.09290-442.24128     0.
222    152.29290-442.24128     0.
223    384.79290-273.32014     0.
224    473.60000    0.         0.
225   -921.40000    0.         0.
226   -743.78580-546.64028     0.
227   -279.78580-884.48256     0.
228    295.98580-884.48256     0.
229    760.98580-546.64028     0.
230    938.60000    0.         0.
231   -1386.4000    0.         0.
232   -1119.9787-819.96043     0.
233   -422.47871-1326.7238     0.
234    439.67871-1326.7238     0.
235   1137.17871-819.96043     0.
236   1403.60000    0.         0.
```

```
 27  28  29  30  31  32  61  62  63  64  65  66  95  96  97  98  99 100 129 130
131 132 133 134 163 164 165 166 167 168 197 198 199 200 201 202 231 232 233 234
235 236
205 206 207 208 209 210 211 212 213 214 215 216 217 218 219 220 221 222 223 224
225 226 227 228 229 230
  2   1   1   1  34   2  33   2  36   3  35   3  68   4  67   4  70   5  69   5
102   6 101   6 104   7 103   7 136   8 135   8 138   9 137   9 170  10 169  10
172  11 171  11 204  12 203  12 206  13 205  13
  1
  157600000.   .2
  1   4   1
  1   3   4   5  35  37  38  39  33
  2   4   1
  2   1   5   6  36  35  39  40  34  33
  3   4   1
  8   2   6   7  42  36  40  41      34
  4   4   1
  3   9  10   4  37  43  44  38
  5   4   1
  4  10  11   5  38  44  45  39
  6   4   1
  5  11  12   6  39  45  46  40
  7   4   1
  6  12  13   7  40  46  47  41
  8   4   1
  7  13  14   8  41  47  48  42
  9   4   1
  9  15  16  10  43  49  50  44
 10   4   1
 10  16  17  11  44  50  51  45
  .
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  .
129   4   1
185 191 192 186 219 225 226 220
130   4   1
186 192 193 187 220 226 227 221
131   4   1
187 193 194 188 221 227 228 222
132   4   1
188 194 195 189 222 228 229 223
133   4   1
189 195 196 190 223 229 230 224
134   4   1
191 197 198 192 225 231 232 226
135   4   1
192 198 199 193 226 232 233 227
136   4   1
193 199 200 194 227 233 234 228
137   4   1
194 200 201 195 228 234 235 229
138   4   1
195 201 202 196 229 235 236 230
  0
```

1	2			
2	36	42	8	34
2	2			
8	42	48	14	
3	2			
14	48	54	20	
4	2			
20	54	60	26	
5	2			
26	60	66	32	
6	2			
36	70	76	42	68
7	2			
42	76	82	48	
8	2			
48	82	88	54	
9	2			
54	88	94	60	
10	2			
60	94	100	66	
11	2			
70	104	110	76	102
12	2			
76	110	116	82	
13	2			
82	116	122	88	
14	2			
88	122	128	94	
15	2			
94	128	134	100	
16	2			
104	138	144	110	136
17	2			
110	144	150	116	
18	2			
116	150	156	122	
19	2			
122	156	162	128	
20	2			
128	162	168	134	
21	2			
138	172	178	144	170
22	2			
144	178	184	150	
23	2			
150	184	190	156	
24	2			
156	190	196	162	
25	2			
162	196	202	168	
26	2			
172	206	212	178	204
27	2			
178	212	218	184	
28	2			
184	218	224	190	
29	2			
190	224	230	196	
30	2			
196	230	236	202	

For antisymmetric dynamic analysis, these records may be omitted.

2. Subprograms 2 to 6 run – static analysis

```
   0   1   1   1   0   1   0
  45000    2   1   3   0
  1       61  16
236 138   30465.
128  61   27  16   16  11    6
  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.          91.967
 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   -71.409   325.5       250.261
 17 0   -38.288   279.        218.663
 18 0   -24.832   186.        200.138
 19 0   -13.077   139.5       160.448
 20 0   9.845     93.         139.122
  .
  .
  .
  .
  .
  .
  .
  .
  .
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  .
  .
  .
  .
  .
  .
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.        63.2
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
  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    92.9750
 6     -22.3360      465.0000   127.4680
 7      55.0000      465.0000   150.0000
 8     -39.4000      465.0000   167.3240
 9      -2.2000      465.0000   183.6620
10      35.0000      465.0000   200.0000
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  .
180       75.0000    93.0000    50.0000
181       75.0000    93.0000   100.0000
182       75.0000    93.0000   150.0000
183       75.0000    93.0000   200.0000
184       75.0000    46.5000     0.
185       75.0000    46.5000   100.0000
186       75.0000    46.5000   150.0000
187       75.0000     0.         0.
186       75.0000     0.        50.0000
189       75.0000     0.       100.0000
  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
167 174 178 163 186 187 188 189
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  69  66  80  68  81  65
  4   2
 86 109 112  89 103 111 104  68
  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
```

3. Subprograms 2 to 6 run – symmetric dynamic analysis

```
  0    1    1    1    1    1    0
  45000    2    1    3    125.  <---
```

For antisymmetric dynamic analysis, this record should read:

```
45000    1    1    3    125.
```

```
  1   18   61   16
236  138
128   61   27   16   16   11    64720.
  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
  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
  .
  .
  .
  .
  .
  .
  .
  .
  .
  .
  .
  .
 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    92.9750
  6     -22.3360     465.0000   127.4880
  7      55.0000     465.0000   150.0000
  8     -39.4000     465.0000   167.3240
  9      -2.2000     465.0000   183.6620
 10      35.0000     465.0000   200.0000
  .
  .
  .
  .
  .
  .
  .
  .
  .
  .
  .
  .
180      75.0000      93.0000    50.0000
181      75.0000      93.0000   100.0000
182      75.0000      93.0000   150.0000
183      75.0000      93.0000   200.0000
184      75.0000      46.5000     0.
185      75.0000      46.5000   100.0000
186      75.0000      46.5000   150.0000
187      75.0000       0.          0.
188      75.0000       0.         50.0000
189      75.0000       0.        100.0000
  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   69   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
129    1    4  131  143   32   35  145  138   24   25  139    2    3    5  130   33   34   36  144
  2    4
143   32   35  145  157   63   66  159  152   55   56  153   33   34   36  144   64   65   67  158
  3    4
157   63   66  159  168   86   89  170  164   80   81  165   64   65   67  158   87   88   90  169
  4    4
168   86   89  170  179  109  112  181  175  103  104  176   87   88   90  169  110  111  113  180
  .
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  .
  .
  .
  .
  .
```

```
 .
 .
 .
 14   4
147  41  47 149 161  72  78 163 154  58  60 155  42  44  48 148  73  75  79 162
 15   4
161  72  78 163 172  95 101 174 166  83  85 167  73  75  79 162  96  98 102 173
 16   4
 16  14  20  22  47  45  51  53  29  28  30  31  15  18  21  19  46  49  52  50
 17   4
135  16  22 137 149  47  53 151 141  29  31 142  17  19  23 136  48  50  54 150
 18   5
131  10 133 145  41 147 139  27 140   7  11 132  38  42 146
 19   5
145  41 147 159  72 161 153  58 154  38  42 146  69  73 160
 20   5
159  72 161 170  95 172 165  83 166  69  73 160  92  96 171
 21   5
170  95 172 181 118 183 176 106 177  92  96 171 115 119 182
 22   5
 45  76  51  47  78  53  46  77  52  59  61  49  60  62  50
 23   5
 47  78  53 149 163 151  48  79  54  60  62  50 155 156 150
 24   5
 93 116  99  95 118 101  94 117 100 105 107  97 106 108  98
 25   5
 95 118 101 172 183 174  96 119 102 106 108  98 177 178 173
 26   5
112 127 116 181 189 118 113 128 117 121 122 114 185 123 115
 27   5
118 118 118 181 189 183 115 123 119   0   0   0 185 186 182
  1   2
129 143 145 131 138 144 139 130
  2   2
143 157 159 145 152 158 153 144
  3   2
157 168 170 159 164 169 165 158
  4   2
168 179 181 170 175 180 176 169
  5   2
179 187 189 181 184 188 185 180
  6   2
131 145 147 133 139 146 140 132
  7   2
145 159 161 147 153 160 154 146
  8   2
159 170 172 161 165 171 166 160
  9   2
170 181 183 172 176 182 177 171
 10   2
133 147 149 135 140 148 141 134
 11   2
147 161 163 149 154 162 155 148
 12   2
135 149 151 137 141 150 142 136
 13   2
161 172 174 163 166 173 167 162
 14   3
149 163 151 155 156 150
 15   3
172 183 174 177 178 173
 16   3
181 189 183 185 186 182
  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  58  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   2
 20  51  53  22  30  52  31  21
  2   2
 51  76  78  53  61  77  62  52
  3   2
 76  99 101  78  84 100  85  77
  4   2
 99 116 118 101 107 117 108 100
  5   2
116 127 189 118 122 128 123 117
  6   2
 22  53 151 137  31  54 142  23
  7   2
 53  78 163 151  62  79 156  54
  8   2
 78 101 174 163  85 102 167  79
  9   2
101 118 183 174 108 119 178 102
 10   3
118 189 183 123 186 119
 11   2
127 124 187 189 126 125 188 128

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

4. Subprogram 7 run -- earthquake analysis

```
   0    0    0    0    0    0    1
   45000    2    1    3    125.
   1   18   61   16
 236  138
 128   61   27   16   16   11    64720.
   1   12    8    1    3    0    0
   1    1    1    1
  60    1                  60    2                  60    490.              13    1
  13    2                  13    490.               44    426.5             44    2
  44    4116.5              1    456.2               1    2                  1    4146.2
   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    .5318    .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
   .
   .
   .
   .
   .
   .
 -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
```

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APPENDIX A: MESH GENERATION PROGRAM TO PREPARE INPUT DATA TO EACD-3D

A.1 Introduction

The mesh generation program to prepare input data to EACD-3D is an adaptation of one of the four program modules of the Practical Mesh Generator (PMG), which is a general purpose mesh generation program for both two- and three-dimensional problems. PMG is designed for practical applications including those in which frequent modifications of the finite element mesh are made to refine the mesh or to meet new design modification.

The PMG computer program is written in Fortran 77 and has been originally developed on virtual memory VAX computers operating in the UNIX system. It features special algorithms to optimize the storage (by avoiding generation of already existing data like boundaries common to adjacent substructures) and selection of algebraical procedures rather than iterative methods to increase the speed of computations. The program consists of the following four modules:

1. pmg (batch mode and interactive)
2. assemble
3. duplicate
4. propagate

Mesh generation is basically centered around the pmg module. A large choice of grid generation and a general element library are available to help the user to construct a solution strategy which best meets his specific need. The three other modules together form a global mesh editor which makes mesh generation for many complex problems feasible and effective.

The PMG program has been developed by Charbel Farhat, Department of Civil Engineering, University of California, Berkeley. It has been specialized to generate finite element meshes for analysis of three-dimensional dam-water-foundation systems by the EACD-3D program. This specialized program, which is implemented on VAX computers operating in the UNIX system, is included with the EACD-3D program for convenience of the user.

A.2 General Concepts

The purpose of a mesh generator is to generate the large amount of finite element data needed in analysis of three-dimensional dam-water-foundation rock systems with a minimal amount of input. The nodal point coordinates and element connectivity are the usual data required in finite element analysis. Using PMG, these required data can be generated with a relatively small amount of input. As mentioned in Section A.1, the mesh generation program is an adaptation of one of the four modules of PMG. Since the rest of this presentation is concerned with the mesh generation program, for convenience, it is hereafter also referred to as PMG.

The basic idea behind PMG is to divide the three-dimensional system to be modelled into a few relatively larger blocks and then subdivide each block into a number of finite elements that are used in the analysis (Figure A.1). The input data to PMG basically consists of the coordinates of the "points" (see Section A.3.1) and connectivity of these "points" defining the blocks. Since the number of blocks is much smaller than the number of finite elements in the final idealization of the system, the amount of input data required to define the blocks is much less than that necessary to define the finite elements.

In addition to the block concept as mentioned above, PMG has several features that facilitate the generation of the block information and provide different ways of subdividing the blocks into finite elements. Different geometrical curves like circle, ellipse, parabola and cubic spline are available to represent the boundaries of a system so that the coordinates of the "points" defining the blocks of the system can be generated easily. In certain cases, the connectivity information for several blocks can be automatically generated with one command, further reducing the amount of input data. The desired grading and mesh refinement can be achieved with the several features available in PMG. Blocks of different sizes can be achieved by appropriately selecting the locations of the "points" defining the blocks; these locations may be automatically generated using certain commands with weighting parameters. The number of subdivisions (or finite elements) within each block can be with the EACD-3D program for convenience of the user.

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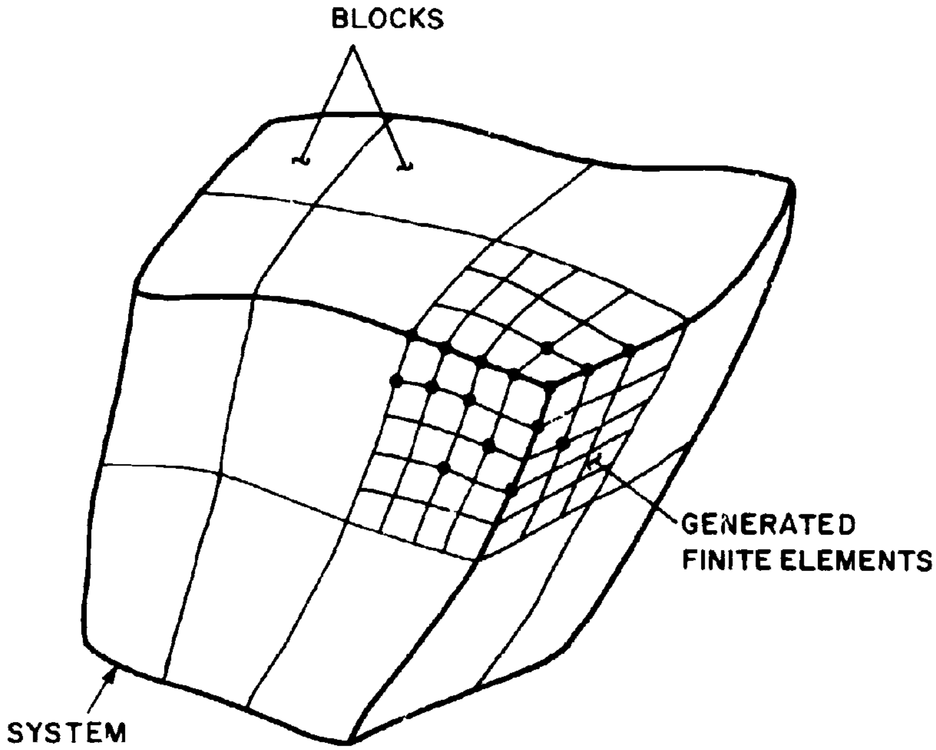


Figure A.1 Basic idea of Practical Mesh Generator.

freely selected in each of the three parametric directions of the block, and weighting parameters can also be specified to achieve a weighted subdivision in any parametric direction. Furthermore, element of different orders (number of nodes per finite element), e.g. 8-node, 16-node, 20-node element, are available in the element library to specify the type of element generated in each block (all elements generated in one block must be of the same order). Some special types of elements are available to ensure compatibility of elements at the interfaces of blocks of different element orders. All of the aforementioned features of PMG are described next.

A.3 Features of PMG

A.3.1 Essential Terminology

The basic terminology essential for the user is listed below:

POINT

A "point", which is identified by a positive integer number, is a point located on a "line" (see below) or at the boundary of a block; it is used in defining the geometry of the "line" or block. The "points" are not directly related to the generated finite element mesh nodes (though a "point" may coincide with a generated mesh node), and the numbering of the "points" is totally unrelated to the numbering of the mesh nodes.

LINE

A "line" is any straight line or curve in the three-dimensional space, defined by its end "points" and perhaps also by some "points" on the "line" in between its two ends. It is identified by a set of three integer numbers. These numbers are respectively: number of the first "point" on the "line", number of the last "point" on the "line", and increment of the numbers of the "points" on the "line". "Lines" are used to model or define the boundary of a block.

BLOCK

A block is a three-dimensional solid component of the system that is modelled with finite elements. The three-dimensional system is comprised of several blocks with no overlapping or gaps between them. It is from a block that subdivisions are made to generate finite elements (Sections A.2, A.3.3).

A.3.2 Generation Capabilities

PMG has different commands available to the user for efficiently constructing the blocks of a system. These commands specify or generate the "points" and "lines" for constructing the blocks, and define or generate the connectivity of the blocks. These features are described below:

POINTS

A "point" can be defined by explicitly specifying its three cartesian coordinates using the 'poin' command (see Section A.4) or generated by a "line" command (see the paragraph on LINES below). Any number can be used to identify a particular "point" provided different "points" are numbered differently (the numbering system for all the "points" does not need to be in sequence starting from 1).

LINES

A "line" can simply be defined by a sequence of specified "points" or it can be generated by certain commands which generate the "points" defining the "line". These commands are generally named after the types of line they generate. The current available library of line type includes: straight line (using the 'line' command; see Section A.4), circle (and circular arcs) (using the 'circ' command), ellipse (and elliptical arcs) (using the 'elli' command), parabola (using the 'para' command), spline (modified piecewise cubic Hermite) (using the 'spli' command). The cubic spline is especially recommended for modelling the boundary of a system that does not have a particular form, whereas other types of line can be used to model boundaries that are of one of those forms.

Two operations on the "lines" are available: arbitrary translation of a "line" (using the 'tran' command), and arbitrary rotation of a "line" (using the 'rota' command). Any block boundary can be efficiently modelled by the "lines" with the commands that operate on it.

BLOCKS

A block is developed from an isoparametric curvilinear mapping of a cube; it is defined by the specified or generated "points" that are located, before mapping, on the edges of the cube, using the 'isop' command (see Section A.4). The proper order of numbering these "points" (connectivity) on the cube as used in the 'isop' command is shown in Figure A.2. The eight corner "points" must be specified (some may be identical for degeneration into a triangular prism block), whereas the mid-side "points" are optional. The orientation of the block is defined by the I, J, K parametric directions of the cube (Figure A.2), which may not be straight after mapping from the cube to the block.

More than one block may be defined with one single 'isop' command by specifying a flag, provided that the numbers of the "points" of one block differ from the corresponding numbers of the corresponding "points" of the next block all by a single constant increment (see Section A.4). It is the connectivity information of the "points" defining the blocks that is generated with the 'isop' command; these "points" defining the blocks have to be specified or generated prior to calling the command.

A.3.3 Semi- and Fully-Automatic Options

Two options are available in PMG to construct the blocks of a system and to subdivide the blocks into finite elements. These are the semi-automatic and fully-automatic options. With the semi-automatic option, the system can be divided into blocks in any pattern as long as all the blocks, without overlapping, together fill up the entire system [Figure A.3(a)]. Each block can be constructed in any orientation (characterized by the I, J, K parametric directions) and the connectivity of the blocks can be specified or generated in any sequence of the blocks. Each block is subdivided into finite elements by specifying the number of subdivisions in each of the I, J, and K parametric directions in the 'isop' command input record that defines or generates the connectivity of that block (Section A.4). Any number of subdivisions in each of the three parametric directions can be selected for a block as long as the resulting finite element mesh within that block is compatible with the meshes of adjacent blocks. In addition to the element orders that are available in both the semi- and fully-automatic options (8-node, 16-node, and 20-node elements), there are two element orders (10-node and 12-node elements; see the 'isop' command in Section A.4) that are available only in the semi-

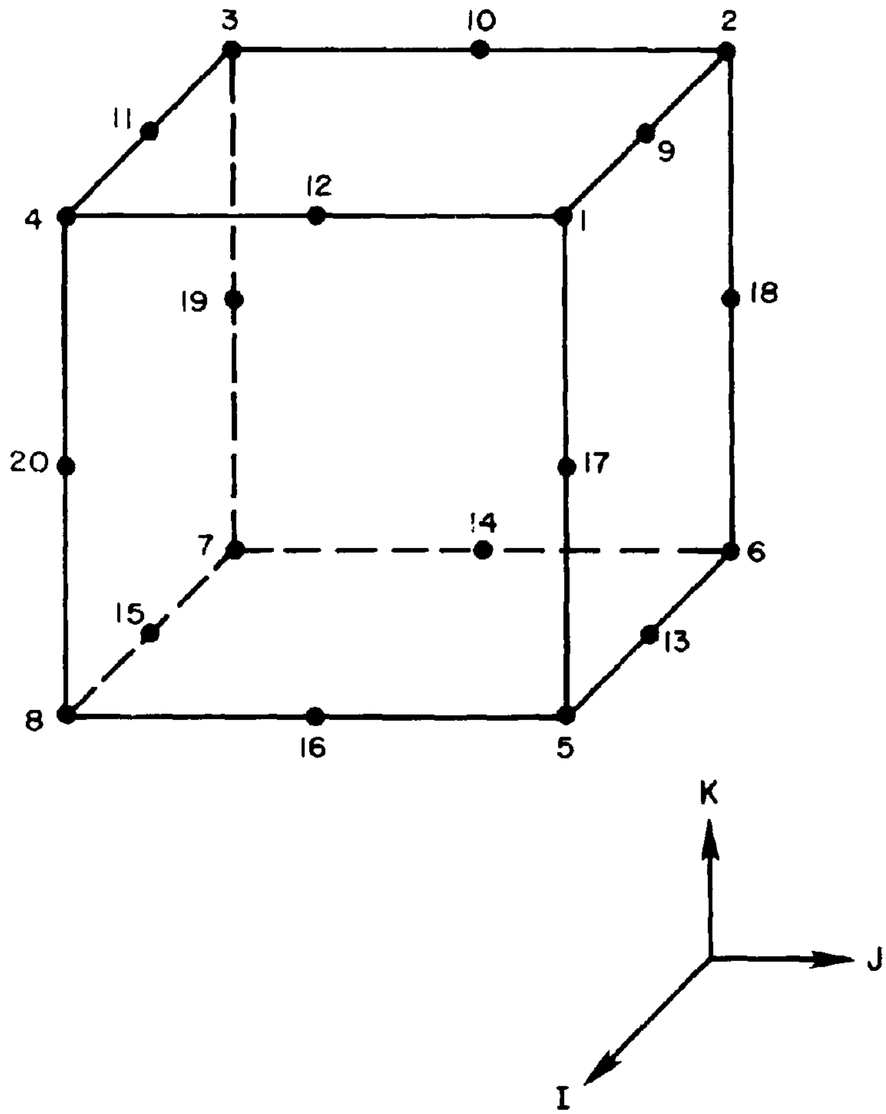
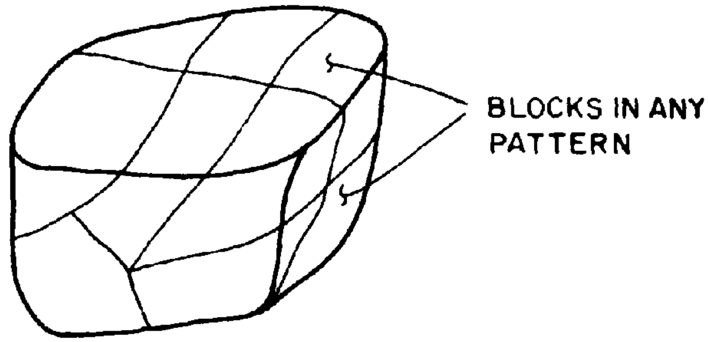
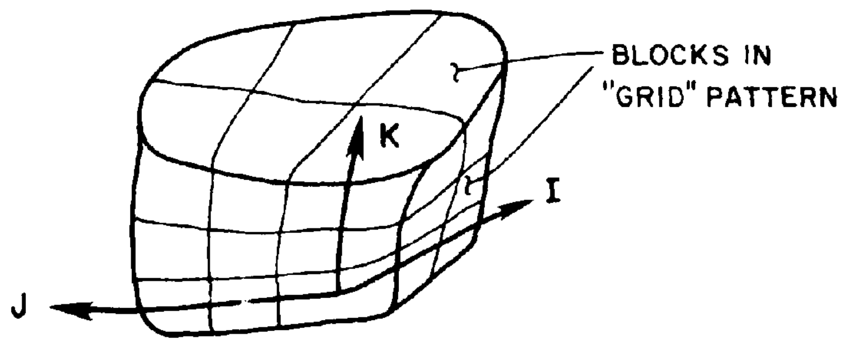


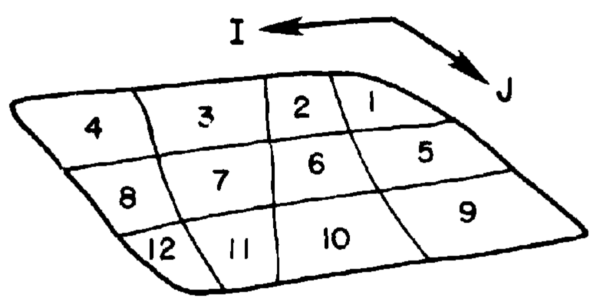
Figure A.2 Proper numbering of nodes of a block which is shown as a cube before mapping.



(a) Semi-automatic option



(b) Fully-automatic option



(c) Input sequence of blocks at a K level for fully-automatic option

Figure A.3 Blocks in semi- and fully-automatic options of PMG.

automatic option and not in the fully-automatic option. In the semi-automatic option, the generated mesh nodes and elements are numbered starting with the block whose connectivity is first specified with the 'isop' command, then following the same sequence of the blocks in which the connectivity information is specified or generated. Within each block, the numbering follows first the I direction, then the J direction, and then the K direction of the block. In this way, for the nodes on the interface of any two blocks, more than one node number will be assigned to any one of these nodes. Therefore, the 'tie' command has to be included in the input data for semi-automatic option to eliminate this situation (Section A.4).

With the fully-automatic option, the system has to be divided into blocks in a "three-dimensional grid-like" manner [Figure A.3(b)]. The orientation of all the blocks must be the same or similar in the sense that each of the I, J, and K parametric directions of any one block points in the same general direction as the corresponding direction of the adjacent blocks. Thus, three global parametric directions I, J, K (not necessarily straight) can be constructed for the entire system by "connecting" respectively the I, J and K directions of the blocks [Figure A.3(b)]. The connectivity information of the blocks has to be specified or generated with the 'isop' command following the sequence of the blocks: first in the global I direction, then in the global J direction, and then in the global K direction [Figure A.3(c)]. The blocks are subdivided into finite elements in a way such that a three-dimensional grid results for the generated mesh. Thus, the number of subdivisions in a parametric direction (I or J or K) is the same in all the blocks that are at the same position along that global parametric direction (or that form a layer transverse to that global parametric direction). These numbers of subdivisions in each of the three parametric directions in different layers of blocks of the system are specified in the 'cont' command (Section A.4). The generated mesh nodes and elements are not numbered sequentially in each block but sequentially in each global mesh layer (K-plane), first following the global I direction then the global J direction, going from one mesh layer to the next mesh layer following the global K direction. This numbering scheme of the finite element nodes results in a favorable bandwidth for the system and also makes it easy for the user to identify any particular node and element.

A.3.4 Grading and Refinement

The finite element mesh grading and refinement can be achieved in several ways in PMG. Firstly, division of the system into blocks of different sizes can be used by appropriately selecting the locations of the "points" defining the blocks. Weighting parameters are available in the "lines" command to generate unequally spaced "points" on the "lines". Secondly, subdivision of a block into finite elements of different sizes can be used. The latter can be achieved in two ways. The first way of achieving weighted subdivisions is to locate the mid-side "points" of a block away from their neutral position (at mid-side for the isoparametric mapping; see Figure A.2). The second way is the use of weighting parameters in subdividing the block.

Generating unequally spaced "points" on a "line" and unequally subdividing a block into finite elements are both achieved with the same weighting parameters family. The weighting in one direction is controlled by a parameter W whose value lies within the closed interval [-1., 1.]. The analytical procedure behind this is to re-evaluate the natural coordinate in a given direction (which also lies within the closed interval [-1., 1.]) according to the following equation:

$$\xi' = \xi + W(\xi^2 - 1)/2$$

where ξ is the natural coordinate in a given direction and ξ' the re-evaluated natural coordinate in the same direction.

Figure A.4 indicates the trend of the discretization with different values of W: the discretization concentrates around the initial "point" if W is positive, and around the final "point" if W is negative. If W = 0, the weighting has no effect.

A.3.5 Errors

PMG first reads all the input data and checks both the syntax and the compatibility of each data. If no error has been encountered, mesh generation is activated. Otherwise execution is stopped at the reading input level and a message is sent to the echo file (Section A.3.6) showing where an error has been found and what is its type.

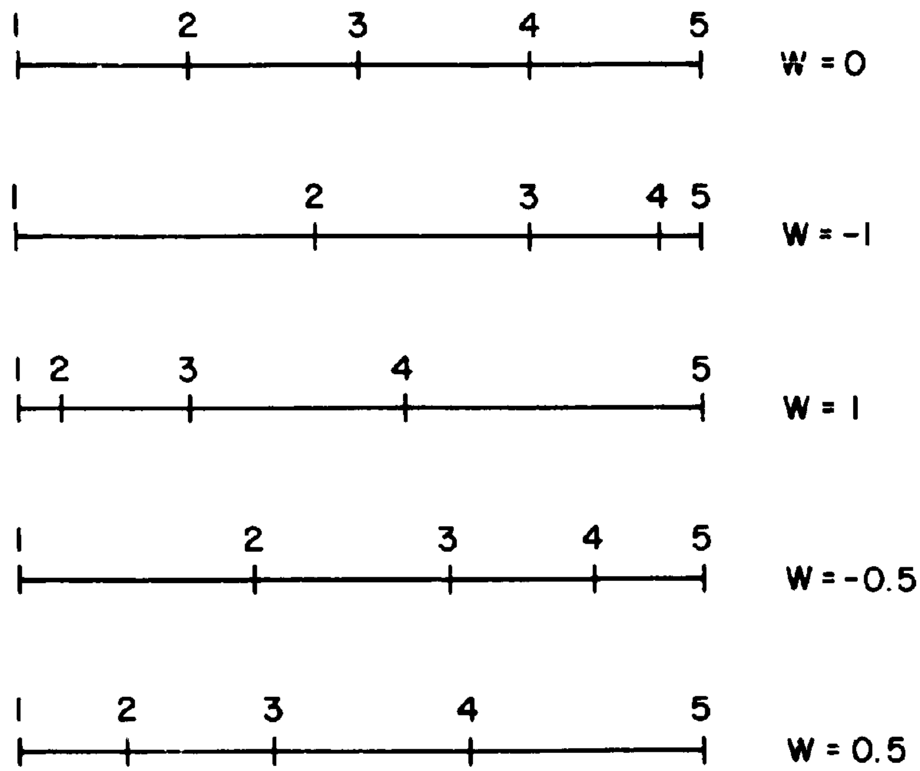


Figure A.4 Examples of weighted subdivision with different values of weighting parameter W.

A list of error messages and their explanation is presented in Section A.4.

A.3.6 Output

PMG outputs two files in addition to the usual output file 6: file 11 which is called the echo file and file 13 which is called the fem (finite element) file; these names are used to refer these files because of the nature of the contents of these files. The echo file basically consists of the following information: (1) echo of all activated commands with their input; (2) error messages if error encountered; and (3) echo of defined "points" and blocks. The output of the echo file can be suppressed using the 'nopr' command (Section A.4) if it is not needed (except for error messages).

The fem file consists of the nodal point coordinates and element connectivity of the finite element mesh generated. It is in the same format as the input data to the computer program EACD-3D. It is this file that the user should retain and use as part of the input data to EACD-3D (see Section A.5.4).

A.4 Input Data Description

This section is intended to provide a brief users guide to the PMG program. The following pages describe the specific function and the input data required for each of the available commands in the program. The input data is in free format; F stands for floating point number and I stands for integer. Adjacent numbers on a record of input are separated by one comma. Some commands require a set of input records that terminate with a blank record (see example in Section A.6). The error messages are listed at the end of this section.

PMG is run in batch mode with file 5 as the input file. The "command cards" (command and its required data) can be placed anywhere and any number of times in the input file with the following exceptions: (1) the first command in the input file must be either 'auto' or 'semi' (except for comment cards); (2) the 'cont' command must be the second in the input file (except for comment cards); and (3) the 'end' command must be at the end of the input file. The first four characters are sufficient to identify each of the commands which listed in alphabetical order are:

aspe. auto, circ. cont. elli. end. isop. line. nopr. para, poin, rota, semi, spli, tie, tran

Comment cards are identified by a '#' (without the ' ') in column 1. They are used in the input file to provide reference and comments to the user.

The function and use of each of the commands is described next:

aspe
lolim

The command 'aspe' (without the ' ') will write automatically in the echo file all the generated elements with an aspect ratio less than the specified lower limit (lolim) (1).

Value name	Type	Note	Description
lolim	F		lower limit of aspect ratio for generated elements

Notes
(1) PMG displays the identity of the element and its aspect ratio.

auto

If the fully-automatic option of PMG is desired, this command must be input as the first command in the input file (except for comment cards).

circ
nstart, narc, ninc, xbeg, ybeg, zbeg, xcen, ycen, zcen, unor, vnor, wnor, angle, weight
<repeat ...., terminate with a blank record>

Value name	Type	Note	Description
nstart	I		number of the first "point" on the circle or circular arc generated with this record
narc	I		number of arcs to be generated on the circle or circular arc (the portion of of line between two adjacent "points" defines an arc)
ninc	I	(1)	number increment for generated "points" on the circle or circular arc
xbeg	F		
ybeg	F		coordinates of the first "point"
zbeg	F		defining the circle or circular arc
xcen	F		
ycen	F		coordinates of the center of the
zcen	F		circle or circular arc
unor	F		components of the normal to the plane
vnor	F	(2)	containing the circle or circular
wnor	F		arc (not necessarily normalized)
angle	F	(3)	total angle between the first "point" and the last "point" generated on the circle or circular arc (> 0)
weight	F		weight for repartition of the generated "points"

Notes
(1) ninc can be a negative integer.
(2) Direction of the normal is determined from the direction of the circle or circular arc using the right-hand rule.

(3) angle is specified in degrees.

cont

nsp, nblock, nesno, nesel (1)
or
nsp, nbli, nblj, nblk (2)
isub(n), n = 1, nbli
jsub(n), n = 1, nblj
ksub(n), n = 1, nblk
wi(n), n = 1, nbli
wj(n), n = 1, nblj
wk(n), n = 1, nblk

This command has to be in the second position after either the command 'auto' or 'semi' (except for comment cards), since it governs the dynamic storage allocation. Note that two options are available.

Value name	Type	Note	Description
nsp	I	(3)	total number of specified "points" in the system
nblock	I	(1)&(4)	total number of defined blocks in the system
nesno	I	(1)&(5)	an estimated total number of mesh nodes generated in this run
nesel	I	(1)&(5)	an estimated total number of mesh elements generated in this run
nbli	I	(2)	total number of layers of blocks in the global I direction
nblj	I	(2)	total number of layers of blocks in the global J direction
nblk	I	(2)	total number of layers of blocks in the global K direction
isub(n), n = 1, nbli	I	(2)	number of subdivision in the I direction for the nth layer of blocks in the global I direction
jsub(n), n = 1, nblj	I	(2)	number of subdivision in the J direction for the nth layer of blocks in the global J direction
ksub(n), n = 1, nblk	I	(2)	number of subdivision in the K direction for the nth layer of blocks in the global K direction
wi(n), n = 1, nbli	I	(2)	weight for subdivision in the I direction for the nth layer of blocks in the global I direction
wj(n), n = 1, nblj	I	(2)	weight for subdivision in the J direction for the nth layer of blocks in the global J direction

wk(n), n = 1, nblk	I	(2)	weight for subdivision in the K direction for the nth layer of blocks in the global K direction

Notes
(1) For semi-automatic option.
(2) For fully-automatic option.
(3) Not to be confused with number of finite element nodes; may be an upper bound.
(4) May be an upper bound.
(5) May be an upper bound. If the specified value is not large enough, PMG will catch it, display it with the exact required value and ask the user to rectify his estimate. This is intended to avoid the user counting the mesh nodes and elements he is generating.

elli
nstart, narc, ninc, xc, yc, zc, xa, ya, za, xb, yb, zb, ang, stang, weight
<repeat ..., terminate with a blank record>

Value name	Type	Note	Description
nstart	I		number of the first "point" on the ellipse or elliptical arc generated with this record
narc	I		number of arcs to be generated on the ellipse or elliptical arc (the portion of line between two adjacent "points" defines an arc)
ninc	I	(1)	number increment for generated "points" on the ellipse or elliptical arc
xc	F		coordinates of the center
yc	F		of the ellipse or elliptical arc
zc	F		
xa	F		coordinates of the "point"
ya	F		defining the major axis of the
za	F		ellipse or elliptical arc
xb	F		coordinates of the "point"
yb	F		defining the minor axis of the
zb	F		ellipse or elliptical arc
ang	F	(2)	total angle between the first "point" and the last "point" generated on the ellipse or elliptical arc (> 0)
stang	F	(2)	angle between the first "point" on the ellipse or elliptical arc and the major axis
weight	F		weight for repartition of the generated "points"

Notes
(1) Can be negative.
(2) In degrees.

end

The presence of this command at the end of the input file is necessary. Any data written below it will be ignored by PMG.

isop
nelty, matnu, gflag, negen, inc, (node(i), i = 1, 20), isub, jsub, ksub, noel, wi, wj, wk (1)
or
nelty, matnu, noel, gflag, negen, inc, (node(i), i = 1, 20) (2)
<repeat until all blocks of the system are specified or generated; terminate with a blank record>

Each record of the 'isop' command is used to generate one or several blocks (by specifying the connectivity information) which are then subdivided into finite elements. Every block defined by the 'isop' command is developed from an isoparametric mapping of a cube. The proper order of numbering the "points" on the cube is specified according to Figure A.2. The eight corner "points" of the cube must be specified (some may be identical for degeneration to a triangular prism block), the mid-side "points" are optional.

See Sections A.3.3 and A.3.4 respectively for the proper sequence of specification or generation of the connectivity information of the blocks under the fully-automatic option and for the ways of getting unequal subdivisions of a block.

By reducing the concept of a block to a single element (with no subdivision), this command provides a manual mesh element definition (by specifying the element connectivity) with possibility of element generation.

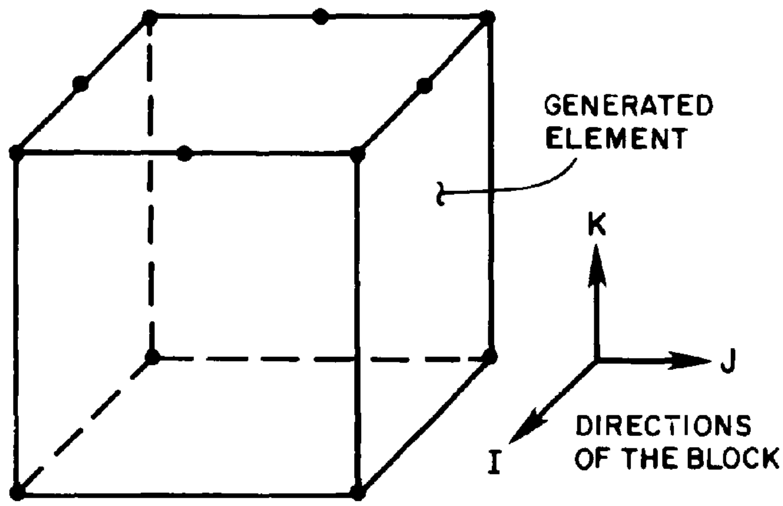
Value name	Type	Note	Description
nelty	I	(3)	type of elements generated with this record
matnu	I	(4)	material number to be assigned to all generated elements with this record
gflag	I=-1	(5)	flag for generation of more than one block with this record; = -1 if generation is desired
negen	I	(5)	total number of blocks to generate with this record
inc	I	(5)	number increment for block "points" when going from one block to the next block in the sequence of blocks generated with this record
node(i), i = 1, 20	I	(6)	"point" numbers for first block defined with this record (see Figure A.2 for the proper order of numbering)
isub	I	(1)	number of subdivisions in the I direction to be assigned to all blocks generated with this record
jsub	I	(1)	number of subdivisions in the J direction to be assigned to all blocks generated with this record
ksub	I	(1)	number of subdivisions in the K direction to be assigned to all blocks generated with this record
noel	I	(7)	number of nodes per element for each element generated in each block with this record

wi	F	(1)	weight for subdivision in the I direction to be assigned to each block generated with this record
wj	F	(1)	weight for subdivision in the J direction to be assigned to each block generated with this record
wk	F	(1)	weight for subdivision in the K direction to be assigned to each block generated with this record

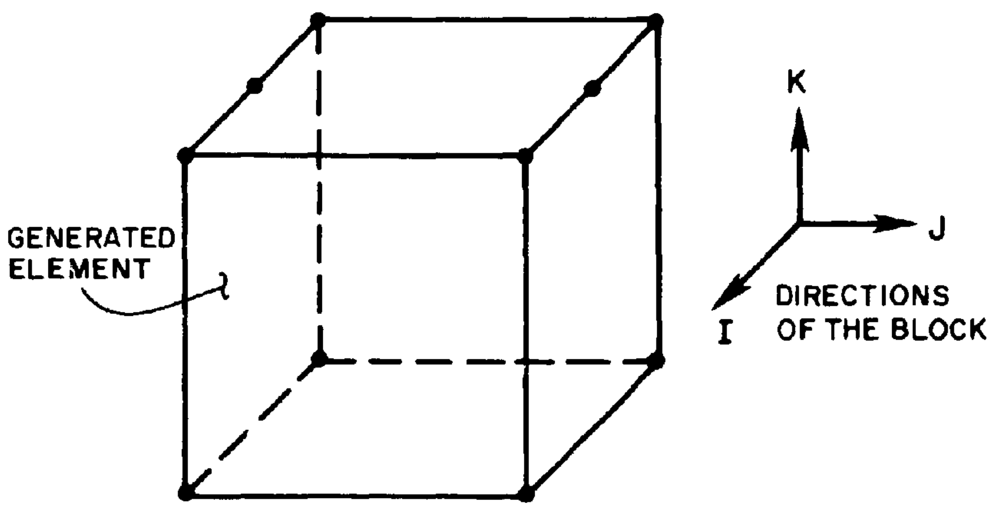
Notes
(1) For semi-automatic option.
(2) For fully-automatic option.
(3) nelty = 4, 5, 6, and 7 respectively for rectangular prism, triangular prism, rectangular shell, and triangular shell elements. See Chapter 5 and Section A.5 for the selection of the type of element in different substructures of the dam-water-foundation system. For triangular prism or triangular shell elements, they are generated from a triangular prism block, which is numbered in the same way as in Figure A.2, except that "points" 12 and 16 are not specified and "points" 1 and 4, 17 and 20, 5 and 8 correspond to the same "point" numbers. Also, there should not be subdivisions in both the I and the J directions of the block, and the command 'tie' must be included in the input data.
(4) matnu needs to be arbitrarily specified for generating finite elements for the impounded water substructure, though this information will not be used in EACD-3D; see Section A.5.4.
(5) Omit this data if generation of more than one block with this record is not desired; generating more than one block with this record is possible only if the corresponding block "point" numbers are all in a single constant increment (the value of inc) when going from one block to the next block.
(6) node(i) = 0 for each optional block "point" not specified.
(7) The current available library is: 8, 16, 20 for fully-automatic option; 8, 10, 12, 16, 20 for semi-automatic option. When noel = 12 or 10, it is necessary that ksub = 1 (i.e., no subdivision in the K direction of block); see Figure A.5 for the location of the nodal points of a generated element as determined by the orientation of the block. When generating triangular prism elements, noel = 20, 16, 8 respectively for 15-node, 12-node, and 6-node triangular prism elements. When generating triangular shell elements, noel = 16 and 8 respectively for 6-node and 3-node (mid-surface) triangular shell elements (see Chapter 5 and Section A.5).

line
nstart, xstart, ystart, zstart, nstop, xstop, ystop, zstop, ninc, weight
<repeat ..., terminate with a blank record>

Value name	Type	Note	Description
nstart	I	(1)	number of the first "point" on the straight line generated with this record
xstart ystart zstart	F F F		coordinates of the first "point" on the straight line
nstop	I	(1)	number of the last "point" on the straight line
xstop ystop zstop	F F F		coordinates of the last "point" on the straight line



(a) Location of the nodes for 12-node element



(b) Location of the nodes for 10-node element

Figure A.5 Location of nodes for 12- and 10-node generated elements with respect to the orientation of the block.

ninc	I	(1)	number increment for generated "points" on the straight line
weight	F		weight for repartition of the generated "points"

Notes
(1) ninc can be negative if nstart > nstop.

nopr

The use of the 'nopr' (without the ' ') command will switch off the output on the echo file (except for error messages).

para
nstart, nstop, ninc, (def(i,j), i = 1,3), j = 1,3), weight
<repeat .... terminate with a blank record>

Value name	Type	Note	Description
nstart	I	(1)	number of the first "point" on the parabola generated with this record
nstop	I	(1)	number of the last "point" on the parabola
ninc	I	(1)	number increment for generated "points" on the parabola
def(i,j), i = 1,3 j = 1,3	F		coordinates of the three points defining the parabola
weight	F		weight for repartition of the generated "points"

Notes
(1) ninc can be negative if nstart > nstop.

poin
num, xcoor, ycoor, zcoor
<repeat ..., terminate with a blank record>

Value name	Type	Note	Description
num	I		specified number of the "point" generated with this record
xcoor ycoor zcoor	F F F		specified coordinates of the "point"

rota
ninstart, ninstop, nininc, noustart, noustop, nouinc, xc, yc, zc, u, v, w, ang
<repeat ..., terminate with a blank record>

Value name	Type	Note	Description

ninstart	I	(1)	number of the first "point" on the "line" (2) to be rotated with this record
ninstop	I	(1)	number of the last "point" on the "line" (2) to be rotated
nininc	I	(1)	number increment for the "points" on the "line" (2) to be rotated
noustart	I	(1)	number of the first "point" on the rotated "line" (2)
noustop	I	(1)	number of the last "point" on the rotated "line" (2)
nouinc	I	(1)	number increment for the "points" on the rotated "line"
xc	F		coordinates of a point through
yc	F		which the axis of rotation
zc	F		passes
u	F		vector components of the axis
v	F	(3)	of rotation
w	F		(not necessarily normalized)
ang	F		angle of rotation (degrees)

Notes
(1) n( )inc can be negative if n( )start > n( )stop; ( ) stands for 'in' or 'ou'. If the "point" numbers in the "line" to be rotated are desired in the "point" numbers in the rotated "line", ninstart = noustart, ninstop = noustop, and nininc = nouinc.
(2) "line" stands for any parametric curve (not necessarily straight) (Section A.3.1).
(3) Direction of the vector representing the axis of rotation determines the direction of rotation by the right-hand rule.

semi

If the semi-automatic option of PMG is desired, this command must be input as the first command in the input file (except for comment cards).

spli
npsp, nstart, nstop, ninc, weight
(spcoor(i), i = 1,3)
repeat last record npsp times

Many structures have boundaries that do not have a particular form and often we are given only design curves modelling them. Measurements can be taken from these curves and then used to define a cubic spline which will fit the data on the boundary and "look smooth". The command 'spli' (without the ' ') generates a piecewise-cubic Hermite spline. However in practice it is often difficult to acquire the needed derivatives, therefore the mathematical formulation of Hermite spline is slightly modified with an approximation of the derivatives by Bessel interpolation.

Value name	Type	Note	Description
npsp	I	(1)	number of points defining the spline (points of interpolation)

nstart	I	(2)	number of the first "point" on the spline generated with this command
nstop	I	(2)	number of the last "point" on the spline
ninc	I	(2)	number increment for generated "points" on the spline
weight	F		weight for repartition of the generated "points"
spcoor(i), i = 1,3	F		coordinates of one of the interpolation points defining the spline

One spline is defined by one 'spli' command. If more than one spline are desired, repeat the command 'spli'.

Notes
(1) npsp is limited to a maximum value of 50, but it has to be greater than or equal to 4 because at least 4 points are needed to define a cubic spline.
(2) ninc can be negative if nstart > nstop.

tie

A mesh can be generated in PMG in which there is more than one node (with different node numbers) corresponding to the same coordinates (e.g. under the semi-automatic option, or when triangular elements are generated). In these cases, the 'tie' (without the ' ') command should be used to merge these nodes and modify the element connectivity so that the mesh is uniquely defined. Node numbering is consequently modified.

tran
ninstart, ninstop, nininc, noustart, noustop, nouinc, (trans(i), i = 1,3)
<repeat ..., terminate with a blank record>

Value name	Type	Note	Description
ninstart	I	(1)	number of the first "point" on the "line" (2) to be translated with this record
ninstop	I	(1)	number of the last "point" on the "line" (2) to be translated
nininc	I	(1)	number increment for the "points" on the "line" (2) to be translated
noustart	I	(1)	number of the first "point" on the translated "line" (2)
noustop	I	(1)	number of the last "point" on the translated "line" (2)
nouinc	I	(1)	number increment for the "points" on the translated "line" (2)
trans(i), i = 1,3	F		components of the translational vector

Notes
(1) n( )inc can be negative if n( )start > n( )stop; ( ) stands for 'in' or 'ou'. If the "point" numbers in the "line" to be translated are desired in the "point" numbers in the translated line, ninstart =

noustart, ninstop = noustop, and nininc = nouinc.
(2) "line" stands for any parametric curve (not necessarily straight) (Section A.3.1).

Error Messages

The system is very strict but relatively generous in error messages. These messages are almost always self-explanatory. For more information see below:

**** FIRST COMMAND SHOULD BE AUTO OR SEMI **** First command has to be 'auto' or 'semi' since it selects the option of PMG.

**** SECOND COMMAND MUST BE CONTROL **** Second command has to be 'cont' since it allocates the dynamic storage.

**** MAXIMUM STORAGE CAPACITY EXCEEDED **** Self explanatory. Increase the allocated storage of the computer system.

**** YOU HAVE EXCEEDED THE DECLARED # OF SPECIFIED POINTS **** One (or more) of the specified "points" or generated "points" (not to be confused with finite element nodes) has been assigned a number greater than the declared total number of specified "points" in the 'cont' command. Check for mistyping or increase nsp in the command 'cont'.

**** "xxxx" IS NOT A VALID COMMAND **** Check proper spelling of the commands and also for the blank records required at the end of certain commands.

**** CIRCLE STARTING AT N = xxxxx IS BADLY DEFINED **** Check circle definition and especially your normal vector.

**** ELLIPSE STARTING AT N = xxxxx IS BADLY DEFINED **** Check the definition of your ellipse starting at "point" number n = xxxxx.

**** ERROR EITHER IN ISOP OR IN CONTROL : NODE xxxxx IS > # SPECIFIED POINTS **** Check for mistyping of the "point" number xxxxx in 'isop' command or increase nsp in 'cont' command.

**** "LINE" STARTING AT N = xxxxx IS BADLY DEFINED **** Number assigned to starting "point" and number assigned to last "point" on the straight line are not compatible with the number increment for "points" on the line.

**** TRANSLATION OF LINE STARTING AT N = xxxxx IS BADLY DEFINED : ERROR IN THE LINE TO BE TRANSLATED **** For the "line" to be translated, number assigned to starting "point" and number assigned to last "point" are not compatible with the number increment for "points" on that "line".

**** TRANSLATION OF LINE STARTING AT N = xxxxx IS BADLY DEFINED : ERROR IN THE TRANSLATED LINE **** For the defined translated "line", number assigned to starting "point" and number assigned to last "point" are not compatible with the number increment for "points" on that "line".

**** ROTATION OF LINE STARTING AT N = xxxx IS BADLY DEFINED : ERROR IN THE LINE TO BE ROTATED **** For the defined "line" to be rotated, number assigned to starting "point" and number assigned to last "point" are not compatible with the number increment for "points" on that "line".

**** ROTATION OF LINE STARTING AT N = xxxx IS BADLY DEFINED : ERROR IN THE ROTATED LINE **** For the defined rotated "line", number assigned to starting "point" and number assigned to last "point" are not compatible with the number increment for "points" on that "line".

**** TRANSLATION OF LINE STARTING AT N = xxxx IS BADLY DEFINED : TRANSLATED LINE DOES NOT HAVE THE SAME # OF POINTS AS INPUT LINE **** Self explanatory.

**** ROTATION OF LINE STARTING AT N = xxxx IS BADLY DEFINED : ROTATED LINE DOES NOT HAVE THE SAME # OF POINTS AS INPUT LINE **** Self explanatory.

**** ERROR IN POINT NUMBERING OF SPLINE STARTING AT N = xxxxx **** numbers assigned to "points" on output "line" are not compatible.

**** ERROR IN SPLINE DEFINED WITH xxxxx POINTS : ONLY UP TO 50 POINTS DEFINING ONE SPLINE ARE ALLOWED **** There is no limitation on the number of "points" to be generated on a spline but up to only 50 points can define a spline!

**** ERROR IN SPLINE DEFINED WITH xxxxx POINTS : AT LEAST 4 POINTS HAVE TO DEFINE A SPLINE **** Self explanatory.

**** ERROR IN CONTROL COMMAND : GENERATED NODES = xxxxx REQUESTED STORAGE FOR ONLY xxxxx NODES **** Self explanatory; increase nesno in 'cont' command.

**** ERROR IN CONTROL COMMAND : GENERATED ELEMENTS = xxxxx REQUESTED STORAGE FOR ONLY xxxxx ELEMENTS **** Increase nesel in 'cont' command.

**** ERROR IN CONTROL COMMAND : DECLARED # OF BLOCKS EXCEEDED **** Increase nblock in 'cont' command.

**** PARABOLA STARTING AT N = xxxxx IS BADLY DEFINED **** Check compatibility of numbers of the "points" identifying the parabolic line.

**** MORE BLOCKS ARE INPUTED THAN DECLARED IN CONTROL (NBLI * NBLJ * NBLK) **** Check your blocks input or the values of nbli, nblj, nblk in 'cont' command.

A.5 Application of PMG to a Three-Dimensional Dam-Water-Foundation System

The following sections describe how to use PMG to generate the finite element meshes of the dam, impounded water, and foundation substructures that are input to the computer program EACD-3D. Because of certain restrictions of numbering the nodal points and orienting the finite elements (Chapter 5), the shape of the foundation-rock region recommended (Chapter 2), the characteristics of a three-dimensional dam-water-foundation system, and the way that PMG works, there are some points that the user should take note of in using PMG correctly and effectively; these are described below.

A.5.1 Dam Substructure

The geometry of a dam can be easily defined using the commands of PMG that specify or generate "points" (Section A.3.2); e.g., if parts of the upstream and downstream faces of the dam are described by circular arcs, the command 'circ' would be very useful (Section A.4). As mentioned in Section 5.2, there are two types of element that can be used to discretize a dam: solid elements and shell elements. If solid elements are selected to discretize a dam, these elements can be generated using PMG by subdividing the blocks into finite elements with the command 'isop' with nelty = 4 or 5 (for rectangular and triangular prism elements, respectively) and noel = 8 or 20 (for linear and quadratic shape functions, respectively); see Section A.4 for description of this command. Either the semi-automatic or the fully-automatic option of PMG may be used; the former has a better control over the bandwidth of the mesh generated by selecting the sequence of input of the blocks (note that the presence of a foundation substructure causes coupling of all the degrees of freedom of the dam at the dam-foundation interface), whereas the latter generates a mesh with easily-identified node and element numbers (Section A.3.3). Because of the restriction of the orientation of the solid elements (Table 5.1), that $s \times t$ (or r) should have a component in the +x direction, the blocks should be oriented with the K direction having a component in the +x direction (Figure A.2), as the r direction of each solid element generated within a block points toward the K direction of that block. This should be observed for both semi- and fully-automatic options of PMG.

If shell elements are selected to discretize a dam, these elements can be generated using PMG by subdividing the blocks into finite elements with the command 'isop' with nelty = 6 or 7 (for rectangular and triangular shell elements, respectively) and noel = 8 or 16 (for linear and quadratic shape functions, respectively); see Section A.4 for description of this command. For shell elements, noel = 20 is never used because only the upstream and downstream auxilliary nodes are input to define the geometry of the dam (Section 5.2). Only the fully-automatic option of PMG should be used to generate shell elements for the dam, because of the restriction that the upstream auxilliary nodes of the finite element mesh are numbered first followed by the downstream auxilliary nodes in the same order (Section 5.2, Chapter 8 - Subprogram 2). By orienting the global K parametric direction of the dam (or K directions of the blocks) opposite to the x direction (Figure A.2), this restriction on node numbering would be automatically satisfied. In addition, the restriction on the orientation of the shell elements (Table 5.1), that s × t (or r) should have a component in the +x direction, would also be satisfied because the r direction of each shell element generated within a block points opposite to the K direction of that block. Using the fully-automatic option with appropriate selection of the I and J global parametric directions would result in a favorable bandwidth if the foundation rock is assumed rigid (when coupling of all the degrees of freedom at dam-foundation interface does not occur).

A.5.2 Impounded Water Substructure

The coordinates of all the nodal points (Type 1 and Type 2; see Section 5.1) in the impounded water can be generated using PMG; however, only Mesh 1 element data and connectivity are generated. The element cards for Meshes 2, 3, 4, and 5 have to be prepared manually (Section A.5.4). Three-dimensional rectangular and triangular prism elements can be generated with the command 'isop' with nelty = 4 or 5, respectively, and noel = 8 or 20 (for linear and quadratic shape functions, respectively); see Section A.4. Either the semi- or the fully-automatic option of PMG may be used, though the latter generates a mesh with easily-identified node and element numbers; and, with proper choice of the I, J, K directions (Figure A.2), the fully-automatic option generates a mesh with a favorable bandwidth. Since there is no restriction on the orientation of Mesh 1 elements (Table 5.1), the blocks can be oriented in any direction under either option, although certain orientation under the fully-automatic option may give a smaller bandwidth for the system as mentioned above. In order to ensure compatibility of the generated meshes of the dam and of the impounded water at the dam-water interface, for these two substructures, same "points" should be used to define the interface which is subdivided in the same manner (see example in Section A.6).

A.5.3 Foundation Substructure

The shape of the foundation-rock region and the pattern of discretization are idealized using a procedure described in References [3] and [8]. The geometry of the semi-circular inclined plane of the foundation (Section 2.6.3 in Reference [3]) can be easily defined using the commands 'circ' and 'rota' of PMG (see the example in Section A.6). Eight-node three-dimensional solid elements are usually used to discretize this substructure. These elements can be generated using PMG by subdividing the blocks into finite elements with the command 'isop' with nelty = 4 (since only rectangular prism elements are used) and noel = 8 (Section A.4). If 20-node solid elements or 16-node shell elements are used in the dam, for compatibility between the dam and foundation elements, 20-node (noel = 20) or 16-node (noel = 16) solid elements are respectively used in the layer of foundation elements next to the dam-foundation interface. 12-node (noel = 12) and 10-node (noel = 10) elements are also available to connect these 20-node or 16-node solid foundation elements to the eight-node solid elements in the rest of the foundation away from the dam-foundation interface (when generating 12-node or 10-node elements, there should be no subdivision in the K direction of the block; see Section A.4). The orientation of these 12-node and 10-node connecting elements has to be correctly selected so that compatibility with the adjacent foundation elements is achieved (see Figure A.5 and example in Section A.6). Only the semi-automatic option of PMG should be used for the foundation substructure because the pattern of discretization does not permit a "grid-like" pattern of blocks (Section A.3.3), and because the 12-node and 10-node elements are available only in the semi-automatic option. By appropriately numbering the "points" of the blocks, the connectivity of the blocks between different inclined planes along the dam-foundation interface can be automatically generated with the command 'isop' with gflag = -1 (see the example in Section A.6). In order to ensure compatibility of the generated meshes of the dam and of the foundation at the dam-foundation interface, for these two substructures, same "points" should be used to define the interface which is subdivided in the same manner (see example in Section A.6).

A.5.4 Use of the Output from PMG

As mentioned in Section A.3.6, the fem (finite element) file (file 13) output from PMG consists of the nodal point coordinates and element connectivity of the finite element mesh generated. For the dam substructure, the fem file from PMG provides only for Card set 1 and Card set 5 of the input data to Subprogram 2 (Chapter 8). The user still has to prepare the other card sets in Subprogram 2 and the card set in Subprogram 3 to run the program EACD-3D for the dam substructure. In particular, the nodal point numbers of fixed nodal points and nodal points on plane of symmetry need to be identified from the generated mesh. In addition, if solid elements are used to discretize the dam, the input data NUPSM and NDNSM needs to be prepared for Card set 5 of Subprogram 2 by identifying those elements with a face on the upstream or downstream face of the dam.

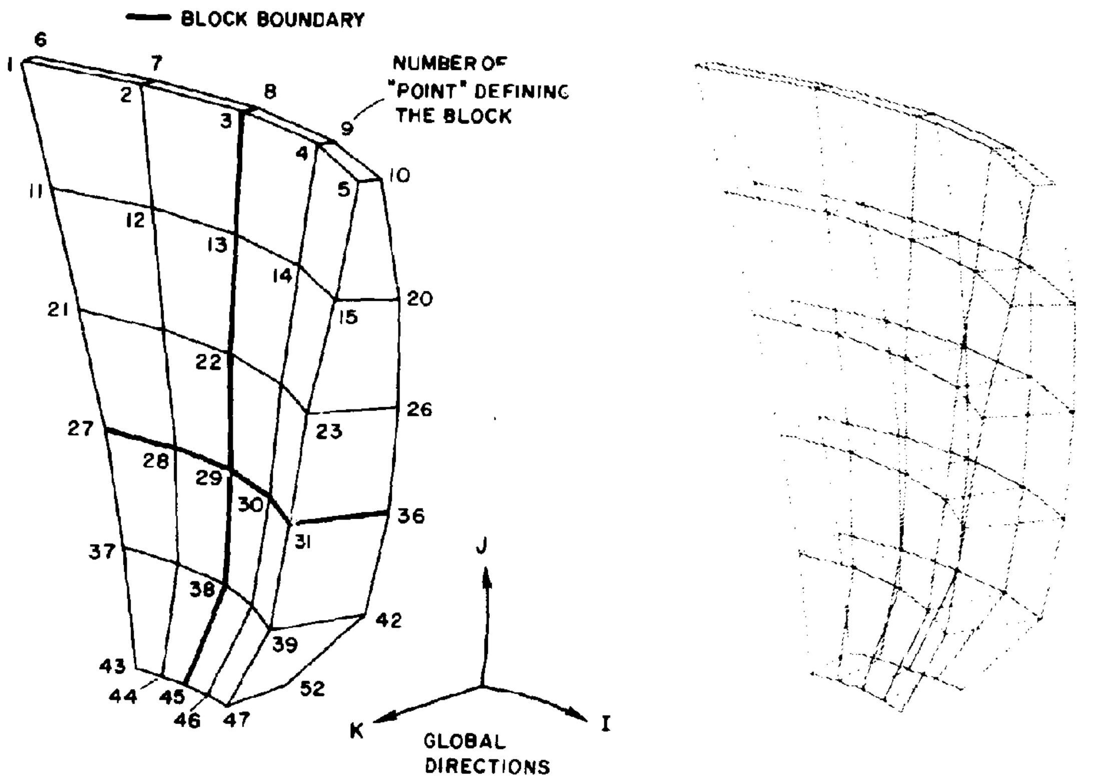
For the impounded water substructure, the fem file from PMG provides only for Card set 1 and Card set 7 (for Card set 7, the material type number for each Mesh 1 element is also generated by PMG: however, this information is not needed for fluid elements) of the input data to Subprogram 4 (Chapter 8). The user still has to prepare the other card sets in Subprogram 4 to run the program EACD-3D for the impounded water substructure. In particular, the nodal point numbers of nodal points on the free surface, on the plane of symmetry, and on the dam-water interface, and Mesh 4 and Mesh 5 nodal points need to be identified from the generated mesh. Furthermore, the Meshes 2, 3, 4, and 5 element cards need to be prepared from the generated mesh.

For the foundation substructure, the fem file from PMG provides only for Card set 1 and Card set 6 of the input data to Subprogram 1 (Chapter 8). The user still has to prepare the other card sets in Subprogram 1 to run the program EACD-3D for the foundation substructure. In particular, the nodal point numbers of fixed nodal points and nodal points on plane of symmetry, and the surface elements in contact with the impounded water need to be identified from the generated mesh. Furthermore, the nodal point numbers of the foundation nodes and of the dam nodes that are on the dam-foundation interface need to be identified from the generated meshes of the foundation and dam.

A.6 Examples

The following examples demonstrate the use of PMG to generate finite element meshes for the dam substructure, impounded water substructure, and foundation substructure for the Morrow Point Dam-water-foundation system. For each substructure, the input data to PMG and the output fem file are presented ; the generated finite element meshes for the three substructures are shown in Figures A.6, A 7, and A.8.

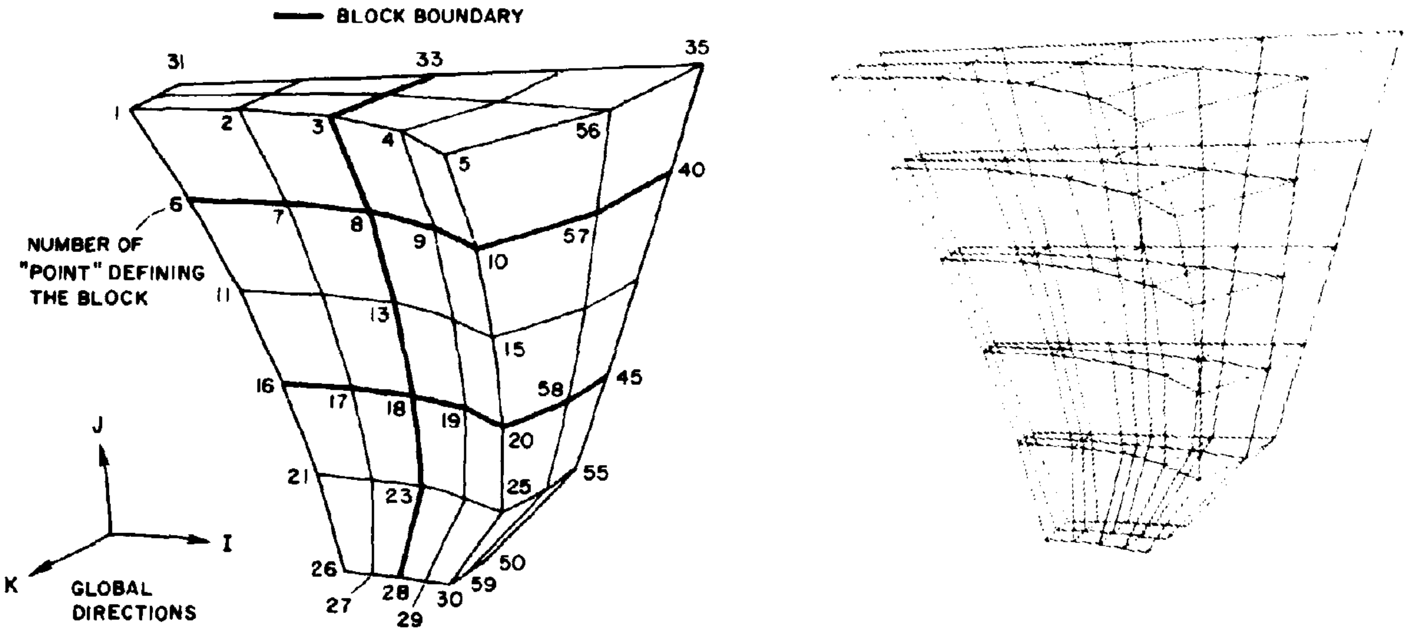
As shown in Figure A.6(a), the entire dam is divided into two layers of blocks in the global I direction, two layers in the global J direction, and one layer in the global K direction. The fully-automatic option of PMG is used. For the impounded water, as shown in Figure A.7(a), it is divided into two layers of blocks in the global I direction, three layers in the global J direction, and one layer in the global K direction. Again, the fully-automatic option of PMG is used. However, for the foundation, the semi-automatic option of PMG is used. As shown in Figure A.8(a), the foundation is divided into seven layers of blocks with eight semi-circular planes along the dam-foundation interface. The "points" of the blocks are numbered such that there is a constant difference of one between the numbering of corresponding "points" in any two adjacent layers of blocks along the dam-foundation interface. This makes the automatic generation of the connectivity information of the blocks possible along this interface (with gflag = -1 in the 'isop' command records; see the input data in the following pages).



(a) Blocks and Their Subdivisions

(b) Generated Finite Element Mesh

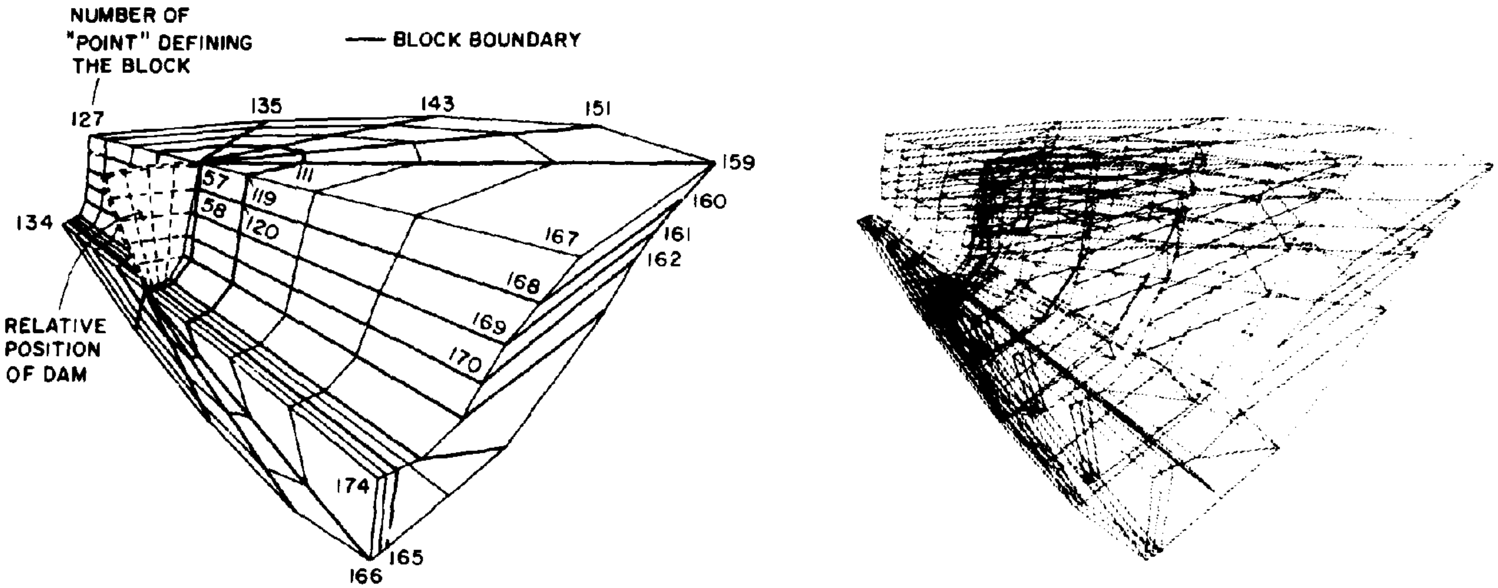
Figure A.6 Using PMG to generate finite element mesh of the dam substructure of Morrow Point Dam-water-foundation system.



(a) Blocks and Their Subdivisions

(b) Generated Finite Element Mesh

Figure A.7 Using PMG to generate finite element mesh of the impounded water substructure of Morrow Point Dam-water-foundation system.



(a) Blocks and Their Subdivisions

(b) Generated Finite Element Mesh

Figure A.8 Using PMG to generate finite element mesh of the foundation substructure of Morrow Point Dam-water-foundation system.

Input Data to PMG for the Examples

1. Dam substructure

```
auto
cont
100,2,3,1
2,2
2,2,1
1
0.,0.
0.,0.,0.
0.
circ
1,4,1,-12.,465.,0.,-375.,465.,0.,0.,-1.,0.,56.2,0.
6,4,1,0.,465.,0.,-375.,465.,0.,0.,-1.,0.,56.2,0.
11,4,1,-6.42,372.,0.,-322.5,372.,0.,0.,-1.,0.,54.92,0.
16,4,1,28.905,372.,0.,-323.9,372.,0.,0.,-1.,0.,54.01,0.
21,2,1,-0.84,279.,0.,-258.8,279.,0.,0.,-1.,0.,56.16,0.
24,2,1,46.3,279.,0.,-278.6,279.,0.,0.,-1.,0.,50.38,0.
27,4,1,2.578,186.,0.,-208.2,186.,0.,0.,-1.,0.,58.53,0.
32,4,1,52.914,186.,0.,-243.6,186.,0.,0.,-1.,0.,46.97,0.
37,2,1,-2.684,93.,0.,-174.,93.,0.,0.,-1.,0.,58.07,0.
40,2,1,49.007,93.,0.,-217.7,93.,0.,0.,-1.,0.,41.76,0.
43,4,1,-17.227,0.,0.,-153.8,0.,0.,0.,-1.,0.,35.04,0.
48,4,1,34.427,0.,0.,-200.4,0.,0.,0.,-1.,0.,23.06,0.

isop
6,1,16,29,27,43,45,34,32,48,50,28,37,44,38,33,40,49,41,0,0,0,0
6,1,16,31,29,45,47,36,34,50,52,30,38,46,39,35,41,51,42,0,0,0,0
6,1,16,13,11,27,29,18,16,32,34,12,21,28,22,17,24,33,25,0,0,0,0
6,1,16,15,13,29,31,20,18,34,36,14,22,30,23,19,25,35,26,0,0,0,0
6,1,16,3,1,11,13,8,6,16,18,2,0,12,0,7,0,17,0,0,0,0,0
6,1,16,5,3,13,15,10,8,18,20,4,0,14,0,9,0,19,0,0,0,0,0

end
```

2. Impounded water substructure

```
auto
cont
100,2,3,1
2,2
2,2,1
2
0.,0.
0.,0.,0.
0.
circ
1,4,1,0.,465.,0.,-375.,465.,0.,0.,-1.,0.,56.2,0.
6,4,1,28.905,372.,0.,-323.9,372.,0.,0.,-1.,0.,54.01,0.
11,2,2,46.3,279.,0.,-278.6,279.,0.,0.,-1.,0.,50.38,0.
16,4,1,52.914,186.,0.,-243.6,186.,0.,0.,-1.,C.,46.97,0.
21,2,2,49.007,93.,0.,-217.7,93.,0.,0.,-1.,0.,41.76,0.
26,4,1.34.427,0.,0.,-200.4,0.,0.,0.,-1.,0.,23.06,0.

line
31,75.,465.,0.,35,75.,465.,400.,2,0.
36,75.,372.,0.,40,75.,372.,350.,2,0.
41,75.,186.,0.,45,75.,186.,250.,2,0.
46,75.,0.,0.,50,75.,0.,100.,2,0.
51,75.,93.,0.,55,75.,93.,200.,2,0.
.
poin
56,-55.,465.,380.
57,-30.,372.,335.
58,15.,186.,245.
59,45.327,0.,95,993

isop
4,1,20,18,16,26,28,43,41,46,48,17,21,27,23,0,51,0,53,0,0,0,0
4,1,20,20,18,28,30,45,43,48,50,19,23,29,25,0,53,0,55,58,0,0,59
4,1,20,8,6,16,18,38,36,41,43,7,11,17,13,0,0,0,0,0,0,0,0
4,1,20,10,8,18,20,40,38,43,45,9,13,19,15,0,0,0,0,57,0,0,58
4,1,20,3,1,6,8,33,31,36,38,2,0,7,0,0,0,0,0,0,0,0,0
4,1,20,5,3,8,10,35,33,38,40,4,0,9,0,0,0,0,0,56,0,0,57

end
```

```
semi
cont
200,100,1500,250

# define the "points" on the first plane
poin
1,-166.389,465.,311.619
9,-173.065,465.,301.647
17,-159.713,465.,306.633
57,-179.741,465.,306.633
25,-159.713,465.,313.309
49,-179.741,465.,313.309
33,-166.389,465.,318.628
41,-173.065,465.,307.99

circ
79,5,8,186.533,465.,306.633,-169.727,465.,306.633,0.,-1.,0.,180.,0.
127,5,8,1225.27,465.,306.633,-169.727,465.,306.633,0.,-1.,0.,180.,0.

# define the "points" on the next plane
poin
65,-141.463,418.5,298.540
72,-156.954,418.5,280.156
2,-116.576,372.,285.461
10,-140.843,372.,258.664
18,-92.357,372.,272.0665
58,-165.119,372.,272.0665
26,-92.357,372.,296.321
50,-165.119,372.,296.321
34,-116.611,372.,310.74
42,-140.865,372.,281.901

circ
80,5,8,247.3,372.,272.0665,-128.738,372.,272.0665,0.,-1.,0.,180.,0.
128,5,8,1266.262,372.,272.0665,-128.738,372.,272.0665,0.,-1.,0.,180.,0.

# define the "points" on the next plane
poin
66,-92.116,325.5,267.655
73,-126.907,325.5,235.223
3,-71.414,279.,250.268
11,-115.148,279.,214.261
19,-27.712,279.,232.26
59,-158.779,279.,232.26
27,-27.712,279.,275.949
51,-158.779,279.,275.949
35,-71.401,279.,295.305
43,-115.09,279.,256.593

circ
81,5,8,304.654,279.,232.26,-93.246,279.,232.26,0.,-1.,0.,180.,0.
129,5,8,1301.75,279.,232.26,-93.246,279.,232.26,0.,-1.,0.,180.,0.

# define the "points" on the next plane
poin
67,-54.462,232.5,233.299
74,-105.567,232.5,195.776
4,-41.264,186.,216.751
12,-98.163,186.,179.775
20,15.645,186.,198.254
60,-155.076,186.,198.254
28,15.645,186.,255.161
52,-155.076,186.,255.161
36,-41.262,186.,274.927
44,-98.169,186.,235.395
```

```
circ
82,5,8,343.055,186.,198.254,-69.716,186.,198.254,0.,-1.,0.,180.,0.
130,5,8,1325.284,186.,198.254,-69.716,186.,198.254,0.,-1.,0.,180.,0.

# define the "points" on the next plane
poin
68,-31.496,139.5,203.007
75,-94.109,139.5,166.660
5,-18.752,93.,177.63
13,-83.394,93.,145.395
21,45.888,93.,161.5065
61,-148.023,93.,161.5065
29,45.888,93.,226.144
53,-148.023,93.,226.144
37,-18.749,93.,244.407
45,-83.386,93.,207.88

circ
83,5,8,370.399,93.,161.5065,-51.068,93.,161.5065,0.,-1.,0.,180.,0.
131,5,8,1343.932,93.,161.5065,-51.068,93.,161.5065,0.,-1.,0.,180.,0.

# define the "points" on the next plane
poin
69,-3.033,46.5,140.621
76,-66.016,46.5,115.979
6,15.662,0.,91.981
14,-41.981,0.,78.413
22,73.283,0.,85.202
62,-99.601,0.,85.202
30,73.283,0.,142.83
54,-99.601,0.,142.83
38,15.655,0.,155.868
46,-41.973,0.,129.792

circ
84,5,8,400.423,0.,85.202,-13.159,0.,85.202,0.,-1.,0.,180.,0.
132,5,8,1381.841,0.,85.202,-13.159,0.,85.202,0.,-1.,0.,180.,0.

# define the "points" on the next plane
poin
70,23.810,0.,69.812
77,-31.343,0.,60.469
7,29.688,0.,46.938
15,-23.562,0.,41.114
23,82.938,0.,44.026
63,-76.812,0.,44.026
31,82.938,0.,97.276
55,-76.812,0.,97.276
39,29.688,0.,100.188
47,-23.562,0.,94.364

circ
85,5,8,411.719,0.,44.026,3.063,0.,44.026,0.,-1.,0.,180.,0.
133,5,8,1398.063,0.,44.026,3.063,0.,44.026,0.,-1.,0.,180.,0.

# define the "points" on the last plane
poin
71,33.239,0.,23.588
78,-18.820,0.,20.800
8,34.427,0.,0.
16,-17.227,0.,0.
24,86.081,0.,0.
64,-68.881,0.,0.
32,86.081,0.,51.654
56,-68.881,0.,51.654
40,34.427,0.,51.654
```

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48,-17.227,0.,51.654

circ
86,5,8,415.461,0.,0.,8.6,0.,0.,0.,-1.,0.,180.,0.
134,5,8,1403.6,0.,0.,8.6,0.,0.,0.,-1.,0.,180.,0.

# rotate the "lines" to the inclined positions
rota
127,167,8,127,167,8,0.,465.,306.633,1.,0.,0.,20.39
79,119,8,79,119,8,0.,465.,306.633,1.,0.,0.,20.39
17,57,8,17,57,8,0.,465.,306.633,1.,0.,0.,20.39
128,168,8,128,168,8,0.,372.,272.0665,1.,0.,0.,21.7
80,120,8,80,120,8,0.,372.,272.0665,1.,0.,0.,21.7
18,58,8,18,58,8,0.,372.,272.0665,1.,0.,0.,21.7
129,169,8,129,169,8,0.,279.,232.26,1.,0.,0.,21.52
81,121,8,81,121,8,0.,279.,232.26,1.,0.,0.,21.52
19,59,8,19,59,8,0.,279.,232.26,1.,0.,0.,21.52
130,170,8,130,170,8,0.,186.,198.254,1.,0.,0.,20.8
82,122,8,82,122,8,0.,186.,158.254,1.,0.,0.,20.8
20,60,8,20,60,8,0.,186.,198.254,1.,0.,0.,20.6
131,171,8,131,171,8,0.,93.,161.5065,1.,0.,0.,28.08
83,123,8,83,123,8,0.,93.,161.5065,1.,0.,0.,28.08
21,61,8,21,61,8,0.,93.,161.5065,1.,0.,0.,28.08
132,172,8,132,172,8,0.,0.,85.202,1.,0.,0.,58.64
84,124,8,84,124,8,0.,0.,85.202,1.,0.,0.,58.64
22,62,8,22,62,8,0.,0.,85.202,1.,0.,0.,58.64
133,173,8,133,173,8,0.,0.,44.026,1.,0.,0.,90.
85,125,8,85,125,8,0.,0.,44.026,1.,0.,0.,90.
23,63,8,23,63,8,0.,0.,44.026,1.,0.,0.,90.
134,174,8,134,174,8,0.,0.,0.,1.,0.,0.,90.
86,126,8,86,126,8,0.,0.,0.,1.,0.,0.,90.
24,64,8,24,64,8,0.,0.,0.,1.,0.,0.,90.

isop
4,1,-1,5,1,34,33,1,2,26,25,17,18,0,0,65,0,0,0,0,0,0,0,0,0,1,1,1,16,0.,0.,0.
4,1,-1,2,1,39,38,6,7,31,30,22,23,0,0,70,0,0,0,0,0,0,0,0,0,2,1,1,16,0.,0.,0.
4,1,-1,5,1,42,41,9,10,34,33,1,2,0,0,72,0,0,0,65,0,0,0,0,0,1,1,1,16,0.,0.,0.
4,1,-1,2,1,47,46,14,15,39,38,6,7,0,0,77,0,0,0,70,0,0,0,0,0,2,1,1,16,0.,0.,0.
4,1,-1,5,1,50,49,57,58,42,41,9,10,0,0,0,0,0,0,72,0,0,0,0,0,1,1,1,16,0.,0.,0.
4,1,-1,2,1,55,54,62,63,47,46,14,15,0,0,0,0,0,0,77,0,0,0,0,0,2,1,1,16,0.,0.,0.
4,1,-1,5,1,26,25,17,18,88,87,79,80,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,12,0.,0.,0.
4,1,-1,2,1,31,30,22,23,93,92,84,85,0,0,0,0,0,0,0,0,0,0,0,0,2,1,1,12,0.,0.,0.
4,1,-1,5,1,34,33,25,26,96,95,87,88,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,10,0.,0.,0.
4,1,-1,2,1,39,38,30,31,101,100,92,93,0,0,0,0,0,0,0,0,0,0,0,0,2,1,1,10,0.,0.,0.
4,1,-1,5,1,42,41,33,34,104,103,95,96,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,10,0.,0.,0.
4,1,-1,2,1,47,46,38,39,109,108,100,101,0,0,0,0,0,0,0,0,0,0,0,0,2,1,1,10,0.,0.,0.
4,1,-1,5,1,50,49,41,42,112,111,103,104,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,10,0.,0.,0.
4,1,-1,2,1,55,54,46,47,117,116,108,109,0,0,0,0,0,0,0,0,0,0,0,0,2,1,1,10,0.,0.,0.
4,1,-1,5,1,58,57,49,50,120,119,111,112,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,12,0.,0.,0.
4,1,-1,2,1,63,62,54,55,125,124,116,117,0,0,0,0,0,0,0,0,0,0,0,0,2,1,1,12,0.,0.,0.
4,1,-1,5,1,87,79,80,88,135,127,128,136,0,0,0,0,0,0,0,0,0,0,0,0,1,1,3,8,0.,0.,0.
4,1,-1,2,1,92,84,85,93,140,132,133,141,0,0,0,0,0,0,0,0,0,0,0,0,1,2,3,8,0.,0.,0.
4,1,-1,5,1,95,87,88,96,143,135,136,144,0,0,0,0,0,0,0,0,0,0,0,0,1,1,3,8,0.,0.,0.
4,1,-1,2,1,100,92,93,101,148,140,141,149,0,0,0,0,0,0,0,0,0,0,0,0,1,2,3,8,0.,0.,0.
4,1,-1,5,1,103,95,96,104,151,143,144,152,0,0,0,0,0,0,0,0,0,0,0,0,1,1,3,8,0.,0.,0.
4,1,-1,2,1,108,100,101,109,156,148,149,157,0,0,0,0,0,0,0,0,0,0,0,0,1,2,3,8,0.,0.,0.
4,1,-1,5,1,111,103,104,112,159,151,152,160,0,0,0,0,0,0,0,0,0,0,0,0,1,1,3,8,0.,0.,0.
4,1,-1,2,1,116,108,109,117,164,156,157,165,0,0,0,0,0,0,0,0,0,0,0,0,1,2,3,8,0.,0.,0.
4,1,-1,5,1,119,111,112,120,167,159,160,168,0,0,0,0,0,0,0,0,0,0,0,0,1,1,3,8,0.,0.,0.
4,1,-1,2,1,124,116,117,125,172,164,165,173,0,0,0,0,0,0,0,0,0,0,0,0,1,2,3,8,0.,0.,0.

tie
end
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Fem Files Output from PMG for the Examples

1. Dam substructure

```
  1      34.4270      0.          0.
  2      34.1286      0.         11.6238
  3      33.2393      0.         23.5680
  4      31.7592      0.         35.2926
  5      29.6882      0.         46.9375
  6      27.0325      0.         58.4630
  7      23.8097      0.         69.6121
  8      20.0199      0.         80.9846
  9      15.6632      0.         91.9805
 10      43.0511    46.5000       0.
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149    -156.9537   418.5000   280.1558
150     -12.0000   465.0000     0.
151     -14.7961   465.0000    44.7216
152     -22.8594   465.0000    86.1250
153     -36.1900   465.0000   130.2103
154     -54.7879   465.0000   170.9773
155     -78.3188   465.0000   209.1105
156    -105.8753   465.0000   243.5998
157    -137.4572   465.0000   274.4455
158    -173.0647   465.0000   301.6474
  1    6    1
  1   15   17    3   10   16   11    2
  2    6    1
  3   17   19    5   11   18   12    4
  3    6    1
  5   19   21    7   12   20   13    6
  4    6    1
  7   21   23    9   13   22   14    8
  5    6    1
 15   29   31   17   24   30   25   16
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 16    6    1
 49   63   65   51   55   64   56   50
 17    6    1
 57   71   73   59   66   72   67   58
 18    6    1
 59   73   75   61   67   74   68   60
 19    6    1
 61   75   77   63   68   76   69   62
 20    6    1
 63   77   79   65   69   78   70   64
```

2. Impounded water substructure

```
  1      75.0000     0.         0.
  2      75.0000     0.        12.5000
  3      75.0000     0.        25.0000
  4      75.0000     0.        37.5000
  5      75.0000     0.        50.0000
  6      75.0000     0.        62.5000
  7      75.0000     0.        75.0000
  8      75.0000     0.        87.5000
  9      75.0000     0.       100.0000
 10      75.0000    46.5000     0.
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288   -141.4827   418.5000   298.5403
289      0.       465.0000     0.
290     -2.8885   465.0000    46.2000
291    -11.2184   465.0000    91.0382
292    -24.9697   465.0000   134.5147
293    -44.2024   465.0000   176.6295
294    -68.5112   465.0000   216.0232
295    -96.9786   465.0000   251.6527
296   -129.6046   465.0000   283.5181
297   -166.3892   465.0000   311.6192
  1   4   1
124 110 112 126  15   1   3  17  85  80  81  86 119 111 120 125  10   2  11  16
  2   4   1
126 112 114 128  17   3   5  19  86  81  82  87 120 113 121 127  11   4  12  18
  3   4   1
128 114 116 130  19   5   7  21  87  82  83  88 121 115 122 129  12   6  13  20
  4   4   1
130 116 118 132  21   7   9  23  88  83  84  89 122 117 123 131  13   8  14  22
  5   4   1
138 124 126 140  29  15  17  31  90  85  86  91 133 125 134 139  24  16  25  30
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 36   4   1
281 267 269 283 172 158 160 174 212 207 208 213 273 268 274 282 164 159 165 173
 37   4   1
289 275 277 291 180 166 168 182 214 209 210 215 284 276 285 290 175 167 176 181
 38   4   1
291 277 279 293 182 168 170 184 215 210 211 216 265 278 286 292 176 169 177 183
 39   4   1
293 279 281 295 184 170 172 186 216 211 212 217 286 280 287 294 177 171 178 185
 40   4   1
295 281 283 297 186 172 174 188 217 212 213 218 287 282 288 296 178 173 179 187
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3. Foundation substructure

```
  1    -159.7130   465.0000   306.6330
  2    -126.0350   418.5000   289.3498
  3     -92.3570   372.0000   272.0605
  4    -159.7130   463.8370   309.7618
  5     -92.3570   367.5160   283.3344
  6    -159.7130   462.6740   312.8907
  7    -126.0350   412.8530   303.7464
  8     -92.3570   363.0320   294.6022
  9    -166.3890   465.0000   311.6190
 10    -141.4830   418.5000   298.5400
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423  -1063.1556     0.0001    44.0260
424  -1072.0878     0.0001    64.6140
425   -734.3743     0.0001    44.0260
426   -744.1274     0.0001    64.6140
427  -1386.4000     0.0001    -0.0000
428  -1389.1686     0.0001    22.0130
429  -1057.0204     0.0001    -0.0000
430  -1060.0881     0.0001    22.0130
431   -727.6406     0.0001    -0.0000
432   -731.0075     0.0001    22.0130
  1    4    1
 14    9   11   16    6    1    3    8    0    0    0    0   12   10   13   15    4    2    5    7
  2    4    1
 16   11   23   26    8    3   18   21    0    0    0    0   13   22   24   25    5   17   19   20
  3    4    1
 26   23   33   36   21   18   28   31    0    0    0    0   24   32   34   35   19   27   29   30
  4    4    1
 36   33   43   46   31   28   38   41    0    0    0    0   34   42   44   45   29   37   39   40
  5    4    1
 46   43   53   56   41   38   48   51    0    0    0    0   44   52   54   55   39   47   49   50
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 23   4   1
167 164 169 172 119 116 121 124   0   0   0   0 165 168 170 171 117 120 122 123
 24   4   1
172 169 174 180 124 121 126 132   0   0   0   0 170 173 177 179 122 125 129 131
 25   4   1
180 174 176 182 132 126 128 134   0   0   0   0 177 175 178 181 129 127 130 133
 26   4   1
182 176 184 190 134 128 136 142   0   0   0   0 178 183 187 189 130 135 139 141
 27   4   1
190 184 186 192 142 136 138 144   0   0   0   0 187 185 188 191 139 137 140 143
 28   4   1
  6   1   3   8 195 193 194 196   0   0   0   0   4   2   5   7   0   0   0   0
 29   4   1
  8   3  18  21 196 194 197 198   0   0   0   0   5  17  19  20   0   0   0   0
 30   4   1
 21  18  28  31 198 197 199 200   0   0   0   0  19  27  29  30   0   0   0   0
 31   4   1
 31  28  38  41 200 199 201 202   0   0   0   0  29  37  39  40   0   0   0   0
 32   4   1
 41  38  48  51 202 201 203 204   0   0   0   0  39  47  49  50   0   0   0   0
 33   4   1
 51  48  58  64 204 203 205 207   0   0   0   0  49  57  61  63   0   0   0   0
 34   4   1
 64  58  60  66 207 205 206 208   0   0   0   0  61  59  62  65   0   0   0   0
 35   4   1
 66  60  78  84 208 206 209 211   0   0   0   0  62  77  81  83   0   0   0   0
 36   4   1
 84  78  80  86 211 209 210 212   0   0   0   0  81  79  82  85   0   0   0   0
 37   4   1
 14   6   8  16 213 195 196 214   0   0   0   0   0   7   0  15   0   0   0   0
 38   4   1
 16   8  21  26 214 196 198 215   0   0   0   0   0  20   0  25   0   0   0   0
 39   4   1
 26  21  31  36 215 198 200 216   0   0   0   0   0  30   0  35   0   0   0   0
 40   4   1
 36  31  41  46 216 200 202 217   0   0   0   0   0  40   0  45   0   0   0   0
 41   4   1
 46  41  51  56 217 202 204 218   0   0   0   0   0  50   0  55   0   0   0   0
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 59   4   1
167 119 124 172 237 227 228 236   0   0   0   0   0 123   0 171   0   0   0   0
 60   4   1
172 124 132 180 238 228 229 239   0   0   0   0   0 131   0 179   0   0   0   0
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 61    4    1
180 132 134 182 239 229 230 240    0    0    0    0    0 133    0 181    0    0    0    0
 62    4    1
182 134 142 190 240 230 231 241    0    0    0    0    0 141    0 189    0    0    0    0
 63    4    1
190 142 144 192 241 231 232 242    0    0    0    0    0 143    0 191    0    0    0    0
 64    4    1
145 150 152 147 243 233 234 244    0    0    0    0 148 151 149 146    0    0    0    0
 65    4    1
147 152 157 154 244 234 235 245    0    0    0    0 149 156 155 153    0    0    0    0
 66    4    1
154 157 162 159 245 235 236 246    0    0    0    0 155 161 160 158    0    0    0    0
 67    4    1
159 162 167 164 246 236 237 247    0    0    0    0 160 166 165 163    0    0    0    0
 68    4    1
164 167 172 169 247 237 238 248    0    0    0    0 165 171 170 168    0    0    0    0
 69    4    1
169 172 180 174 248 238 239 249    0    0    0    0 170 179 177 173    0    0    0    0
 70    4    1
174 180 182 176 249 239 240 250    0    0    0    0 177 181 178 175    0    0    0    0
 71    4    1
176 182 190 184 250 240 241 251    0    0    0    0 178 189 187 183    0    0    0    0
 72    4    1
184 190 192 186 251 241 242 252    0    0    0    0 187 191 188 185    0    0    0    0
 73    4    1
259 257 258 260 255 253 254 256    0    0    0    0    0    0    0    0    0    0    0    0
 74    4    1
263 261 262 264 259 257 258 260    0    0    0    0    0    0    0    0    0    0    0    0
 75    4    1
193 194 196 195 263 261 262 264    0    0    0    0    0    0    0    0    0    0    0    0
 76    4    1
257 267 268 258 253 265 266 254    0    0    0    0    0    0    0    0    0    0    0    0
 77    4    1
261 269 270 262 257 267 268 258    0    0    0    0    0    0    0    0    0    0    0    0
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203    4    1
393 400 430 423 391 398 428 421    0    0    0    0    0    0    0    0    0    0    0    0
204    4    1
402 401 431 432 400 399 429 430    0    0    0    0    0    0    0    0    0    0    0    0
205    4    1
395 402 432 425 393 400 430 423    0    0    0    0    0    0    0    0    0    0    0    0
206    4    1
241 242 252 251 402 401 431 432    0    0    0    0    0    0    0    0    0    0    0    0
207    4    1
240 241 251 250 395 402 432 425    0    0    0    0    0    0    0    0 .  0    0    0    0
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UCB/EERC-79/01 "Hysteretic Behavior of Lightweight Reinforced Concrete Beam-Column Subassemblages," by B. Forzani, E.P. Popov and V.V. Bertero - April 1979(PB 298 267)A06

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