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EAGD-SLIDE: A COMPUTER PROGRAM FOR THE EARTHQUAKE ANALYSIS OF CONCRETE GRAVITY DAMS INCLUDING BASE SLIDING

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ABSTRACT

A numerical method has been implemented in a computer program, EAGD-SLIDE, to evaluate the earthquake response of concrete gravity dams, including sliding at the interface between the base of the dam and the foundation rock surface. The analysis method uses the hybrid frequency-time domain procedure, which accounts for the nonlinear base sliding behavior of the dam and the frequency-dependent response of the impounded water and the flexible foundation rock, to solve the equations of motion. The program can be used to obtain stresses, displacements, and base sliding of gravity dams subjected to free-field ground motion.

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Chapter 1

INTRODUCTION

A numerical procedure has been developed to evaluate the earthquake response of concrete gravity dams including sliding at the base [Chávez and Fenves, 1993]. The earthquake response of the dam is influenced by the interaction between the dam and the compressible water in the reservoir, by the interaction between the dam and foundation rock, and by the dam-foundation rock interface properties. This report presents the computer program, EAGD-SLIDE, that implements the numerical procedure used for the analysis of concrete gravity dams.

The dam monolith is modeled by a finite element discretization with linear elastic, orthotropic material behavior. The water in the reservoir is modeled as a continuum and the hydrodynamic effects of the impounded reservoir are modeled by the two-dimensional wave equation. The effect of reservoir bottom materials is accounted for by the wave reflection coefficient [Fenves and Chopra, 1984]. The foundation rock is modeled as a linear viscoelastic half-plane [Dasgupta and Chopra, 1979]. A friction model based on the Mohr-Coulomb law is used to approximate the force-displacement relationship at the interface. Base sliding is the only source of nonlinearity in the system. Rocking (or rigid body tipping) of the monolith about the toe or heel by overturning moments during an earthquake is not considered because rocking effects are small compared with sliding [El-Aidi, 1988; Chopra and Zhang, 1981]. Other nonlinearities, such as concrete cracking, opening and sliding of joints, and water cavitation are not represented in the model. The system is subjected to horizontal and vertical components of free-field earthquake ground motion acting at the base of the dam.

The hybrid frequency-time domain procedure [Kawamoto, 1983; Darbre and Wolf, 1988] is used to solve the nonlinear and frequency-dependent equations of motion. The linearized equations, including the frequency-dependent terms due to dam-water interaction and dam-foundation-rock interaction, are solved in the frequency domain, and the determination of nonlinear inertia forces due to sliding at the base is performed in the time domain. Since the sliding forces are a function of the current state of the system, it is necessary to iterate to obtain a solution that satisfies the specified sliding law at the base interface.

The objective of this report is to document the use of the computer program EAGD-SLIDE for computing the nonlinear sliding response of concrete gravity dams during earthquakes. The outline of the analysis procedure, modeling of the dam, program organization including installation parameters, and input and output are also presented. As an example, Pine Flat dam is analyzed to demonstrate the use of the computer program.

Chapter 2

SOLUTION PROCEDURE

The idealized concrete gravity dam is a two-dimensional monolith with rigid base, supported by flexible foundation rock, and impounding a reservoir of compressible water. The dam is allowed to slide along the interface between the dam base and the foundation rock surface. The base interface may be inclined. The system, shown in Figure 2.1, is subjected to horizontal and vertical components of free-field ground motion acting at the base of the dam.

The analytical procedure is described by Chávez and Fenves [1993]. The equations of motion for the dam-water-foundation rock system are formulated using the substructure concept, and they are solved using the hybrid frequency-time domain (HFTD) procedure. Iterative calculations in the frequency domain and in the time domain are performed to obtain the solution.

2.1 Equations of Motion for the Dam

The equations of motion for a finite element discretization of the dam with a rigid, but sliding, interface at the base are:

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{C}\dot{\mathbf{U}} + \mathbf{K}\mathbf{U} + \mathbf{M}\mathbf{R}\ddot{\mathbf{U}}_f + \mathbf{F}_{sd}(\ddot{U}_{s\beta}) = -\mathbf{M}\mathbf{R}\ddot{\mathbf{U}}_g(t) + \mathbf{P}(t) \tag{2.1}$$

$$\mathbf{R}^T\mathbf{M}\ddot{\mathbf{U}} + \mathbf{M}_t\ddot{\mathbf{U}}_f + \mathbf{F}_f(t) + \mathbf{F}_{sb}(\ddot{U}_{s\beta}) = -\mathbf{M}_t\ddot{\mathbf{U}}_g(t) + \mathbf{R}^T\mathbf{P}(t) \tag{2.2}$$

where $\mathbf{U}$ is the $2N_d$ vector (N_d is the number of nodal points above the base) of displacements relative to the dam base; $U_{s\beta}(t)$ is the sliding displacement of the dam along the interface

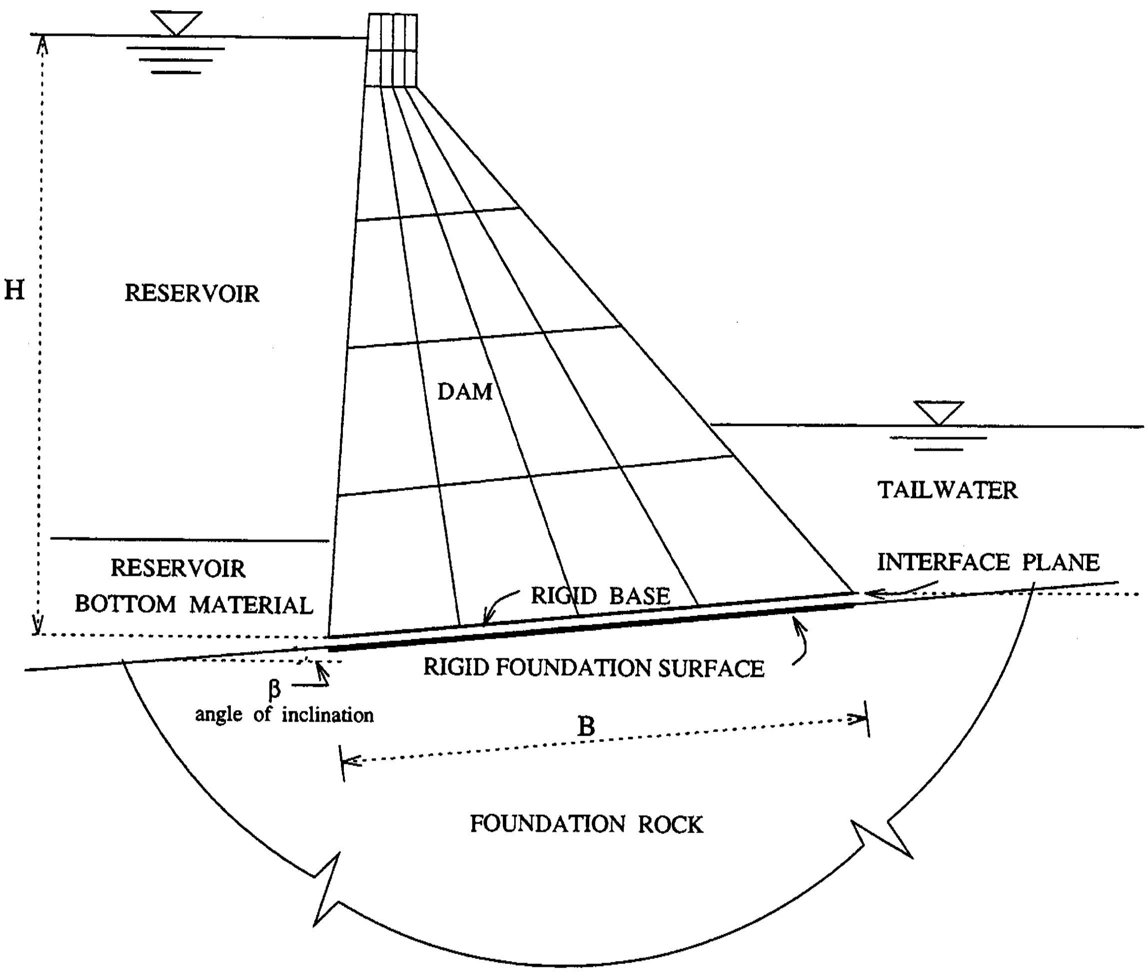


Figure 2.1. Dam-reservoir-foundation rock system with interface plane for base sliding.

plane relative to the foundation rock surface, defined positive for the dam sliding in the downstream direction; $\mathbf{U}_f$ is the vector of rigid body displacements of the foundation rock surface relative to the free-field ground motion; $\ddot{\mathbf{U}}_g(t)$ contains the specified horizontal and vertical components of the free-field ground acceleration at the foundation rock surface; $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the mass, damping and stiffness matrices for the dam associated with the nodes above the base; $\mathbf{M}_t$ contains the total translational mass and the rotational inertia of the dam about the center of the base; $\mathbf{R}$ is the $2N_d$x3 influence matrix for rigid body motion of the dam about the center of the base; $\mathbf{P}(t)$ is the vector of equivalent nodal forces due to hydrodynamic pressure acting on the dam; $\mathbf{F}_f(t)$ is the vector of foundation rock interaction forces at the base of the dam; and $\mathbf{F}_{sd}(\ddot{U}_{s\beta})$ and $\mathbf{F}_{sb}(\ddot{U}_{s\beta})$ are the inertia forces for the dam due to sliding at the interface.

The response of gravity dams to earthquake ground motion is dominated by a few modes of vibration. A Rayleigh-Ritz procedure is used to reduce the degrees-of-freedom to a small number of generalized coordinates. Representing the displacement of the dam, $\mathbf{U} = \mathbf{\Psi Z}$, by a linear combinations of J Ritz vectors, , and generalized coordinates, $\mathbf{Z}$, the equations of motion become:

$$\mathbf{M}^*\ddot{\mathbf{Z}} + \mathbf{C}^*\dot{\mathbf{Z}} + \mathbf{K}^*\mathbf{Z} + \mathbf{L}\ddot{\mathbf{U}}_f + \mathbf{\Psi}^T\mathbf{F}_{sd}(\ddot{U}_{s\beta}) = -\mathbf{L}\ddot{\mathbf{U}}_g(t) + \mathbf{\Psi}^T\,\mathbf{P}(t) \tag{2.3}$$

$$\mathbf{L}^T\ddot{\mathbf{Z}} + \mathbf{M}_t\ddot{\mathbf{U}}_f + \mathbf{F}_f(t) + \mathbf{F}_{sb}(\ddot{U}_{s\beta}) = -\mathbf{M}_t\ddot{\mathbf{U}}_g(t) + \mathbf{R}^T\mathbf{P}(t) \tag{2.4}$$

where $\mathbf{M}^* = \mathbf{\Psi}^T\mathbf{M}\mathbf{\Psi}$, $\mathbf{C}^* = \mathbf{\Psi}^T\mathbf{C}\mathbf{\Psi}$, and $\mathbf{K}^* = \mathbf{\Psi}^T\mathbf{K}\mathbf{\Psi}$ are the generalized mass, damping and stiffness matrices for the dam; and the matrix $\mathbf{L} = \mathbf{\Psi}^T\mathbf{M}\mathbf{R}$ gives the participation of the Ritz vectors in the rigid body motion of the dam.

2.2 Hybrid Frequency-Time Domain Procedure

The hybrid frequency-time domain (HFTD) procedure [Kawamoto, 1983; Darbre and Wolf, 1988] is used to solve the nonlinear and frequency-dependent equations of motion, governing the earthquake sliding response of the dam-water-foundation rock system. Iteration of the solution over time is required to converge to the final solution.

2.2.1 Linearization of Equations of Motion

The sliding inertia forces, $\mathbf{F}_{sd}$ and $\mathbf{F}_{sb}$ are functions of the sliding acceleration. An estimate of these forces for iteration $k+1$ is obtained from the sliding acceleration history for iteration k, $\ddot{U}_{s\beta}^{[k]}(t)$:

$$\mathbf{F}_{sd}^{[k+1]}(\ddot{U}_{s\beta}) = \mathbf{MRT}_{\beta}\ddot{U}_{s\beta}^{[k]}(t) \tag{2.5}$$

$$\mathbf{F}_{sb}^{[k+1]}(\ddot{U}_{s\beta}) = \mathbf{M}_t\mathbf{T}_{\beta}\ddot{U}_{s\beta}^{[k]}(t) \tag{2.6}$$

where $\mathbf{T}_{\beta}$ is a transformation vector for the sliding displacement. The linearized equations of motion for iteration $k+1$ become:

$$\mathbf{M}^*\ddot{\mathbf{Z}}^{[k+1]} + \mathbf{C}^*\dot{\mathbf{Z}}^{[k+1]} + \mathbf{K}^*\mathbf{Z}^{[k+1]} + \mathbf{L}\ddot{\mathbf{U}}_f^{[k+1]}(t) = -\mathbf{L}\ddot{\mathbf{U}}_g(t) - \mathbf{LT}_{\beta}\ddot{U}_{s\beta}^{[k]}(t) + \mathbf{\Psi}^T\mathbf{P}^{[k+1]}(t) \tag{2.7}$$

$$\mathbf{L}^T\ddot{\mathbf{Z}}^{[k+1]} + \mathbf{M}_t\ddot{\mathbf{U}}_f^{[k+1]} + \mathbf{F}_f^{[k+1]}(t) = -\mathbf{M}_t\ddot{\mathbf{U}}_g(t) - \mathbf{M}_t\mathbf{T}_{\beta}\ddot{U}_{s\beta}^{[k]}(t) + \mathbf{R}^T\mathbf{P}^{[k+1]}(t) \tag{2.8}$$

Since equations 2.7 and 2.8 contain frequency-dependent terms due to the hydrodynamic forces, $\mathbf{P}(t)$, and dam-foundation rock interaction forces, $\mathbf{F}_f(t)$, it is necessary to transform the equations of motion to the frequency domain. The equations of motion for the entire system in the frequency domain are:

$$\mathbf{S}(\omega)\left\{\begin{array}{c}\bar{\mathbf{Z}}^{[k+1]}(\omega)\\ \bar{\mathbf{U}}_f^{[k+1]}(\omega)\end{array}\right\} = \mathbf{L}^x(\omega)\bar{\ddot{U}}_g^x(\omega) + \mathbf{L}^y(\omega)\bar{\ddot{U}}_g^y(\omega) + \mathbf{L}^s(\omega)\bar{\ddot{U}}_{s\beta}^{[k]}(\omega) \tag{2.9}$$

where $\bar{\mathbf{Z}}^{[k+1]}(\omega)$ and $\bar{\mathbf{U}}_f^{[k+1]}(\omega)$ are the Fourier transforms of the generalized displacements and foundation displacements, respectively; $\bar{\ddot{U}}_g^x(\omega)$, $\bar{\ddot{U}}_g^y(\omega)$, and $\bar{\ddot{U}}_{s\beta}^{[k]}(\omega)$ are the Fourier transforms of the free-field ground acceleration components and sliding acceleration; and the force vectors $\mathbf{L}^x(\omega)$, $\mathbf{L}^y(\omega)$ and $\mathbf{L}^s(\omega)$ are complex-valued functions associated with these accelerations that contain frequency-dependent terms due to hydrodynamic pressure. The symmetric dynamic stiffness matrix, $\mathbf{S}(\omega)$, is:

$$\mathbf{S}(\omega) = \left[\begin{array}{ll} -\omega^2\mathbf{M}^* + (1+i\eta)\mathbf{K}^* + \omega^2\mathbf{B}_{\Psi z}(\omega) & -\omega^2\mathbf{L} + \omega^2\mathbf{B}_{\Psi f}(\omega)\\ -\omega^2\mathbf{L}^T + \omega^2\mathbf{B}_{Rz}(\omega) & -\omega^2\mathbf{M}_t + \mathbf{K}_f(\omega) + \omega^2\mathbf{B}_{Rf}(\omega)\end{array}\right]$$

The complex-functions $\mathbf{B}_{\Psi z}(\omega)$, $\mathbf{B}_{\Psi f}(\omega)$, $\mathbf{B}_{Rz}(\omega)$, and $\mathbf{B}_{Rf}(\omega)$ represent the effect of hydrodynamic forces due to dam-water interaction [Fenves and Chopra, 1984], and result from the matrices $\mathbf{\Psi}^T\mathbf{P}$ and $\mathbf{R}^T\mathbf{P}$; $\mathbf{K}_f(\omega)$ is the impedance matrix for the rigid interface at the surface of the foundation rock [Dasgupta and Chopra, 1979].

2.2.2 Solution of Equations of Motion

The solution of the equation 2.9 gives:

$$\left\{\begin{array}{c}\bar{\mathbf{Z}}^{[k+1]}(\omega)\\ \bar{\mathbf{U}}_f^{[k+1]}(\omega)\end{array}\right\} = \bar{\mathbf{Y}}^x(\omega)\bar{\ddot{U}}_g^x(\omega) + \bar{\mathbf{Y}}^y(\omega)\bar{\ddot{U}}_g^y(\omega) + \bar{\mathbf{Y}}^s(\omega)\bar{\ddot{U}}_{s\beta}^{[k]}(\omega) \tag{2.10}$$

where $\bar{\mathbf{Y}}^l(\omega)$, $l = x, y, s$ is the frequency response function for unit harmonic base acceleration of component l. The frequency response functions are obtained from the solution of:

$$\mathbf{S}(\omega)\bar{\mathbf{Y}}^l(\omega) = \mathbf{L}^l(\omega) \tag{2.11}$$

To minimize storage, the frequency response functions, $\bar{\mathbf{Y}}^l(\omega)$, can be computed for a few frequencies, and the responses for other frequencies are obtained by interpolation [Tajirian, 1981; Fok and Chopra, 1985].

2.2.3 Forces at the Interface

The interface forces must be computed to determine the sliding state. After rearranging equation 2.8, and performing a transformation, using a matrix $\mathbf{T}$, the components of the interface force, $\mathbf{T}^T\mathbf{F}_f^{[k+1]}(t)$, in the inclined coordinate system are the shear force $V_\beta^{[k+1]}(t)$, normal force $N_\beta^{[k+1]}(t)$, and moment at the center of the base $M_\beta^{[k+1]}(t)$, which are defined as:

$$\left\{ \begin{array}{c} V_\beta^{[k+1]}(t) \\ N_\beta^{[k+1]}(t) \\ M_\beta^{[k+1]}(t) \end{array} \right\} = \left\{ \begin{array}{c} V^{[k+1]}(t) \\ N^{[k+1]}(t) \\ M^{[k+1]}(t) \end{array} \right\} - \left\{ \begin{array}{c} m_V \\ m_N \\ m_M \end{array} \right\} \ddot{U}_{s\beta}^{[k+1]}(t) \tag{2.12}$$

The coefficients m_V, m_N and m_M are the masses associated with sliding acceleration. The forces $V^{[k+1]}(t)$, $N^{[k+1]}(t)$, and $M^{[k+1]}(t)$ exclude sliding at the current step, and are defined as:

$$\left\{ \begin{array}{c} V^{[k+1]}(t) \\ N^{[k+1]}(t) \\ M^{[k+1]}(t) \end{array} \right\} = -\mathbf{T}^T\mathbf{L}^T\ddot{\mathbf{Z}}^{[k+1]}(t) - \mathbf{T}^T\mathbf{M}_t\ddot{\mathbf{U}}_f^{[k+1]}(t) - \mathbf{T}^T\mathbf{M}_t\ddot{\mathbf{U}}_g(t)$$
$$+\mathbf{T}^T\mathbf{R}^T \left[\mathbf{P}_g(t) + \mathbf{T}^T\mathbf{P}_s^{[k]}(t) + \mathbf{T}^T\mathbf{P}_{zf}^{[k+1]}(t) \right] \tag{2.13}$$

Since the system has frequency-dependent characteristics, the interface forces are evaluated first in the frequency domain and then transformed to the time domain. Substituting equation 2.10 in equation 2.13 gives the interface forces expressed in the frequency domain:

$$\left\{ \begin{array}{l} \bar{V}^{[k+1]}(\omega) \\ \bar{N}^{[k+1]}(\omega) \\ \bar{M}^{[k+1]}(\omega) \end{array} \right\} = \mathbf{C}_x(\omega)\bar{\ddot{U}}_g^x(\omega) + \mathbf{C}_y(\omega)\bar{\ddot{U}}_g^y(\omega) + \mathbf{C}_s(\omega)\bar{\ddot{U}}_{s\beta}^{[k]}(\omega) \tag{2.14}$$

where $\bar{V}^{k+1}(\omega)$, $\bar{N}^{k+1}(\omega)$, and $\bar{M}^{k+1}(\omega)$ are the Fourier transforms of the interface forces; and $\mathbf{C}_x(\omega)$, $\mathbf{C}_y(\omega)$, and $\mathbf{C}_s(\omega)$ are complex-valued functions associated with the base accelerations. Equation 2.14 is very convenient for computing the interface forces during the iterative solution. All terms are evaluated at the beginning of the computation and remain unchanged, except for the transform of the sliding acceleration, $\bar{\ddot{U}}_{s\beta}^{[k]}$, which is the only function that must be computed and updated in an iteration.

2.2.4 State Determination

Applying the Mohr-Coulomb law for iteration $k+1$ gives:

$$[V_\beta^{[k+1]}(t) + V_{\beta,st}] = e^{[k]}(t)\ [c + \mu(N_\beta^{[k+1]}(t) + N_{\beta,st})] \tag{2.15}$$

where $V_{\beta,st}$ and $N_{\beta,st}$ are the resultant normal and shear forces due to hydrostatic, uplift and other static loads on the dam. The cohesion force, c, and the friction coefficient, μ, are specified properties of the sliding interface. The function $e^{[k]}(t)$ defines the direction of sliding. It is +1 when the dam is sliding in the downstream direction, -1 when the dam is sliding in the upstream direction, or zero when the dam is not sliding. The sliding acceleration that satisfies the Mohr-Coulomb law is obtained by substituting the shear and normal forces from equation 2.12 into equation 2.15:

$$\ddot{U}_{s\beta}^{[k+1]}(t) = \frac{[V^{[k+1]}(t) + V_{\beta,st}] - e^{[k]}(t)\,[c + \mu N^{[k+1]}(t) + \mu N_{\beta,st}]}{m_R(t)} \tag{2.16}$$

where $m_R(t)$ is a effective mass resisting sliding acceleration along the interface plane.

The dam slides when the total shear force at the base exceeds the resistance at the interface:

$$|V^{[k+1]}(t) + V_{\beta,st}| \geq |c + \mu(N^{[k+1]}(t) + N_{\beta,st})| \tag{2.17}$$

and the direction of sliding is given by:

$$e^{[k+1]}(t) = \frac{V^{[k+1]}(t) + V_{\beta,st}}{|V^{[k+1]}(t) + V_{\beta,st}|} \tag{2.18}$$

Sliding stops when the sliding velocity is zero. The sliding velocity is computed from the integration of the sliding acceleration.

2.3 Convergence and Accuracy of Solution

The HFTD procedure involves iterative evaluation of equations 2.16 to 2.14 in the frequency and time domains. The total duration of response is divided into segments of time, and the solution is obtained over one segment. After convergence is achieved in a segment, the analysis proceeds to the next segment. Numerical stability of the HFTD procedure has been confirmed by Darbre and Wolf [1988]. Convergence for a segment is achieved when the maximum difference between successive iterations of the response quantities is less than a tolerance, ϵ, at every time step in the segment. Thus, iteration $k+1$ terminates when:

$$[\Delta A(t)] = max\frac{|A^{[k+1]}(t) - A^{[k]}(t)|}{|A^{[k+1]}(t)|} \leq \epsilon \tag{2.19}$$

where the quantity A represents the generalized displacements, the foundation displacements, and the sliding acceleration.

2.4 Energy Balance Equations

A further verification of the solution accuracy is obtained by computing the energy balance for the system [Uang and Bertero, 1988]. The energy balance is expressed as:

$$E_i = E_s + E_f + E_d$$

E_i is the input energy due to ground motion. It represents the work done by the forces produced by the free-field ground motion:

$$\begin{aligned} E_i &= \int_0^t \{\mathbf{\Psi}^T\mathbf{P}(\ddot{\mathbf{U}}_g)\}^T d\mathbf{Z} + \int_0^t \{\mathbf{R}^T\mathbf{P}(\ddot{\mathbf{U}}_g)\}^T d\mathbf{U}_b \\ &\quad - \int_0^t \{\mathbf{L}\ddot{\mathbf{U}}_g(t)\}^T d\mathbf{Z} - \int_0^t \{\mathbf{M}_t\ddot{\mathbf{U}}_g(t)\}^T d\mathbf{U}_b \end{aligned} \tag{2.20}$$

E_d represents a number of energy terms in the dam and impounded water due to deformation of the dam. It contains the conservative kinetic and strain energy in the dam and the work dissipated by hysteretic damping, and the work performed by the hydrodynamic forces acting through the dam displacements:

$$\begin{aligned} E_d &= \int_0^t \{\mathbf{M}^*\ddot{\mathbf{Z}}\}^T d\mathbf{Z} + \int_0^t \{\mathbf{L}\ddot{\mathbf{U}}_b\}^T d\mathbf{Z} + \int_0^t \{\mathbf{C}^*\dot{\mathbf{Z}}\}^T d\mathbf{Z} \\ &\quad + \int_0^t \{\mathbf{K}^*\mathbf{Z}\}^T d\mathbf{Z} + \int_0^t [-\mathbf{\Psi}^T\mathbf{P}(\ddot{\mathbf{Z}}, \ddot{\mathbf{U}}_b)]^T d\mathbf{Z} \end{aligned} \tag{2.21}$$

E_f is the work performed by the forces acting through the foundation rock displacement:

$$\begin{aligned} E_f &= \int_0^t \{\mathbf{L}^T\ddot{\mathbf{Z}}\}^T d\mathbf{U}_f + \int_0^t \{\mathbf{M}_t\ddot{\mathbf{U}}_b\}^T d\mathbf{U}_f \\ &+ \int_0^t [-\mathbf{R}^T\mathbf{P}(\ddot{\mathbf{Z}},\ddot{\mathbf{U}}_b)]^T d\mathbf{U}_f + \int_0^t \{\mathbf{F}_f(t)\}^T d\mathbf{U}_f \end{aligned} \tag{2.22}$$

E_s is the energy associated with the sliding displacement at the base of the dam:

$$\begin{aligned} E_s &= \int_0^t \{\mathbf{L}^T\ddot{\mathbf{Z}}\}^T \mathbf{T} dU_{s,\beta} + \int_0^t \{\mathbf{M}_t\ddot{\mathbf{U}}_b\}^T \mathbf{T} dU_{s,\beta} \\ &+ \int_0^t [-\mathbf{R}^T\mathbf{P}(\ddot{\mathbf{Z}},\ddot{\mathbf{U}}_b)]^T \mathbf{T}\ dU_{s,\beta} + \int_0^t \{\mathbf{F}_f(t)\}^T \mathbf{T}\ dU_{s,\beta} \end{aligned} \tag{2.23}$$

In the energy equations, $\mathbf{U}_b = \mathbf{U}_f + \mathbf{T}_\beta U_{s,\beta}$, is the total displacement of the dam base relative to the free-field ground motion.

Chapter 3

MODELING PARAMETERS

This chapter describes and gives guidelines on the the parameters that are needed in the modeling of a dam system. Selection of these parameters is important in order to assure an accurate representation of the dam response in an earthquake. The dimensional units are arbitrary, but they must be consistent for the analysis with the EAGD-SLIDE computer program.

3.1 Dam Discretization

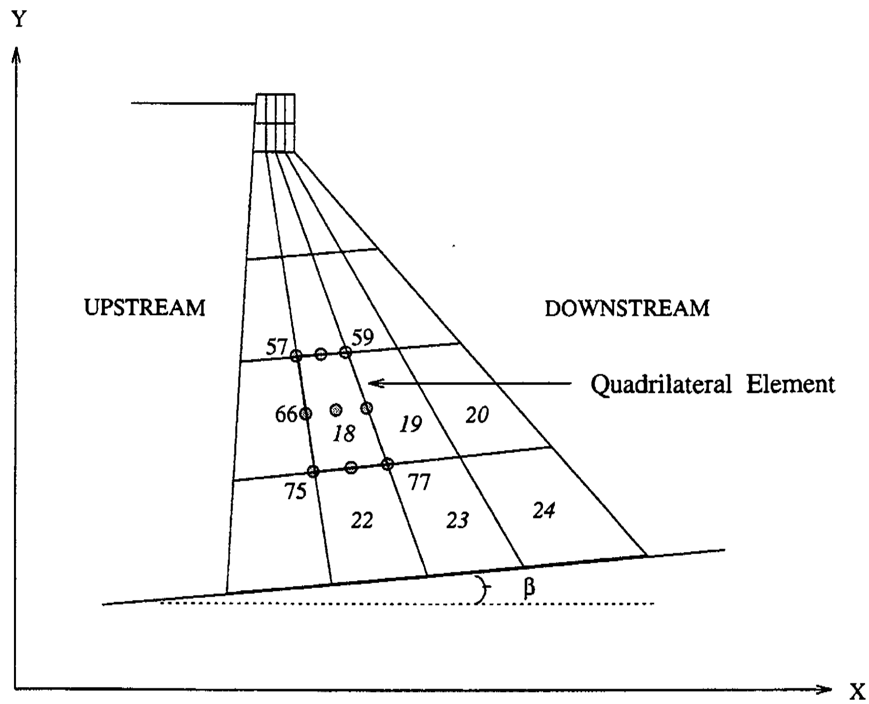
The monolith, shown in Figure 3.1(a), is modeled using planar, nine-node quadrilateral finite elements allowing representation of a general cross-section geometry. The base of the dam monolith is modeled as a straight line and it may be at an angle of inclination, β, with the horizontal. The angle β is defined by the program according the coordinates of the nodes of the base at the downstream and upstream directions. The base of the dam is assumed rigid because the base deformation has little effect on the dam response [Fenves and Chopra, 1984]. Partial uplifting of the base due to release of tensile stresses is not represented with this kinematic assumption.

The nodal points in the finite element model are located with reference to a global X-Y coordinate system, where the X-axis must be positive in the downstream direction and the Y-axis must be positive in the upward direction, as shown in Figure 3.1(a). Node generation (linear generation and quadrilateral generation), shown in Figure 3.2, is available in the program to reduce the amount of data required to describe the finite element model. Linear generation is useful for generating equally spaced nodes along a straight line. Quadrilateral interpolation allows a series of nodes to be generated, given the nodes at the four corners and the node increment in each direction. Nodes generated along the sides are equally spaced and nodes generated inside the quadrilateral are at the intersection of the lines joining nodes in opposite directions.

The nodes defining each nine-node quadrilateral element are numbered from J1 to J9, as shown in Figure 3.1(b). The numbering of elements is arbitrary. The numbering of nodal points for the elements, however, determines the bandwidth of the structural stiffness matrix, and hence affects the computational effort. Therefore, it is recommended to number the nodal points such that the difference in the numbers for the nodal points for an element is minimized. Element generation is available in the program. Element generation is applied when the elements generated are formed by incrementing the node numbers of the basic element, as shown in Figure 3.1(a).

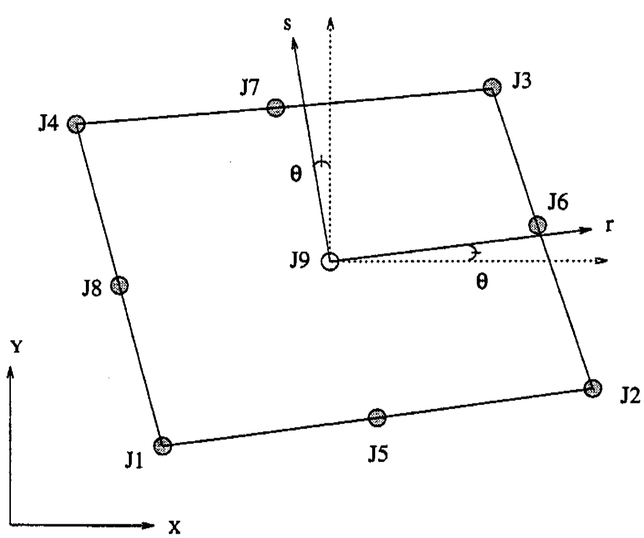
All elements are assumed to be in state of plane stress with linear elastic, orthotropic material properties. Orthotropic properties are defined with respect to the orthogonal directions r and s, which are at an angle of inclination θ with respect to the global X-Y coordinate system, as shown in Figure 3.1(b). The angle θ is positive counter-clockwise. When isotropic materials are used, properties defined in the r and s directions are the same and it is recommended to define the angle of inclination as zero. The elastic properties of the materials can be defined independently for each element. In addition, elements can have different thicknesses, with exception of elements in contact with the base which must have the same thickness.

Energy dissipation in the dam concrete is represented by constant hysteretic damping



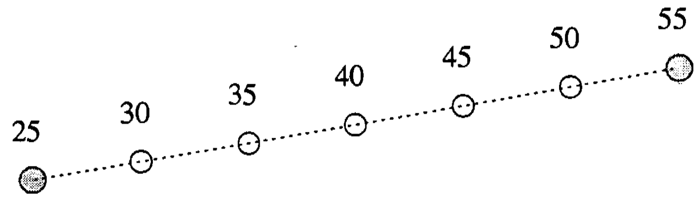
TO GENERATE ELEMENTS 18,19,20,22,23,24
N=75,77,59,57,76,68,58,66,67 G=3,2,1,4

(a) Finite element discretization and coordinate system



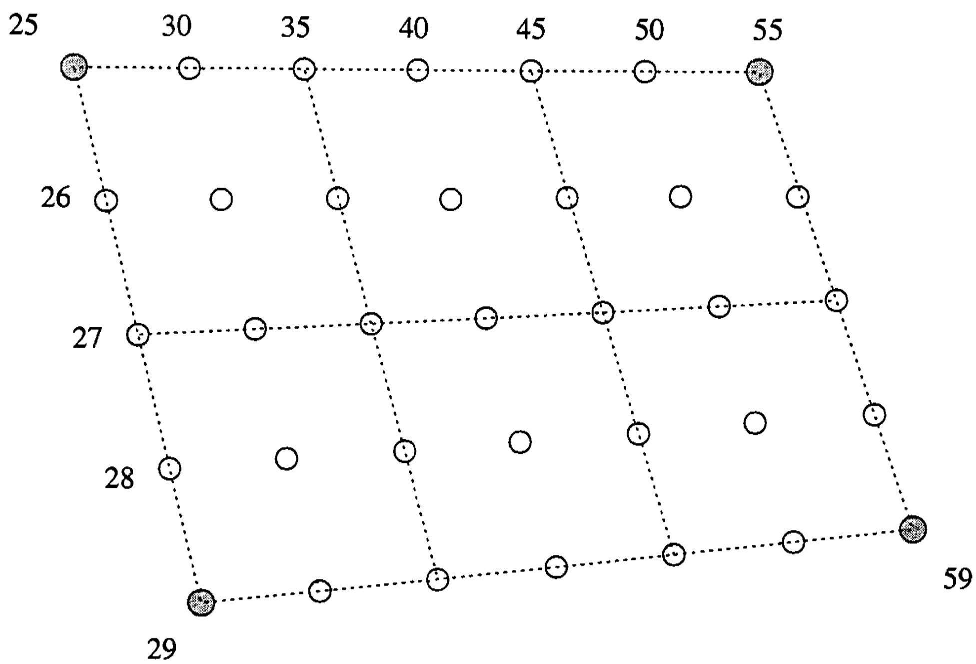
(b) Element definition

Figure 3.1. Dam idealization.



g1=25 g2=55 i=5 or g1=55 g2=25 i=-1

(a) Linear generation



Q=25,29,55,59,1,5 or Q=59,29,55,25,-5,-1 etc

(b) Quadrilateral generation

Figure 3.2. Node generation.

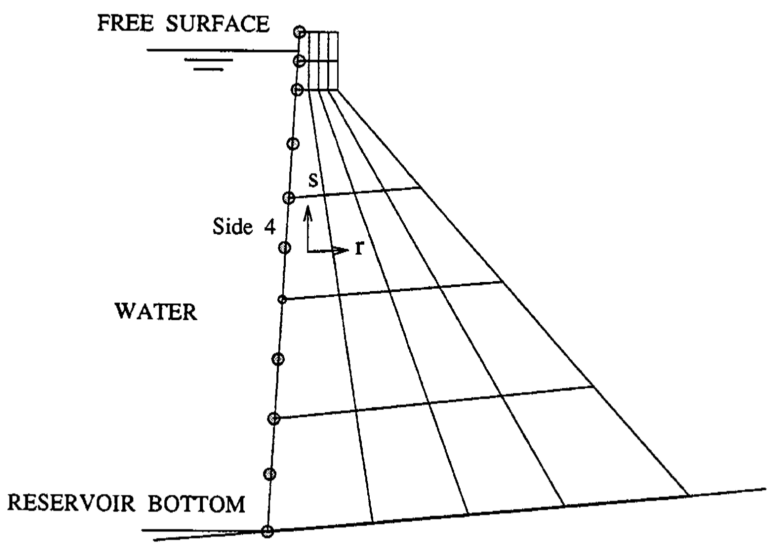
with a factor η_s. A damping factor η_s corresponds to a viscous damping ratio of $\eta_s/2$ at resonant vibration frequencies of the dam.

Gravity loads due to the own weight of the dam, head water and tail water are computed by the program. In addition, uplift forces and concentrated loads acting at any location can be included in the analysis.

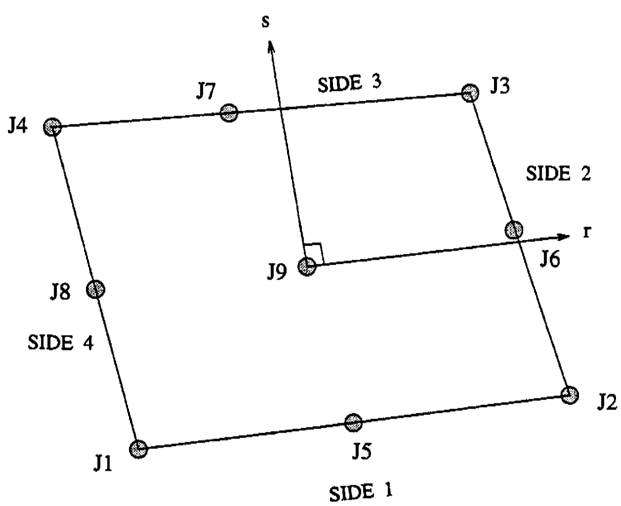
3.2 Water Reservoir

The water in the reservoir is idealized as a two-dimensional domain extending to infinity in the upstream direction. The water is treated as an inviscid and compressible fluid. The upstream face of the dam should be vertical, or near vertical, because the hydrodynamic pressure acting on the dam is computed assuming the upstream face is vertical. The reservoir bottom is assumed to be horizontal. This assumption is considered to be valid when the angle of base inclination is small. Hydrodynamic and hydrostatic forces due to the impounded water are computed by the program using the information given for the reservoir.

The elevation of the free-surface of the impounded water and the list of elements in contact with the reservoir at the upstream face must be specified. The interface is defined by indicating the element side associated with the wet surface, as shown in Figure 3.3(a). The elevation of the reservoir bottom is computed from the smallest Y-coordinate of the nodal point for the wet element. Element side numbers 1, 2, 3, and 4 are defined by the nodes J1-J2, J2-J3, J3-J4, and J4-J1, respectively, as shown in Figure 3.3(b). Other properties for the impounded water, such as velocity of pressure waves, and mass density and unit weight must be defined.



(a) Identification of wet elements in contact with reservoir



(b) Identification of sides of elements

Figure 3.3. Model of water impounded in reservoir.

The effect of the reservoir bottom materials is accounted for by the wave reflection coefficient, α. A wave reflection coefficient of unity indicates that pressure waves are reflected from the reservoir bottom without attenuation; a wave reflection coefficient of zero indicates that vertically propagating waves are fully absorbed into the reservoir bottom material without reflection.

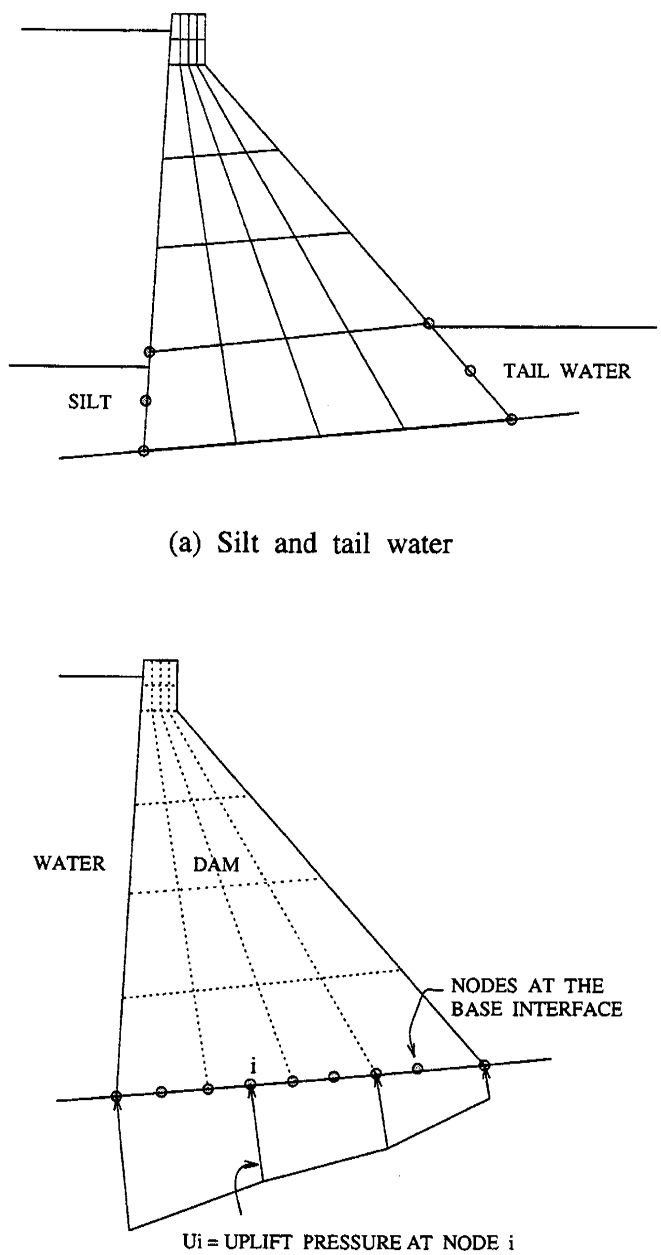
Hydrostatic pressures due to the impounded water are determined by the program using the information given for the reservoir. Other hydrostatic effects, however, due to silt and the tail water are defined separately, as shown in Figure 3.4(a). The list of elements in contact with these materials is used for computing the hydrostatic pressures.

Uplift pressures at the base are defined at each node at the base of the dam. These pressures act perpendicular to the base interface. The program computes the uplift pressures at intermediate points given the uplift pressure at two nodes. The uplift forces are computed assuming that all the elements at the base have the same thickness. Uplift pressures are shown in Figure 3.4(b).

3.3 Foundation Rock

The foundation rock is idealized as a homogeneous, isotropic and viscoelastic half-plane for the purpose of computing the impedance functions that characterize the dam-foundation rock interaction. This half-plane idealization of the foundation rock is valid for dams with a base having a small angle of inclination.

If the effects of dam-foundation rock interaction are included, the stiffness matrix for the foundation-rock region appears in the equation of motion of the dam. Since the dam base is assumed rigid, the frequency-dependent impedance matrix is defined with respect to the three rigid body displacements at the the center of the base. An impedance matrix is



(a) Silt and tail water

(b) Definition of uplift pressure

Figure 3.4. Hydrostatic and uplift forces.

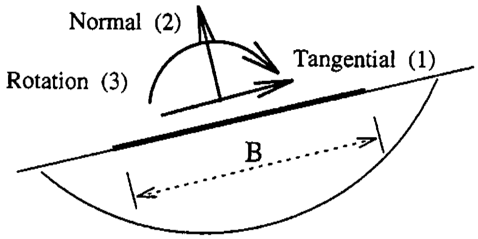
defined for a given damping ratio. Figure 3.5 shows the impedance matrix for a foundation rock with η_f=0.10. A data file is supplied with EAGD-SLIDE for the impedance functions for a Poisson's ratio of 1/3 and the following values of hysteretic damping factor for the foundation rock: $\eta_f = 0.01, 0.10, 0.25$ and 0.50. Other impedance functions can be used, as specified in Appendix A.

3.4 Interface

The properties of the sliding interface for the Mohr-Coulomb friction model are defined by a constant cohesion force and a constant coefficient of friction. The friction properties at the base interface should be determined based on site specific investigation of the dam and foundation rock. The cohesion force can be reasonably taken to be zero, which represents the fact that little cohesive resistance can be expected during earthquake-induced sliding of the dam. Values of the coefficient of friction can be assumed to be relatively high, ranging from 0.8 to 1.2, to consider the roughness of the interface surface after the formation of cracks.

$$K_{f\beta} = E_{fr} \begin{bmatrix} \bar{K}_{11} & 0 & B\,\bar{K}_{13} \\ 0 & \bar{K}_{22} & 0 \\ B\,\bar{K}_{31} & 0 & B^2\bar{K}_{33} \end{bmatrix}$$

$$\bar{K}_{ij} = K_{ij} + i\,a_o C_{ij}$$



C_s = shear velocity at the foundation rock

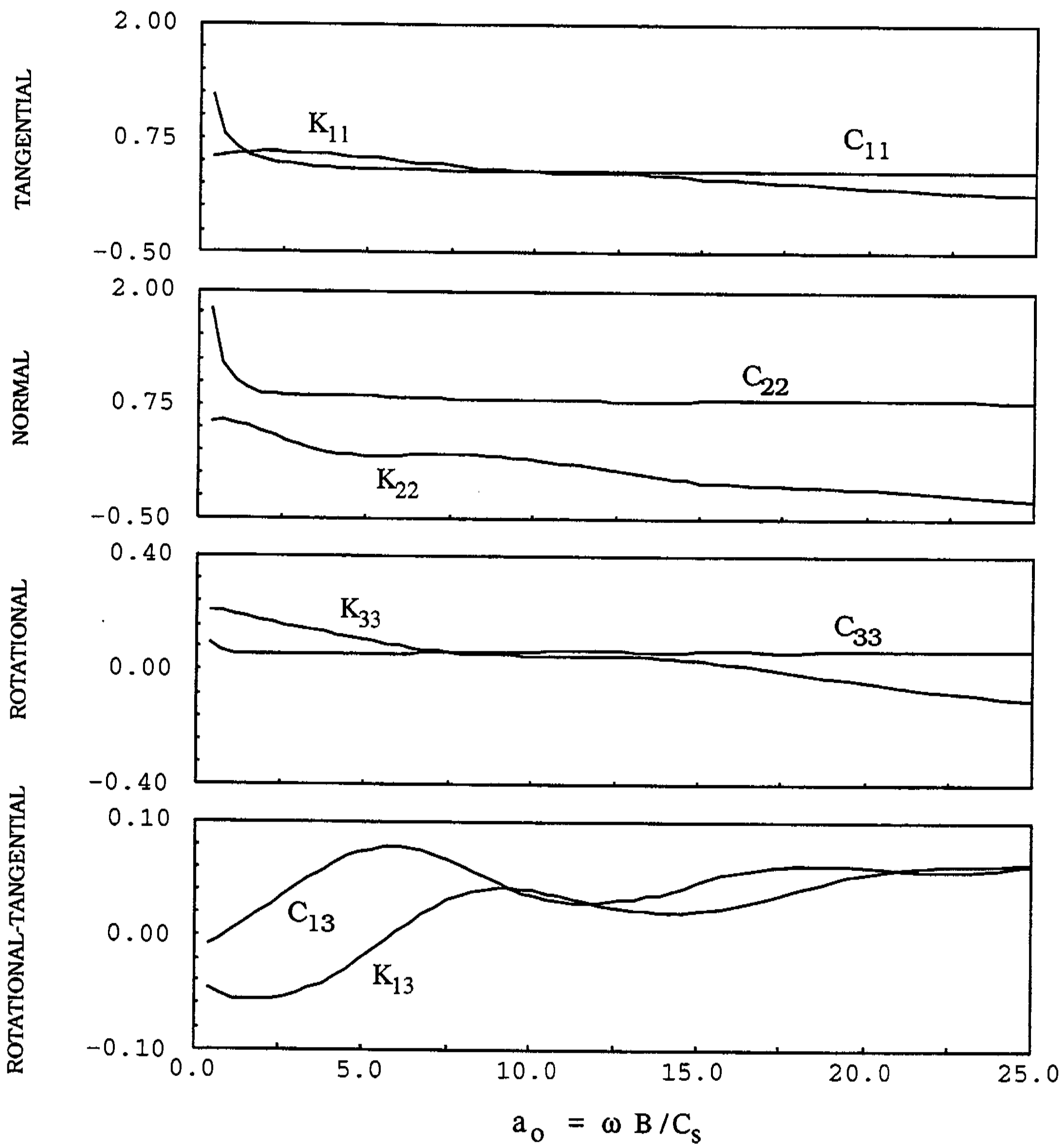


Figure 3.5. Impedance functions for foundation rock (η_f =0.10).

Chapter 4

RESPONSE PARAMETERS

This chapter provides guidelines for the selection of response parameters which must be selected carefully to obtain accurate response results.

4.1 Number of Generalized Coordinates

The number of Ritz vectors required to represent the earthquake response of gravity dams is much less than the degrees-of-freedom in the finite element model of the dam. It is recommended to use at least five modes to obtain accurate response, particularly for higher excitation frequencies.

4.2 Maximum Excitation Frequency

The selection of the frequency range in the frequency domain solution, which ranges from 0 to F, for which the response of the dam is computed depends on the following criteria:

1. The maximum frequency, F, should be greater than the frequencies contained in the free-field ground acceleration records. Frequencies up to 25 Hertz are represented in most processed records. Therefore it is recommended that:

$$F \geq 25 \text{ Hz}$$

2. The maximum frequency should be large enough to include the range of frequencies over which the dam has significant dynamic response. For this purpose, it is recommended that $F > F_J$, where F_J is the vibration frequency of the highest Ritz vector included in the analysis.

4.3 Time Step

The time step, Δt, is an important parameter in the frequency domain solution.

1. The following relation is required for the maximum excitation frequency:

$$\Delta t \leq \frac{1}{2F}$$

2. When sliding is included in the response, the change in sliding status can be checked only at successive time intervals, although in reality sliding may occur between two steps. The program has an algorithm to correct this problem. To avoid propagation of errors it is recommended to use a minimum time step for the analysis:

$$\Delta t \leq 0.01$$

4.4 Parameter for Fourier Transforms

The following parameters are necessary for the application of the FFT in the frequency domain solution:

1. The Fourier transforms of a response history are computed for the total duration, which includes the duration of response, T_r, and the duration of the quiet zone, T_q,

as shown in Figure 4.1(a):

$$T = T_r + T_q$$

To reduce aliasing errors, it is recommended that:

$$T_q \geq \frac{1.5}{\eta_s}\frac{1}{f_1}$$

where η_s is is the constant hysteretic damping factor for the dam concrete, and f_1 is the fundamental resonant frequency, in Hertz, of the dam system.

2. The number of frequencies, N, depends on the total duration and the time interval.

$$T = N * DT$$

It is recommended that N be a product of small primes, usually primes of twos, $N = 2^M$. However, other values of N may be used, although the computation for the FFT will increase.

3. The frequency increment, Δf, and maximum frequency are computed as follows:

$$\Delta f = \frac{1}{T}$$

$$F = N\Delta f$$

4. The frequency increment Δf must be small enough to represent the frequency response functions for the generalized coordinates, especially near the fundamental resonant peak. It is recommended that:

$$\Delta f \leq f_1/50$$

4.5 Parameters for Interpolation of Frequency Response Functions

The frequencies for interpolating the frequency response function are determined as follows [Fok and Chopra, 1985]:

$$(\Delta f)_i = (\Delta f)_{i-1} \frac{b}{max \frac{|\Delta \tilde{Y}_{j,i-1}|}{|\tilde{Y}_{ji}|}} \tag{4.1}$$

where the recommended values for b, Δf_{min} and Δf_{max} are:

$$b = 0.5 \qquad \Delta f_{min} = 0.01\, f_f \qquad \Delta f_{max} = 0.20\, f_f \tag{4.2}$$

and f_f is computed from:

$$f_f = min(\frac{C}{4H}, f_1)$$

in which $\frac{C}{4H}$ is the fundamental frequency of the impounded water and f_1 is the fundamental frequency of the dam.

4.6 Parameters for the HFTD Analysis

The following parameters, shown in Figure 4.1, are necessary for the hybrid-frequency time domain procedure using a segmentation approach:

1. **Length of Segments**

   There are no general rules to select the length of each segment, although segments with small number of time steps are recommended to achieve fast convergence when large sliding is expected. From experience, segments of 20 to 50 time steps provide a good rate of convergence for many problems.

2. **Length of Transition Zone**

A transition zone must be appended at the end of the segment to avoid sudden unloading. It is recommended to have a short length for the transition zone, not greater than the length of the segment.

3. **Tolerances**

The tolerances determine when iterates have converged. Tolerances of 0.005 are recommended.

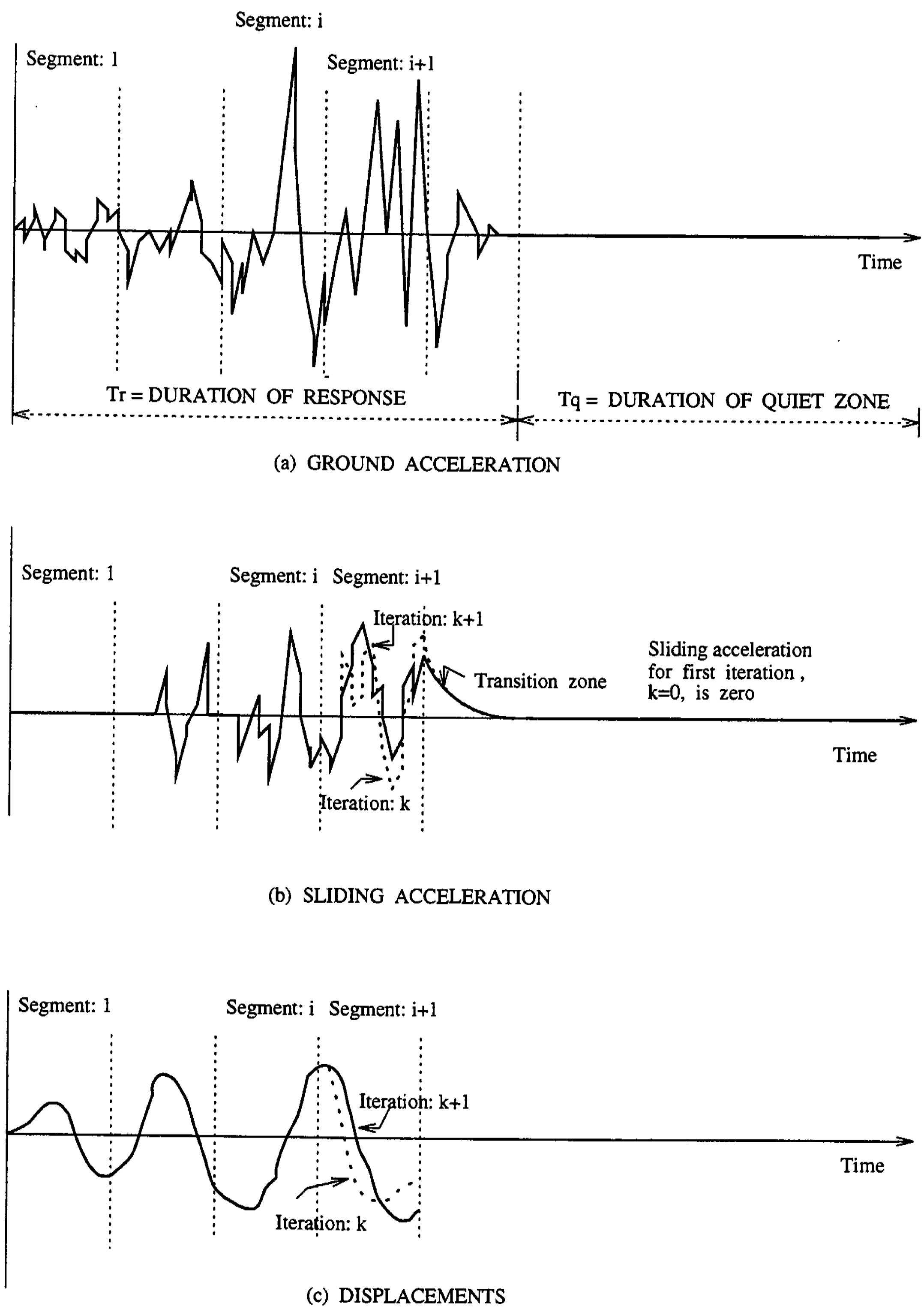


Figure 4.1. Response parameters used in iteration for a segment.

Chapter 5

INPUT DESCRIPTION

5.1 Input for EAGD-SLIDE

The input data for EAGD-SLIDE are entered in a free-field format. Each block has a name and data defined for the block. A blank line indicates the end of the block. Blocks may be entered in any order. Default data values [value] or previous input value [pv] are indicated when they can be used. There are no built-in units in the program; the user is responsible for using a consistent set of units.

TITLE

One line for title of the problem

SYSTEM

`F=name   N=nodes   E=elements   V=vectors   T=tol   I=iter   P=post`

`name`	[EAGD]	name (8 char or less) to identify output files
`nodes`		number of nodes in the model of dam
`elements`		number of elements in the model of dam
`vectors`	[0]	number of Ritz vectors for dynamic analysis
`tol`	[1.e-8]	orthogonality tolerance for Ritz vectors
`iter`	[5]	orthogonality iterations for Ritz vectors
`post`	[0]	=1, save data and response values in a binary file for additional post-processing (using EAGD-POST); =0, do not save

NODE COORDINATES

```
nid  X=x  Y=y  S=s  G=g1,g2,i  Q=q1,q2,q3,q4,in,jn
```

`nid`		node number between 1 and `nodes`
`x,y`	[pv]	global X, Y coordinates of nodes
`s`	[1, pv]	scale factor for node coordinates

Linear generation:

`g1,g2`		node numbers for linear generation
`i`		node number increment

Quadrilateral generation:

`q1,q2,q3,q4`		node numbers for quadrilateral generation
`in`		node number increment in q1, q2 direction
`jn`		node number increment in q1, q3 direction

Enter as many lines as necessary.

BASE

```
n1,n2,inc  U=u1,u2  T=thick
```

`n1,n2,inc`		first and last node number and node increment defining base of dam
`u1`	[0]	uplift pressure at node n1
`u2`	[0]	uplift pressure at node n2
`thick`	[1, pv]	width for computing uplift force from pressure

Enter as many lines as necessary.

NOTE: The base may be at an angle, which is reported in degrees. A warning is issued if the base nodes are not on a straight line. Uplift pressures at base nodes are used only for dynamic analysis when sliding is considered.

RESTRAINTS

`n1,n2,inc   R=r1,r2`

n1,n2,inc		first and last node number, and node increment
r1	[0]	X-translation code
r2	[0]	Y-translation code

Enter as many lines as necessary.

NOTE: Normally it is not necessary to specify restraints, other than those implied by the BASE nodes. A code=1 means a restraint in the specified direction.

MATERIAL

`N=nmat   nm  W=w   M=m   E=er,es   U=ur,us   G=grs   T=tz   A=ar,as`

nmat	[1]	number of materials
nm		material identification number, 1 to nmat
w	[0]	weight per unit volume
m	[0]	mass per unit volume
er,es		modulus of elasticity in the r and s directions
ur,us		Poisson's ratio in the r and s directions
grs	$[\frac{er}{(2+2ur)}]$	shear modulus in r,s plane
tz	[0]	reference temperature
ar,as	[0]	coefficient of thermal expansion in the r and s directions

Enter one line for each nmat material data.

ELEMENT

`nel N=j1,j2,...j8,j9  M=mat  H=th  G=g1,g2,i1,i2  A=a`

nel		element number
j1,...j9		element node numbering
mat	[pv]	material identification number for element
th	[pv]	element thickness (default is one)
g1,g2		g1 = number of elements generated in the j1,j5,j2 direction; g2 = number of elements generated in the j1,j8,j4 direction
i1,i2	[1]	increment for element numbering in the j1,j5,j2 and j1,j8,j4 directions, respectively
a		angle with respect to X-Y coordinate system for which orthotropic materials are defined

Enter as many lines as necessary.

NOTE: Element generation is applied when the node node numbers of the generated elements are formed by incrementing the node numbers of the basic element.

DAMPING

`H=h`

h	[0]	hysteretic damping factor for dam

INTERFACE

`U=u  F=c`

u	[1]	coefficient of friction for the base interface
c	[0]	cohesion force for the base interface

NOTE: If this block is not included, sliding is not allowed at the base (linear response).

RESERVOIR

`V=c   M=m   H=w,y   A=a`

`e1,e2,inc   S=n`

c		wave propagation velocity in water
m		mass density of water
w		unit weight of water
y		Y-coordinate of the free-surface of the reservoir
a	[1]	wave reflection coefficient for the reservoir bottom
e1,e2,inc		first and last element and element increment defining the wet surface on the upstream face
n		element side associated with wet surface

Enter as many lines as necessary.

NOTE: The elevation of the bottom reservoir is equal to the smallest Y-coordinate of the nodes defining the wet elements.

HYDROSTATIC PRESSURE

`e1,e2,inc   S=n   H=w1,y1   T=w2,y2`

e1,e2,inc		first and last element, and element increment
n	[pv]	element side associated with wet surface
w1		unit weight of head water or silt at upstream face
y1		Y-coordinate of the free surface at upstream face
w2		unit weight of tail water or silt at the downstream face
y2		Y-coordinate of the free surface at downstream face

Enter as many lines as necessary.

NOTE: Hydrostatic pressure for reservoir should not be defined here.

MASSES

`n1,n2,inc  M=m1,m2`

`n1,n2,inc`		first and last node number, and node increment
`m1`	[0]	X-translation mass
`m2`	[0]	Y-translation mass

Enter as many lines as necessary.

STATIC LOADS

`n1,n2,inc  F=fx,fy`

`n1,n2,inc`		first and last node number, and node increment
`fx`	[0]	static load in X-direction
`fy`	[0]	static load in Y-direction

Enter as many lines as necessary.

FOUNDATION

`E=e  U=u  M=m  D=d  I=filef  P=prn`

`e`		modulus of elasticity for foundation rock
`m`		mass density for foundation rock
`u`	[0.333]	Poisson's ratio for the foundation rock
`d`	[0.10]	hysteretic damping coefficient for foundation rock
`filef`	[IMP3.DAT]	input file containing the frequency-dependent impedance functions
`prn`	[0]	=0, no print; =1, print impedance functions

NOTE: If this block is not given, the foundation rock is assumed to be rigid. If foundation rock is flexible, the impedance functions are read from `filef`, with the format shown in Appendix A.

FREQUENCY RESPONSE

`D=dt   N=n   I=r   B=b   W=dmax,dmin   N=maxfrq`

`dt`		time step
`n`		total number of points
`r`	[n]	=n, no interpolation; =y, interpolation
`b`	[0.5]	constant for interpolation
`dmin`	[0.01]	lower limit for interpolation
`dmax`	[0.20]	upper limit for interpolation
`maxfrq`	[500]	assumed number of frequencies

NOTE: If this separator is not given, frequency response analysis (and dynamic analysis) is not performed.

FOUT

`n1,n2,inc   R=r   D=d`

`n1,n2,inc`	first and last node number and node increment for printing frequency response function for response quantity r
`r`	=d, for displacement; =a, for acceleration
`d`	x,y,s for frequency response function due to harmonic horizontal acceleration, vertical acceleration, or sliding acceleration

DYNAMIC

`T=time  N=nstep,niter,ndie  E=told,tolf,tols`

`time`		maximum duration for response analysis
`nstep`	[20]	number of steps per segment
`niter`	[500]	maximum number of iterations per segment
`ndie`		number of points for transition zone
`told`		tolerance for dam generalized displacements
`tolf`		tolerance for foundation displacements
`tols`		tolerance for sliding acceleration

NOTE: If this separator is not given, the time history dynamic analysis is not performed.

GROUND ACCELERATION

`D=d  P=flag  N=ng  T=dtg  S=scale  N=fileg`

`d`		=x, horizontal ground acceleration; =y, vertical ground acceleration
`pflag`	[0]	=0, do not print; =1, print ground motion
`ng`		number of acceleration data points
`dtg`		uniform time step for acceleration data
`scale`	[1]	scale factor for ground acceleration
`fileg`		file with `ng` points at `dt` interval

WOUT

`I=i   S=scale`

`i`	[1]	step interval for output (time interval = i Δt)
`scale`	[1]	scale factors for printing energy terms

BOUT

`I=i   S=scald,scalf`

`i`	[1]	step interval for output (time interval = i Δt)
`scald,f`	[1,1]	scale factors for printing sliding responses and base shear forces, respectively

NOUT

`n1,n2,inc   I=i   O=optst,optd,opta   S=scale`

`n1,n2,inc`		first and last node number and node increment
`i`	[1]	step interval for output (time interval = i Δt)
`optst`		=0, static displacements not included; =1, static displacements included
`optd`		displacement is due to following effects: =1, dam deformation; =2, (1) and foundation displacements; =3, (2) and sliding
`opta`		acceleration is due to following effects: =1, dam acceleration; =2, (1) and foundation acceleration; =3, (2) and sliding acceleration; =4, (3) and ground acceleration
`S`	[1]	scale factor for printing displacements and accelerations

Enter as many lines as necessary.

EOUT

`n1,n2,inc   I=i   O=opt   S=scale`

`n1,n2,inc`		first and last node number and node increment
`i`	[1]	step interval for output (time interval = i Δt)
`opt`		=0, static effects not included;
		=1, static and dynamic effects included
`scale`	[1]	scale factor for printing element stresses

Enter as many lines as necessary.

ENVELOPE

`O=opt   S=scale`

`opt`		=0, static stresses not included;
		=1, static and dynamic stresses included
`scale`	[1]	scale factor for printing stress envelopes

END

Last separator at the end of input data. One blank line is needed after this separator.

5.2 Input for EAGD-POST

The program EAGD-POST can be used for further post-processing (after finishing the execution of EAGD-SLIDE), if the option `P=post` was set to unity, in the **SYSTEM** separator. The input data for EAGD-POST are entered in free format too. To process

EAGD-POST only the following separators are necessary: **TITLE**, **SYSTEM**, **WOUT**, **BOUT**, **NOUT**, **EOUT**, and **ENVELOPE**.

In the **SYSTEM** separator only the file name defined in `F=name` is necessary. This file name should be same as the one used during the execution of EAGD-SLIDE. Other separators are defined in the previous section. Notice that the same input file used in EAGD-SLIDE can be used for EAGD-POST.

Chapter 6

OUTPUT DESCRIPTION

EAGD-SLIDE prints the input data and results of analysis in several files, which are identified by **name.ext**, where **name** is the same name given in SYSTEM and **ext** indicates the contents of the file.

name.out Output of all input quantities, summary of major steps, vibration properties, and maximum values of response.

name.sta The nodal displacements and element stresses due to static loads.

name.rit The vibration mode shapes (Ritz vectors). This file is generated when the variable `vectors` in the separator SYSTEM is greater than zero.

name.frf The frequency response functions (real value, imaginary value and absolute value) for accelerations or displacements for nodes selected in **FOUT**. The parameter d=x,y,s in **FOUT** define when the frequency response functions are due to harmonic free-field horizontal or vertical acceleration, or sliding acceleration, respectively.

name.itr The number of iterations for convergence of each segment, as well as the total number of iterations at the end of the computation.

name.nod The response histories of displacements and accelerations, in the horizontal and vertical directions, for nodes selected in **NOUT**.

name.elm The stress response histories at given time intervals, for elements selected in **EOUT**. For each element and time, stress components and principal stresses at the nodes for the elements are printed.

name.bas The history of sliding displacement, sliding velocity, sliding acceleration, base shear force, normal force and eccentricity for each time step. This file is created by the **BOUT** separator.

name.str The envelopes of principal stresses for all elements, if the **ENVELOPE** separator is specified.

name.wrk The history of energy balance terms, if the **WOUT** separator is specified.

name.res A binary file that contains general data, frequency responses, time history of generalized coordinates, to be used for later post-processing. This file is generated by specifying `P=1` in the **SYSTEM** separator.

Chapter 7

EARTHQUAKE RESPONSE OF PINE FLAT DAM

The analysis procedure is used to compute the earthquake-induced sliding response of Pine Flat dam. The tallest monolith of this dam, shown in Figure 7.1, has a typical cross section for gravity dams. Pine Flat dam is a 561 m (1840 ft) long concrete gravity dam near Fresno, California. The tallest of the thirty-seven monoliths is 122 m (400 ft) high. A two-dimensional, plane stress finite element idealization for the monolith is shown in Figure 7.1.

7.1 Modeling Parameters

The model consists of 36 nine-node quadrilateral elements and 171 nodes. The base is horizontal. The dam concrete is assumed to be isotropic, homogeneous and elastic with the following properties: modulus of elasticity = 22.4 GPa (3.25 million psi), unit weight = 24.3 kN/m^3 (155 pcf), and Poisson's ratio = 0.2. The hysteretic damping factor for the dam is 0.10.

The impounded water has a depth of 116.2 m (381 ft) and the following properties: unit weight = 9.8 kN/m^3 (62.4 pcf), wave velocity = 1440 m/sec (4720 ft/sec). The wave reflection coefficient for the reservoir bottom materials is $\alpha = 1$, implying a rigid reservoir bottom. The uplift force at the base is evaluated assuming a triangular distribution of internal pressure from 1.14 MPa (24 ksf) at the upstream face to zero at the downstream face. To account for drainage only 40 percent of the resultant uplift force is considered in

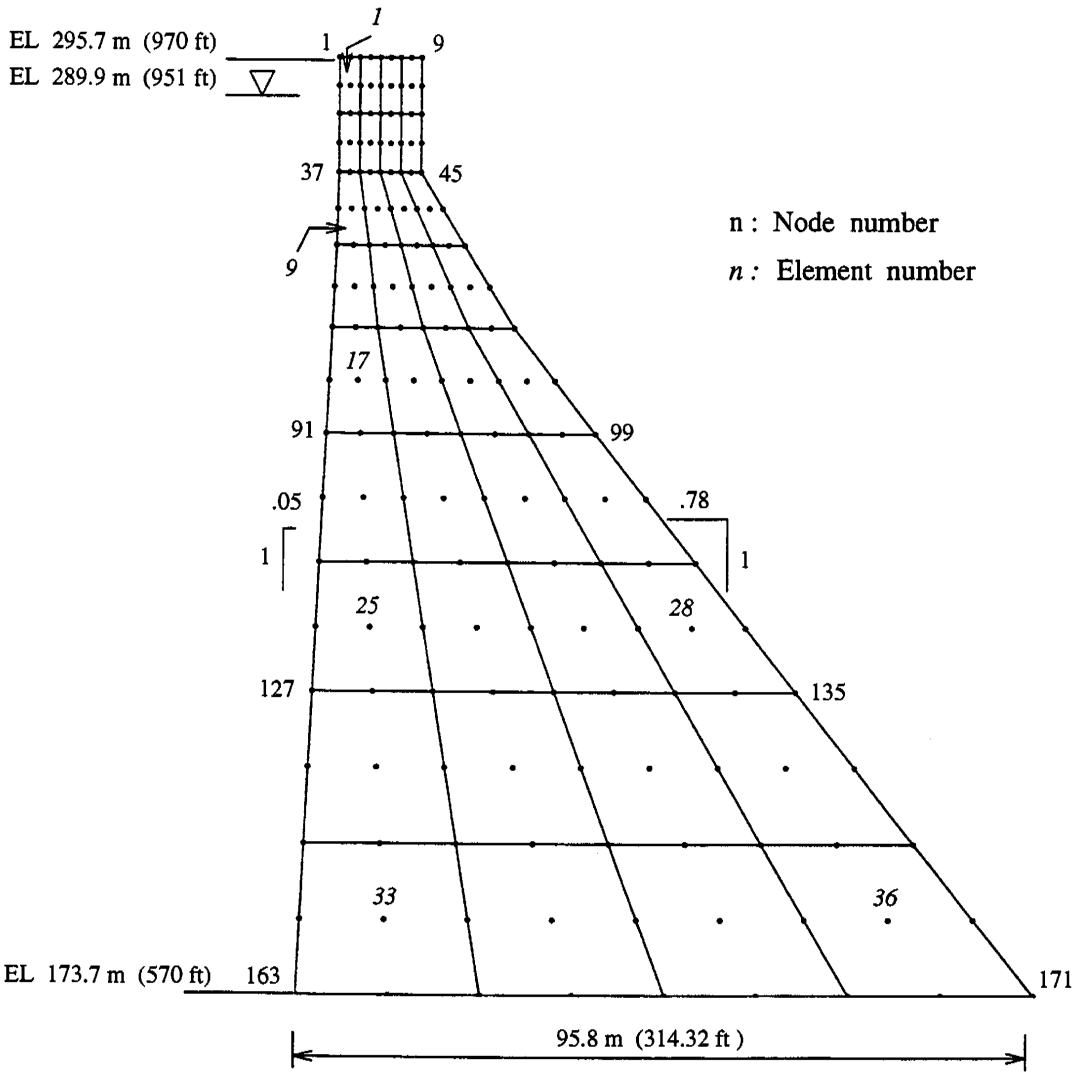


Figure 7.1. Finite element idealization of tallest monolith of Pine Flat dam.

the earthquake analysis.

The foundation rock is idealized as a homogeneous, isotropic, viscoelastic half-plane with the following properties: Poisson's ratio = 0.33, unit weight = 25.9 kN/m^3 (165 pcf), and hysteretic damping coefficient = 0.10. Two ratios between the modulus of elasticity of the concrete dam, E_{cd}, and the modulus of elasticity of the foundation rock, E_{fr}, $E_{fr}/E_{cd} = \infty$, 0.25, are considered to examine the the effects of the foundation rock flexibility on the dam response. The first case corresponds to a dam with rigid foundation rock, and the second case is a very flexible, although not untypical, foundation rock.

The cohesion force at the base interface is assumed to be zero and the coefficient of friction is 1.0 for this example.

7.2 Earthquake Ground Motion

The dam is subjected to the S69E horizontal component of the Taft record, obtained at the Lincoln School Tunnel in the 1952 Kern County earthquake. The ground motion is scaled to a peak acceleration of 0.4g, which is a typical value for moderate to strong earthquakes.

7.3 Response Parameters

The analysis is performed using a time step of 0.01 sec. This time step is adequate for the nonlinear sliding analysis, and it is comparable to the time step used for analysis of the linear response. The response is computed for the first 20 sec of ground motion and a quiet zone of 20.46 sec is appended to the acceleration data for a total duration of 40.46 sec. This corresponds to $2^{12} = 4096$ time steps for the discrete Fourier transforms. The maximum frequency represented is 50 Hz, which is beyond the frequencies included in the processed ground motion acceleration records.

The total duration of response is divided into segments of equal length. Each segment consists of 20 time steps. The convergence of the solution is relatively fast using these short segments. The normal force is assumed to be constant during the determination of siding state, so the change in normal forces due to dam deformation is not considered. This is necessary to ensure convergence of the solution for all cases.

7.4 Response Results

The crest deformation with respect to the base of the dam (not including sliding or foundation displacements) is shown in Figure 7.2. The maximum crest deformation for a dam on rigid foundation rock is 80 mm. Sliding initiates at 4 sec, and the maximum sliding displacement is 124 mm. A large percentage of the input energy is dissipated through damping of the dam, E_d. The energy dissipated by sliding of the dam, E_s, is much less.

For a dam on flexible foundation rock, the maximum crest displacement, shown in Figure 7.3, is 61 mm. Sliding initiates at 4 sec, and the there is a second larger sliding at about 7 sec, conincίding with the occurrence of maximum deformation in the dam. The maximum sliding displacement is 38 mm (one third of the sliding of the dam on rigid foundation rock). The plots of the energy balance show that sliding dissipates very little energy, so for this case sliding is not an effective energy dissipation mechanism.

The envelopes of maximum principal stresses for the dam on rigid and flexible foundation rock are shown in Figure 7.4. The indicated stresses are due to dynamic loads only to show directly the influence of sliding on the response. The dynamic stresses are reduced by the very flexible foundation rock compared with the case of rigid foundation rock.

The location of the resultant of forces on the dam at the base determines when the dam will begin to rock (or tip) about the toe or heel. When the resultant is outside the base, tipping can occur. The eccentricity ratio plotted in Figures 7.2 and 7.3 is defined as the distance of the resultant base force from the center of the base divided by one-half of the base width, When the absolute value of this ratio exceeds unity the resultant is outside of the base, indicating that the dam will tend to rock about the toe or heel. The eccentricity ratios are less than one for the dam on rigid and flexible foundation rocks. Thus rocking does not appear to be important for any of the cases. However, tensile forces do develop when the eccentricity ratio exceeds about ± 0.33.

7.5 Input and Output Files for the Example

The input data and output result files are shown in Appendix B. Notice that English units are used in the input data for the dam, but the printing of the output results is in SI units, using the conversion scale factors.

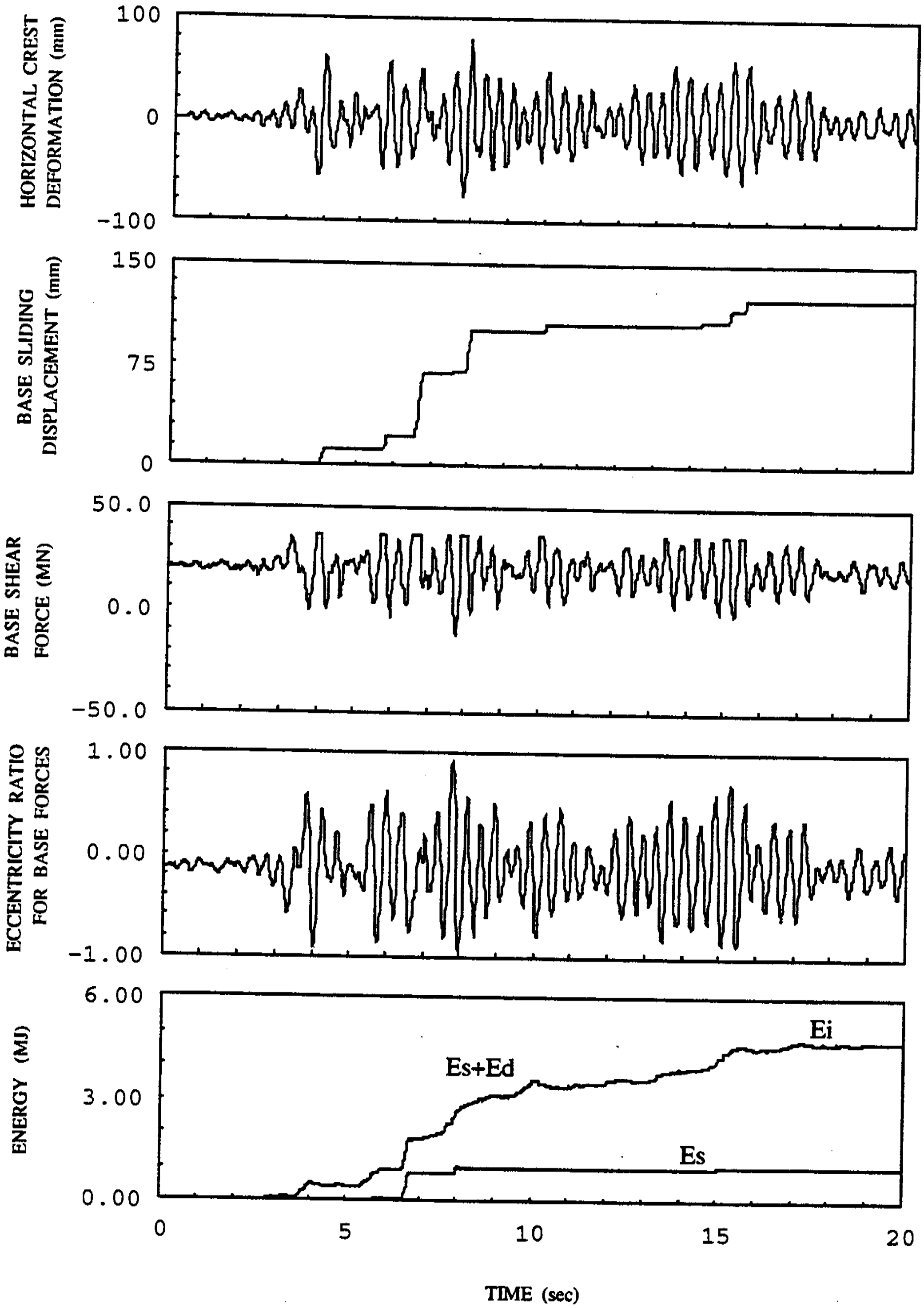


Figure 7.2. Response of Pine Flat dam with rigid foundation rock and $\mu = 1$, subjected to the horizontal S69E component of Taft ground motion, scaled to 0.40g peak ground acceleration.

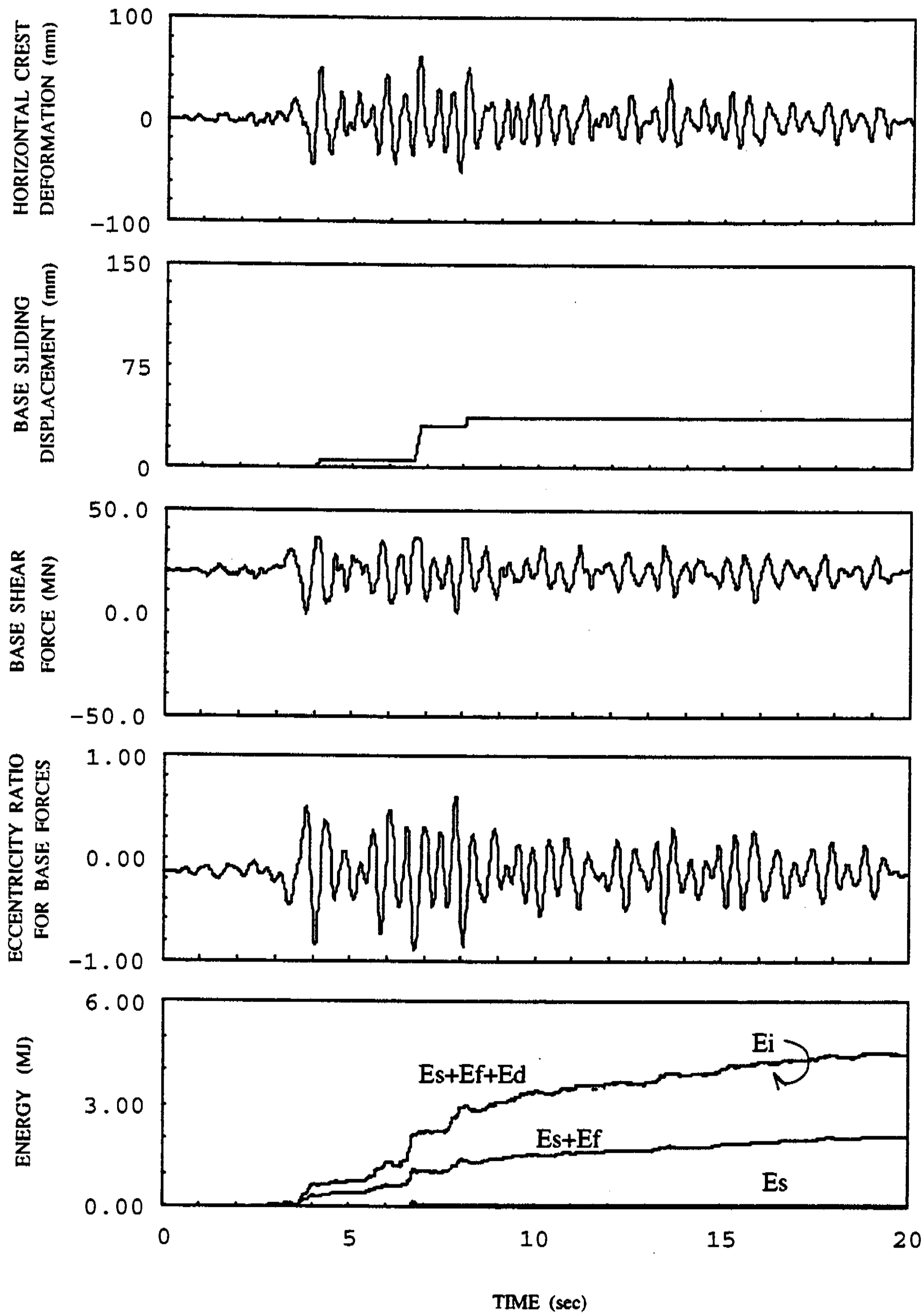
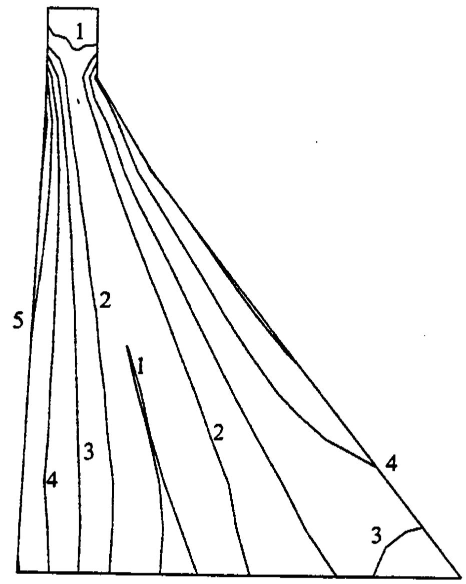
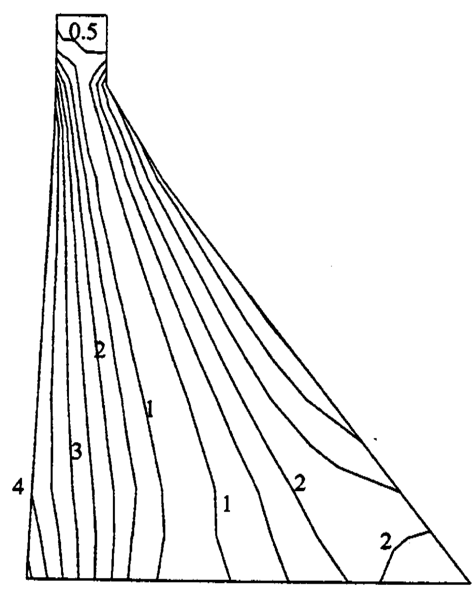


Figure 7.3. Response of Pine Flat dam with flexible foundation rock, $E_{fr}/E_{cd} = 0.25$, and $\mu = 1$, subjected to the horizontal S69E component of Taft ground motion, scaled to 0.40g peak ground acceleration.



RIGID FOUNDATION ROCK



FLEXIBLE FOUNDATION ROCK ($E_{fr}/E_{cd} = 1$)

Figure 7.4. Envelope of maximum principal stresses (in MPa) in Pine Flat dam with rigid and flexible foundation rock, $\mu = 1$, and subjected to the horizontal S69E component of Taft ground motion, scaled to 0.40g peak ground acceleration.

Chapter 8

PROGRAM ORGANIZATION AND INSTALLATION

8.1 Modular Organization

The computer program EAGD-SLIDE is organized in a modular form, in which each module does a specific task. The modulus are:

- **main**: main program and definition of installation parameters.
- **eagdsl**: perform the analysis of concrete gravity dams including sliding.
- **femdam**: define finite element model of dam, perform static analysis and generate Ritz vectors.
- **fresp**: generate frequency response functions.
- **dyndam**: perform dynamic analysis.
- **ppresp**: post processing.

8.2 Memory Allocation

The memory requirements for EAGD-SLIDE consists of a fixed sector and a variable sector. The fixed sector contains the executable statements and variables independent of the problem size. The variable sector is assigned to a blank COMMON under the array name A in the main program. Arrays dependent on problem size are stored in this blank common.

8.3 Installation Parameters

The user-defined parameters in the main program control the memory manager, input and output, and title information.

1. Parameters for Memory Manager

   - The amount of blank common, `mtot`, determines the size of the model that can be analyzed. The default value is:

     ```
     parameter(mtot = 1000000 )
     ```

   - The allocation of blank common depends on how the computer stores integers, double precision, double complex, and character integers. The default installation stores an integer in one integer word (`mint=1`), a double precision in two integer words (`mfloat=2`), a double complex in four integer words (`mcompl=4`), a `char*8` in two integer words (`mchar=2`), and all variables must be aligned on an even number of integer words (`malign=2`):

     ```
     parameter(mint=1, mfloat=2, mcompl=4, mchar=2, malign=2
     )
     ```

   - The termination of the memory manager is controlled by the variable `irem`. `If irem is zero all files are removed after execution.` `If irep` is non-zero a summary of memory usage is printed at the end of the output file. The default is:

     ```
     parameter(irem = 1, irep = 1 )
     ```

2. Parameters for Input-Output

- The unit for processing input file is defined by `ninfil`. If `ninfil` is zero, the input must be presented in standard input for the system. If `ninfil` is non-zero, the system-dependent subroutine **getinp** must be customized to get the input file name. The default installation is to use the standard input:

```
parameter(ninfil=0, ninsc=1 )
parameter(ninpa=20 )
```

The parameters `nifil`, `ninsc` and `ninpa` should be not changed.

- The units for output files are:

```
parameter(nout=4, nswap=9, ndata=8 )
parameter ( nerro=nout )
```

The parameters should not changed.

3. Parameters for Title and Page Header

- The name of the organization is printed on the header for each output page. The name of the organization can have a maximum of 60 characters. The default is:

```
data org/'University of California at Berkeley'/
```

- If `idate` is non-zero, the system-dependent subroutine `datset` must be customized to return the date:

```
data idate/1/
```

Chapter 9

CONCLUSIONS

A rigorous and accurate numerical procedure for the earthquake analysis of concrete dams including sliding at the base has been developed using the hybrid frequency-time domain procedure. Each domain is modeled as a separate substructure in the formulation of the equations of motion. The analysis accounts for the nonlinear sliding response of the dam and the frequency-dependent interaction effects between the dam and water and between the dam and foundation rock. The computer program can be used for the evaluation of the sliding response and safety of concrete gravity dams in earthquakes.

The frictional model does not consider the nonlinear behavior of the materials at the contact surface. The local nonlinearity due to sliding is reduced to a single relationship, the Mohr-Coulomb law for the dam-foundation interface. Thus there is only one nonlinearity in the multi-degree-of-freedom finite element representation of the dam system. Therefore, the convergence of the iterative procedure is relatively fast.

The response of the Pine Flat dam indicates that the earthquake-induced sliding of dams occurs in the downstream direction because the resisting frictional forces against sliding is exceeded in this direction due to the hydrostatic forces from the impounded water. The response results indicate that rocking of the dam is less important compared with the sliding displacement of the dam.

Realistic estimates of foundation flexibility reduces the sliding displacement compared with the unrealistic assumptions of rigid foundation rock. Dramatic reduction in sliding is observed for taller dams. Smaller reduction in sliding is observed for shorter dams, where the dam-foundation interaction effects are less important.

Sliding may occur during a strong earthquake ground motion, but the response results show that the dam-system will remain stable. For the 122 m Pine Flat dam on flexible foundation, the earthquake induced sliding displacement of less than 50 mm (sliding displacement to dam height ratio = 0.0004) is very small, and does not indicate unstable behavior. Well designed and constructed dams should tolerate this deformation at the foundation interface, although there may be local damage to drains and grout curtains.

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Appendix A

IMPEDANCE FUNCTIONS

The impedance functions are read from file `filef` specified in the separator **FOUNDATION**. The following data should be included in the file:

`nd nf`

`Ef` μ_f

h_1 h_2 .... h_{nd}

Ao_1 Ao_2 .... Ao_{nf}

K_{ij} functions for h_1 (`nf` data lines)

K_{ij} functions for h_2 (`nf` data lines)

....

K_{ij} functions for h_{nd} (`nf` data lines)

where:

`nd`		number of hysteretic damping coefficients
`nf`		number of frequencies for impedance matrix
`Ef`	[1]	modulus of elasticity at which impedance functions are calculated
μ_f		Poisson ratio
$h_1, h_2, ...h_{nd}$		hysteretic damping ratios
$Ao_1, Ao_2, ...Ao_{nf}$		frequency ratios
K_{ij}		Impedance functions for each frequency ratio. Eight values per line in the following order: Re(K_{11}), Im(K_{11}), Re(K_{22}), Im(K_{22}), Re(K_{33}), Im(K_{33}), Re(K_{13}), Im(K_{13}).

Appendix B

EXAMPLE OF INPUT AND OUTPUT

Summary of input and output files for analysis of Pine Flat dam on rigid foundation rock.

```
TITLE
Pine Flat dam. Rigid foundation rock.

SYSTEM
F=pinel  N=171  E=36  V=5  P=1

NODES
  1 X= 16.75 Y=400.00
  9 X= 52.00 Y=400.00
 19 X= 16.75 Y=376.00
 27 X= 52.00 Y=376.00 Q=1,19,9,27,9,1
 37 X= 16.75 Y=351.00
 45 X= 52.00 Y=351.00 Q=19,37,27,45,9,1
 55 X= 16.00 Y=320.00
 63 X= 70.80 Y=320.00 Q=37,55,45,63,9,1
 73 X= 14.25 Y=285.00
 81 X= 92.02 Y=285.00 Q=55,73,63,81,9,1
 91 X= 12.00 Y=240.00
 99 X=127.12 Y=240.00 Q=73,91,81,99,9,1
127 X=  6.50 Y=130.00
135 X=212.92 Y=130.00 Q=91,127,99,135,9,1
163 X=  0.00 Y=  0.00
171 X=314.32 Y=  0.00 Q=127,163,135,171,9,1

BASE
163,171  U=10,0

MATERIAL
N=1
1  M=0.155/32.2  W=0.155  E=3250*144  U=0.20

ELEMENT
1  N=19,21,3,1,20,12,2,10,11  M=1  G=4,9,1,4

RESERVOIR
V=4720  M=0.0624/32.2  H=0.0624,381  A=1.0
1,33,4  S=4

DAMPING
H=0.10

INTERFACE
U=1.0  F=0

FREQUENCY RESPONSE
D=0.010  N=4096

cFOUNDATION
cE=1.0*468000  U=0.33  M=0.165/32.2  D=0.10  N=90

GROUND ACCELERATION
W=TAFT-S69  D=x  N=1200  T=0.02  P=0  S=32.2/1759*0.4
cW=TAFT-VRT D=y  N=1200  T=0.02  P=0  S=32.2/1029*0.26

DYNAMIC
T=20  N=20,1000,20  E=0.005,0.005,0.005  V=1,0,0,1,0

FOUT
1,1,1  R=a  D=x

BOUT
I=1  S=304.8,4.448/1000

WOUT
I=1  S=1.356/1000

NOUT
1  I=1  O=0,1,4  S=304.8

EOUT
1,4   I=500  O=0  S=47.88/1000
33,36

ENVELOPE
O=0  S=47.88/1000
```

The angle of the base with respect to the x-axis is 0.00 degrees.

University of California at Berkeley
EAGD-SLIDE $Revision$
Pine Flat dam. Rigid foundation rock.
Name: PINE1 Fri Oct 14 00:03:36 1994

M A T E R I A L   P R O P E R T I E S

Mater	Unit weight & Unit mass	Modulus of Elasticity r-s	Shear Modulus	Poisson Ratio r-s	Thermal Coefficient r-s	Refer Temp
1	1.550E-01	4.680E+05	1.950E+05	0.200	0.000E+00	0.0
	4.814E-03	4.680E+05		0.200	0.000E+00	

E L E M E N T   D E F I N I T I O N S

Elem	Corner Nodes n1	n2	n3	n4	Side Nodes n5	n6	n7	n8	Center n9	Mater	Thick	Angle
1	19	21	3	1	20	12	2	10	11	1	1.00	0.00
2	21	23	5	3	22	14	4	12	13	1	1.00	0.00
3	23	25	7	5	24	16	6	14	15	1	1.00	0.00
4	25	27	9	7	26	18	8	16	17	1	1.00	0.00
5	37	39	21	19	38	30	20	28	29	1	1.00	0.00
6	39	41	23	21	40	32	22	30	31	1	1.00	0.00
7	41	43	25	23	42	34	24	32	33	1	1.00	0.00
8	43	45	27	25	44	36	26	34	35	1	1.00	0.00
9	55	57	39	37	56	48	38	46	47	1	1.00	0.00
10	57	59	41	39	58	50	40	48	49	1	1.00	0.00
11	59	61	43	41	60	52	42	50	51	1	1.00	0.00
12	61	63	45	43	62	54	44	52	53	1	1.00	0.00
13	73	75	57	55	74	66	56	64	65	1	1.00	0.00
14	75	77	59	57	76	68	58	66	67	1	1.00	0.00
15	77	79	61	59	78	70	60	68	69	1	1.00	0.00
16	79	81	63	61	80	72	62	70	71	1	1.00	0.00
17	91	93	75	73	92	84	74	82	83	1	1.00	0.00
18	93	95	77	75	94	86	76	84	85	1	1.00	0.00
19	95	97	79	77	96	88	78	86	87	1	1.00	0.00
20	97	99	81	79	98	90	80	88	89	1	1.00	0.00
21	109	111	93	91	110	102	92	100	101	1	1.00	0.00
22	111	113	95	93	112	104	94	102	103	1	1.00	0.00
23	113	115	97	95	114	106	96	104	105	1	1.00	0.00
24	115	117	99	97	116	108	98	106	107	1	1.00	0.00
25	127	129	111	109	128	120	110	118	119	1	1.00	0.00
26	129	131	113	111	130	122	112	120	121	1	1.00	0.00
27	131	133	115	113	132	124	114	122	123	1	1.00	0.00
28	133	135	117	115	134	126	116	124	125	1	1.00	0.00
29	145	147	129	127	146	138	128	136	137	1	1.00	0.00
30	147	149	131	129	148	140	130	138	139	1	1.00	0.00
31	149	151	133	131	150	142	132	140	141	1	1.00	0.00
32	151	153	135	133	152	144	134	142	143	1	1.00	0.00
33	163	165	147	145	164	156	146	154	155	1	1.00	0.00
34	165	167	149	147	166	158	148	156	157	1	1.00	0.00
35	167	169	151	149	168	160	150	158	159	1	1.00	0.00
36	169	171	153	151	170	162	152	160	161	1	1.00	0.00

Number of DOF = 324
Half-bandwidth = 42

University of California at Berkeley
EAGD-SLIDE $Revision$
Pine Flat dam. Rigid foundation rock.
Name: PINE1 Fri Oct 14 00:03:36 1994

R E S E R V O I R (UPSTREAM)

Wave propagation velocity = 4720.00000
Mass density = 0.00194
Wave reflection coefficient = 1.00000

Unit weight = 0.06240
Y-coordinate of free surface = 381.00000

Elements in contact with reservoir at upstream face:

Element	Side
1	4
5	4
9	4
13	4
17	4
21	4
25	4
29	4
33	4

University of California at Berkeley
EAGD-SLIDE $Revision$
Pine Flat dam. Rigid foundation rock.
Name: PINE1 Fri Oct 14 00:03:36 1994

S T A T I C   F O R C E S   A T   B A S E

Type of Force	Forces at center of the base Fx	Fy	Moment	Resultant Forces Magnitude	Angle	Eccentric.
External	4.529E+03	-9.727E+03	8.442E+04	-1.073E+04	-14.79	0.06
Uplift	0.000E+00	1.572E+03	8.233E+04	1.572E+03	0.00	-0.33
Total	4.529E+03	-8.155E+03	1.668E+05	-9.329E+03	-17.21	0.13

For resultant force:
Magnitude : (+) compression
Angle wrt vertical line : (+) clock-wise
Eccentricity = distance / (base/2): (+) downstream

```
1-----------------------------------------------------------------------------
University of California at Berkeley
EAGD-SLIDE $Revision$
Pine Flat dam. Rigid foundation rock.
Name: PINE1                                          Fri Oct 14 00:03:36 1994
-----------------------------------------------------------------------------
```

R I T Z   V E C T O R   G E N E R A T I O N

5 vectors generated with 0.14E-01 residual of the load vector neglected.

SUMMARY OF RITZ VECTOR GENERATION

			----- Mass Participation Factors -----			
	Frequency	Period	Horizontal Direction		Vertical Direction	
Mode	(Hz)	(sec)	Factor	Sum	Factor	Sum
1	3.1045	0.3221	38.062	38.062	2.067	2.067
2	6.5313	0.1531	18.961	57.024	11.223	13.291
3	8.6841	0.1152	2.418	59.442	54.402	67.692
4	11.3839	0.0878	27.040	86.482	1.780	69.473
5	19.0475	0.0525	0.781	87.263	9.949	79.422

The period(s) of the first 1 ritz vector(s) are approximations
of the natural vibration periods.

```
1-----------------------------------------------------------------------------
University of California at Berkeley
EAGD-SLIDE $Revision$
Pine Flat dam. Rigid foundation rock.
Name: PINE1                                          Fri Oct 14 00:03:36 1994
-----------------------------------------------------------------------------
```

F R E Q U E N C Y   R E S P O N S E

PARAMETERS

```
Time step                              =     0.010
Frequency interval                     =    0.1534
Maximum frequency                      =  314.1593
Total number of points                 =      4096

Interpolation is not used
```

FOUNDATION PROPERTIES

```
Rigid foundation rock
```

DAM

```
Constant hysteretic damping            =     0.100
```

```
1-----------------------------------------------------------------------------
University of California at Berkeley
EAGD-SLIDE $Revision$
Pine Flat dam. Rigid foundation rock.
Name: PINE1                                          Fri Oct 14 00:03:36 1994
-----------------------------------------------------------------------------
```

D Y N A M I C   A N A L Y S I S

PARAMETERS

```
Time step                                        =     0.0100
Maximum time of calculation                      =    20.0000
Time of quiet zone                               =    20.9600

Number of steps per segment                      =         20
Maximum number of iterations per segment         =       1000
Number of steps for transition zone              =         20

Tolerance for generalized displacements          =     0.0050
Tolerance for foundation displacements           =     0.0050
Tolerance for sliding acceleration               =     0.0050

Code for N & M forces and Mass (g(slid))         = 1 0 0 1 0
=0, not include,  =1, include contribution of
     code(1), ground acceleration
     code(2), dam deformation
     code(3), foundation displacement
     code(4), hydrodynamic pressures
     code(5), variation of mass due to sliding
in state determination of sliding acceleration
```

INTERFACE ZONE

```
Sliding is considered, with following parameters
   Cohesion force at the base interface     =      0.00
   Coefficient of friction                  =      1.00
```

ACCELERATION RECORD

```
File name for record                        =  TAFT-S69
Direction of motion                         =         X
Number of data points defining record       =      1200
Time step of acceleration record            =     0.020
Scale factor                                =     0.007
```

```
1-----------------------------------------------------------------------------
University of California at Berkeley
EAGD-SLIDE $Revision$
Pine Flat dam. Rigid foundation rock.
Name: PINE1                                          Fri Oct 14 00:03:36 1994
-----------------------------------------------------------------------------
```

p1d **Fri Oct 14 11:22:55 1994** **1**

S U M M A R Y   O F   D Y N A M I C   R E S P O N S E

MAXIMUM ENERGY RATIO

Energy ratio (Eout / Einp)   1.000

MAXIMUM SLIDING RESPONSE AND FORCES AT THE BASE

Sliding displacement:

Xs-max	Time	Xs-min	Time
123.989	15.550	0.000	0.000

Sliding acceleration:

As-max	Time	As-min	Time
5537.945	8.110	-7024.732	8.090

Base shear force:

Fv-max	Time	Fv-min	Time
36.321	6.790	-12.729	7.770

Base normal force:

Fn-max	Time	Fn-min	Time
36.505	8.110	0.000	0.000

Eccentricity ratio:

Ecc-max	Time	Ecc-min	Time
0.931	7.780	-0.966	7.960

MAXIMUM NODAL DISPLACEMENTS AND ACCELERATIONS

Node	D-max	Time	D-min	Time	A-max	Time	A-min	Time
1	80.060	7.990	-75.182	7.790	28260.3	8.250	-46590.4	8.000
	23.297	7.990	-20.154	7.800	0.0	8.110	-12950.3	8.000

PRINCIPAL STRESSES FOR ELEMENT 1

Node	S1-max	time	S1-min	time	S2-max	time	S2-min	time
19	1.656	8.000	-0.002	5.360	0.003	15.220	-1.311	8.250
21	0.730	8.000	-0.003	5.360	0.006	15.220	-0.569	8.250
3	0.421	8.250	0.000	1.170	0.000	2.190	-0.543	8.000
1	0.314	8.000	0.000	0.000	0.000	0.000	-0.242	8.250
20	1.122	8.000	-0.002	5.360	0.005	15.220	-0.883	8.250
12	0.389	8.000	0.000	4.110	0.001	15.220	-0.341	8.000
2	0.160	8.250	0.000	0.000	0.000	0.000	-0.200	8.000
10	0.981	8.000	0.000	16.980	0.000	4.200	-0.774	8.250
11	0.586	8.000	0.000	5.360	0.001	15.220	-0.463	8.250

PRINCIPAL STRESSES FOR ELEMENT 2

Node	S1-max	time	S1-min	time	S2-max	time	S2-min	time
21	1.537	8.000	-0.002	9.640	0.005	6.460	-1.193	8.250
23	0.776	8.250	-0.001	6.490	0.002	4.380	-0.986	8.000
5	0.221	8.250	0.000	0.000	0.000	0.000	-0.292	8.000
3	0.225	7.990	-0.004	5.930	0.001	17.520	-0.183	8.000
22	0.951	8.000	-0.001	5.140	0.003	7.700	-0.728	8.250
14	0.526	8.250	-0.001	4.200	0.000	16.360	-0.669	8.000
4	0.168	8.000	0.000	0.880	0.000	0.850	-0.206	8.000
12	0.893	8.000	0.000	5.140	0.002	5.930	-0.689	8.250
13	0.593	8.000	0.000	5.370	0.001	15.220	-0.460	8.250

PRINCIPAL STRESSES FOR ELEMENT 3

Node	S1-max	time	S1-min	time	S2-max	time	S2-min	time
23	1.000	8.000	0.000	16.170	0.001	7.270	-0.767	8.250
25	1.135	8.250	-0.007	15.230	0.004	15.160	-1.419	8.000
7	0.177	8.000	-0.001	17.520	0.004	15.230	-0.182	8.000
5	0.334	8.000	0.000	0.000	0.000	0.000	-0.247	8.250
24	0.707	8.250	-0.004	4.200	0.003	4.380	-0.890	8.000
16	0.643	8.250	-0.003	15.230	0.001	7.270	-0.805	8.000
6	0.234	8.000	0.000	0.000	0.000	0.000	-0.183	8.250
14	0.679	8.000	0.000	0.000	0.000	0.000	-0.521	8.250
15	0.429	8.250	-0.001	4.200	0.000	7.270	-0.532	8.000

PRINCIPAL STRESSES FOR ELEMENT 4

Node	S1-max	time	S1-min	time	S2-max	time	S2-min	time
25	0.312	8.000	-0.013	15.240	0.010	8.410	-0.328	8.000
27	1.290	8.250	-0.003	8.210	0.002	7.680	-1.578	8.000
9	0.203	8.250	-0.002	15.240	0.002	8.420	-0.243	8.000
7	0.486	8.000	0.000	0.660	0.001	5.500	-0.374	8.250
26	0.730	8.250	-0.008	8.210	0.005	8.420	-0.868	8.000
18	0.743	8.250	0.000	0.000	0.000	0.000	-0.906	8.000
8	0.204	8.000	0.000	8.830	0.000	10.160	-0.157	8.250
16	0.420	8.000	-0.002	15.660	0.001	7.650	-0.313	8.250
17	0.402	8.250	-0.002	8.210	0.001	7.650	-0.476	8.000

PRINCIPAL STRESSES FOR ELEMENT 33

Node	S1-max	time	S1-min	time	S2-max	time	S2-min	time
163	5.106	7.970	-1.062	7.780	0.720	7.960	-6.817	7.780
165	1.245	7.970	-0.153	8.570	0.232	7.970	-1.266	7.760
147	2.100	7.970	-0.164	7.820	0.179	7.960	-2.414	7.780
145	4.562	7.970	-0.217	8.110	0.115	3.700	-4.971	7.800
164	3.196	7.970	-0.452	7.810	0.450	7.970	-4.037	7.780
156	1.732	7.970	-0.141	3.870	0.216	7.970	-2.061	7.770
146	3.337	7.970	-0.002	6.970	0.000	0.000	-3.704	7.790
154	4.836	7.970	-0.062	7.810	0.063	7.940	-5.878	7.790
155	3.301	7.970	-0.081	3.870	0.120	7.970	-3.984	7.790

PRINCIPAL STRESSES FOR ELEMENT 34

Node	S1-max	time	S1-min	time	S2-max	time	S2-min	time
165	1.519	7.960	-0.232	7.840	0.323	7.970	-1.968	7.770
167	1.939	7.790	-0.091	15.580	0.090	4.160	-1.257	7.990
149	1.580	7.780	-0.008	5.030	0.015	14.380	-0.904	8.000
147	1.843	7.970	-0.083	3.880	0.086	7.970	-2.283	7.770
166	0.706	8.100	-0.060	8.230	0.044	5.890	-1.016	7.760
158	1.798	7.790	-0.048	15.580	0.038	5.890	-1.126	7.990
148	0.969	8.400	-0.107	8.590	0.100	9.090	-1.408	7.760
156	1.682	7.970	-0.142	8.210	0.204	7.970	-2.158	7.770
157	0.835	8.400	-0.080	8.590	0.071	9.090	-1.255	7.760

PRINCIPAL STRESSES FOR ELEMENT 35

Node	S1-max	time	S1-min	time	S2-max	time	S2-min	time
167	1.820	7.790	-0.064	15.580	0.060	4.160	-1.204	7.940
169	3.287	7.790	-0.095	15.580	0.079	4.160	-2.399	7.980
151	3.142	7.790	-0.008	6.820	0.009	5.890	-2.326	7.980
149	1.821	7.790	-0.002	0.200	0.018	14.380	-1.172	7.990
168	2.499	7.790	-0.094	15.580	0.082	4.160	-1.753	7.980
160	3.235	7.790	-0.053	15.580	0.039	5.890	-2.393	7.980
150	2.430	7.790	0.000	0.000	0.000	0.660	-1.709	7.980
158	1.823	7.790	-0.010	4.560	0.018	5.890	-1.202	7.980
159	2.477	7.790	-0.041	15.580	0.032	5.890	-1.758	7.980

PRINCIPAL STRESSES FOR ELEMENT 36

Node	S1-max	time	S1-min	time	S2-max	time	S2-min	time
169	3.039	7.790	-0.059	15.580	0.049	5.890	-2.203	7.980
171	2.479	7.780	-0.032	5.870	0.043	8.160	-1.583	7.960
153	3.408	7.790	-0.005	4.130	0.018	6.840	-2.382	7.990
151	3.743	7.790	0.000	0.000	0.000	0.000	-2.854	7.980
170	2.755	7.790	-0.059	15.580	0.045	5.890	-1.895	7.990
162	2.915	7.780	-0.021	7.930	0.035	8.160	-1.954	7.990
152	3.564	7.790	-0.001	3.610	0.000	0.000	-2.597	7.980
160	3.356	7.790	-0.024	15.580	0.021	5.890	-2.489	7.980
161	3.127	7.790	-0.027	15.580	0.021	5.890	-2.206	7.990

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University of California at Berkeley
EAGD-SLIDE $Revision$
Pine Flat dam. Rigid foundation rock.
Name: PINE1 Fri Oct 14 00:03:36 1994

C O M M O N M E M O R Y U S A G E

Locations allocated...... 2000000
Max. locations used...... 670244 (33.5%)
Locations currently used. 391936 (19.6%)

PROGRAM EXECUTION COMPLETED Fri Oct 14 01:56:09 1994