

TECHNICAL REPORT

L-1227(2)-3/94

**DIGES USERS MANUAL
(WORKING VERSION 1.0)**

By

**N. Simos
A.J. Philippacopoulos**

March 1994

**DEPARTMENT OF ADVANCED TECHNOLOGY
BROOKHAVEN NATIONAL LABORATORY, ASSOCIATED UNIVERSITIES, INC.
P.O. BOX 5000, UPTON, NEW YORK 11973-5000**



Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation
Contract No. DE-AC02-76-CH00016

9404260241 940419
PDR ORG NRRB
PDR

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency, contractor or subcontractor thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency, contractor or subcontractor thereof.

ABSTRACT

DIGES is a computer program that can perform dynamic analyses of structures. The dynamic loads exciting the structural system can be seismic or loads acting directly on the structure.

This report is complimentary to the *Theoretical Basis of Diges* where the mathematical concept and background, the goals and capabilities of the DIGES program are presented in detail. Specifically, the capabilities include the *direct generation of spectra, earthquake simulation, deterministic earthquake solutions* and *system response under dynamic superstructure loads*.

In this manual the procedure to execute the program and apply it to particular problem cases is provided in detail. The detailed information is associated with the *on-line* interaction with the program, the structure of the required input files, which contain information on the dynamic input, the foundation and the superstructure, and the extraction of the desired solution variables.

EXECUTIVE SUMMARY

DIGES is a computer program written to perform dynamic analyses of structure/foundation systems excited by earthquake or superstructure loads.

The DIGES USERS MANUAL is a report containing information regarding the execution of the DIGES program. The description of the overall system to be analysed, the different approaches that can be employed for the solution of the dynamic problem and the mathematical foundations of the various approaches are all contained in the *Theoretical Basis of Diges* report. The focus of this manual is primarily the DIGES software written to implement the solution procedures described in the theoretical report.

The contents of the DIGES USERS MANUAL are outlined below:

- *Definition of the overall system.* The overall system consists of the superstructure, the foundation, the soil medium and the dynamic excitation. The selection of the most suitable analysis procedure for a study problem is based on the available information regarding the listed system components.
- *Description of the DIGES algorithm.* A step by step procedure that outlines the interaction with the program. This includes the selection of the analysis, the specification of the dynamic excitation, the modeling of the superstructure and the implementation of foundation and soil medium properties. The formulation of the input files containing the required input is also discussed in detail. Also, the selection of the solution output is outlined.
- *Sample Runs.* The complete sequence of steps that lead to the solution of sample cases along with the interactive program responses is presented.

ACKNOWLEDGMENTS

A sincere appreciation to the NRC sponsors of the Structural and Geosciences Branch and particularly G. Bagchi, D. Jeng, H. Ashar and S. Lee for his thorough review of the document.

Special thanks to Professors Y.K. Lin and P. Spanos for their valuable comments.

TABLE OF CONTENTS

ABSTRACT	1
EXECUTIVE SUMMARY	2
ACKNOWLEDGMENTS	3
TABLE OF CONTENTS	4
1.0 Introduction	5
1.1 Problem Definition	5
1.2 Diges Profile	6
1.3 Hardware/Software Requirements 12	
2. DIGES Algorithm	13
2.1 Main Program	13
2.2 Program Input and Output 21	
2.3 Model Input File	30
2.4 Input File of Foundation Input Motion and Impedance	32
2.5 Input File of Free Field Excitation	33
2.6 Sample Runs with the Diges	39
APPENDIX I. System Excitation	62
APPENDIX II. Impedances and Found. Input Motions.....	68
APPENDIX III. Superstructure Modeling	79
References.....	84

1.0 INTRODUCTION

1.1 Problem Definition

The need to develop acceptable floor response spectra has been an ongoing process. Such spectra are affiliated with seismic loads that the structure is subjected to and they represent the prediction of the response of various elevations within the structure that in turn can be utilized to predict the response of sensitive equipment resting on a particular elevation. These seismic loads are conventionally expressed in the form of *design response spectra* for a number of reasons.

Consequently, the development of computational schemes which can incorporate the information, or assessment, pertaining to the seismic load and, in conjunction with the dynamic characteristics of the structure, predict the elevation spectral responses has been the focus of earthquake response prediction. The definition of the seismic load, which determines the theoretical basis of the link between excitation and response, has been deduced from both deterministic as well as stochastic models.

On one hand, the deterministic approaches seek to assess the elevation response due to a prescribed ground excitation or a prescribed dynamic load on the structure itself. On the other, the stochastic approaches attempt to define the floor response to an anticipated ground excitation that belongs to a family of earthquakes which in turn is described by *target* response or power spectra.

Within the stochastic processes, however, the statistics that accompany the definition of the ground excitation are *usually* carried over to the floor response with an ensemble of realizations of the stochastic process that defines the ground excitation. This simulation of earthquakes procedure that attempts to *match* the statistics of the target spectrum has been used extensively both by *directly* linking the target response spectrum to an artificial earthquake or by implementing the constraint of the power spectral density function of the ground motion. The latter earthquake simulation process, more sophisticated in nature, matches some of the statistics of the target spectrum with realizations (sample earthquakes) deduced from the power spectrum of the stochastic process.

The direct link between a stochastic characterization of the ground excitation and the stochastic floor response has received less attention (that

is what the *usually* above stands for). Through this process, the statistical properties of an anticipated family of earthquakes, expressed in its power spectrum, are transferred to the structure of deterministically defined dynamic properties.

1.2 DIGES Profile

The present effort has been undertaken so that an efficient theoretical/computational tool can be devised such that seismic problems of concern to the regulatory agencies can be effectively treated. In this study, the *direct* link between the input excitation and the output response in the stochastic sense is explored (from which DIGES is deduced). This dimension of the seismic analysis, along with the earthquake simulation procedures and the deterministic seismic and dynamic response of the structure, define the DIGES computational domain.

Figure 1.2.1 depicts the physical system whose response to the action of dynamic loads is sought. Participating in the generic physical system are the superstructure, which is the focus of the resulting response, the foundation and the soil medium the foundation/superstructure is resting on. Further, the different dynamic loads that can excite the physical system are shown.

An overall description of DIGES can be seen in Figure 1.2.2 where the general capabilities are listed. According to Fig. 1.2.2, analyses of both stochastic and deterministic nature can be undertaken. While in the deterministic analysis the consideration of dynamic superstructure loads has been implemented (an important element of dynamic analysis) alongside with the classical treatment of defined ground motion, the stochastic analysis mode incorporates both the earthquake simulation and the direct transferring of stochastic properties.

The relationships that connect the dynamic input to the system response are schematically shown in Figures 1.2.3 and 1.2.4 (stochastic and deterministic modes respectively). In both modes of analysis the *link* is the transfer function $H(\omega)$ of the system which identifies the superstructure/foundation/soil medium interaction.

The stochastic mode of Figure 1.2.3, which implements both the simulation and the direct stochastic transferring) seeks to evaluate elevation response spectra induced by ground excitations that can be defined as both target response spectra or cross-spectral densities of the stochastic process describing the excitation

The *direct* stochastic mode determines the cross spectral density matrix of the response $[\Phi_Y(\omega)]$ for a stochastic process with cross spectral density $[\Phi_X(\omega)]$. For a statistic process that defines the free field in terms of *target* response spectra a *consistent* cross spectral matrix is formed and eventually transferred to the elevation. The *simulation* seeks the elevation response spectra through by utilizing statistical properties of the responses at the same elevation due to an ensemble of ground accelerations whose response spectra *match* the target spectrum over some of its statistic properties. As shown, both simulation procedures are implemented (one leads to ground motions from a response spectrum through its power spectrum and the other to ground motions directly from the response spectrum).

It should be emphasized here that the redundancy of transferring the free field motion (either directly or through simulation) which appears to exist in the DIGES computational capabilities, is not for real. Considering that structures are dynamically treated mostly as *linear* systems, so all of the above listed alternative procedures can be utilized, room must be left to explore the *non-linear* behavior of systems. While the *direct* mode of spectra generation it will be shown to work well in linear systems and for stationary stochastic processes, work needs to be done to generalize its applicability. This gap can be filled with the help of simulated earthquakes, which as an ensemble can equivalently represent the stochastic process, by exciting the non-linear system in the time space rather than frequency.

The *deterministic* mode of Figure 1.2.4 utilizes the system transfer function $H(\omega)$ to evaluate the response spectrum at a specified elevation due to a defined ground acceleration. The process requires that the input ground motion is expressed in the Fourier expansion of the record. The evaluation of the response of the superstructure due to applied dynamic loads is also incorporated. Wind loads, impact loads and floor dynamic loads due to equipment can be treated by utilizing a modified system transfer function which relates the dynamic superstructure loads with the motion of the foundation.

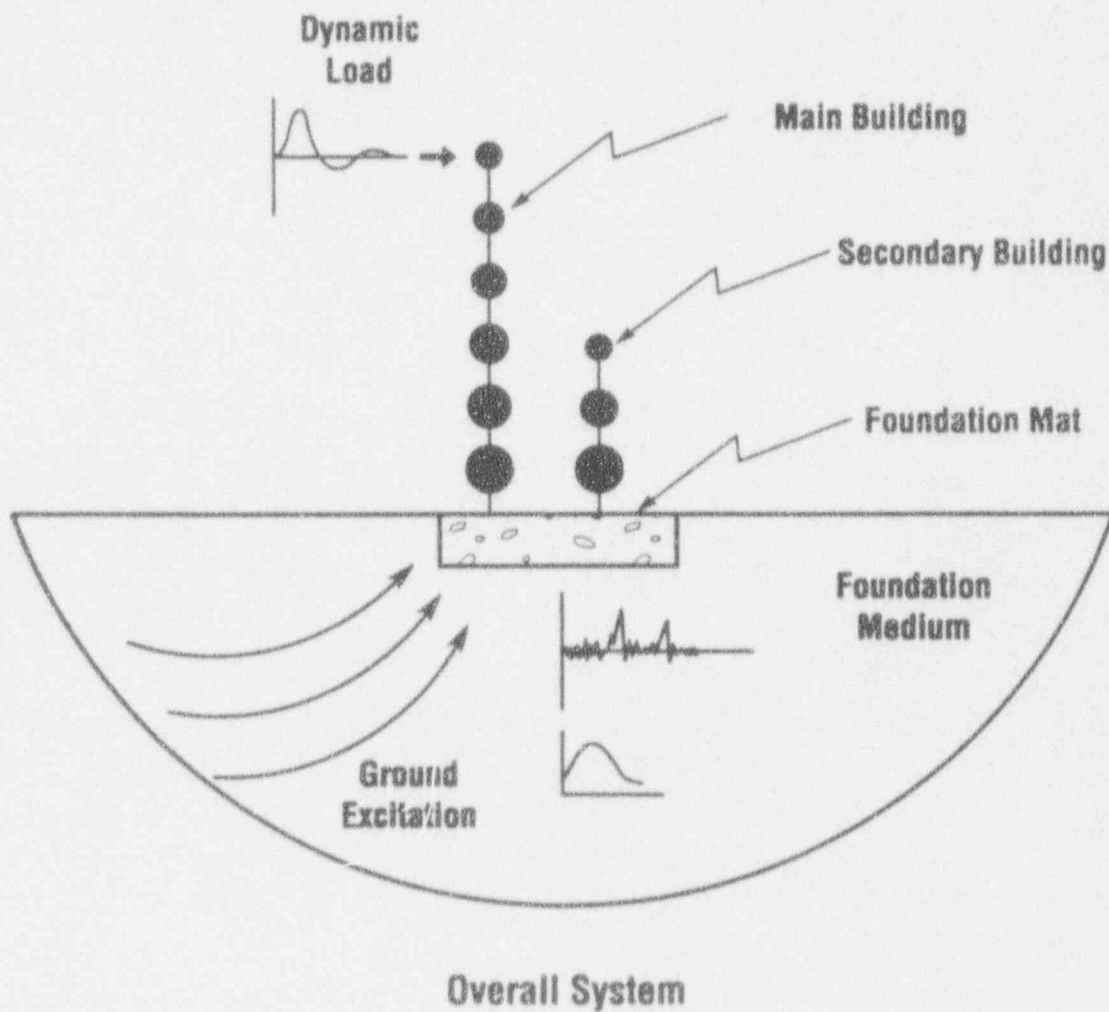


Figure 1.2.1

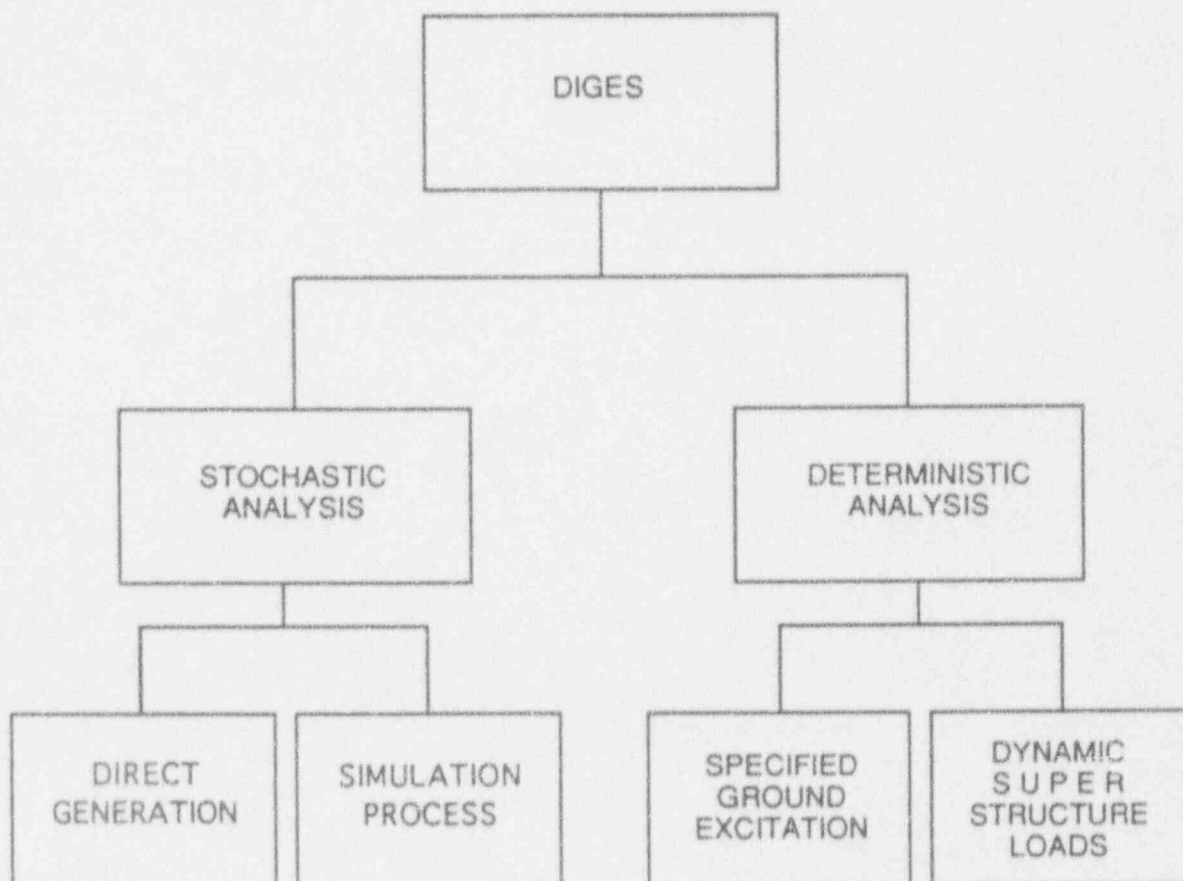


Figure 1.2.2

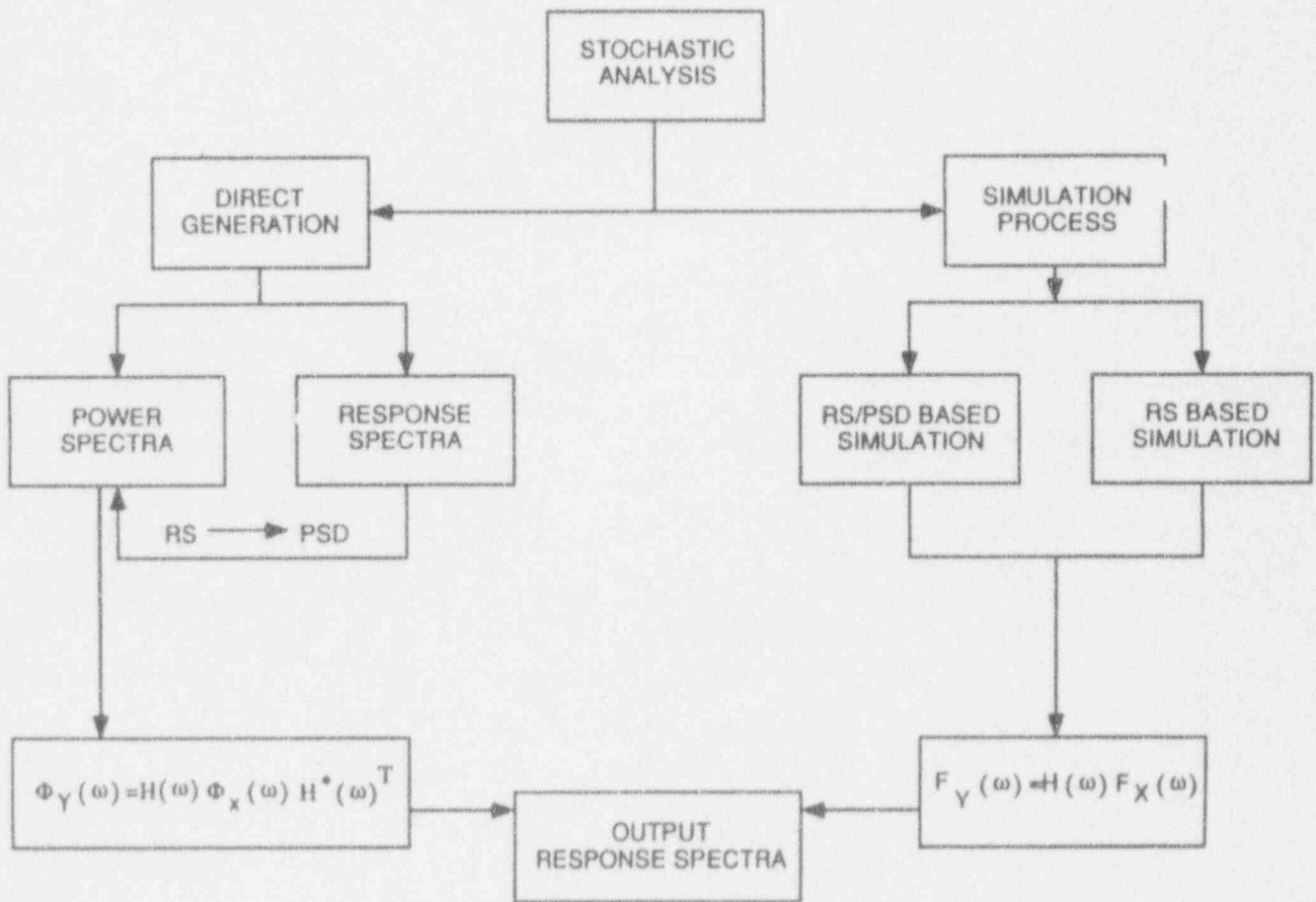


Figure 1.2.3

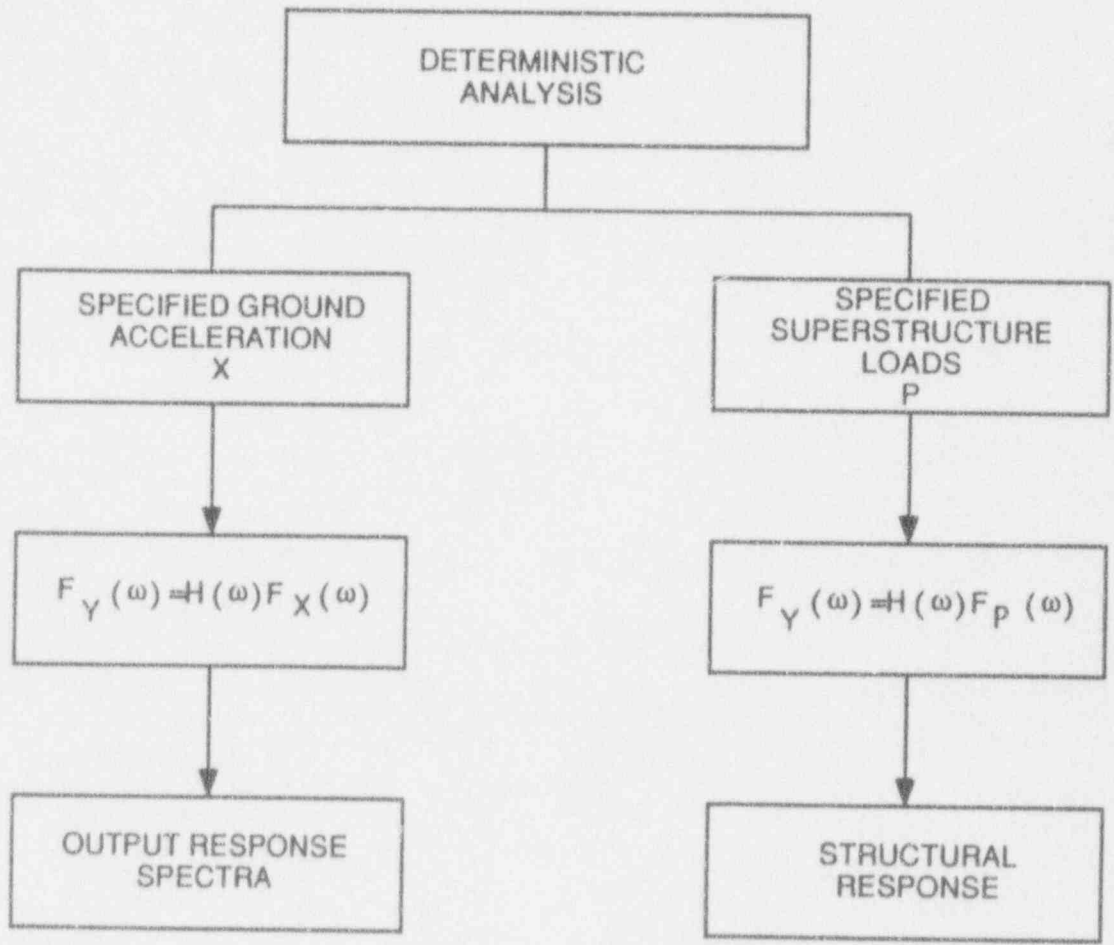


Figure 1.2.4

1.3 Hardware/Software requirements

The DIGES program that implements the various modes of dynamic analysis has been developed on a SUN SPARCstation 1+ machine with UNIX operating system. The program is written in FORTRAN-77 and it is a stand-alone entity. Specifically, no external libraries or subroutines are invoked by the program. The only input to the program is interactive information pertaining to the various aspects of the problem under solution as well as external files containing tabulated information of both the structural system and the dynamic excitation.

Since the SPARC 1+ is a virtual machine, specifications of the memory requirements for the execution of the DIGES program are meaningless because of the internal memory swamping during execution.

To invoke the DIGES program a user need only type *rundiges* and the program will direct the user to the solution mode appropriate for the specified problem.

2. DIGES Algorithm

The implementation of the theoretical background, pertaining to the transferring of the free-field motion onto the superstructure, into a computational tool has been achieved with the DIGES computer program which utilizes the FORTRAN 77 computer language. The program itself resides in the a SPARC 1+ Workstation with open window capabilities. The workstation is part of an *ethernet* network that allows login from a remote host. This gives it the capability of window sharing between two remote hosts for on-line communication.

The program itself reflects the capabilities already described in the main text, such as *direct generation of spectra, earthquake simulation, deterministic earthquake solutions* and *system response under dynamic superstructure loads*.

In the following the main programming features of the program will be outlined as well as the sequence of processes that are incorporated for a complete solution of any of the four major modules of analysis. Figure 2.1 outlines the basic solution flow chart while Figures 2.2-2.5 describe in more detail the operations executed in each solution module.

2.1 Main Program

The main program of DIGES plays the role of the driver of the program. It identifies the module of analysis, the form of free-field input, the frequency content of the input along with the size of the dynamic problem, the geometric/dynamic properties of the soil/structure system and the locations where the response is to be evaluated. With this provided information (both interactively and externally) the program has been designed to allocate memory space exactly equal to what the solution needs. This has the advantage of utilizing all the working memory the host system may allow instead of confining the computer code to a specified problem size. Further, the ability of swamping memory space while the program is in execution allows even further flexibility.

The sequence of operations are dictated by the main subroutine of the program which calls appropriate subroutine families that calculate:

- a. The **modal properties** of the superstructure are evaluated by successively invoking the subroutines that (1) identify the nodal locations

with the degrees of freedom, (2) calculate the stiffness of the finite element system representing the superstructure (3) evaluate the bandwidth and the global stiffness and mass matrices and (4) call the eigen-solution subroutine that returns the eigenvalues and the eigenvectors of the superstructure.

- b. The **equivalent mass matrix** of the superstructure is calculated (it represents the transferring of superstructure information on the foundation) by invoking subroutines that (1) calculate the rigid displacement matrix (2) the modal participation matrix (3) the mass matrix of the superstructure for displacement about a reference point on the foundation and (4) the mass matrix of the rigid foundation.

To this point the calculated information is independent of the dynamic frequency. From this point on the evaluation of system properties takes place at every selected frequency value of the specified frequency range of the harmonic solution.

- c. The appropriate set (to the analysis module) of transfer functions $H_i(\omega)$ is established for the entire frequency range. For example, for modules 1 thru 4 $H_i(\omega)$ represents the transfer function that links the free-field earthquake excitation with the total structural response. Such transfer function is the product of (1) a transfer function which transfers the total foundation input characteristics to any d.o.f. of the superstructure, (2) a transfer function relating the foundation input motion to the total foundation motion and (3) the scattering matrix that incorporates the modification of the free-field motion due to the presence of the massless foundation.

Specifically, the program invokes the modal amplification matrix routine, the frequency dependent equivalent mass matrix routine and on the basis of the type of foundation the impedance (or compliance) matrices. Finally the scattering matrix is called and the total transfer matrix of the system (complex) is calculated for every frequency.

- d. The **free-field input** is established in the frequency domain. If (1) the *direct* transfer option has been chosen and the control motion is in the form of a power spectral density, the cross spectral matrix over the frequency range is formed. If the control motion is in response spectra form, the consistent cross spectral matrix is evaluated for the

solution frequency range by invoking the subroutines that generate *psd* functions consistent with the free-field response spectrum. If (2) the *simulation* process is chosen then, depending on the spectra type (power or response) chosen as representative of the stochastic process, the fourier coefficients of the simulated earthquakes are calculated by going through the process as many times as the number of simulations chosen. If (3) the deterministic analysis for an actual earthquake is to take place, the fourier coefficients of the record are established. This is similar to the previous process for a single simulation except that the time history is not generated. Finally, (4) if the system is excited by a dynamic load in the superstructure, the fourier coefficients of the dynamic load are established by invoking the appropriate Fourier Transform subroutine.

- e. On the basis of the final form of the free-field motion (*psd* or Fourier expansion coefficients) the routines that calculate either the cross-spectral matrix of the output or the Fourier coefficients of the time history of the output are called appropriately. If the output response is in a *psd* form, its response spectrum is calculated directly from processes inherent to the program, see *Theoretical Basis of Diges*. If the response is in the form of a time history (or the Fourier coeff.), the linear acceleration method is employed to calculate its response spectrum.

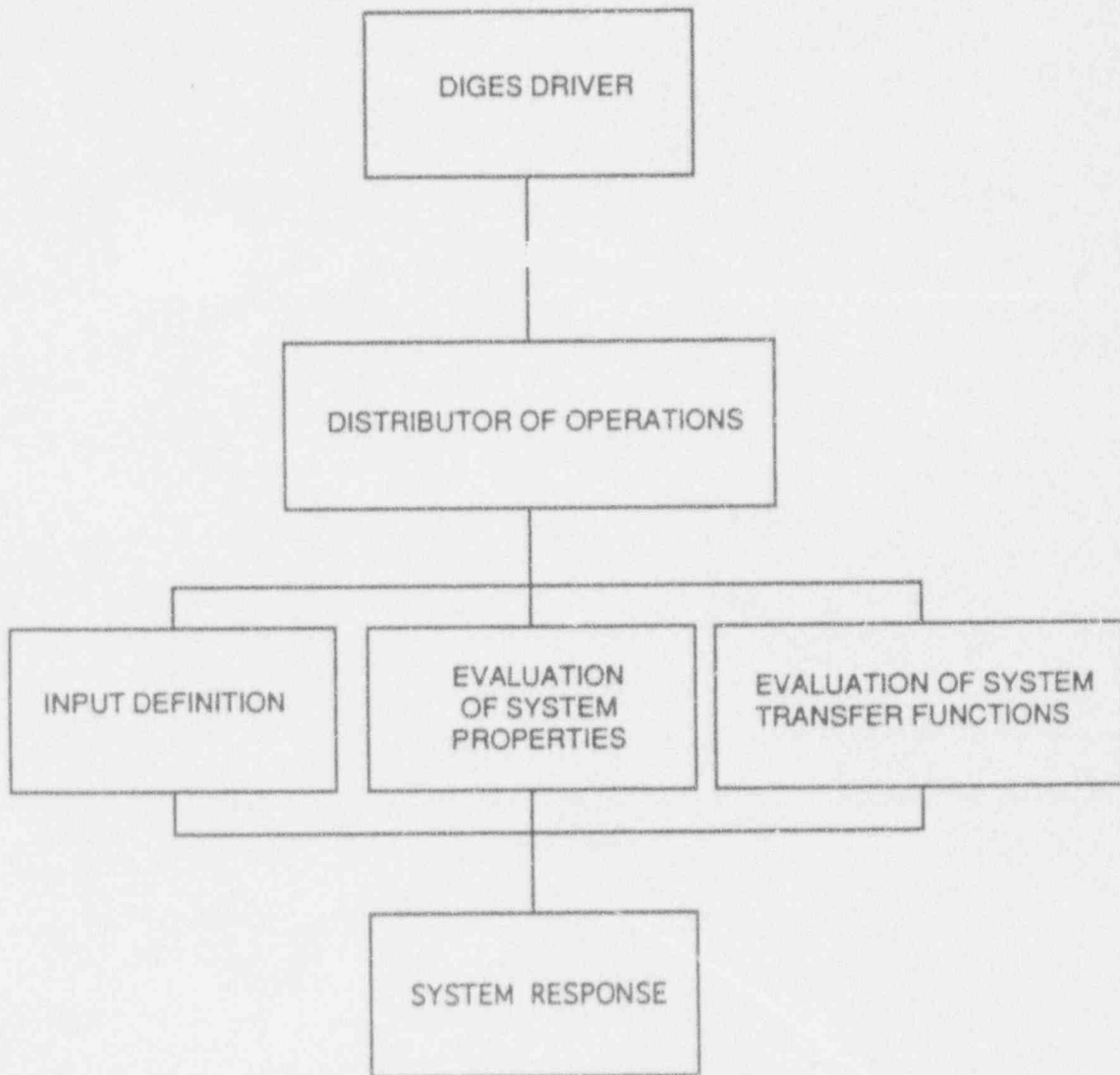


Figure 2.1

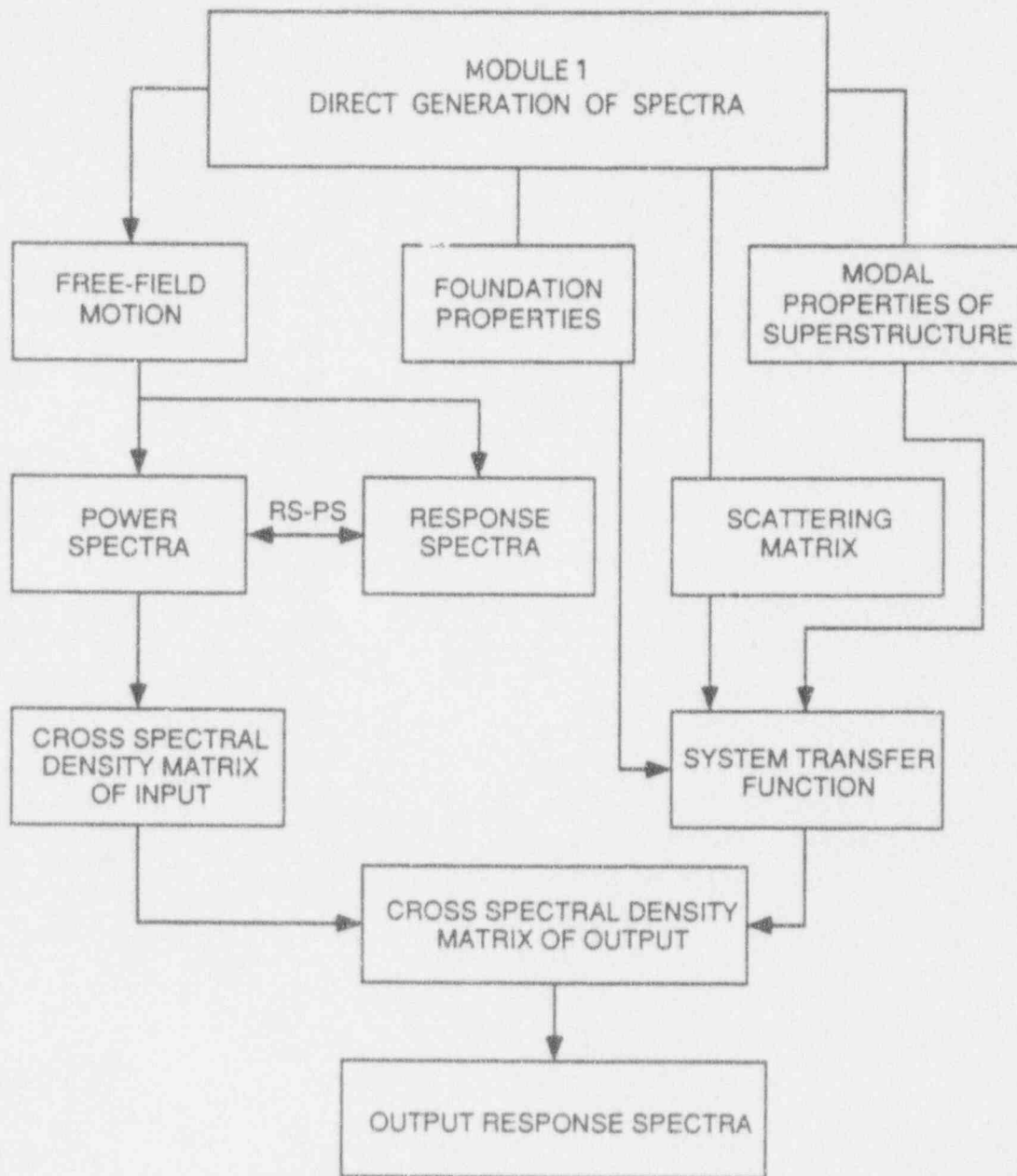


Figure 2.2

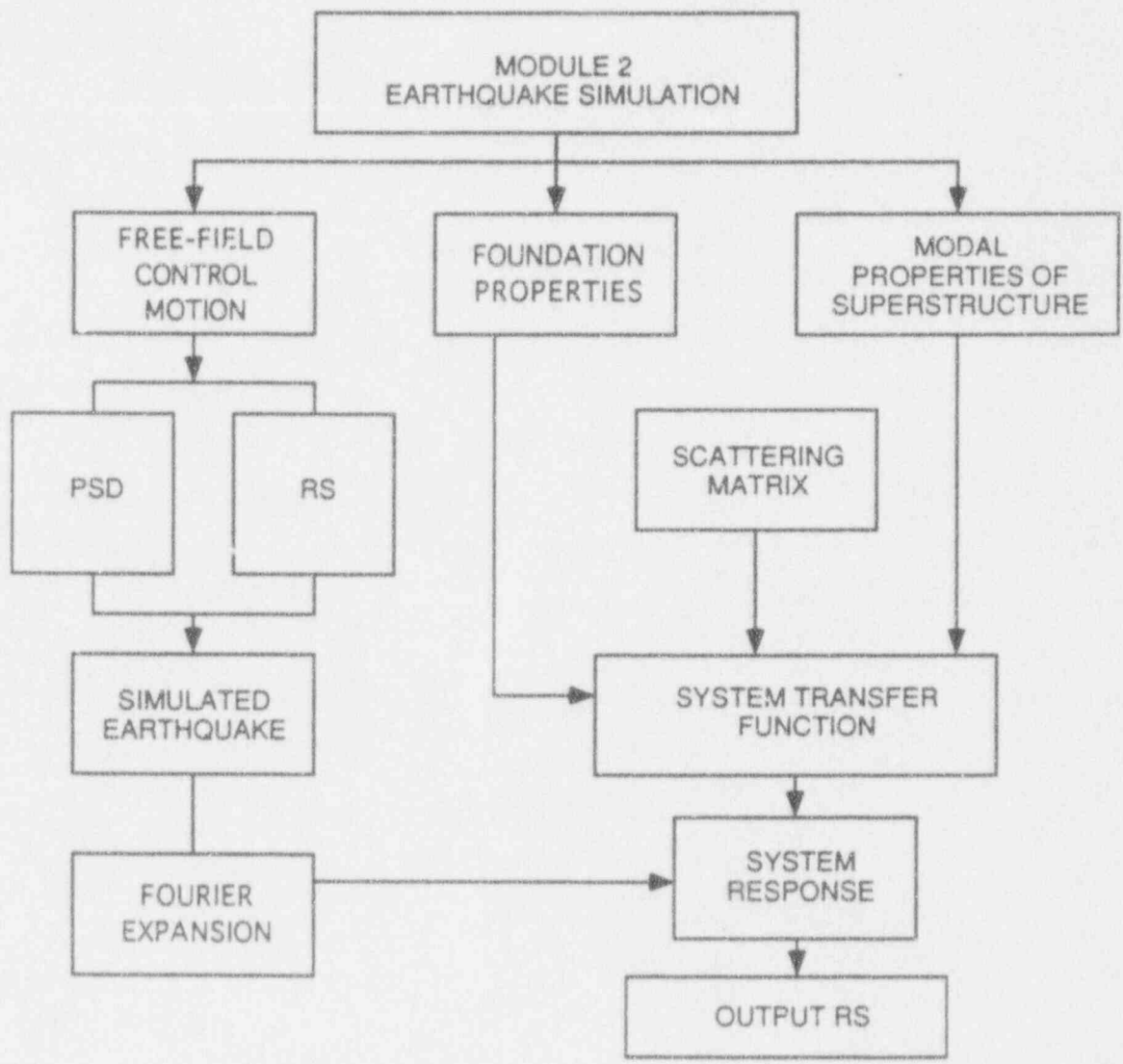


Figure 2.3

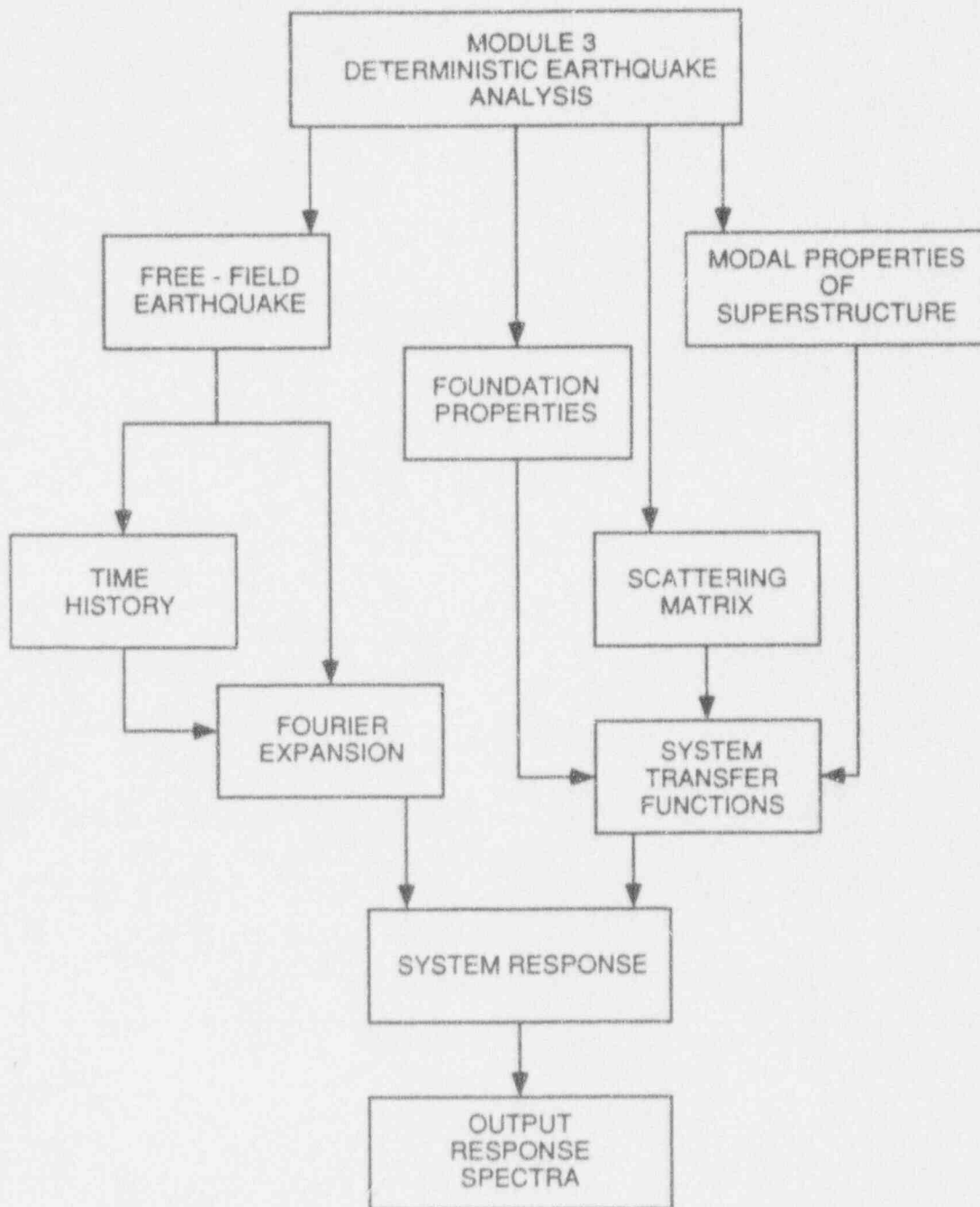


Figure 2.4

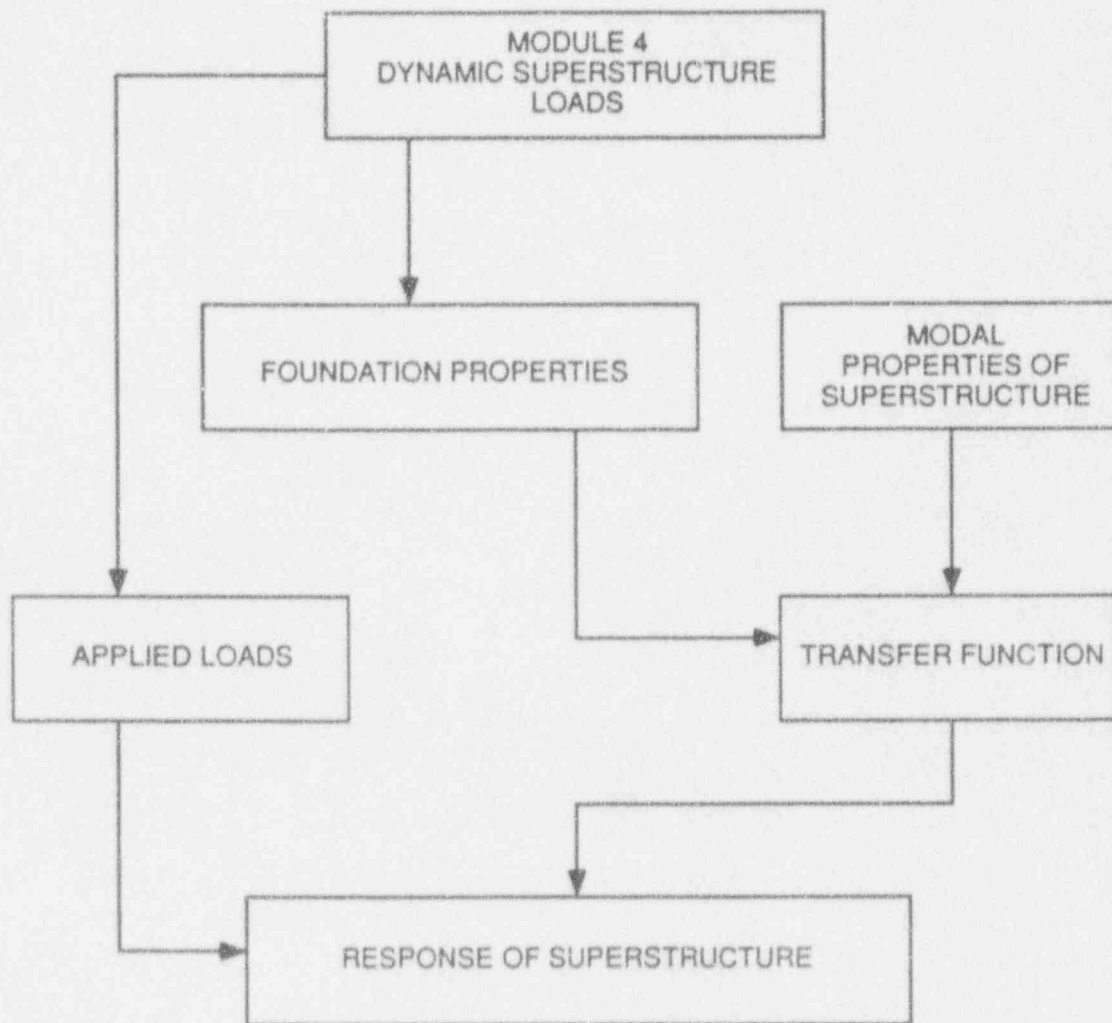


Figure 2.5

2.2 Program Input and Output

In the following, a description of the necessary input (interactive or read from an existing external file) that is required in order for the program to execute any of the possible four modes of analysis. The description of the input will be in the same sequence with the information that the program requests as it is executing and it will be complimented with the request messages and verification statements appearing on the screen during execution. This way, the problem-specific input will appear more meaningful to a user that wants to execute DIGES.

The input consists of information pertaining to the free-field ground excitation or supestructure load description on one hand and description of the geometric as well as dynamic properties of the overall system consisting of the superstructure, the foundation mat and the soil medium that is resting on.

Four (4) external files whose name will be identified interactively during execution are essential. The variable identity of these files will make the distinction between various problems possible without the need to overwrite neither the input or the output. These files contain the following information:

- Free-field control motion information or superstructure loads.
- Nodal and elemental description of the superstructure, foundation characteristics, soil medium properties and locations where response is to be calculated.
- Frequency dependent **impedance** and **scattering** matrix values consistent with the foundation type and the free-field ground motion.
- System OUTPUT response information that also includes the INPUT model and excitation as well as the complete output requested.

Upon request of execution of DIGES, which can be invoked by typing

rundiges

at the system prompt, the first requested input is:

PROBLEM TITLE ?

The input title (less than 80 characters) will help the user identify the output file for later processing.

The selection of the analysis mode follows next with the system response:

```

Type of analysis : (a)  DIRECT generation of RS ?
                   (b)  SIMULATION process      ?
                   (c)  SUPERSTRUCTURE loads    ?
                   (d)  SINGLE actual earthq    ?
ANSWER WITH      a , b , c or d
```

The statement

Type of Analysis ?

The response to the request will be one of the following:

- **Direct** implying that the free-field input motion is to be transferred to the structure directly.
- **Simulation** specifying that a simulated earthquake process will be used to calculate the response
- **Single** implying that a single earthquake event will be transferred to the structure from the free field.
- **Superstructure** indicating that the system is subjected to superstructure dynamic loads.

If your selection is either **direct** or **simulation** the program requests the form that the free-field input is expressed in, specifically **PSD** (power spectrum) or **RS** (response spectrum).

- **power** implies that the free-field control motion is in the form of a cross spectral density matrix. This matrix will be transferred to the structure directly (if the *direct* option has been chosen) or it will be used as the

stochastic process from which a number of simulated earthquakes will be generated (*simulation* option).

- **response** indicates that the free-field motion is in response spectra form which in turn implies that if *direct* transferring is to take place, a *consistent* power spectral density matrix will be calculated and transferred or a set of simulated earthquakes will be generated based on the response spectra and then transferred (*simulation* option).

If your selection is **Superstructure loads** the program anticipates that there will be a file whose name will be interactively specified (that step follows) and which contains

- a. the number of concentrated nodal loads
- b. the nodal location and the local degree of freedom of the node the load is acting (e.g. a force in x-direction F_x is identified with d.o.f = 1, a rotational moment with vector along the z axis M_z is identified with d.o.f = 6)
- c. The time history of the concentrated load (t vs. $P(t)$). Note that the number of points should be a power of 2 (for Fast Fourier purposes) and coincide with the number of harmonic frequencies you will eventually select.

If your selection is **Single actual earthquake** the program requests to identify the form of the given earthquake specifically whether it is in the **time** or **frequency** domain. If **time** is selected the program expects to find in the free-field input file the time variation of the ground acceleration. If **frequency** is selected the Fourier sine and cosine coefficients of the earthquake must be in your free-field input file.

The **DYNAMIC INPUT FILE** is requested next. The program provides the following information and the **filename** is to be selected on the basis of the type of analysis you have already selected.

- (a) PSD parameters (direct-PSD based analysis)
- (b) PSD guess parameters & target Resp. Spectrum
(direct-RS based)
- (c) PSD parameters for PSD-BASED earthq. simulation
- (d) TARGET Response Spectrum for earthq. simulation
- (e) FOURIER expansion / Time hist. of ACTUAL earthq
- (f) FOURIER expansion / Time hist. of SUPERSt. load

The **GEOMETRIC MODEL filename** is requested by the program next. This file contains the nodal, elemental, foundation mat and soil information as well as the locations for output response. Further details on the two files will be provided later in the volume.

N O T E :

If the **analysis type** selected is other than **superstructure** loads the program seeks information associated with the **SEISMIC WAVES** impinging on the structure. The user is responsible in making the right selection of

- a. the type of wave his seismic input represents (body or surface)
- b. the way waves propagate (vertical, inclined etc.)
- c. the directional sense of the control point motion

The program provides **ON SCREEN** information in an effort to ensure compatibility between the selections of this step. Below is a copy of the interactive response of the program during the identification of the seismic excitation.

CONTROL POINT MOTION : 1-D, 2-D or 3-D ?

respond by 1, 2 or 3

=====

S E L E C T CONTROL POINT INPUT ORIENTATION
CONSIDERING THE FOLLOWING.

- o Plane of propagation = x-z plane
- o x-z plane : P (body) - SV (shear) waves
- o y - direction : SH (shear) waves
- o Horizontally propp. SH waves : y -dir.
- o Horizontally propp. Rayleigh : x,z dir.
- o NOTE : for Vertical propagation : SV = SH

=====

DIRECTION OF 1-D CONTROL POINT MOTION = ?

x = 1
y = 2
z = 3

respond by 1, 2 or 3

W A V E I N C I D E N C E
A N D N A T U R E O F W A V E S

S E I S M I C W A V E S A R E :

- (a) BODY WAVES ?
- (b) SURFACE WAVES ?

ANSWER WITH a or b

DIRECTION OF WAVE PROPAGATION : (a) VERTICAL ?
(b) HORIZONTAL ?
(c) INCLINED ?

ANSWER WITH a, b or c

How CONTROL POINT MOTION (free-field) will
transfer to the foundation ?

- (a) DIRECTLY ?
- (b) thru Convolution/Deconvolution ?
- (c) thru SCATTERING ?

N O T E :

- o For DIRECT analysis DO NOT use convl/deconvl
- o For multilayered medium USE convl/deconvl

ANSWER WITH a, b or c

The next layer of information requested by the program is associated with the transferring of the CONTROL POINT MOTION to the foundation. Specifically, three transfer choices exist:

- a. Control point motion is placed **directly** on the foundation of the structure. This is the simplest of the three choices since the free-field input is not altered.
- b. Motion is transferred to the foundation through **convolution or deconvolution** of the given free-field ground acceleration.
- c. Motion is transferred to the foundation through **scattering** of the impinging waves.

If the selection is the **direct** transfer no further information is requested in this step.

If the foundation motion is obtained through **scattering** of the free-field then the program requests whether the scattering matrix is **analytical** or **tabular**. For SURFACE circular or rectangular foundations and for (a) BODY waves and (b) SURFACE SH waves there are analytical procedures inherent to the program that evaluate the foundation input motion matrix. For all other cases the user has to supply the frequency dependent scattering matrix coefficients in an external file whose name is provided at the prompt:

SCATTERING MATRIX TABLE IN file ?'

If the selected option for foundation input motion is through **convolution or deconvolution** the program seeks to find from the user whether the control point motion is given at the

- a. OUTCROP rock
- b. Soil SURFACE

It also requests whether the soil medium is **COMPLEX** meaning multi-layered or **single** layered. If the medium is a **single layer** (in the case of OUTCROP rock motion) overlying a rock formation or a uniform half space (for Soil SURFACE motion) the program requests information on the soil layer thickness, rock shear modulus, rock shear velocity and the depth from the surface the foundation input motion is to be evaluated. If the soil medium is **MULTI-LAYERED** the program seeks the number of distinct horizontal layers. The properties of the layers will be interactively provided by the user when the convolution routine is called. Note that when

convolution/deconvolution is involved the **free-field input** can ONLY be in terms of the Fourier coefficients of the earthquake. This implies that in generating output Response Spectra DIRECTLY from a free-field Power or Response spectrum one CANNOT form the foundation input motion through convolution or deconvolution. If that is desired then the selected ANALYSIS should be the SIMULATION of earthquakes which can result from a given Power or a Response Spectrum.

After the program collects all the information on the input it specifies the size of the harmonic problem. Specifically, it requests for:

- a. **minimum frequency** (hz) of the harmonic analysis
- b. **maximum frequency** (hz)
- c. **number of harmonic frequencies** in the interval or TIME POINTS.
When the frequency step is large the program asks the user to increase the number of harmonic frequencies to the next power of 2.

Following the size of the harmonic problem, the program asks for further information regarding the **direct generation** or **simulation** analyses type (if any of those have been selected).

- a. If the selected analysis is **direct** the program requests from the user to specify whether the free-field is in Power spectra form or response spectra.
 1. **Direct analysis - power** spectra. The program requests the specification of either **analytic** or **tabular** form of *psd* input representing the stochastic process in the free field. If **analytic**, the analytic *psd* form must be specified (1 or 2 or ... 6) as well as the number of parameters (constants) specific to each form. If **tabular**, then the input file that has been defined as the one with the earthquake record must contain the list of *frequencies* and corresponding *power spectral values* for a number of frequency points equal to the size of the dynamic problem defined earlier.
 2. **Direct analysis - response** spectra. This implies that a *consistent* power spectral matrix must be deduced from the given target response spectra. Thus, an analytical *psd* form is requested to be used in the fitting process (1 through 6) along with the size of the parameter vector that is form-specific and represents the initial guess. Next, the target response spectrum is requested in terms of the number of frequencies it

is specified at (*psd* to *RS* consistency will be achieved over these many frequencies). The input free-field motion file must accordingly contain the *vector of initial parameters* followed by the frequencies and the corresponding *target spectra* values.

- b. The analysis type is **simulation** based on either POWER or RESPONSE spectra.

- 1. **Simulation** analysis - **power** spectra. If the *psd-based* earthquake simulation is to utilize an **analytic** form then the **form** and the length of **parameter vector** is specified. If a **tabular** *psd* is to be used for the artificial generation, the *frequencies* along with the corresponding *psd values* at uniform spacing must be contained in the earthquake input file. The input request of this branch is completed by the specification of the number of artificial earthquakes that are to be generated.

- 2. **Simulation** analysis - **response** spectra. This analysis requires that a target response spectrum is to represent the process in the free field. The *frequencies* along with the corresponding response spectra values must make up the free-field input earthquake file. Again, the number of artificial earthquakes to be generated from the target response spectrum is requested.

At the end of this step the program seeks information on the IMPEDANCE matrix of the foundation. The frequency dependent [6X6] matrix is common to all types of analysis and can be **analytical** or **tabular**. The program contains analytic formulation for circular and rectangular foundations that can be either on the surface or embedded. These analytical expressions are discussed in App. II. If **tabulated** results of the matrix exist for a particular site then the program requests for the **filename** of the external table containing the coefficients of the matrix (see Table 2.2.1).

In order to help the program allocate the appropriate memory space, the user is asked to respond to questions regarding

- a. The **number** of nodal locations where the output response is to be evaluated
- b. The **number** of nodal points in the idealized stick model.

When the system prompt **OUTPUT SEND TO FILE ?** appears, the user must specify the name of the **output file** where all the output results are going to be written.

During the execution of the program the following information is requested and should be provided interactively,

- a. STRUCTURAL DAMPING RATIO (10% = 0.10)
- b. Whether the Foundation Mass matrix (diagonal terms only) is provided in the INPUT file (see Model Input File) or should be calculated by the program.
- c. GEOMETRY of the foundation (rectangular or circular)
- d. POSITION of the foundation (surface or embedded)

2.3 Model Input File

This external file whose name has been interactively defined during execution of the program contains complete information regarding the superstructure/foundation/soil system. Table 2.1 is a listing of a typical such file with added headings on each category of input so the user can follow the instructions easily (note that the headings SHOULD NOT be on the input file). Specifically:

1. The first record lists the number of nodal locations and the number of beam elements used in the idealization of the superstructure (4 and 3 respectively for the sample model)
2. A listing of a number of records equal to the number of nodes specified above. Each record contains the node number, the three global locations and six (6) ID numbers corresponding to each degree of freedom. For $ID > 1$ the d.o.f. is not constrained. For $ID = -nodex$ the node of the record is slaved on the master node $nodex$. If $ID = 0$ then the corresponding d.o.f. is constrained (a node with all six IDs = 0 is a fixed node). It should be emphasized that **no particular order** is required in numbering the nodal location.
3. The record that follows the nodal listing is a single number that can be either zero or a positive integer other than zero. A zero on the record indicates that the Mass Matrix of the superstructure is lumped at the nodes. A positive integer indicates that the Mass matrix is **consistent** and must be evaluated by the program. If the mass matrix is to be consistent then the equivalent density of the beam element representing the floor must be provided in the next set of records.
4. The number of records that follow reflect the number of elements in the model. Each such record contains the element number, its connectivity (the end nodes), the *equivalent* elasticity modulus, poisson ratio, axial area, the three moments of inertia (in the local coord. system) and the two shear areas. If consistent mass matrix has been specified from the previous record then the equivalent density of the element must be added as the last element of each row.
5. A set of records equal to the number of nodes follow and each record identifies the nodal location and the equivalent lumped mass properties

at each node (both translational and rotational masses). These records should only be in the input file when the **lumped** mass matrix has been selected.

6. The next record provides information on the foundation with a single row of four values. Specifically, the first three values represent the dimensions of the foundation such as the length, the width and the height. For a circular foundation the value in the position of the length corresponds to the radius of the foundation while the width is irrelevant. The last value is the density of the foundation medium.
7. During the execution of the program the user is asked to specify if the [6 x 6] Mass Matrix of the foundation (diagonal) is provided or must be calculated by the program. If the mass matrix is to be calculated by the program the row of the 6 diagonal elements should not be in the file.
8. The next record contains four (4) properties of the soil medium under the foundation. These are (a) the soil density (b) the shear modulus (c) the poisson's ratio and (c) the soil damping. ratio.
9. The number of response output locations is specified in the next record and it should be the same with the number to be interactively specified during execution.
9. The actual nodal locations for response output.

2.4 Input Files of Foundation Input Motion and Impedance

This files that are specified interactively during execution are to be invoked during the formulation of the transfer functions of the complete system provided that no available analytic expressions for the two matrices exist.

For a particular type of seismic wave the complete characterization of the response of the foundation requires that the foundation input motion (scattering) and the dynamic stiffness (impedance) are known for the type of foundation as well as the soil profile. Through a number of studies, numerical results pertaining to these two matrices have been calculated for various types of waves and foundation geometries. For available such numerical results and in accordance with the specifics of the soil type, the foundation geometry and the type of seismic waves the input file will be formed as follows (see Table 2.2).

The non-zero impedance coefficients of the $[6 \times 6]$ matrix are provided first in Table 2.2.1 in two sets of columns. The first set lists the number of the frequency (dimensionless), the frequency itself followed by the values of K_{11} , K_{15} , K_{22} and K_{24} . The same set of columns will follow by listing K_{33} , K_{44} , K_{55} and K_{66} . Each K_{ii} is represented by two columns (one for the real and one for the imaginary part of the coefficient).

Similarly for the foundation input motion, Table 2.2.2, the three non-zero elements of the $[6 \times 3]$ complex matrix that correspond to the given wave type, will be provided in separate columns that list the frequency number, the frequency (dimensionless) and the three frequency dependent elements of the matrix each of which is represented by two columns (real and imaginary).

The available solutions are tabulated for a limited number of frequencies. To apply these results in a much larger dynamic problem (harmonic analysis frequencies), interpolation should be used to complete the vector of the coefficients.

2.5 Input File of Free Field Excitation

This external file, also interactively specified during execution, contains the necessary information that describes either the free-field excitation or the dynamic loads on the structure. Therefore, the contents of this file will be mode-specific. Below is a description of what will DIGES be looking for to read from this external file after the analysis mode has been assigned.

1a. Direct analysis - Power spectra - analytic form

The only contents will be vectors of size equal to the one specified interactively during execution and whose elements are the parameters describing the *psd* form. The length of the vector must coincide with the form of *analytic psd* that has been selected (i.e. it form 6 requires 7 such parameters). Depending on the number of directions the excitation is specified, the number of such vectors will be determined (3 consecutive vectors will be needed for a 3-D input).

1b. Direct analysis - Power spectra - tabular form

Depending on the size of the dynamic problem which has been *interactively* specified, records, as many as the size of the dynamic problem and within the specified frequency range, must be listed in the input file. Each of these records the number identifying the harmonic, the frequency and the corresponding to the number of directions of the input *psd* values (i.e. two such columns for a 2-D input).

2. Direct analysis - Response spectrum.

This mode requires a *target spectrum*, an *analytic psd form*, a vector with elements the *initial parameter guesses* and certain *statistical properties* of the target spectrum. Table 2.3 is a sample listing of a free-field description of this mode. The first record contains the initial parameter guesses, the second are keys determining whether variation of the corresponding parameter is allowed in the *least square fitting process* (1 allows variation, 0 holds parameter constant). The third record contains the *peak factor* of the target spectrum, the p-percentile, the tolerance for matching and the number of iterations. The fourth record lists the viscous damping ratio of the response spectrum and the strong motion duration of the earthquake. Finally, a list of records (equal to the size of the dynamic problem and within the specified frequency range) containing the number of the harmonic, the frequency and the

corresponding ordinate of the target response spectrum. The input is repeated (with its own values) for additional directions of the free-field excitation.

3. **Simulation** analysis - **Power** Spectrum

The dynamic input of this mode will depend on the level of sophistication one wishes to implement in the earthquake generation. Hence,

- 3a. If the three components of free-field motion are considered to be independent and not statistically correlated, then the *psd* of each direction must be provided. Thus, if the power densities can be described by any of the six (6) analytic forms, so the *analytic* form has been selected, then the vectors of the parameters must be the only records in the input file. If on the other hand the power spectral densities for the three directions are available in tabular form, so the *tabular* mode has been selected, then the input file must contain a number of records equal to the size of the dynamic problem (number of frequencies) listing the harmonic number, the frequency and the three *psd* values (if all three components are simulated).
- 3b. If the *psd*-based simulated earthquakes are to have the three directions correlated (a more sophisticated approach) then the input must include the complete cross spectral density matrix must be provided for all the frequencies that define the dynamic problem. Specifically, eleven columns of data must be available representing the harmonic number, the frequency, the three diagonal elements of the cross spectral matrix and the three off diagonal elements each of which is represented by two columns (one for amplitude and the other for phase angle).

4. **Simulation** analysis - **Response** spectrum

With this mode the simulated earthquakes utilize specified target response spectra. For the general case where all three earthquake components are required, the three target spectra (each for the corresponding direction) must be available for all the frequencies of the dynamic problem. Thus the input file will consist of five (the most) columns which contain the harmonic number, the frequency and the spectral values of the three directions.

5. Analysis of a given **Single Earthquake**

This mode requires that the input of an actual earthquake be in the form of *time history* of the ground acceleration or be already decomposed in its Fourier coefficients.

- If the time history is available then the input file contains a record indicating the *uniform time step* and the *number of time points* (this number should be a power of 2 and twice the solution frequency number to take advantage of the fast Fourier transform) followed by a vector of size equal to the number of time points representing the acceleration at the corresponding time.

- If the earthquake is already expressed in its Fourier coefficients, four columns containing the harmonic number, the frequency and the two coefficients will represent the dynamic input.

6. Superstructure dynamic loads

The first record in the external file contains three (3) elements which indicate:

- a. the number n of nodal concentrated loads that apply on the superstructure
- b. the time increment Δt of the record(s)
- c. the number of time points (= number of harmonic frequencies).

For n number of such loads n sets of the following records must be listed. The first record of the set contains the nodal location of the superstructure and the degree of freedom along which the load applies (a value from 1 to 6). The set is completed with three columns of data containing the time point number, the time value and the corresponding force value.

```

# of nodes      # of elements
4                3

nod #           x      y      z      DOF--x  -y  -z  -xx  -yy  -zz
16             0.0    0.0   129.0      1    1    1    1    1    1
15             0.0    0.0   110.0      1    1    1    1    1    1
14             0.0    0.0    56.0      1    1    1    1    1    1
13             0.0    0.0    0.0       0    0    0    0    0    0

key indicating that mass matrix of structure is LUMPED
0

elem nd1 nd2      E      P.R.      Ax      Ixx      Iyy      Izz      Ay      Az
1  13  14  6.10E8  0.17  1394  4526287  2263144  2263144  742  742
2  14  15  6.10E8  0.17  1394  4526287  2263144  2263144  742  742
3  15  16  6.10E8  0.17  1394  4526287  2263144  2263144  742  742

Node #           Mx           My           Mz           Mxx           Myy           Mzz
16          273600    273600    273600    204308000    204308000    650863000
15          330600    330600    330600    424677000    424677000    1009021000
14          335200    335200    335200    601716000    601716000    1036850000
13           0.000     0.000     0.000     0.00000     0.00000     0.00000

Foundation Radius (or a)      b      Thickness      Density
10.0                          0.0       3.0          150.0

M(1,1)  M(2,2)  M(3,3)  M(4,4)  M(5,5)  M(6,6)
3116100  3116100  3208900  13391025000  13391025000  22643080000

Underlying Soil :      Density      Shear Modulus      P.R.      Damping
                      3.63          400000             0.33      0.05

# of locations for OUTPUT
1

ACTUAL nodal output location (floor)
16

```

Table 2.1 Listing of input record for *Model Input File*

Impedance Coefficients

	frq	K-11		K-15		K-22		k-24	
1	0.0	4.8900	0.4890	-0.3990	-0.0399	4.8900	0.4890	0.3990	0.0399
2	0.5	4.8000	1.9300	-0.4720	-0.0552	4.8000	1.9300	0.4720	0.0552
3	1.0	4.6500	3.4100	-0.5270	0.0229	4.6500	3.4100	0.5270	-0.0229
.
20	9.5	3.1400	29.7000	-0.0377	0.1400	3.1400	29.7000	0.0381	0.1400
21	10.0	3.0500	31.2000	-0.0138	0.1640	3.0500	31.2000	0.0142	0.1640

	frq	K-33		K-44		K-55		K-66	
1	0.0	6.1900	0.6190	4.3500	0.4350	4.3500	0.4350	5.7700	0.5770
2	0.5	5.9500	3.1100	4.1000	0.5350	4.1000	0.5350	5.5200	0.6710
3	1.0	5.4400	5.6900	3.6400	0.9670	3.6400	0.9670	5.0100	1.1100
.
20	9.5	1.1600	58.9000	1.5900	15.0000	1.5900	15.0000	3.3400	15.3000
21	10.0	1.0100	62.1000	1.5000	15.8000	1.5000	15.8000	3.2900	16.1000

Table 2.2.1 Typical Listing of Foundation Impedance Matrix

Scattering Coefficients (horiz. SH waves)

	frq	S-ii		R-ij		R-ik	
1	0.0	1.00	0.00	.00	0.00	0.00	0.00
2	0.5	.957	0.00477	.000847	-.000131	-.0115	-.243
3	1.0	.831	0.0240	.00365	-.00169	-.0180	-.454
.
20	9.5	.110	.0606	-.00016	-.00111	-.150	-.155
21	10.0	.0666	.0964	-.00075	-.0004	-.0813	-.202

Table 2.2.2 Typical Listing of Foundation Input Motion Matrix

initial parameter values for the PSD form
 9.90 10.998 949.85 3.871 23.211 182.02 0.0086

keys defining variation of parameters
 1 1 1 1 1 1 1

target spectra properties
 3.0 0.84 0.05 20

damping ratio and earthquake strong motion
 0.05 20.0

TARGET RESPONSE SPECTRUM		
1	0.500000	0.831821
2	0.514813	0.852060
3	0.530065	0.872792
4	0.545768	0.894028
5	0.561937	0.915780
6	0.578585	0.938062
7	0.595726	0.960886
8	0.613375	0.984265
9	0.631547	1.00821
10	0.650257	1.03274
...
...
100	8.99987	2.61022
101	9.26650	2.55441
102	9.54103	2.49993
...
156	46.1621	1.00000
157	47.5297	1.00000
158	48.9379	1.00000
159	50.3877	1.00000
160	51.8805	1.00000
161	53.4175	1.00000
162	55.0000	1.00000

Table 2.3 Typical listing of input of free-field control motion.

2.6 Sample Runs with the DIGES Program

In this section the step-by-step procedure to execute DIGES is outlined and the interactive response of the program is listed. The sample problems are used to invoke the different solution moduli of DIGES for the user to familiarize with the procedures. The goal of these sample runs is to present (a) the physical problem, (b) the selection of the appropriate modulus based on the excitation input and (c) the solution output for the system variables of interest.

Outline of a Generic Sample Problem:

Two system configurations, shown in Figure 2.6, have been used to outline the solution procedure. Specifically, Model-1 is a representation of a structure with a single floor connected to a cylindrical surface foundation resting on uniform elastic half space and its input file can be seen in Table 2.4. Model-2 is a 4-node, 3-element structure described in Table 2.1 and it also rests on similar foundation. For both models the *lumped* mass matrix option is selected.

The diagonal [6 x 6] mass matrix of the foundation is also provided along with the properties of the soil medium.

The frequency-dependent impedances are evaluated via an analytic approximate expression (from Pais and Kausel) due to the geometric simplicity of the interacting systems (circular foundation - uniform half space).

The models are excited by either a vertically propagating *SH* seismic wave or a time varying superstructure load. Since the propagation is vertical the foundation input motion will simply be the motion of the control point on the surface (i.e. $R_{zz} = 1.0$ and the rest of the scattering matrix is equal to zero).

The free-field earthquake is in the form of power spectra that are compatible to either RG-1.60 or Newmark-Hall Response spectra. These spectra will be used for the Direct generation of floor spectra or the Simulation option. The superstructure dynamic load is an assumed time-varying **concentrated** load applying at one of the nodes of Model-2.

The basic steps followed in all the sample cases are summarized below:

- a. The analysis mode is defined and the applicable input is supplied.
- b. The *eigensolution* of the structural model is performed.

- c. The excitation input is identified and transferred to the structure through the appropriate relations. This input includes the superstructure loads.
- d. The response spectrum at the specified floor and direction is calculated. In the case of the dynamic load, the resulting foundation forces and the time-varying displacements at the specified floor are calculated.

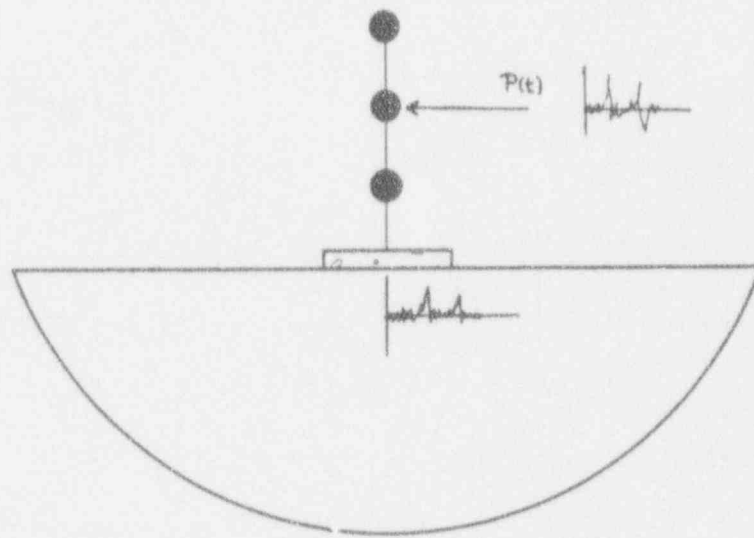
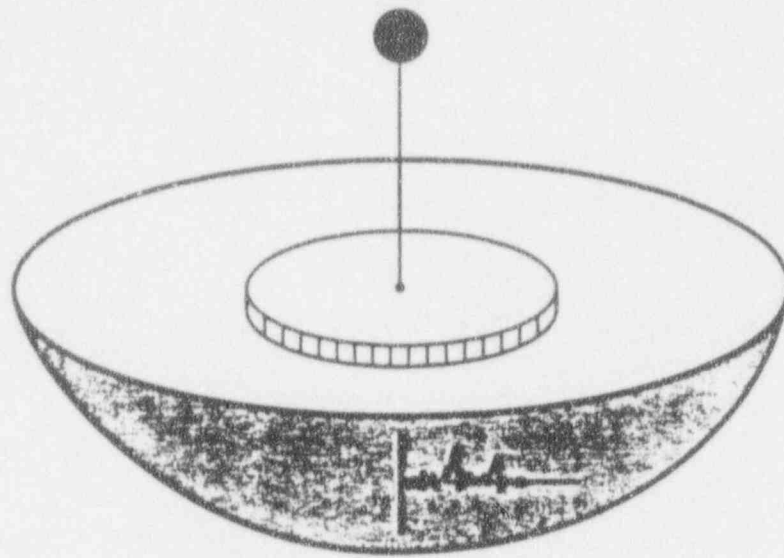


Figure 2.6 Sample Model Configurations.

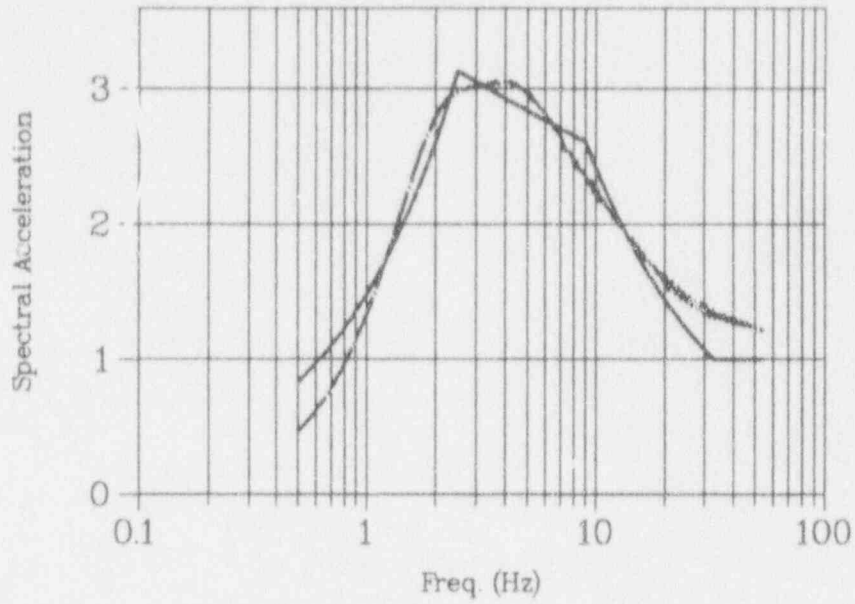


Figure 2.7 RG.1.60 Target and Spectrum from Compatible PSD.

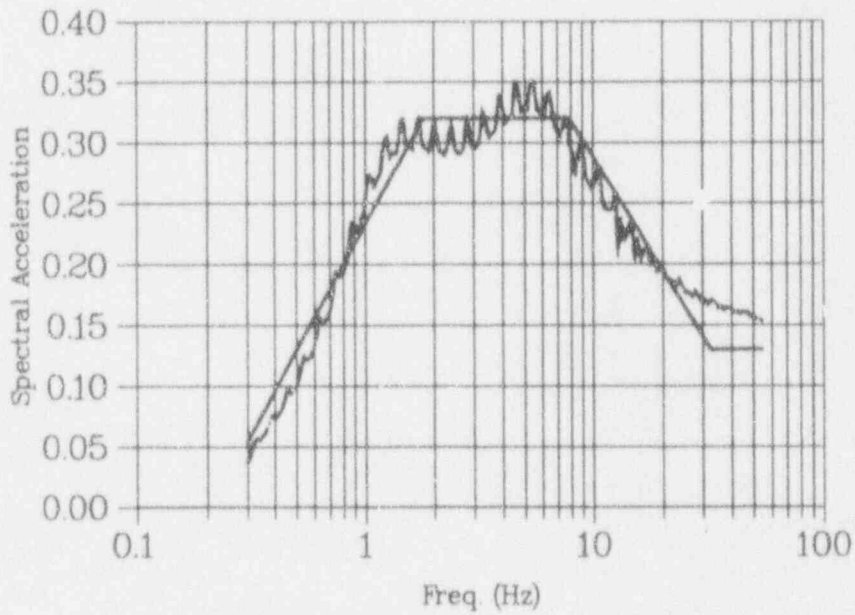


Figure 2.8 Newmark-Hall and Spectrum from Compatible PSD.

Sample Run 1. The *Direct Generation Option* is selected for the 1-floor system of Table 2.4 that is subjected to a vertically propagating P-wave expressed in the form of a PSD that led to the matching in Figure 2.1 (Newmark-Hall). The solution output is the Response Spectrum at the floor in the vertical direction (only direction that will be excited). The interactive steps present the entire procedure along with the graphical representation of the input and output PSD and the output response spectra.

Table 2.4 Input file for Model-1.

```

2      1
14     0.0 0.0 100.0      1  1  1  1  1  1
13     0.0 0.0  0.0      0  0  0  0  0  0
0
1 13 14      1.0E8 0.17 67.7  24060 12030 12030 33 33
14     11900 11900 11900  171600 171600 188500
13     0.000 0.000 0.000  0.0000 0.0000 0.00000
840.0  840.0  100.0  150.0
107100 107100 107100 1339102 1339102 2264300
0.000172 19514 0.33      0.05
1
14

```

PROGRAM EXECUTION

```

=====
=
=   Direct Generation   =
=       of              =
=   Response Spectra   =
=
= Dr. N. Simos & Dr. A.M. Philippopoulos =
=====

PROBLEM TITLE ?
study of vertical spectra for HFBR
Type of analysis : (a) DIRECT generation of RS ?
                   (b) SIMULATION process      ?
                   (c) SUPERSTRUCTURE loads    ?
                   (d) SINGLE actual earthq    ?
ANSWER WITH a , b , c or d
a
Form of Free-Field Input : (a) POWER Spectra ?
                           (b) RESPONSE Spectra ?
ANSWER WITH a OR b
a

```

DYNAMIC INPUT FILE

INPUT is one of following data sets :

- (a) PSD parameters (direct-PSD based analysis)
- (b) PSD guess parameters & target Resp. Spectrum (direct-RS based)
- (c) PSD parameters for PSD-BASED earthq. simulation
- (d) TARGET Response Spectrum for earthq. simulation
- (e) FOURIER expansion / Time hist. of ACTUAL earthq
- (f) FOURIER expansion / Time hist. of SUPERSt. load

FILENAME ?
pdcip.inpt
GEOMETRIC MODEL IN FILE ?
hfbr00.dat

CONTROL POINT MOTION : 1-D, 2-D or 3-D ?

respond by 1, 2 or 3

1

SELECT CONTROL POINT INPUT ORIENTATION
CONSIDERING THE FOLLOWING.

- o Plane of propagation = x-z plane
- o x-z plane : P (body) - SV (shear) waves
- o y - direction : SH (shear) waves
- o Horizontally propg. SH waves : y-dir.
- o Horizontally propg. Rayleigh : x,z dir.
- o NOTE : for Vertical propagation : SV = SH

DIRECTION OF 1-D CONTROL POINT MOTION = ?

x = 1
y = 2
z = 3

respond by 1, 2 or 3

3

WAVE INCIDENCE
AND NATURE OF WAVES

SEISMIC WAVES ARE :

- (a) BODY WAVES ?
- (b) SURFACE WAVES ?

ANSWER WITH a or b

a

DIRECTION OF WAVE PROPAGATION : (a) VERTICAL ?
(b) HORIZONTAL ?
(c) INCLINED ?

ANSWER WITH a, b or c

a

How CONTROL POINT MOTION (free-field) will
transfer to the foundation ?

- (a) DIRECTLY ?
- (b) thru Convolution/Deconvolution ?
- (c) thru SCATTERING ?

NOTE :

- o For DIRECT analysis DO NOT use convl/deconvl
- o For multilayered medium USE convl/deconvl

ANSWER WITH a, b or c

a

FOUNDATION INPUT MOTION applied DIRECTLY

FREQUENCY RANGE for the Analysis (Hz)

MINIMUM FREQUENCY (Hz) = ?
0.3
MAXIMUM FREQUENCY (Hz) = ?
33.0
NUMBER of freq. or time points = ?
1024
Free-Field POWER SPECTRA : (a) ANALYTIC ?
(b) TABULAR ?
ANSWER WITH a OR b
a
PSD FORM (of 6) describing free-field ?
6

=====
You CHOSE an ANALYTIC PSD form hence your input seismic file must contain the corresponding number of parameter values (many as the input directions)
=====

form of IMPEDANCE MATRIX: (a) ANALYTIC ?
(b) TABULAR ?
ANSWER WITH a OR b
a

=====
EVALUATE RESPONSE at # of locations = ?
1
=====

=====
HOW MANY NODES ARE THERE IN STICK MODEL = ?
IMPORTANT : Should coincide with number shown in MODEL input file
=====

=====
OUTPUT SEND TO FILE ?
=====

output.out
=====
INPUT SUMMARY
=====

ANALYSIS SELECTED = direct
INPUT FILE model-found-soil info = hfbr00.dat
INPUT FILE (earthq. PSD,RS,th - load) = psdcp.inpt
INPUT FILE imp = imped.dat
INPUT FILE scat = scater.dat
OUTPUT FILE = output.out
=====

=====
NUMBER OF NODES = 2
NUMBER OF ELEMENTS = 1
=====

TOTAL NUMBER OF DOF = 6 NUMBERED AS
NODE DOF-1 DOF-2 DOF-3 DOF-4 DOF-5 DOF-6

TOTAL NUMBER OF DOF = 6 NUMBERED AS
NODE DOF-1 DOF-2 DOF-3 DOF-4 DOF-5 DOF-6
(ux) (uy) (uz) (thx) (thy) (thz)
14 1 2 3 4 5 6
13 0 0 0 0 0 0

=====

LUMPED MASS MATRIX
of SUPERSTRUCTURE

(Nodal masses in input file)

=====

ELEMENT NUMBER BANDWIDTH
 1 6
MAXIMUM BANDWIDTH IN M & K MATRICIES = 6
EIGENVALUES & EIGENVECTORS

=====

No. =	1	eigenvalue =	15.5239
No. =	2	eigenvalue =	15.5239
No. =	3	eigenvalue =	75.4260
No. =	4	eigenvalue =	417.602
No. =	5	eigenvalue =	417.602
No. =	6	eigenvalue =	233.552

STRUCTURAL DAMPING RATIO = ?
0.07

MASS MATRIX OF THE FOUNDATION : ?

1 = Diagonal elements provided in INPUT file
0 = Matrix to be evaluated by the program
respond with 1 or 0

1

GEOMETRY OF THE FOUNDATION : ?

1 = CIRCULAR
2 = RECTANGULAR
respond with 1 or 2

1

POSITION OF FOUNDATION : ?

0 = SURFACE
1 = EMBEDDED
respond with 0 or 1

0

=====

FOUNDATION SUMMARY

=====

MASS MATRIX	=	1
GEOMETRY	=	1
EMBEDMENT	=	0
DIMENSION - a	=	840.000
DIMENSION - b	=	0.
THICKNESS	=	100.0000
DENSITY	=	150.000

=====

PAUSE: To resume execution, type: go
Any other input will terminate the program.
go
Execution resumed after PAUSE.

=====

SEISMIC INPUT SUMMARY

=====

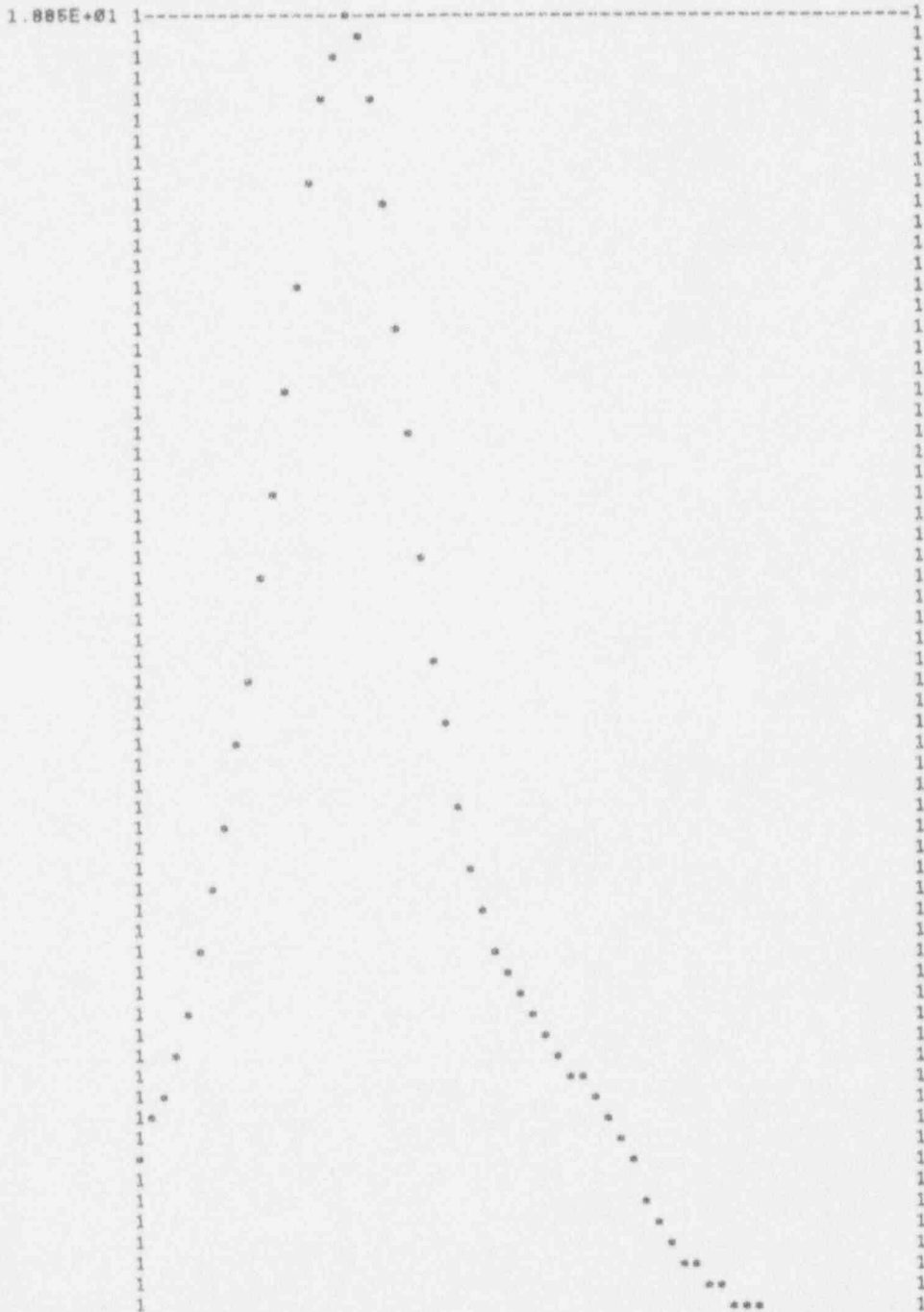
ANALYSIS SELECTED	=	direct
FORM OF INPUT FREE-FIELD SPECTRA	=	power
EARTHQUAKE DIRECTION	=	3
FREQUENCY RANGE (f-min ; f-max)	=	0.300000 33.0000
NUMBER OF FREQUENCIES IN RANGE	=	1024
EARTHQUAKE INPUT FILE	=	psdcp.inpt

=====

FREE-FIELD PSD INPUT. DIR. = 3
Enter x1,x2 (= to stop)

1

2



Enter x1,x2 (= to stop)

1

```
1
=====
Soil PROPERTIES :
density, shear mod., pr, damp
      1.72000E-04   39020.0   0.330000   2.00000E-02
=====
```

```
=====
NODAL LOCATIONS (output) : 14
=====
```

```
=====
STARTING HARMONIC ANALYSIS
=====
```

```
completed frequency = 128 of 1024
completed frequency = 256 of 1024
completed frequency = 512 of 1024
completed frequency = 768 of 1024
```

```
END OF HARMONIC ANALYSIS
```

```
PSD OUTPUT AT CHOSEN D.O.F.
```

```
d.o.f. = 1
Enter x1,x2 ( = to stop)
1
1
DO YOU WANT THE Response Spectrum of PSD ?
type yes or no
no
PSD OUTPUT AT CHOSEN D.O.F.
```

```
d.o.f. = 2
Enter x1,x2 ( = to stop)
1
1
DO YOU WANT THE Response Spectrum of PSD ?
type yes or no
no
```

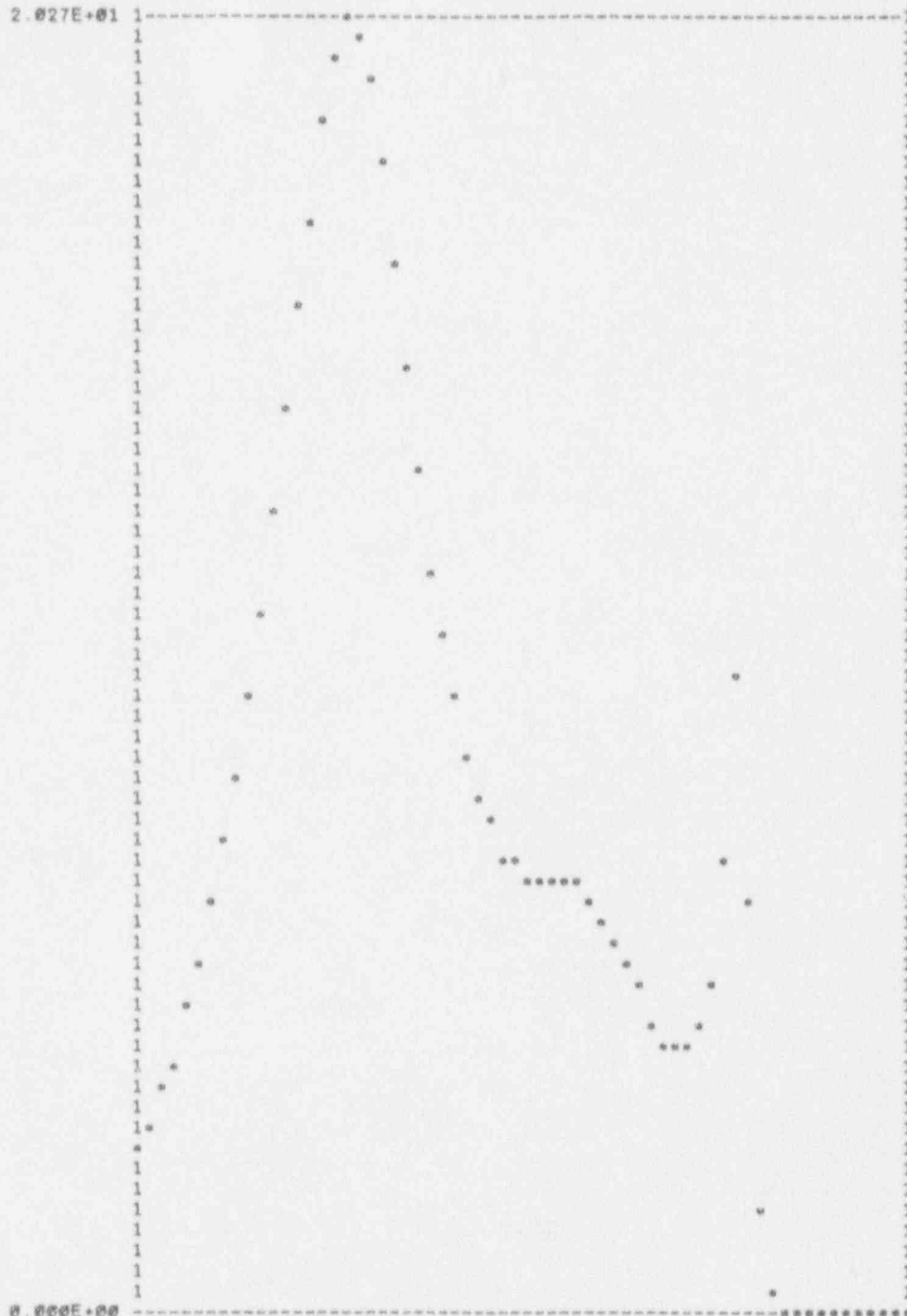
PSD OUTPUT AT CHOSEN D.O.F.

d.o.f. = 3

Enter x1,x2 (= to stop)

1

2



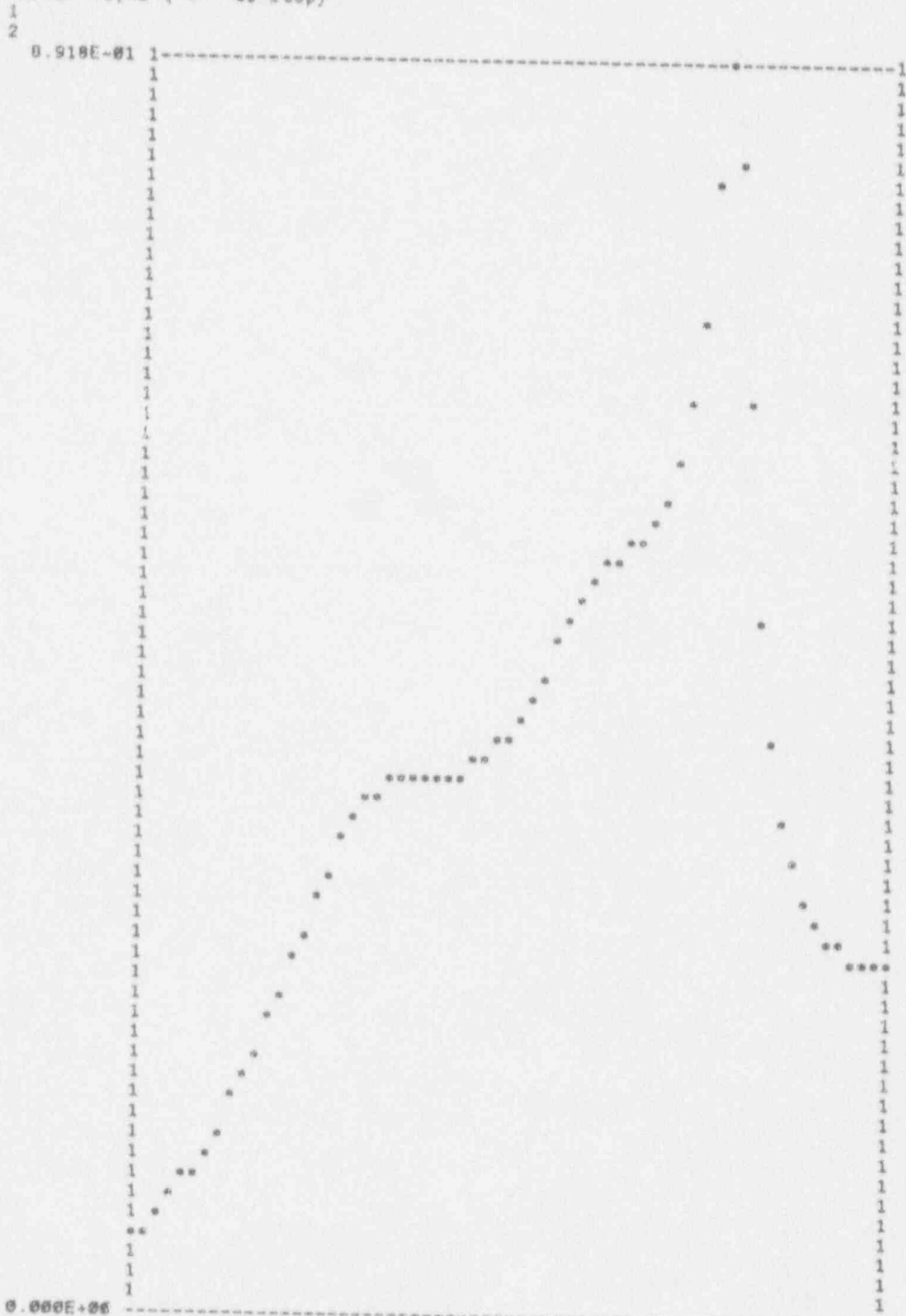
Enter x1,x2 (= to stop)

1

```

1
DO YOU WANT THE Response Spectrum of PSD ?
type yes or no
yes
RESPONSE SPECTRUM damping = 5.00000E-02
>>>>> ONE MORE ITERATION WAS DONE
PLOT of RESPONSE SPECTRUM at DOF : 3
Enter x1,x2 ( = to stop)

```



```

0.000E+00 1.885E+00 2.073E+02
Enter x1,x2 ( = to stop)
1
1

```

Sample Run 2. The *simulation mode* of Diges is executed with the Model-1 (Table 2.4) and a vertically propagating SH wave. The free field accelerations are generated from the compatible to RG.1.60 power spectra. For demonstration purposes 3 earthquakes are generated and transferred to the structure. The output is an equivalent response spectrum deduced from the ensemble of earthquake responses at the floor that is evaluated based on the specified (by the user) standard deviation.

```

=====
=           Direct Generation           =
=           o f                         =
=           Response Spectra           =
= Dr. N. Simos & Dr. A.M. Philippopoulos =
=====

          PROBLEM TITLE ?
Response Spectra Generation Via SIMULATION
Type of analysis : (a) DIRECT generation of RS ?
                   (b) SIMULATION process      ?
                   (c) SUPERSTRUCTURE loads    ?
                   (d) SINGLE actual earthq    ?
ANSWER WITH a , b , c or d
b
=====

          OUTLINE of SIMULATION process selected

PSD or RS --> Time Hist --> Harm. Soln --> floor RS
=====

SIMULATION process based on : (a) POWER spectra ?
                              (b) RESPONSE spectra ?
ANSWER WITH a OR b
a

          D Y N A M I C   I N P U T   F I L E

=====

INPUT is one of following data sets :
-----

(a) PSD parameters (direct-PSD based analysis)
(b) PSD guess parameters & target Resp. Spectrum
    (direct-RS based)
(c) PSD parameters for PSD-BASED earthq. simulation
(d) TARGET response Spectrum for earthq. simulation
(e) FOURIER expansion / Time hist. of ACTUAL earthq
(f) FOURIER expansion / Time hist. of SUPERSt. load
=====

FILENAME      ?
psdcp.inpt
GEOMETRIC MODEL IN FILE ?
hfbr00.dat

```

CONTROL POINT MOTION : 1-D, 2-D or 3-D ?

respond by 1, 2 or 3

1

=====

S E L E C T CONTROL POINT INPUT ORIENTATION
CONSIDERING THE FOLLOWING.

- o Plane of propagation = x-z plane
 - o x-z plane : P (body) - SV (shear) waves
 - o y - direction : SH (shear) waves
 - o Horizontally propg. SH waves : y -dir.
 - o Horizontally propg. Rayleigh : x,z dir.
 - o NOTE : for Vertical propagation : SV = SH
- =====

DIRECTION OF 1-D CONTROL POINT MOTION = ?

x = 1
y = 2
z = 3

respond by 1, 2 or 3

1

W A V E I N C I D E N C E
A N D N A T U R E O F W A V E S

S E I S M I C W A V E S A R E :

- (a) BODY WAVES ?
- (b) SURFACE WAVES ?

ANSWER WITH a or b

a

DIRECTION OF WAVE PROPAGATION : (a) VERTICAL ?
(b) HORIZONTAL ?
(c) INCLINED ?

ANSWER WITH a, b or c

a

How CONTROL POINT MOTION (free-field) will
transfer to the foundation ?

- (a) DIRECTLY ?
- (b) thru Convolution/Deconvolution ?
- (c) thru SCATTERING ?

N O T E :

- o For DIRECT GENERATION of SPECTRA
DO NOT use convl/deconvl. NOT APPLICABLE !
- o For multilayered medium USE convl/deconvl

ANSWER WITH a, b or c

c

form of SCATTERING MATRIX: (a) ANALYTIC ?
(b) TABULAR ?

NOTE : if soil formation is other
than uniform half space = TABULAR

ANSWER WITH a OR b

a

FREQUENCY RANGE for the Analysis (Hz)

MINIMUM FREQUENCY (Hz) = ?
 0.3
 MAXIMUM FREQUENCY (Hz) = ?
 33.0
 NUMBER of freq. or time points = ?
 512
 Power of point-size = 9
 SIMULATION SPECIFICATION

PSD FORM (of the 0) to GENERATE artificial T.Hs. ?
 6

NUMBER of ARTIFICIAL EARTHQUAKES = ?
 3

EVALUATE RESPONSE at # of locations = ?
 (NOTE : Solution at all DOF of node)
 1

HOW MANY NODES ARE THERE IN STICK MODEL = ?

IMPORTANT !!! : Should coincide with number
 shown in MODEL Input file

2

NUMBER OF NODES = 2
 NUMBER OF ELEMENTS = 1

TOTAL NUMBER OF DOF = 6 NUMBERED AS
 NODE DOF-1 DOF-2 DOF-3 DOF-4 DOF-5 DOF-6

TOTAL NUMBER OF DOF =	6 NUMBERED AS					
NODE	DOF-1	DOF-2	DOF-3	DOF-4	DOF-5	DOF-6
	(ux)	(uy)	(uz)	(thx)	(thy)	(thz)
14	1	2	3	4	5	6
13	0	0	0	0	0	0

=====

LUMPED MASS MATRIX
 of SUPERSTRUCTURE

(Nodal masses in input file)

=====

ELEMENT NUMBER BANDWIDTH
 1 6
 MAXIMUM BANDWIDTH IN M & K MATRICES = 6

EIGENVALUES & EIGENVECTORS

=====

No. = 1 eigenvalue = 15.5239
 No. = 2 eigenvalue = 15.5239
 No. = 3 eigenvalue = 75.4260
 No. = 4 eigenvalue = 417.602
 No. = 5 eigenvalue = 417.602
 No. = 6 eigenvalue = 233.552

STRUCTURAL DAMPING RATIO = ?
 0.05

=====

SEISMIC INPUT SUMMARY

=====

ANALYSIS SELECTED = simulation
 FORM OF INPUT FREE-FIELD SPECTRA = power
 EARTHQUAKE DIRECTION = 3
 FREQUENCY RANGE (f-min ; f-max) = 0.300000 33.0000
 NUMBER OF FREQUENCIES IN RANGE = 512
 EARTHQUAKE INPUT FILE = frfield.dat

=====

READ-IN PSD parameters = 7
= ?
9.9
10.998
949.85
3.871
23.211
102.02
0.0006

=====

Soil PROPERTIES :
density, shear mod., pr, damp
1.72000E-04 39028.0 0.30000 2.00000E-02

=====

=====

NODAL LOCATIONS (output) : 14

=====

=====

STARTING HARMONIC ANALYSIS

=====

completed frequency = 64 of 512
completed frequency = 128 of 512
completed frequency = 256 of 512
completed frequency = 384 of 512

END OF HARMONIC ANALYSIS

CALLING SIMULATION
M O D E

=====

ZPA of EARTHQUAKE FAMILY (in G-s) = ?
1.0

=====

DAMPING of GROUND SPECTRUM = ?
(to define input ground accel.)
0.05

DAMPING for FLOOR SPECTRUM = ?
0.05

=====

output : 14
d.o.f. : 1 2 3 4 5 6

=====

SUPPLY seeds for 3 earthquakes

333333
555555
777777

=====

TRANSFERRING EARTHQ. : 1

=====

=====

TRANSFERRING EARTHQ. : 2

=====

=====

TRANSFERRING EARTHQ. : 3

=====

=====

O U T P U T L O C A T I O N S

=====

	x	y	z	Rx	Ry	Rz
node =	14					
Global D.O.F :	1	2	3	4	5	6
Output Rank :	1	2	3	4	5	6

S P E C I F Y the Rank of the D.O.F for output
3

=====

R E S P O N S E S P E C T R A

=====

at DOF due to all fictitious earthquakes

=====

(freq)

0.405	0.023	0.019	0.018
0.810	0.048	0.050	0.057
1.215	0.109	0.116	0.101
1.620	0.123	0.205	0.211
2.025	0.210	0.266	0.304
.....			
19.439	4.376	4.723	4.891
19.844	4.250	4.751	4.963
20.249	3.905	4.962	4.902
20.654	4.025	4.949	4.652
21.058	4.177	4.901	4.204
21.463	4.155	4.782	4.333
.....			
71.600	6.257	7.062	7.307
72.005	6.543	7.117	7.440
72.490	6.794	7.163	7.413
72.895	7.003	7.209	7.307
73.300	7.169	7.255	7.307
73.705	7.290	7.298	7.632
74.110	7.366	7.327	7.750
74.515	7.400	7.330	7.760
74.920	7.380	7.293	7.724
75.325	7.320	7.201	7.077
75.730	7.319	7.044	7.993

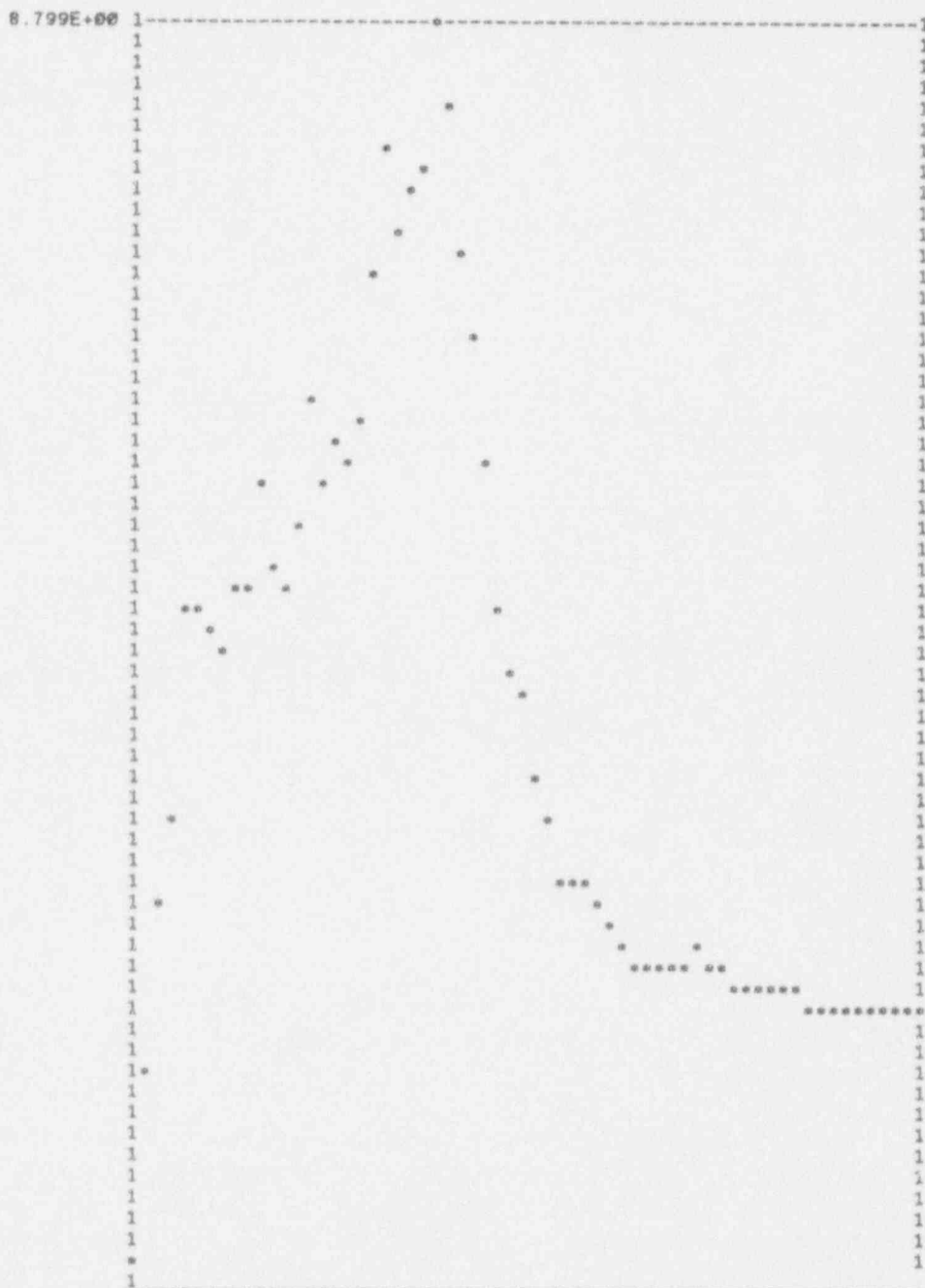
E Q U I V A L E N T
R E S P O N S E S P E C T R U M

STANDARD DEVIATIONS ABOVE THE MEAN ?
1.0

```

P L O T R. Spectrum of output rank : 1
Enter x1,x2 ( x1 = x2 to skip or move on)
1
P L O T R. Spectrum of output rank : 2
Enter x1,x2 ( x1 = x2 to skip or move on)
1
P L O T R. Spectrum of output rank : 3
Enter x1,x2 ( x1 = x2 to skip or move on)
1
2

```



Sample Run 3. The *superstructure load* option is executed in this sample run for a time varying concentrated load, shown in Figure 2.9, applying on the middle floor (node) of Model-2. The load input is in a file named *loads.dat*, Table 2.5, and the output is the forces exerted on the foundation as well as the resulting displacements on the top nodal location.

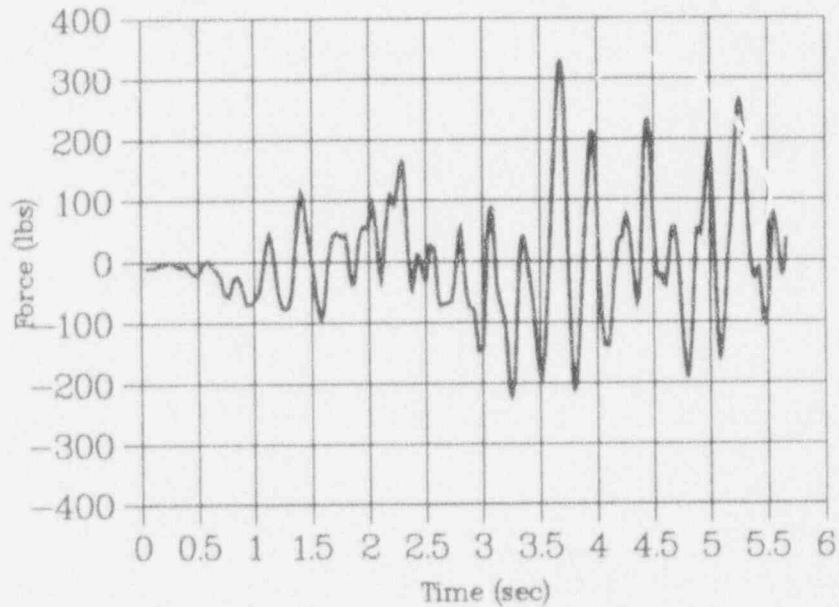


Figure 2.9 Superstructure Load

Table 2.5 Input File of Dynamic Load

# of acting loads	Time step	# time points
1	0.068	128
nodal location	d.o.f	along which force is acting
14	1	
3.90625E-02	-8.934128	
7.81250E-02	-9.099678	
.....		
1.445313	67.84847	
1.484375	16.98985	
.....		
4.570313	-23.27728	
4.609375	-39.84630	
.....		
5.585938	40.33439	
5.625000	-19.47718	
5.664063	36.67180	

```

=====
=           Direct Generation           =
=           of                         =
=           Response Spectra          =
= Dr. N. Simos & Dr. A.M. Philippopoulos =
=====

```

PROBLEM TITLE ?

Superstructure Load

- Type of analysis : (a) DIRECT generation of RS ?
 (b) SIMULATION process ?
 (c) SUPERSTRUCTURE loads ?
 (d) SINGLE actual earthq ?

ANSWER WITH a , b , c or d

c

STRUCTURE IS SUBJECTED TO CONCENTRATED
 NODAL FORCES
 expressed in TIME domain. The number of time points
 should be equal with the number of HARMONIC freq.
 of the analysis.

DYNAMIC INPUT FILE

INPUT is one of following data sets :

- ```

(a) PSD parameters (direct-PSD based analysis)
(b) PSD guess parameters & target Resp. Spectrum
 (direct-RS based)
(c) PSD parameters for PSD-BASED earthq. simulation
(d) TARGET Response Spectrum for earthq. simulation
(e) FOURIER expansion / Time hist. of ACTUAL earthq
(f) FOURIER expansion / Time hist. of SUPERSt. load

```

FILENAME ?

loads.dat

GEOMETRIC MODEL IN FILE ?

exmpl3.dat

FREQUENCY RANGE for the Analysis (Hz)

MINIMUM FREQUENCY (Hz) = ?

0.3

MAXIMUM FREQUENCY (Hz) = ?

15.0

NUMBER of freq. or time points = ?

128

FREQUENCY STEP TOO LARGE !

GOTO THE NEXT POWER OF 2

256

form of IMPEDANCE MATRIX: (a) ANALYTIC ?  
 (b) TABULAR ?

ANSWER WITH a OR b

a

EVALUATE RESPONSE at # of locations = ?

1

HOW MANY NODES ARE THERE IN STICK MODEL = ?

IMPORTANT : Should coincide with number  
 shown in MODEL input file

4

OUTPUT SEND TO FILE ?

output.out

=====

INPUT SUMMARY

=====

ANALYSIS SELECTED = superstructu  
 INPUT FILE model-found-soil info = exmpl3.dat  
 INPUT FILE (earthq. PSD,RS,th - load) = loads.dat  
 INPUT FILE imp = impd.dat  
 INPUT FILE scat = scater.dat  
 OUTPUT FILE = output.out

=====

NUMBER OF NODES = 4  
 NUMBER OF ELEMENTS = 3

TOTAL NUMBER OF DOF = 18 NUMBERED AS  
 NODE DOF-1 DOF-2 DOF-3 DOF-4 DOF-5 DOF-6

TOTAL NUMBER OF DOF = 18 NUMBERED AS  
 NODE DOF-1 DOF-2 DOF-3 DOF-4 DOF-5 DOF-6  
           (ux) (uy) (uz) (thx) (thy) (thz)

|    |   |   |   |    |    |    |
|----|---|---|---|----|----|----|
| 16 | 1 | 4 | 7 | 10 | 13 | 16 |
| 15 | 2 | 5 | 8 | 11 | 14 | 17 |
| 14 | 3 | 6 | 9 | 12 | 15 | 18 |
| 13 | 0 | 0 | 0 | 0  | 0  | 0  |

=====

LUMPED MASS MATRIX  
 of SUPERSTRUCTURE

(Nodal masses in input file)

=====

| ELEMENT NUMBER | BANDWIDTH |
|----------------|-----------|
| 1              | 16        |
| 2              | 17        |
| 3              | 17        |

MAXIMUM BANDWIDTH IN M & K MATRICIES = 17

EIGENVALUES & EIGENVECTORS

=====

|          |                       |
|----------|-----------------------|
| No. = 1  | eigenvalue = 52.9404  |
| No. = 2  | eigenvalue = 290.180  |
| No. = 3  | eigenvalue = 161.631  |
| No. = 4  | eigenvalue = 52.9404  |
| No. = 5  | eigenvalue = 290.180  |
| No. = 6  | eigenvalue = 161.631  |
| No. = 7  | eigenvalue = 104.1761 |
| No. = 8  | eigenvalue = 576.070  |
| No. = 9  | eigenvalue = 319.238  |
| No. = 10 | eigenvalue = 604.649  |
| No. = 11 | eigenvalue = 493.846  |
| No. = 12 | eigenvalue = 312.948  |
| No. = 13 | eigenvalue = 604.649  |
| No. = 14 | eigenvalue = 493.846  |
| No. = 15 | eigenvalue = 312.948  |
| No. = 16 | eigenvalue = 336.302  |
| No. = 17 | eigenvalue = 314.042  |
| No. = 18 | eigenvalue = 221.510  |

STRUCTURAL DAMPING RATIO = ?  
0.05

MASS MATRIX OF THE FOUNDATION : ?

1 = Diagonal elements provided in INPUT file  
0 = Matrix to be evaluated by the program  
respond with 1 or 0

1

GEOMETRY OF THE FOUNDATION : ?

1 = CIRCULAR  
2 = RECTANGULAR  
respond with 1 or 2

1

POSITION OF FOUNDATION : ?

0 = SURFACE  
1 = EMBEDDED  
respond with 0 or 1

0

=====

FOUNDATION SUMMARY

=====

MASS MATRIX = 1  
GEOMETRY = 1  
EMBEDMENT = 0  
DIMENSION - a = 10.00000  
DIMENSION - b = 0.  
THICKNESS = 3.00000  
DENSITY = 150.000

=====

SEISMIC INPUT SUMMARY

=====

ANALYSIS SELECTED = superstructu  
FREQUENCY RANGE (f-min ; f-max) = 0.300000 15.0000  
NUMBER OF FREQUENCIES IN RANGE = 256  
EARTHQUAKE INPUT FILE = loads.dat

=====

DYNAMIC ANALYSIS = superstructu

SUPERSTRUCTURE load : concentrated

=====

UNDERLYING SOIL PROPERTIES :

Density = 3.33750  
Shear Modulus = 2.01002E+06  
Poisson Ratio = 0.330000  
Soil Damping = 5.00000E-02

=====

NODAL LOCATIONS (output) : 16

=====

=====  
 STARTING HARMONIC ANALYSIS  
 =====

completed frequency = 16 of 128  
 completed frequency = 32 of 128  
 completed frequency = 64 of 128  
 completed frequency = 96 of 128

=====  
 END OF HARMONIC ANALYSIS  
 =====

CALLING LOADS

=====  
 number of concentrated loads : 1  
 CONCENTRATED LOAD : 1  
 nodal location : 14 LOCAL dof : 1  
 NODAL location : 14 GLOBAL dof : 3  
 =====

=====  
 PLOT SUPERSTRUCTURE FORCE 1 ?  
 type : yes or no  
 =====  
 no

=====  
 FOUNDATION FORCES due to SUPERSTRUCTURE LOADS  
 =====

| Fx       | Fy | Fz | Mx | My       | Mz |
|----------|----|----|----|----------|----|
| 5.77174  | 0. | 0. | 0. | -531.222 | 0. |
| -3.05094 | 0. | 0. | 0. | -687.623 | 0. |
| -5.41287 | 0. | 0. | 0. | -492.740 | 0. |
| 2.63456  | 0. | 0. | 0. | -256.150 | 0. |
| 0.469598 | 0. | 0. | 0. | 13.7735  | 0. |
| -7.39591 | 0. | 0. | 0. | -127.581 | 0. |
| -3.06698 | 0. | 0. | 0. | -343.609 | 0. |
| 5.91683  | 0. | 0. | 0. | -224.459 | 0. |
| -2.99491 | 0. | 0. | 0. | -98.4200 | 0. |
| -12.7748 | 0. | 0. | 0. | -528.587 | 0. |
| .....    |    |    |    |          |    |
| -30.6796 | 0. | 0. | 0. | -464.883 | 0. |
| -7.80916 | 0. | 0. | 0. | -1344.61 | 0. |
| 9.78600  | 0. | 0. | 0. | -1371.32 | 0. |
| -27.8201 | 0. | 0. | 0. | -1180.75 | 0. |
| -38.6844 | 0. | 0. | 0. | -3520.67 | 0. |
| -7.91444 | 0. | 0. | 0. | -4338.62 | 0. |
| -59.7789 | 0. | 0. | 0. | -2632.16 | 0. |
| -124.128 | 0. | 0. | 0. | -4290.24 | 0. |
| 32.1458  | 0. | 0. | 0. | -6465.87 | 0. |
| 33.1957  | 0. | 0. | 0. | 8312.93  | 0. |
| -8.51175 | 0. | 0. | 0. | 12673.7  | 0. |
| 71.6213  | 0. | 0. | 0. | -375.226 | 0. |

=====  
 PLOT FOUNDATION FORCES ?  
 type : yes or no  
 =====  
 no

=====  
 TOTAL SUPERSTRUCTURE DISPLACEMENT at  
 NODAL location : 16  
 with GLOBAL d.o.f. : 1 4 7 10 13 16  
 =====

| Ux(t)       | Uy(t) | Uz(t) | Rx(t) | Ry(t)       | Rz(t) |
|-------------|-------|-------|-------|-------------|-------|
| 7.02141E-08 | 0.    | 0.    | 0.    | 3.67111E-09 | 0.    |
| 9.95254E-08 | 0.    | 0.    | 0.    | 3.75810E-09 | 0.    |
| 1.27376E-07 | 0.    | 0.    | 0.    | 3.85262E-09 | 0.    |
| 1.52807E-07 | 0.    | 0.    | 0.    | 3.93121E-09 | 0.    |
| 1.77385E-07 | 0.    | 0.    | 0.    | 4.00215E-09 | 0.    |
| 2.00385E-07 | 0.    | 0.    | 0.    | 4.06996E-09 | 0.    |
| 2.23148E-07 | 0.    | 0.    | 0.    | 4.14054E-09 | 0.    |
| .....       |       |       |       |             |       |

## APPENDIX I. System Excitation

A free-field earthquake may be in the form of a **response spectrum, power spectrum or time varying acceleration.**

By selecting the DIRECT approach in the first level of branching it is automatically implied that a power spectrum is to be transferred directly to the floor. For a specified free-field **power spectrum** (either in a closed form expression, equations I.1 thru I.5 below, or a tabular representation) no manipulation of the input takes place prior to the solution. If, however, the DIRECT approach is selected while the free-field earthquake is in the form of a response spectrum a power spectrum compatible to the given response spectrum must be established. This is achieved through the process described below:

### I.1 Response spectra to power spectra

The response spectrum characterizing the free-field motion  $RS_t(\omega, \xi)$  is known for the frequency range of interest. This spectrum could also be called *target* Response Spectrum. Assume that the power spectrum consistent with the target response spectrum is  $\Phi_t(\omega, \lambda)$  where  $\lambda$  is a vector of parameters that are specific of the power spectrum. These parameters define the shape of the analytical expression of the *psd* and they are unknown until the consistency between the power and the response spectra is achieved.

In order to begin the iterative process, an analytic expression for the *psd* is chosen and initial values of parameter vector  $\lambda$  are assumed. Over the years, several closed form expressions that can describe the power spectrum of earthquake ground accelerations have been proposed. The expressions that the DIGES program utilizes are the following:

### I.2 Analytical Forms of PSD in DIGES

#### i. Kanai-Tajimi (Form 1)

$$S_x(\omega, \lambda) = S_0 \frac{1 + 4\zeta_g^2 \left(\frac{\omega}{\omega_g}\right)^2}{\left[1 - \left(\frac{\omega}{\omega_g}\right)^2\right]^2 + 4\zeta_g^2 \left(\frac{\omega}{\omega_g}\right)^2}$$



$$\lambda = [\zeta_g, \omega_g, S_0]^T \quad (I.1)$$

ii. Ruiz-Penzien (Form 2)

$$S_x(\omega, \lambda) = S_0 \frac{1 + 4\zeta_g^2 \left(\frac{\omega}{\omega_g}\right)^2}{[1 - \left(\frac{\omega}{\omega_g}\right)^2]^2 + 4\zeta_g^2 \left(\frac{\omega}{\omega_g}\right)^2} \frac{\left(\frac{\omega}{\omega_p}\right)^4}{[1 - \left(\frac{\omega}{\omega_p}\right)^2]^2 + 4\zeta_p^2 \left(\frac{\omega}{\omega_p}\right)^2}$$

$$\lambda = [\zeta_g, \omega_g, S_0, \zeta_p, \omega_p]^T \quad (I.2)$$

iii. Superposition (Form 3)

$$S_x(\omega, \lambda) = S_0 \sum_{k=1}^2 P_k \frac{(1 + 4\zeta_k^2) [1 - e^{-\frac{\omega^4}{\omega_k^4}}]}{[1 - \left(\frac{\omega}{\omega_k}\right)^2]^2 + 4\zeta_k^2 \left(\frac{\omega}{\omega_k}\right)^2}$$

$$\lambda = [\zeta_1, \omega_1, S_1, \zeta_2, \omega_2, S_2]^T \quad (I.3)$$

By multiplying the above expressions with the filter

$$\frac{1}{1 + \alpha^2 \omega^2} \quad (I.4)$$

where  $\alpha$  is a small parameter ( $\alpha \ll 1.0$ ), new forms of analytic *psd* are deduced, specifically:

Form 1  $\rightarrow$  Form 4

Form 2  $\rightarrow$  Form 5

Form 3  $\rightarrow$  Form 6

(I.5)

### I.3 Earthquake Simulation

If the **simulation** option is selected to transfer the free-field earthquake to the structure it is implied that an ensemble of generated earthquakes will be transferred by utilizing the Transfer Function of the system  $H(\omega)$  according to the relationship

$$F_y(\omega) = H(\omega)F_x(\omega) \quad (I.6)$$

where  $F_x(\omega)$  and  $F_y(\omega)$  are the Fourier expansions of the input and output respectively.

The artificial earthquakes can be generated from either a **power** or a **response** spectrum characterizing the free-field stochastic process. The required information for the generation and transferring of the earthquake ensemble based on the two possible types of free-input are listed below:

#### *PSD Based Ground Acceleration Simulation*

A time history  $g(t)$  of an artificial acceleration generated from the form

$$g(t) = \zeta(t) \left[ 2 \sum_{i=1}^N \sqrt{\Phi_a(\omega_i) \Delta\omega} \cos(\omega_i t + \phi_i) \right] \quad (I.7)$$

$$\omega_i = i \Delta\omega \quad \Delta\omega = \frac{\omega_u}{N}$$

where  $\omega_u$  is a cutoff frequency above which the power spectrum is assumed to vanish and is a parameter specified by the user when he is interactively asked to define the frequency range of the analysis and  $N$  is the number of **uniform** frequency increments.

$\{\phi_i\}$  is a vector of random phase angles uniformly distributed between 0 and  $2\pi$  and is selected by the program on the basis of a SEED number provided by the user (interactively). Different choices of the vector of random phase angles will lead to a different simulated earthquake that has both the mean and the autocorrelation of the stochastic process described by the *PSD* of the stochastic free-field process.

$\Phi_a(\omega)$  is the power spectral density of the process and is also specified by the user when the program requests the *psd* form (of the 6) that the generation is to be based on.

$\zeta(t)$  is a modulating function, see Figure I.1, that introduces the nonstationarity in the generated record. Three (3) parameters are associated with this function,  $t_1, t_2$  and  $c$ , and are specified by the user interactively. Thus, the earthquake duration must be assessed.

The simulated earthquake  $g(t)$  is periodic with a period

$$T_0 = \frac{2\pi}{\Delta\omega} \quad (I.8)$$

so the duration of the generated ground motion can be determined on the basis of the selected cutoff frequency  $\omega_u$  and number of frequency increments  $N$ . Since Fast Fourier processes are invoked in the transferring of the simulated earthquakes the value of  $N$  should be large enough ( $N \geq 1024$ ) and a power of 2.

### Simulation Based on Response Spectra

Simulated earthquakes that belong to the family the target response spectrum represents can assume the form,

$$g(t) = \zeta(t) \sum_{i=1}^N C_i(\omega) \sin(\omega_i t + \phi_i) \quad (I.9)$$

where  $C_i(\omega)$  is the amplitudes of the  $i_{th}$  contributing sinusoid and  $\phi_i$  is its phase angle.  $\zeta(t)$  is the deterministic envelope function described in the previous section.

Similarly, any choice of the vector  $\phi$  which contains the uniformly distributed in the interval  $[0, 2\pi]$  non-correlated phase angles and a set of amplitudes  $C(\omega)$  will define a ground motion.

In order for the generated ground motion to be consistent with the target response spectrum, the amplitudes  $C(\omega)$  have to be iteratively adjusted so that the difference between the target response spectrum, which characterizes the random process, and the generated one from  $g(t)$  is minimized over the control frequencies. This iterative consists of the following steps:

- a. The frequency range and the number of **uniform** increments  $N$  are interactively defined by the user.

- b. A random vector of phase angles is selected based on the supplied SEED number (the user provides as many SEEDS as are simulated earthquakes)
- c. An initial set of amplitudes  $C_{initial}(\omega)$  is chosen. While it is desirable to minimize the iterations by starting at the *best guess* for the vector  $C_{initial}(\omega)$ , that can be achieved by assigning the amplitudes of the Fourier expansion of the zero-damping target spectrum, theoretically any choice should work. In this study the entire initial vector is set equal to one (1.0) by the program so the user does not need to specify it.
- d.  $\zeta(t)$  is specified by providing the three parameters  $t_1, t_2$  and  $c$ .

When the complete ensemble of generated earthquakes has been transferred to the structure, the response of the system at any d.o.f. can be then seen as a single Response Spectrum which is deduced from the average of the ensemble of response spectra each deterministic process will provide,

$$\overline{RS}_y(\omega_i, \xi) = \frac{\sum_{j=1}^n RS_y(\omega_i, \xi)}{n} \quad (I.10)$$

along with the statistical properties of the ensemble of amplifications at every specified frequency  $\omega_i$ ,  $[m + \sigma] * RS(\omega_i)$ . The number of standard deviations  $\sigma$  is provided by the user interactively after all the simulated earthquakes have been transferred to the structure.

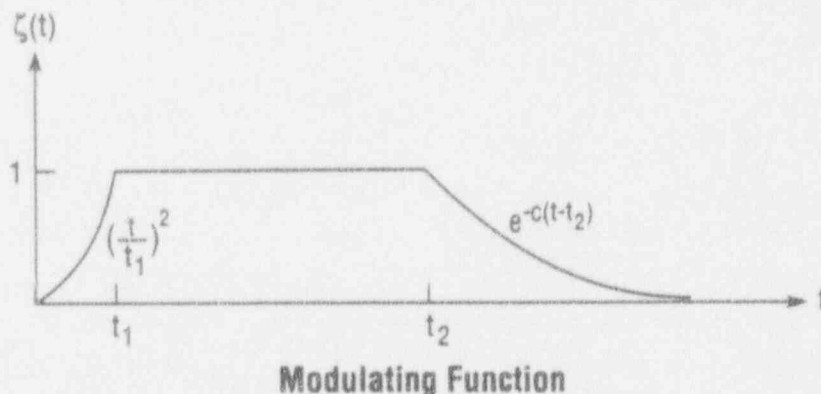


Figure I.1 Non-stationary Modulating Function

## I.4 Deterministic Input Analysis

For the particular case of a recorded accelerogram of an actual earthquake event that represents the free-field motion a deterministic analysis can be utilized. This analysis will resemble a single transfer of the simulation process discussed previously.

Thus, the accelerogram of the seismic event in the form of its Fourier expansion,

$$a(t)_{actual} = \sum_{i=1}^N C_x(\omega) e^{i\omega_i t} \quad (I.11)$$

is transferred to the floor through equation (I.6). The user interactively specifies the frequency range and the number **N** of **uniform** increments.

## I.5 Superstructure Dynamic Loads

Dynamic loads acting on the superstructure will be in the form of a time history of the intensity. Periodic or not the time history record will be equivalently represented by its Fourier decomposition,

$$p(t) = \sum_{k=1}^{\infty} A_k(\omega) e^{ik\Delta\omega t}$$
$$\Delta\omega = \frac{2\pi}{T} \quad (I.12)$$

The available time history record is specified by the user by the name of the file that contains it along with the number of **uniformly** spaced time points **N** and the frequency range of the Fourier decomposition (same as that of the analysis). Similarly, since Fourier transform processes are implemented the number of points should be large and also a power of 2.

The Fourier decomposition of the dynamic load is transferred to the structure through the transfer function  $H_4^*(\omega)$  listed in the *Theoretical Basis of Diges* according to the relation,

$$U_t(\omega) = H_4^*(\omega)P(\omega) \quad (I.13)$$

## APPENDIX II. Impedances and Foundation Input Motions

### II.1 Foundation Impedances

The relationship of harmonic generalized external forces and moments exciting a rigid foundation and the response of such foundation is expressed in terms of the [6 x 6] frequency dependent impedance matrix. In addition this matrix depends on the geometry of the foundation as well as the properties of the underlying soil medium. The complexity that accompanies the exact description of the kinematic interaction between the foundation and the soil has limited the number of generic analytic solutions. To circumvent this difficulty so studies of parametric nature can be conducted, *approximate* analytical solutions have been deduced for simple geometry foundations such as circular and rectangular. The problem, even for the simple geometries, gets further complicated for foundations that are embedded in the soil. Still, approximate relations have been derived to accommodate the two simple geometries.

In the process of deducing the approximate formulae models, for embedded foundations in particular, sophisticated numerical analyses have been utilized (finite or boundary element methods) leading to various analytic expressions that approximately describe the same response.

Listed below is one of the several sets of approximate impedance formulae the same way they have been implemented into the DIGES computational process. Each of the elements reflect both the stiffness and the damping contribution according to the relation  $K = k + ia_0c$  where  $k$  and  $c$  are normalized stiffness and damping coefficients and  $a_0$  is the dimensionless frequency  $a_0 = \frac{\omega a}{\beta}$  with  $\beta$  = the shear wave velocity and  $a$  the characteristic length.

#### I. Surface Foundations

##### a. Circular Geometry

Horizontal:

$$K_H = K_h^s(k_h^0 + ia_0c_h^0)$$

where,

$$K_h^s = \frac{32(1-\nu)Gr}{7-8\nu} \quad ; \quad k_h^0 = 1.0 \quad ; \quad c_h^0 = 0.576$$

Vertical:

$$K_V = K_v^s(k_v^0 + ia_0c_v^0)$$

where,

$$K_v^s = \frac{4Gr}{1-\nu} \quad ; \quad k_v^0 = 1.0 \quad ; \quad c_v^0 = 0.85$$

Rocking:

$$K_R = K_r^s(k_r^0 + ia_0c_r^0)$$

where,

$$K_r^s = \frac{8Gr^3}{3(1-\nu)} \quad ; \quad k_r^0 = 1.0 \quad ; \quad c_r^0 = \frac{0.30}{1+B_\psi}$$

$$B_\psi = \frac{3(1-\nu)I_0}{8\rho r^5}$$

Torsion:

$$K_T = K_t^s(k_t^0 + ia_0c_t^0)$$

where,  $K_t^s = \frac{16Gr^3}{3} \quad ; \quad k_t^0 = 1.0$

$$c_t^0 = \frac{V_s}{r(1 + \frac{2I_t}{\rho r^5})} \sqrt{\frac{I_t}{k_t}}$$

$\nu$  = Poisson's ratio of foundation medium

$G$  = Shear Modulus of foundation medium

$r$  = radius of circular basemat

$\rho$  = mass density of foundation medium

$I_0$  = total mass moment of inertia of structure and basemat about the rocking axis of the base

$I_t$  = polar moment of inertia of structure basemat.

## b. Rectangular Geometry

Vertical:

$$K_v = K_v^0(k + ia_0c)$$

$$k = 1.0 - \frac{da_0^2}{b + a_0^2} \quad ; \quad c = \frac{4\alpha \frac{L}{B}}{K_v^0}$$

$$d = 0.4 + \frac{0.2}{\frac{L}{B}} \quad b = \frac{10}{1 + 3(\frac{L}{B} - 1)}$$

Horizontal:

$$K_{h_x} = K_{h_x}^0(k + ia_0c)$$

$$k = 1.0 \quad c = \frac{4 \frac{L}{B}}{K_{h_x}^0}$$

$$K_{h_v} = K_{h_v}^0(k + ia_0c)$$

$$k = 1.0 \quad c = \frac{4 \frac{L}{B}}{K_{h_v}^0}$$

Rocking:

$$K_{R_x} = K_{R_x}^0(k + ia_0c)$$

$$k = 1.0 - \frac{da_0^2}{b + a_0^2} \quad c = \frac{\frac{4\alpha}{3} \frac{L}{B} a_0^2}{K_{R_x}^0 f + a_0^2}$$

$$d = 0.55 + 0.1 \sqrt{\frac{L}{B} - 1}$$

$$b = 2.4 - \frac{0.4}{(\frac{L}{B})^3} \quad f = 2.2 - \frac{0.4}{(\frac{L}{B})^3}$$

$$K_{R_v} = K_{R_v}^0(k + ia_0c)$$

$$k = 1.0 - \frac{0.55a_0^2}{b + a_0^2} \quad c = \frac{\frac{4\alpha}{3} (\frac{L}{B})^3 a_0^2}{K_{R_v}^0 f + a_0^2}$$

$$b = 0.6 + \frac{1.4}{(\frac{L}{B})^3} \quad f = \frac{1.8}{1.0 + 1.75(\frac{L}{B} - 1)}$$



Torsion:

$$K_t = K_t^0(k + ia_0c)$$

$$k = 1.0 - \frac{da_0^2}{b + a_0^2} \quad c = \frac{4[(\frac{L}{B})^3 + (\frac{L}{B})]}{3K_t^0} \frac{a_0^2}{f + a_0^2}$$

$$d = 0.33 - 0.03\sqrt{\frac{L}{B} - 1} \quad f = \frac{1.4}{1 + 3(\frac{L}{B} - 1)^{0.7}}$$

$$b = \frac{0.8}{1 + 0.33(\frac{L}{B} - 1)}$$

where,

$$K_v^0 = \frac{GB}{1 - \nu} [3.1(\frac{L}{B})^{0.75} + 1.6]$$

$$K_{H_s}^0 = \frac{GB}{2 - \nu} [6.8(\frac{L}{B})^{0.65} + 2.4]$$

$$K_{H_v}^0 = K_{H_s}^0(2 - \nu) + 0.8GB(\frac{L}{B} - 1)$$

$$K_{R_s}^0 = \frac{GB^3}{1 - \nu} [3.2(\frac{L}{B}) + 0.8]$$

$$K_{R_v}^0 = \frac{GB^3}{1 - \nu} [3.73(\frac{L}{B})^{2.4} + 0.27]$$

$$K_t^0 = GB^3 [4.25(\frac{L}{B})^{2.45} + 4.06]$$

$$\alpha = \sqrt{\frac{2(1 - \nu)}{1 - 2\nu}}$$

and L and B are half of each side of the rectangular foundation (always  $L \geq B$ ).

## II. Embedded Foundations

### a. Cylindrical Foundations

Vertical:

$$K_v = K_v^s(k + ia_0c)$$

$$k = 1.0 \quad c = \frac{\pi(\alpha + 2r_1)}{\frac{K_v^s}{GR}}$$

Horizontal:

$$K_h = K_h^s(k + ia_0c)$$

$$k = 1.0 \quad c = \frac{\pi[1.0 + (1.0 + \alpha)r_1]}{\frac{K_h^s}{GR}}$$

Rocking:

$$K_R = K_R^s(k + ia_0c)$$

$$k = 1.0 - \frac{0.35a_0^2}{1.0 + a_0^2}$$

$$c = \frac{\pi\left[\frac{\alpha}{4} + r_1 + \left(\frac{1+\alpha}{2}\right)r_1^3\right]\frac{a_0^2}{b+a_0^2} + 0.84(1+\alpha)r_1^{2.5}\frac{b}{b+a_0^2}}{\frac{K_R^s}{GR^3}}$$

$$b = \frac{2}{1 + r_1}$$

Torsion:

$$K_t = K_t^s(k + ia_0c)$$

$$k = 1.0 - \frac{0.35a_0^2}{1.0 + a_0^2} \quad c = \frac{\frac{\pi}{2}(1 + 4r_1)\frac{a_0^2}{b+a_0^2}}{\frac{K_t^s}{GR^3}}$$

$$b = \frac{1.0}{0.37 + 0.87r_1^{\frac{2}{3}}}$$

Coupling:

$$K_{RH} = (0.4r_1 - 0.03)K_H$$

where the static coefficients are given by the formulae:

$$K_V^s = K_V^0(1 + 0.54r_1)$$

$$K_H^s = K_H^0(1 + r_1)$$

$$K_R^s = K_R^0[1 + 2.3r_1 + 0.58r_1^3]$$

$$K_t^s = K_t^0(1 + 2.67r_1)$$

$$K_{RH}^s = (0.4r_1 - 0.03)K_H^s$$

where the 0 superscript denotes the static surface coefficients previously listed while  $R$  and  $E$  are the radius of the foundation and the depth of the embedment respectively and  $r_1 = \frac{E}{R}$ .

#### b. embedded rectangular foundations

vertical:

$$K_V = K_V^s(k + ia_0c)$$

$$k = 1.0 - \frac{da_0^2}{b + a_0^2} \quad c = \frac{4[\alpha r_1 + r_2(1 + r_1)]}{K_V^s}$$

$$d = 0.4 + \frac{0.2}{r_1} \quad b = \frac{10.0}{1 + 3(r_1 - 1)}$$

Horizontal:

$$K_{H_x} = K_{H_x}^s(k + ia_0c)$$

$$k = 1.0 \quad c = \frac{4[r_1 + r_2(\alpha + r_1)]}{K_{H_x}^s}$$

$$K_{H_v} = K_{H_v}^s(k + ia_0c)$$

$$k = 1.0 \quad c = \frac{4[r_1 + r_2(1 + \alpha r_1)]}{K_{H_v}^s}$$

Rocking:

$$K_{R_x} = K_{R_x}^s(k + ia_0c)$$

$$k = 1.0 - \frac{da_0^2}{k + a_0^2} \quad d = 0.55 + 0.1\sqrt{r_1 - 1} \quad b = 2.4 - \frac{0.4}{r_1^3}$$

$$c = \frac{4(r_2 + \frac{r_2^3}{3} + \frac{\alpha}{3}r_1r_2^3 + r_2r_1 + \frac{\alpha}{3}r_1)}{K_{R_x}^s} \frac{a_0^2}{f + a_0^2} + D \frac{f}{f + a_0^2}$$

$$f = 2.2 - \frac{0.4}{r_1^3} \quad D = \frac{4(\alpha r_1 + 1)r_2^3}{3K_{R_x}^s}$$

$$K_{R_v} = K_{R_v}^s(k + ia_0c)$$

$$k = 1.0 - \frac{0.55a_0^2}{b + a_0^2} \quad b = 0.6 + \frac{1.4}{r_1^3}$$

$$c = \frac{4(r_1^3r_2 + \alpha r_2^3r_1 + r_2^3 + 3r_2r_1^2 + \alpha r_1^2)}{3K_{R_v}^s} \frac{a_0^2}{f + a_0^2} + D \frac{f}{f + a_0^2}$$

$$f = \frac{1.8}{1.0 + 1.75(r_1 - 1)} \quad D = \frac{4(r_1 + \alpha)r_2^3}{3K_{R_v}^s}$$

Torsion:

$$K_t = K_t^s(k + ia_0c)$$

$$k = 1.0 - \frac{da_0^2}{b + a_0^2} \quad d = 0.33 - 0.03\sqrt{r_1 - 1} \quad b = \frac{0.8}{1 + 0.33(r_1 - 1)}$$

$$c = \frac{4(3r_1r_2 + \alpha r_1^3r_2 + r_1^2r_2 + \alpha r_2 + r_1^3 + r_1)}{3K_t^s} \frac{a_0^2}{f + a_0^2}$$

$$f = \frac{1.4}{1 + 3(r_1 - 1)^{0.7}}$$

Coupling:

$$K_{HR_x} = \frac{r_2}{3}K_{H_x}$$

$$K_{HR_v} = \frac{r_2}{3}K_{H_v}$$

where the corresponding static coefficients are approximated with the expressions:

$$K_V^s = K_V^0 \left[ 1.0 + \left( 0.25 + \frac{0.25}{r_1} \right) r_2^{0.8} \right]$$

$$K_H^s = K_H^0 \left[ 1.0 + \left( 0.33 + \frac{1.34}{1 + r_1} \right) r_2^{0.8} \right]$$

$$K_{R_s}^s = K_{R_s}^0 \left[ 1.0 + r_2 + \left( \frac{1.6}{0.35 + r_1} \right) r_2^2 \right]$$

$$K_{R_v}^s = K_{R_v}^0 \left[ 1.0 + r_2 + \left( \frac{1.6}{0.35 + r_1^4} \right) r_2^2 \right]$$

$$K_t^s = K_t^0 \left[ 1.0 + \left( 1.3 + \frac{1.32}{r_1} \right) r_2^{0.9} \right]$$

while the two ratios  $r_1$  and  $r_2$  represent

$$r_1 = \frac{L}{B} \quad ; \quad r_2 = \frac{E}{B}$$

## II.2 Foundation Input Motion

DIGES distinguishes three general cases relating the free-field motion with the foundation input motion:

### A: Free-field directly applied as input motion

According to this case the foundation input motion is equal to the free-field motion (i.e.,  $U_G = U_G^0$ ). This case represents early stages of seismic analyses of building foundation systems according to which the criteria motion was directly applied at the bottom of the soil springs. This reflects primarily cases involving surface foundations. Since the free-field is applied directly as the excitation of the building foundation system the  $[6 \times 3]$  matrix  $H_5(\omega)$  takes the form

$$H_5(\omega) = \begin{bmatrix} [I] \\ - - - \\ [0] \end{bmatrix} \quad (II.2.1)$$

where  $[I]$  and  $[0]$  are  $[3 \times 3]$  unit and null matrices respectively.

### B: Convolution/Deconvolution

In this case the foundation input motion is the free-field motion at some depth, depending on the characteristics of the embedded foundation. The free-field motion at a given depth is obtained through convolution or deconvolution depending on whether or not the criteria motion is treated as an outcrop motion or a surface (or near surface for very soft top layers) motion. The current version of DIGES utilizes vertically propagating body waves, i.e. shear waves (for horizontal motion) and dilatational waves (for vertical motion) for computing  $H_5(\omega)$ , i.e.

$$H_5(\omega) = \begin{bmatrix} H_h(\omega) & 0 & 0 \\ 0 & H_h(\omega) & 0 \\ 0 & 0 & H_v(\omega) \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (II.2.2)$$

$H_h(\omega)$ ,  $H_v(\omega)$  are transfer functions for convolution/deconvolution operations related to the one dimensional propagation of shear and dilatational waves respectively. DIGES has the option to allow the user to input convolution/deconvolution data from external sources (e.g., CARES, SHAKE). Inherent to the program are a set of analytical models that allow the convolution and deconvolution of the control point motion in uniform half space or a single layer overlying the bedrock.

### C: Kinematic Interaction

In the case of foundation input motion incorporating kinematic interaction effects due to the scattering of the seismic waves by the rigid foundation  $H_5(\omega)$  is a [6 x 3] frequency dependent matrix containing the scattering coefficients which depend on the types of seismic waves considered, the properties of the underlying medium and the geometry of the foundation itself. DIGES has generally two (2) options regarding the formation of  $H_5(\omega)$ . The first option corresponds to user supplied scattering data. These values reside on external file(s) while their format has been specified in the section discussing the Foundation Input Motion input file (Table 2.2.2). The second option involves analytical models that can be used directly with minimum input data. They correspond to the scattering matrix of surface foundations (circular or rectangular) for body waves impinging at any angle and for surface SH waves. The analytical formulae can be found in Reference 18. Through either approach, however, the transfer function will take the form

$$H_5(\omega) = \begin{bmatrix} R_{xx}(\omega) & 0 & R_{xz}(\omega) \\ 0 & R_{yy}(\omega) & 0 \\ R_{zx}(\omega) & 0 & R_{zz}(\omega) \\ 0 & \frac{R_{xy}(\omega)}{L} & 0 \\ \frac{R_{yx}(\omega)}{L} & 0 & \frac{R_{yz}(\omega)}{L} \\ 0 & \frac{R_{xy}(\omega)}{L} & 0 \end{bmatrix} \quad (II.2.3)$$

where  $L$  is a reference length. It should be noted that in the most general of cases which is the non-vertical incidence of seismic waves all of the coefficients appearing above must be evaluated.



### APPENDIX III. Superstructure Modeling

The Diges formulation idealizes the superstructure with a stick model description consisting of flexible members with equivalent stiffness and mass matrices. The finite element representation utilizes the 3-D elastic beam properties which allows for six degrees of freedom in each nodal location. The special feature that allows rigid links between nodal locations in the finite element idealization has been incorporated. The presence of such links will allow for a **master/slave** relationship between two nodes and enable the evaluation of the response of a superstructure with such particularities.

The selection of (a) **consistent** mass matrix or (b) **lumped** mass matrix is made possible by the specifying the value of the **key** in the input file. It is a single record on the line of data immediately after the nodal specifications. **key = 0** implies that the lumped mass matrix is used (diagonal) and **key = 1** that the consistent matrix will be formed. **Note** that for the latter case the density of each finite element must be provided as the last column of the element connectivity records that immediately follow. The stiffness matrix is always consistent.

The *consistent* stiffness matrix in the coordinates of the finite element is shown in Equation III.1 and the mass matrix in Equation III.2.



|               |                                        |                  |                                      |                                      |                  |                                      |                                      |
|---------------|----------------------------------------|------------------|--------------------------------------|--------------------------------------|------------------|--------------------------------------|--------------------------------------|
| $\frac{1}{3}$ | $\frac{13}{35} + \frac{6I_z}{5AL^3}$   | $\frac{I_z}{34}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{34}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ |
| 0             | 0                                      | 0                | 0                                    | 0                                    | 0                | 0                                    | 0                                    |
| 0             | $\frac{13}{35} + \frac{6I_z}{5AL^3}$   | $\frac{I_z}{34}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{34}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ |
| 0             | 0                                      | 0                | 0                                    | 0                                    | 0                | 0                                    | 0                                    |
| 0             | $\frac{11I_z}{210} + \frac{I_z}{104L}$ | $\frac{I_z}{34}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{34}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ |
| 0             | 0                                      | 0                | 0                                    | 0                                    | 0                | 0                                    | 0                                    |
| $\frac{1}{6}$ | $\frac{9}{70} + \frac{6I_z}{5AL^3}$    | $\frac{I_z}{64}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{64}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ |
| 0             | 0                                      | 0                | 0                                    | 0                                    | 0                | 0                                    | 0                                    |
| 0             | $\frac{9}{70} + \frac{6I_z}{5AL^3}$    | $\frac{I_z}{64}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{64}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ |
| 0             | 0                                      | 0                | 0                                    | 0                                    | 0                | 0                                    | 0                                    |
| 0             | $\frac{13I_z}{420} + \frac{I_z}{104L}$ | $\frac{I_z}{64}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{64}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ |
| 0             | 0                                      | 0                | 0                                    | 0                                    | 0                | 0                                    | 0                                    |
| 0             | $\frac{13I_z}{420} + \frac{I_z}{104L}$ | $\frac{I_z}{64}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{64}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ | $\frac{I_z}{105} + \frac{2I_z}{15A}$ |

where:

$$\phi_y = \frac{12EI_x}{GA_{s_x}L^2} \quad ; \quad \phi_z = \frac{12EI_y}{GA_{s_y}L^2}$$

E = Young's modulus

$I_i$  = moment of inertia normal to direction i

G = Shear modulus =  $\frac{E}{2(1+\nu)}$

A = Cross sectional area

$A_{s_i}$  = shear area normal to direction i

L = length of element connecting nodes I and J.

$\nu$  = Poisson's ratio

J = torsional moment of inertia (=  $J_x$  if  $I_x = 0$ , =  $I_x$  otherwise)

$J_x$  = polar moment of inertia =  $I_y + I_z$

$\rho$  = density

The global solution, however, must be expressed in the global rather than local coordinates since the superstructure degrees of freedom are expressed in these coordinates. Thus, in order to form the final system matrices in the global coordinates, specified as **X**, **Y** and **Z** on Figure 5-1, a transformation matrix  $[T_r]$  is utilized such that,

$$[K_{gl}] = [T_r]^T [K_{loc}] [T_r] \quad (III.3)$$

and similarly,

$$[M_{gl}] = [T_r]^T [M_{loc}] [T_r] \quad (III.4)$$

$[T_r]$  relates the vector of displacements in the element Cartesian coordinates to the Global Cartesian coordinates through the relation

$$u_l = [T_r]u \quad (III.5)$$

The formation of the global stiffness and mass matrices  $[K]$  and  $[M]$  will involve the assemblage of the individual stiffnesses which are already transformed while for the special case of *lumped* global mass matrix,  $[M]$  will take the diagonal form,

$$[M_{glb}] = \begin{bmatrix} m_1^{eq} & & & & & \\ 0 & m_2^{eq} & & & & \\ 0 & 0 & m_3^{eq} & & & \\ \cdot & \cdot & \cdot & \cdot & & \\ 0 & 0 & 0 & 0 & 0 & m_n^{eq} \end{bmatrix} \quad (III.6)$$

It should be expected that slight changes in the eigensolution of the superstructure will be observed by using the lumped mass matrix.

## References

1. R.A. Parmelee, *Building-Foundation Interaction Effects*, J. Eng. Mech. Div. ASCE, 93, pp. 131-152, 1967.
2. T.H. Lee, D.A. Wesley, *Soil-Foundation Interaction of Reactor Structures Subjected to Seismic Excitation*, Proc. 1st Int. Conf. Struct. Mech. in Reactor Technology, Berlin, Paper K3/5, 1971.
3. S.C. Liu, L.W. Fagel, *Earthquake Interaction By Fast Fourier Transform*, J. Engrg. Mech., Div. ASCE, 97, EM4, pp. 1223-1237, 1971
4. J. E. Luco, *Linear Soil-Structure Interaction - Seismic Safety Margins Research Program*, UCRL-15272, PSA No.7249809, 1980.
5. Y.K. Lin, *Probabilistic Theory of Structural Dynamics*, Krieger, 1976.
6. R.W. Clough, J. Penzien, *Dynamics of Structures*, McGraw Hill, 1975.
7. D. Gasparini, E. Vanmercke, *Simulated Earthquake Motions Compatible with Prescribed Response Spectra*, MIT/Dept. of Civil Engrg, Report No. R76-4, 1976.
8. E.H. Vanmarcke, D.A. Gasparini, *Simulated Earthquake Ground Motion*, Proceedings, 5th International Conference on Structural Mechanics in Reactor Technology, Berlin, West Germany, Paper K 1/9, 1977.
9. P.D. Spanos, L.M. Vargas Loli, *A Statistical Approach to Generation of Design Spectrum Compatible Earthquake Time Histories*, Soil Dynamics and Earthquake Engineering, Vol.4, No.1, 1985.
10. J. Pires, H. Hwang, M. Reich, *Reliability Evaluation of Containments Including Soil-Structure Interaction*, NUREG/CR-4329, 1985.
11. H.L. Wong, J.E. Luco, *Tables of Impedance Functions and Input Motions for Rectangular Foundations*, Univ. of Southern California Report, Report No. CE 78-15, 1978.
12. A. Pais, E. Kausel, *Stochastic Response of Foundations*, MIT/Dep. of Civil Engrg. Report, Research Report R85-6, 1985.
13. A.S. Valetsos, Y.T. Wei, *Lateral and Rocking Vibrations of Footings*, J. Soil Mechanics and Foundations Division, ASCE, Vol. 97, pp. 1227-1248, 1971.

14. J.E. Luco, A. Mita, *Response of a Circular Foundation on a Uniform Half-Space to Elastic Waves*, Earthquake Engrg. and Struct. Dynamics, Vol. 15, pp.105-118, 1987.
15. ASCE, *Seismic Analysis of Safety-Related Nuclear Structures and Commentary on Standard for Seismic Analysis of Safety Related Nuclear Structures*, 1986.
16. M. Shinozuka, G. Deodatis, *Ground Acceleration Time History Generation Under Specified PSD Function and Calculation of Response Spectra*, BNL Technical Report A-3962-1-11/89, 1989.
17. M. Shinozuka, G. Deodatis, *Ground Acceleration Time History Generation as Multivariate Stochastic Process*, BNL Technical Report A-3962-2-1/90, 1990.
18. B.Li, F.G.A Al-Bermani and S. Kitipornchai, *Maximum Response of Assymmetric Structures Subject to a Multicomponent Earthquake*, Earthquake Engineering and Structural Dynamics, Vol.22, pp. 1047-1066, 1993.
19. K.-J. Bathe, *Finite Element Procedures in Engineering Analysis*, Prentice Hall, 1982.
20. W. Press, W. Vetterling, S. Teulolsky, B. Flamney, *Numerical Recipes in Fortran, 2nd Edition*, Cambridge Univ. Press, 1992.
21. ANSYS - Engineering Analysis System. *Theoretical Manual*, Swanson Analysis Systems Inc., 1989.
22. N. Simos, A.J. Philippacopoulos, *Theoretical Basis of Diges*, BNL Technical Report, 1993.