Session 2
SASSI Approach
(General/Coherent)

NRC Seismic Seminar

Soil-Structure Interaction (SSI) Including Coherent and Incoherent Ground Motion

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August 29, 2007

Rockville, Maryland

CONTENTS

SASSI

- The original release from UC Berkeley, UCB/GT/81-02 (J Lysmer, Ostadan, F, Tabatabaie, M, Tajirian, F, Vahdani, S)
- SASSI2000, December 1999 (J Lysmer, Ostadan, Chin, C)
- Right, title and licensing of the program stays with the Regents of UC Berkeley and its authorized agents

SSI

SOIL-STRUCTURE INTERACTION (SSI)

- The interaction problem involves the determination of the response of structures(s) on a flexible soil foundation system
- The interaction effects related to the stiffness of the structure is called the kinematic interaction. The mass related effect is called the inertial interaction
- The loading may be the impinging seismic waves or other sources such as the vibration from a machine vibration.

SOIL-STRUCTURE INTERACTION (SSI)

SSI Methods are divided into two main groups

0 The continuum methods

0 The finite element methods

- » The complete methods
- » The substructure methods

Continuum methods are practically limited to simple soil profiles and structures with surface foundations.

The finite element methods are more versatile and can handle practical problems

FINITE ELEMENT METHODS

Complete Methods

– Motions of the soil mass and the structure are simultaneously obtained from a large combined equation of motion. The soil mass and the structure are discretized using finite element or finite element difference techniques. These models become very large for 3D application. Hence, the complete methods are applicable to 2D and axisymmetric conditions e.g. computer program FLUSH.

FINITE ELEMENT METHODS

Substructure Methods

– The SSI problem is divided into a series of simpler problems. Each problem is solved separately and the results are combined in the final step of the analysis to provide the complete solution. Substructure methods employ the principle of superposition. Hence these methods can handle linear and equivalent linear properties. These methods are often formulated in the frequency domain.

– Major steps of analysis using the substructure methods are as follows

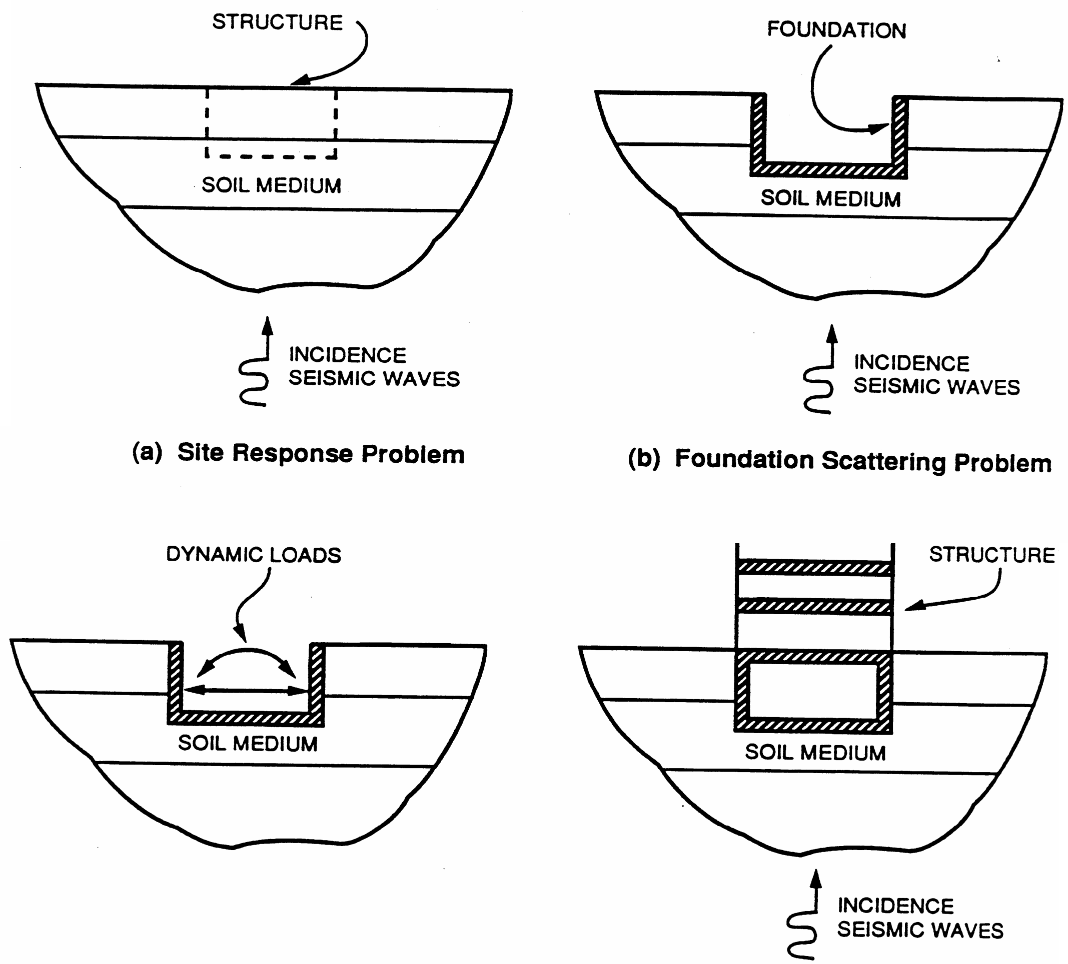
  » 1- Site response analysis

  » 2- Foundation impedance analysis

  » 3- Foundation scattering analysis

  » 4- Modeling of the structure and final SSI analysis

SSI



(a) Site Response Problem

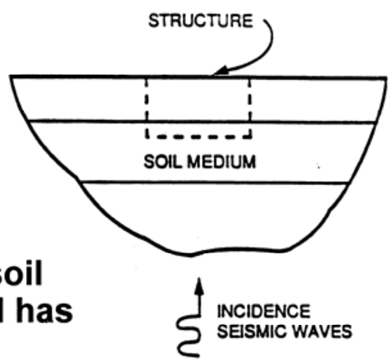
(b) Foundation Scattering Problem

(c) Foundation Impedance Problem

(d) Structural Modelling Problem and Interaction Response Analysis Problem

SUBSTRUCTURE METHODS
1- Site Response Analysis

Involves determination of ground motion within the supporting soil medium

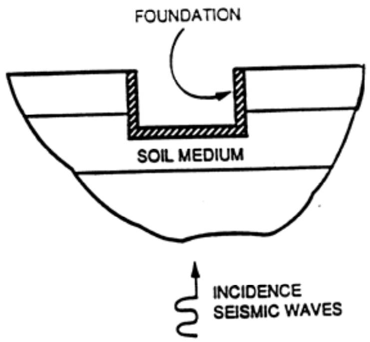


Basic data needed:

- Soil profile and dynamic soil properties including soil nonlinear properties. The equivalent linear method has proved to be effective in modeling soil nonlinear properties.
- Design motion and location of the the motion in the free-field (control point)
- Wave field and wave composition

Ground motion within the soil profile are defined. Degraded soil properties compatible with the level of excitation are obtained.

SUBSTRUCTURE METHODS
2- Foundation Scattering Analysis



Involves the determination of an effective foundation motion as supported by soil medium and as subjected to earthquake waves.

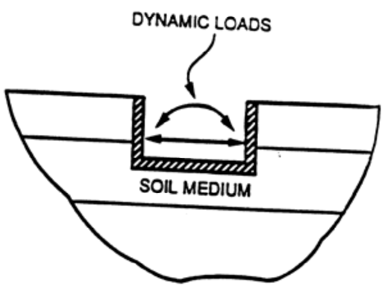
Basic data needed:

- Degraded strain-compatible soil properties
- Foundation geometry, stiffness and effective depth of embedment
- Free-field solution including type of waves, input time histories and their frequency contents

Depending on the problem, the scattered motion may include rocking and torsional components in addition to translational motion.

SUBSTRUCTURE METHODS
3- Foundation Impedance Analysis

Involves the determination of foundation spring and damping coefficients.



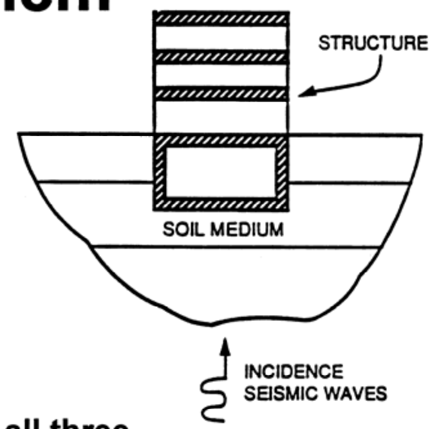
Basic data needed:

- Degraded strain-compatible soil properties
- Foundation geometry and effective depth of embedment
- Frequency and mode of excitation

In many practical cases, the impedance functions are highly frequency-dependent.

SSI

SUBSTRUCTURE METHODS
4- Modeling of the Structure and Solving the SSI Problem

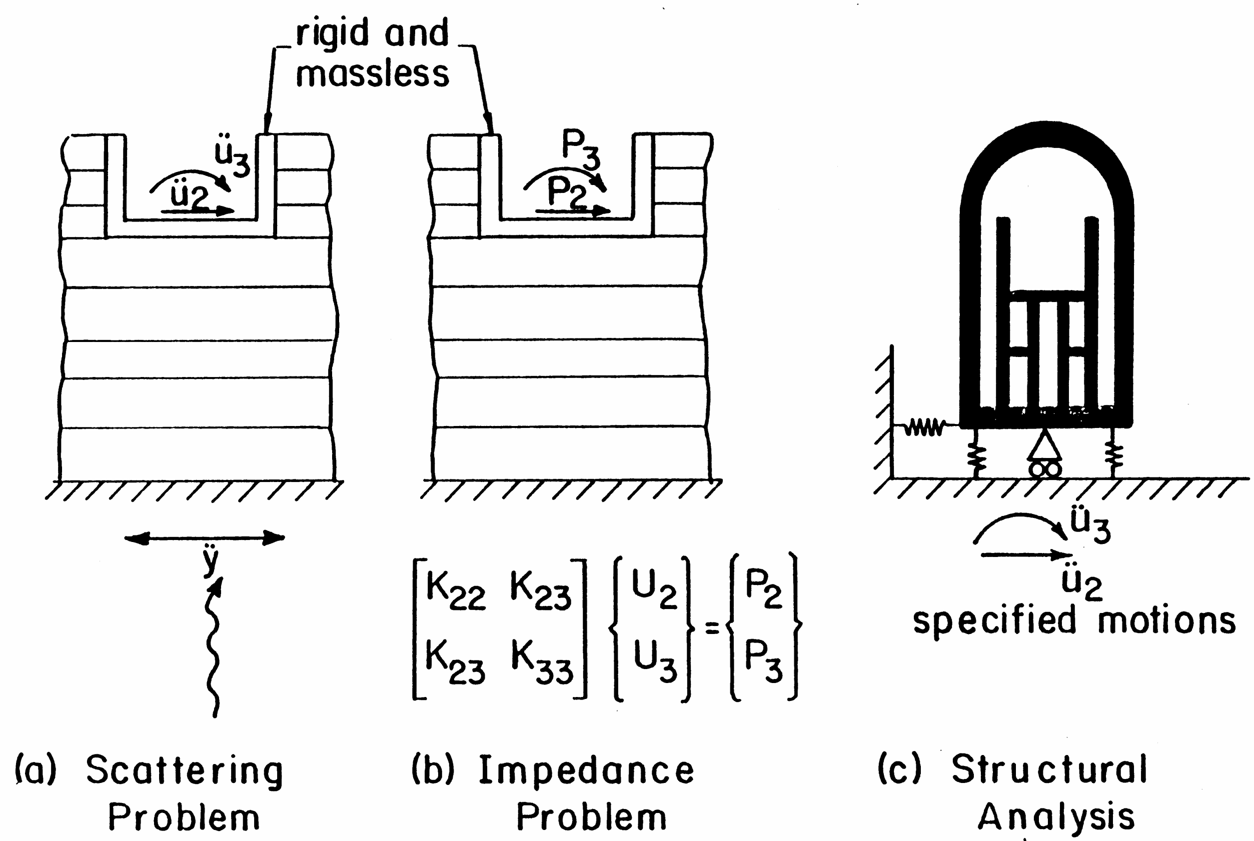


Involves developing the structural dynamic model and the final solution of the equation of motion using the scattered foundation motion and foundation impedance coefficients.

Depending on the SSI method selected

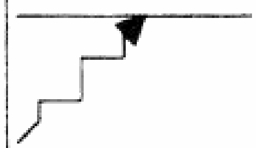
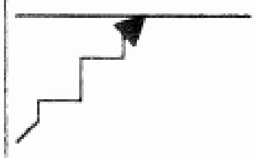
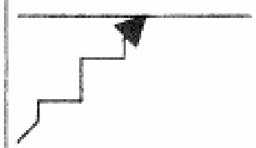
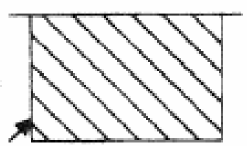
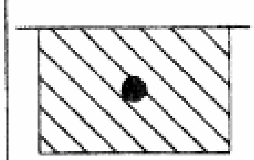
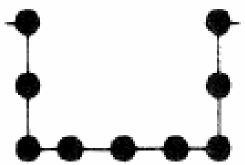
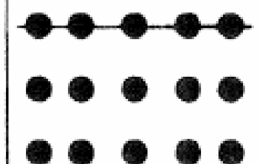
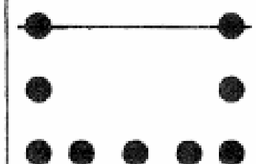
- The dynamic characteristics of the structure in all three directions including torsional properties can be recognized.
- The seismic soil pressure on the embedded walls of the structure may be obtained.
- The final responses in terms of seismic forces and response motions can be generated.

SSI



3-STEP METHOD FOR INTERACTION ANALYSIS

SUBSTRUCTURE METHODS

Method	Rigid Boundary	Flexible Boundary	Flexible Volume	Subtraction
Site Response Problem				
Scattering Problem			None	None
Impedance Problem				
Structural Response Problem	Standard	Standard +	Standard +	Standard +

MOST COMMONLY USED SSI COMPUTER PROGRAMS

Programs Based on the Soil Spring Approach

– Dynamic structural programs have been modified to incorporate the soil spring constants. Depending on the program, frequency-dependent stiffness and/or damping coefficients may be considered. Both the foundation impedance and scattered motion should be provided.

CLASSI(Substructuring - Rigid Boundary)

– Continuum Linear Analysis for Soil-Structure interaction was developed by Wong and Luco (1976). The industry version of CLASSI can handle structures with surface rigid foundation. The CLASSI programs work with other dynamic structural programs to develop modal properties.

SSI

MOST COMMONLY USED SSI COMPUTER PROGRAMS.......

LUSH, ALUSH, FLUSH (Complete Method)

- These programs are based on 2D and axisymmetric SSI methods using linear and nonlinear soil properties(Lysmer et al., 1974, 1975). These programs, and in particular the FLUSH program, have been widely used for SSI analyses of nuclear structures and earth dams. These programs can not handle the 3D effects. Modeling structural properties in 2D often requires approximation and a follow up detailed 3D analysis of the structure.

SASSI (Substructuring-Flexible Volume Method)

- System for Analysis of Soil-Structure Interaction was developed by Lysmer et al. (1981). In recent years, this program has been widely used for SSI analyses of structures in particular structures with embedded and/or flexible foundations. Both 2D plane strain and 3D options are available in SASSI.

OTHER SSI COMPUTER PROGRAMS

HASSI-8 (Katayama et al., 1991)

- Hybrid model of SSI system, linear and equivalent linear

TRANL (Baylor et al., 1974; Isenberg et al., 1978)

- Nonlinear 3D program based on soil island approach

TELDYN (Pyke, 1979)

- 2D nonlinear time history analysis of the SSI systems

Programs from the University of British Columbia

(Finn et al.)

- Based on 2D effective stress nonlinear analysis

Other SSI computer programs

SSI

SOIL-STRUCTURE INTERACTION (SSI)

There is a significant difference in the complexity of the SSI problem involving partly or fully embedded foundations vs surface foundations particularly for 3D problems. The ability of the SSI method to handle embedded and in general flexible foundations is a practical measure for ranking various SSI methods and computer programs.

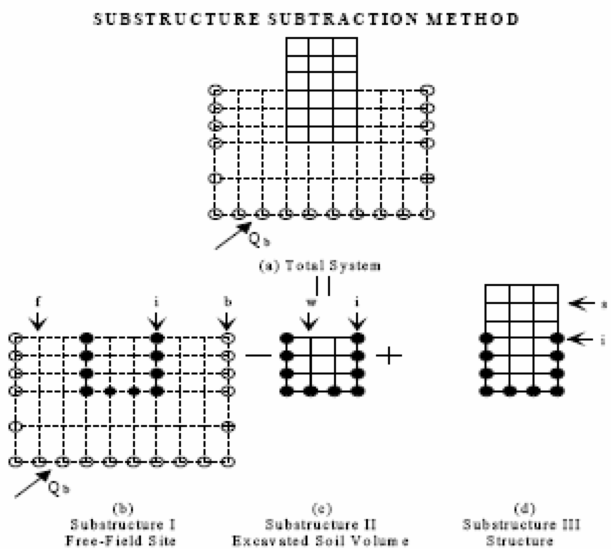
SSI COMPUTER PROGRAMS

Due to the complexity of the SSI problems with respect to dynamic modeling of soil and structural systems, boundary conditions, wave propagation etc., it is crucial that the documentation of the SSI program includes a comprehensive verification manual verifying the features/options often used in practice .

COMPUTER PROGRAM SASSI

Brief Theoretical Background

SASSI



$$\begin{bmatrix} C_{ii}^{III} - C_{ii}^{II} + X_{ii} & -C_{iw}^{II} & C_{is}^{III} \\ -C_{wi}^{II} & -C_{ww}^{II} & 0 \\ C_{si}^{III} & 0 & C_{ss}^{III} \end{bmatrix} \begin{Bmatrix} U_i \\ U_w \\ U_s \end{Bmatrix} = \begin{Bmatrix} X_{ii} U_i' \\ 0 \\ 0 \end{Bmatrix}$$

$$[C_i^*] = [K_i^*] - \omega^2 [M_i]$$

Subscript Nodes

b	the boundary of the total system
i	at the boundary between the soil and the structure
w	within the excavated soil volume
g	at the remaining part of the free-field site
s	at the remaining part of the structure
f	combination of i and w nodes

SASSI-Site Response Analysis

SOIL PROFILES AND PROPERTIES

1

2

H_i, γ_i, V_{si}, V_{pi}, β_{si}, β_{pi} I

N

FOR LAYER I

H_i: THICKNESS

γ_i: DENSITY

V_{si}: SHEAR WAVE VELOCITY

V_{pi}: P-WAVE VELOCITY

β_{si}: DAMPING ASSOCIATED WITH SHEAR WAVE VELOCITY

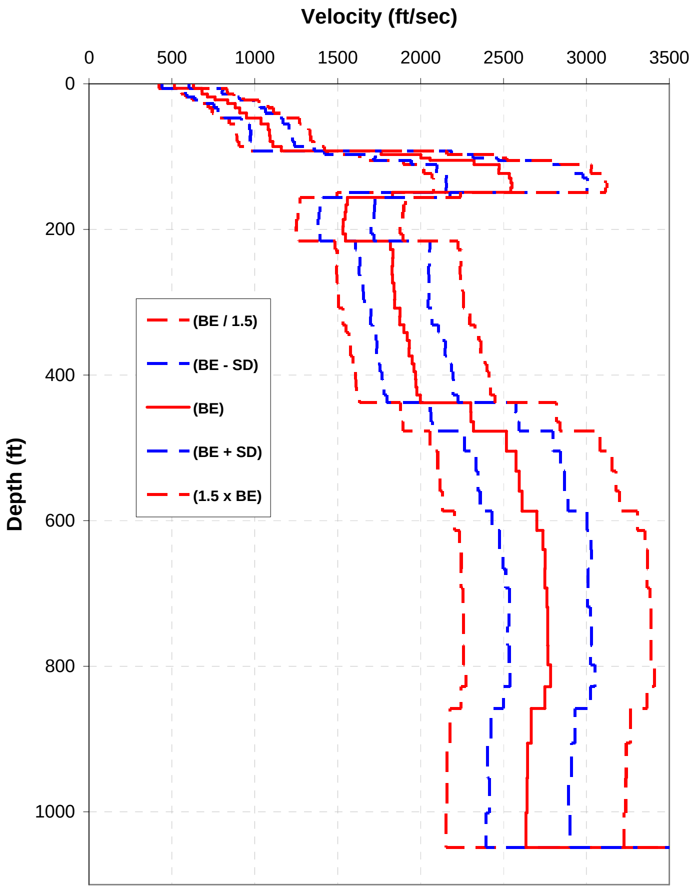
β_{pi}: DAMPING ASSOCIATED WITH P-WAVE VELOCITY

SASSI-Site Response Analysis

Strain-Compatible Vs

Site response analysis is based on:

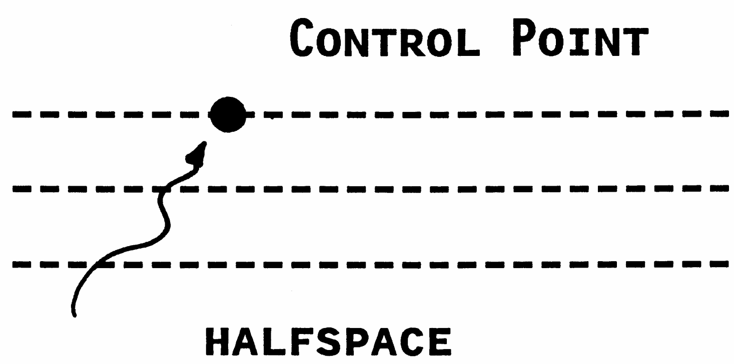
- 60 randomized profiles
- Randomized soil curves
- De-aggregated input motion (ARS or t.h.)
- Strain-compatible soil properties is used for SSI



SASSI-Site Response Analysis

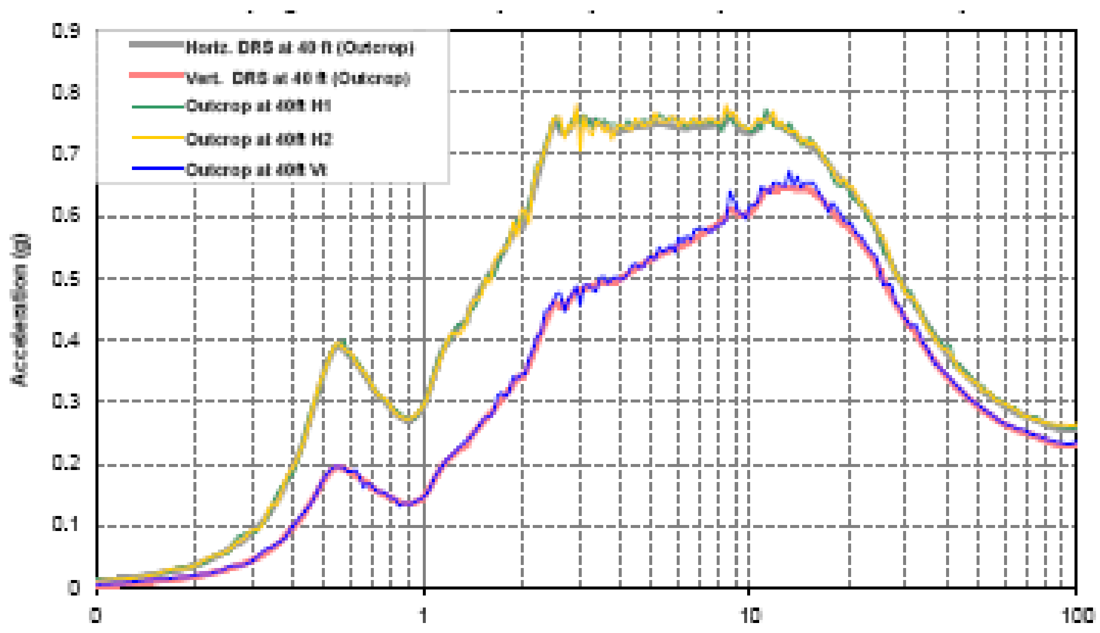
INPUT MOTION

- CONTROL POINT
- CONTROL MOTION

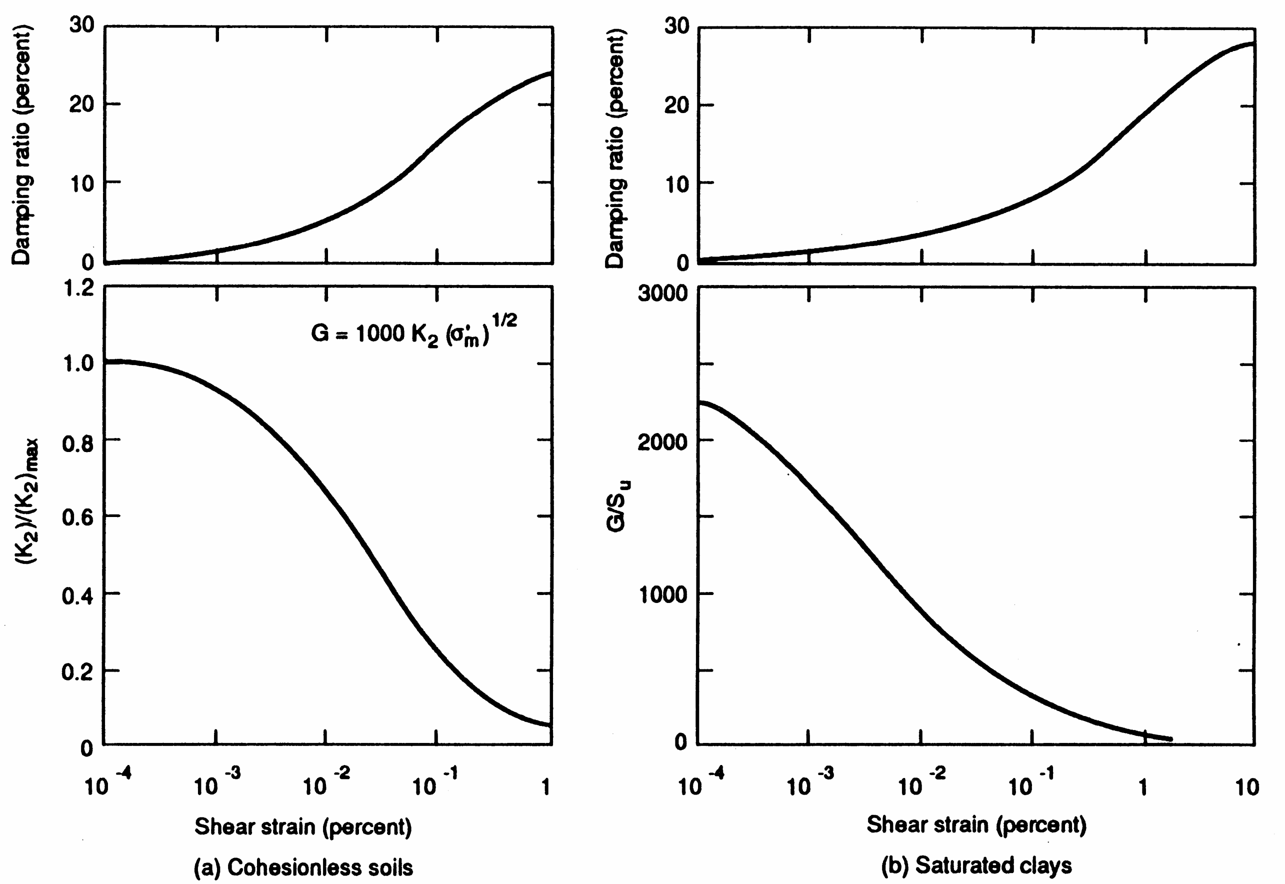


SASSI-Site Response Analysis

FIRS-Outcrop at the Depth of 40 ft



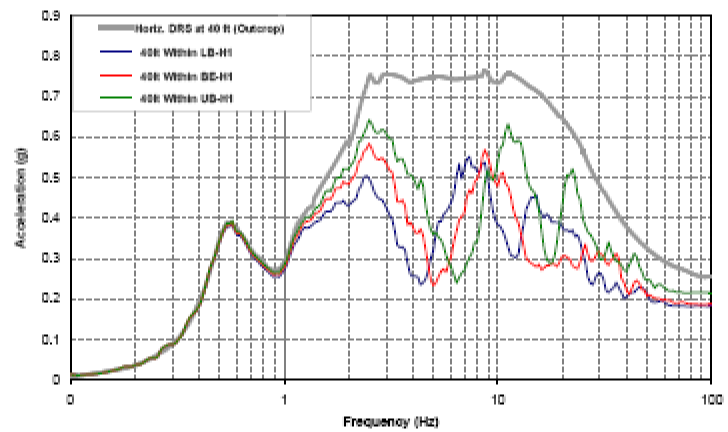
SASSI-Site Response Analysis



Shear Moduli and Damping Characteristics of Soils

SASSI-Site Response Analysis

- ✓Perform site response analysis using the FIRS outcrop motion as input
- ✓Strain-compatible soil properties from GMRS calculation, no further iteration
- ✓Obtain in-column motion for SASSI analysis



SASSI-Site Response Analysis

FREE-FIELD MOTION

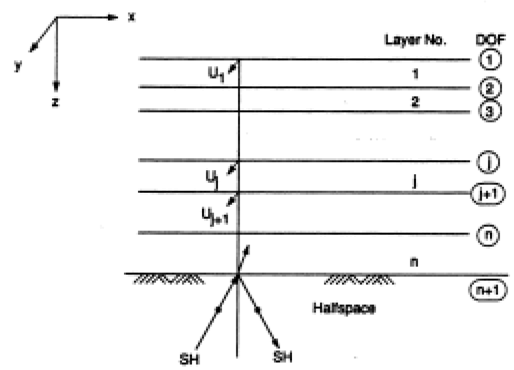
- Inclined SV- and P-Waves

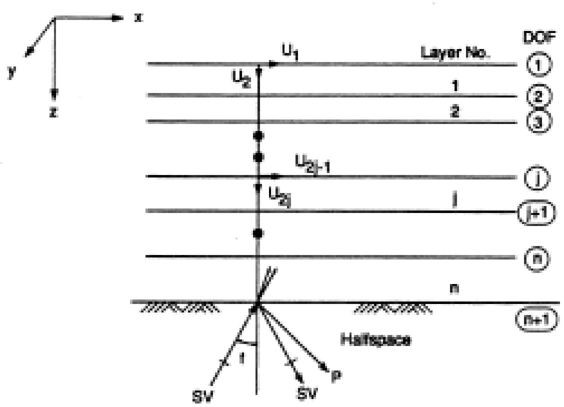
$$([A]K2+[B]K+[G]-\omega^2[M])\{U\}=\{P_b\}$$

- Inclined SH-Waves

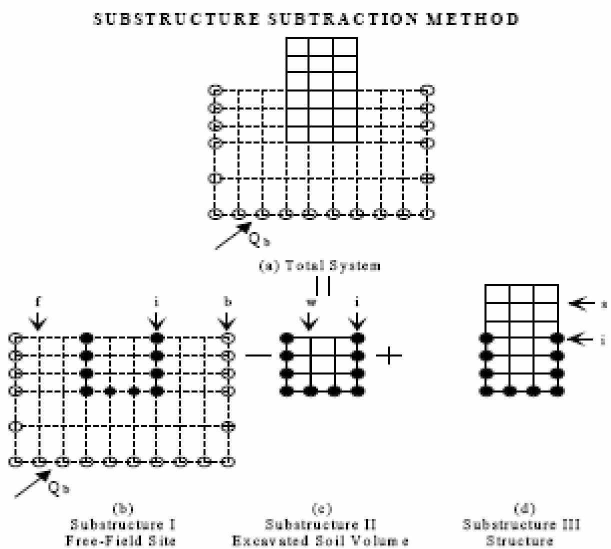
$$([A]K^2[G]-\omega^2[M])\{U\}=\{PB\}$$

- Love Wave
- Rayleigh Wave
  - o The Least-Decay Method
  - o The Shortest Wave Length





SASSI-Impedance Analysis



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$$[C_f^*] = [K_f^*] - \omega^2 [M_f]$$

Subscript Nodes

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s	at the remaining part of the structure
f	combination of i and w nodes

SASSI-Impedance Analysis

IMPEDANCE ANALYSIS

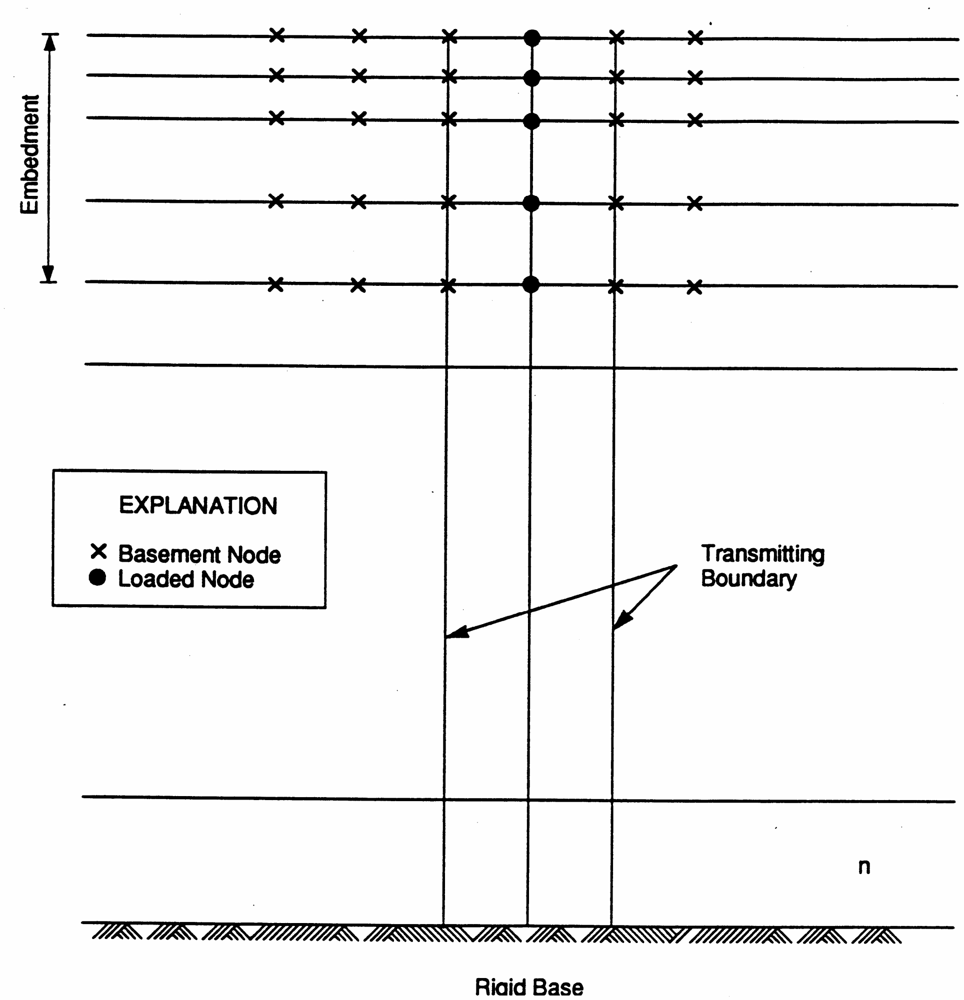
1 - FLEXIBILITY MATRIX

- o 2-D DYNAMIC FLEXIBILITY MATRIX
- o 3-D DYNAMIC FLEXIBILITY MATRIX

2 - IMPEDANCE MATRIX

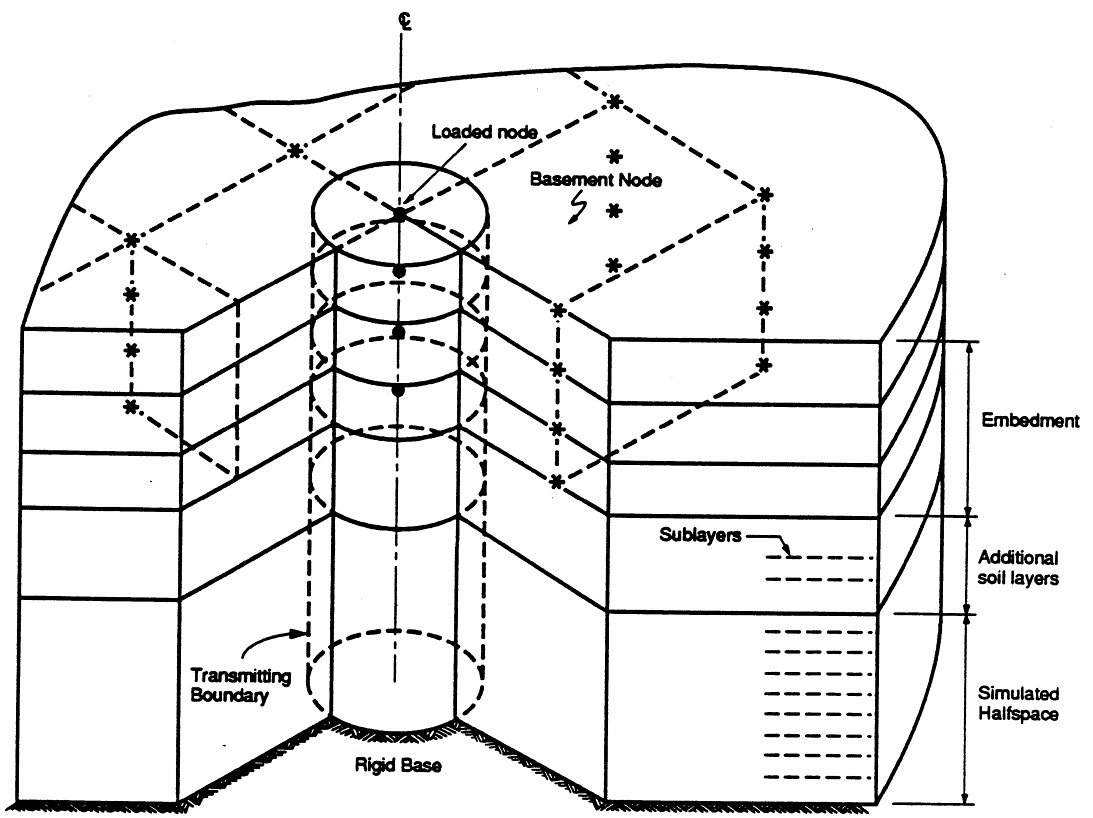
- o DIRECT METHOD
- o SKIN METHOD

SASSI-Impedance Analysis



Plane-Strain Model for Impedance Analysis

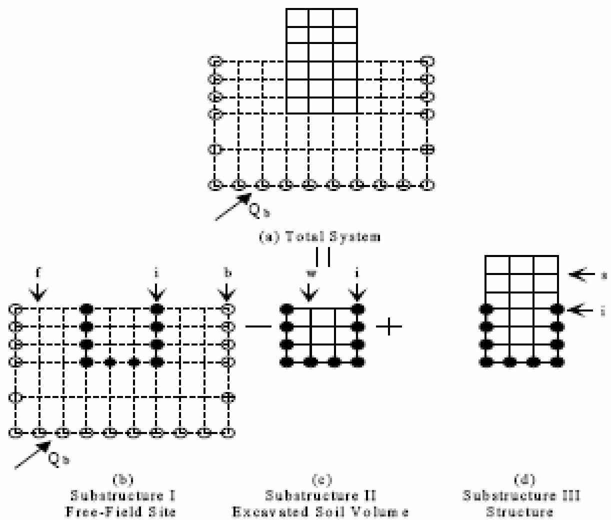
SASSI-Impedance Analysis



Axisymmetric Model for Impedance Analysis

SASSI-Structural Modeling

SUBSTRUCTURE SUBTRACTION METHOD



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$$[C_i^*] = [K_i^*] - \omega^2 [M_i]$$

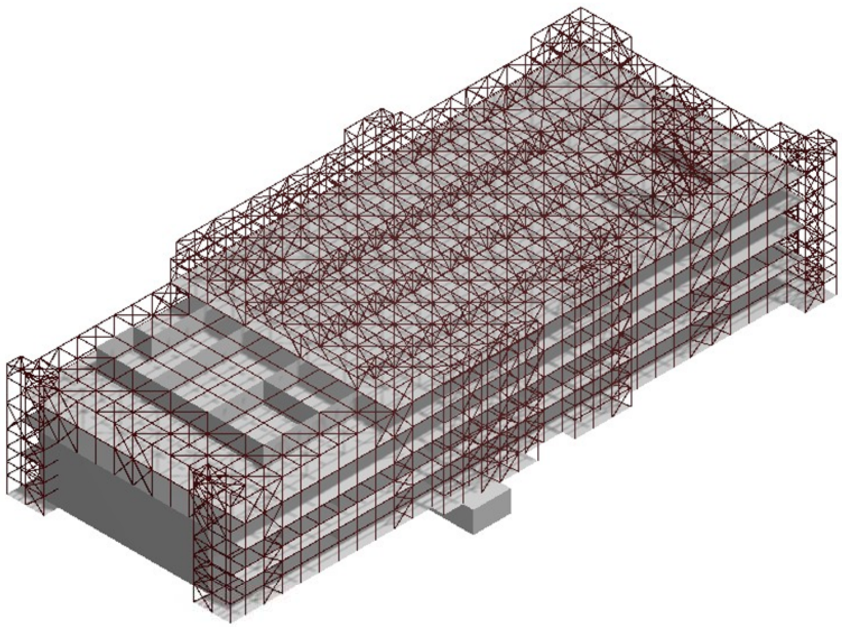
SASSI-Structural Modeling

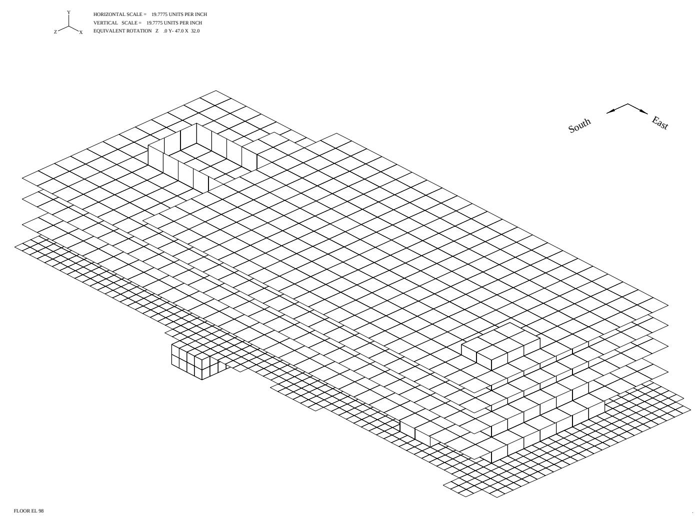
COMPUTER PROGRAM SASSI

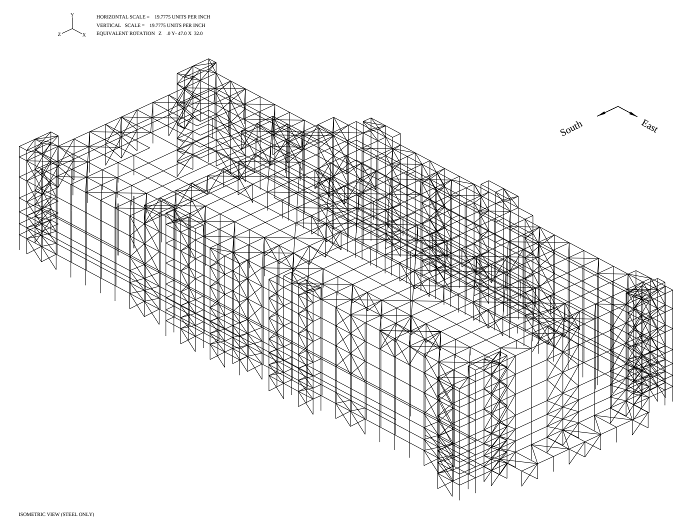
Finite Element Library

- Beam element (2D and 3D)
- Plane strain element
- Brick element
- Plate element
- Spring element
- Mass and stiffness element
- Pile element (2D and 3D)

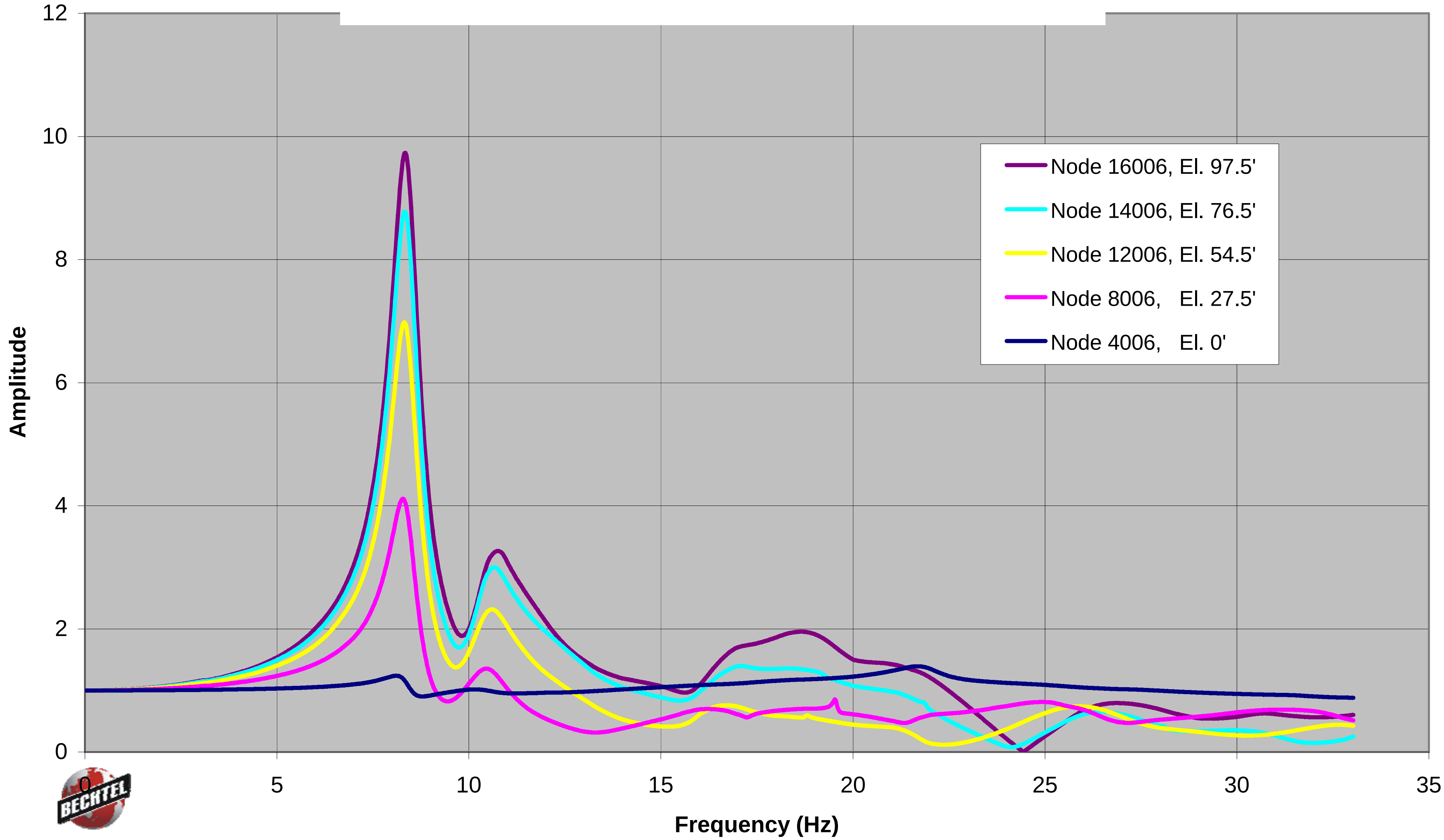
SASSI-Structural Modeling



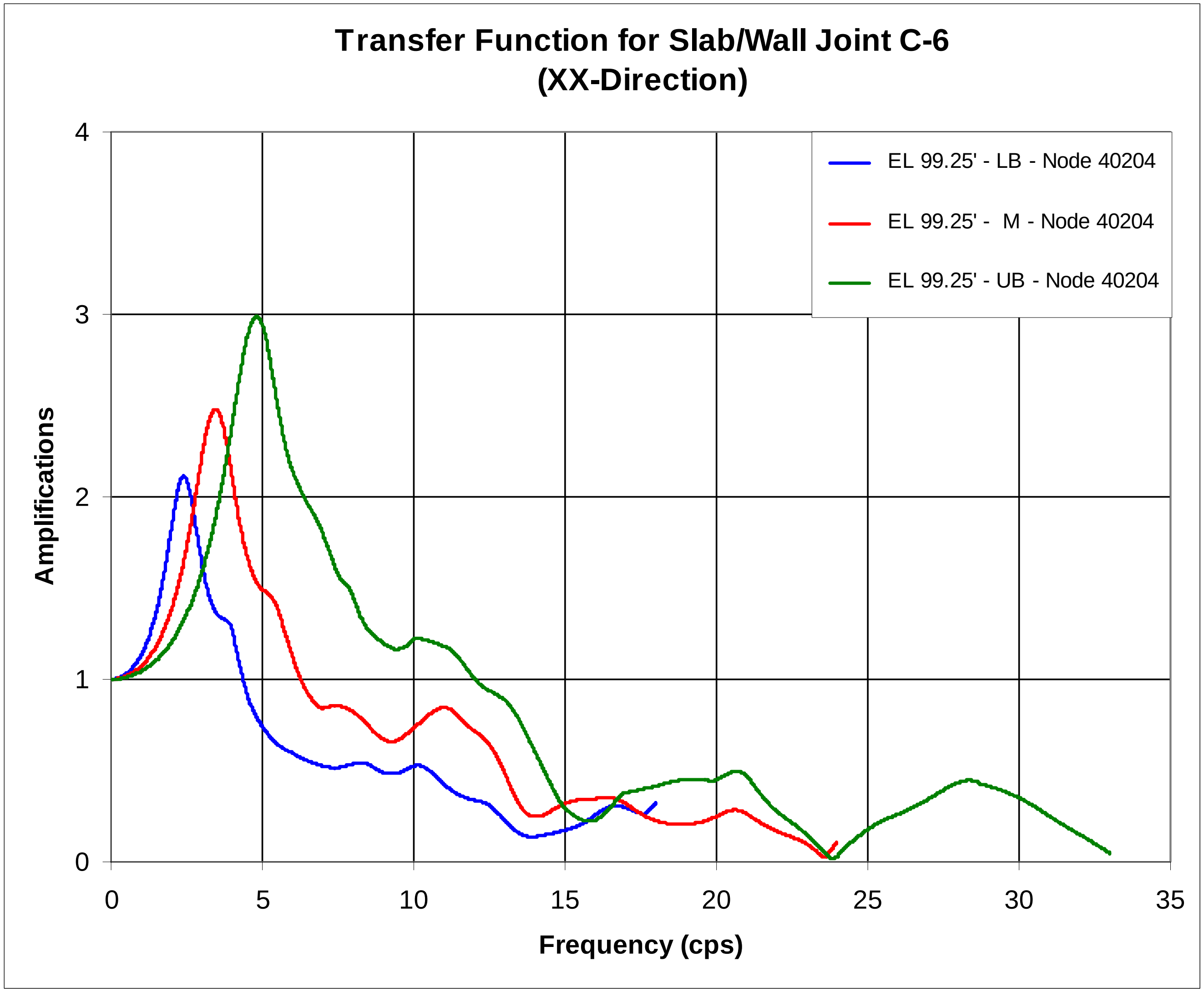




SASSI-Structural Analysis



SASSI-Structural Analysis

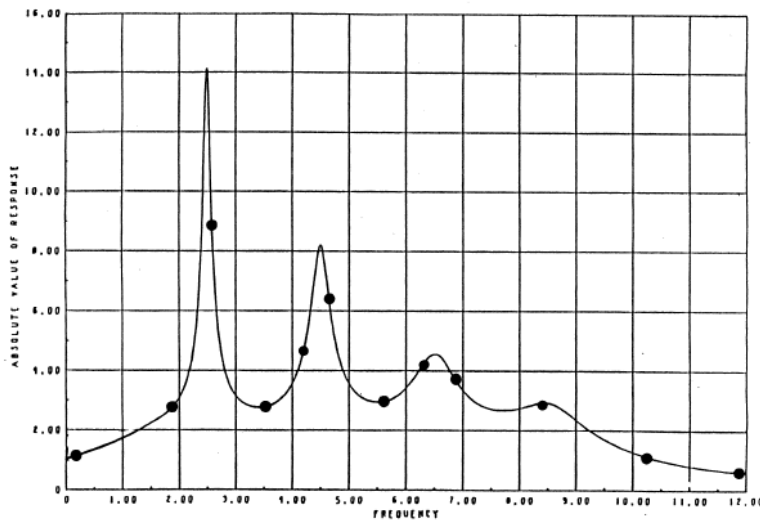


SASSI-Frequency of Analysis

✓Typically 20-50 frequency points are used

✓The remaining solution is obtained from interpolation on TF

✓The interpolation is based on the two degree-of-freedom system

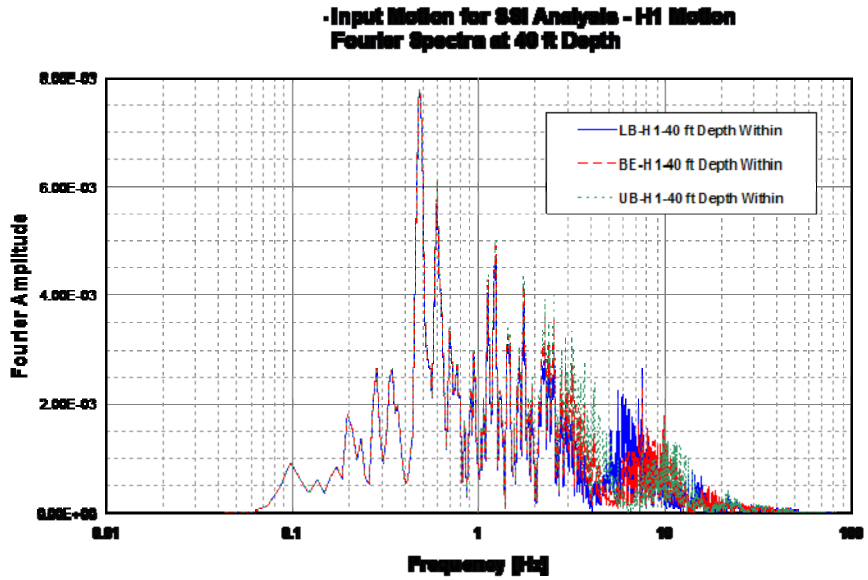


Response of a Multi-Degrees-of-Freedom System

SASSI-Frequency Cut Off

Frequency cut off is selected based on the following:

- ➢Nyquist frequency
- ➢Frequency contents of input motion
- ➢SSI response characteristics
- ➢The cut off frequency can be reduced from upper bound, to medium, to lower bound soil profile

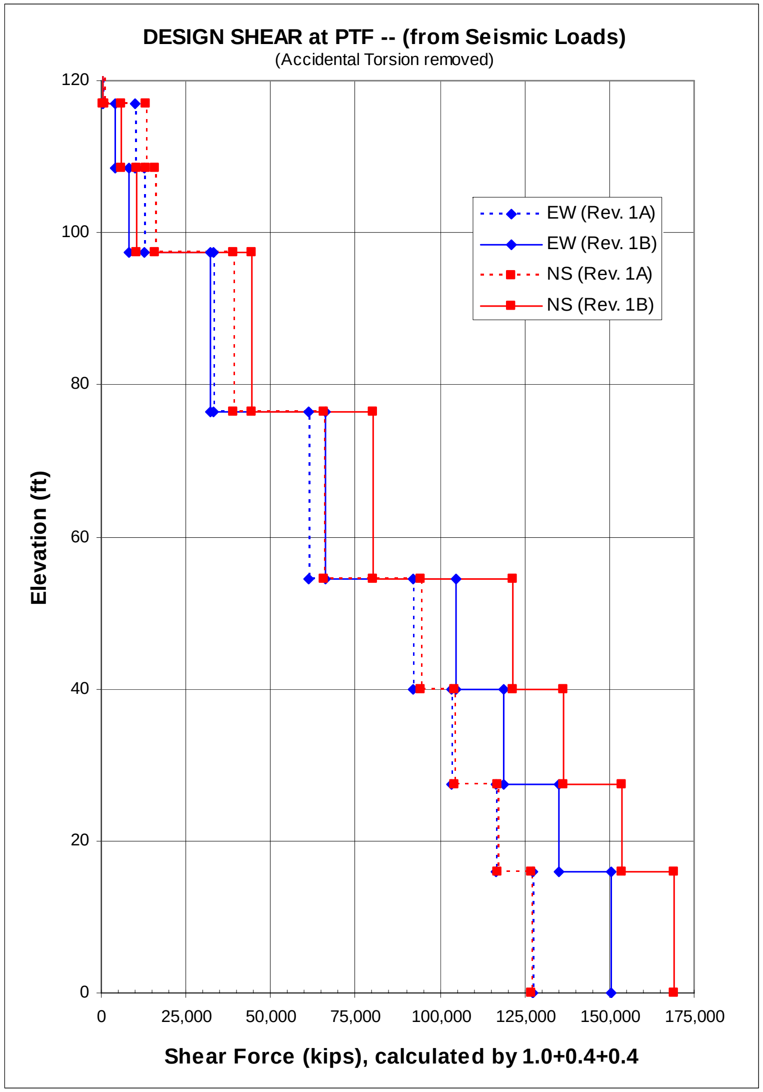


SASSI-Structural Analysis

SASSI-Structural Analysis

- For detail stress analysis and design, seismic loads in terms of maximum acceleration at all nodal points were obtained.
- The acceleration responses were enveloped for 3 soil cases and adjusted to take into account accidental torsional effects
- The maximum accelerations were subsequently applied as static load to a detailed static model of the structure for load combination and design of each member

SASSI-Structural Analysis

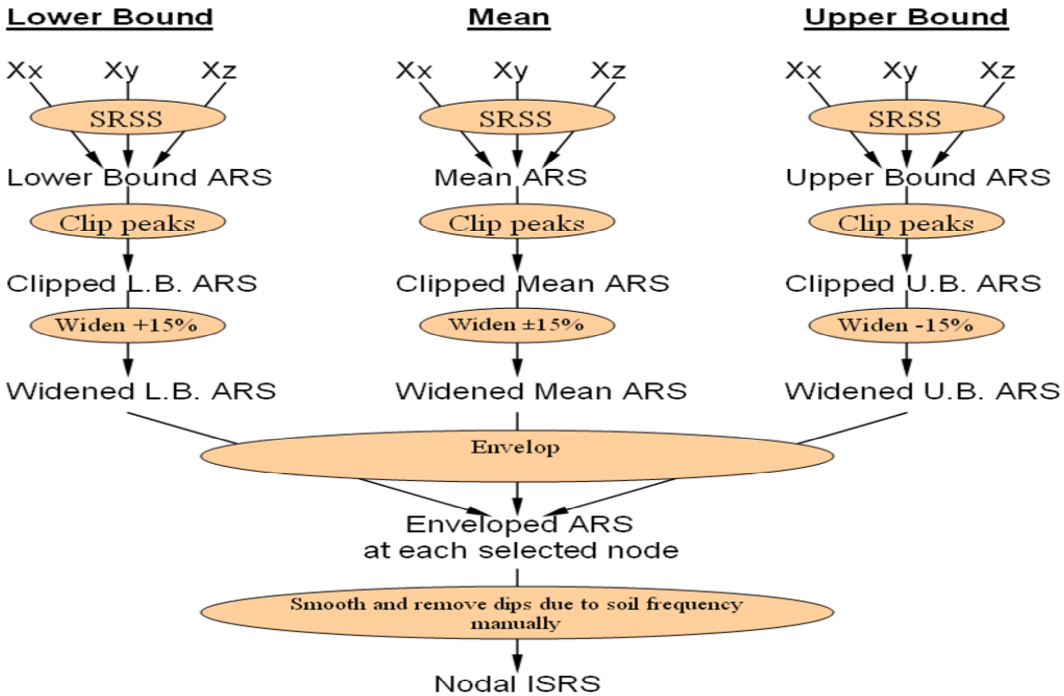


Ratio (1B)/(1A) at Base

Weight = 1.09
EW Shear = 1.18
NS Shear = 1.33

SASSI-Structural Analysis

Flow Chart for Calculating ISRS at a Node



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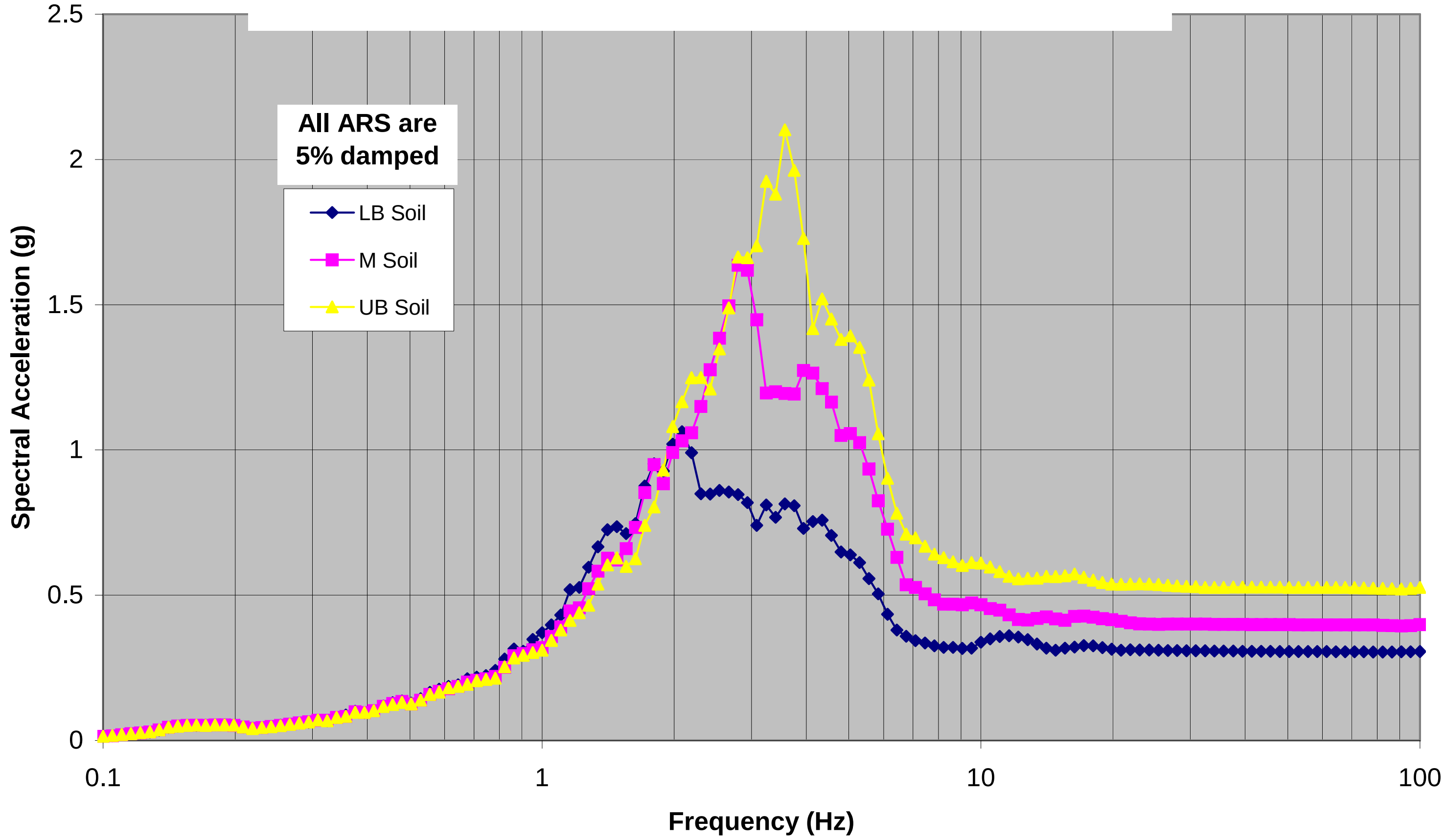
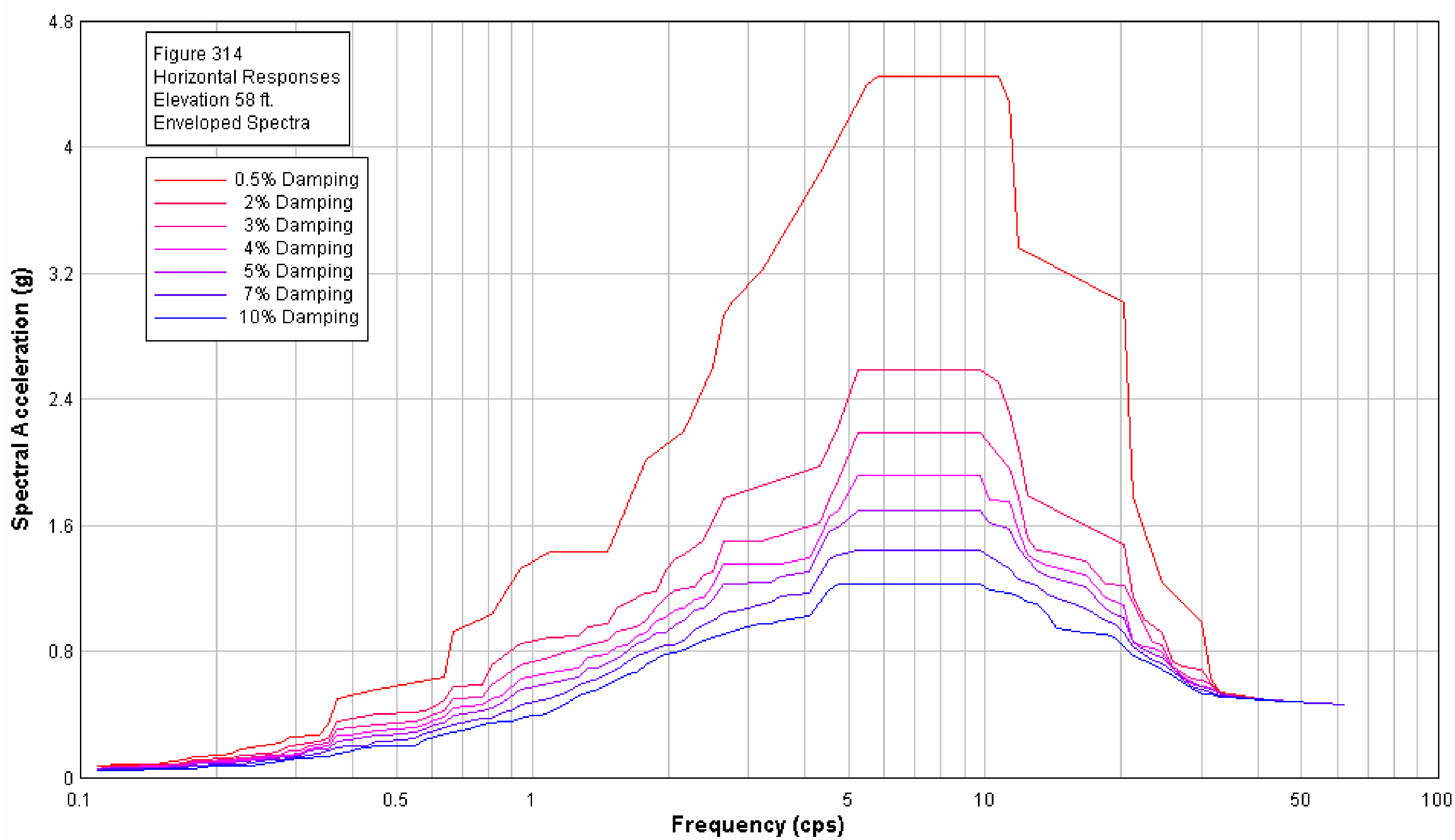
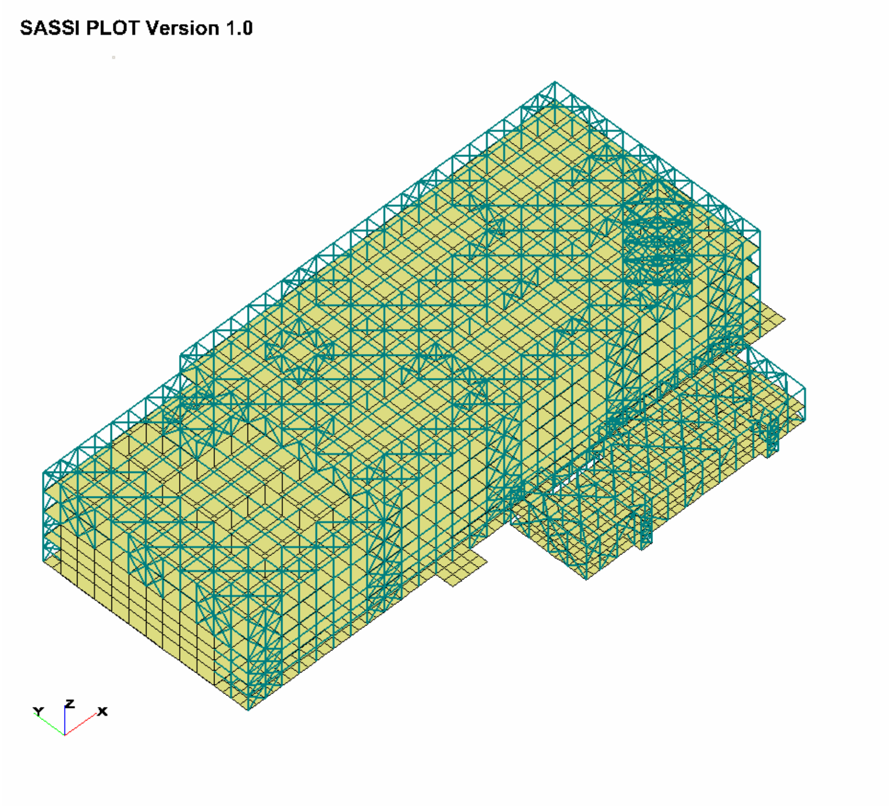
SASSI-Structural Analysis



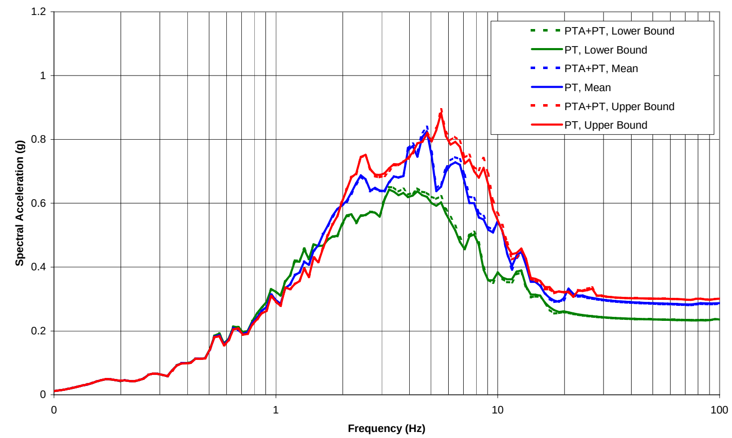
SASSI-Structural Analysis



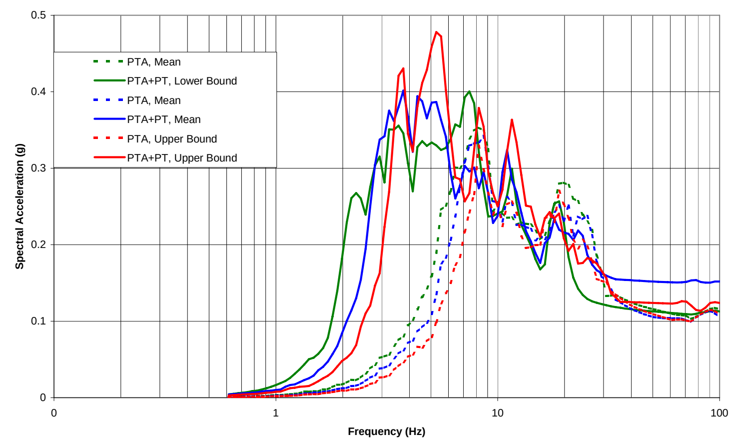
Through Soil Structure-to-Structure Interaction



X due to X - ARS, 5% Damped, PT Building, at Node 14672 (El. 77 ft), SASSI 4% Run



Z due to Y - ARS, 5% Damped, PT Annex, at Lines 22 & N.2, El. 0 ft, SASSI 4% Run



BECHTEL

SASSI-Program Layout

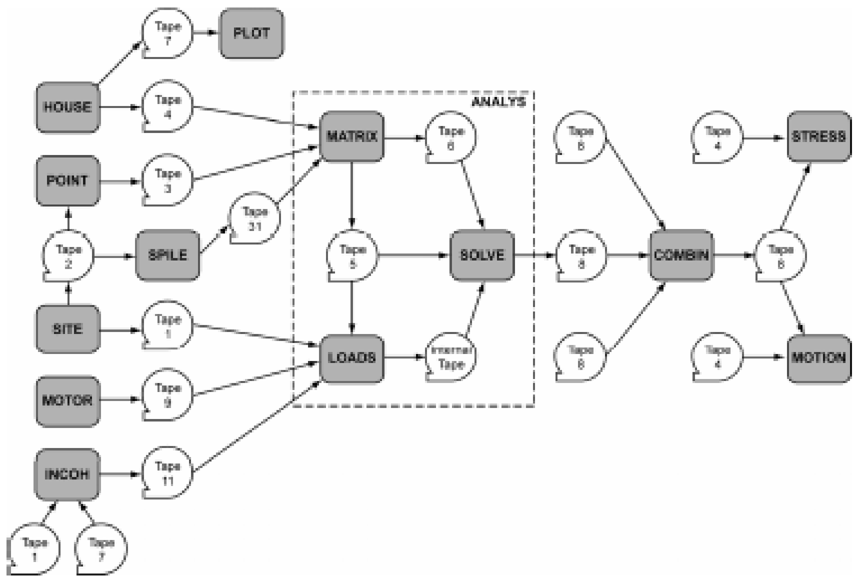


Figure 5.1 SASSI2000 Layout with Incoherency Feature

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SASSI

COMPUTER PROGRAM SASSI CAPABILITIES/LIMITATIONS

SASSI is applicable to the seismic or forced vibration SSI analysis of nuclear structures, offshore structures, underground structures and structures on a pile foundation. It can handle:

- Two- and three-dimensional SSI problems
- Rigid and flexible embedded foundations of any arbitrary shape
- Structure-soil-structure interaction
- Pile groups with battered piles
- Machine vibration problems
- Torsional ground motion
- Seismic waves involving vertical or inclined body waves (SV-, P-, and SH-waves) and surface waves (Rayleigh and Love waves)

Lotung ¼ Model

LOTUNG SSI EXPERIMENT

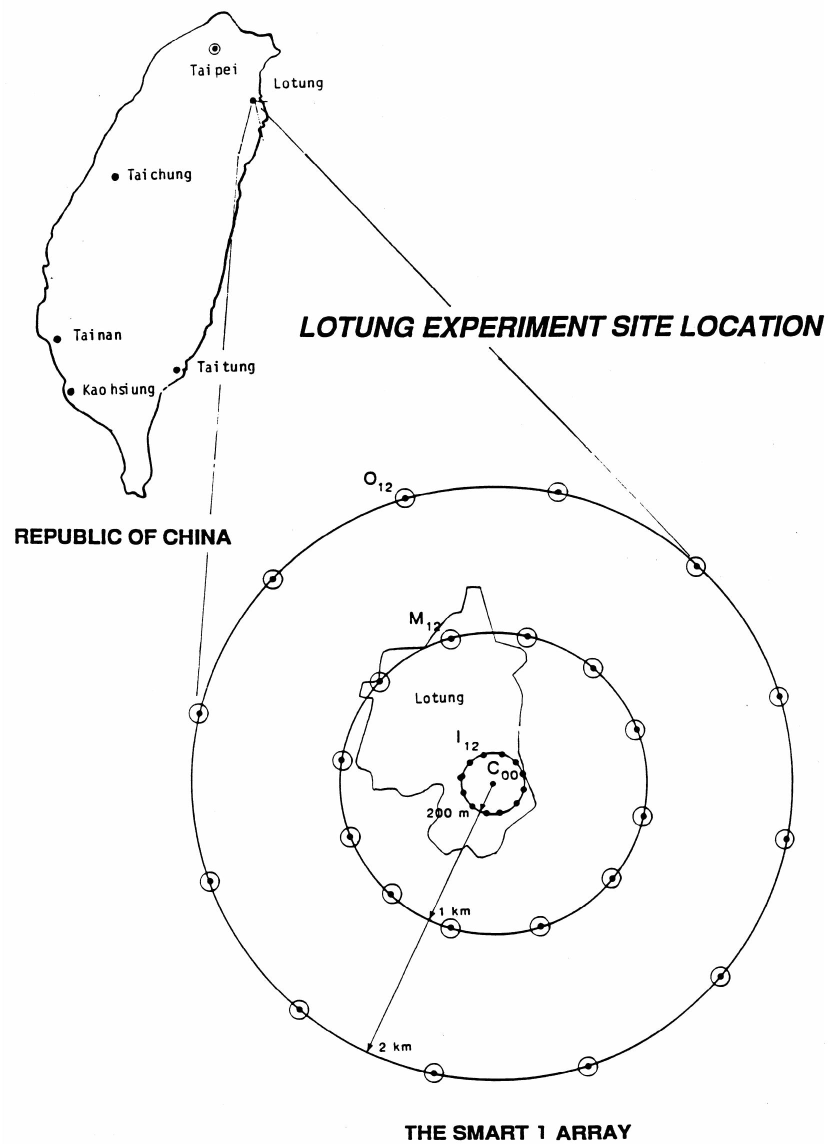
- The experiment was conducted by the Electric Power Research Institute (EPRI, 1989) with the cooperation from Taiwan Power Company (TPC) and the US NRC with the objective of validating the SSI methodologies used by the industry.
- A 1/4-scale concrete containment building model was constructed on a relatively soft soil site in Lotung, Taiwan (within SMART 1). .
- Both the free-field (at the surface and at depth) and the model were extensively instrumented.
- During the program plan, more than 18 earthquakes ranging in magnitudes from 4.5 to 7.5 were recorded. Maximum ground accelerations up to 0.25g were recorded.

Lotung ¼ Model

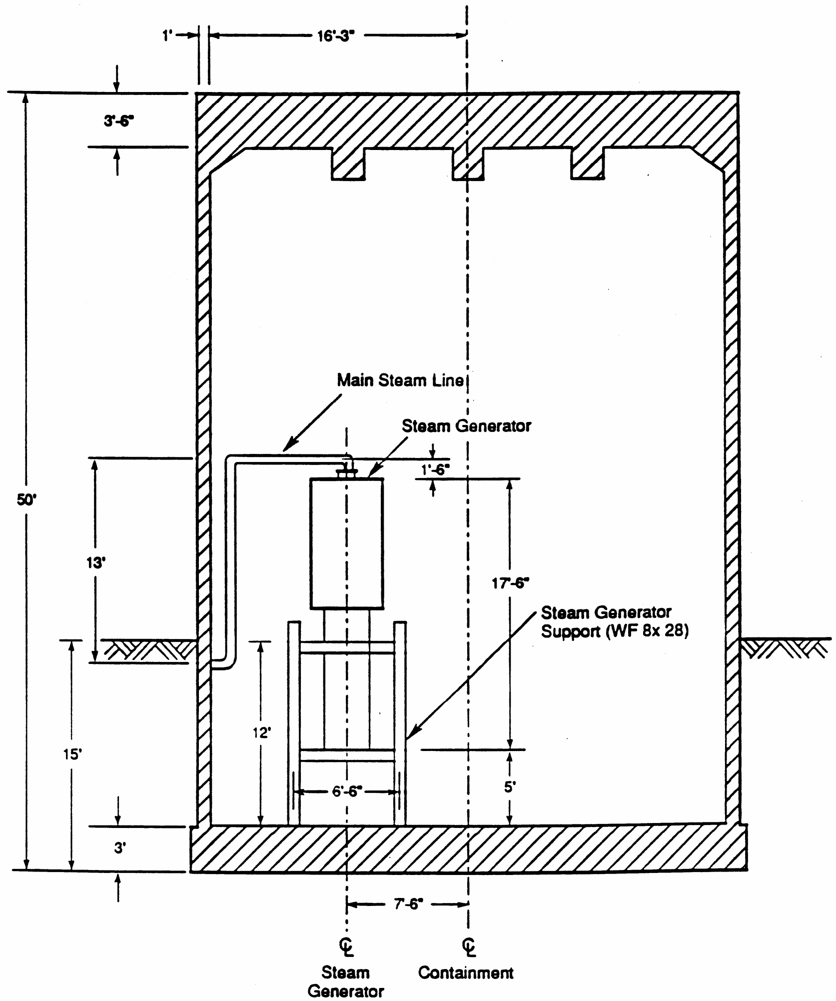
LOTUNG SSI EXPERIMENT....

- Total of 13 participants including industry and university groups participated in the SSI analysis.
- The recorded responses were made available to the participants only after their predictions had been documented.

Lotung ¼ Model

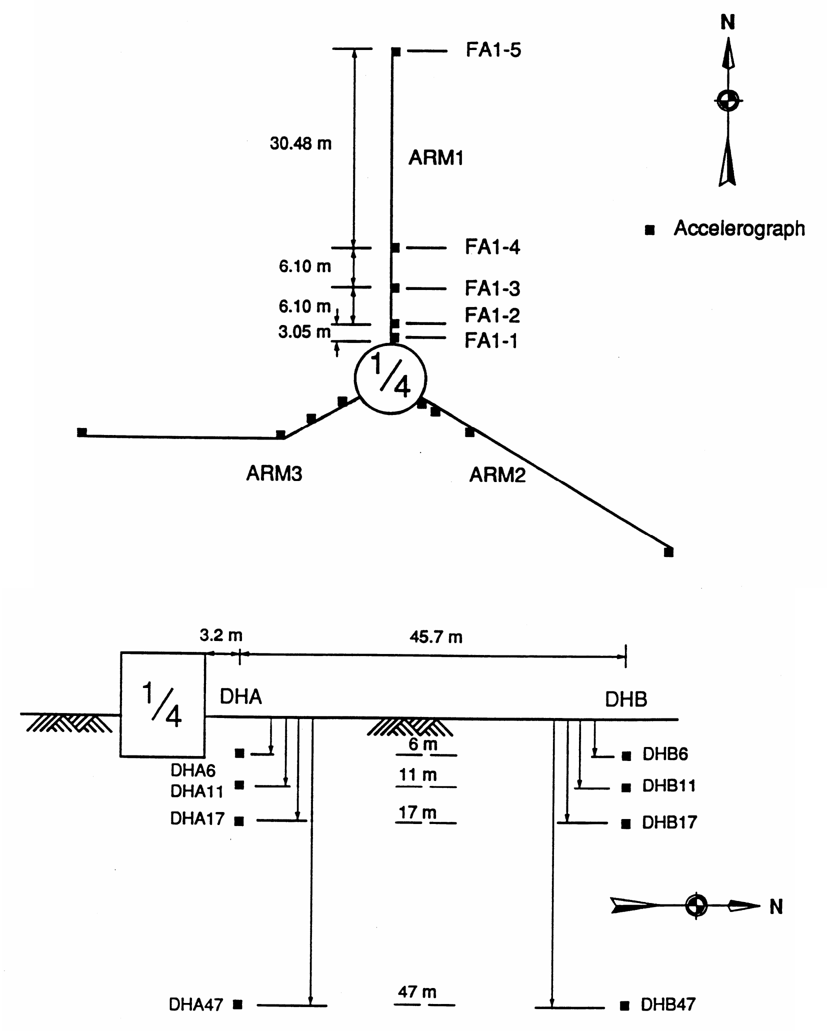


Lotung ¼ Model



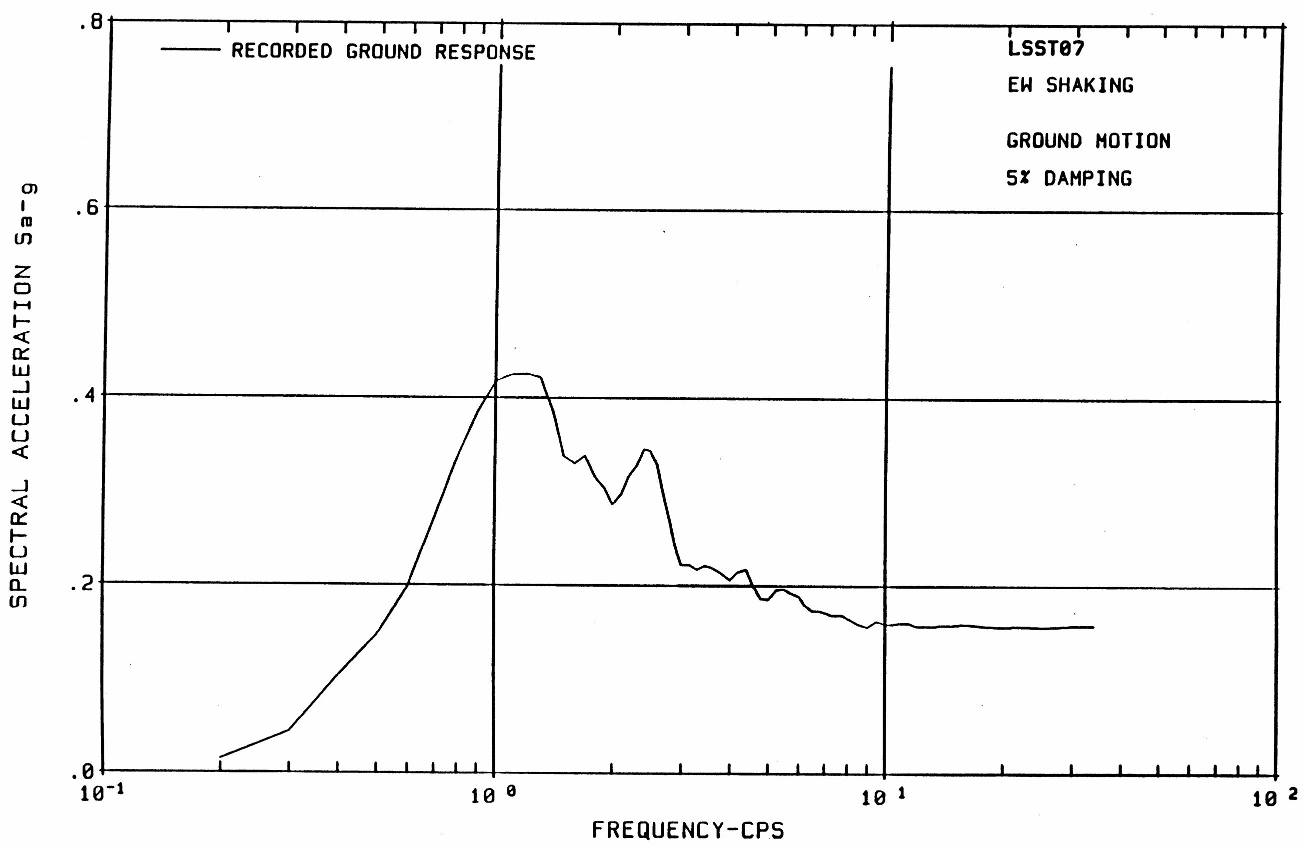
Vertical Cross-Section View of the 1/4-Scale Containment Model

Lotung ¼ Model



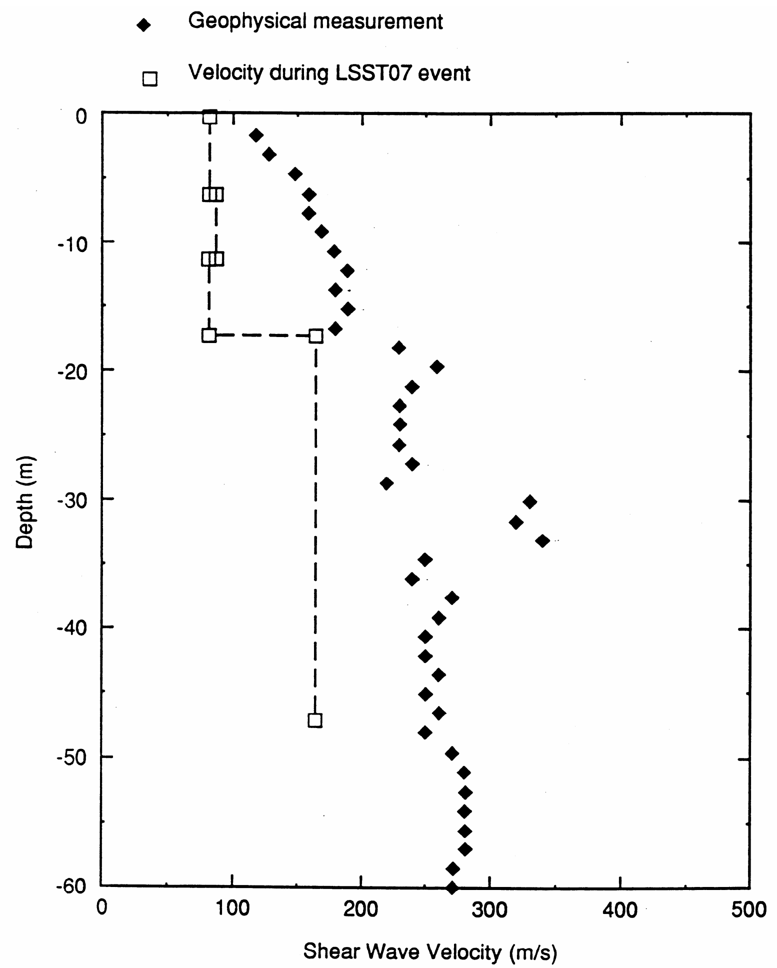
ACCELEROGRAPHS IN SOIL REGION

Lotung ¼ Model



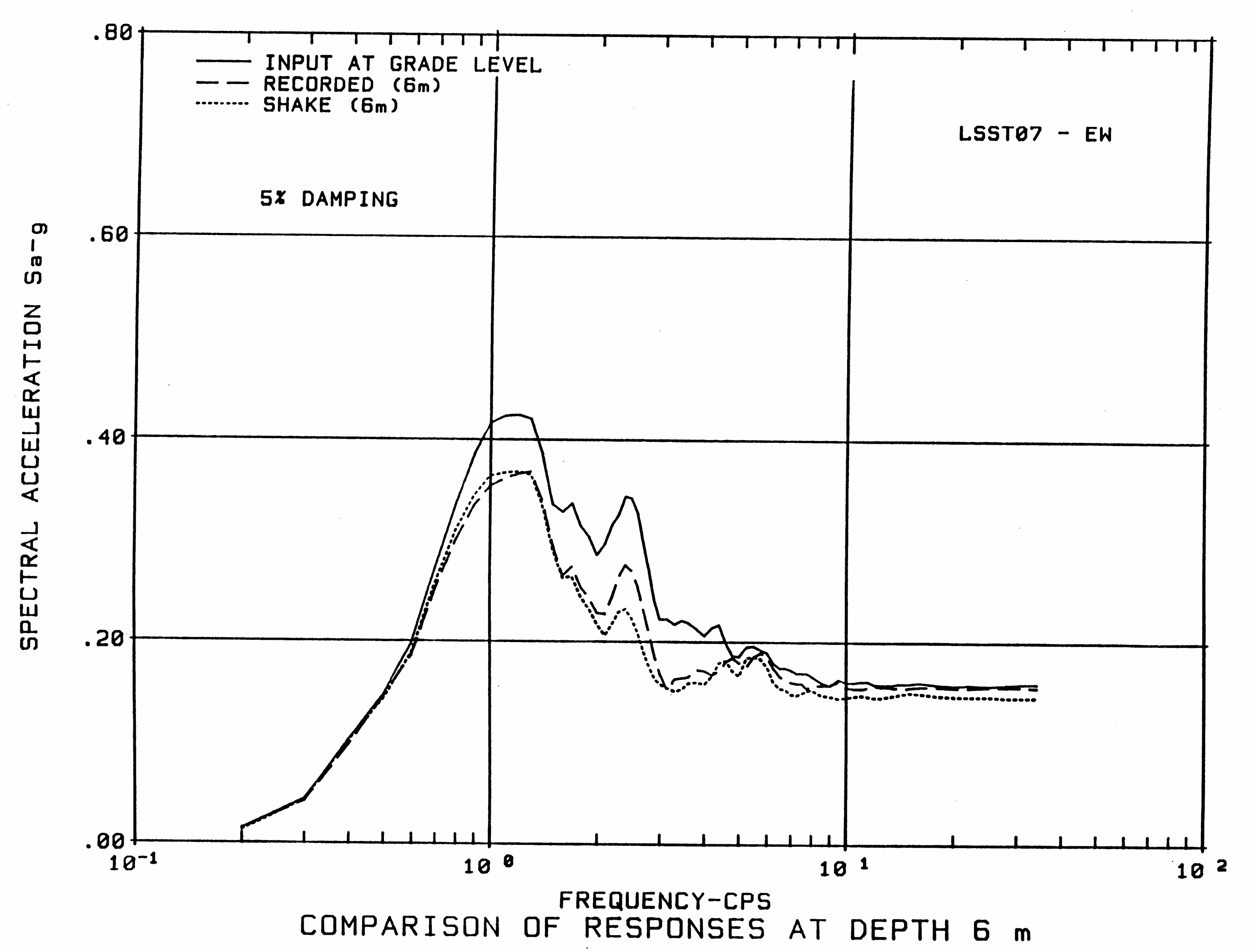
Acceleration Response Spectrum of Input Motion

Lotung ¼ Model

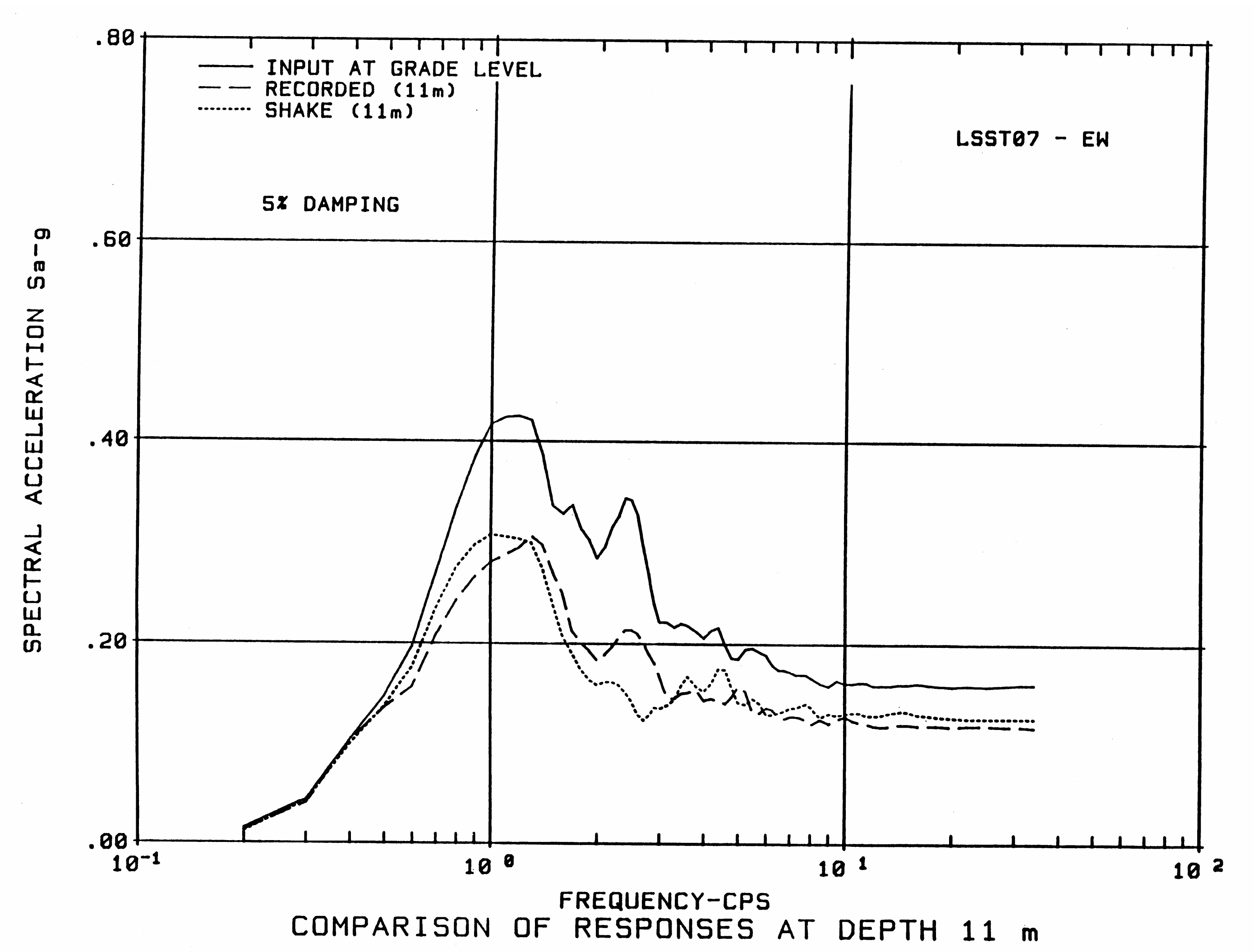


IN-SITU AND DEGRADED SHEAR WAVE VELOCITY PROFILE (LOTUNG EXPERIMENT)

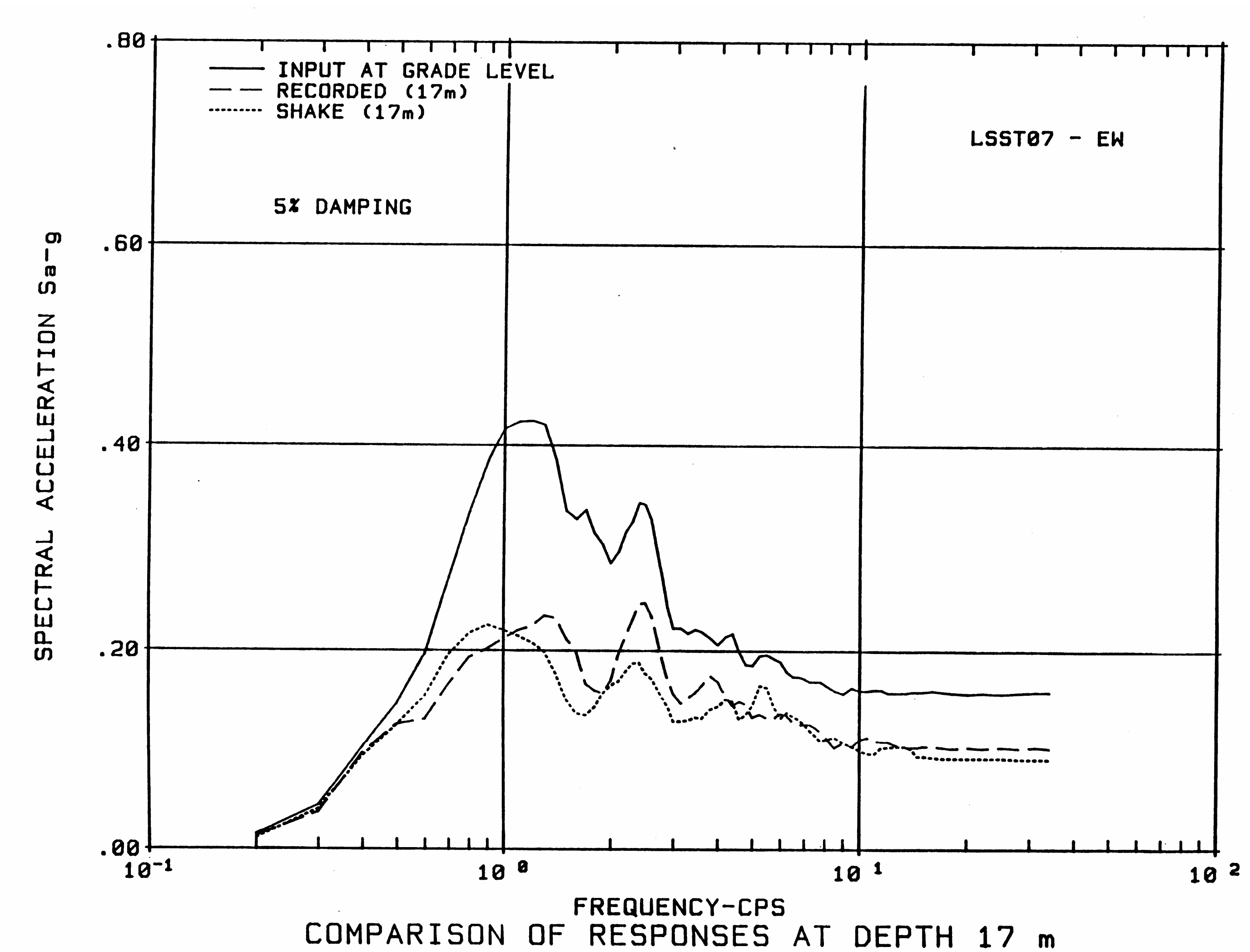
Lotung ¼ Model



Lotung ¼ Model

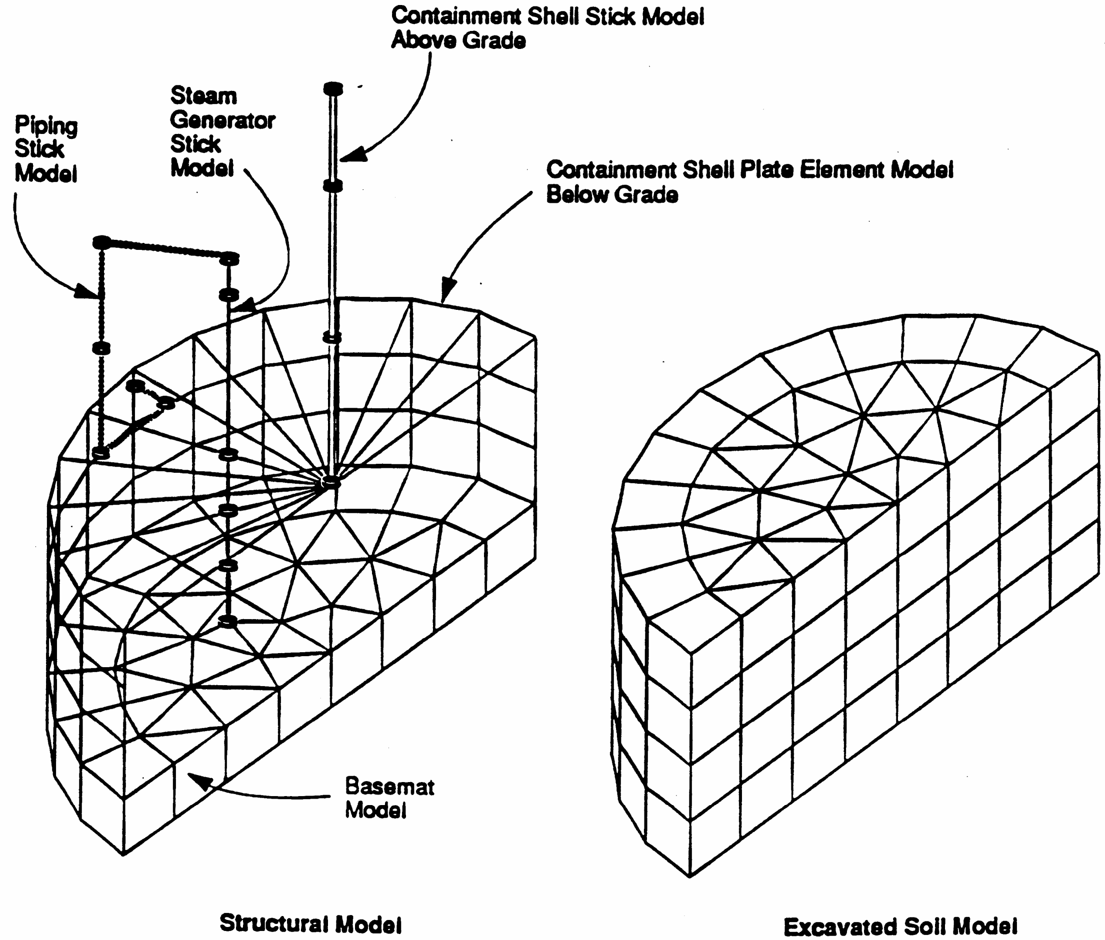


SASSI



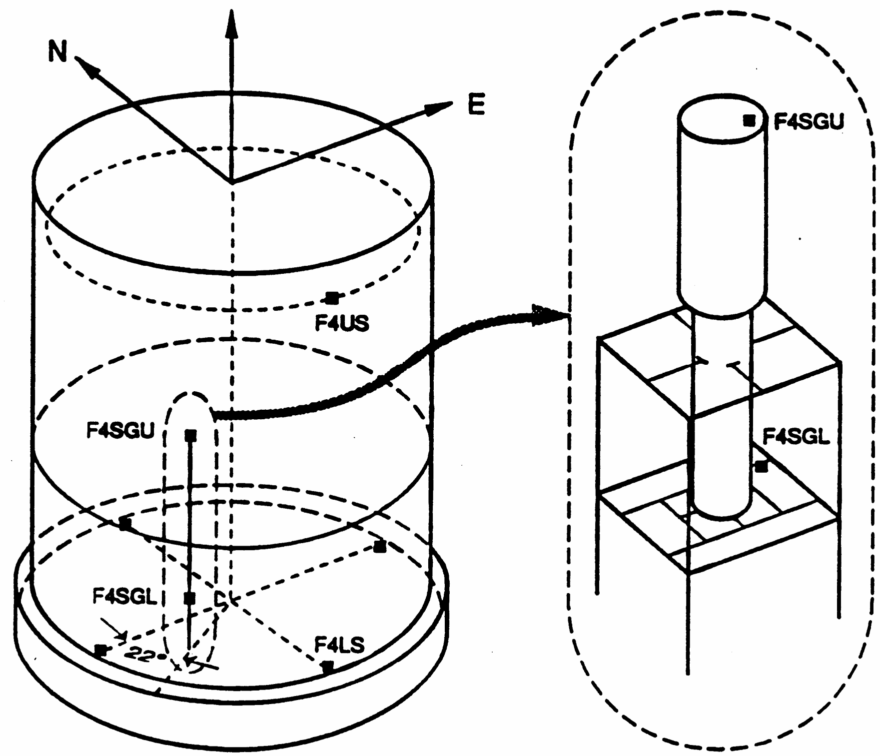
INPUT AT GRADE LEVEL
RECORDED (17m)
SHAKE (17m)
LSST07 - EW
5% DAMPING
.80
.60
.40
.20
.00
SPECTRAL ACCELERATION Sa-g
10⁻¹
10⁰
10¹
10²
FREQUENCY-CPS
COMPARISON OF RESPONSES AT DEPTH 17 m

Lotung ¼ Model



Configuration of SASSI Finite Element Model C

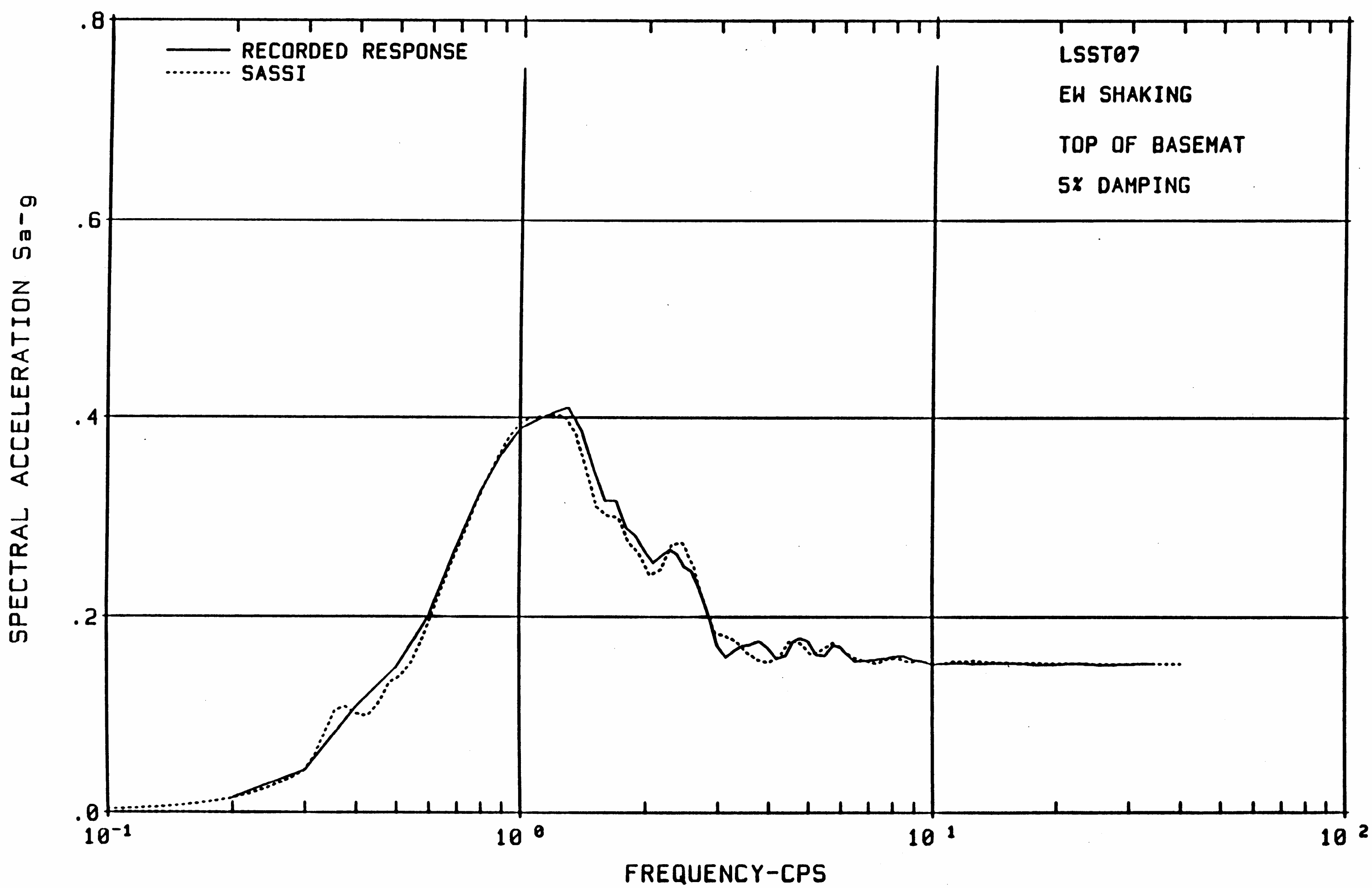
Lotung ¼ Model



■ Denotes accelerometer within containment

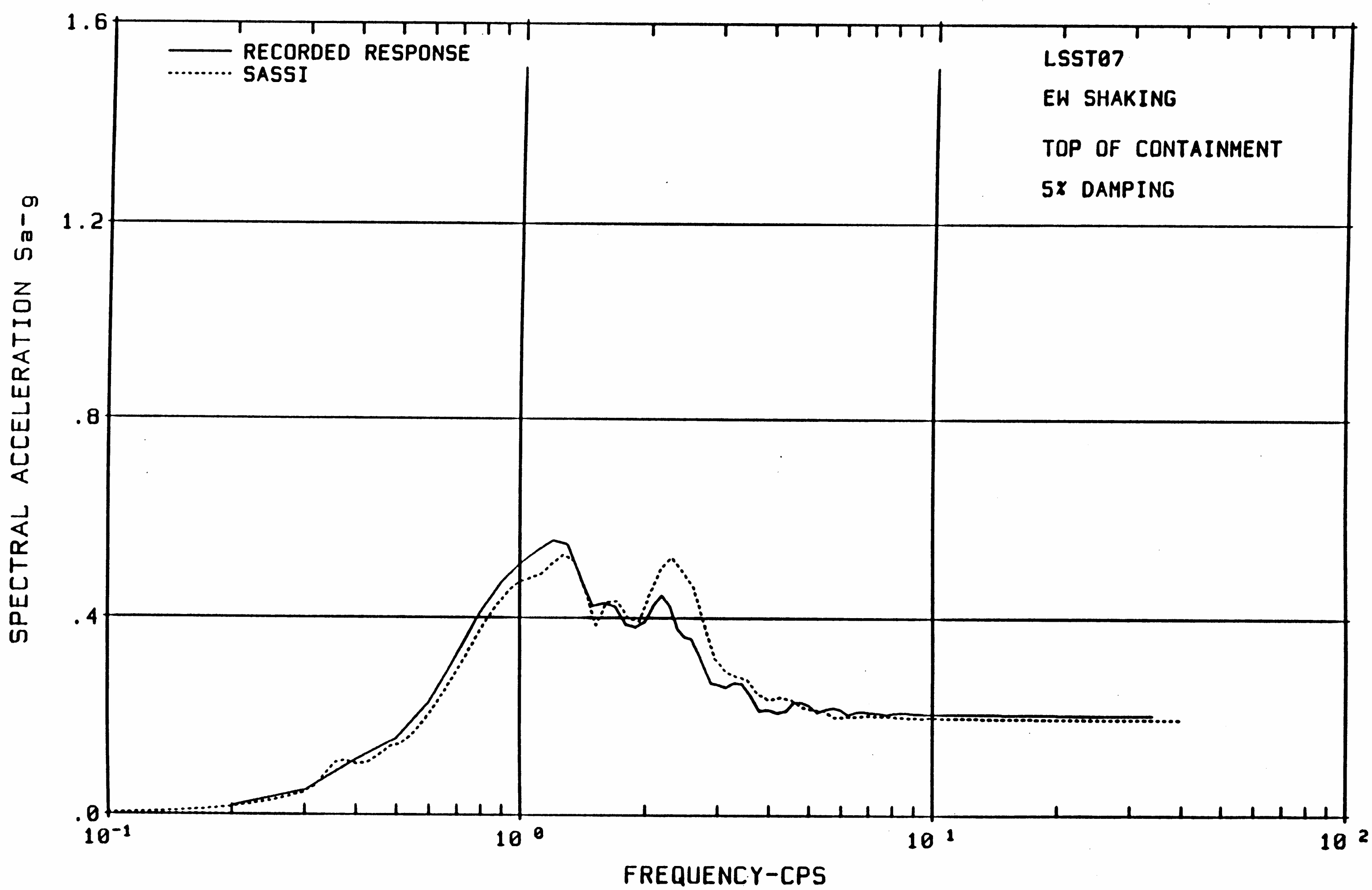
Locations of Accelerometers

Lotung ¼ Model



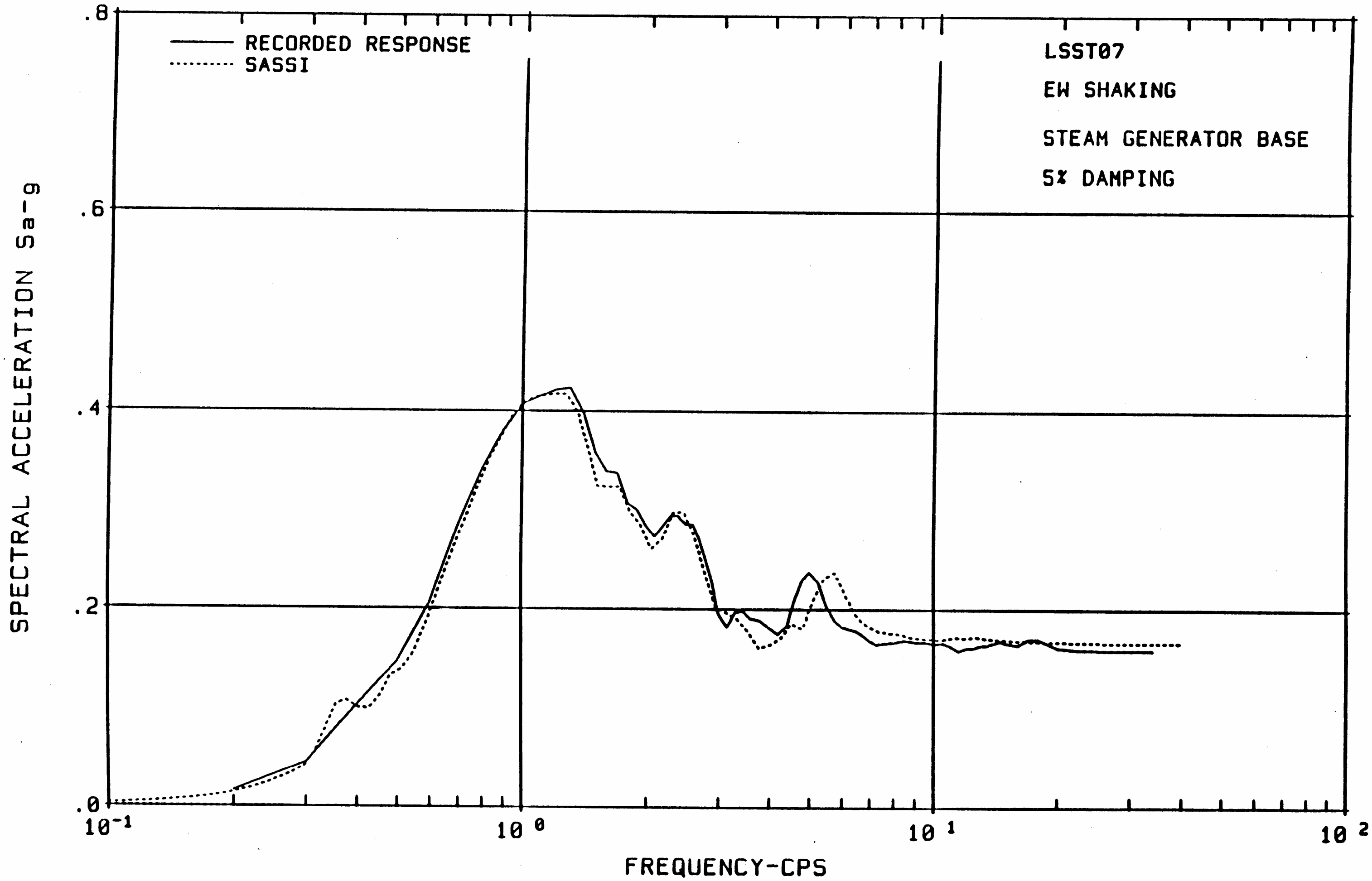
Comparison of Responses at the Top of the Basemat

Lotung ¼ Model



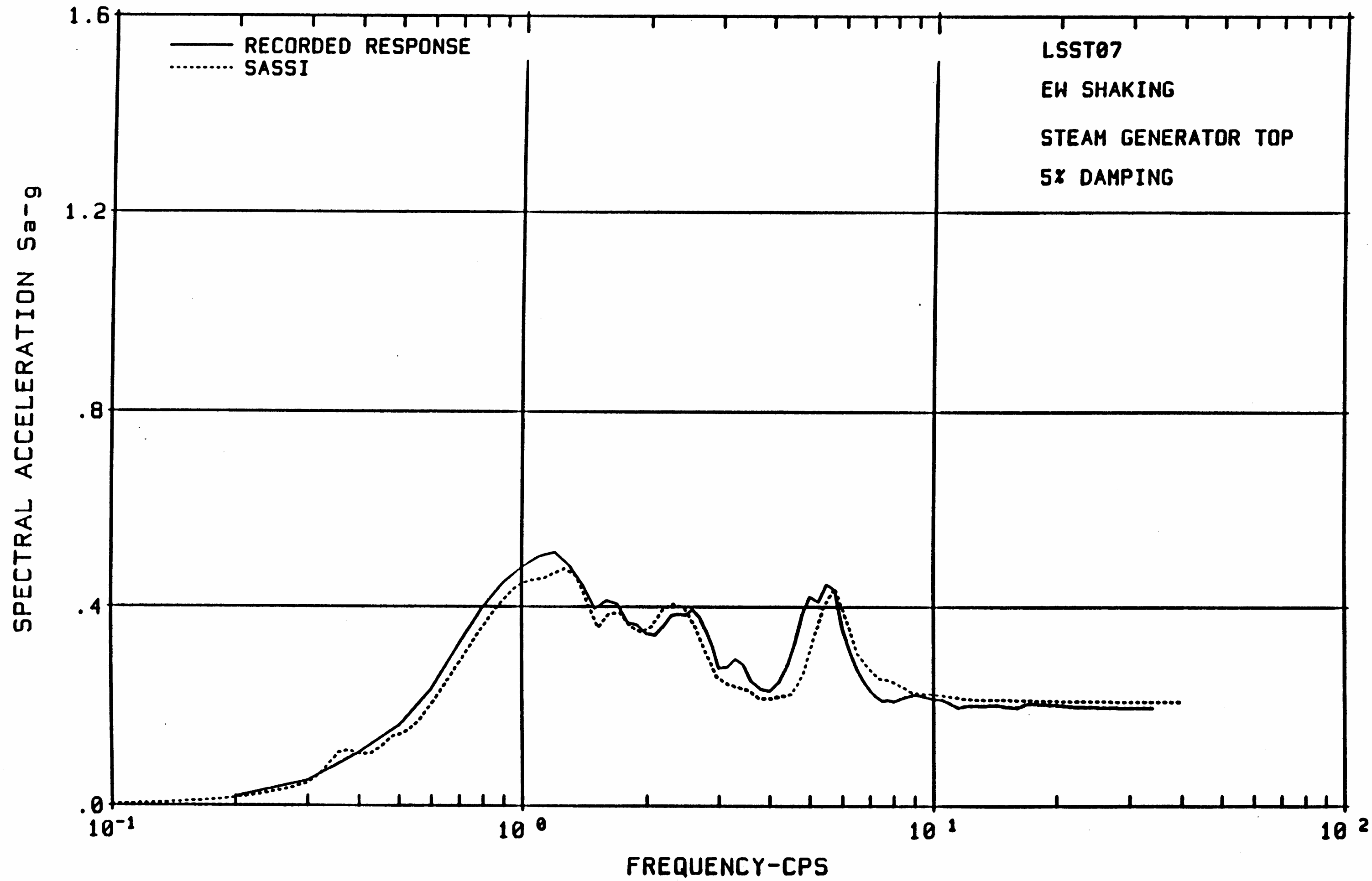
Comparison of the Responses at the Top of the Containment

Lotung ¼ Model



Comparison of the Responses at the Base of Steam Generator

Lotung ¼ Model



Comparison of the Responses at the Top of Steam Generator

Lotung ¼ Model

LOTUNG SSI EXPERIMENT....

- All four different methods of SSI analysis (soil -spring, FLUSH, CLASSI, SASSI) were used.
- In general all methods were found to be capable of predicting conservative results if the limitations in each method are properly recognized.
- The methods capable of rigorous analyses of scattering and impedance problems predicted more accurate responses as compared to the recorded motions.

GENERAL GUIDELINES FOR SSI ANALYSIS

Site Characterization

- Stratigraphy of supporting soil/rock medium under and around the structures and depth to base rock
- Soil/rock properties in particular shear wave velocity and its variation, depth to water table, density of the material
- Soil nonlinear properties

Ground Motion

- Location of the motion in the free-field (control point)
- Frequency characteristics of the motion
- Wave field

Foundation Model

- Effective embedment depth
- Three-dimensional effect
- Structure-to-structure interaction effects
- Seismic soil pressure on the embedded walls
- Flexibility of the foundation and basement

GENERAL GUIDELINES FOR SSI ANALYSIS........

SSI Model (Structure)

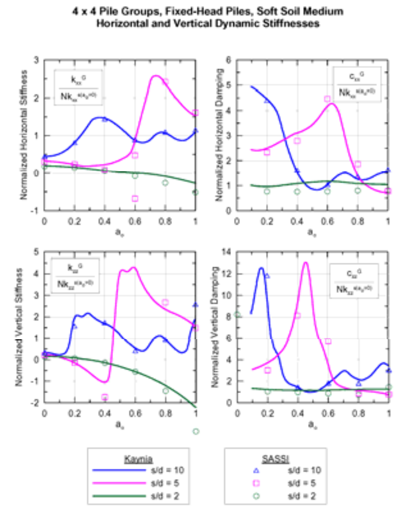
- Modal frequencies and modal mass distribution
- Torsional eccentricity
- Fixed base analysis is often useful

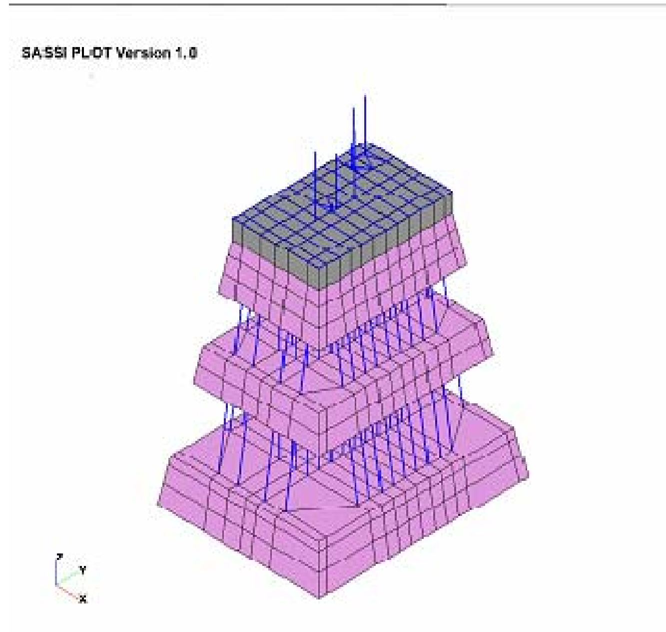
SASSI-Pile Foundation

Two methods implemented in SASI2000 for pile foundations:

✓One method computes the impedance function

✓The more complete method solves for the total SSI problem





SUMMARY GENERAL SSI EFFECTS ON THE SEISMIC RESPONSE OF STRUCTURES

- SSI responses represent a more realistic behavior of structures during seismic excitation.
- SSI effects generally provide beneficial effects. These effects reduce the seismic responses in terms of acceleration and seismic forces. However, some other responses such as displacement (hence the P -delta effects, structural ponding etc.) tend to increase.
- The beneficial effects of SSI increase as the embedment depth of the structure increases.

SUMMARY
GENERAL SSI EFFECTS....

- For partly embedded structures, maximum seismic shear and moment occur at about the ground surface elevation.
- Seismic soil pressure on the embedded walls of the structures are significantly affected by the SSI effects. The dynamic inertial SSI characteristics of the structure control the magnitude and the distribution of the soil pressure. Seismic soil pressure in between two adjacent structures may increase significantly due to through-soil structure-to-structure interaction effects.
- SSI effects increase the period of the structure and/or introduce a new period of vibration.

SUMMARY
GENERAL SSI EFFECTS...

- **Erroneous properties may result from characterizing dynamic properties of the structural systems from analytical models and vibration tests without due consideration to SSI effects.**
- **SSI alters the free-field motions, stresses and deformations in the soil mass. For this reason, SSI effects may become beneficial for soil sites prone to liquefaction (Seed et al., 1990)**
- **Large structures with significant SSI effects alter the motions of ground in their proximity. The response of nearby smaller structures can be influenced by the vibration of the large structure.**

SUMMARY
GENERAL SSI EFFECTS...

- The SSI methods currently available are capable of predicting SSI effects for practical engineering analysis and design. The challenge today is to reduce the complex SSI effects to simple and practical relationships for design application.

Session 7

SASSI Approach to Incoherency (SRSS)

NRC Seismic Seminar

Soil-Structure Interaction (SSI) Including Coherent and Incoherent Ground Motion

Farhang Ostadan

August 29, 2007

Rockville, Maryland

Contents

- Incoherency Models
- Implementation in SASSI
- Modal Truncation
- Verification
- General Guidelines

SASSI Incohrency Analysis (SRSS)

Abrahamson Model (Empirical)

$$\gamma_{pw}(f,\xi)=\left[1+\left(\frac{f\ \ Tanh(a_3\xi)}{a_1 f_c}\right)^{n1}\right]^{-1/2}\left[1+\left(\frac{f\ \ Tanh(a_3\xi)}{a_2 f_c}\right)^{n2}\right]^{-1/2}$$

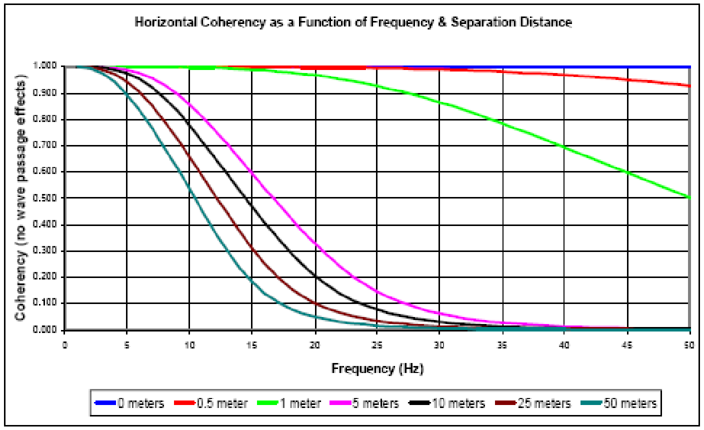
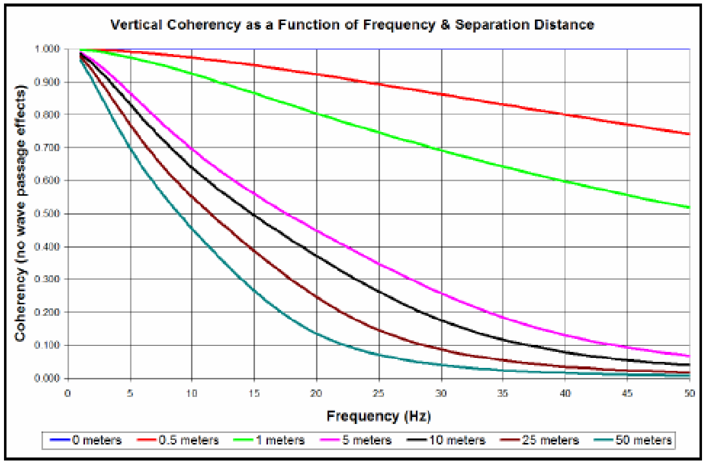


Figure 2-1
Coherency Function for Horizontal Ground Motion



SASSI Incohrency Analysis (SRSS)

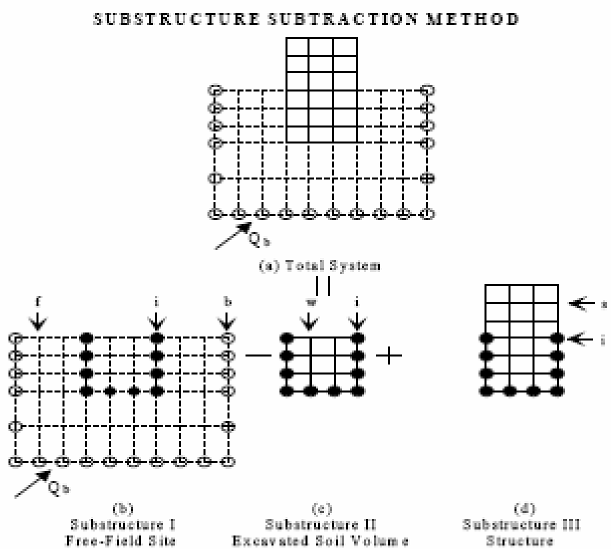
Mita and Luco (1986)

(theoretical model)

Used for few published SSI solution

$$\gamma_{ij}(r,\omega) = \exp\left\{-[\gamma\omega\,|\,\vec{r}_j - \vec{r}_i\,|\,/V_s]^2\right\}$$

SASSI-Subtraction Method



Subscript Nodes

b	the boundary of the total system
i	at the boundary between the soil and the structure
w	within the excavated soil volume
g	at the remaining part of the free-field site
s	at the remaining part of the structure
f	combination of i and w nodes

$$\begin{bmatrix} C_{ii}^{III} - C_{ii}^{II} + X_{ii} & -C_{iw}^{II} & C_{is}^{III} \\ -C_{wi}^{II} & -C_{ww}^{II} & 0 \\ C_{si}^{III} & 0 & C_{ss}^{III} \end{bmatrix} \begin{Bmatrix} U_i \\ U_w \\ U_s \end{Bmatrix} = \begin{Bmatrix} X_{ii} U_i' \\ 0 \\ 0 \end{Bmatrix}$$

$$[C_i^*] = [K_i^*] - \omega^2 [M_f]$$

SASSI Incohrency Analysis (SRSS)

$$[\Gamma(\omega)] = \begin{bmatrix} 1 & \gamma_{1,2} & \cdots & \gamma_{1,m} \\ \gamma_{2,1} & 1 & \cdots & \gamma_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{m,1} & \gamma_{m,2} & \cdots & 1 \end{bmatrix}$$

$$\gamma_{pw}(f,\xi) = \left[1 + \left(\frac{f \;\; Tanh(a_3 \xi)}{a_1 f_c}\right)^{n1}\right]^{-\frac{1}{2}} \left[1 + \left(\frac{f \;\; Tanh(a_3 \xi)}{a_2 f_c}\right)^{n2}\right]^{-\frac{1}{2}}$$

$$[S_g(\omega)] = \sum_{i=1}^{m} \lambda_i \{\phi\}_i \{\phi\}_i^*$$

$$[S_g(\omega)]\{\phi\}_i = \lambda_i \{\phi\}_i$$

$$\{\phi\}_i^* \cdot \{\phi\}_j = \delta_{i,j} = \begin{cases} 1, & i = j \\ 0 & i \neq j \end{cases}$$

SASSI Incohrency Analysis (SRSS)

➢Spatial modes, j = 1, m

$$\{u_g\}_j = \sqrt{\lambda_j}\{\phi\}_j$$

➢SSI Equation of Motion

$$\begin{bmatrix} C_{ii} + X_{ii} & C_{is} \\ C_{si} & C_{ss} \end{bmatrix} \begin{Bmatrix} u_i \\ u_s \end{Bmatrix}_j = \begin{Bmatrix} X_{ii} u_{g,j} \\ 0 \end{Bmatrix}$$

$$\{u\}_j = [H]\{u_g\}_j$$

➢PSD of Structural Response

$$[S_u(\omega)] = \sum_{j=1}^{m} \{u\}_j \{u\}_j^*$$

$$\sum_{j=1}^{m} \{u\}_j \{u\}_j^* = \sum_{j=1}^{m} [H]\{u_g\}_j \{u_g\}_j^* [H]^* = [H]\left(\sum_{j=1}^{m} \lambda_j \{\phi\}_j \{\phi\}_j^* \right)[H]^* = [H][S_g][H]^*$$

$$S_{u,kk} = \sum_{j=1}^{m} u_{k,j} \overline{u_{k,j}} = \sum_{j=1}^{m} |u_{k,j}|^2$$

$$|H(\omega)|_k = \sqrt{\sum_{j=1}^{m} |u_{j,k}|^2}$$

SASSI Incohrency Analysis (SRSS)

- Truncation Error

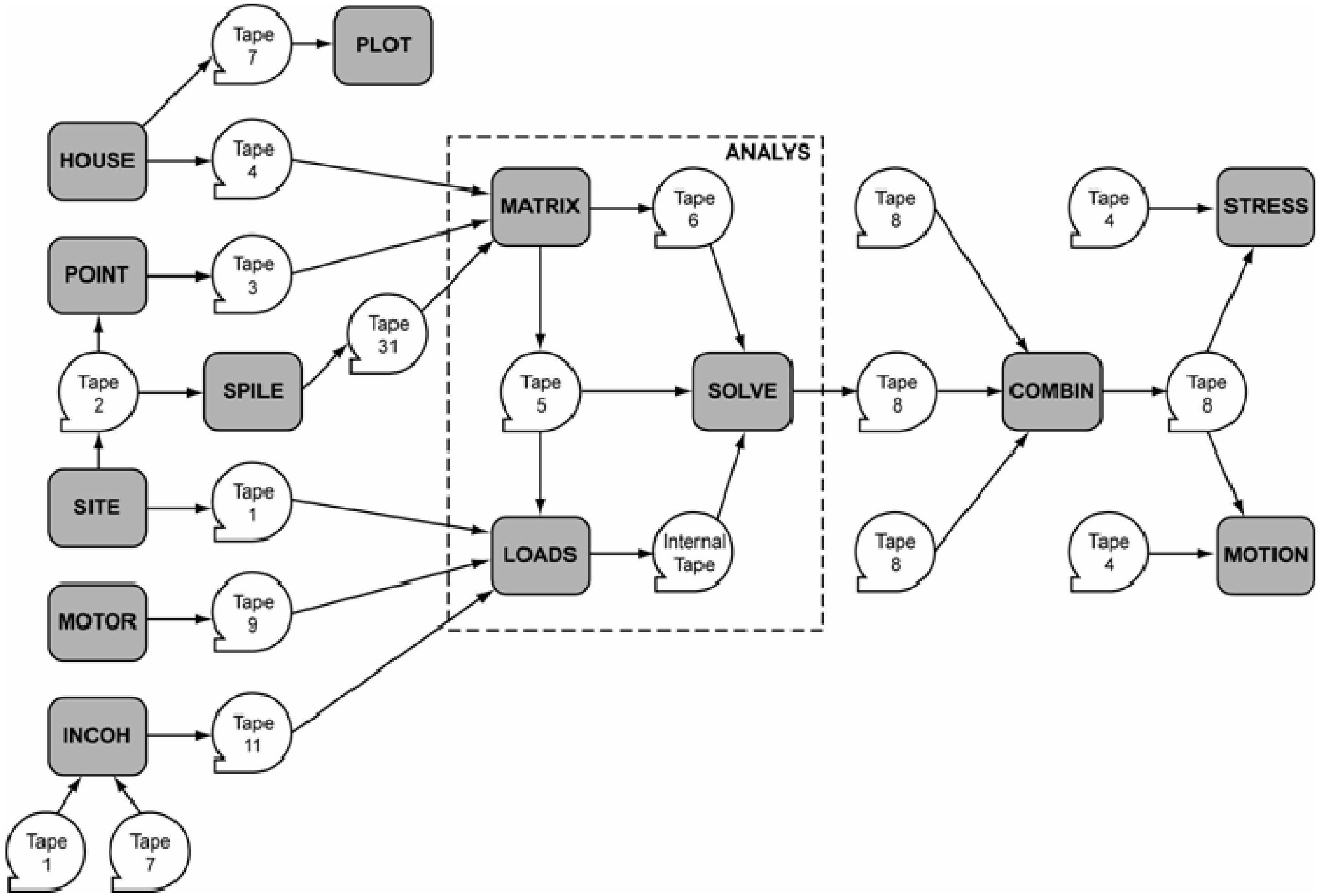
$$|\{u_j\}|^2 = \{u_j\}^*\{u_j\} = \sum_{k=1}^{n} \overline{u_{k,j}} \cdot u_{k,j} = |\lambda_j| \cdot \|\{\phi\}_j^*[H]^*[H]\{\phi\}_j\| = |\lambda_j| \cdot C_j$$

C_j is the determinant of the matrix $\|\{\phi\}_j^*[H]^*[H]\{\phi\}_j\|$

$$\sum_{j=1}^{m} |\{u_j\}|^2 = \left(\sum_{j=1}^{m} |\lambda_j|\right) . C$$

$$|\varepsilon|_s = \frac{1 - \sqrt{\sum_{j=1}^{s} |u_j|^2}}{\sqrt{\sum_{j=1}^{m} |u_j|^2}} = \frac{1 - \sqrt{\sum_{j=1}^{s} |\lambda_j|}}{\sqrt{\sum_{j=1}^{m} |\lambda_j|}}$$

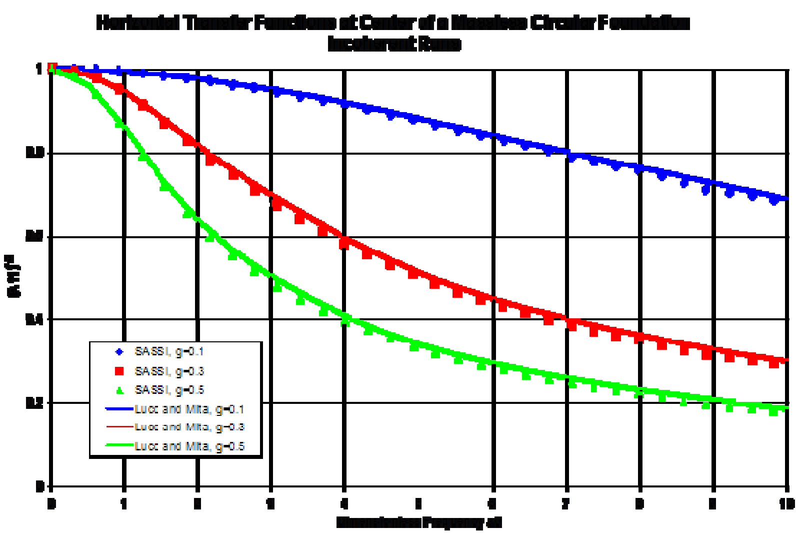
SASSI Incohrency Analysis (SRSS)-Program Layout

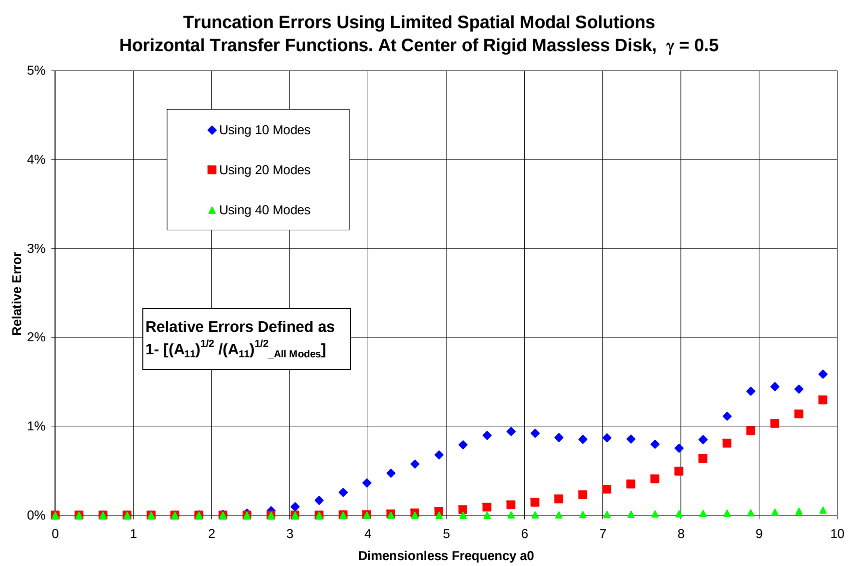


SASSI Incohrency Analysis (SRSS)-Verification

Luco, J. E., and Mita, A. (1987) "Response of Circular Foundation to Spatially Random Ground Motion," ASCE *Journal of Engineering Mechanics*, Vol. 113, No. 1, pp. 1-15, January.

Rigid massless circular foundation on uniform halfspace

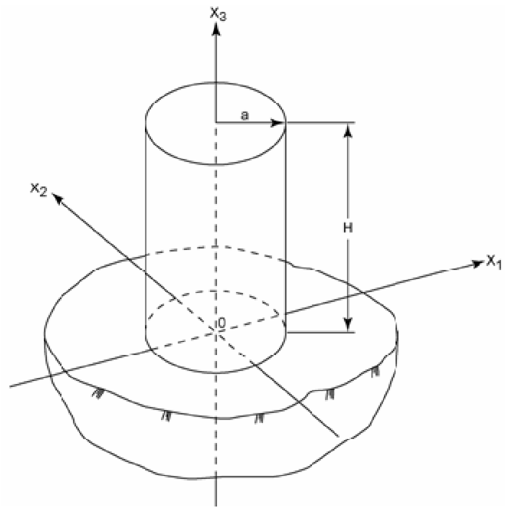


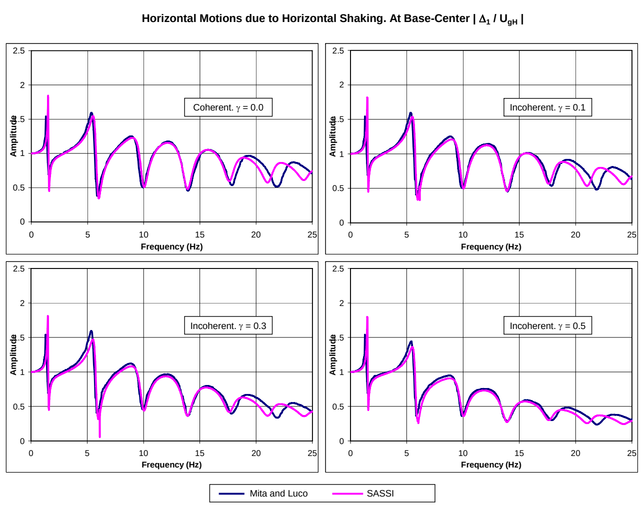


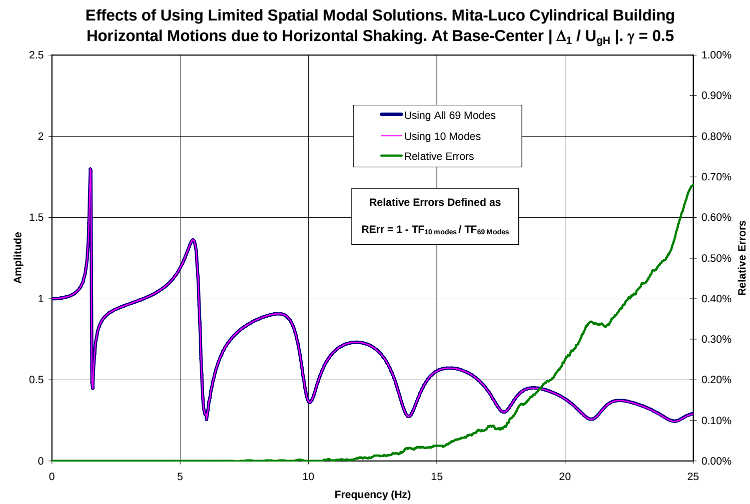
SASSI Incohrency Analysis (SRSS)-Verification

Mita, A. and Luco J.E. (1986): "Response of Structures to Spatially Random Ground Motion," Proceedings of the Third U.S. Conference on Earthquake Engineering, Charlston, South Carolina.

Cylindrical Building on Uniform Halfspace







SASSI Incohrency Analysis (SRSS)-Verification

Multi-Stick Model for a NPP

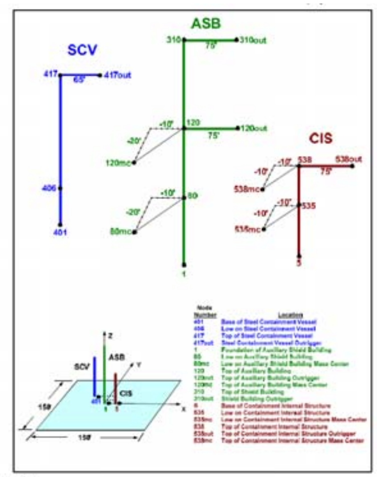
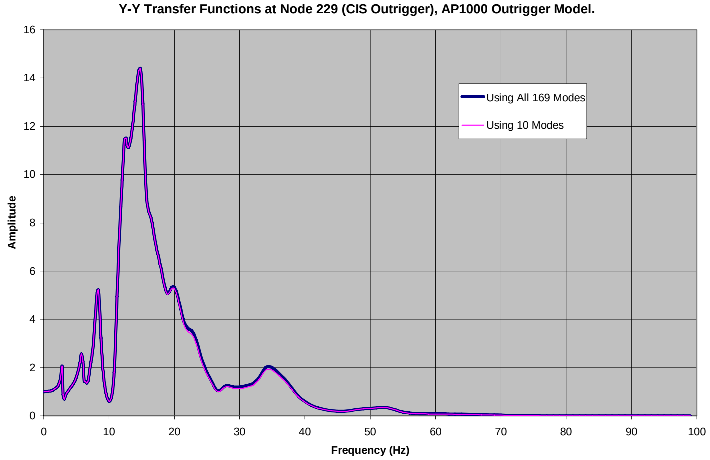


Figure 2-6
Advanced Reactor Structure Stick Model with Outriggers and Offset Mass Centers

Effects of Using Limited Spatial Modal Solutions for Incoherent Motion Analysis
Y-Y Transfer Functions at Node 229 (CIS Outrigger), AP1000 Outrigger Model.



Effects of Using Limited Spatial Modal Solutions for Incoherent Motion Analysis
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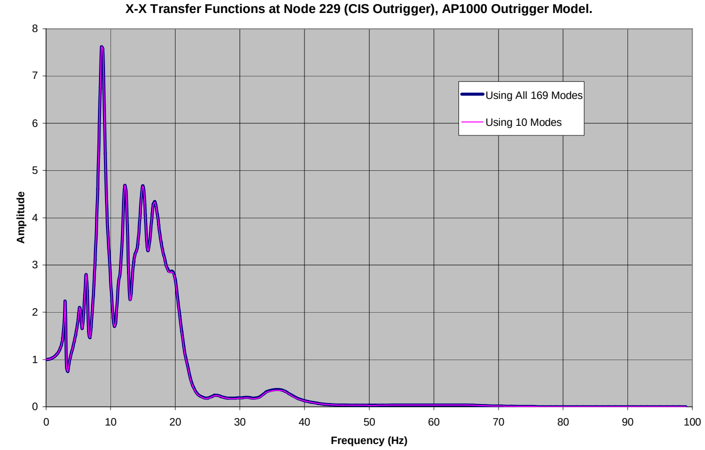

SASSI Incohrency Analysis (SRSS)-Documentation

- EPRI (2007), Final Report: “Validation of CLASSI and SASSI to Treat Seismic Wave Incoherence in SSI Analysis of Nuclear Power Plant Structures, August.
- Ostadan, F., Deng. N. (2007), SASSI-SRSS Approach for SSI Analysis with Incoherent Ground Motions, Bechtel National, SF, CA.

SASSI Incohrency Analysis (SRSS)-General Guidelines

- Additional rocking and torsional modes of vibrations
- Frequencies of analysis, 50-100
- User can decide on the number of spatial modes, 10 modes appear to be adequate, error can be estimated
- Incoherency is a 3D effect (no symmetry or 2D modeling)
- Effect of foundation flexibility for vertical analysis needs further evaluation