

## ESBWR IN-PROCESS STATUS FORM

<b>Document Title</b>	Validation Summary Report for SASSI 2010 and Appendix with Validation Problems for RAI 03.07.02-10 / RAI 03.07.02-26 Response
<b>Document Type</b>	Shimizu Engineering Report
<b>Revision ID (if applicable)</b>	SER-DMN-020, Rev.1 (in Shimizu's doc. number)
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<b>Date (Last Update/Revision)</b>	6/26/15
<b>Document/Work Status e.g. Pending, Active, On-hold, Complete-In Verification, Verified-Waiting eCM</b>	Issued for Use Verification has been performed. (ES1506-V13).
<b>Specific Cautions To Users e.g.</b> Enumerate/list specific incomplete content. Enumerate/list specific complete but unverified content. Enumerate/list key areas of technical uncertainty and parameters impacted.	
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# Shimizu Engineering Report

Project	GE-Hitachi Nuclear Energy Dominion NA 3 ESBWR Project	Shimizu Document No.	SER-DMN-020
Title	Validation Summary Report for SASSI 2010 and Appendix with Validation Problems for RAI 03.07.02-10 / RAI 03.07.02-26 Response	Rev.	1
		Issued Date	4/15/15
		Revised Date	6/26/15

**NOTE:**

This document provides Validation Summary Report for SASSI 2010. Appendix with three Validation Problems are also provided for RAI 03.07.02-10 / RAI 03.07.02-26 response. This document is provided in accordance with Reference 1.


GEH comments provided in References 2 and 3 are incorporated in this revision.

- References:
1. Purchase Order (437080093), Revision 28, dated June 8, 2015
  2. E-mail from Ms. Tanya Kirby titled "FW: Action items and notes from April 15 Dominion NRC meeting on July SCP deliverables" dated April 21, 2015
  3. E-mail from Mr. Taylor Blake titled "RE: SZGE-ESB-2015-0024 Validation Summary Report for SASSI2010 and Appendix with Validation Problems for RAI 03.07.02-10 / RAI 03.07.02-26 Response Rev. 0" dated June 24, 2015

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1	6/26/15	GEH comments in Appendix A are incorporated	Y.O.	Y.F.	R.I.
0	4/15/15	Initial Issue	Y.O.	S.O.	R.I.
Rev.	Date	Note	Approve	Review	Prepare
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## 1. PURPOSE

This report documents the validation and verification (V&V) of the computer program “SASSI 2010” that is used for the seismic response analysis of structures considering soil structure interaction (SSI) effects.

## 2. DESCRIPTION

SASSI 2010 is a computer program for seismic response analyses of systems with ability to consider the effects of the interaction of the structure with the surrounding soil/rock that is modeled as a horizontally layered media. The program employs the complex response method, the finite element method and substructuring technique to provide solutions for the seismic response of SSI models in frequency domain.

The SASSI 2010 seismic response analyses provide the following numerical results that serve for developing the basis for seismic design of systems and subsystems:

1. Maximum accelerations and acceleration time histories of the seismic response of the system at different nodal locations
2. Acceleration Response Spectra (ARS) for different damping values at different nodal locations
3. Displacement of the system at different nodal locations relative to the selected reference location or the free field motion
4. Structural member force and stresses

### 2.1 Computational Modules

The following modules of SASSI 2010 are used to perform the core numerical calculations of the seismic response analysis:

1. SITE that forms and solves transmitting boundary eigenvalue and the site response problem for each specified frequency of analyses (the program models the site as horizontally infinite elastic layers).
2. POINT that provides solutions for the site impedance for each frequency of analysis by applying at surface of the site layers point harmonic loads with frequency equal to the frequency of analysis
3. HOUSE that computes the frequency independent global mass and stiffness matrices for the structure and excavated soil. These global matrices are computed by using different types of finite elements



4. INCOH that computes the incoherency characteristics of the input free-field ground motion with respect to the foundation size and the frequency range of analysis. The SRSS method is used to formulate of influence factors for the modal vectors used in the ground motion input
5. ANALYS that performs the core computations that provide the response of the SSI system under specified input ground motion at each selected frequency of analysis in terms of complex acceleration transfer functions.
6. MOTION that interpolates the acceleration transfer function results from the ANALYS solutions for the selected set of frequencies. It provides the following results for the seismic response at specified nodal locations:
  - a. Interpolated acceleration transfer functions
  - b. Acceleration time histories
  - c. Relative displacement time histories
  - d. Acceleration response spectra, and
  - e. Maximum accelerations and relative displacements
7. STRESS that provides time histories and maximum values for the finite element results for stresses, forces and moments
8. COMBIN that combines the results of two or more different runs of ANALYS module for two or more sets of frequencies of analyses. This module enables multiple computers to be used independently for the analyses of large problems.

## 2.2 Program Limitations

- Number of Fourier transform; 65,536 (Restricted by input column)
- Number of calculating frequencies : 100
- Number of Layers; 100 for layered medium and 20 for simulated halfspace
- Number of Nodes; 99,999
- Number of Interaction nodes; 20,000

## 3. SOFTWARE AND HARDWARE SPECIFICATIONS

### 3.1 Hardware Specifications

- Hardware used for the SASSI 2010 analysis are commercially available computers installed Microsoft Windows OS.



- Operations of data input or execution of the program, etc. should be performed by project members with their client computers through the network system of Shimizu Corporation.
- The calculated result files output on computers can be transferred to project member's client computers through the network, and printed out to the printer set up in Nuclear Project Division.

## 3.2 Software Specifications

### 3.2.1 *Software module*

The software is provided by the form of executable modules in Windows operating system.

### 3.2.2 *Input*

- Soil Model; Number of layers, thickness of each layer and dynamic properties (unit weight, damping, shear and compression wave velocity) of each layer. Condition at the bottom boundary of the site model; fixed or halfspace modeled by additional layers and viscous dampers to account for geometric damping.
- Configuration and properties of finite element structural (HOUSE) model such as node numbering, coordinates and lumped mass inertia properties, interaction nodes, material properties of beam, shell, spring and solid elements that compose the structure model
- Parameters defining the frequency domain analysis; Fourier transformation number, time step, analysis frequencies etc.
- Control motion input data; input acceleration time histories, wave characteristics, control point location.

### 3.2.3 *Process*

- Complex transfer functions of nodal responses and element stresses are calculated in frequency domain for selected number of frequencies of analysis.
- Transfer functions are interpolated for the range of frequencies of interest



- Time histories for response in terms of nodal accelerations and finite element stresses are calculated using Fast Fourier Transform and Inverse Fast Fourier Transform.

### **3.2.4 Output**

- The echo list of input data
- Transfer functions of nodal acceleration responses
- Acceleration time histories of response at specified nodal locations
- Time histories for stresses at specified elements

## **4. VALIDATION AND VERIFICATION (V&V)**

This chapter describes the test report for validation and verification of SASSI 2010 solutions of seismic response of SSI systems for frequencies up to 70 Hz.

### **4.1 Methodology**

The following methods are used to validate and verify the specified capabilities and limitations of SASSI 2010 program.

- i. Comparisons with classical solutions, analytical results or experimental test data published in technical literature,
- ii. Comparisons with results obtained from other software
- iii. Comparisons of the results from the analyses of various problems and model sizes to validate the program and modeling limitations such as maximum number of soil layers, maximum value of Poisson ratio, maximum element aspect ratio.

### **4.2 Acceptance Criteria**

The acceptance criteria used for the validation and verification are as follows:

- NUMERICAL ACCURACY criterion based on requirement that the difference in computed values be less than 1%
- GOOD AGREEMENT criterion based on numerical matching against benchmark from classical solutions, analytical results or experimental test data
- EXPECTED BEHAVIOR criterion based on basic knowledge and sound engineering judgment



## 4.3 Tested Application Range

The following capabilities, options and limitations of SASSI 2010 are validated and verified.

1. Calculation of frequency dependent translation and rocking impedance functions
2. Kinematic (wave scattering) SSI solution
3. Ability of the following finite elements to model dynamic properties of structural members and excavated soil:
  - a. 3-D eight-node solid element
  - b. 3-D beam element
  - c. Three to four-node quadrilateral thin shell element
  - d. 3-D spring element
4. Solution for seismic response of embedded foundations using flexible volume(direct) method
5. Use of symmetric and anti-symmetric boundary conditions to model and analyze a half model of a structure with symmetry about the two horizontal axes
6. Calculation of response due to incoherent input seismic motion
7. Accuracy of the program post-processing for generation of
  - a. interpolated transfer functions,
  - b. maximum accelerations,
  - c. acceleration response spectra
  - d. relative displacement time histories
8. Accuracy of calculation of relative displacements from spring element force results.
9. Ability of the following finite elements to accurately calculate stresses, internal forces and moments
  - a. 3-D beam element,
10. Accuracy of the program different restart options
11. Evaluation of maximum aspect ratio for 3-D solid brick elements and 3-D thin shell elements
12. Evaluation of program ability to model sites using up to 100 horizontally infinite soil layers
13. Evaluation of computed solutions for values of the soil Poisson's ratio up to 0.48.
14. Evaluation of program ability for analysis of model with a large number of interaction nodes (up to about 20,000 interaction nodes)





15. Accuracy of the program results obtained by combining results from different computer runs

Not all capabilities, features and options of the SASSI 2010 program described in the User's manual are covered by this validation report. The following are some of the features that are not included in the range of this V&V application:

- The program is validated and verified only for seismic analyses of 3-D models. The capability of the program for 2-D analysis is not validated.
- No validation and verification is performed of the following types of finite elements:
  - a. 2-D four-node plane strain element
  - b. 3-D inter-pile element
  - c. Three to four-node quadrilateral thick shell element

## 5. CONCLUSIONS

The results of the validation tests meet the corresponding acceptance criteria in Section 4.2. This confirms that the SASSI 2010 computer program is adequate for 3-D seismic response analyses of SSI systems for frequencies up to 70 Hz.

**APPENDIX A SASSI 2010 VALIDATION PROBLEMS FOR RAI 03.07.02-10 / RAI 03.07.02-26 RESPONSE**

This appendix presents SASSI 2010 Validation Problems. The relationship between the No.s of validation problem and the No.s of application range are shown in Table below. For the validation problems performed using multiple computers, multiple sets of results are presented.

Validation Problem No.	Tested Application Range																				Page
	1	2	3a	3b	3c	3d	4	5	6	7a	7b	7c	7d	8	9a	10	11	12	13	14	15
3		●						●		●											A.3-1
9		●																			A.9-1
10																	●				A.10-1

## **Validation Problem NO.3**

### **A.3.1 Tested Program Applications**

- 2: Kinematic SSI solution
- 5: Use of symmetric and anti-symmetric boundary conditions to analyze a structure with symmetry about the two horizontal axes
- 7a: Accuracy of calculated interpolated transfer functions

### **A.3.2 Tested Program Modules**

- SITE
- POINT3
- HOUSE
- ANALYS
- MOTION

### **A.3.3 Problem Description**

Transfer function results for the scattering responses of embedded rigid massless cylinders subjected to vertically propagating SV-wave are computed to validate: (1) the use of symmetric and anti-symmetric boundary conditions for analyses of structures with symmetry about the two horizontal axes and (2) the accuracy of transfer function calculations.

Half models of rigid massless cylinder with symmetric and anti-symmetric boundary conditions are used for the analysis that have the same geometry as the ones used in Example Problem 2, of SASSI 2010 User's Manual (Ref.1) and a refined finite element mesh that allows these analyses to be performed for frequencies up to 70 Hz. Figure A.3-1 and A.3-2 shows the outline of the model. The transfer function results obtained from the analyses of these half-cylinder models are compared to the transfer function results obtained from full models to validate the use of symmetric and anti-symmetric boundary conditions. To validate the kinematic (wave scattering) solution and accuracy of interpolated transfer function calculations, the calculated responses are also compared to the theoretical solution provided in Day S.M. Ph.D. Dissertation, "Finite Element Analysis of Seismic Scattering Problem", University of California San Diego, 1977 (Ref. 2).

### **A.3.4 Acceptance Criteria**

The GOOD AGREEMENT acceptance criterion is used for validation of the use of symmetric and anti-symmetric boundary conditions based on comparisons of transfer function results obtained from the half and full cylinder models.

The GOOD AGREEMENT acceptance criterion is used for validation of the kinematic (wave scattering) solution and accuracy of interpolated transfer function calculations based on comparisons of calculated responses with theoretical solution.

### **A.3.5 Modeling**

The SASSI soil layer models consist of top layers resting on the surface of a halfspace. The halfspace is modeled by 40 uniform layers with thickness of 8.125 ft and additional 10 layers with varying thickness as a function of frequency and a viscous boundary at the base. The site model is shown in Fig. A.3-1. The input soil properties are summarized in Table A.3-1.

The foundations are rigid massless cylinders with a radius (R) of 65 ft and are fully embedded to a depth of 32.5 ft. The geometry of the foundation cross-sections are shown in Fig. A.3-2. Stiff material properties are assigned to the cylinder model to ensure the rigidity of the foundation.

#### **A.3.5.1 Excavated Soil Models**

The nodes and the elements of the excavated soil half model at elevations -32.5, -24.375, -16.25, -8.125 and 0. ft, are shown in Figs. A.3-3, A.3-4, A.3-5, A.3-6, and A.3-7, respectively. The maximum size of the finite elements is 10.364 ft which is less than 20% of the wavelength of seismic waves with frequency of 70 Hz.

#### **A.3.5.2 Structural Models**

The cylinder foundations are discretized using brick elements. The nodes and elements of the foundation model are shown in Figs. A.3-8 through A.3-12.

#### **A.3.5.3 SSI Frequencies and Wave Fields**

The SASSI analysis for this problem is performed for frequencies up to 70 Hz as shown in Table A.3-2. These frequencies of analysis are determined from the product of frequency step (DF) and the frequency numbers (NF):

$$F = DF * NF$$

DF is set to 0.02 Hz. The control motion is specified to be vertically propagating SV-wave with a control point defined at the ground surface.

#### **A.3.5.4 Analysis Cases**

The SASSI runs for this validation test problem consists of 3 of seismic analysis cases. The analysis models for the considered 3 cases are summarized in Table A.3-3.

The SASSI analyses have been performed using seismic excitation in the form of vertically propagating SV-waves. The SASSI sequence of runs and input/output files for this problem are shown in Table A.3-4.

#### **A.3.6 Analysis Results**

The SASSI results for the responses of foundation central node from the analyses of the three models are shown in Figs. A.3-13 and A.3-14. The comparison of these results shows that the good agreement acceptance criteria is met over the frequency range of analysis.

#### **A.3.7 Conclusion**

The good agreement of the responses obtained from the analyses of the full model and the half models with symmetric and anti-symmetric boundary conditions validates the accuracy of the results obtained from the SASSI2010 analyses of half models with symmetric and anti-symmetric boundary conditions. This validated the SASSI2010 ability for analysis of half models of structures with symmetry about the two horizontal axes.

#### **A.3.8 References**

1. Computer Program SASSI2010 – User's Manual, May 2012.
2. Day, S. M., "Finite Element Analysis of Seismic Scattering Problem," Ph.D. Dissertation, University of California, San Diego, 1977.

Table A.3-1 Soil Properties

Layer No.	Top EL [ft]	Layer thickness [ft]	Unit weight [pcf]	Vs [ft/sec]	Vp [ft/sec]	Damping [%]	Remark
1	0.0	8.125	126.68	3700.0	6409.0	1.0	
2	-8.125	8.125	126.68	3700.0	6409.0	1.0	
3	-16.25	8.125	126.68	3700.0	6409.0	1.0	
4-39	-24.375	8.125	126.68	3700.0	6409.0	1.0	
40	-316.875	8.125	126.68	3700.0	6409.0	1.0	
	-325.00	-	126.68	3700.0	6409.0	1.0	Halfspace

Table A.3-2 Frequencies of Analysis

NF	f (Hz)	a0	NF	f (Hz)	a0
1	0.02	0.002	1800	36.00	3.974
50	1.00	0.110	1850	37.00	4.084
100	2.00	0.221	1900	38.00	4.194
150	3.00	0.331	1950	39.00	4.305
200	4.00	0.442	2000	40.00	4.415
250	5.00	0.552	2050	41.00	4.526
300	6.00	0.662	2100	42.00	4.636
350	7.00	0.773	2150	43.00	4.746
400	8.00	0.883	2200	44.00	4.857
450	9.00	0.993	2250	45.00	4.967
500	10.00	1.104	2300	46.00	5.077
550	11.00	1.214	2350	47.00	5.188
600	12.00	1.325	2400	48.00	5.298
650	13.00	1.435	2450	49.00	5.409
700	14.00	1.545	2500	50.00	5.519
750	15.00	1.656	2550	51.00	5.629
800	16.00	1.766	2600	52.00	5.740
850	17.00	1.876	2650	53.00	5.850
900	18.00	1.987	2700	54.00	5.961
950	19.00	2.097	2750	55.00	6.071
1000	20.00	2.208	2800	56.00	6.181
1050	21.00	2.318	2850	57.00	6.292
1100	22.00	2.428	2900	58.00	6.402
1150	23.00	2.539	2950	59.00	6.512
1200	24.00	2.649	3000	60.00	6.623
1250	25.00	2.760	3050	61.00	6.733
1300	26.00	2.870	3100	62.00	6.844
1350	27.00	2.980	3150	63.00	6.954
1400	28.00	3.091	3200	64.00	7.064
1450	29.00	3.201	3250	65.00	7.175
1500	30.00	3.311	3300	66.00	7.285
1550	31.00	3.422	3350	67.00	7.395
1600	32.00	3.532	3400	68.00	7.506
1650	33.00	3.643	3450	69.00	7.616
1700	34.00	3.753	3500	70.00	7.727
1750	35.00	3.863			

Table A.3-3 Cases of Validation Problem No.3

Case No	Model	Remark
1	XZ-Symmetry	Half Model
2	Y-Anti-Symmetry	Half Model
3	Full Model	Full Mode

Table A.3-4 Input/Output Files of Validation Problem No.3

	SASSI SEQUENCE OF RUNS			
SASSI MODULE	INPUT	OUTPUT	TAPEIN	TAPEOUT
SITE	vv08cN*ex2_site.dat	vv08cN*ex2_site.txt		SASSI.T1 SASSI.T2
POINT	vv08cN*ex2_point.dat	vv08cN*ex2_point.txt	SASSI.T2	SASSI.T3
HOUSE	Cylinder_Full.hou Cylinder_Half-sym-xz.hou Cylinder_Half-anti-y.hou	vv08cN*ex2_house.txt		SASSI.T4
ANALYS	vv08cN*ex2_analys.dat	vv08cN*ex2_analys.txt	SASSI.T1 SASSI.T3 SASSI.T4	SASSI.T8
MOTION	vv08cN*ex2_motion.dat	vv08cN*ex2_motion.txt	SASSI.T8	SASSI.T13

N\*: Case number 1,2,3



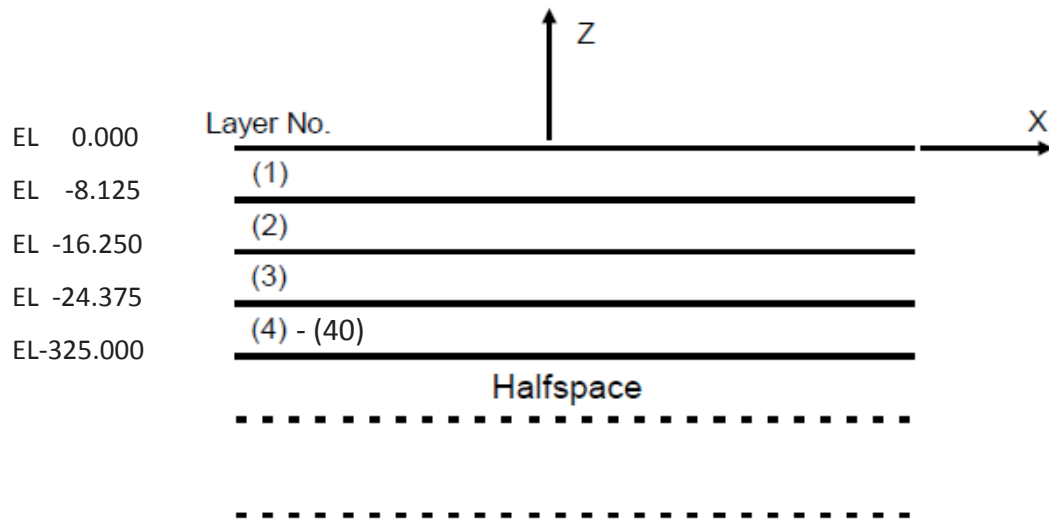


Figure A.3–1. SASSI Soil Layer Model

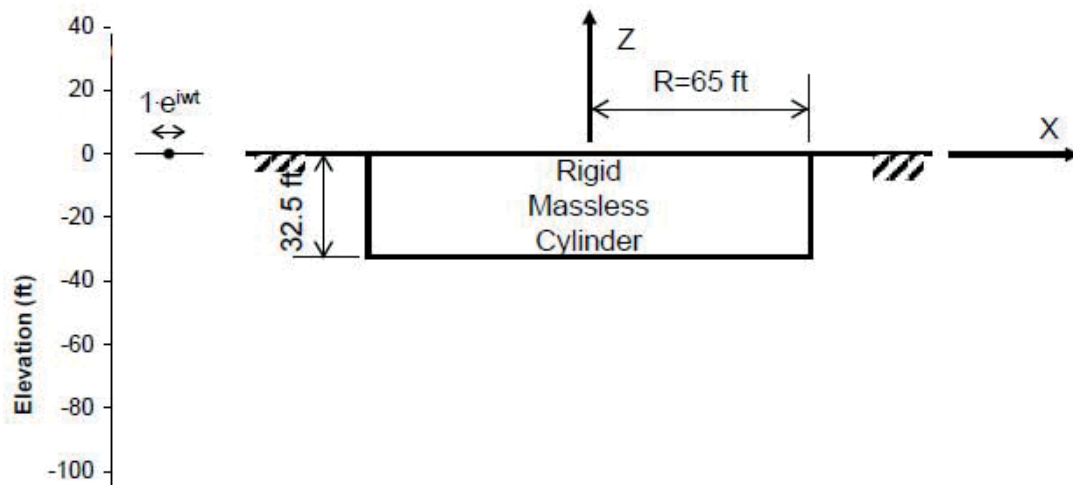


Figure A.3–2. Geometry of Cylinder Foundation Cross Section

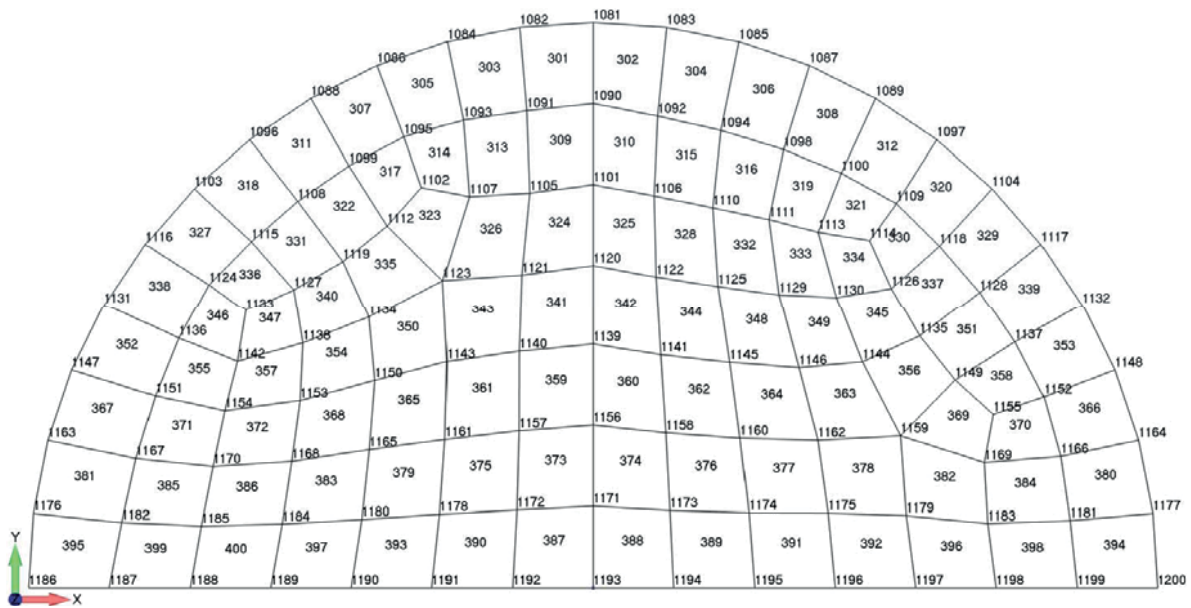


Figure A.3-3. Excavated Soil Model at Elevation -32.5 ft

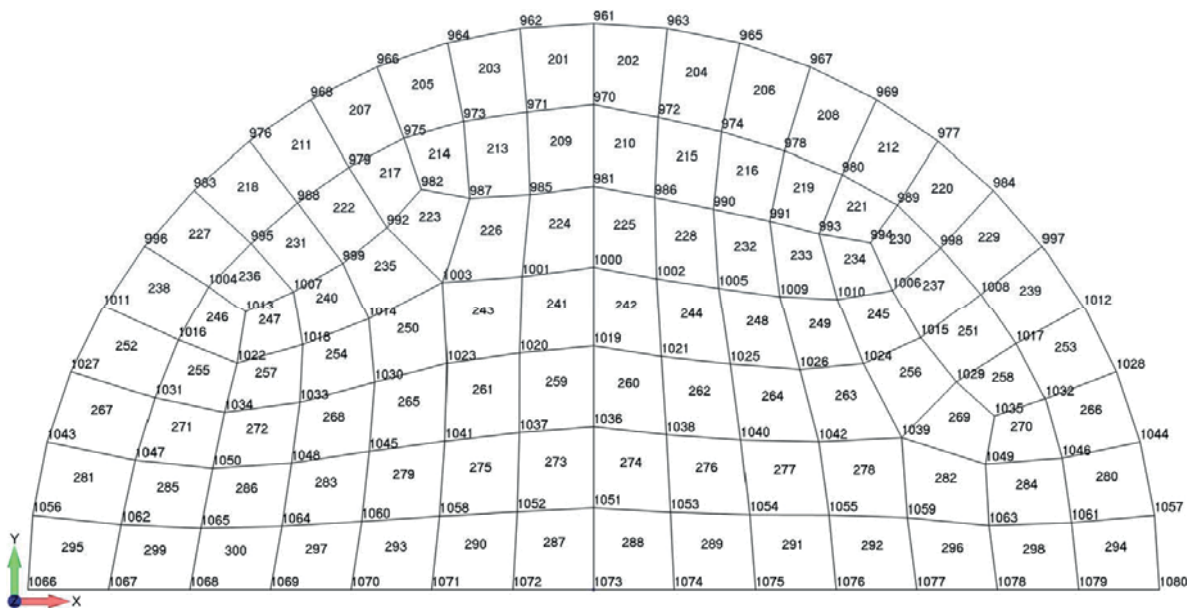


Figure A.3-4. Excavated Soil Model at Elevation -24.375 ft

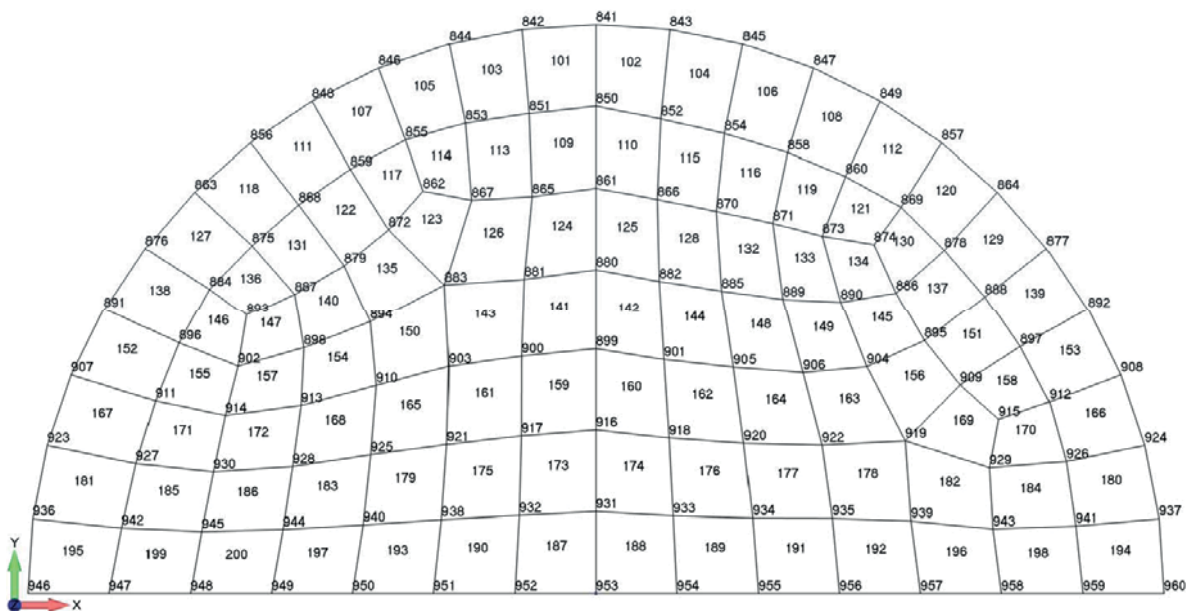


Figure A.3-5. Excavated Soil Model at Elevation -16.25 ft

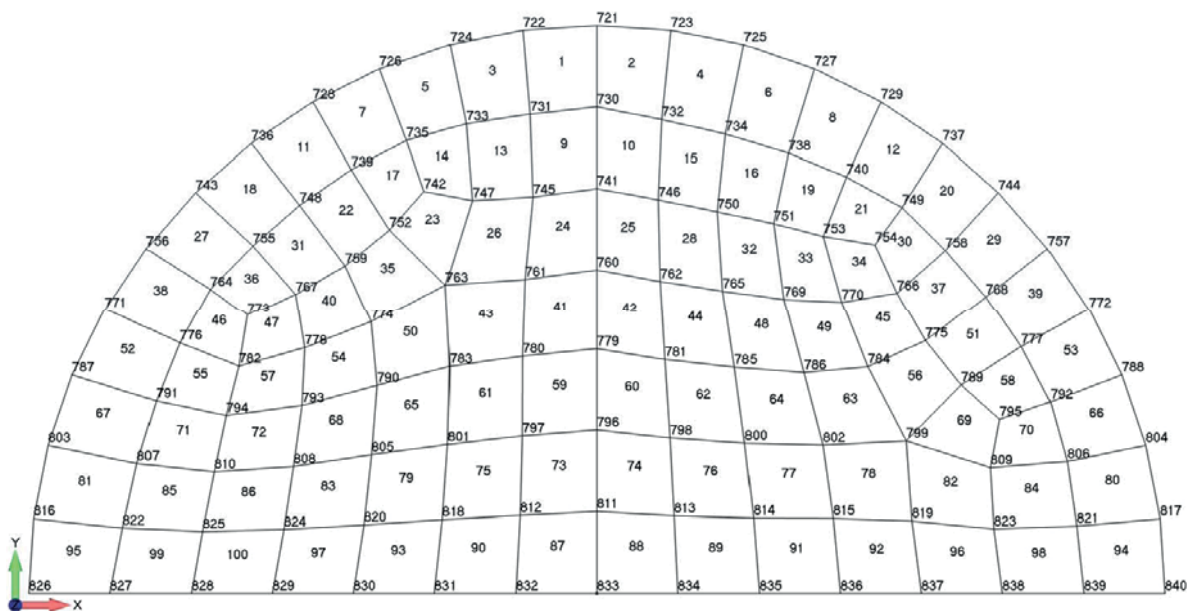


Figure A.3-6. Excavated Soil Model at Elevation -8.125 ft

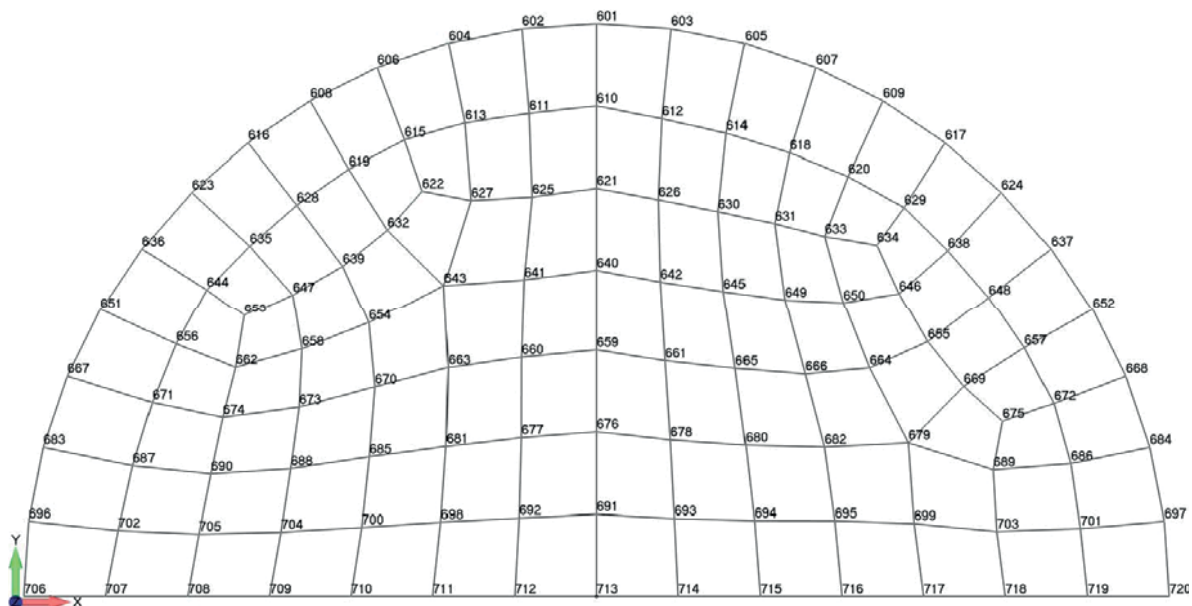


Figure A.3-7. Excavated Soil Model at Elevation 0 ft

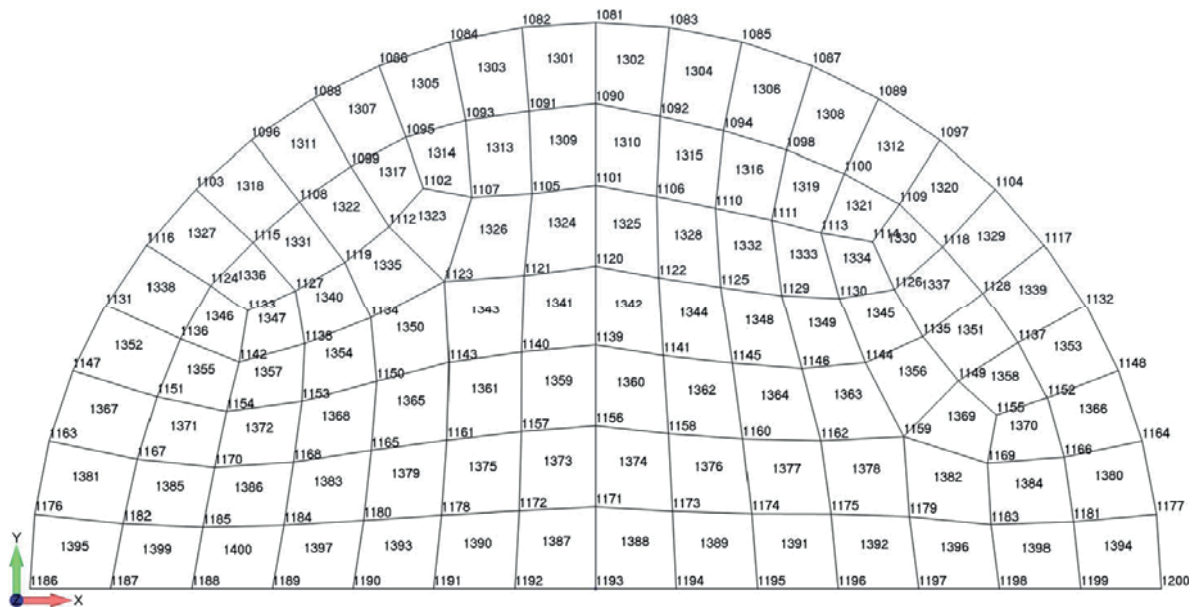


Figure A.3-8. Cylinder Foundation Model at Elevation -32.5 ft

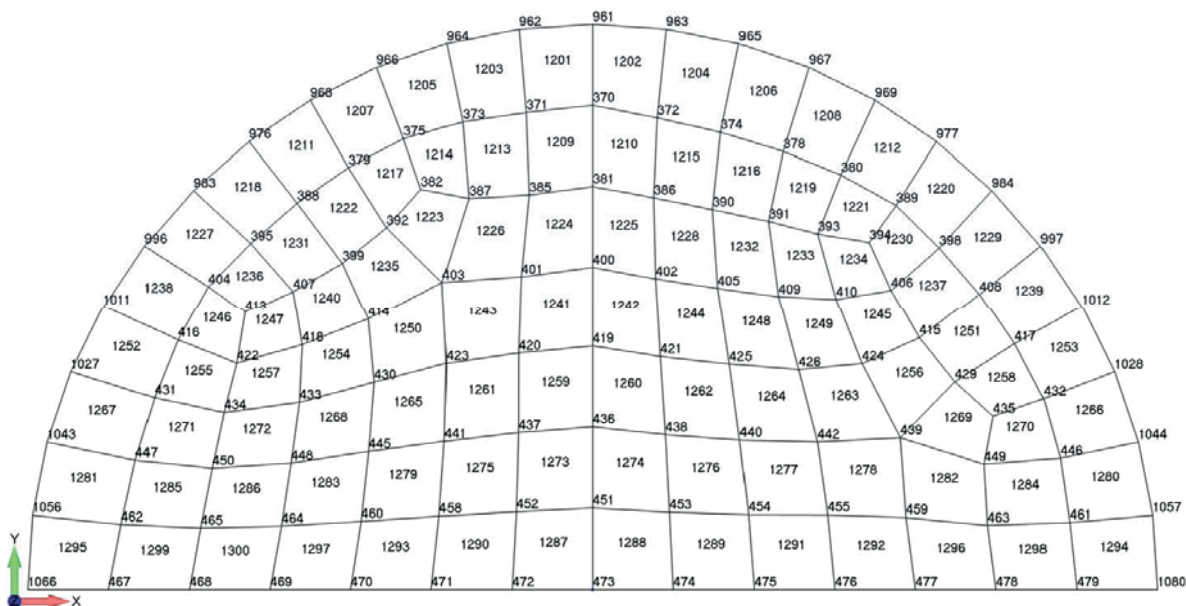


Figure A.3-9. Cylinder Foundation Model at Elevation -24.375 ft

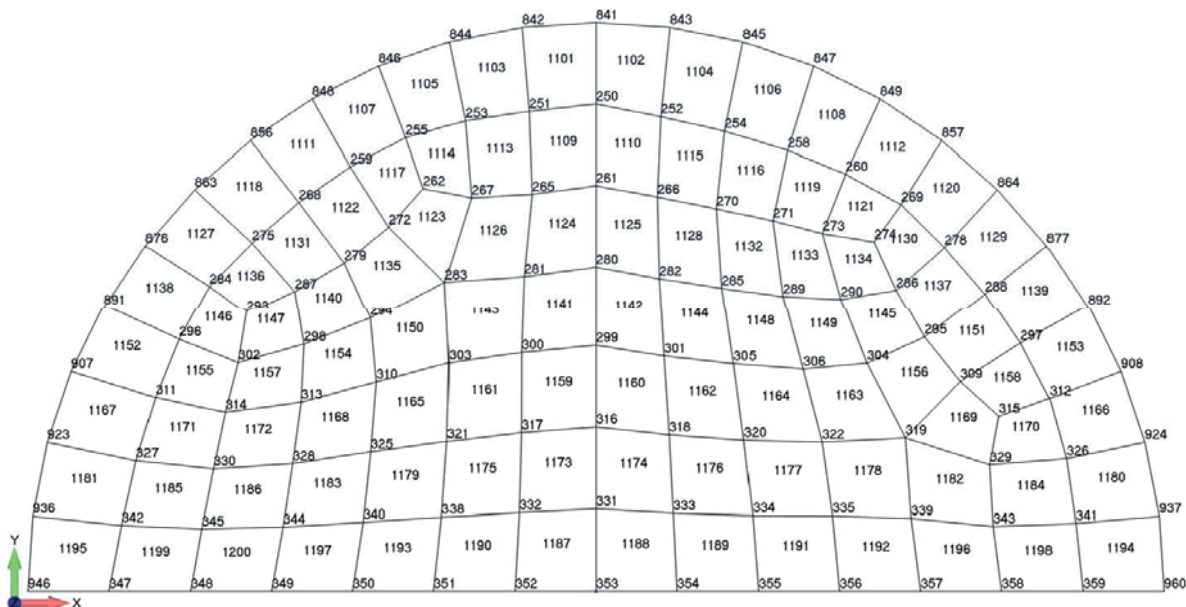


Figure A.3-10. Cylinder Foundation Model at Elevation -16.25 ft



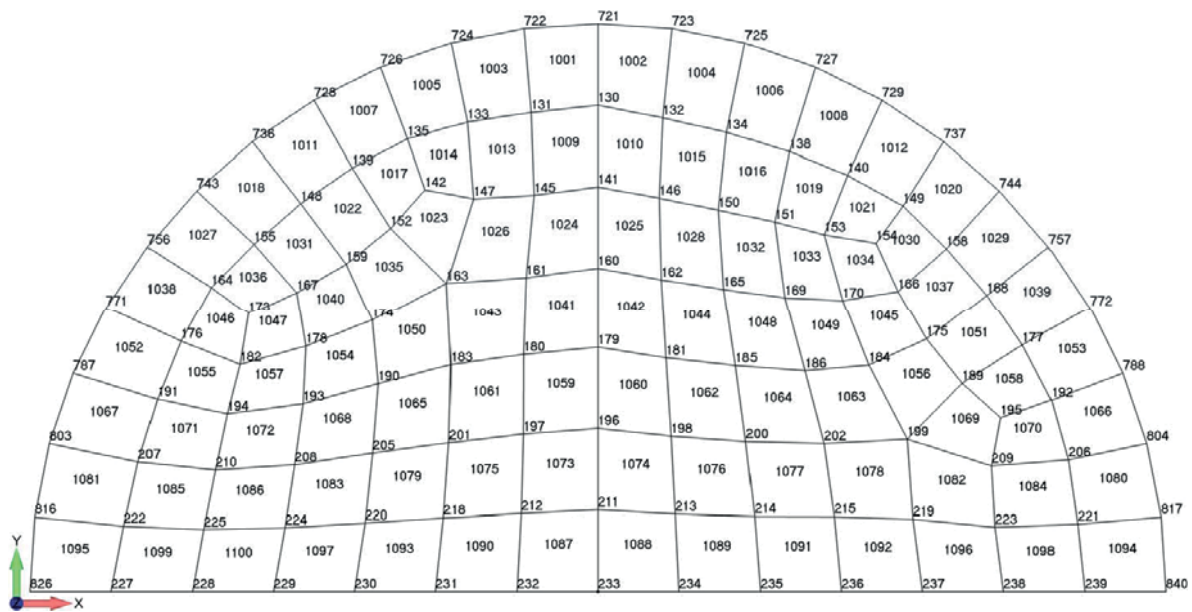


Figure A.3-11. Cylinder Foundation Model at Elevation -8.125 ft

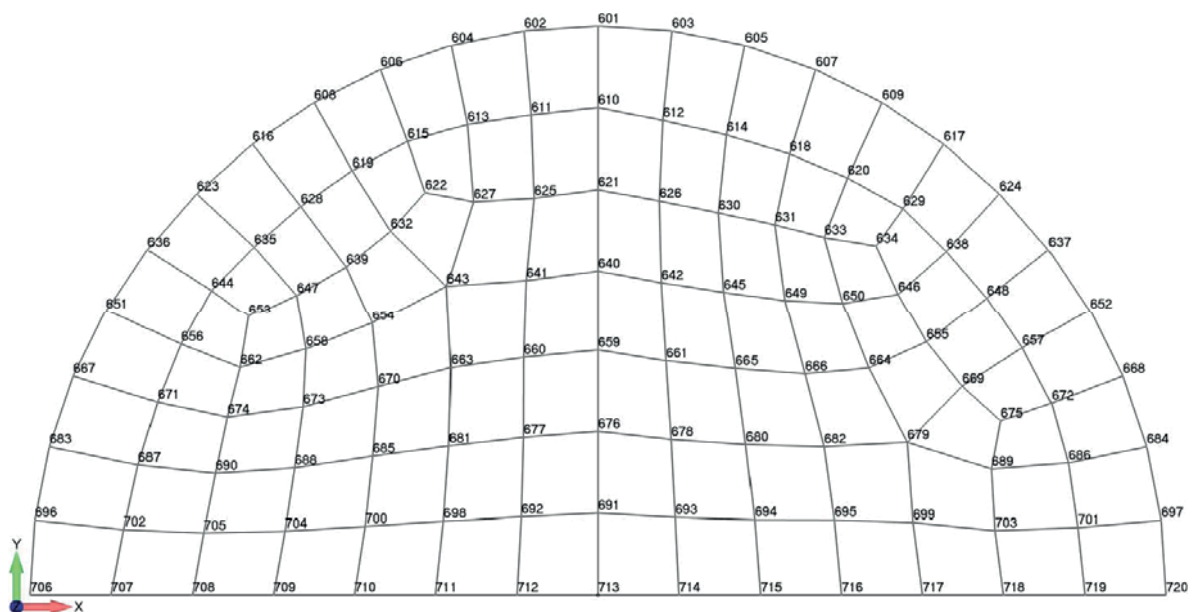


Figure A.3-12. Cylinder Foundation Model at Elevation 0 ft

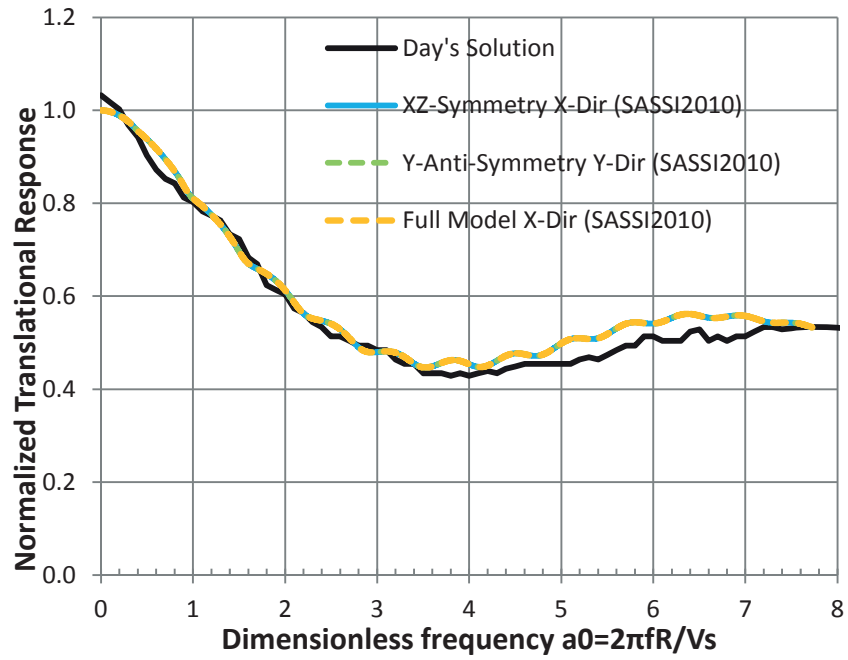


Figure A.3-13. Response of Foundation due to Vertically Propagating SV-wave (Translational)

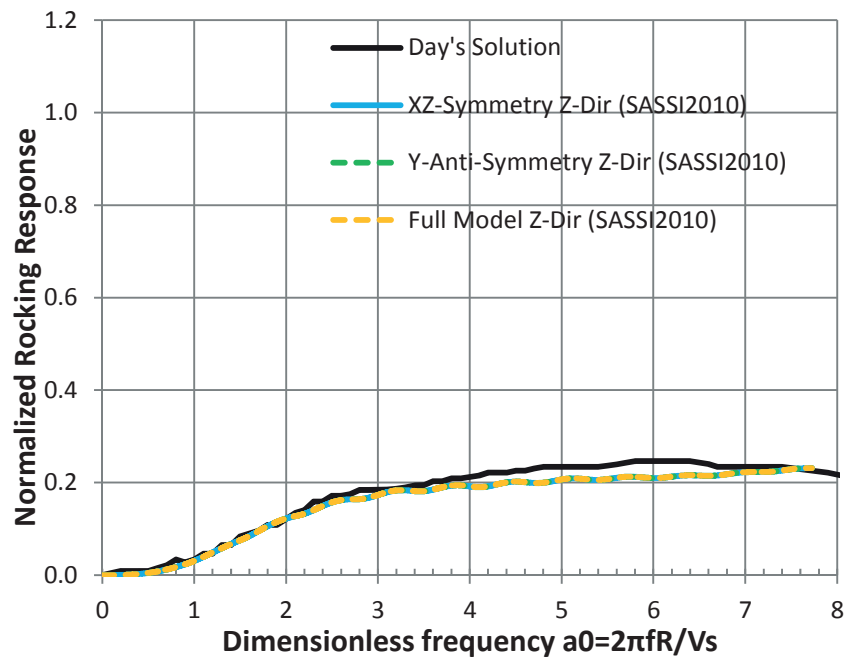


Figure A.3-14. Response of Foundation due to Vertically Propagating SV-wave (Rocking)

## Validation Problem NO.9

### A.9.1 Tested Program Applications

2: Kinematic SSI solution for frequencies up to 70 Hz

### A.9.2 Tested Program Modules

- SITE
- POINT3
- HOUSE
- ANALYS
- MOTION

### A.9.3 Problem Description

Seismic response analyses are performed of a rigid massless cylinder embedded in a halfspace and subjected to vertically propagating SV waves. Section A3.3 describes the half model with symmetry conditions used for the SSI analyses that is same as the one used in Validation Problem No. 3 and is more refined than Example Problem 2 of SASSI 2010 User's Manual (Ref. 1).

Transfer function results are calculated for frequencies up to 70 Hz for the response at the bottom of the cylinder and compared with to the theoretical solution provided in Day S.M. Ph.D. Dissertation, "Finite Element Analysis of Seismic Scattering Problem", University of California San Diego, 1977 (Ref. 2).

### A.9.4 Acceptance Criteria

The GOOD AGREEMENT acceptance criterion is used for validation of the SASSI2010 kinematic (wave scattering) solution for frequencies up to 70 Hz based on comparisons of calculated responses with theoretical solutions.

### A.9.5 Modeling

The SASSI soil layer models consist of top layers and halfspace. Depending on the embedment depth considered, the top layers used are 40 layers. Each of the top layers has a thickness of 8.125 ft. The halfspace is modeled by an additional 10 layers with varying thicknesses as a function of frequency and a viscous boundary at the base. The 40-top-layer site model is shown in Figs A.9-1. The shear-wave velocity ( $V_s$ ) and P-wave velocity ( $V_p$ ) of the soil layers are summarized in Table A.9-1.

The used soil properties are:

Weight Density       $\gamma = 128.68$  pcf



Poisson's Ratio	$\nu = 1/4$
Material Damping	$\beta = .01$

Note that the halfspace in all cases has the same shear-wave velocity ( $V_s=3700$  ft/sec) and P-wave velocity ( $V_p= 6409$  ft/sec).

The foundations are rigid massless cylinders with a radius (R) of 65 ft and are fully embedded to a depth of 32.5 ft. Geometries of the foundation cross-sections are shown in Fig. A.9-2. High stiffness properties are used to ensure the rigid foundation behavior.

#### **A.9.5.1 Excavated Soil Models**

The nodes and the elements of the excavated soil half model at elevations -32.5, -24.375, -16.25, -8.125 and 0. ft, are shown in Figs. A.9-3, A.9-4, A.9-5, A.9-6, and A.9-7, respectively. The maximum size of the finite elements is 10.364 ft which is less than 20% of the wavelength of seismic waves with frequencies of 70 Hz.

#### **A.9.5.2 Structural Models**

The cylinder foundations are discretized using brick elements. The nodes and elements of the foundation model are shown in Figs. A.9-8 through A.9-12.

#### **A.9.5.3 SSI Frequencies and Wave Fields**

The SASSI analysis for this problem is performed for frequencies shown in Table A.9-2. These frequencies are determined from the product of frequency step (DF) and the frequency numbers (NF):

$$f = DF * NF \quad (A.9-1)$$

In the analysis, DF is specified as 0.02 Hz. The dimensionless frequency ratio  $a_0$  shown in Table A.9-2 is computed from

$$a_0 = 2\pi f R / V_s \quad (A.9-2)$$

Where R is the radius of the cylinder and  $V_s$  is the shear wave velocity of the soil material. Note that the  $a_0$  definition is only applicable to this problem. Also note that the model mesh constructed for this problem is valid up to the frequency limit of 70.0 Hz corresponding to  $a_0 = 7.7$ .

The control motion is specified as vertically propagating SV-wave with a control point defined at the ground surface.

#### **A.9.5.4 Analysis Cases**

The SASSI analyses have been performed using seismic excitation in the form of vertically propagating SV-waves. The SASSI sequence of runs and input/output files for this problem are shown in Table A.9-3.

The flexible volume (direct) method is used where all nodes in the excavated soil volume are defined as interaction nodes. The results of analyses are compared with the reference solution in Reference 2.

#### **A.9.6 Analysis Results**

The amplitude of the translational response motion at Node 1 ( $|U_{1x}|$ ) and the amplitude of the rocking motion ( $|U_{66z}|$ , assuming that  $|U_{1z}|$  is negligible) of the foundation subjected to vertically propagating SV-waves is normalized to the amplitude of free-field motion ( $U_o=1$ ) and plotted in Figs. A.9-13 and A.9-14, respectively. The results are compared with results reported by Day(1977) (Ref. 2). The comparison with theoretical solution demonstrates that SASSI2010 results satisfy the good agreement acceptance criteria.

#### **A.9.7 Conclusion**

The good agreement obtained between SASSI2010 results and the reference solution (Ref. 2) validates the SASSI2010 calculations of frequency dependent translation and rocking impedance functions for embedded structures and the acceptability of computed solutions up to frequency of 70 Hz.

#### **A.9.8 References**

1. Computer Program SASSI2010 – User's Manual, May 2012.
2. Day, S. M., "Finite Element Analysis of Seismic Scattering Problem," Ph.D. Dissertation, University of California, San Diego, 1977.

Table A.9-1. Cases of Example Problem

Case No	Embedment Depth (ft)	Vs and Vp (ft/sec)	Seismic Loading
1	32.5 (4 layers)	Vs=3700.0 & Vp=6409.0	Vertically Propagating SV-wave

Table A.9-2. Frequencies of Analysis

NF	f (Hz)	a0	NF	f (Hz)	a0
1	0.02	0.002	1800	36.00	3.974
50	1.00	0.110	1850	37.00	4.084
100	2.00	0.221	1900	38.00	4.194
150	3.00	0.331	1950	39.00	4.305
200	4.00	0.442	2000	40.00	4.415
250	5.00	0.552	2050	41.00	4.526
300	6.00	0.662	2100	42.00	4.636
350	7.00	0.773	2150	43.00	4.746
400	8.00	0.883	2200	44.00	4.857
450	9.00	0.993	2250	45.00	4.967
500	10.00	1.104	2300	46.00	5.077
550	11.00	1.214	2350	47.00	5.188
600	12.00	1.325	2400	48.00	5.298
650	13.00	1.435	2450	49.00	5.409
700	14.00	1.545	2500	50.00	5.519
750	15.00	1.656	2550	51.00	5.629
800	16.00	1.766	2600	52.00	5.740
850	17.00	1.876	2650	53.00	5.850
900	18.00	1.987	2700	54.00	5.961
950	19.00	2.097	2750	55.00	6.071
1000	20.00	2.208	2800	56.00	6.181
1050	21.00	2.318	2850	57.00	6.292
1100	22.00	2.428	2900	58.00	6.402
1150	23.00	2.539	2950	59.00	6.512
1200	24.00	2.649	3000	60.00	6.623
1250	25.00	2.760	3050	61.00	6.733
1300	26.00	2.870	3100	62.00	6.844
1350	27.00	2.980	3150	63.00	6.954
1400	28.00	3.091	3200	64.00	7.064
1450	29.00	3.201	3250	65.00	7.175
1500	30.00	3.311	3300	66.00	7.285
1550	31.00	3.422	3350	67.00	7.395
1600	32.00	3.532	3400	68.00	7.506
1650	33.00	3.643	3450	69.00	7.616
1700	34.00	3.753	3500	70.00	7.727
1750	35.00	3.863			

Table A.9-3. Input/Output Files of Validation Problem 9 – Case 1

VERTICALLY PROPAGATING SV ANALYSIS				
SASSI MODULE	INPUT	OUTPUT	TAPEIN	TAPEOUT
SITE	vv16c3r8vsd.dat	vv16c3r8vso.out	-	SASSI.T1 SASSI.T2
POINT3	E2C1PD.dat	vv16c3r8po.out	-	SASSI.T3
HOUSE	Cylinder_Half- sym-xz.hou	vv16c3r8vho.out	-	SASSI.T4 SASSI.T7
ANALYS	E2C1AD.dat	vv16c3r8ao.out	SASSI.T1 SASSI.T3 SASSI.T4	SASSI.T5 SASSI.T8
MOTION	E2C1VOD.dat	vv16c3r8voo.out	SASSI.T8	SASSI.T13

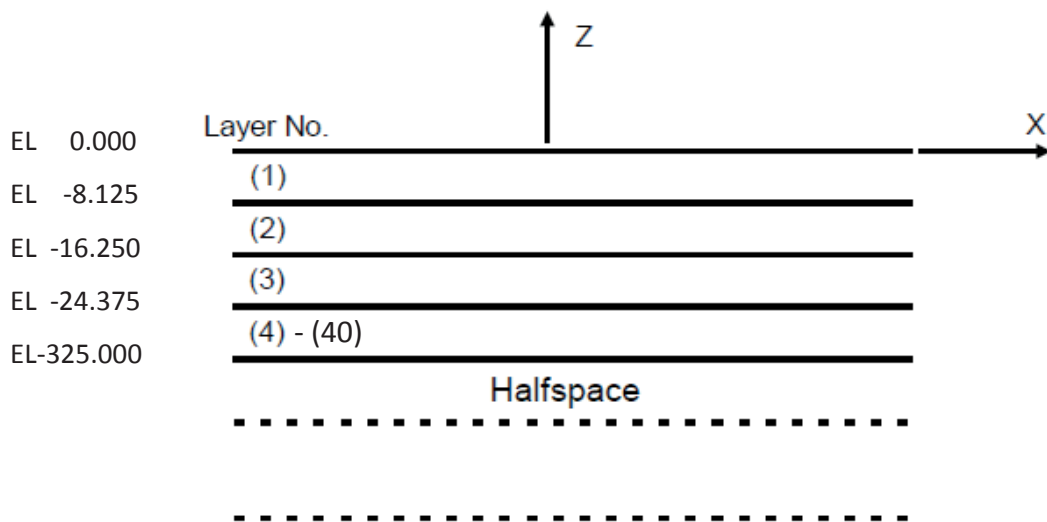


Figure A.9–1. SASSI Soil Layer Model

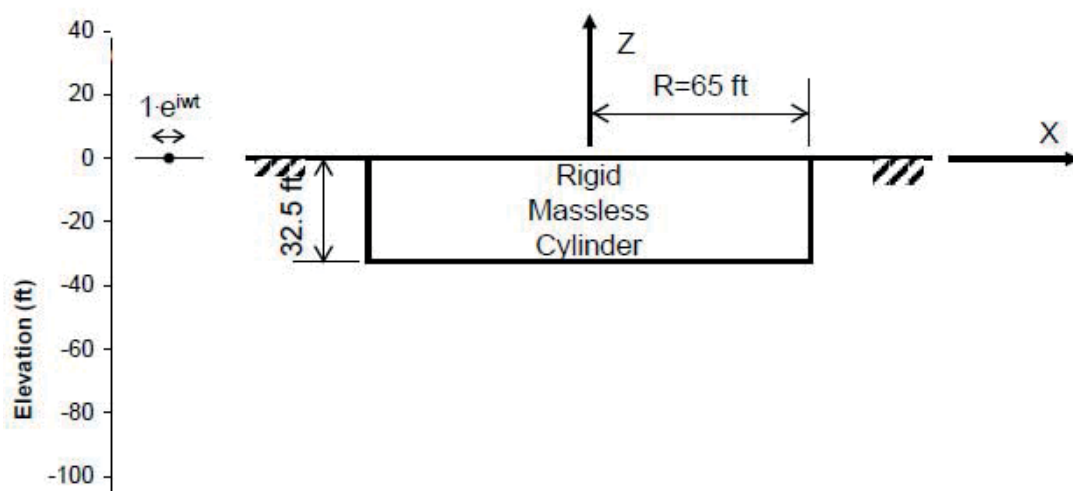


Figure A.9–2. Geometry of Cylinder Foundation Cross Section

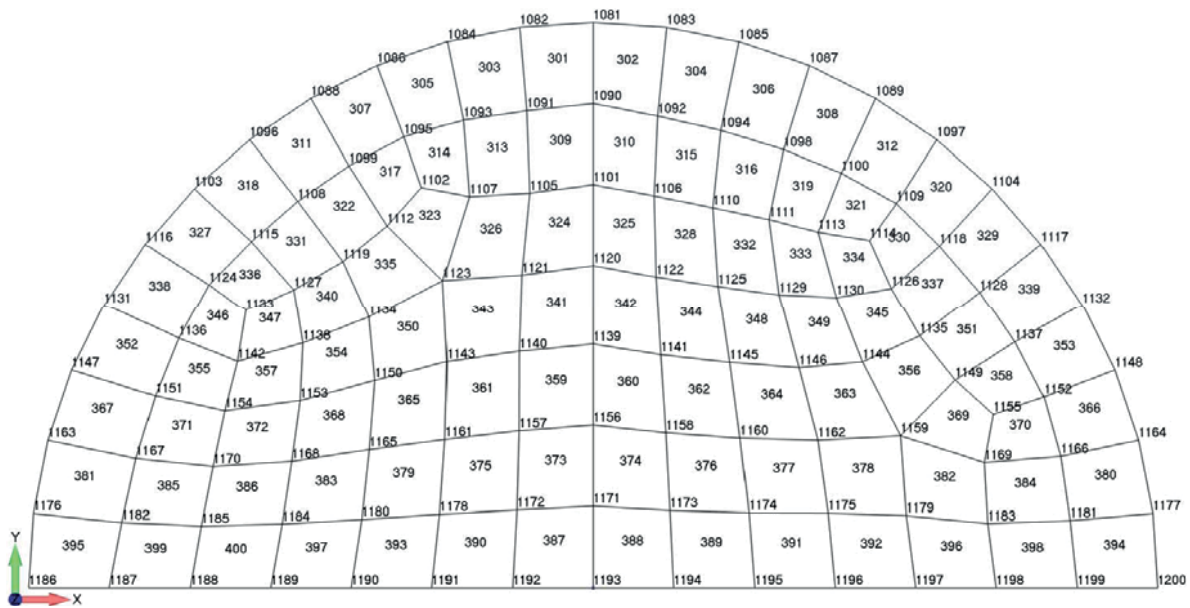


Figure A.9-3. Excavated Soil Model at Elevation -32.5 ft

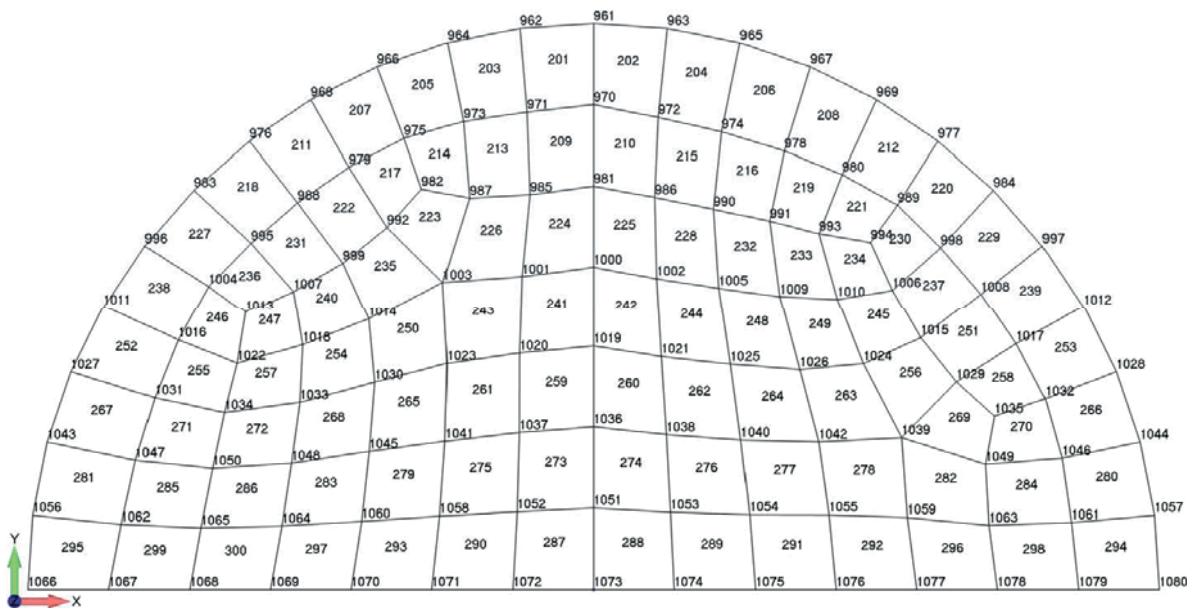


Figure A.9-4. Excavated Soil Model at Elevation -24.375 ft

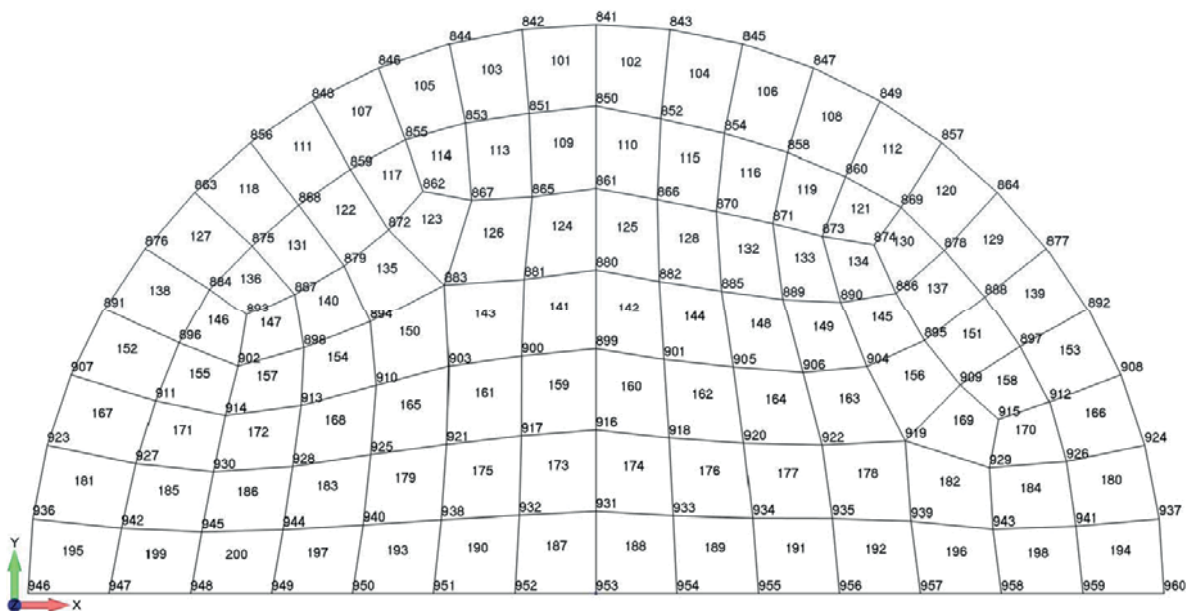


Figure A.9-5. Excavated Soil Model at Elevation -16.25 ft

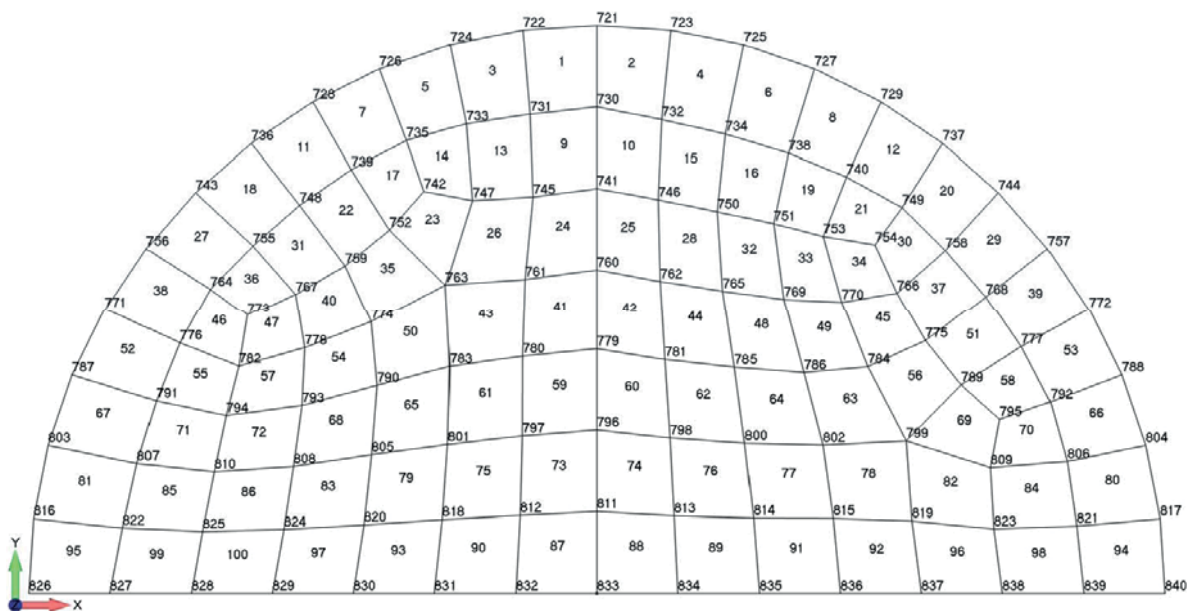


Figure A.9-6. Excavated Soil Model at Elevation -8.125 ft



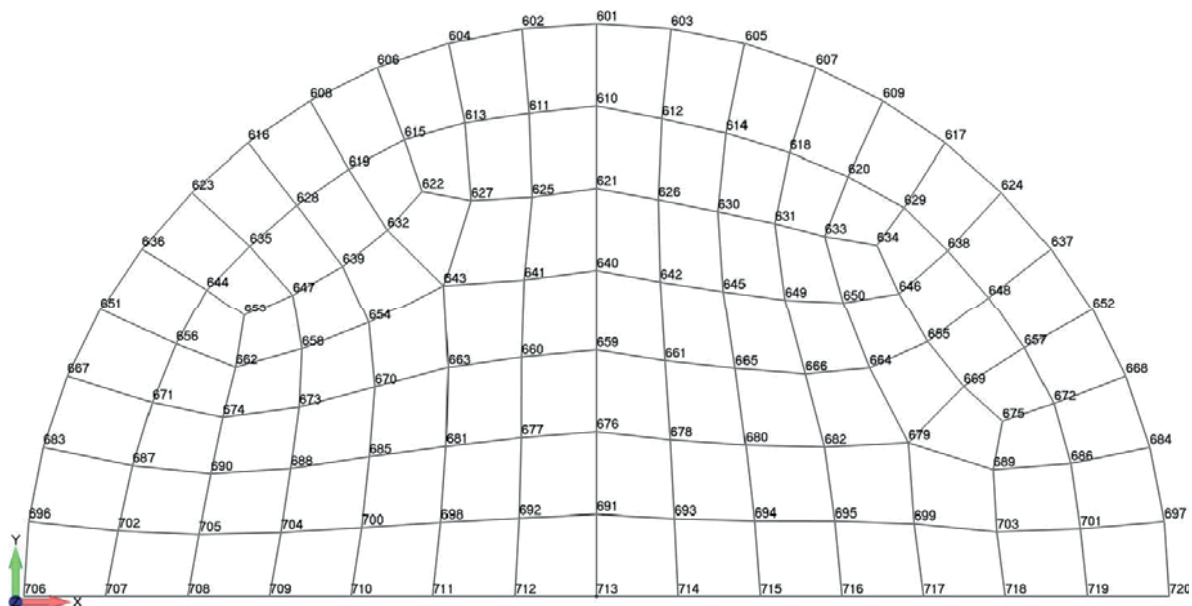


Figure A.9-7. Excavated Soil Model at Elevation 0 ft

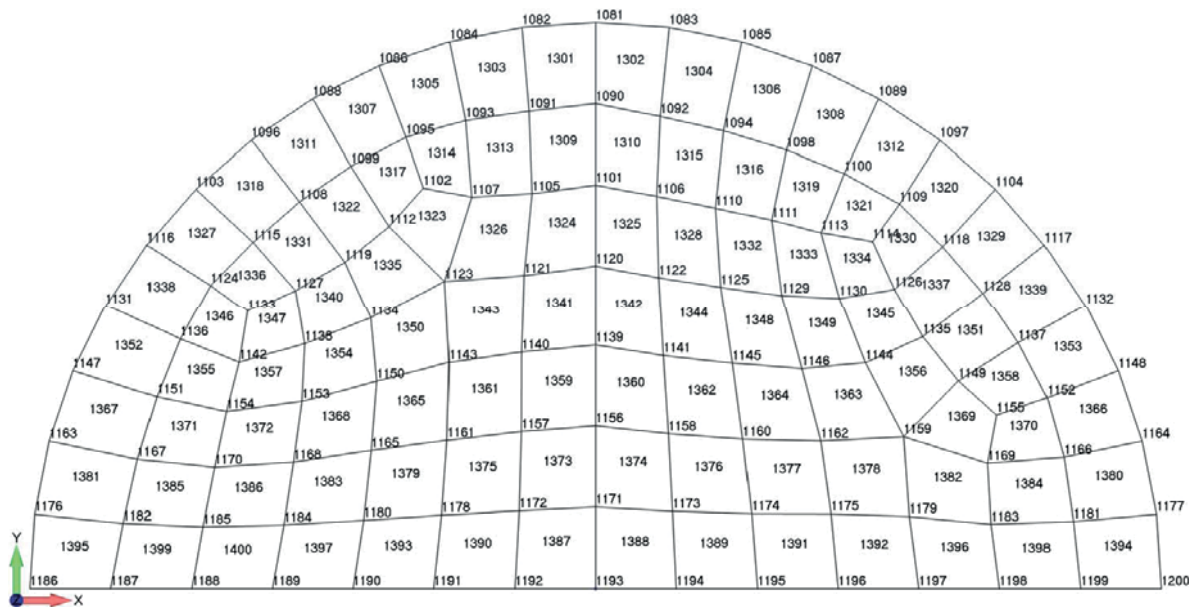


Figure A.9-8. Cylinder Foundation Model at Elevation -32.5 ft



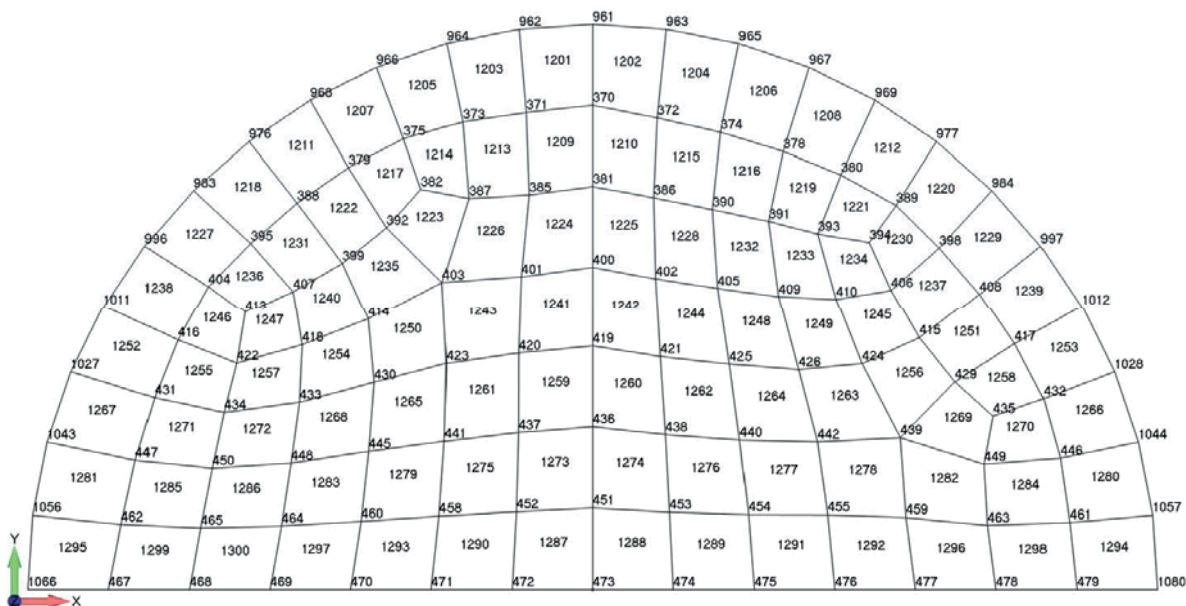


Figure A.9-9. Cylinder Foundation Model at Elevation -24.375 ft

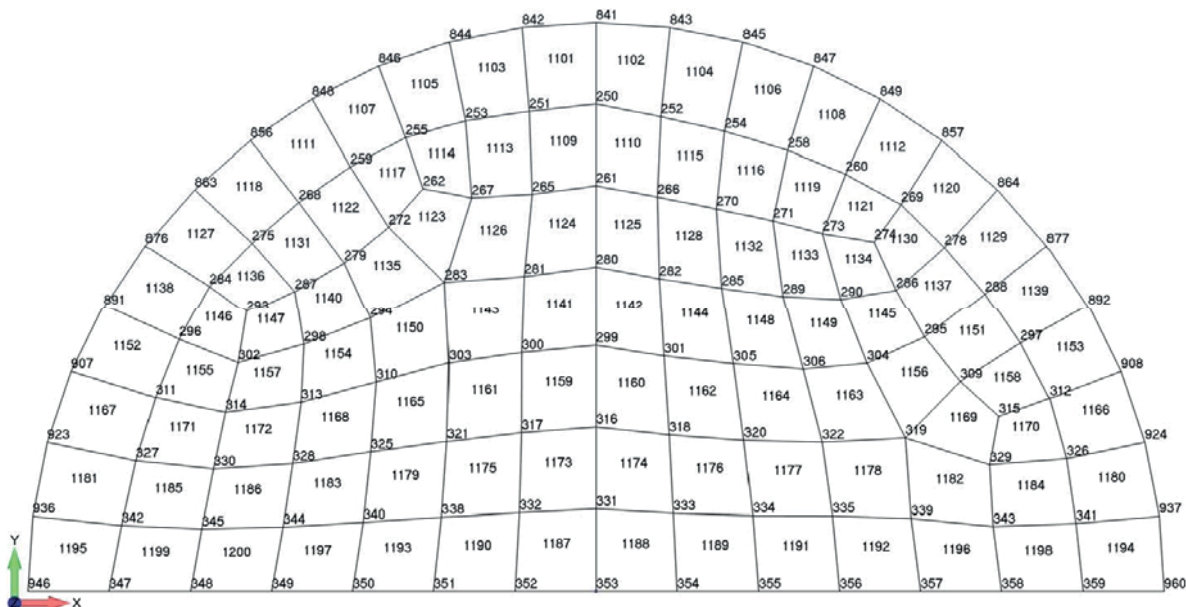


Figure A.9-10. Cylinder Foundation Model at Elevation -16.25 ft

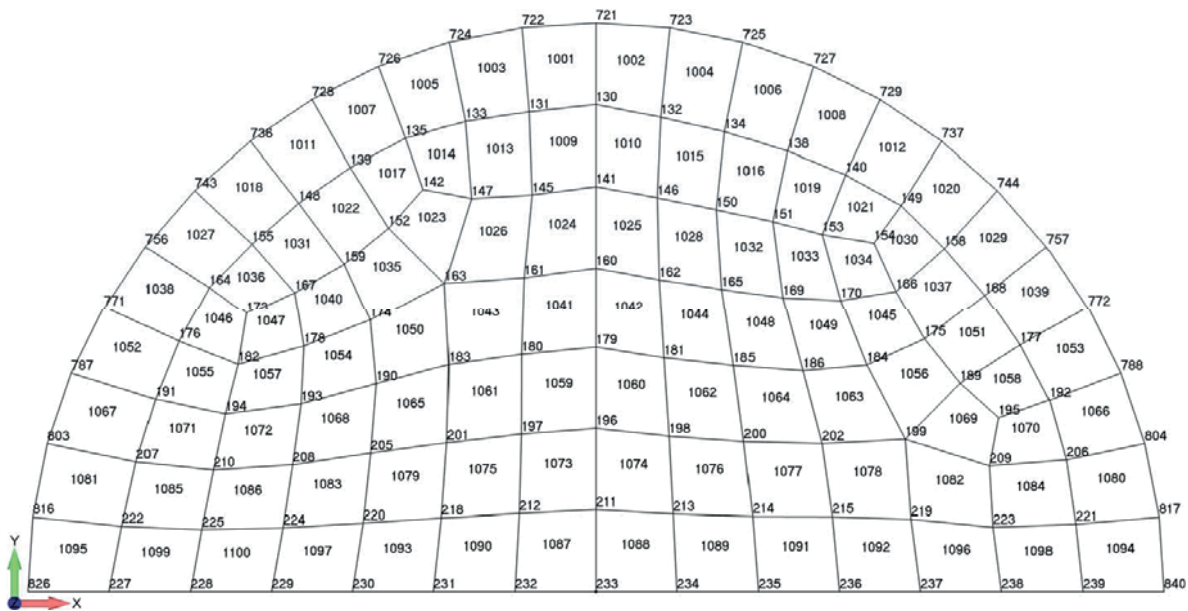


Figure A.9-11. Cylinder Foundation Model at Elevation -8.125 ft

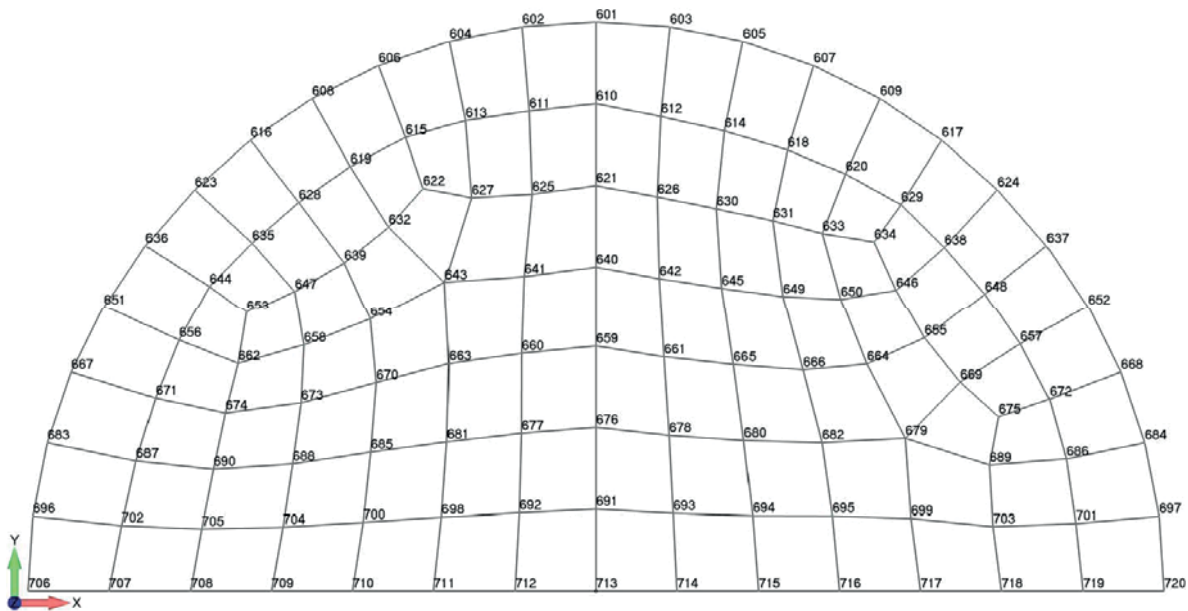


Figure A.9-12. Cylinder Foundation Model at Elevation 0 ft

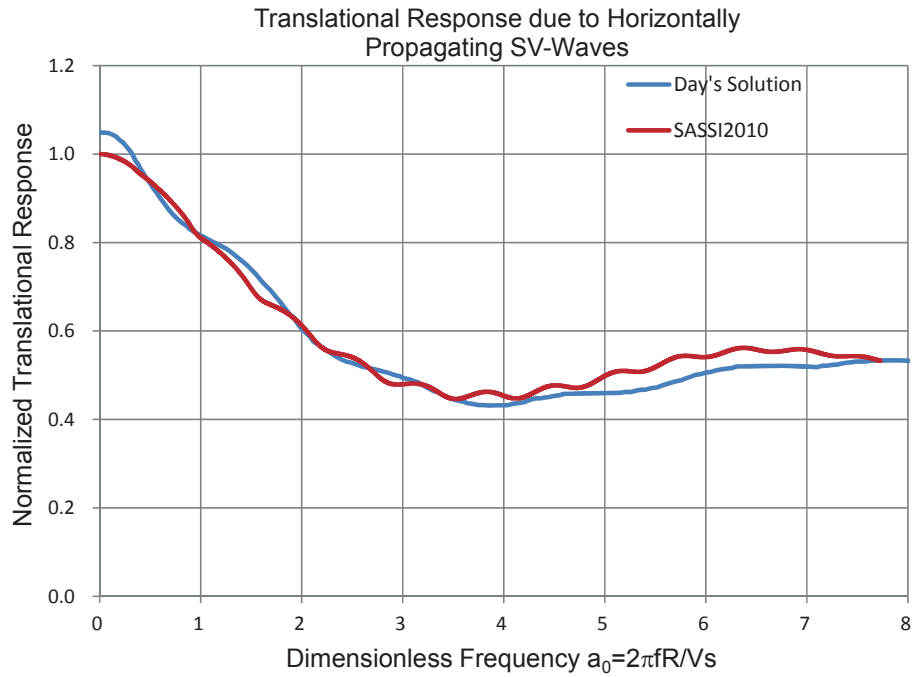


Figure A.9–13. Response of Foundation due to Vertically Propagating SV-Wave (Translation Response, Case1)

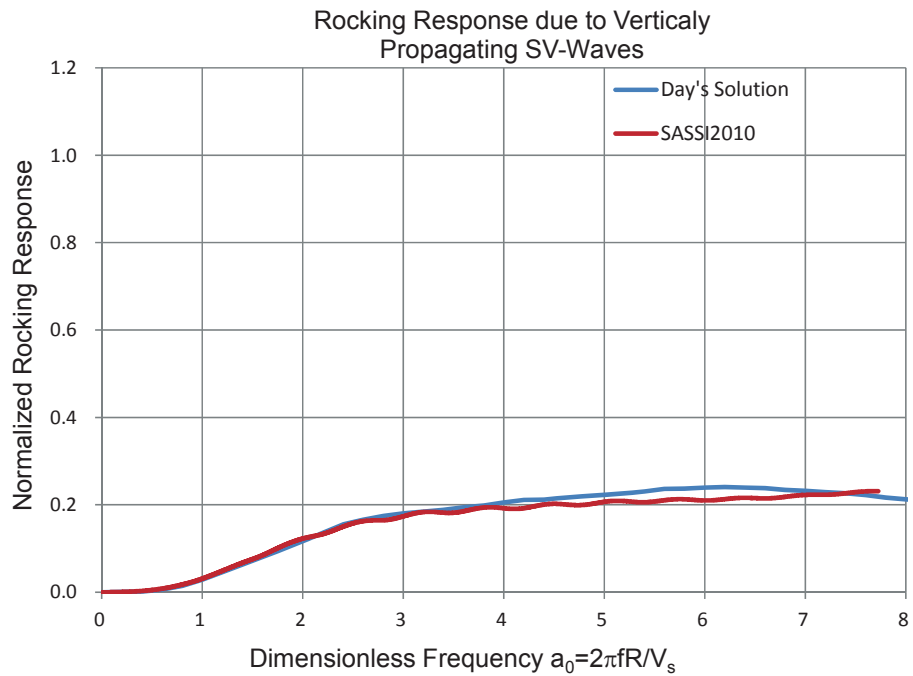


Figure A.9–14. Response of Foundation due to Vertically Propagating SV-Wave (Rocking Response, Case1)

## Validation Problem NO.10

### A.10.1 Tested Program Applications

- 11: Evaluation of maximum aspect ratio for 3-D solid brick elements and 3-D thin shell elements

### A.10.2 Tested Program Modules

- SITE
- POINT3
- HOUSE
- ANALYS
- MOTION

### A.10.3 Problem Description

A seismic response analysis is performed on the ESBWR control building (CB) model (Ref.2, 3) to establish the maximum acceptable aspect ratio for 3-D solid brick elements and 3-D thin shell elements.

Figure A.10-1 shows the CB model consisting of a lumped mass stick model representing the dynamic properties of the building above grade, 3-D thin shell elements modeling the below grade exterior walls and the foundation basemat and 3-D solid elements modeling excavated soil volume and the concrete fill placed around and below the foundation. The meshes of the concrete fill and excavated soil volume models are consistent with the mesh of the shell element models of the basemat and below grade exterior walls.

Seven models of ESBWR CB are developed with meshes that have aspect ratio of 1:1.3, 1:1.5, 1:1.7, 1:2, 1:3 and 1:4. The maximum aspect ratios of the model shown in Figure A.10-1 are 1:1.5 for the 3-D solid brick elements and 1:1.7 for the 3-D thin shell elements. Seismic response analyses are performed on the models with different meshes with the input free field in layer control motion applied at bottom of the CB foundation. The results for maximum absolute accelerations and acceleration response spectra obtained from the analyses of the different CB models are compared in order to evaluate the acceptability of the used element aspect ratio.

### A.10.4 Acceptance Criteria

The evaluation of maximum acceptable aspect ratio for 3-D solid and thin shell elements is based on

- NUMERICAL ACCURACY criterion that is used for comparison of maximum acceleration results obtained from the models with different meshes
- GOOD AGREEMENT criterion that is used for comparison of acceleration response spectra results obtained from the models with different meshes

### A.10.5 Analysis Model

Figure A.10-1 shows the analysis model considered in this validation problem. The model consists of single stick model, and the exterior walls below grade and the foundation basemat along with the supporting soil medium and the backfill surrounding the building. The stick model is a three-dimensional lumped mass-beam model that considers shear, bending, torsion and axial deformations. In this model, the basemat and the exterior walls are modeled by plate elements. The excavated soil volume elements are part of the structural

models. The excavated soil volumes have mesh that is consistent with the FE mesh of the basemat and basement exterior walls finite elements. The excavated soil elements are assigned with in-situ strain compatible soil properties as the ones used in the site profile models representative of a typical rock site in Central and Eastern US (Ref. 3).

The maximum aspect ratios of the model shown in Fig. A.10-1 are about 1:1.5 for the 3-D solid brick elements and 1:1.7 for the 3-D thin shell elements. The various analytical models with various maximum aspect ratios, 1:1.3, 1:2, 1:3 and 1:4 are produced, and earthquake response analyses are performed.

The acceleration time history of the motion specified at the bottom of the basemat, EL -10.4m is shown in Fig. A.10-2. The input wave has maximum acceleration of 0.73g with duration of 40.96 seconds digitized at time intervals of 0.005 second. The cut-off frequency used for the analysis is 50 Hz.

#### **A.10.5.1 Soil Model**

The maximum allowable layer thickness is computed according to the criterion described in item 8 of Section 4.2.2 (Ref. 1):

$$\text{Maximum allowable thickness} = 616[\text{m/sec}]/(5 \times 50[\text{Hz}]) = 2.46\text{m}$$

Based on this value, the soil profile for the SASSI analysis is selected as shown in Table A.10-1 and Table A.10-2. This profile consists of 17 top layers and 10 extra layers with variable thickness plus viscous dashpots. The extra 10 layers and viscous dashpots are added by the program at the user's request to simulate a halfspace condition.

#### **A.10.5.2 Structural Model**

The structural finite element model used in the SASSI analysis is shown in Fig. A.10-3. The structures are modeled by stick model (in black), plate (in blue), and rigid beams elements (in red). The stick model consists of lumped masses and beam elements as shown in Fig. A.10-4. A uniform SSE damping of 7% was used for the structural model. The basemat is modeled with plate elements with stick model connected with using the rigid beams to be able to transmit the moment/rotation at the connection.

The wavelength criterion described in item 9 of Section 4.2.2(Ref. 1) is used to select the element sizes of the plate elements in the all directions.

$$\text{Maximum allowable element size} = 616[\text{m/sec}]/(5 \times 50[\text{Hz}]) = 2.46\text{m}$$

#### **A.10.5.3 Excavated Soil Model**

Mesh size for Excavated Soil Model is determined by using soil profile shown in Table A.10-1.

#### **A. 10.5.4 Mesh Size**

Mesh size for Excavated Soil Model including concrete fill and CB exterior walls are shown in Fig.A.10-5. The maximum aspect ratio of 3-D solid brick elements is 1:1.5. The maximum aspect ratio of 3-D thin shell element below grade is 1:1.7.

### A.10.6 Analyses Cases

The SASSI runs for this validation test problem consists of 7 cases. The aspect ratios for the 7 cases are summarized in Table A.10-3. The original mesh size of the model in Ref.3 is shown in Fig. A.10-5 and is referred to as the case 2 model. Other models defined in Table A.10-3 are derived from case 2 model for other aspect ratios.

Aspect ratio of each case is set by the H0, H1, H2, H3, H4, H5 and W1, W2, W3 parameters as shown in Figs. A.10-6 through A.10-12.

### A.10.7 Results and Comparison

The SASSI sequence of runs and input/output files for this validation problem are shown in Table A.10-4. This table also includes the names that are assigned to the tapes for conveniences of tapein / tapeout activity.

Tables A.10-5 and A.10-6 show the maximum absolute acceleration at the top of the stick outer walls and the nodes associated with the elements having the maximum aspect ratios obtained from the various SASSI models with different element mesh. The maximum acceleration values obtained from the different CB models are almost the same with minor differences less than 2%, thus demonstrating that the NUMERICAL ACCURACY criterion is satisfied.

The 5% acceleration spectrums are computed for the horizontal motions at the top of the stick outer walls, top of Basemat and the nodes associated with the elements having the maximum aspect ratios. The comparisons of the results obtained from the analyses of the seven models are presented in Figs. A.10-13 through A.10-36. The comparisons of the acceleration response spectra results demonstrate that the good agreement criterion is met for all CB models with different mesh.

### A.10.8 Conclusion

The comparison in Table A.10-5 of the maximum acceleration results demonstrate that the NUMERICAL ACCURACY criterium is satisfied. The good agreement is demonstrated in Figs. A.10-13 through A.10-36 between the acceleration response spectra results from the models with five different meshes and. Therefore, the maximum aspect ratio of 1:4 for 3-D solid brick elements and 3-D thin shell is validated.

### A.10.9 References

1. Computer Program SASSI2010 – User’s Manual, May 2012.
2. 26A6642AL, ESBWR Design Control Document Tier 2 Chapter 3 Appendices 3A – 3F, Rev. 9, Dec. 2010.
3. SER-DMN-003, CB Licensing Basis Seismic Analysis Report (Basis document for FSAR Markup), Dominion NA3 ESBWR Project, Dec. 2013.

Table A.10-1 Soil Properties

Layer No.	Top EL [m]	Layer thickness [m]	Unit weight [ton/m <sup>3</sup> ]	Vs [m/sec]	Vp [m/sec]	Damping [%]	Remark
1	-3.12	1.525	2.32	616	1882	6.2	
2	-4.645	1.525	2.32	616	1882	6.2	
3	-6.17	1.230	2.32	753	2301	6.3	
4	-7.40	1.500	2.32	753	2301	6.3	
5	-8.90	1.500	2.32	753	2301	6.3	
6	-10.40	1.860	2.32	753	2301	6.3	
7	-12.26	1.525	2.32	810	2474	5.3	
8	-13.785	1.525	2.32	810	2474	5.3	
9	-15.31	3.050	2.61	1976	4225	1.0	
10	-18.36	6.100	2.61	2128	4273	1.0	
11	-24.46	3.040	2.61	2421	4613	1.0	
12	-27.50	3.050	2.63	2638	4772	1.0	
13	-30.55	3.050	2.63	2512	4787	1.0	
14	-33.60	3.050	2.63	2639	4937	1.0	
15	-36.65	3.050	2.63	2689	4722	1.0	
16	-39.70	3.040	2.63	2847	5150	1.0	
17	-42.74	3.050	2.63	2804	5245	1.0	
	-45.79	-	2.63	2804	4794	1.0	halfspace

Table A.10-2 Backfill Properties for CB

Layer No.	Top EL [m]	Layer thickness [m]	Unit weight [ton/m <sup>3</sup> ]	Vs [m/sec]	Vp [m/sec]	Damping [%]	Remark
-	-	-	2.32	2134	3325	1.0	

Table A.10-3 Case of Validation Problem No.10

Case No	Max. Aspect Ratio		H0(mm)	H1(mm)	W1(mm)	W2(mm)	W3(mm)	H2(mm)	H3(mm)	H4(mm)	H5(mm)	Remark
	Brick Element	Shell Element										
1	1:1.3	1:1.7	1427.0	1636.7	1865.0	1865.0	-	1100.0	1100.0	1000.0	1120.0	
2	1:1.5	1:1.7	1230.0	1860.0	1240.0	1240.0	1250.0	1100.0	1100.0	1000.0	1120.0	
3	1:2	1:1.7	1230.0	1860.0	930.0	1400.0	1400.0	1100.0	1100.0	1000.0	1120.0	
4	1:3	1:1.7	1230.0	1860.0	620.0	1555.0	1555.0	1100.0	1100.0	1000.0	1120.0	
5	1:4	1:1.7	1230.0	1860.0	465.0	1632.5	1632.5	1100.0	1100.0	1000.0	1120.0	
6	1:1.3	1:1.5	1427.0	1636.7	1865.0	1865.0	-	1300.0	1300.0	1300.0	1120.0	
7	1:1.3	1:4	1427.0	1636.7	1865.0	1865.0	-	425.0	1775.0	1000.0	1120.0	



Table A.10-4 Input/Output Files of Validation Problem No.10

	SASSI SEQUENCE OF RUNS			
SASSI MODULE	INPUT	OUTPUT	TAPEIN	TAPEOUT
SITE	V17_site.dat	V17_site.out	-	V17_T1 V17_T2
POINT	V17_pointN*.dat	V17_pointN*.out	V17_T2	V17_T3_CN*
HOUSE	V17_houseN*.dat	V17_houseN*.out		V17_T4_CN*
ANALYS	V17_analys.dat	V17_analysN*.out	V17_T1_CN* V17_T4_CN* V17_T5_CN*	V17_T6_CN* V17_T8_CN*
MOTION	V17_motion.dat	V17_motionN*.out	V17_T8_CN*	V17_T12_CN*

N\*: Case number 1,2,3,4,5,6,7

Table A.10-5 Maximum Acceleration at Top of Stick

Case No	Max Aspect Ratio		X-dir [g]	Y-dir [g]	Z-dir [g]
	Brick Element	Shell Element			
1	1:1.3	1:1.7	1.328	1.157	1.137
2	1:1.5	1:1.7	1.343	1.156	1.141
3	1:2	1:1.7	1.344	1.155	1.142
4	1:3	1:1.7	1.345	1.155	1.143
5	1:4	1:1.7	1.345	1.155	1.143
6	1:1.3	1:1.5	1.328	1.157	1.137
7	1:1.3	1:4	1.329	1.157	1.137
Max. Difference (%)			1.3	0.2	0.5

Table A.10-6 Maximum Acceleration at Nodes

Case No	Max. Aspect Ratio		Node 1170 or 1234			Node 1426			Node 16488 or 16513			Node 8380		
	Brick Element	Shell Element	X-dir [g]	Y-dir [g]	Z-dir [g]	X-dir [g]	Y-dir [g]	Z-dir [g]	X-dir [g]	Y-dir [g]	Z-dir [g]	X-dir [g]	Y-dir [g]	Z-dir [g]
1	1:1.3	1:1.7	-	-	-	-	-	-	0.460	0.471	0.818	0.413	0.401	0.702
2	1:1.5	1:1.7	-	-	-	0.678	0.836	0.722	0.463	0.467	0.817	0.420	0.420	0.701
3	1:2	1:1.7	-	-	-	-	-	-	0.461	0.469	0.816	0.420	0.402	0.701
4	1:3	1:1.7	-	-	-	-	-	-	0.462	0.468	0.817	0.420	0.402	0.701
5	1:4	1:1.7	-	-	-	-	-	-	0.462	0.468	0.817	0.420	0.402	0.701
6	1:1.3	1:1.5	0.562	0.724	0.875	0.672	0.828	0.724	-	-	-	-	-	-
7	1:1.3	1:4	0.563	0.710	0.874	0.672	0.831	0.724	-	-	-	-	-	-
Max. Difference (%)			0.2	2.0	0.1	0.9	1.0	0.3	0.7	0.9	0.2	1.7	4.7	0.1



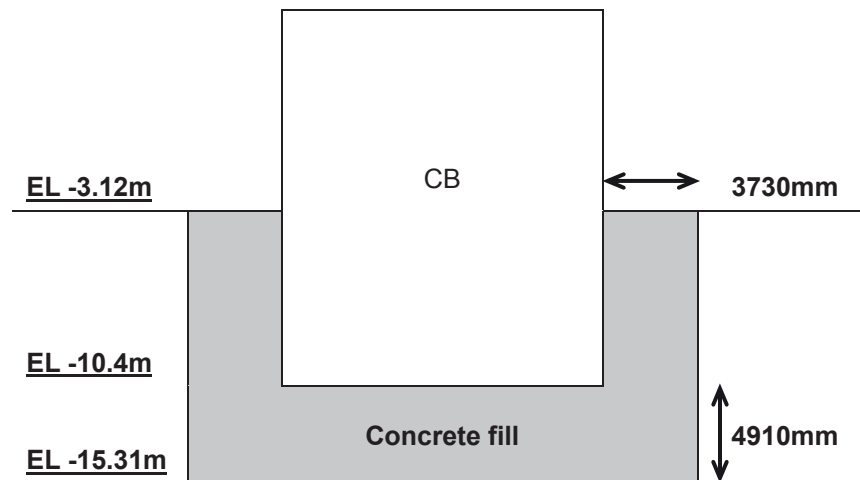
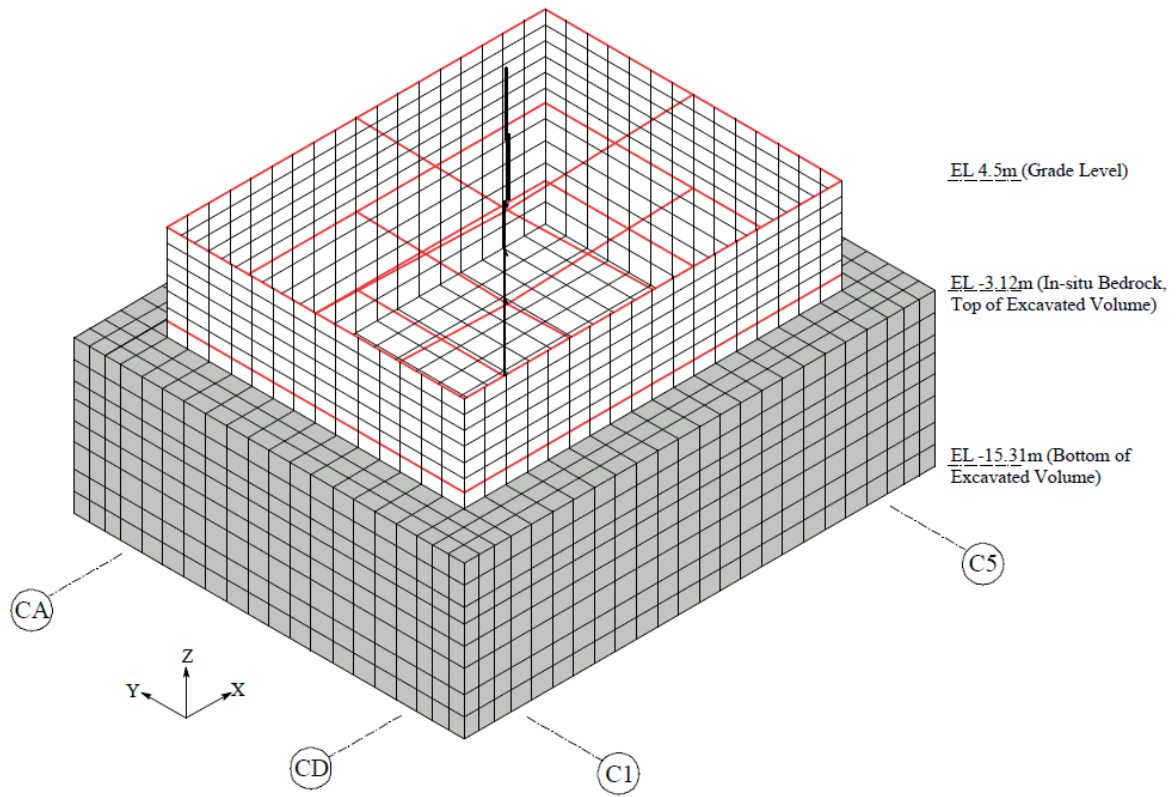


Figure A.10-1 CB SASSI Model

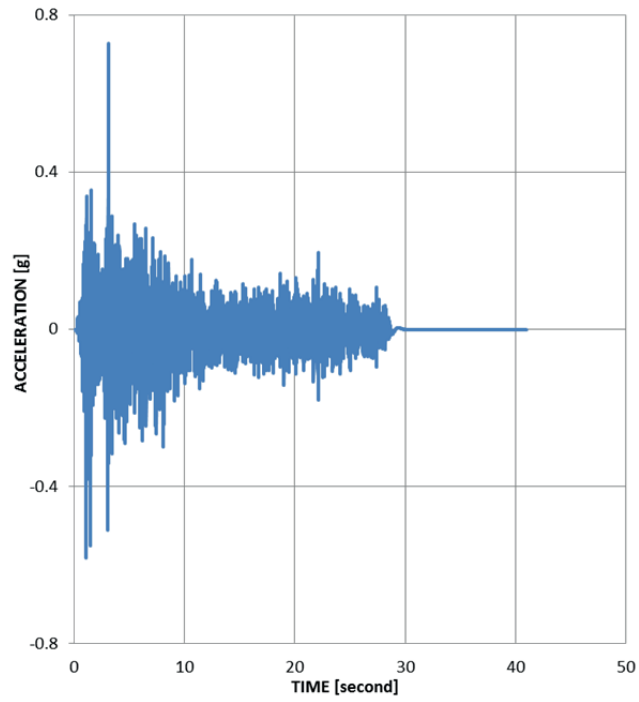


Figure A.10-2 Acc. Time History of Input motion

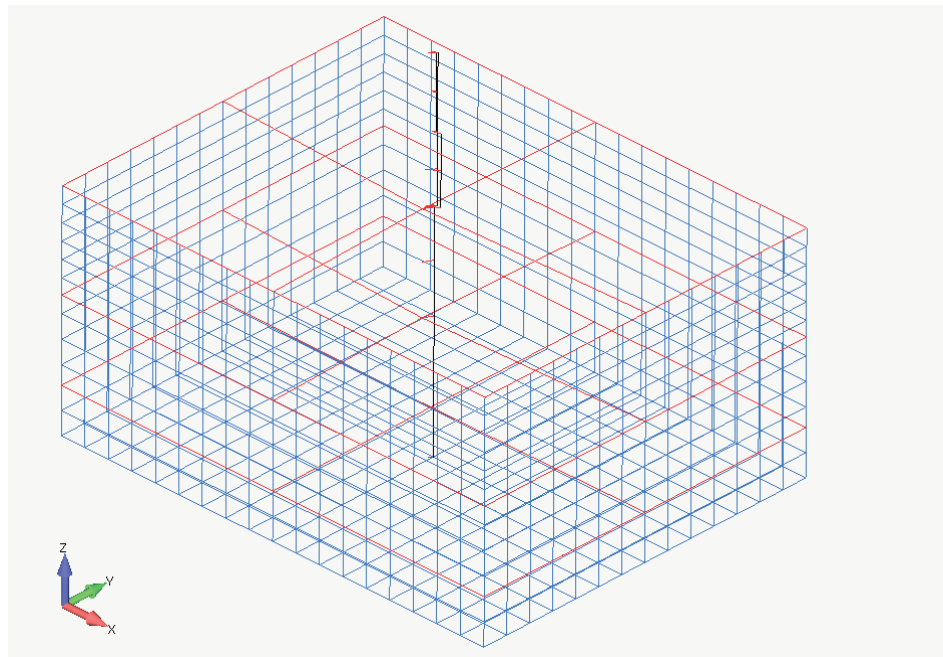


Figure A.10-3 CB Structural Model

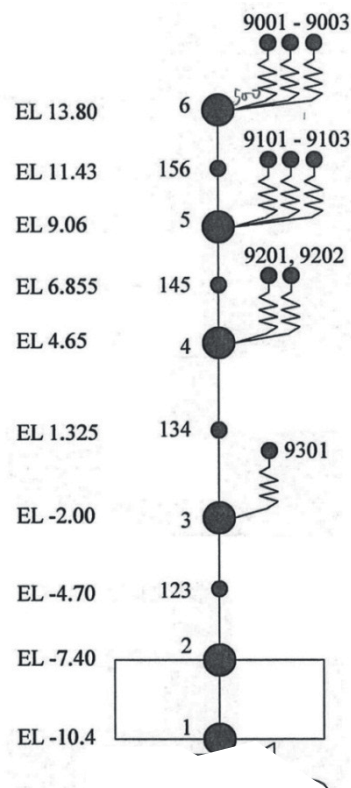


Figure A.10-4 CB Stick Model



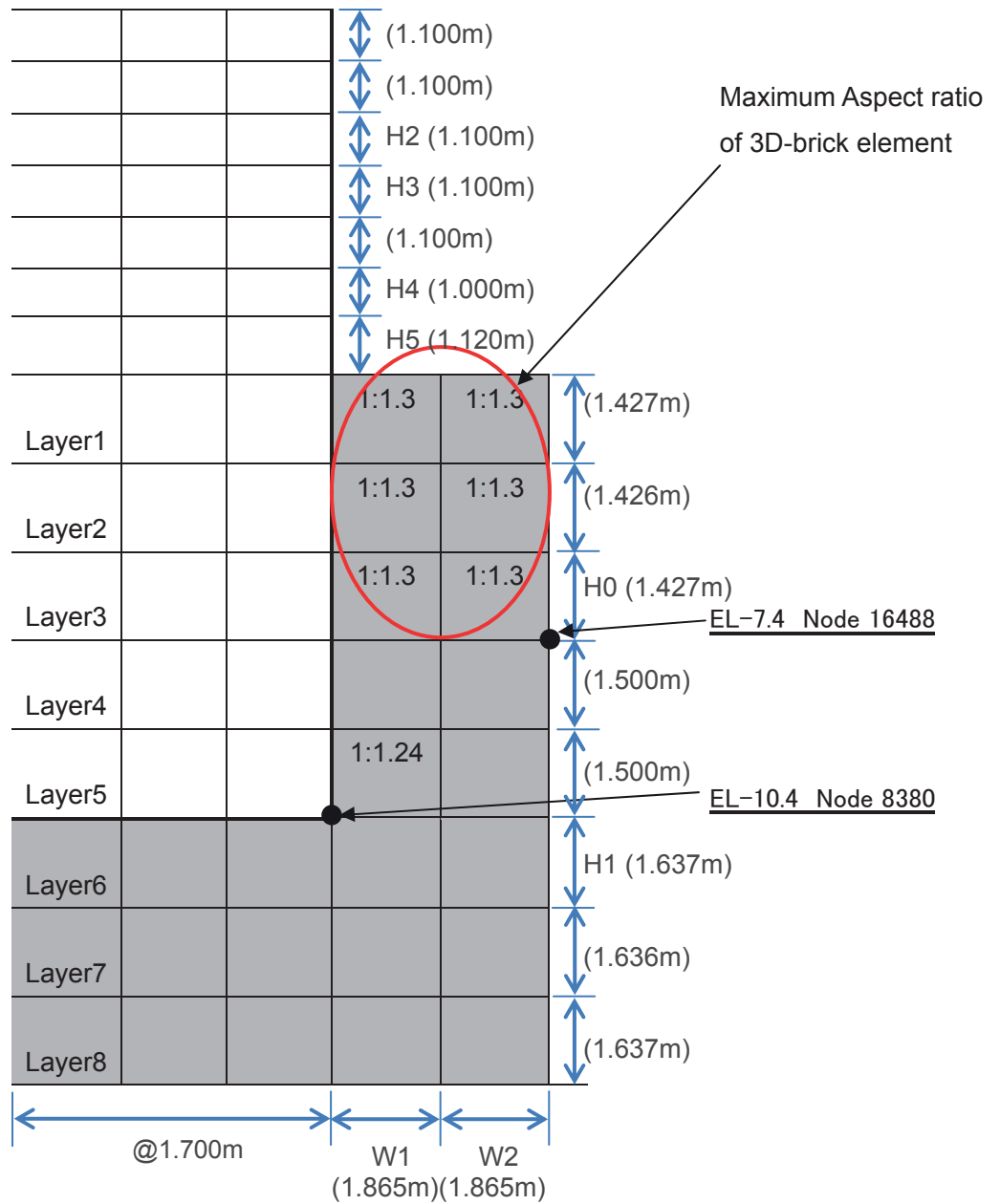


Figure A.10-6 Dimensions of Element Size for Case 1

Maximum Aspect ratio  
of 3D-thin shell element

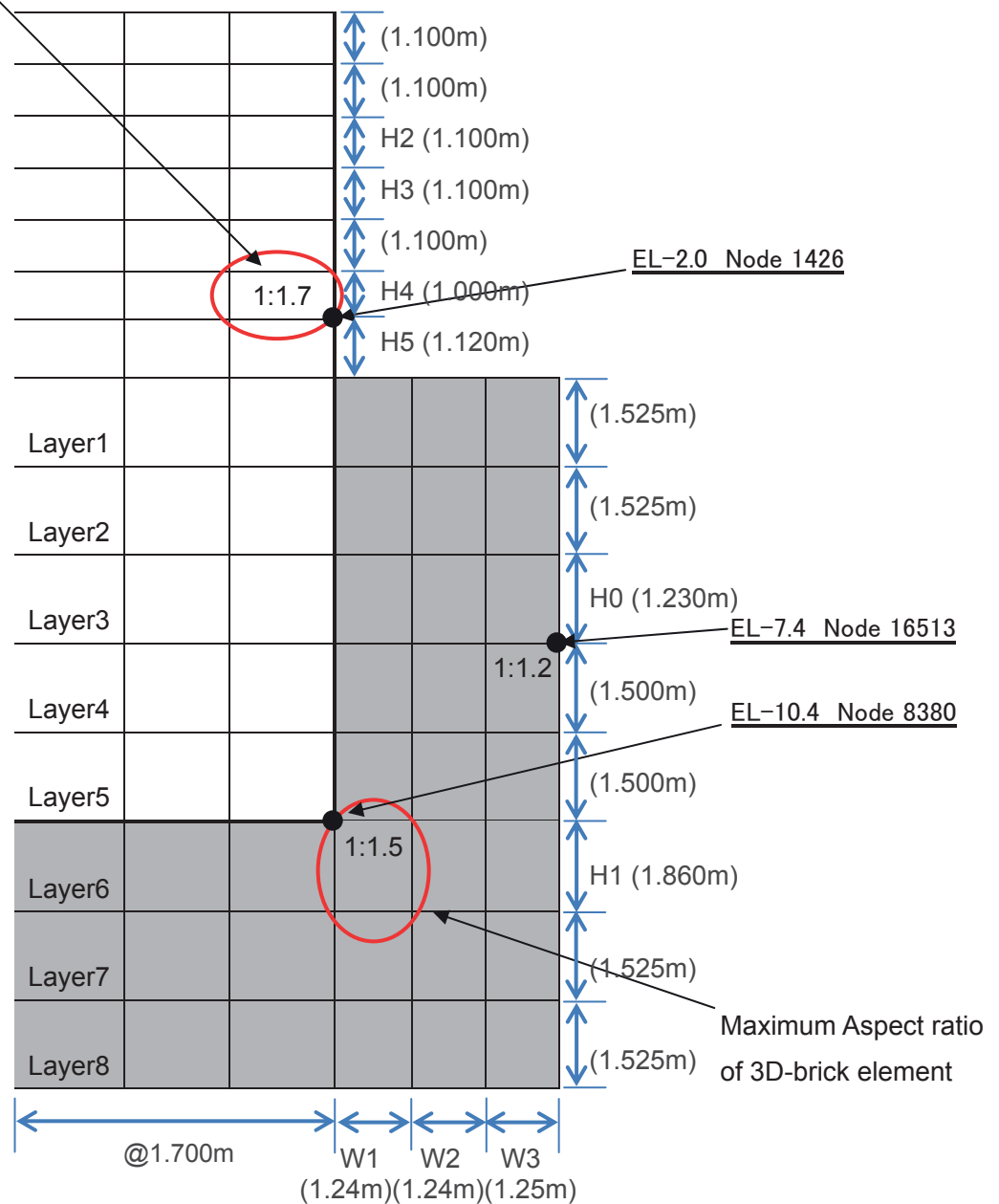


Figure A.10-7 Dimensions of Element Size for Case 2

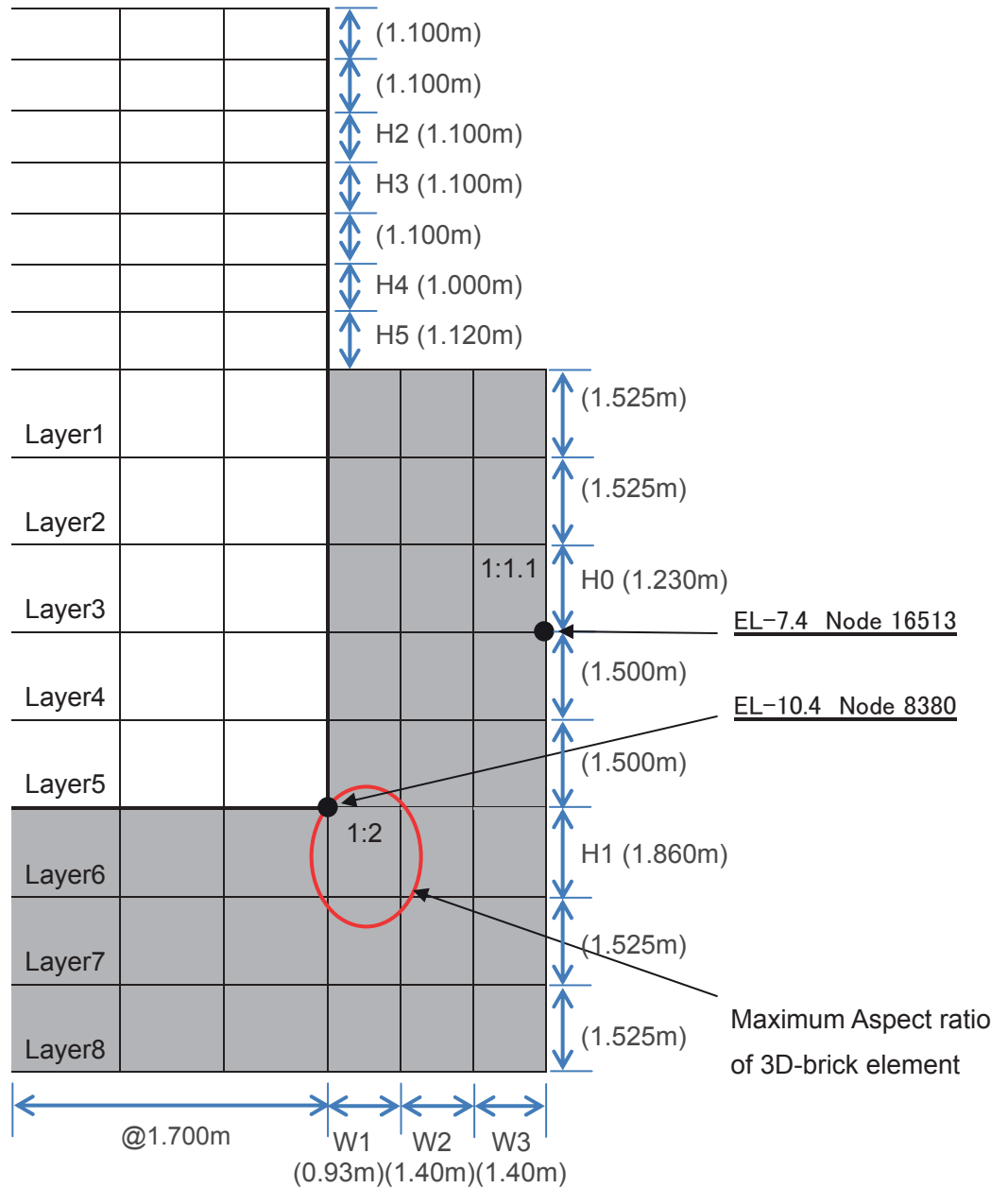


Figure A.10-8 Dimensions of Element Size for Case 3

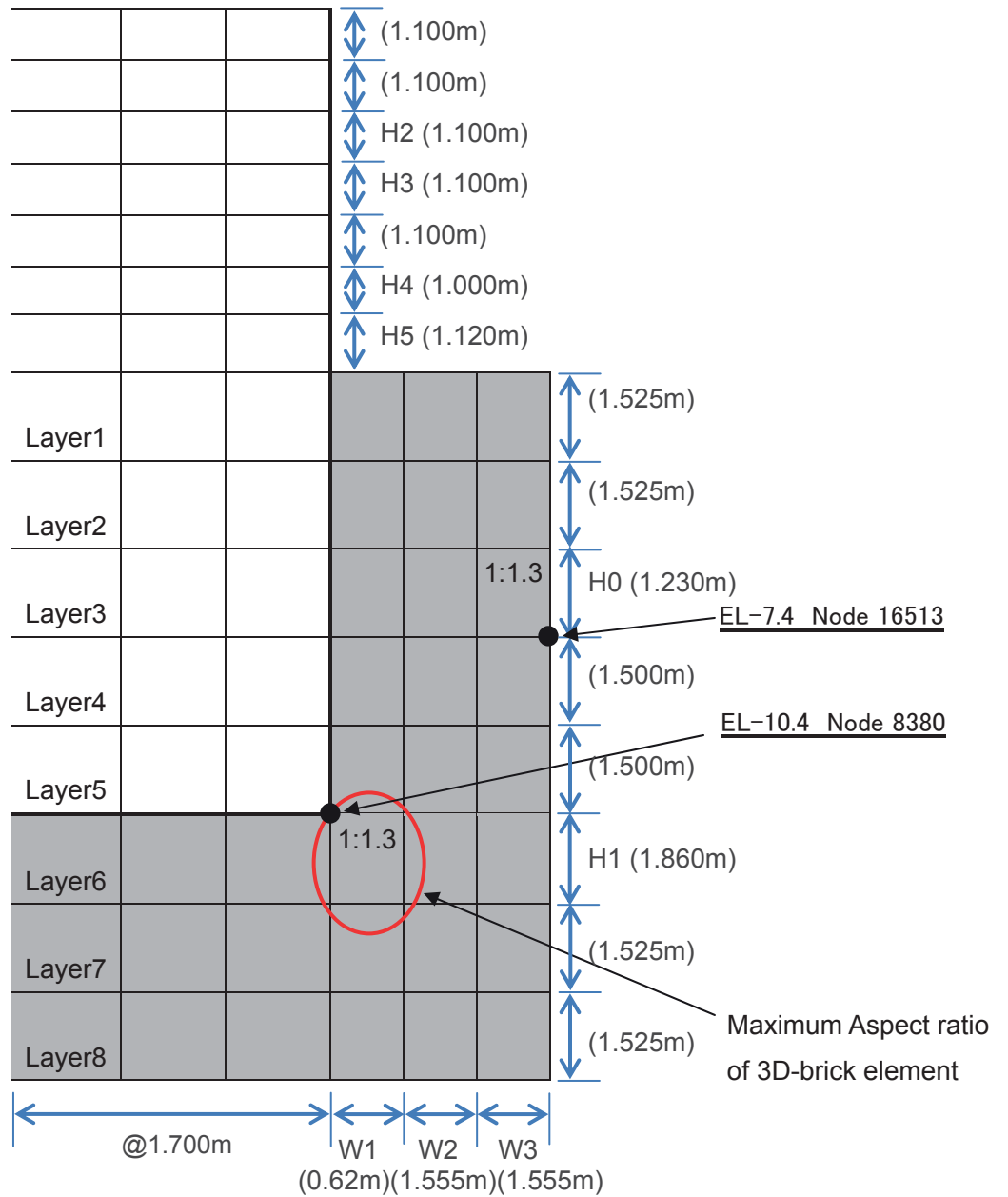


Figure A.10-9 Dimensions of Element Size for Case 4



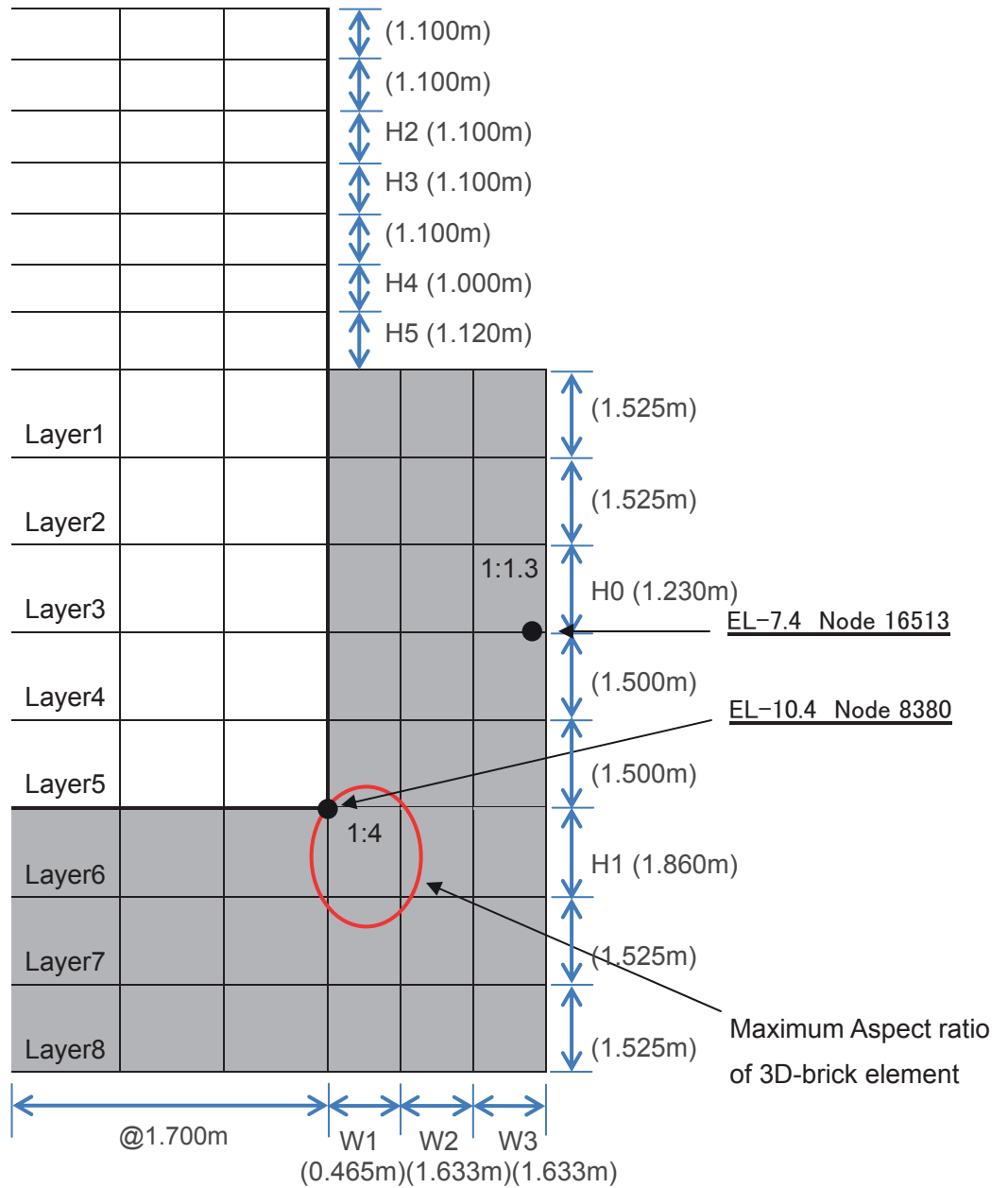


Figure A.10-10 Dimensions of Element Size for Case 5

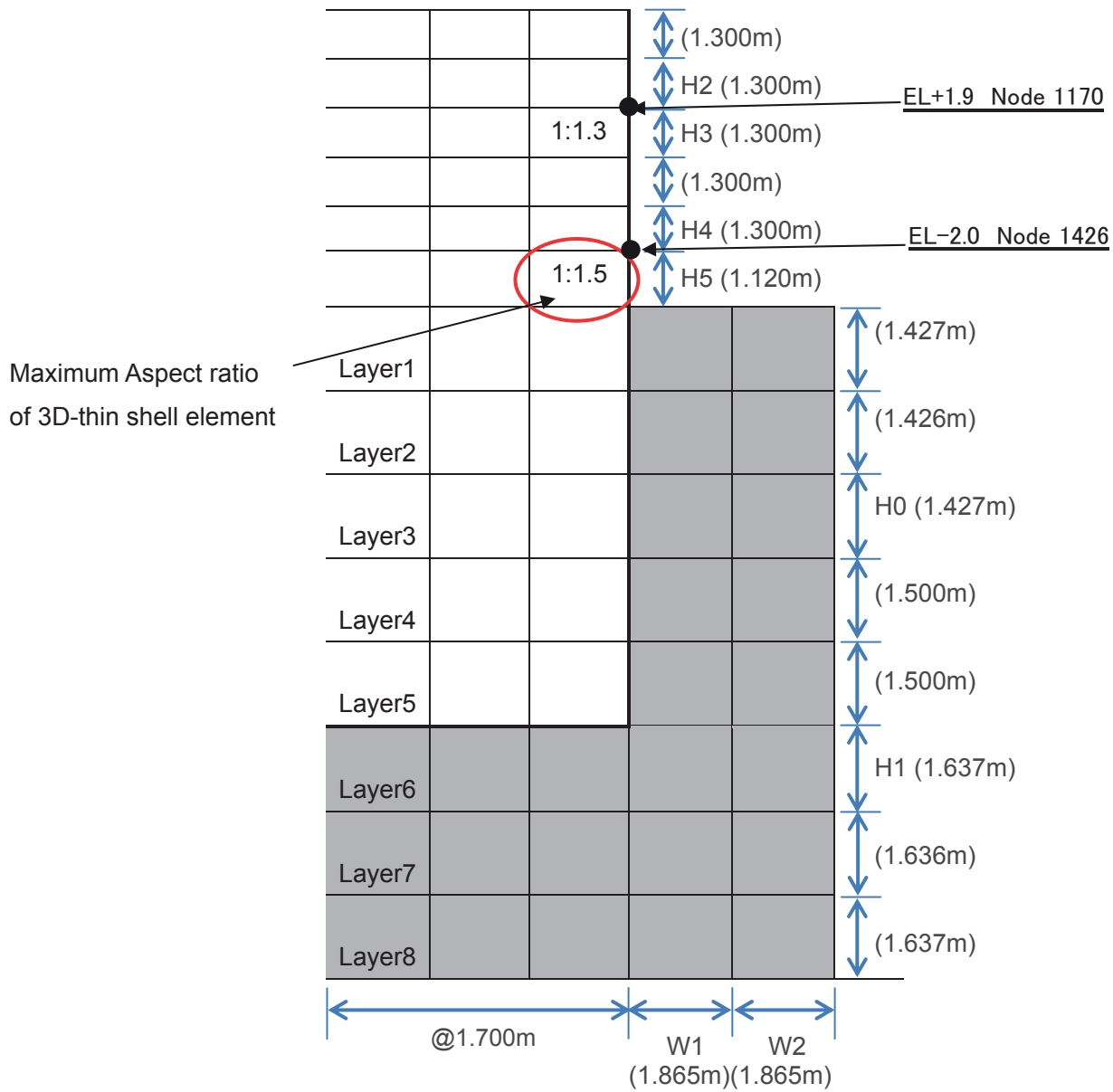


Figure A.10-11 Dimensions of Element Size for Case 6

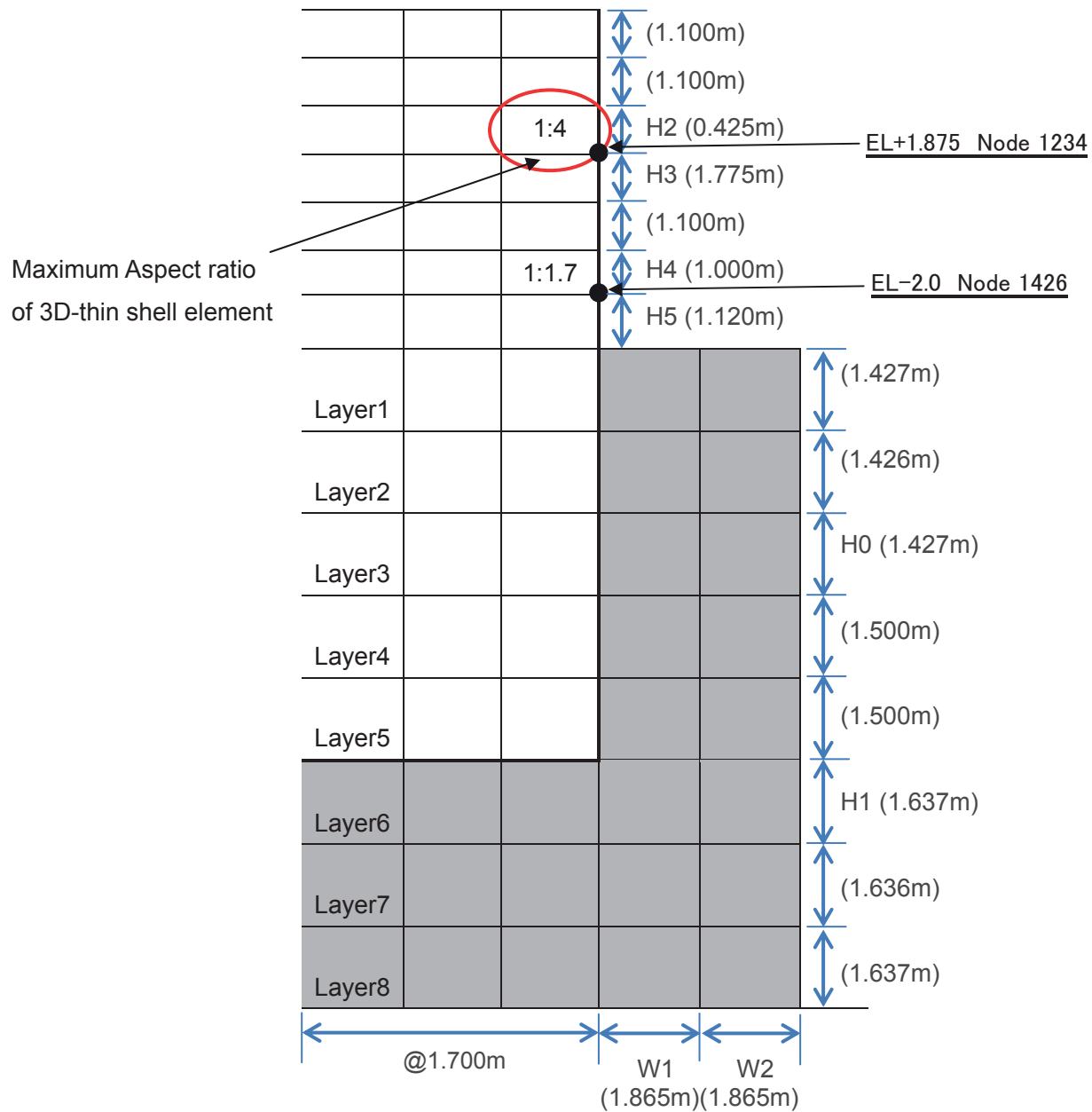


Figure A.10-12 Dimensions of Element Size for Case 7

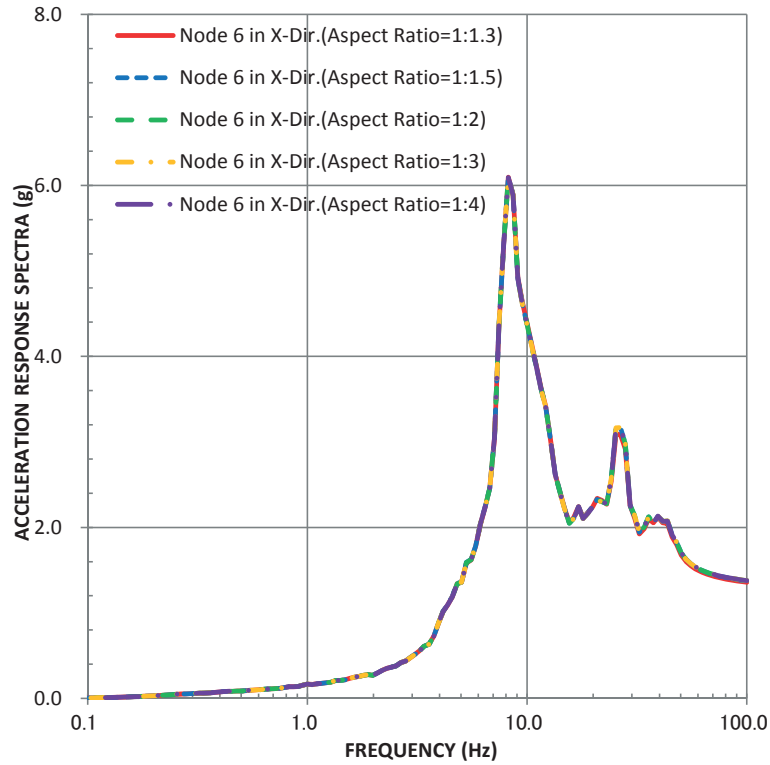


Figure A.10-13 Acceleration Response Spectrum in X-Dir. at Top stick (Node 6) for Cases 1 to 5

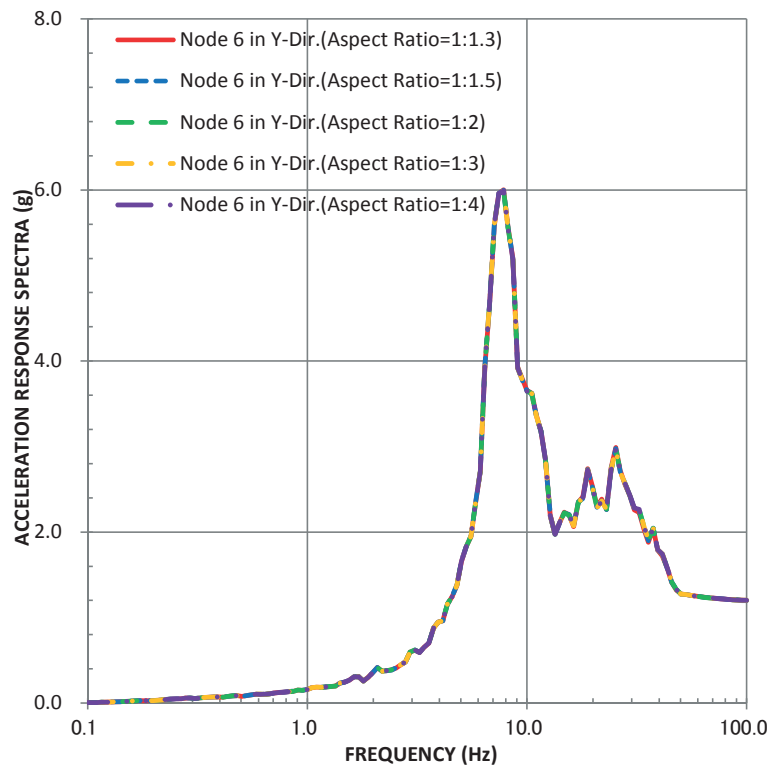


Figure A.10-14 Acceleration Response Spectrum in Y-Dir. at Top stick (Node 6) for Cases 1 to 5

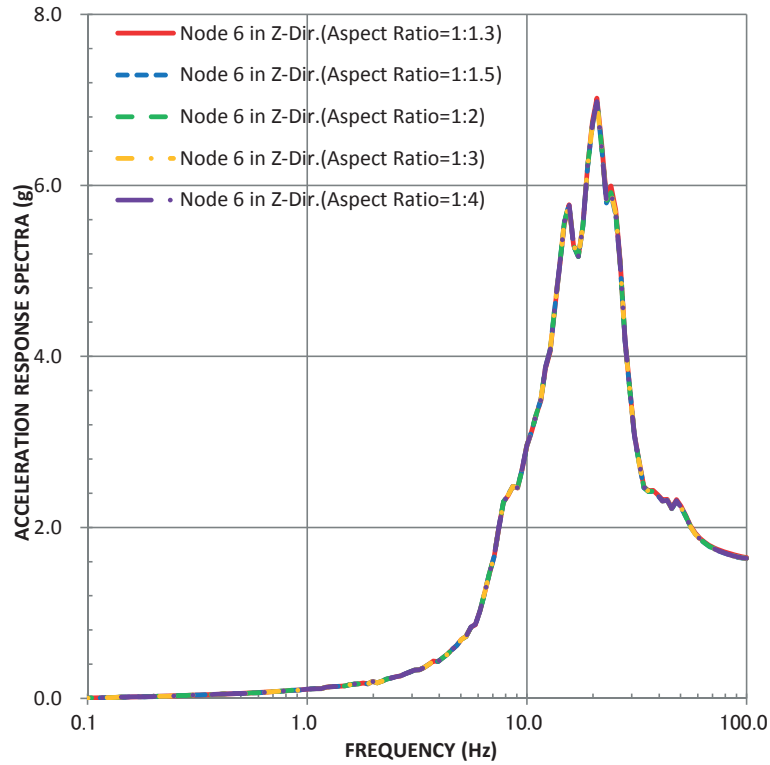


Figure A.10-15 Acceleration Response Spectrum in Z-Dir. at Top stick (Node 6) for Cases 1 to 5

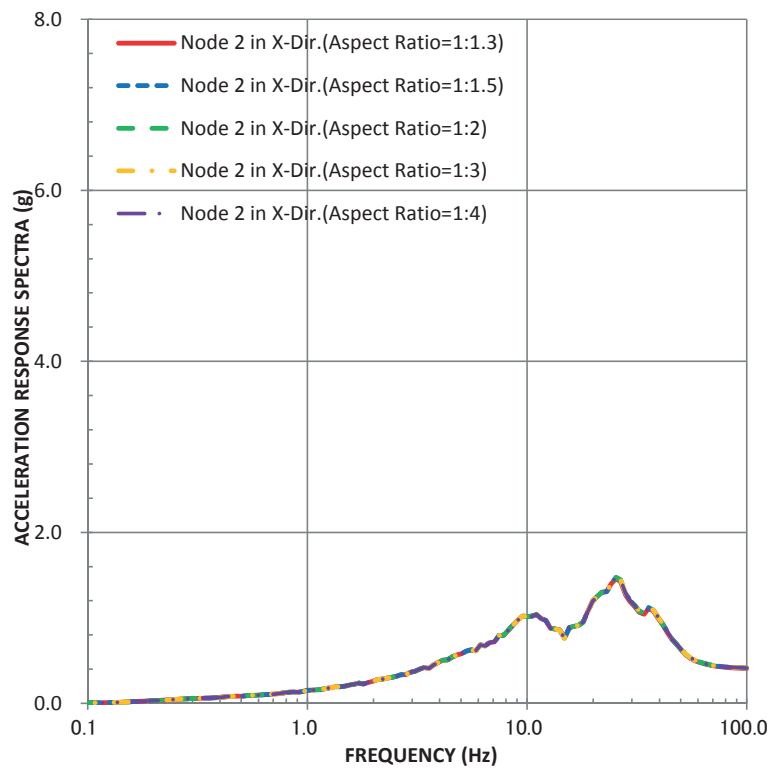


Figure A.10-16 Acceleration Response Spectrum in X-Dir. at Basemat (Node 2) for Cases 1 to 5

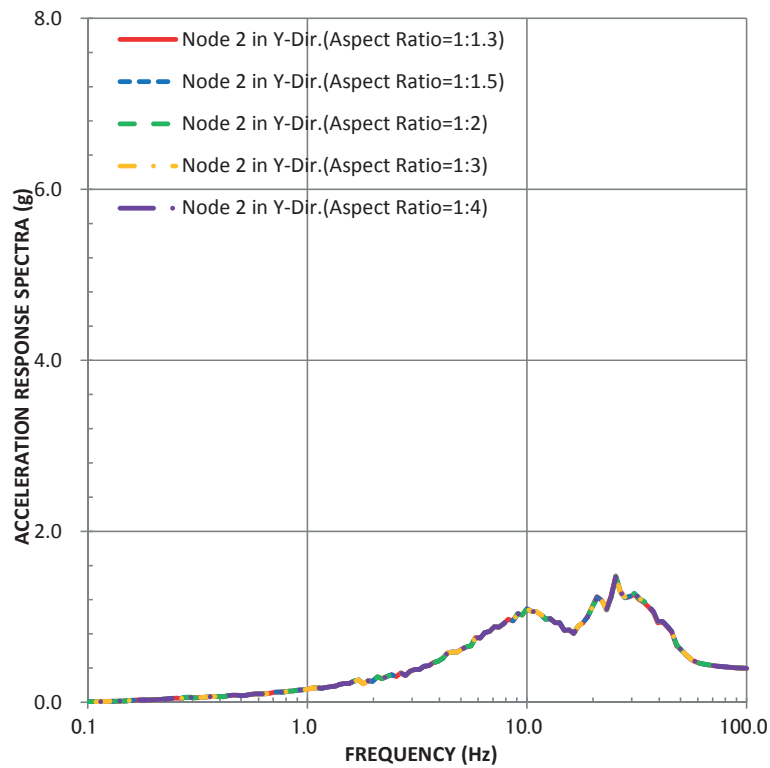


Figure A.10-17 Acceleration Response Spectrum in Y-Dir. at Basemat (Node 2) for Cases 1 to 5

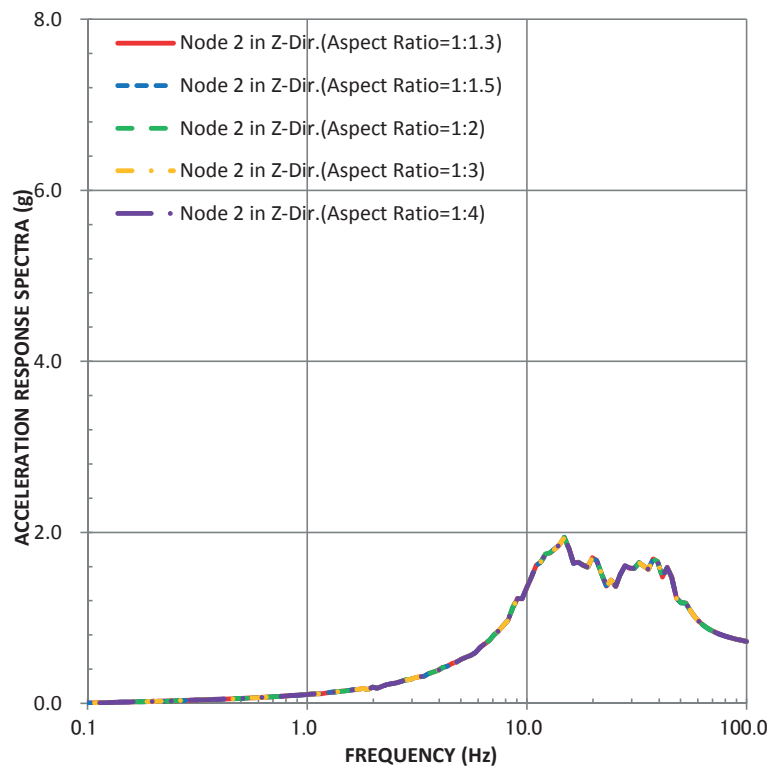


Figure A.10-18 Acceleration Response Spectrum in Z-Dir. at Basemat (Node 2) for Cases 1 to 5

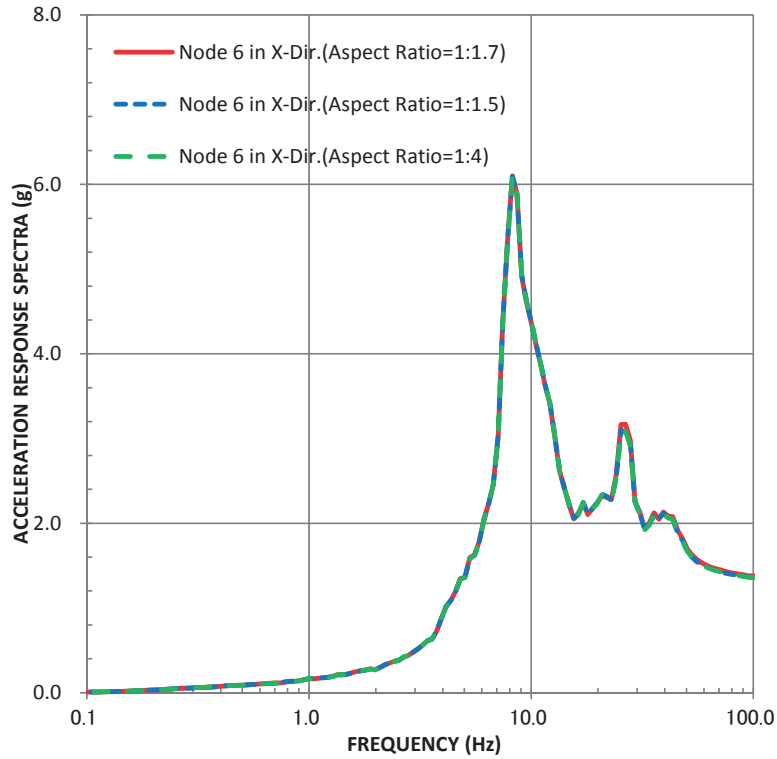


Figure A.10-19 Acceleration Response Spectrum in X-Dir. at Top stick (Node 6) for Cases 2,6 and 7

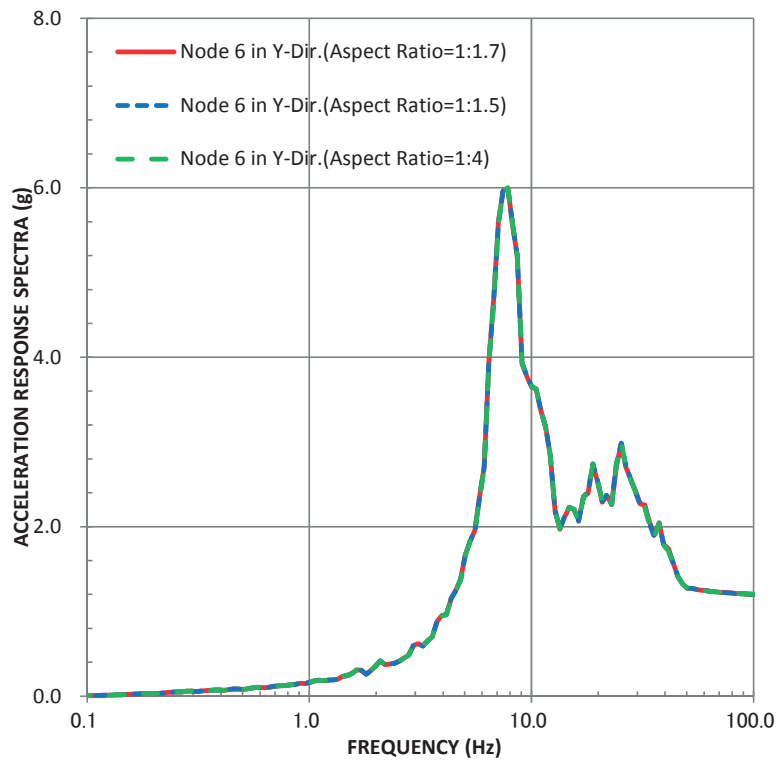


Figure A.10-20 Acceleration Response Spectrum in Y-Dir. at Top stick (Node 6) for Cases 2,6 and 7

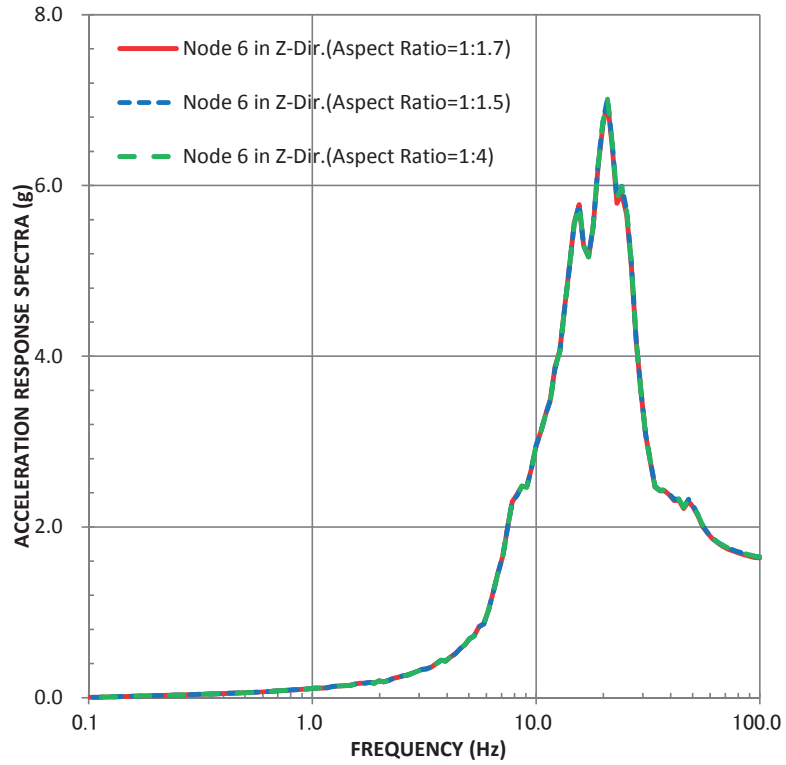


Figure A.10-21 Acceleration Response Spectrum in Z-Dir. at Top stick (Node 6) for Cases 2,6 and 7

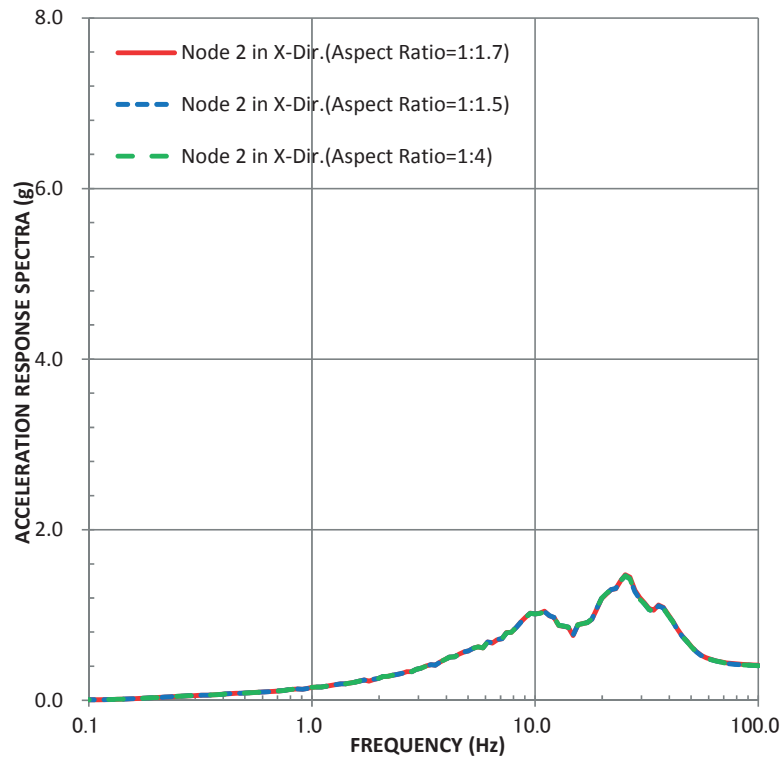


Figure A.10-22 Acceleration Response Spectrum in X-Dir. at Basemat (Node 2) for Cases 2,6 and 7



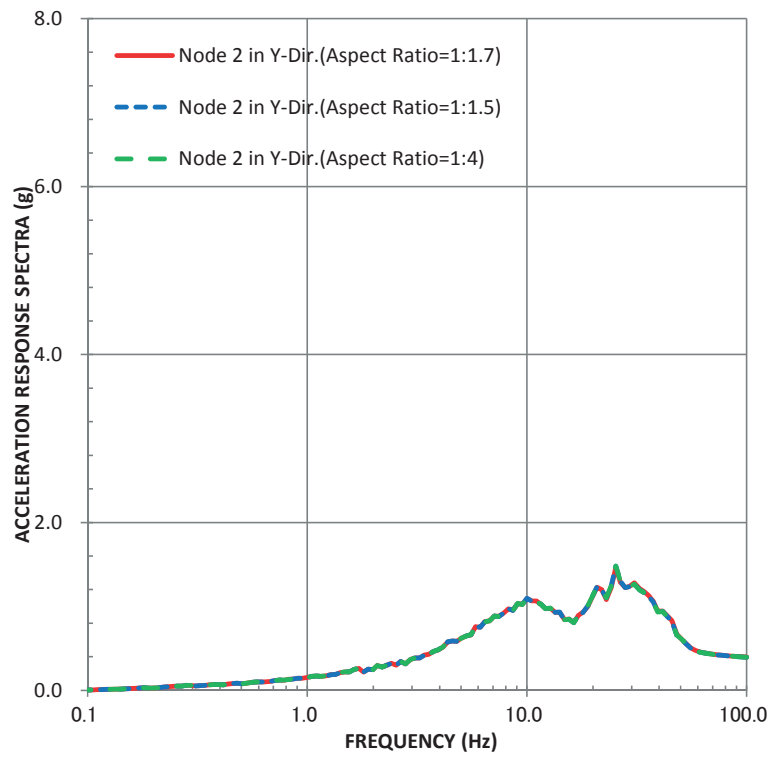


Figure A.10-23 Acceleration Response Spectrum in Y-Dir. at Basemat (Node 2) for Cases 2,6 and 7

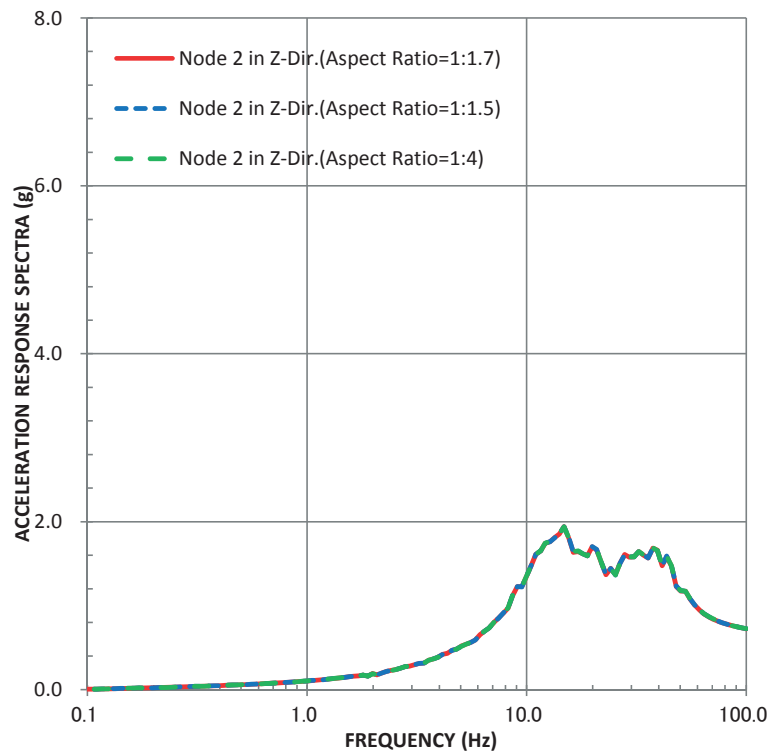


Figure A.10-24 Acceleration Response Spectrum in Z-Dir. at Basemat (Node 2) for Cases 2,6 and 7

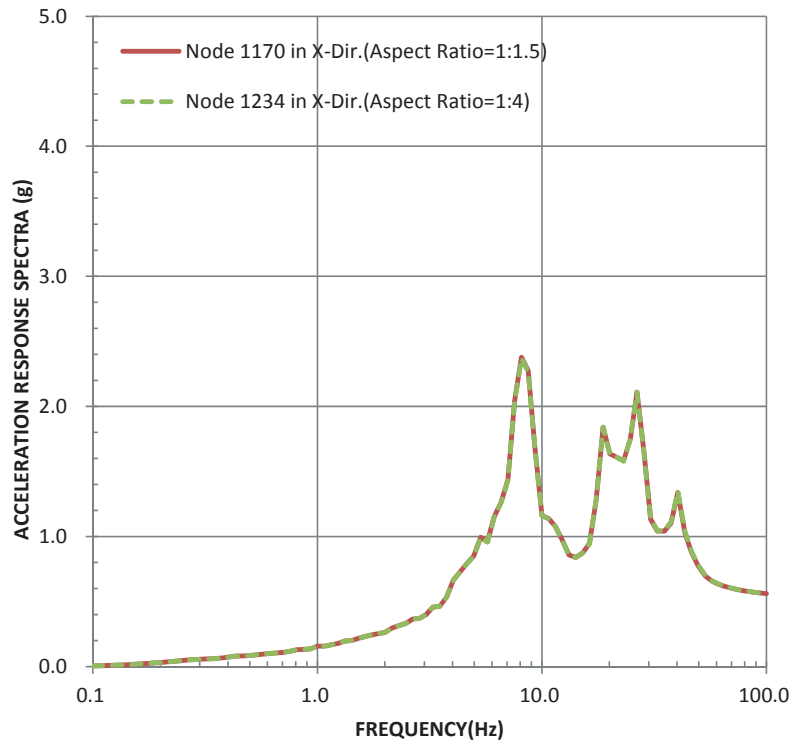


Figure A.10-25 Acceleration Response Spectrum in X-Dir.  
at Node 1170 and 1234 for Cases 6 and 7

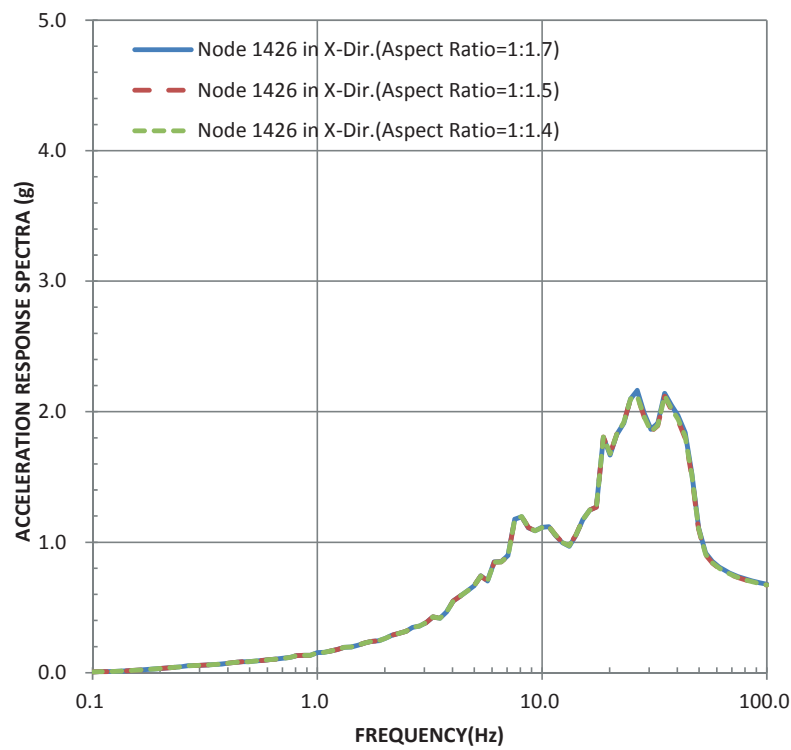


Figure A.10-26 Acceleration Response Spectrum in X-Dir.  
at Node 1426 for Cases 2, 6 and 7

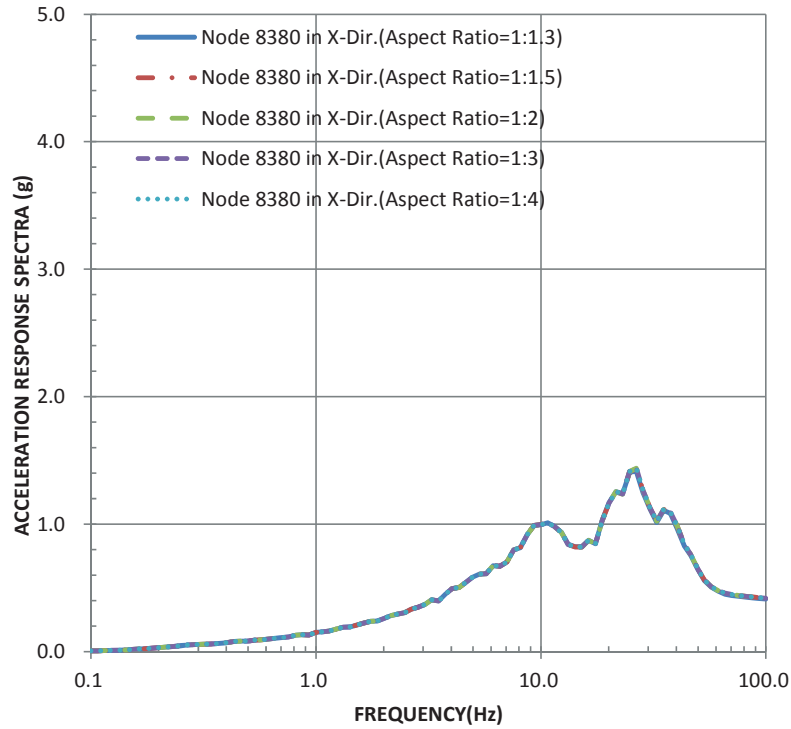


Figure A.10-27 Acceleration Response Spectrum in X-Dir.  
at Node 8380 for Cases 1 to 5

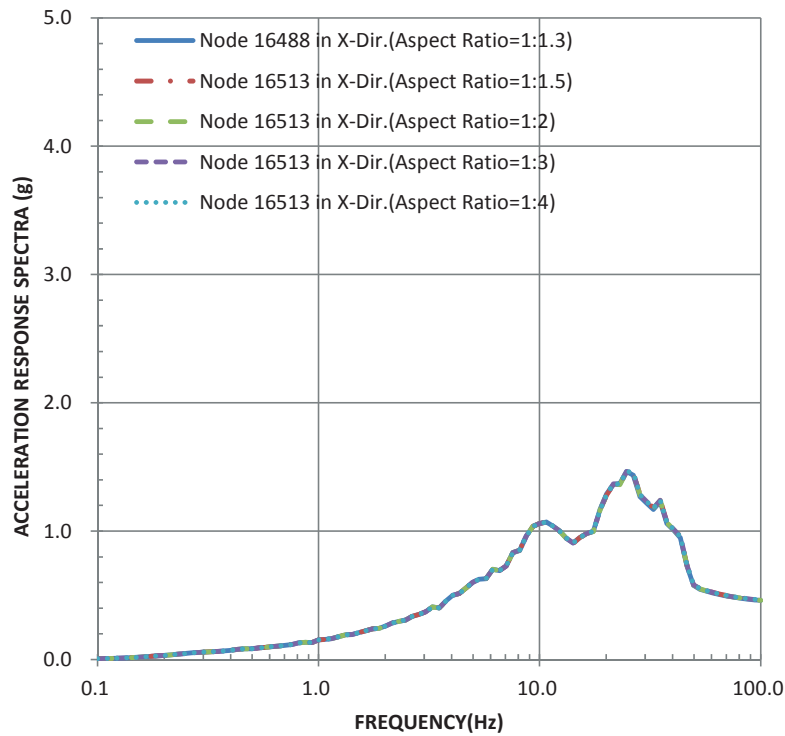


Figure A.10-28 Acceleration Response Spectrum in X-Dir.  
at Node 16488 and 16513 for Cases 1 to 5

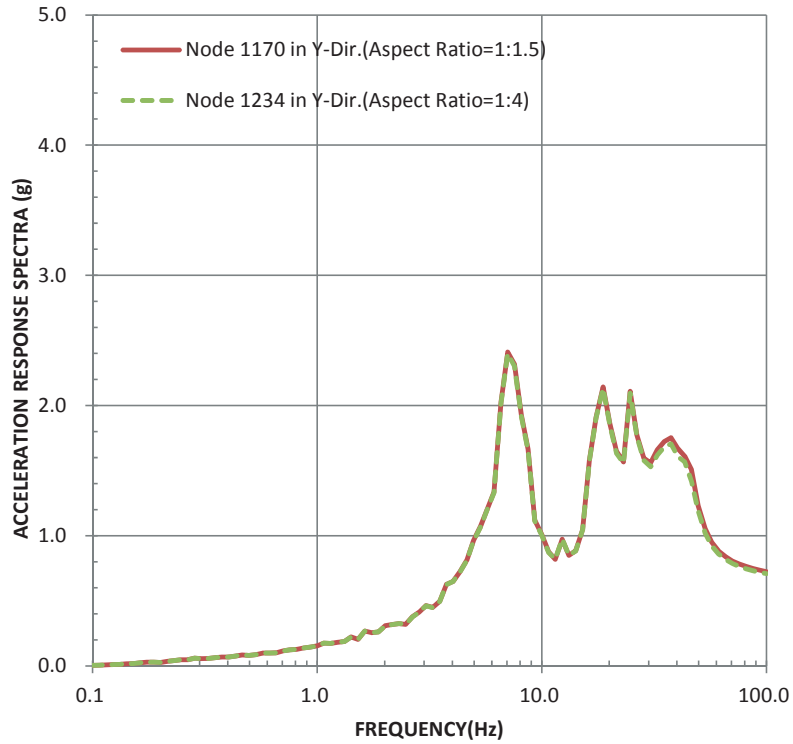


Figure A.10-29 Acceleration Response Spectrum in Y-Dir.  
at Node 1170 and 1234 for Cases 6 and 7

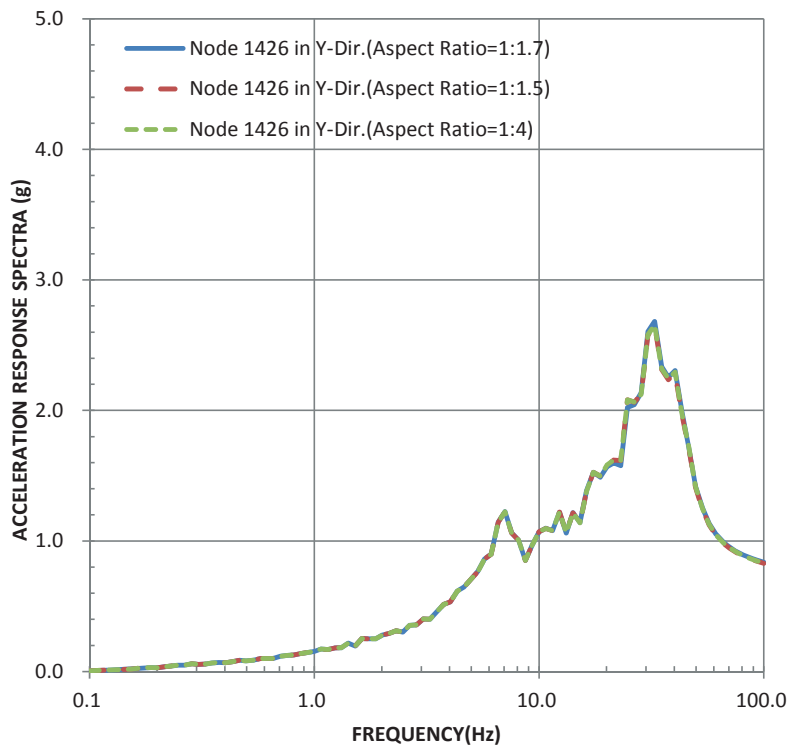


Figure A.10-30 Acceleration Response Spectrum in Y-Dir.  
at Node 1426 for Cases 2, 6 and 7

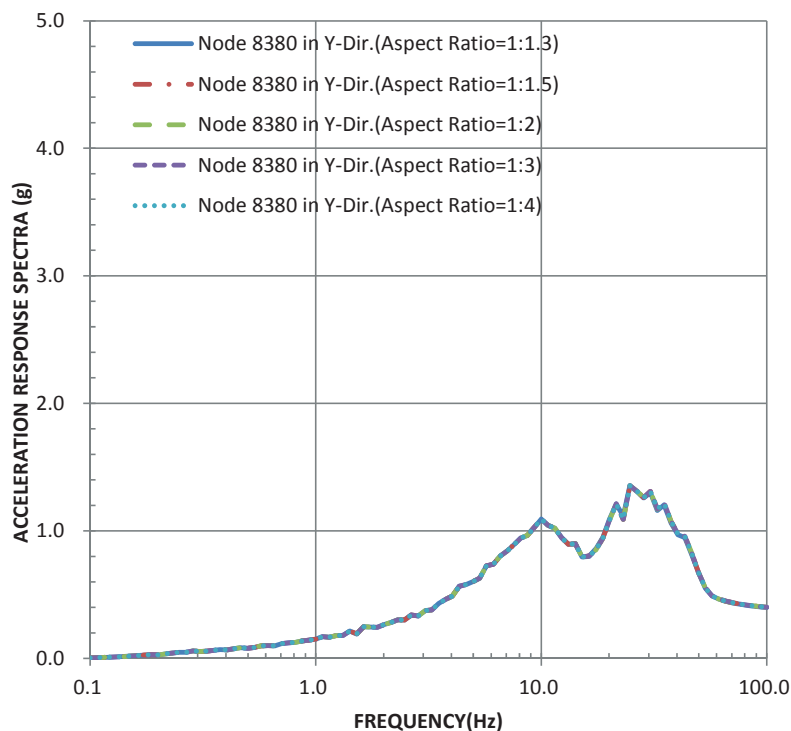


Figure A.10-31 Acceleration Response Spectrum in Y-Dir.  
at Node 8380 for Cases 1 to 5

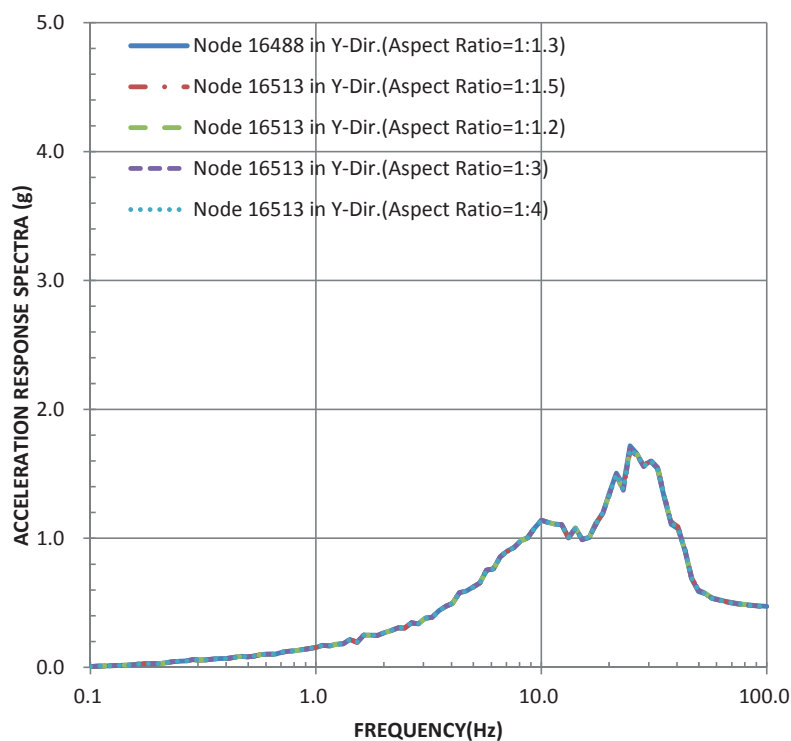


Figure A.10-32 Acceleration Response Spectrum in Y-Dir.  
at Node 16488 and 16513 for Cases 1 to 5

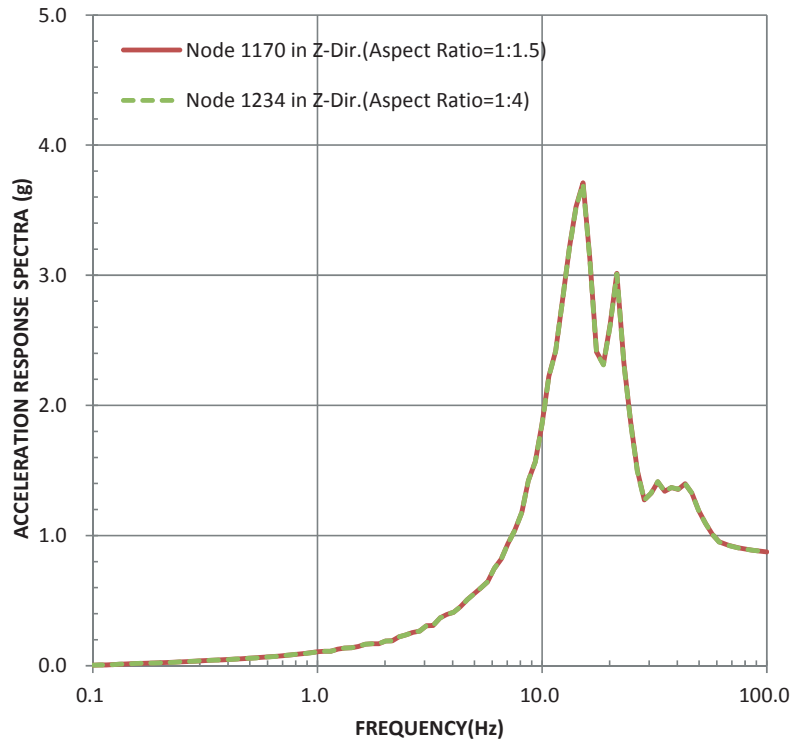


Figure A.10-33 Acceleration Response Spectrum in Z-Dir.  
at Node 1170 and 1234 for Cases 6 and 7

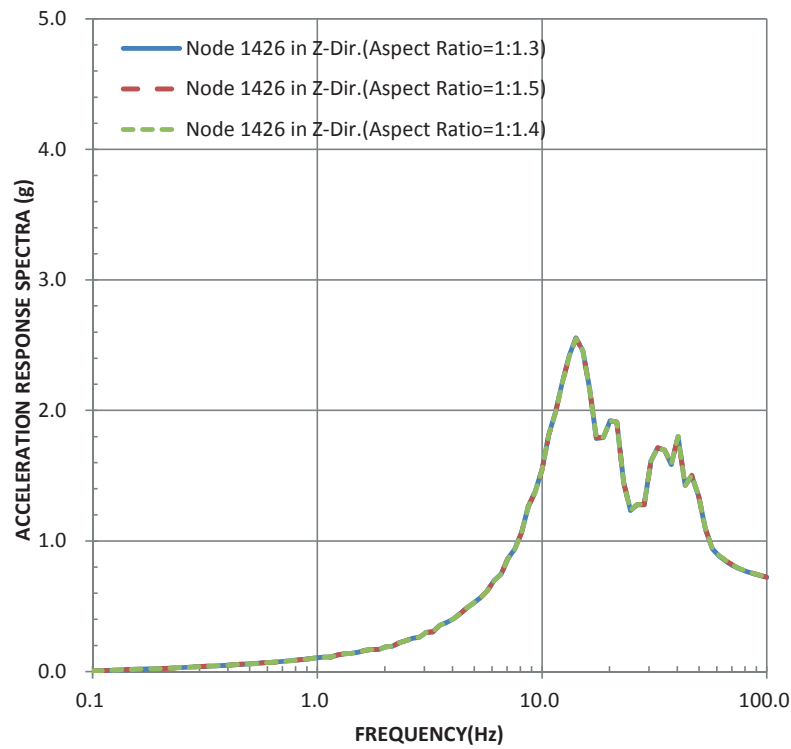


Figure A.10-34 Acceleration Response Spectrum in Z-Dir.  
at Node 1426 for Cases 2, 6 and 7

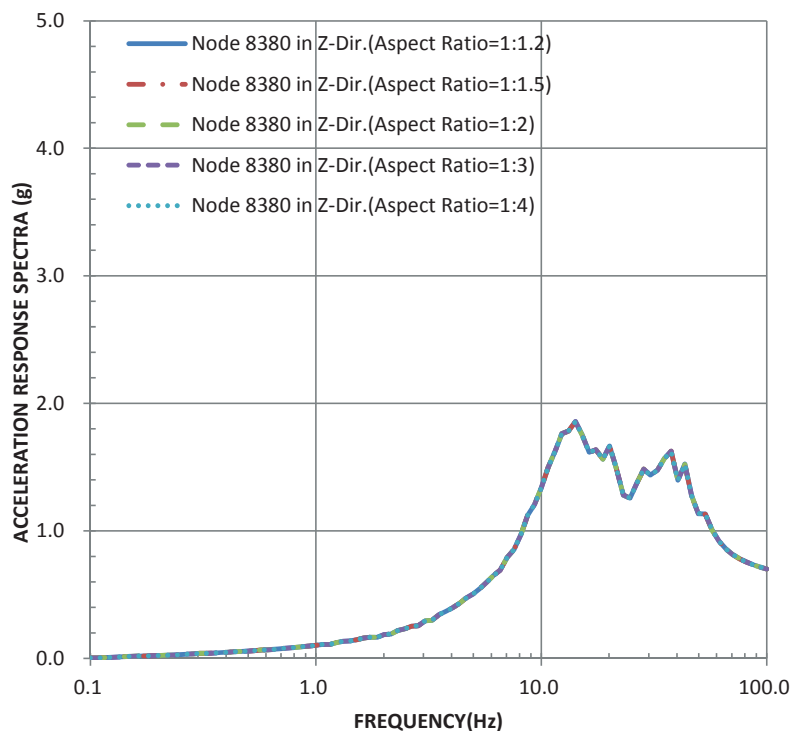


Figure A.10-35 Acceleration Response Spectrum in Z-Dir.  
at Node 8380 for Cases 1 to 5

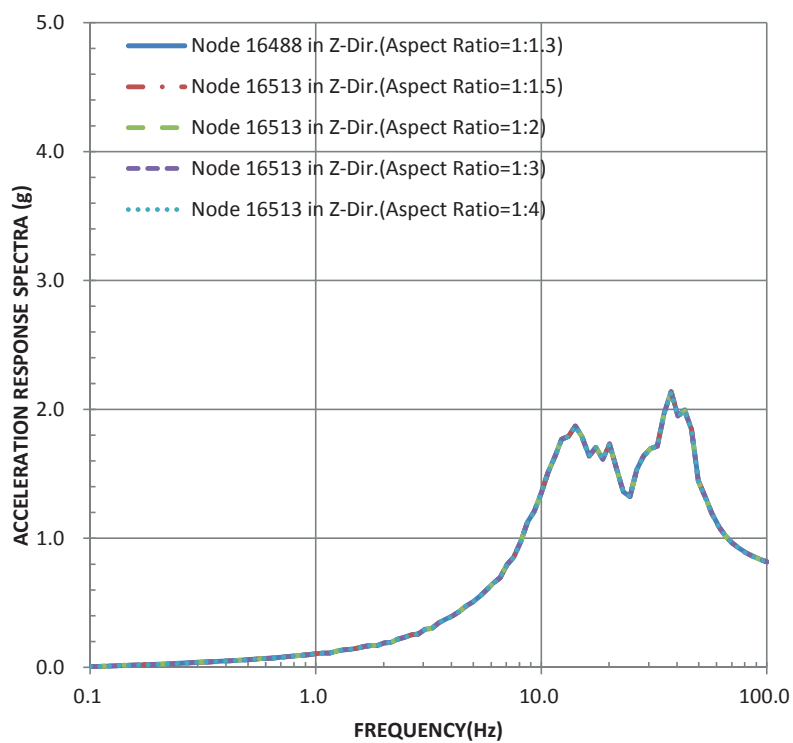


Figure A.10-36 Acceleration Response Spectrum in Z-Dir.  
at Node 16488 and 16513 for Cases 1 to 5