ANALYSIS OF SOIL-STRUCTURE INTERACTION DUE TO AMBIENT VIBRATION

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ABSTRACT

This paper presents the results of a study to evaluate the effects of soil-structure interaction (SSI) on the ambient vibration response of the switchyard/target area (S/TA) buildings at the National Ignition Facility (NIF) presently under construction at the Lawrence Livermore National Laboratory (LLNL) in Livermore, California. This laser facility houses optical and other special equipment whose alignment stability is sensitive to vibrations caused by ambient vibrations or other vibrating sources. In evaluating the deformations and displacements of the S/TA structures, the contribution of the SSI to the overall system flexibility can be very significant. The present study examines the results of fixed-base and SSI analyses of these massive, stiff structures to develop an understanding of the potential contribution of SSI to the overall system displacements and deformations. A simple procedure using a set of factors (β) is recommended for scaling the results of fixed-base analyses to approximately account for the SSI effects.

INTRODUCTION

Design and evaluation of laser facilities to mitigate vibrations caused by ambient vibration sources or other vibrating equipment often results in massive, stiff reinforced concrete (RC) shear wall structures in order to meet stringent vibration requirements. Classical fixed-base analyses of these massive, stiff structures result in small structural deformations or displacements, as may be expected. However, these structures are, often, supported in flexible foundation media that makes the fixed-base (infinitely rigid foundation) assumption invalid. The foundation flexibility can influence the deformations or displacements of these structures in several ways, such as shifting the fixed-base structural frequencies, introducing additional damping through foundation material and scattering effects, allowing rotation of the structure at the base and imparting non-uniform support motions into the structure.

The present study involves SSI analyses of the NIF S/TA buildings using computer code SASSI [1, 2] to evaluate the effects of foundation flexibility on the ambient vibration response of the alignment-sensitive, special equipment supported within these buildings. Fixed-base analyses of the S/TA buildings were performed using SASSI to provide a benchmark against SSI results. The results of fixed-base and SSI analyses are used to (a) quantify the contribution of SSI to overall system deformations and displacements and (b) develop simple factors for scaling the results of fixed-base analyses to approximately account for the SSI effects.

STRUCTURE MODEL

A general view of the NIF is shown in Fig.1. The facility houses alignment-sensitive, special equipment, which consists of steel and/or RC frames, supported on two laser bay slabs and within two switchyards and a target area buildings. The target area building consists of a RC cylinder, approximately 110 feet in diameter, embedded approximately 34 feet below ground surface. On the north and south sides the target area is connected to two switchyard buildings. The switchyard buildings consist of RC box structures, approximately 100 feet by 110 feet in plan dimensions, embedded approximately 22 feet below ground surface. The horizontal supports for the switchyard steel structures are primarily located at the vertical corners of the switchyard concrete walls and cylindrical wall of target bay. Figure 3 shows a typical section through the S/TA buildings. The structural properties for switchyard and target area are summarized in Table 1 and 2, respectively. The material properties for prestressed concrete girders are

f'_c=6,000 psi and $E=4.5\text{x}10^6$ psi, and for concrete floor, roof and walls are f'_c=4,000 psi and $E=3.6\text{x}10^6$ psi.

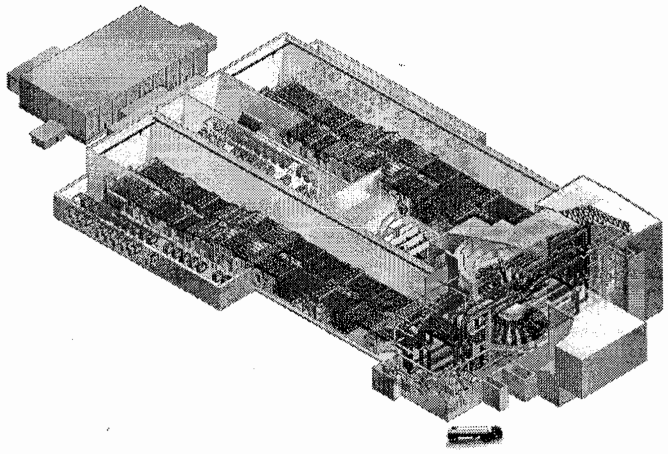

Figure 1 The National Ignition Facility

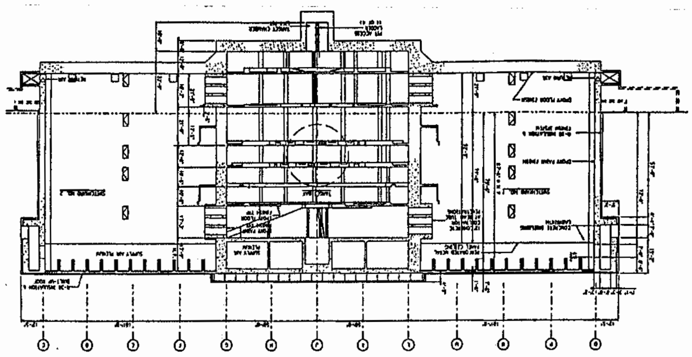

Figure 2 Elevation View of S/TA Building

Table 1 Summary of Structural Properties, Switchyard

Item	Thickness (feet)	Area (sq. feet)	Weight (kips)
Foundation Mat (El. –22')	6	10,000	9,750
Steel Frame (El. 69 & 50')		7,000	371
Steel Frame (El. 7 & 40')		7,000	63
Steel Frame (El. 29')		7,000	420
Steel Frame (El. -4 & 17')		7,000	490
Roof (El. 89')	1.5	10,000	3,100
West Wall	2.75		
North & South Walls	3.25		
East Wall	3.75		
East Stair Walls	2		
East Connector Walls	2.5		

Table 2 Summary of Structural Properties, Target Area

Item	Thickness (feet)	Area (sq. feet)	Weight (kips)
Foundation Mat (El. -34')	6	7,853	7,853
Floor (El. –22')	1	7,538	2,073
Floor (El. –4')	1	6,596	1,814
Floor (El. 17')	1	5,617	1,545
Floor (El. 29')	1	5,617	1,545
Floor (El. 40')	1	3,376	929
Floor (El. 50')	1	6,596	1,814
Floor (El. 69')	2	7,651	3,252
Roof (El. 89')	2.5	7,853	3,141
Cylindrical Wall	6		
Target Sphere			1,130
Target Pedestal			450

A simplified finite element model of the S/TA buildings was developed for this study. To keep the size of the model manageable, the interior details were simplified by incorporating the mass and stiffness of the framing and equipment into the floor slabs. Furthermore, advantage was taken of symmetry by modeling only one-half of the buildings about y-axis. Figure 3 shows the finite element structural model. The Structural properties for switchyard and target area models are presented in Tables 3 and 4, respectively. Floor masses are tabulated in Table 5.

FIXED-BASE STRUCTURAL FREQUENCIES

Fixed-base modal frequency analyses of the S/TA buildings were performed using computer codes SASSI and SAP90 [3]. The input motion for SASSI analysis consisted of unit amplitude harmonic motions applied at the base of the structure in the y- and z-directions.

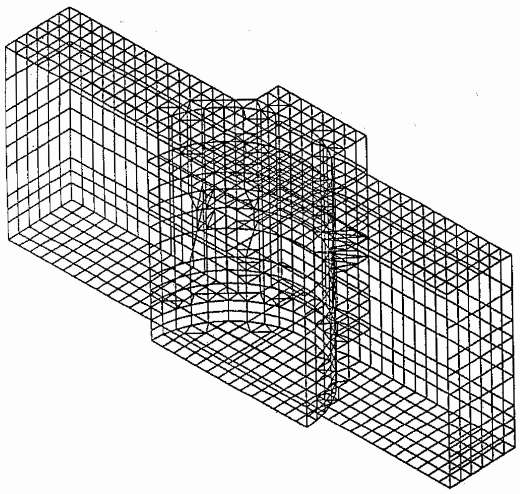

Figure 3 Finite Element Structural Model

Table 3 Properties of F.E. Model, Switchyard

Item	Switchyards				
	Base-mat	Roof Slab	North Wall	East Wall	South Wall
Element Type	Four-Node Flat Plate				
No. of Elements	208	208	54	432	54
MaterialType	Concrete				
Thickness (feet)	6.0	1.5	3.25	3.75	3.25
Young Modulus (psi)	3.6E6				
Poisson's Ratio	0.17				
Unit Weight(1) (pcf)	153.7	195.4	150	150	150
Structural Damping	0.02				

Table 4 Properties of F.E. Model, Target Area

Item	Target Area			
	Basemat	Lower Roof Slab	Upper Roof Slab	Cylindrical Walls
Element Type	Four-Node Flat Plate			
No. of Elements	90	90	90	220
Material Type	Concrete			
Thickness (feet)	6.0	2.0	2.5	6.0
Young Modulus (psi)	3.6E6			
Poisson's Ratio	0.17			
Unit Weight(1) (pcf)	159.8	1187.8	145.1	150
Structural Damping	0.02			

Table 5 Summary of Floor Masses

Floor Elevations	Floor Mass (kips)	
(feet)	Switchyard	Target Area
-37	---	3,926.5(1)
-25	9,750(1)	1,036.5
-7.5	490	907
0	63	--
+17	490	7,72.5
+29	420	7,72.5
+40	63	4,64.5
+50	371	907
+68	371	1,626(1)
+88	3,100(1)	1,570.5(1)

[1] Not modeled as lumped mass; unit weight of floor slabs was modified to include these masses.

The transfer functions obtained from SASSI analyses at the center of the switchyard wall, switchyard roof and target area roof are shown in Figures 4, 5 and 6, respectively.

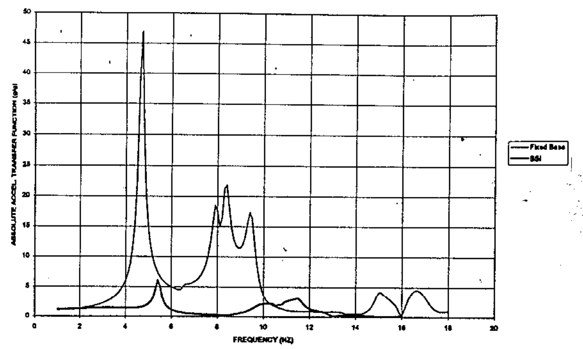

Figure 4 Absolute Horizontal (y) Acceleration Transfer Function, Center of Switchyard Wall

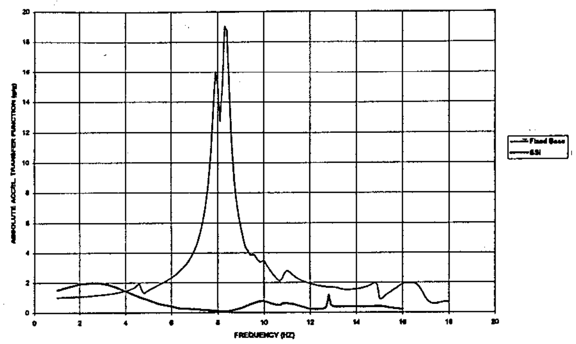

Figure 5 Absolute Horizontal (y) Acceleration Transfer Function, Center of Switchyard Roof

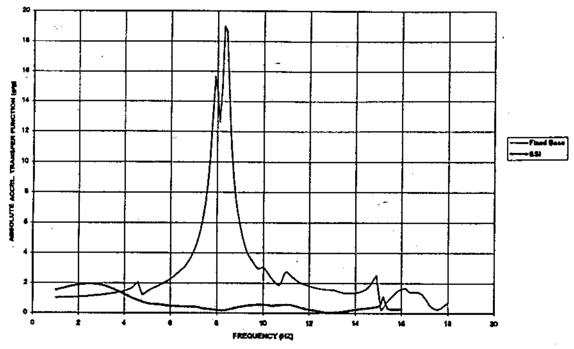

Figure 6 Absolute Horizontal (y) Acceleration Transfer Function, Center of Target Area Roof

Based on the transfer functions shown in Fig. 4, 5 and 6 the first three horizontal modes of the building were estimated (see Table 6). We also performed fixed-base modal analyses of this model using computer code SAP90. The first three horizontal natural frequencies of the fixed-base model computed by SAP90 are also presented in Table 6.

Table 6 Comparison of Fixed-Base Horizontal Modal Frequencies, SASSI vs. SAP90

Description	Modal Frequency (Hz)	
	SASSI	SAP90
Switchyard	4.69	4.59
Switchyard/Target Area	7.93	7.78
Switchyard/Target Area	8.41	8.55

As shown in Table 6 the horizontal fixed-base modal frequencies of S/TA buildings computed from SASSI and SAP90 models are in good agreement. The first mode represents out-of-plane bending of the switchyard shear walls. The next two modes represent the shear deformation of the switchyard wall and target area cylinder. The fixed-base model shape at f=7.78 Hz is shown in Figure 7.

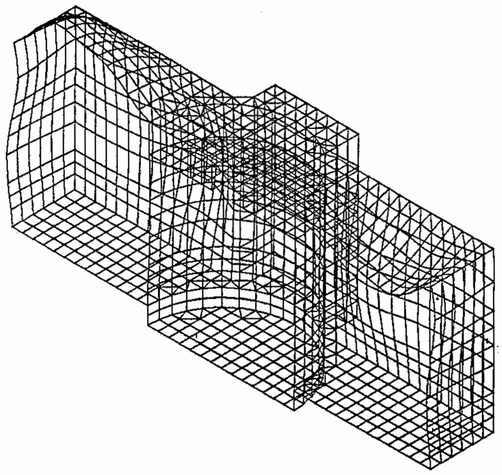

Figure 7 Fixed-Base Structural Mode Shape (f=7.78 Hz)

SOIL CONDITION

The NIF site is blanketed by about 6- to 15-foot thick layer of compacted fill underlain by alluvial deposits consisting of interbedded layers of silty sand, sand, gravely sand and sandy silt [4]. The consistency of subsurface soils, in general, increases with depth. The groundwater table at the site is reported at a depth of about 55 to 75 feet. A typical soil profile across the site is shown in Fig 8.

Low strain dynamic soil properties in terms of compressional (P) and shear (S) wave velocities were estimated from the results of geophysical tests [5] using down-hole procedure. The results of down-hole tests in terms of P- and S-wave velocities versus depth are plotted in Fig. 9 and 10, respectively. These figures also show a lower bound, upper bound and best estimate P- and S-wave velocities developed for this study. The total soil unit weight was set to 135 pound per cubic foot (pcf).

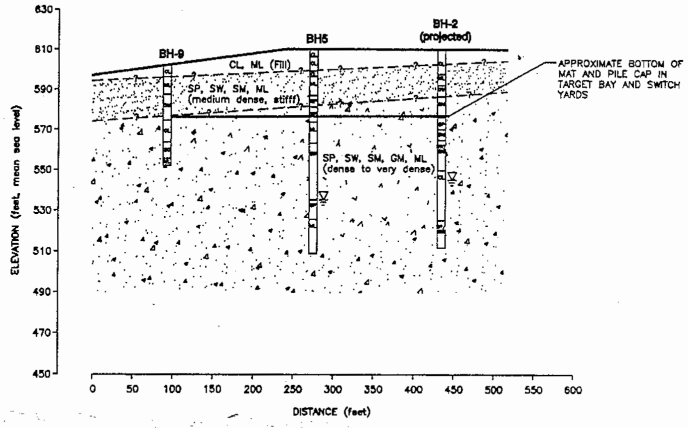

Figure 8 Idealized Soil Profile

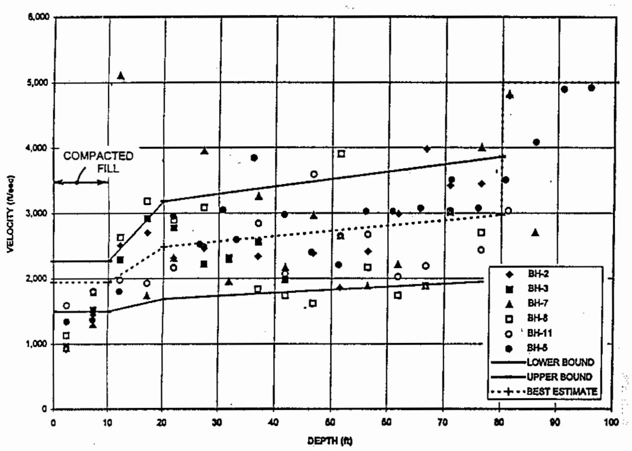

Figure 9 P-Wave Velocity Profile

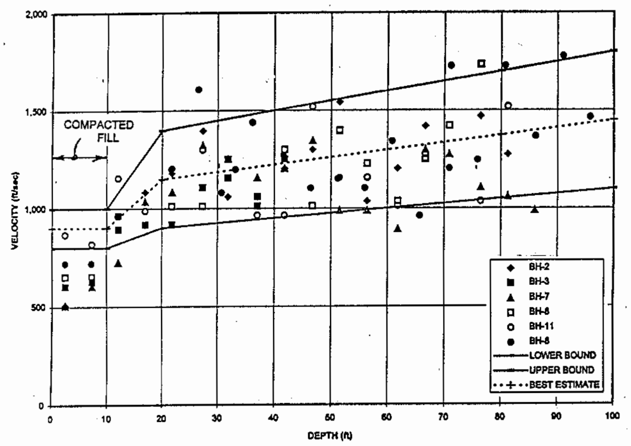

Figure 10 S-Wave Velocity Profile

AMBIENT VIBRATION CHARACTERIZATION

Ambient vibrations at NIF site include such sources as vehicular traffic, micro-seismic activity, nearby vibrating machinery, etc. These ground disturbances were measured in terms of power spectral density (PSD) spectra at various locations at the site [5]. Based on these measurements, the input PSD criteria shown in Table 7 was developed [6]. The RMS displacement for the input PSD spectra is 0.69 $*10^{-6}$ (0.210 Microns). The PSD input is specified at the free field ground surface.

Table 7 - PSD Input Function

Frequency (Hz)	PSD Acceleration Amplitude (g2/Hz)
1	1.0E-13
1 - 2	Linear interpolation on log-log plot
2	1.0E-11
2 - 70	1.0E-11
70	1.0E-11
70 - 80	Linear interpolation on log-log plot
80	1.0E-10

METHODS OF ANALYSES

The computer code SASSI was utilized for the present study. SASSI (System for Analysis of Soil-Structure Interaction) has been developed at the University of California at Berkeley, and is based on a new substructuring procedure, called the Flexible Volume Method. The new method differs from other substructuring methods in the manner in which the mass and stiffness matrices of the structure are partitioned from those of the soil; as a result, the procedure allows the solution of three-dimensional structures supported on foundations with arbitrary shapes founded on or embedded in a layered viscoelastic halfspace. SASSI can also be used to solve fixed-base structures by assigning rigid foundation properties. The entire analysis is performed in the complex frequency domain.

Analyses of the ambient vibration excitation were performed using random vibration analysis procedures. The input excitation is defined in terms of acceleration power spectral density (PSD) spectra.

Fixed-Base Analyses

Fixed-base analyses of the S/TA buildings were performed using SASSI and the results were used as a benchmark against those of SSI analyses. The SASSI model was subjected to uniform base excitation separately in each of the horizontal (y) and vertical (z) directions.

SSI Analysis

SSI analyses of the S/TA-foundation soil system were performed using SASSI to evaluate the effects of foundation flexibility on the ambient vibration response of the structures. The SASSI structural model for SSI analyses is, essentially, the same as those used in fixed-base analyses (see Fig. 3). The corresponding SASSI model for the excavated soil is shown in Fig. 11. The SASSI soil model consists of a layered soil system overlying a uniform half-space.

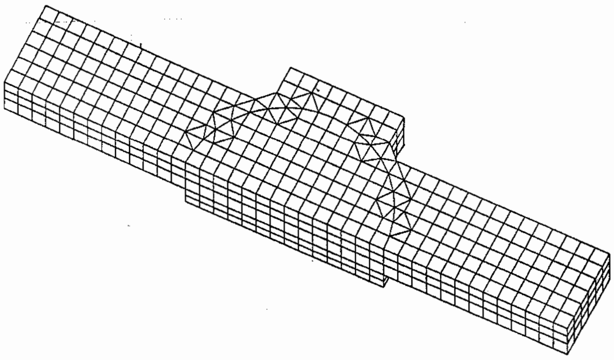

Figure 11 Excavated Soil Model

Ambient vibration wave field, in general, consists of a complex mixture of surface and body waves approaching the site from different directions. This is evidenced by random nature of the measured ambient vibrations in terms of PSD spectra in three directions (two horizontal and one vertical) at the NIF site.

For the present study, the free field ambient vibration input wave field was assumed to consist of 100 percent fundamental Rayleigh waves propagating horizontally in the y-direction. Rayleigh waves, which are similar to gravitational surface waves in liquids, constitute majority (about 70 %) of the waves generated by the ambient vibration sources. Rayleigh waves travel slower than that of body waves and their amplitudes decrease rapidly with depth.

The assumption of ambient vibration wave field consisting of 100 percent fundamental Rayleigh waves propagating in the y-direction results in a fully correlated horizontal (y) and vertical (z) component of the free field ground motions. Therefore, to fully define the input wave field, only one of the either horizontal (y) or vertical (z) component of the free field ground motion needs to be specified. For the present study, the control motion (PSD input) was defined to be the horizontal (y) component of the ground motion at a point corresponding to the centerline of the S/TA buildings at free field ground surface. It should be noted that the control motion defined at this point would be different from the motion computed at the base of the building (this is generally the input to the fixed-base model) due to the SSI effects.

The selected location of the free field control motion within the building footprint is arbitrary and should not affect the response of the structure significantly. This is due to the fact that the attenuation of the Rayleigh wave amplitudes with distance within the NIF building area is expected to be small.

DISCUSSION OF RESULTS

The response of the fixed base and SSI analyses were computed in terms of (a) absolute acceleration and displacement transfer functions due to unit amplitude harmonic input motion and (b) absolute and relative RMS displacements due to the acceleration PSD input motion. The results of the fixed-base and SSI analyses are first examined in terms of transfer functions to gain insight into the dynamic behavior of the system. Then, the final results in terms of RMS displacements due to ambient vibration input PSD are presented and discussed.

Transfer Function Response

Absolute Acceleration Transfer Function. Figures 4, 5 and 6 show comparisons of the fixed-base and SSI results in terms of absolute acceleration transfer functions in y-direction at the center of the switchyard wall, switchyard roof and target area roof, respectively. The results in z-direction at the center of switchyard and target area roofs are shown in Figures 12 and 13, respectively. From examination of the above results, several observations can be made:

(a) There is a significant shift in the fixed-base horizontal modal frequencies of the structure toward higher frequencies when the SSI effects are considered (see Figures 4, 5 and 6). This shift is primarily a result of the lateral stiffening of the basement walls due to the foundation soil confinement. In the vertical direction, the amount of frequency shift due to SSI effects is more significant for the switchyard roof (see Fig. 12) but less pronounced for the target area roof (see Fig. 13). The relatively small shift in the vertical frequency of the target area roof is attributed to the large vertical stiffness of the target area cylindrical walls.

(b) The peak amplitude of the horizontal and vertical response at fixed-base modal frequencies has been reduced significantly due to SSI effects. Such reduction is attributed primarily to the significant radiation damping introduced into the structure as a result of scattering wave effects and due to reduction of the free field ground motions with depth in the SSI model.

(c) A rocking mode is introduced into the response of the structure due to SSI effects. This rocking mode, which does not exist in the fixed-base response occurs at a frequency of about 3.25 Hz. The presence of this rocking mode was further evaluated by computing the horizontal response of the target area roof due to the base rotation only, U_h, from equation 1.

$$U_h = [(U_{v,1} - U_{v,2}) / D] * H \qquad (1)$$

Where $U_{v,1}$ and $U_{v,2}$ are the vertical response of the basemat edges along the centerline of basemat; D is the diameter of basemat and H is the height of the target area cylindrical chamber. The results of U_h for the target area roof in the y-direction are shown in Fig. 14. The rocking peak at a frequency of about 3.25 Hz is clearly shown. The importance of this rocking mode on the SSI response of the system due to ambient vibration PSD input will be discussed in the following sections.

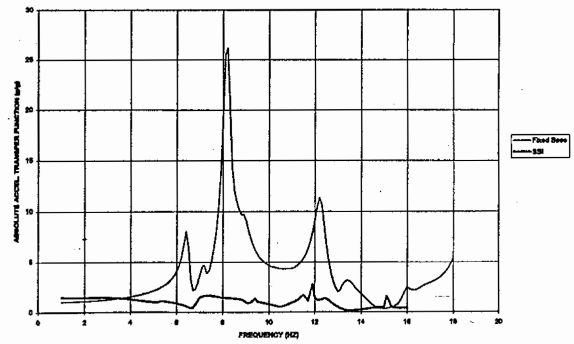

Figure 12 Absolute Vertical (z) Acceleration Transfer Function, Center of Switchyard Roof

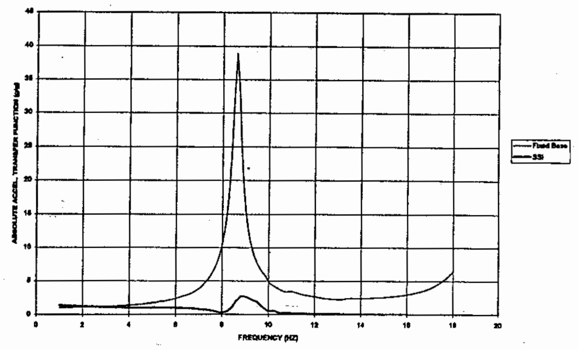

Figure 13 Absolute Vertical (z) Acceleration Transfer Function, Center of Target Area Roof

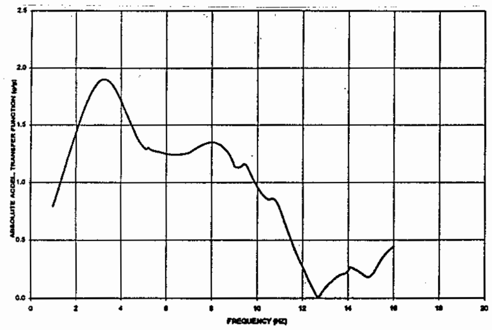

Figure 14 Absolute Horizontal (Y) Acceleration Transfer Function due to Base Rotation only, Center of Target Area Roof

Absolute Displacement Transfer Function. Figures 15, 16 and 17 show a comparison of the fixed-base and SSI results in terms of the absolute displacement transfer functions in y-direction at the center of the switchyard wall, switchyard roof and target area roof, respectively. The results in the z-direction for the center of switchyard and target area roofs are shown in Figures 18 and 19, respectively.

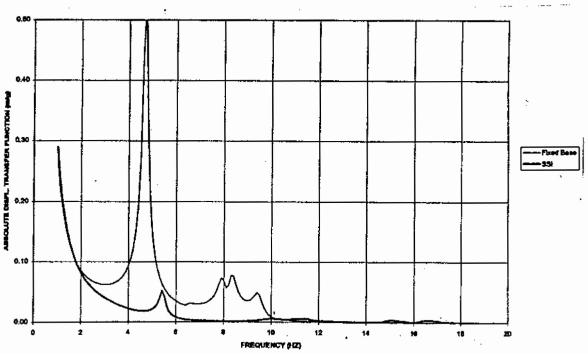

Figure 15 Absolute Horizontal (y) Displacement Transfer Function, Center of Switchyard Wall

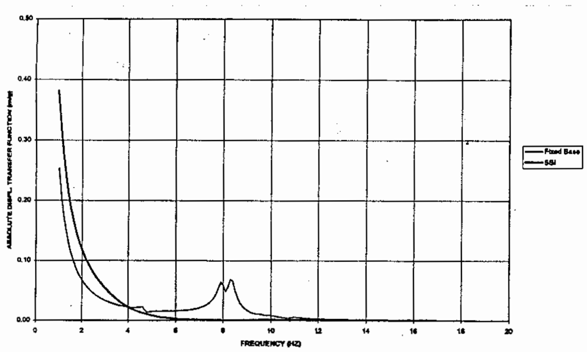

Figure 16 Absolute Horizontal (y) Displacement Transfer Function, Center of Switchyard Roof

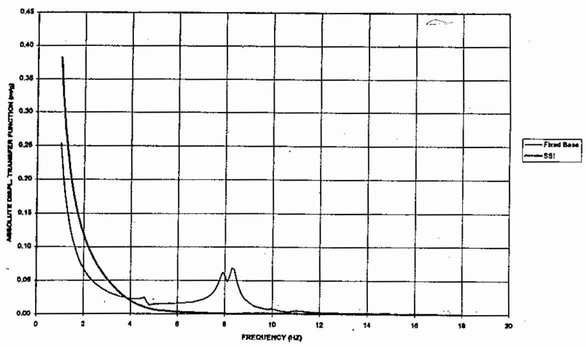

Figure 17 Absolute Horizontal (y) Displacement Transfer Function, Center of Target Area Roof

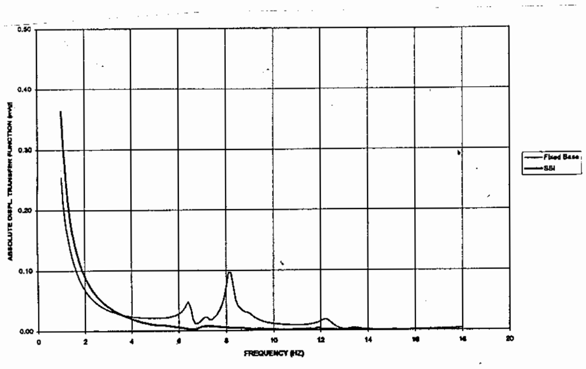

Figure 18 Absolute Vertical (z) Displacement Transfer Function, Center of Switchyard Roof

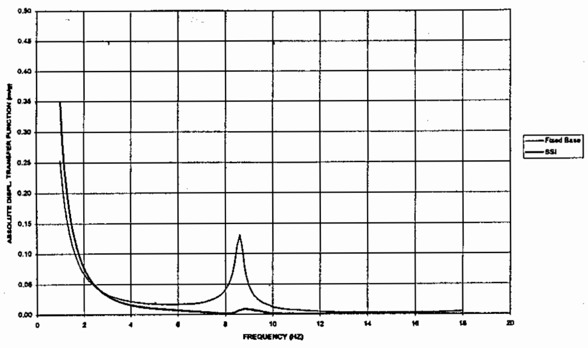

Figure 19 Absolute Vertical (z) Displacement Transfer Function, Center of Target Area Roof

From examination of the above results, the following observations are made:

(a) In evaluating the displacement response, it is shown that the components of the response at lower frequencies have more dominant effect on the response than the higher frequency components (e.g. see displacement transfer functions shown in Figures 16 and 17). This is true for both fixed-base and SSI models and may be explained from Equation 2, which relates the absolute displacement to absolute acceleration transfer function.

$$TR_d = TR_a \;/\; (2\pi f)^2 \qquad (2)$$

Where TR_d and TR_a are the absolute displacement and acceleration transfer functions, respectively, and f is the frequency of excitation. Equation 2 indicates that in evaluating the displacement transfer functions, the high frequency response (f>1 Hz) will be deamplified. The higher the frequency of excitation, the higher the degree of deamplification.

(b) Because SSI causes the fixed-base horizontal modes of the embedded structures to shift to higher frequencies and drop in amplitude, the overall effects of such modes are to reduce the SSI displacement response. On the other hand, SSI introduces a low frequency rocking mode into the response that can cause the SSI displacements to exceed those of fixed base at low frequencies, as shown in Figures 15 and 16 for y-response of the switchyard and target area roofs, respectively.

(c) The ratio of the SSI to fixed-base vertical response at the two nodes examined above appear to be about 1.7, which is consistent with the ratio of vertical to horizontal amplitude of the Rayleigh wave input. In other words the vertical response does not appear to be affected by the SSI effects within the range of frequencies examined.

Response to Ambient Vibration PSD input

Absolute RMS Displacement Response. The results of the SASSI fixed-base and SSI analyses in terms of the absolute RMS displacement response at various nodes in the structure were computed. Figures 20 and 21 show comparison of fixed-base and SSI RMS response of the switchyard and target area walls in terms absolute RMS displacements, respectively. As shown in these figures, the local wall displacements due to SSI can exceed those of fixed base, which is attributed to significant rocking in the structure. It is also noted that the relative displacements (wall rotations) are also significantly larger due to SSI effects.

Tables 8 summarize the range of the ratio of SSI to fixed-base absolute RMS displacements computed at various locations on the structure for the S/TA buildings. Based on an examination of these results, a set of factors (β) are recommended for scaling the fixed-base displacements to approximately account for the SSI effects.

Table 8 Ratio of SSI to Fixed Base Absolute RMS Displ.

Building	Response Location	Range of SSI/F.B. Ratio		β-factor	
		Y-Dir.	Z-Dir.	Y-Dir.	Z-Dir.
Switchyard	Perimeter Wall:				
	Mid Height	0.22-1.00	1.12-1.66	1.00	1.65
	Roof Level	1.14-1.29	1.10-1.67	1.30	1.65
	Center of Roof	1.18-1.21	0.85-1.16	1.20	1.15
Target Area	Perimeter Wall:				
	Mid Height	0.75-0.95	1.06-1.24	0.95	1.55
	Roof Level	1.18-1.24	1.04-1.22	1.25	1.55
	Center of Roof	1.18	0.67	1.20	0.90

Relative RMS Displacement Response. Relative displacements are more difficult to compare between the SSI and fixed base analyses. This is mainly due to the fact that SSI has a rotational component at the base which is absent in the fixed base model. Table 9 presents the ratio of SSI to fixed base relative RMS displacements at various locations on the perimeter wall and roof for the switchyard and target area, respectively. Also shown in these tables are the recommended values of β factors. Relative displacements are computed relative to the base motion.

Table 9 Ratio of SSI to Fixed Base Relative RMS Displ.

Building	Response Location	Range of SSI/F.B. Ratio		β-factor	
		Y-Dir.	Z-Dir.	Y-Dir.	Z-Dir.
Switchyard	Perimeter Wall:				
	Mid Height	0.15-1.47	0.67-3.26	1.50	3.25
	Roof Level	1.35-1.57	0.51-3.03	1.55	3.00
	Center of Roof	1.32-1.36	0.02-0.59	1.40	0.60
Target Area	Perimeter Wall:				
	Mid Height	0.73-1.37	0.28-0.54	1.40	1.00
	Roof Level	1.41-1.54	0.28-0.41	1.55	0.75
	Center of Roof	1.39	0.07	1.40	0.25

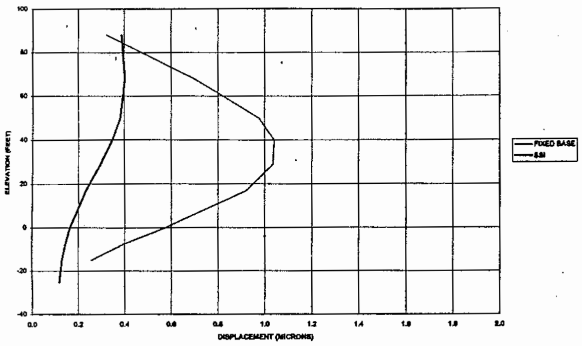

Figure 20 Absolute Horizontal (y) Wall Displacement Vs Height, Switchyard Wall

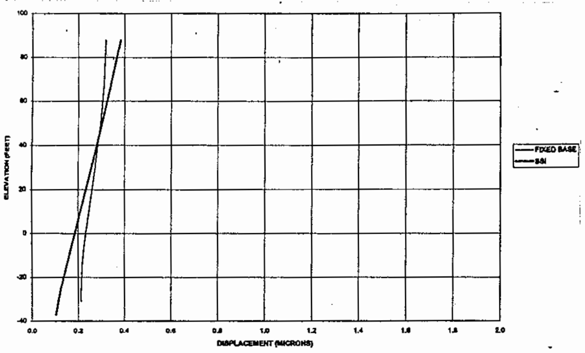

Figure 21 Absolute Horizontal (y) Wall Displacement Vs Height, Target Area Wall

CONCLUSION

Fixed-base and SSI analyses of the NIF switchyard/target area buildings due to ambient vibration excitation were performed using computer code SASSI to evaluate the potential contribution of the foundation flexibility to the overall displacements and deformations of the buildings. Based on the computed absolute and relative RMS displacements, it is shown that the effects of SSI need to be properly accounted in the analyses of massive, stiff structures supporting alignment-sensitive, special equipment when analyses are performed assuming fixed-base foundation condition. A set of factors (β) for scaling the fixed-base displacements to approximately account for SSI effects were presented.

ACKNOWLEDGMENTS

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CONCLUSION

Fixed-base and SSI analyses of the NIF switchyard/target area buildings due to ambient vibration excitation were performed using computer code SASSI to evaluate the potential contribution of the foundation flexibility to the overall displacements and deformations of the buildings. Based on the computed absolute and relative RMS displacements, it is shown that the effects of SSI need to be properly accounted in the analyses of massive, stiff structures supporting alignment-sensitive, special equipment when analyses are performed assuming fixed-base foundation condition. A set of factors (β) for scaling the fixed-base displacements to approximately account for SSI effects were presented.

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