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Seismic Soil-Structure Interaction Analysis of Ventilation Stack Structure

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Introduction

Soil-structure interaction (SSI) is the term commonly used to describe the effect of the foundation and soil on the behaviour of the structure. This phenomenon has played an important role in assessing failure and damage to structures during major earthquakes in the past decades (Resendiz and Roesset 1985; Celebi 1998; Gazetas and Mylonakis 1998; Mylonakis and Gazetas 2000). In general, SSI lengthens the apparent system period, increases the relative contribution of the rocking component of ground motion to the total response, and usually reduces the maximum base shear. The SSI affects the base shear demand through two distinct mechanisms: inertial and kinematic interactions (Wolf 1985). Kinematic interaction effects are produced by the reflection and scattering of the incident seismic waves from the foundation. The scattering of waves modifies the foundation motion compared to the free field motion. The other effect of soil-structure interaction is called inertial interaction, which involves the motion caused by the foundation and structure mass. These inertial loads develop interaction forces at the foundation which deform the soil, further modifying the motion at the base and altering the response of the structure. This paper describes the seismic soil-structure interaction analysis carried out for a deeply embedded ventilation stack proposed at a nuclear power plant building site, Kalpakkam in the state of Tamil Nadu. The SSI analysis of the ventilation stack of 100 m height with an embedded circular raft foundation is carried out by Flexible Volume Substructure Method (FVSM) using the computer code SASSI 2000 (A system for analysis of soil-structure interaction) program. The floor response spectra of the stack at various elevations are obtained for different ground conditions and foundation embedment for the design ground motion with peak horizontal acceleration (PHA) of 0.078 g.

Previous Studies

Researchers namely, Kausel and Roesset 1975; Todorovska and Trifunac 1992**;** Aviles and Rocha 1996; Stewart et al. 1999 and a few others investigated the effects of foundation embedment on soil–structure interaction.

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These authors claimed that foundation embedment significantly increases the horizontal coupling, rocking stiffness and radiation damping. Aviles and Suarez (2002) reported that the embedment could improve the ductility of structures and subsequently change the overall seismic behaviour. Prakash and Thakkar (2004) found that the amplitude of the horizontal input motion at the foundation base is significantly reduced due to the presence of embedded rigid foundation. Takewaki et al. (2003) evaluated the impedances and the effective input motion at the bottom of an embedded foundation. It is noted that the amplitude of transfer function is reduced due to the increase of embedment depth. Senjuntichai et al. (2006) studied the effects of foundation depth, soil permeability and foundation shape on impedances for axisymmetric embedded foundations in a half-space. Their results show that for cylindrical foundation shape, both the stiffness and the damping increase with increasing foundation depth.

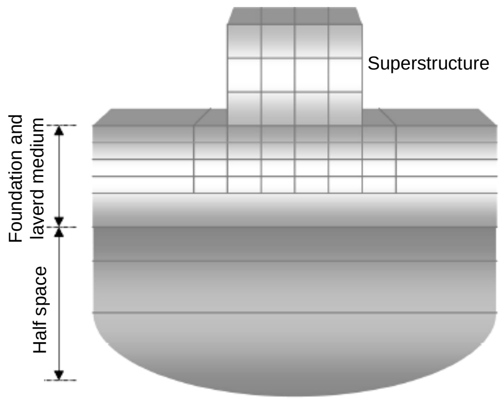
The SSI analysis carried out for a ventilation stack by Makovicka and Makovicka (2001) reveals that the lowest natural vibration mode need not be the dominant mode for the design of the stack structure, but may be replaced with one or several higher modes which determine the seismic response of the structure. Chen and Maslenikov (2004) conducted the SSI analysis of a nuclear structure using SASSI 2000 program and the impact of the foundation modelling techniques and the effect of soil stiffness variations on SSI response were investigated. Sanjur et al. (2007) conducted SSI analysis of a nuclear island for generic soil and rock sites using SASSI 2000 program. Tyapin (2007) added a special frequency dependent element in the code SASSI 2000 which represents both the soil and structure in the SSI model. Livaoglu and Dogangun (2007) conducted the SSI analysis of an elevated tank and found that the tank roof displacements were affected significantly by the embedment in soft soil.

In the case of the foundation embedded in soft soil deposits the effect on the response of the structure becomes more significant. Hence the SSI analyses of slender structures with deep embedment for different soil types and foundation conditions are very much needed in order to provide the quantitative information regarding the seismic safety of ventilation stacks. In the present study, seismic evaluation of a ventilation stack of 100 m height is carried out for different ground conditions with and without foundation embedment.

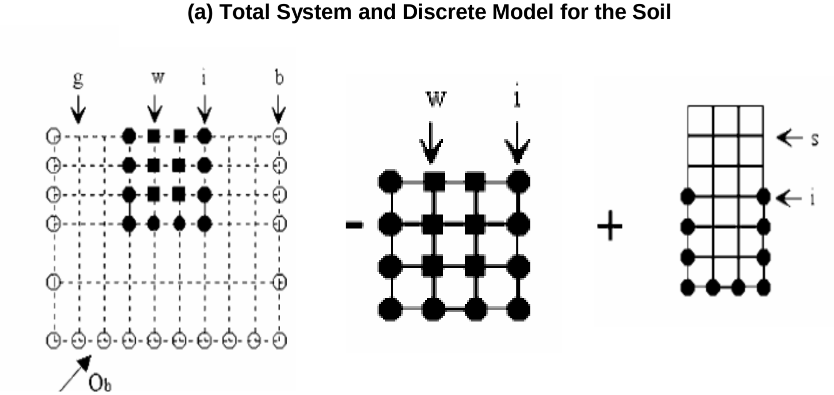
Numerical Analysis Procedure

There are two commonly used numerical methods of seismic SSI analysis: substructure method and direct method (Wolf 1988). The substructure method uses the principle of superposition to combine the effects of kinematic and inertial interactions, and is limited to the analysis of linear or equivalent linear systems. The direct methods solve the SSI problem in one step for linear material and geometric properties or in more steps for nonlinear material and geometric properties. Elementary, viscous, or transmitting boundaries may be used in the direct method. It is more robust than the substructure method, although it is more computationally demanding.

The basic method of analysis adopted in this study for the SSI analysis of the ventilation stack is the flexible volume substructure method (FVSM). The FVSM is based on the concept of partitioning the complete soil–structure system into two independent substructures: (a) the unbounded supporting soil and (b) the structure as a discretized model as shown in Figure 1a. The basic dynamic equilibrium equations of each subproblem are solved separately. In the final step of the analysis, the results are combined by satisfying equilibrium and compatibility conditions at interface nodes to provide the complete solution, based on the principle of superposition. In the case of embedded structures, three subregions are established: the original soil deposit without the presence of the structure (Figure 1b), the soil displaced (excavated soil) for the basemat (Figure 1c) and the structure (Figure 1d).



(a) Total System and Discrete Model for the Soil



(b) Free – field Soil **(c) Excavated Soil** **(d) Structure**

Fig. 1 Flexible Volume Substructure Method

The first subsystem (Figure 1b), the soil deposit consists of semi-infinite horizontal layers. The material properties of soil are assumed to be viscoelastic with complex modulus representation of the stiffness and damping properties of the soil layers. The stiffness and damping of each layer is adjusted using the equivalent linear method to consider the strain dependency of the soil properties. The structure consists of the superstructure plus the basement is discretized by the finite element method. Interaction between the structure and the soil occurs at all basemat nodes. The three subsystems are connected by means of the interaction nodes (*i*). In the FVSM the interaction nodes (*i*) are defined as the nodes of the intersection of the horizontal layers and the volume elements representing the volume to be excavated. A final formulation of the equation of the system for the FVSM can be obtained by coupling the equation of motion of the subsoil with the structure using the concept of substructuring in the frequency domain as given below:

$$\begin{bmatrix} K_{ss} & K_{si} \\ K_{is} & \left(K_{ii}+X_{ff}-K_{ff}\right) \end{bmatrix} \begin{bmatrix} u_s \\ u_f \end{bmatrix} = \begin{bmatrix} P_s \\ P_f \end{bmatrix} \quad (1)$$

where the subscripts refer to degrees of freedom associated with different nodes: *s*- nodes on the superstructure; *i*- the interaction nodes and *f* - the combination of *i* and nodes within the excavated soil volume (*w*). The P_s and P_f are the amplitudes of external forces at the superstructure and basemat nodes, respectively. In the case when the free field displacement is known, the equation of motion leads to

$$\begin{bmatrix} K_{ss} & K_{si} \\ K_{is} & \left(K_{ii}+X_{ff}-K_{ff}\right) \end{bmatrix} \begin{bmatrix} u_s \\ u_{ff} \end{bmatrix} = \begin{bmatrix} 0 \\ X_{ff}u'_{ff} \end{bmatrix} \quad (2)$$

from which the final total motions of the structure can be determined. For the seismic excitation the free-field displacement vector u'_{ff} is a function of the specified wave field and the location of the control point in the free-field soil system. To couple both substructures at interface nodes between the structure and soil, the dynamic stiffness matrix *K* of the structure and the dynamic stiffness matrix *X* of the soil have to be assembled to the soil–structure system. The stiffness of the excavated part K_{ff} has to be subtracted from the structural stiffness matrix in calculations. Therefore, the basemat nodes of the structure have to be identical to the excavated soil model. The impedance matrix X_{ff} represents the dynamic stiffness of the foundation at the interaction nodes. The impedance matrix is determined from the inverse of dynamic flexibility matrix F_{ff} for these nodes. The discrete model for impedance analysis is shown in Figure 2.

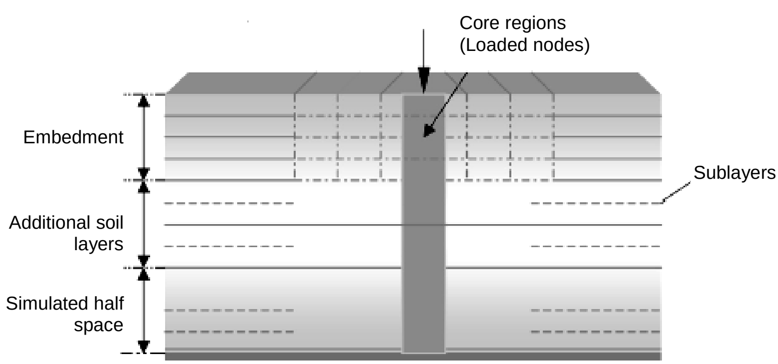


Fig. 2 Discrete Model for Impedance Analysis

The elements of the flexibility matrix, $F_{ff,}$ are obtained by successively applying harmonic unit loads at each degree of freedom of the interaction nodes and calculating related displacement amplitudes at the other interaction nodes.

SASSI 2000, a computer program developed at University of California, Berkeley (USA) for seismic SSI analysis of structures is based on the above method. The seismic SSI analysis in the SASSI 2000 involves the following four main steps:

> Solve the site response problem to determine the free-field motions for the interacting nodes within the embedded volume using the model of free-field soil displayed in Figure 1(b).

> Evaluate the impedance matrix X_{ff} using the discrete model in Figure 2 considering the primary nonlinearities in the soil.

> Determine the load vector for the seismic excitation from the solutions of Steps 1 and 2.

> Set up the structural problem by forming the complex stiffness matrices as given in Equation (2) and solving this system of linear equations of motions for the final displacements.

Stack Structure-SSI Analysis

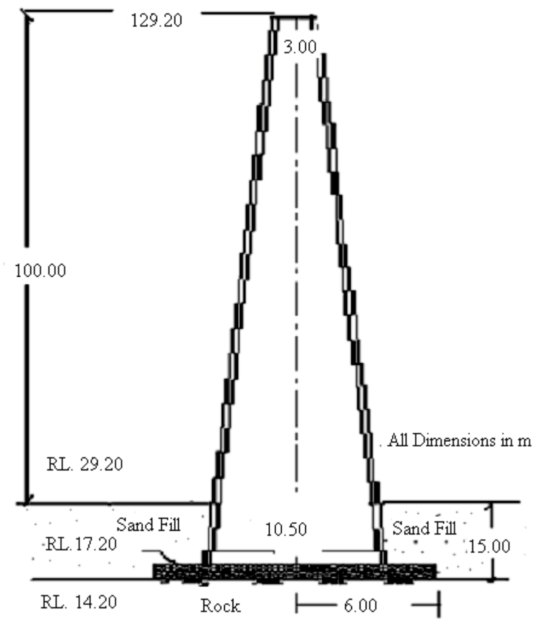


Fig. 3 Details of Ventilation Stack Structure

The seismic SSI analysis is carried out for a Ventilation stack proposed at a nuclear power plant site, Kalpakkam. The stack is a cylindrical reinforced concrete structure of height 100 m above ground level. The inside diameter of the stack at top is 2.6 m and the outside diameter is 3 m. The outside diameter of the stack at the top of foundation is 10.50 m and thickness of the shell is 500 mm. The stack is to be founded on a circular raft of 12 m of diameter at RL. 14.20 m (bottom of raft). The raft is to be embedded upto a depth of 15 m in sand layers overlying the bed rock. The details of the stack structure are shown in Figure 3.

Site Model

The nuclear island site consists mainly of medium-to-very dense sands. For a homogeneous linearly elastic soil deposit it is not necessary to discretize the soil layer. However, soils do experience some form of stiffness degradation depending on the amount of deformation. Thus the soil layer is commonly discretized into smaller segments so that the local degradation effect can be captured accurately. The allowable soil layer thickness is determined using the simple rule that layer thickness must not exceed one fifth the wave length at the highest frequency of analysis. Based on this, in the present study the soil profile is selected by subdividing the soil layers into several sublayers and their properties are given in Table 1. The bender element test is performed in the laboratory to measure shear wave velocities and hence to estimate initial shear modulus of the sand layers at the site. The effect of confining pressure of the soil on the initial shear modulus has been taken into consideration while choosing the initial shear modulus for each sand layer. The average shear wave velocity of soil obtained from the bender element tests is presented in Table 1.

Table 1 Soil Layer Properties

Depth of Soil Layer (m)	Mass Density (kg/m^3)	V_s (m/s)	Initial Shear Modulus (MPa)	Damping ratio (%)
5	1580	185	55	2
10	1650	230	89	2
15	1720	250	110	2
Halfspace (Weathered rock)	2000	1500	-	-

The bed rock below the soil layers are assumed as viscoelastic half-pace. The elastic half-space is modelled using variable depth method and the viscous boundary condition (SASSI 2000). In this method *n* extra layers which represent the half-space are added to the base of the top soil layers. The total depth *H* of the added layers varies with frequency and is set to

$$H = 1.5\frac{V_s}{f} \tag{3}$$

where f is the highest frequency in Hz, and V_s is the shear wave velocity of the half-space. For modelling the half-space with a viscous boundary, the model developed by Lysmer and Kuhlemeyer (1969) is used. The dashpots have the damping coefficients such as vertical dashpot: $C_p = \rho V_p$ and horizontal dashpot: $C_s = \rho V_s$, where ρ is the mass density of the half-space and V_p and V_s are the P- and S-wave velocities, respectively.

To perform soil amplification studies, as well as the soil-structure interaction analyses, it is necessary to know the soil properties in situ, under the existing state of stresses, as well as their variation with strain levels. The dynamic soil properties are thus commonly expressed in the form of shear modulus reduction and damping ratio curves, plotted as functions of the shear strain. The undrained strain controlled cyclic triaxial tests are conducted to evaluate the strain dependent shear modulus and damping ratio of the sand layers at the site (Jaya et al 2008). The developed site-specific modulus reduction and damping ratio curves for different sand layers shown in Figure 4 are used as input parameter for the free-field analysis using SHAKE 91.

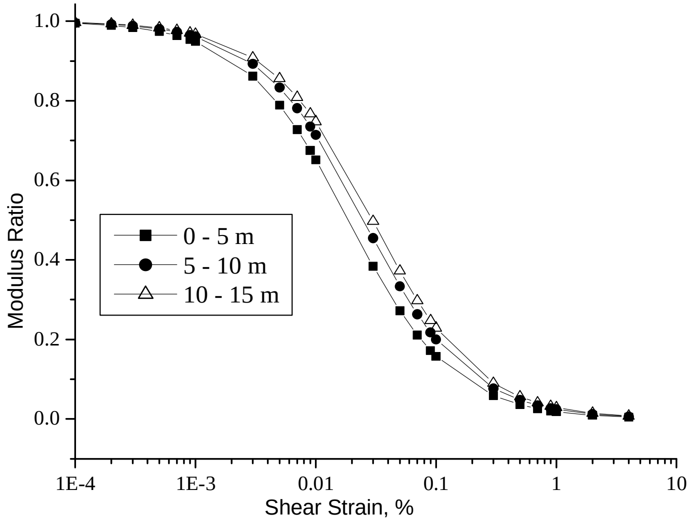


Fig. 4(a) Variation of Shear Modulus with Shear Strain for Sand Layers

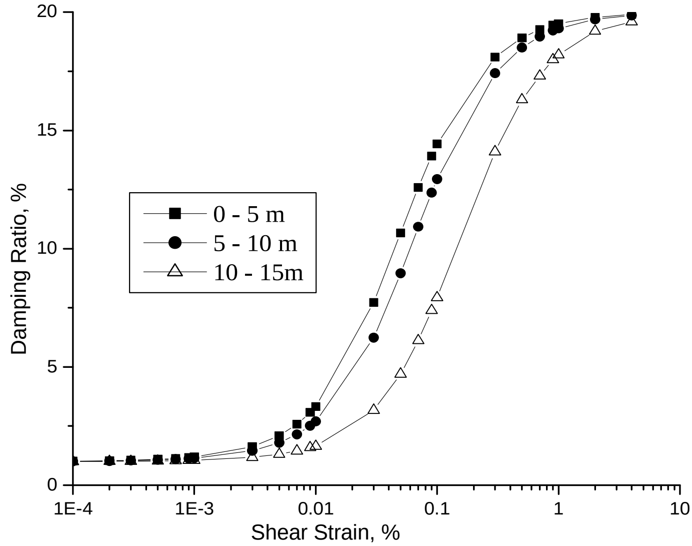


Fig. 4(b) Variation of Damping Ratio with Shear Strain for Sand Layers

The SHAKE 91 program computes the response of a semi-infinite horizontally layered soil deposit overlying a uniform half-space subjected to vertically propagating shear waves. The analysis is done in the frequency domain and an iterative procedure is used to account for the nonlinear behaviour of the soils. The object motion is specified at the top of the soil profile or at the corresponding outcrop. The maximum shear velocity and the modulus reduction and damping relationships are specified by the user.

Structural Model

The structural finite element model used in the present interaction analysis is shown in Figure 5. It includes the superstructure and the circular basemat. The superstructure is modelled by 30 beam elements. The basemat is discretized by 88 solid elements connected to the underlying soil at 69 nodes as shown in Figure 6. The rigid links represented by beams of large flexural and axial rigidities are used to connect the stick model to the basemat.

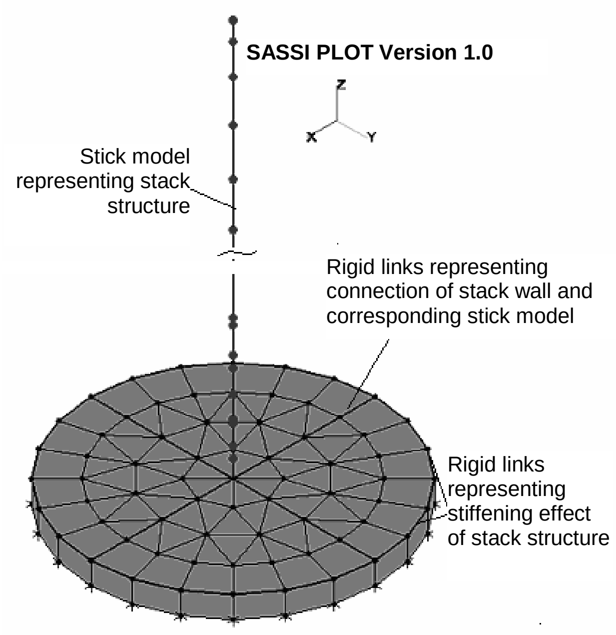


Fig. 5 Finite Element Model for SSI Analysis of the Stack (without Embedment)

The element size of the basemat in the horizontal direction is selected based on the wavelength criterion. The maximum horizontal distance between two adjacent interaction nodes in an excavated volume must be smaller than $V_s/(5f)$, where V_s is the smaller shear wave velocity of the top and bottom soil layers connected to the two interaction nodes and f is the highest frequency of analysis (SASSI 2000). The properties of the structural model of the ventilation stack are given in Table 2.

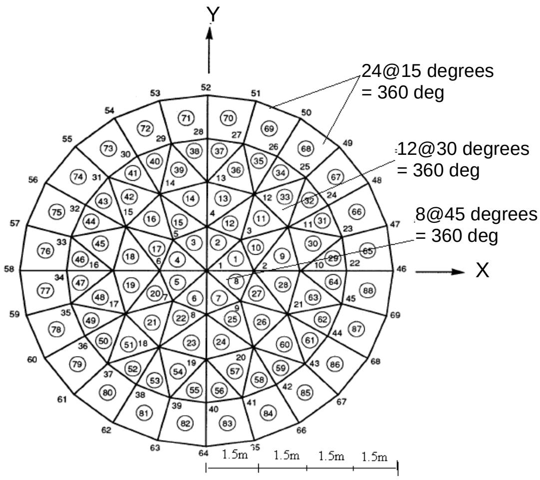


Fig. 6 Finite Element Discretization of Basemat

Table 2 Structural Properties of the Ventilation Stack

Elevation (m)	Area (m^2)	Moment of Inertia (m^4)	Mass (kg)
129.7	7.034	1.81	8601.53
121.7	9.193	3.80	119481.17
101.7	15.861	11.96	201773.09
91.7	19.780	19.11	250474.94
81.7	24.191	29.03	362417.40
71.7	29.036	42.39	363682.54
51.7	39.930	82.27	496945.55
31.1	52.977	118.80	156920.07
22.2	59.210	185.28	366029.55
17.2	62.800	__	188400.00

In the SSI analysis of the embedded structures, the excavated soil zone is modelled using three dimensional solid elements connecting the interaction nodes of the structure. The portion of the structure below the ground surface is modelled with explicit finite elements (e.g., 3-D bricks and shells), while the superstructure above the ground surface is represented with simple lumped masses and 3D beams. A typical SASSI model for embedded structure is shown in Figure 7. Due to the symmetric configuration of the structure, only half of the structure was modelled with the plane y = 0 as the symmetry plane. As shown in this figure, the basemat was modelled with brick elements and the sidewalls and internals were modelled with shell elements. The base of the superstructure is connected to the sidewalls by rigid links to simulate the rigid diaphragm of the floor expected to exist at grade level (Figure 8). In order to apply the subtraction method as implemented in SASSI2000, the nodes at the boundary of the excavation need to be identified as the interaction nodes and the volume of the excavated pit was modelled.

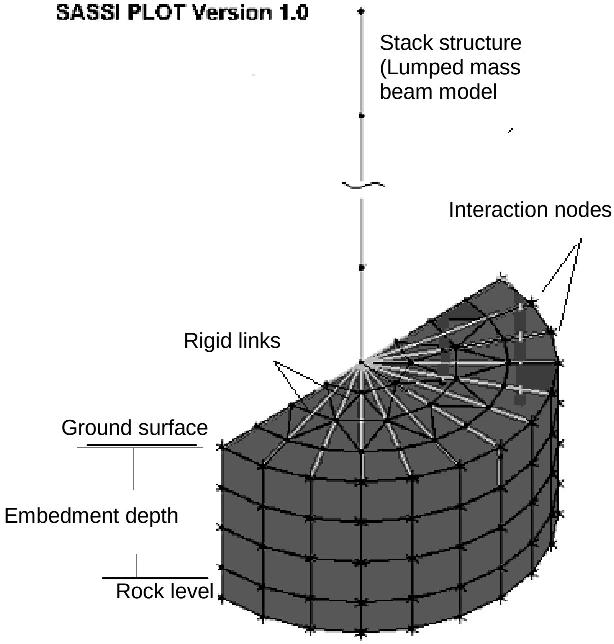


Fig. 7 Finite Element Model for SSI Analysis of the Stack (with Embedment)

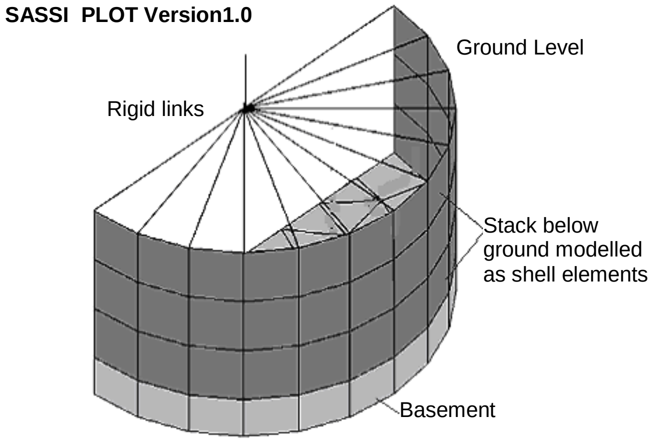


Fig. 8 Finite Element Model of the Stack within the Embedment

Input Ground Motion

Specifying the free-field ground motion is one of the most important factors in SS1 analysis. Three aspects of the free-field motion are important — location of control point, frequency content of the control motion, and the spatial variation of the motions. In this analysis, the control point is located on the ground surface and vertically propagating shear and compression waves defined as the spatial variation of the motion. The design ground motion parameters proposed based on the seismic hazard analysis carried out for the site by Ghosh (1994) is used as the input motion in the present study. The time history and its response spectrum for a damping value of 2 percent of the input motion are shown in Figure 9. The time history is specified at the rock surface as control motion for the SSI analysis of the ventilation stack. The time history is characterized by peak ground acceleration (PGA) of 0.078 g in the horizontal direction and total duration of 20 seconds.

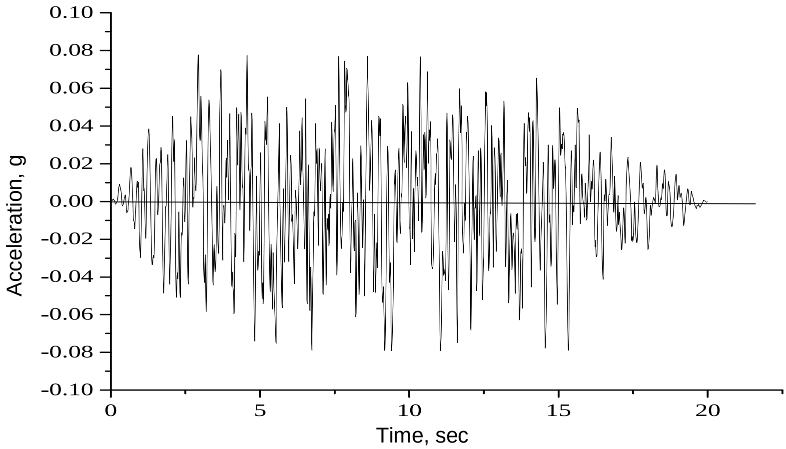


Fig. 9a Time History of Input Motion

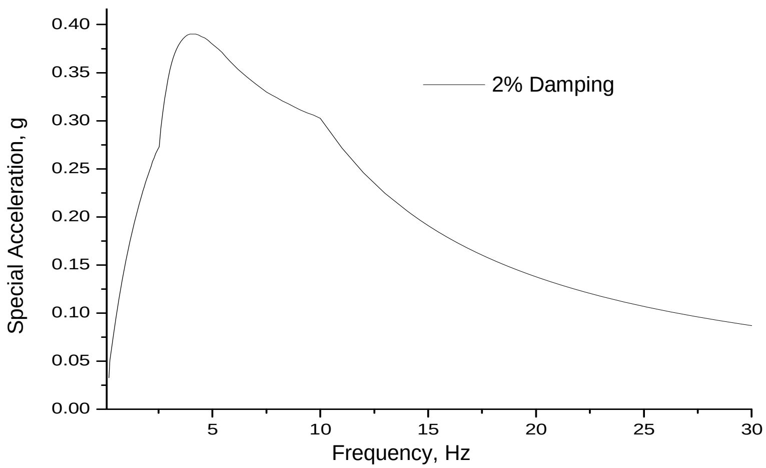


Fig. 9b Response Spectrum of Input Time History

Free-Field Deconvolution Analysis

In the SASSI 2000 program, the free-field analysis of the site is done by one of its module called SITE. For an equivalent linear analysis SITE module requires the average strain compatible soil properties resulting from the site-specific input ground motion. For this purpose, at first seismic free-field input motion along the interaction horizon is determined. This is achieved by the free-field analysis of unexcavated virgin soil in the absence of the structure. For the soil profile given in Table 1, the free-field motions at the level of soil-structure interface are obtained for the in put motion considered using SHAKE 91 program. The final effective strains and the associated shear moduli and damping ratios for each soil layers are given in Table 3.

Table 3 Final Strain Dependent Soil Layer Properties

Depth of Soil Layers (m)	Shear Strain (%)	V_s (m/s)	Damping Ratio (%)
5	0.01	130	2.5
10	0.04	118	5.6
15	0.09	98	8.0

SSI Analysis using SASSI 2000

The soil-structure interaction analyses of the ventilation stack are performed using the program SASSI 2000 by the complex response method in frequency domain. In the first step of SSI analysis, the site response problem for specified frequencies upto 30 Hz is solved using the SITE module of SASSI 2000. The site is modelled as semi-infinite visco-elastic horizontal layers overlying a uniform semi-infinite visco-elastic half space. The dynamic strain compatible soil properties obtained from SHAKE 91 program, given in Table 3 are used as input parameters to represent the equivalent nonlinear soil properties in the SITE module of SASSI 2000. The mode shapes and wave numbers for each specified frequency and the transmitting boundaries are obtained for seismic wave fields for the generation of complex stiffness and mass matrices. The impedance analysis is performed in the second step of the SSI analysis. The SASSI 2000 model for the ventilation stack with circular raft resting on different ground conditions is analyzed for frequencies up to 30 Hz. Results of various frequencies are combined together by running the COMBINE module of the SASSI 2000. The MOTION and STRESS modules of the SASSI are run to obtain transfer functions, peak accelerations, stress resultants and response spectra at critical locations of the stack. The transfer functions are carefully reviewed in order to make sure that amplification has not occurred for frequencies in between the frequency values initially considered. Intermediate values of frequency are added as needed.

The peak acceleration at various levels and Response spectra at floor and top level are investigated as a measure of the SSI effect: Peak acceleration at a particular elevation is the maximum absolute value obtained from the acceleration time history at that elevation, for the analysis under consideration. A parametric SSI analysis is also conducted for the stack structure for various cases i.e for different ground conditions and foundation embedment as shown in Table 4.

Table 4 SSI Analyses - Cases Considered

Case No.	Description	Parameters
I	SSI analysis of the ventilation stack without embedment	a. Fixed base condition b. Hard rock-Vs = 2300 m/s c. Rock -Vs = 1500 m/s d. Soft rock -Vs = 750 m/s
II	SSI analysis of the ventilation stack with embedment in sand and basemat resting on rock	a. Embedment ratio D/R = 0, b. Embedment ratio D/R = 2.5 (D-depth of embedment, R-radius of circular basemat)

Results and Discussion

The results of the SSI analyses are presented in terms of 2 % damped response spectrum of acceleration at the top and bottom of the stack structure, so as to study the variations in the dynamic response characteristics of the SSI system.

The acceleration response spectra at the base of the stack, i.e., top of the basemat (RL 17.20), resting on different ground conditions and without embedment are shown in Figure 10. From the figure it is noted that the spectral values of acceleration at the top of the basemat for sites with hard rock and rock condition matches well with the fixed base response spectrum. Hence, the effect of SSI is insignificant in the above ground conditions and a fixed base analysis considering the input motion at the base of the stack is adequate to estimate the spectral acceleration parameters.

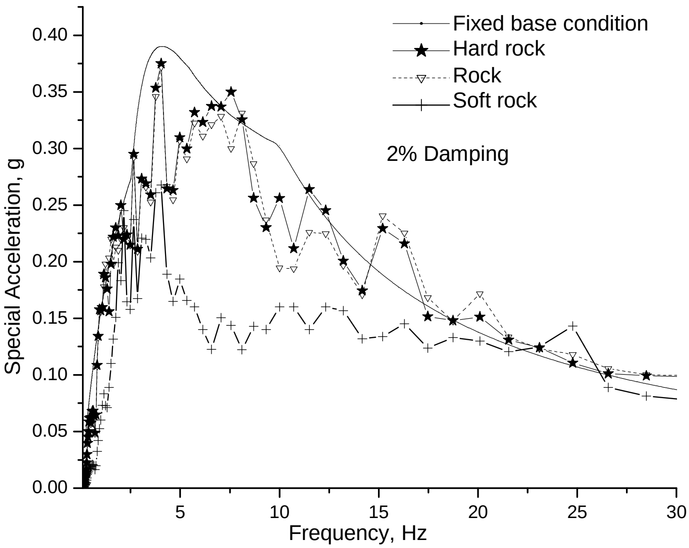


Fig. 10 Acceleration Response Spectrum at the Base of Stack for Different Ground Conditions (without Embedment)

It is also observed from Figure 10 that in the case of soft rock condition, the acceleration response is de-amplified due to the occurrence of radiation damping resulted from the soil-structure interaction. The spectral acceleration values are reduced slightly at the short periods (frequency less than 5 Hz) but they are drastically reduced at relatively long periods of the structure (for frequencies between 5 and 10 Hz) in comparison to fixed base case as depicted in Figure 10. Hence, the effect of SSI appears to be beneficial for the stack structure founded on soft rock.

Figure 11 shows the spectral accelerations at the top of the stack for different ground conditions. In the case of hard rock condition the spectral values of acceleration at the top of the stack drastically amplified within the frequency range of 5 to 10 Hz. The maximum spectral acceleration at the top of the structure occurs at the frequency of 7.5 Hz and it is found to be about 3.5 times the maximum acceleration at the basement.

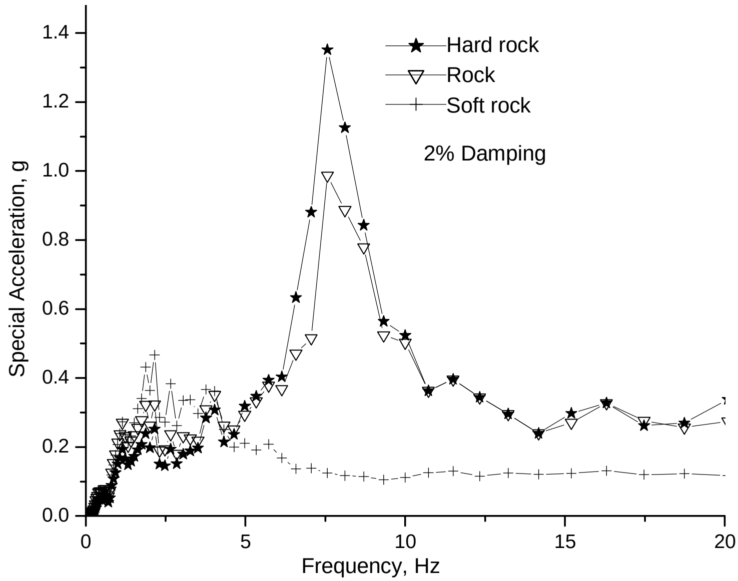


Fig. 11 Acceleration Response Spectrum at the Top of Stack for Different Ground Conditions (without Embedment)

It can be also observed from Figure 11 that in the case of soft rock condition the amplification of spectral acceleration occurs only in the long period of the structure (within the frequency of 0 to 5 Hz) but it is about 2.5 times less in comparison to the other rock conditions. It is also interesting to note the occurrence of deamplification for the short periods i.e. for the high frequency range of the structures. Therefore the SSI effect causes the reduction of the spectral values at all levels for wide range of periods of the structure.

The acceleration response spectra obtained from the SSI analysis carried out for the ventilation stack for the basemat resting on rock (V_s = 1500 m/s) and embedded in the sand is presented in Figure 12. The acceleration response spectra of the stack for the above hard rock condition but without embedment are also shown in Figure 12. It is easily noticed from the figure that the spectral acceleration values for the embedded basement case are less than for the case of without embedment of the basement. It is due to the occurrence of the additional damping of the seismic wave fronts to the side of the embedded portion of the structure. It is also observed for the figure that a slight shift of the predominant frequency to the right side due to the additional stiffness of the surrounding soil mass.

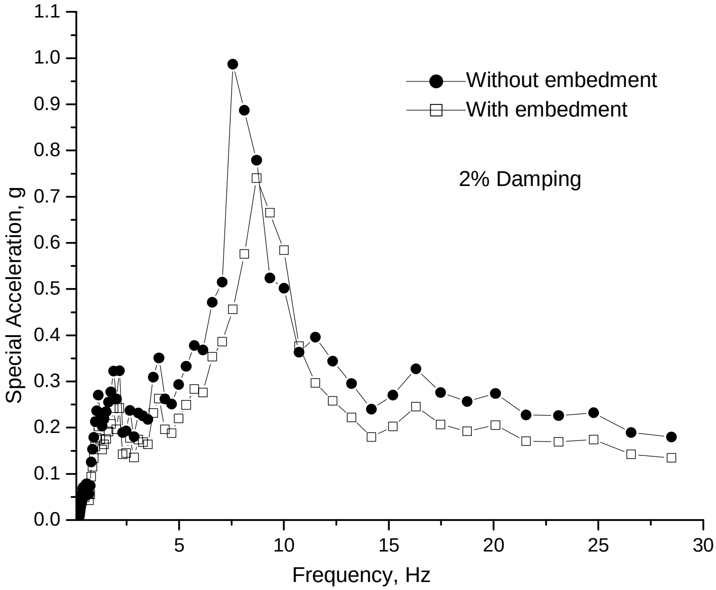


Fig. 12 Effect of Embedment on Acceleration Response Spectrum: Top of the Stack

Table 5 depicts the summary of SSI analyses of the ventilation stack conducted for different ground conditions and foundation embedment. It is noted that the predominant frequency and maximum spectral acceleration of the stack structure, with hard rock and rock conditions, are not affected by the SSI.

Table 5 Effect of Soil Conditions and Foundation Embedment on the Maximum Spectral Acceleration

Description	Ground Condition	Predominant Frequency (Hz)		Max. Spectral Acceleration (g)	
		Base	Top	Base	Top
Without Embedment	Fixed Base	3.5	7.5	0.35	1.3
	Hard Rock	3.5	7.5	0.35	1.3
	Rock	3.5	7.5	0.35	0.94
	Soft Rock	3.0	1.25	0.255	0.45
With Embedment	For D/R = 0	3.5	7.5	0.35	0.94
	For D/R = 2.5	4.0	8.2	0.255	0.75

A decrease in the predominant frequency and reduction in maximum spectral acceleration of the stack resting on soft rock is observed due to SSI. The spectral acceleration at the top of the stack for an embedment ratio of 2.5 is about 20% less in comparison to the surface footing resting directly on the rock.

In this case the damping offered by the sand surrounding the stack below the ground level plays a role in bringing down the spectral acceleration. The sand will add more stiffness to the soil-structure system and hence the predominant frequency is slightly increased compared to the case wherein the stack is supported on the surface footing i.e., without embedment.

Conclusions

In this paper, a seismic SSI analysis of the ventilation stack located in the nuclear power plant site is performed using the SASSI 2000 program, which is capable of handling 3D soil structure interaction problems involving embedded foundations of arbitrary shape. The analyses are performed using the flexible volume substructure method in frequency domain. The parametric study of the SSI model of the stack is carried out using SASSI for different ground conditions with and without foundation embedment for input ground motion having a PHA 0.078 g. The site-specific modulus reduction and damping ratio curves developed for the actual soil conditions are used in the SSI analyses. The seismic responses in terms of response spectra are evaluated at the key locations of the stack structure, which are used for the assessment of the SSI effects for different ground conditions with and without embedment effect.

The response of the stack for hard rock and rock conditions is similar to the fixed base condition and hence it can be concluded that the fixed base analysis is adequate for the stack-like structures on similar sites. From the spectral responses at the top of the stack for different rock conditions it is concluded that, increase in spectral values at 5–10 Hz range is predominantly governed by the rock sites.

The effects of soil-structure interaction on the seismic response of stack-like structure are significant only for sites characterized by an average shear wave velocity lower than 750 m/sec. For soft rock (V_s = 750 m/sec) the effects of SSI on the peak spectral acceleration at the base of the stack can lead to reduction of 25 % depending on the characteristics of the stack structure and of the excitation.

It can be concluded that the amplitude of spectral acceleration at the top of the stack decreases considerably (25%) by the foundation embedment in the dense sand layer. The fundamental frequency of SSI system slightly increased due to presence of surrounding soil. The radiation damping derived from the deep embedment plays an important role in bringing down the structural responses. This can be used to advantage during the design process, because a larger embedment ratio results in a more stable structure.

List of Symbols

b - the nodes at the boundary of the total system

D - depth of embedment

f - the highest frequency of analysis
g - the nodes at the remaining part of the free-field site
H - total depth of added layers for half-space simulation
i - the nodes at the boundary between the ground and the structure
K_{ss} - the dynamic stiffness of the structure
K_{si} - the dynamic stiffness of the structure at interaction nodes
K_{is} - the dynamic stiffness of the structure at interaction nodes
K_{ii} - the dynamic stiffness of the structure within the excavated volume
K_{ff} - the dynamic stiffness of the excavated soil
X_{ff} - the dynamic stiffness of the foundation at the interaction nodes,
u_s - nodal point displacements of the structure
u_f - nodal point displacements of the basemat
P_s - amplitudes of external forces at the superstructure
P_f - amplitudes of external forces at the basemat
R - radius of circular mat
s - the nodes at the remaining part of the structure
u'_{ff} - free-field motion at interaction nodes
F_{ff} - dynamic flexibility matrix
C_p - damping coefficient of vertical dashpot
C_s - damping coefficient of vertical dashpot
V_p - P-wave velocity
V_s - S-wave velocity
w - the nodes within the excavated volume
ρ - mass density of soil
D/R - embedment ratio
PGA - peak ground acceleration
PHA - peak horizonal acceleration

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