SEISMIC RESPONSE ANALYSIS OF NUCLEAR ISLAND BUILDING

V. Jaya
Assistant Professor, Department of Civil Engineering, College of Engineering Trivandrum, Thiruvananthapuram–16, India.
E-mail: jayasraj@gmail.com.

G.R. Dodagoudar
Assistant Professor, Department of Civil Engineering, IIT Madras, Chennai–36, India.
E-mail: goudar@ttm.ac.in.

A. Boominathan
Professor, Department of Civil Engineering, IIT Madras, Chennai–36, India.
E-mail: boomi@ttm.ac.in.

ABSTRACT: The effects of Soil-Structure Interaction (SSI) on seismic response of a deeply embedded Nuclear Island Building (NIB) are presented in this paper. The interaction analysis of the NIB is carried out using Flexible Volume Substructure Method (FVSM). The SSI model of the embedded NIB is subjected to a site-specific design ground motion. Computations required to study the seismic response of the NIB are accomplished using the program SASSI 2000. The present study is restricted to the evaluation of floor acceleration response spectrum and acceleration time-history at the selected locations along the heights of the eight buildings housed in the NIB. The Floor Response Spectra (FRS) are useful for the earthquake resistant design of secondary systems located at different floor levels of the NIB.

1. INTRODUCTION

Earthquake resistance is important for many of the structures related to energy production and resource development such as nuclear power plants, offshore structures, dams, harbour structures and pipelines. The effects of seismic activity on such structures can only be evaluated by considering the interaction between the structure and the soil or rock foundations. Seismic soil-structure interaction is one of the most widely studied phenomena in geotechnical earthquake engineering. Evaluation of seismic response of Nuclear Power Plant (NPP) structures is a very important topic in the design of NPP facility. Generally, a nuclear island building is a finite structure and its surrounding soil or rock medium is infinite in extent. The Floor Response Spectra (FRS) are of primary importance for seismic qualification of the secondary systems of the NPP facilities. They are applied as an input during the design of the secondary structures, thus providing a seismic safety to the secondary structures.

In this paper, the seismic SSI analysis of a deeply embedded Nuclear Island Building (NIB) located at Kalpakkam, India is presented. Prototype Fast Breeder Reactor having a capacity of 500 MW is located in the central portion of the NIB, called Reactor Containment Building (RCB). The NIB houses eight buildings including the RCB. As part of the study, the laboratory tests are conducted on the backfill soil surrounding the NIB, to determine the dynamic soil characteristics such as shear wave velocity, modulus reduction and damping ratio curves. A finite element model of the NIB with embedment is developed using substructure approach of the SSI analysis called Flexible Volume Substructure Method (FVSM). Computations required to study the seismic response of the NIB are accomplished using the program SASSI 2000. The seismic SSI analysis is restricted to the evaluation of the floor acceleration response spectrum and floor acceleration time-history at the selected locations along the heights of the eight buildings housed in the NIB. The FRS are useful for the earthquake resistant design of safety equipments located at different floor levels of the NIB.

2. DESCRIPTION OF NEUCLEAR ISLAND BUILDING

Nuclear Island Building (NIB) housing a 500 MW Prototype Fast Breeder Reactor (PFBR) consists of eight inter-connected buildings constructed on 3.5 m thick base raft. These buildings are: Reactor Containment Building (RCB), two steam generator buildings (SGB1 & SGB2), two electrical buildings (EB1 & EB2), Fuel Building (FB), Control Building (CB) and Radiation Waste Building (RWB). Arrangement of these buildings on the common raft is shown in Figure 1. The common raft (101.80 m × 94.10 m) is resting directly on competent rock having average shear wave velocity of 2300 m/s at a depth of about 15 m below the ground level. The heights of each of the eight buildings of the NIB are given in Table 1.

2.1 Site Conditions

The NIB is located at Kalpakkam, 65 km south of Chennai city in the south-east coast of India. The overburden soil is predominantly consists of sand and followed by a competent rock layer at a depth of about 15 m below the ground level. The
groundwater table is practically very close to the ground surface. The sand available at the site is used as an engineered backfill material surrounding the NIB up to the finished ground level (about EL 27.0 m). The engineered backfill is divided into three layers and their shear wave velocities are measured by conducting bender element tests in the laboratory (Jaya et al. 2007). The effect of confining stress on shear wave velocity is considered during laboratory tests and it is noted that the average shear wave velocity of the sand layer increases from 250 m/s at the surface to 380 m/s at a depth of 15 m. The site-specific modulus reduction and damping curves developed from the bender element and cyclic triaxial tests for the backfill soil layers are used as inputs for the site response analysis to represent the nonlinear behaviour of the backfill (Jaya et al. 2008).

3. SEISMIC SOIL-STRUCTURE INTERACTION

The objective of this study is to estimate the effect of embedment on the seismic response of NIB. Therefore, to achieve modelling and computational efficiency and in conjunction with the objective of the study, a SSI analysis model of the NIB is developed using SASSI 2000. In the Finite Element (FE) model developed using SASSI 2000, the portion of the structure below the ground surface is modelled with finite elements (e.g. brick and shell elements), while the superstructure above the ground surface is represented with simple lumped masses and beams. The interaction analysis method adopted in this study is the Flexible Volume Substructure Method.

3.1 Flexible Volume Substructure Method

The substructuring approach divides the SSI problem into several sub-problems including: (1) the site response problem (the free-field with no presence of structure), (2) the scattering problem, (3) the impedance problem, and (4) the structural response problem. In the Flexible Volume Substructure Method (FVSM), the scattering problem is not required due to the use of superposition to avoid explicit modelling of the
embedment in the free field; although the other three sub-problems still need to be solved.

The first step in the FVSM involves site response analysis. In this study, one-dimensional site response analysis is carried out using equivalent linear approach. The site response analysis of the NPP site is carried out using site-specific design ground motion shown in Figure 2. The strain-compatible iterated soil properties are obtained from the site response analysis. The computer program SHAKE 91 is used to accomplish the site response analysis. The SASSI program uses strain-compatible soil properties for subsequent free-field analysis to obtain the free-field motion at all interaction nodes. Thus the soil nonlinearity in the near-field is incorporated in the analysis.

In the second step of the FVSM, the stiffness and damping characteristics of the foundation-soil interaction characterized by impedance functions are determined. In the FVSM, the impedance matrix needs to be computed for all the interacting nodes in the flexible volume, i.e. the excavated soil volume. The calculation of the impedance matrix is achieved by inverting the dynamic flexibility (compliance) matrix for each frequency of the analysis. The analytical model of embedded portion of the structure is used to compute the compliance matrix \( F \). An impedance analysis method available in the SASSI called, skin method is used to compute the compliance matrix. It is inverted to get the impedance matrix \( [X_s] \) for all the interacting nodes.

### 3.2 Three Dimensional Finite Element Model of NIB

The ANSYS model of the NIB consists of shell elements (SHELL93 and SHELL63), beam elements (BEAM4) and mass elements (MASS21). The shell elements in the model are assigned with 27 different thicknesses, beam elements are modelled with 77 alternate sections. Detailed manual exercise combined with engineering judgment is required to arrive at this geometry and material combinations of the structure with the sole aim of extracting the true dynamic behaviour of the structure (Karlic and Simonovic 1999, Rajasankar et al. 2007). The complete finite element model of the superstructure (NIB) is developed in ANSYS and is shown in Figure 4.

### 3.3 Lumped Parameter Model of NIB

In the interaction analysis of the embedded structures, the excavated soil zone is modelled by three-dimensional solid elements connecting the interaction nodes of the structure. The element size for the excavated soil elements is controlled such that the distance between two interaction nodes in an excavated volume must be smaller than \( V_{sl}/(5 \times f_s) \), where \( V_{sl} \) is the smaller shear wave velocity of the top and bottom soil layers connected to the interaction nodes and \( f_s \) is the highest frequency of the analysis (SASSI 2000). The nodes at the base of the raft in contact with the rock are also identified as the interacting nodes. The nodes of the embedded portion are used for the impedance analysis and the same are acting as interacting nodes in the SSI analysis. All the interaction nodes of the structure which are below the ground surface and on the one side of the retaining wall in contact with soil layer interface are identified (Jaya 2008). The portion of the structure below the ground surface is modelled with finite elements (e.g. brick and shell elements), while the superstructure above the ground surface is represented with simple lumped masses and beams.

The lumped mass beam (stick) models of the eight structures which are housed in the NIB are developed. For calculating the equivalent stick properties, the building has been first divided into different sections based on the geometrical properties. Each stick has been placed in such a way that its axis will pass through its shear center (Sanjur et al. 2007). Portion of the buildings between the respective floors is replaced by an equivalent beam with appropriate stiffness and inertial properties. Each floor of the buildings is represented by different area beam model and each of the individual beams consists of vertical beam elements (located at the center of rigidity) and lumped masses (located at the center of mass). The lumped masses are located at the major floor elevations of the buildings. In each individual stick, the lumped mass at a given floor elevation is connected to the vertical beam elements with rigid horizontal beams. The stick models are then combined with the rigid links of large flexural rigidity to form a composite model of the NIB. The embedded portion of the NIB is connected to the stick model by rigid links to simulate the rigid diaphragm action of the floor expected to exist at the Finished Grade Level (FGL).

### 4. RESULTS AND DISCUSSION

The Floor Response Spectra (FRS) of various buildings of the NIB obtained from the Soil Foundation Structure Interaction (SFSI) analysis considering the effect of embedment and without embedment are presented in the paper. Figures 5–7 show the acceleration response spectra (FRS) at different floor levels of the Steam Generator Buildings (SGB). From the figures it is found that the peaks of the spectra shift slightly towards the high frequency range (lower period range) when the structure is embedded in the sand. This is because of the increase in the stiffness due to side resistance offered by the backfill soil.
Seismic Response Analysis of Nuclear Island Building

![Figure 5: Acceleration Response Spectra at Raft Level of SGB](image)

![Figure 6: Acceleration Response Spectra at Finished Grade Level of SGB](image)

![Figure 7: Acceleration Response Spectra at Top Level of SGB](image)

It is also noted from the figures that the maximum spectral acceleration in case of the NIB with embedment is less than that of the NIB without embedment. This is attributed to the wave radiation effects. The dissipation of wave energy due to the presence of sand in the backfill region caused an increase of radiation damping in the system, and found to be significant in reducing the spectral acceleration values at different floor levels of the eight buildings of the NIB. At the base of the RCB (EL 12 m), the reduction in maximum spectral acceleration is about 30%. At different floor levels of the RCB (from the base to the top), the reduction in spectral acceleration is about 20–30% compared to without embedment, i.e. the NIB is resting on the rock without engineered backfill in the surrounding area.

5. CONCLUSIONS

The Floor Response Spectra (FRS) and acceleration time-histories are evaluated at different levels of the NIB founded on hard rock having a depth of embedment of 15 m in the sand. In the case of NIB founded on hard rock with a depth of embedment of 15 m in the sand, the maximum spectral acceleration at the top of the raft is decreased by about 30% compared to the case of NIB without embedment. Due to deeper embedment of the NIB, soil-structure interaction will cause the natural frequency of the NPP structure to be higher than the natural frequency of the structure with shallow embedment. The soil-structure interaction results in the radiation of the waves propagating away from the structure which will result in an increase of the damping of the final dynamic system. Thus the radiation damping will cause the total damping of a soil-structure system to be greater than that of the structure itself. The restraint effect of the backfill sand to the NIB causes an increase in the stiffness of the soil-structure system and hence frequency corresponding to peak value of the response spectra is shifted to higher values. The maximum spectral accelerations at various levels of the NIB are reduced by about 20–30% due to embedment. Based on the present study it is concluded that the design of NPP structures should take into account the effect of embedment provided by the engineered backfill to reduce the overall cost of the project.

REFERENCES


