

DYNAMIC ANALYSIS OF NUCLEAR REACTOR CONSIDERING SOIL STRUCTURE INTERACTION

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ABSTRACT

In this research paper, the dynamic analysis of complicated structures like nuclear reactor building has been done by considering the site specific response analysis. Analysis is done with and without considering the soil stiffness. First a Nuclear Reactor is considered which is resting on the ground surface and site specific ground response analysis for obtaining free field response of soft soil site is carried out using DEEPSOIL (Youssef M.A.H, 2009). Nuclear reactor is modeled and analyzed using SAP2000 (Computers and Structures, 2007) by considering soil stiffness. The numerical results for the floor response spectra obtained from SAP2000 (Computers and Structures, 2007) are presented in this paper. Secondly the effect of soil-structure interaction on the seismic response of a massive structure with foundation finite element discretization model is used. Using the implemented model and in view of the objective of the work, a parametric study is made. For this purpose, a reactor building deeply embedded into the soil is considered. The results obtained in view of the parameters involved, are presented which suggest that the soil-structure interaction should be considered for the detailed analysis of important structures.

Keywords: Nuclear reactor, Local site effects, Response analysis, DEEPSOIL, SAP2000, Soil Structure Interaction, Finite Element Method.

INTRODUCTION

Seismic design of structures is one of the most important methods of mitigating risk of damage from future earthquakes and the concept of seismic resistant design have become worldwide popular. One of the most important challenges facing structural engineers today is the development and implementation of effective techniques for minimizing the severe and often tragic consequences of earthquakes. To meet this challenge, future structural engineers must possess

an understanding of the dynamic response of structures such as buildings, bridges, and towers to strong ground motion. Such designs are based on the specification of the ground motion which can be expected in the event of an earthquake. A nuclear reactor is a device in which nuclear chain reactions are initiated, controlled and sustained at a steady rate. The most significant use of nuclear reactors is as an energy source for the generation of electrical power. Over the last few decades, many building structures have

been damaged from the devastating earthquakes. This is usually accomplished by methods that involve using heat from the nuclear reaction to power steam turbines. Thus construction of nuclear reactors will increase in the near future. For nuclear power plants it is desirable to have a reliable site specific response analysis. Proper analysis should be done for structures on soft soils since the geometry and the properties of the supporting soil exert large influence on their behavior. Dynamic analyses are performed using the available and highly validated tools which incorporate acceptable methods of combining modal responses or with a multitude of other finite element programs that are either commercially available or developed specifically for the analysis. In this paper dynamic analysis is performed using SAP2000. Although recent advancements in computer technology and software have made this type of analysis more readily available, when performing detailed dynamic analyses, a thorough understanding obtained from experience, is imperative. Time history and response spectrum methods are the two basic methods that are commonly used for the seismic dynamic analysis. The time-history method is relatively more time consuming, lengthy and costly. The response spectrum method, on the other hand, is relatively more rapid, concise and economical. However, time-history method must be employed when geometrical and/or material non-linearity is present in the structural systems. Nowadays, it's more convenient for using time-history method than before for advancing of computer's hardware and software.

This study represents the seismic response analysis of a nuclear reactor on thick soft soils. Initially free field response of the site is found out using DEEPSOIL (Youssef M.A.H, 2009). For this, a soil profile of depth 32.5m is considered and ground response analysis is done in frequency domain. Acceleration time history and frequency vs. amplitude

responses are generated. A nuclear reactor is modeled and analyzed using SAP2000 (Computers and Structures, 2007). Later soil structure interaction analysis of embedded nuclear reactor is performed using finite element model. Time history response results of both the models are shown in the paper. The effect of considering the soil structure interaction can be understood.

METHODOLOGY ADOPTED

It has been a well established fact that a detailed dynamic analysis and design of built environment that takes into account the behavior of local soil deposits, reduces the loss of life and damage to infrastructure. Ground response analysis is an important factor that is to be taken into consideration for evaluation and remediation of geotechnical as well as structural seismic hazards. For site specific ground response analysis three basic input parameters that are essential are input ground motion, shear wave velocity and dynamic soil characteristics (e.g., strain dependent modulus reduction and damping behavior and cyclic strength curves). Linear analysis using DEEPSOIL (Youssef M.A.H, 2009) in frequency domain was used to compute free field response, which is very popular with practitioners. Based on the average shear wave velocity in the top 30 m, a ground response analysis has been carried out for the soft soil profile. Engineering bed rock is modeled as an elastic half space. Analyses were carried out for the stochastically simulated acceleration time histories from local sources using in situ measured shear wave velocities. Shear wave velocity (V_s) is one of the most important input parameter to represent the stiffness of the soil layers. It is preferable to measure V_s by in situ wave propagation tests, however it is often not economically feasible to perform the tests at all locations. Hence, a reliable correlation between V_s and standard penetration test blow counts (N) would be a considerable advantage. Shear wave velocity was measured using the

established empirical relationship developed by Neelima Satyam D and Rao K S (2009) as shown below.

$$V_s = 61 \times N^{0.5} \quad (1)$$

where N = corrected SPT value

In the current study an earthquake of moment magnitude 6 was considered for the analysis with 5% damping. A soil profile with 8 layers is considered. Thickness (m), unit weight (kN/m³) and shear velocity (m/sec) for each layer are given as input as shown in table 1.

Simplified complex shear modulus (Kramer, 1996) is used for the analysis purpose. A simplified form of frequency independent shear modulus is defined as given in Eq.2.

$$G^* = G (1 - \xi^2 + i2\xi). \quad (2)$$

Free field response for the soft soil strata considered is shown in Fig. 1 (a & b).

Table 1. Details of the soil strata considered

| Layer number | Thickness (m) | Unit weight (kN/m ³) | Shear velocity (m/sec) | Damping ratio (%) |
|--------------|---------------|----------------------------------|------------------------|-------------------|
| 1 | 2 | 15.5 | 122 | 5 |
| 2 | 3 | 16.5 | 220 | 5 |
| 3 | 1.5 | 15.5 | 183 | 5 |
| 4 | 4 | 15 | 211 | 5 |
| 5 | 1.5 | 16.5 | 236 | 5 |
| 6 | 5.5 | 16 | 266 | 5 |
| 7 | 1.5 | 16.5 | 324 | 5 |
| 8 | 14.5 | 15 | 236 | 5 |

NUMERICAL MODELING

The validation model of the nuclear reactor with node to node joints and with plates is shown in Fig. 2 (a & b). The model represents a typical Pressurized Heavy Water Reactor containment structure consisting of a primary concrete containment. This model is an idealization of a typical pressurized water reactor and does not represent an actual or existing structure.

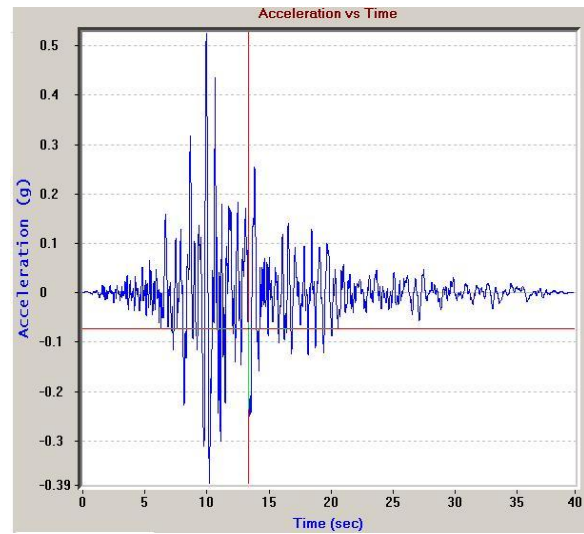


Figure 1(a): Acceleration time history for the soil strata considered.

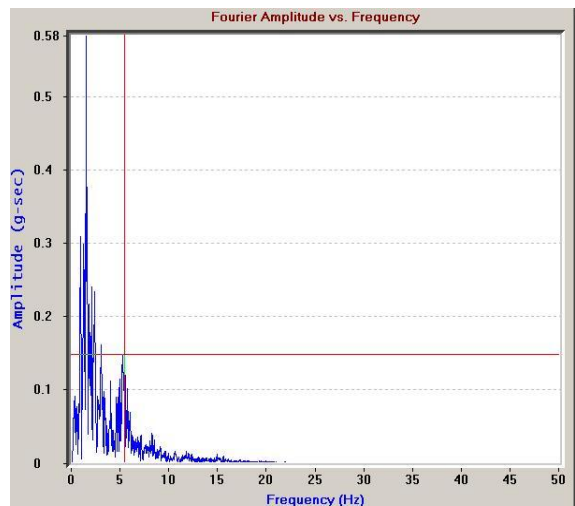


Figure 1(b): Fourier amplitude (g-sec) vs. frequency (Hz) for the soil strata considered.

Floor slabs are simplified and included mainly for their effect on the structural response. The concrete containment cylinder wall and dome are 300mm thick. The reactor vessel mass is included as lumped mass in the model. The concrete containment and internal cylindrical walls are modeled with plate/shell elements. The foundation slab/side walls and reactor cavity are modeled with solid elements. For performance evaluation, a three-dimensional model of the dome was taken and Time history analysis was performed to evaluate the displacements at each floors.

Reactor model

A three-dimensional model of the dome was modeled in computer program SAP2000 and Dynamic analysis was performed on the structure to evaluate the structural response. The time history analysis is an analysis performed in the time domain using time history vibratory input. A direct integration or modal analysis may be performed. The model was analyzed for earthquake ground motion data which is obtained from the DEEPSOIL (Youssef M.A.H, 2009) results.

3D MODEL

The dimensions of the model are the storey height is 30m, the thickness of the concrete wall is 300mm and the radius of the dome is 20m. The Structural plan view of the domed reactor is shown in Fig. 2 (a & b)

ANALYSIS

Several methods exist to input seismic excitation when making the seismic time history analysis for design of nuclear power plant such as to input the displacement time-history at the base (displacement method), to input the inertia loading calculated from the time history of support motion acceleration (acceleration method), and Large mass

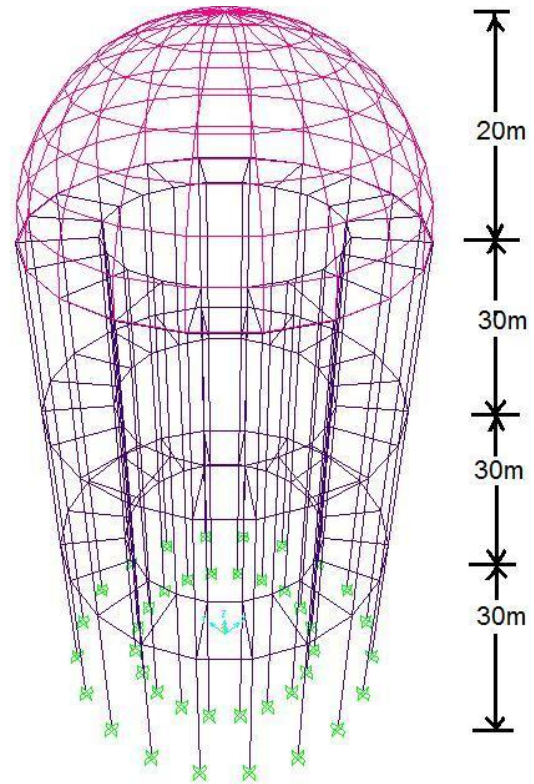


Figure 2 (a): SAP2000 model of Nuclear reactor with node to node joints

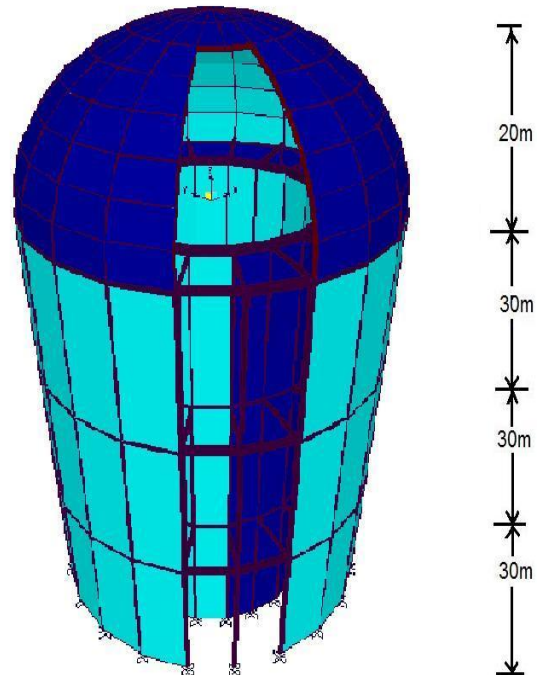


Figure 2 (b): SAP2000 model of Nuclear reactor with plates

method. For the linear response of important structure, both amplitude response spectra and standard accelerograms are used as supplements. Acceleration time history which is developed as a free field response is given as seismic input for the reactor model and analysis has been carried out. The model was analyzed for one of the earthquake ground motion data which has peak ground acceleration (PGA) of 0.053g and moment magnitude (Mw) of 6. Model time history type is used in SAP 2000 (Computers and Structures, 2007). Number of output time steps is taken as 500 and output time step size is taken as 0.02sec. This gives a total of one sec as time period. Fixed-base analyses of the reactor building were performed using SAP 2000. The floor response spectra for the three floor elevations of Nuclear reactor building are developed. The spectra were generated for elevations 30m, 60m and 90m for Nuclear reactor building. All the response spectra were generated for the damping ratio of 5%. Modulus of elasticity of concrete (E_c) is 30,000 N/mm² and Poisson's ratio (μ) is 0.2. The density for concrete (γ_c) is 2500 kg/m³. These values are best estimate values used for obtaining the best estimate values for in-structure response. The displacement time history graph and the response spectrum curves for the third, second and first floors of the Nuclear reactor building with the considered earthquake ground motion is analyzed in detail.

SEISMIC ANALYSIS CONSIDERING SOIL STIFFNESS

A massive structure such as reactor building is embedded in the soil and it will interact with the surrounding and the base level. The seismic analysis of engineering structures is often based on the assumption that the foundation corresponds to a rigid block, which is subjected to a horizontal unidirectional acceleration. Such model constitutes an adequate representation of the physical

situation in case of average size structure founded on a sound rock. Under such conditions, it has been verified that the free field motion at the rock surface, i.e., the motion that would occur without the structure, is barely influenced by its presence. The hypothesis loses validity when the structure is founded on soil deposits, since the motion at the soil surface without the building may be significantly altered by the presence of the structure (Prakesh S and S K Thakkar, 2003). This detailed study has been carried out assuming that the structure and underlying soil remain bonded throughout the period of ground shaking, the motion at the base of foundation is assumed to be the free field ground motion, the behavior of both soil and structure is assumed to be linearly elastic and the side soil and base soil is modeled along with the reactor building but having no mass, only flexibility of soil is considered. Problems involving three dimensional axisymmetric solids or solids of revolution, subjected to axisymmetric loading reduce to simple two dimensional problems because of the total symmetry about the z-axis (Fig.3), with all deformations and stresses independent of the rotational angle θ . Thus the problem needs to be looked at as a two dimensional problem in rz. The dynamic equilibrium equations in the finite element formulation are shown in Eq.3.

$$M\ddot{u} + C\dot{u} + Ku = f(t) \quad (3)$$

where M, K and C are harmonic dependent mass, stiffness and damping matrices, respectively, $f(t)$ is the external force vectors, and \ddot{u} , \dot{u} are second and first derivatives of displacements. The horizontal component of ground acceleration is represented as shown in Eq.4 and the force is calculated using Eq.5.

$$a = \{a_g \cos\theta, a_g \sin\theta, 0\}. \quad (4)$$

$$f(t) = -Ma. \quad (5)$$

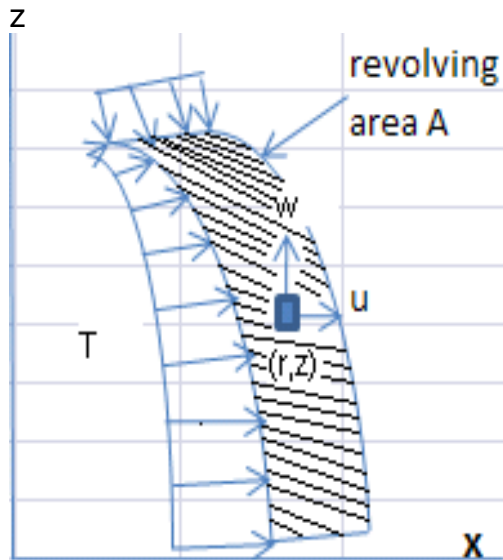
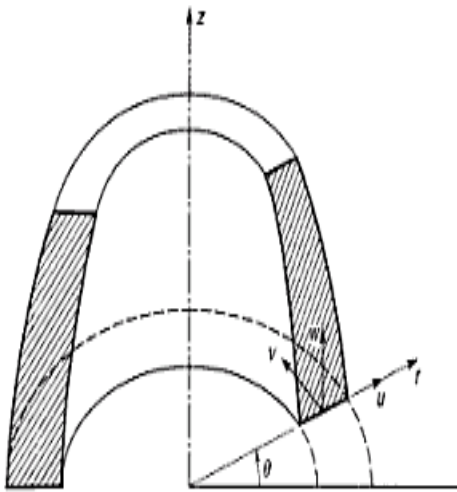


Figure 3: Axisymmetric body and displacements in cylindrical coordinates

The two-dimensional region defined by the revolving area is divided into triangular elements, as shown in Fig 4. Though each element is completely represented by the area in the rz plane, but in reality it is a ring shaped solid of revolution obtained by revolving the triangle about the z axis. Using the three shape functions N1, N2 and N3 displacement is defined as shown in Eq.6.

$$U=Nq. \tag{6}$$

The element stiffness matrix is given as below in Eq.7.

$$K_e=\int BTDBdu \tag{7}$$

Use of finite elements for modeling the soil structure system is the most comprehensive method (S L Chu, 1973). Like the elastic half space model, it permits the radiation damping but has the major advantage of easily allowing changes of soil stiffness both horizontally and vertically to be explicitly formulated. In this study two dimensional soil model which was found considerable use in practical analysis of axisymmetric system, has been used. In this model, the soil boundaries are rotationally symmetric about the vertical axis, so that the radial and vertical coordinates are sufficient to define the geometry of the soil system as well as its finite element idealization. Axisymmetric structure is also rotationally symmetric about the same vertical axis. For the purpose of study, a nuclear reactor building shown in Fig.4 has been taken (S L Kati, 1973). The main structure is symmetrical with respect to vertical axis. It consists of a co-axial cylindrical shell and a spherical dome resting on a massive raft foundation and all made of reinforced concrete. The reactor structure is founded on base and surrounding soil.

The material properties of structure and founding soil used in the analysis are presented in Table 2.

Table 2: Material properties of structure and founding soil.

| Description of the structure | Modulus of elasticity, E, kN/m ² | Poiss on's ratio | Mass density, Kg/m ³ | Damp- ing |
|------------------------------|---|------------------|---------------------------------|-----------|
| Shell, dome, slab and raft | 3x10 ⁷ | 0.20 | 2.5 x 10 ³ | 5% |
| Founding soil | E=2G(1+ν) G=ℓ*V _s *V _s | 0.30 | 2.2 x 10 ³ | 20% |

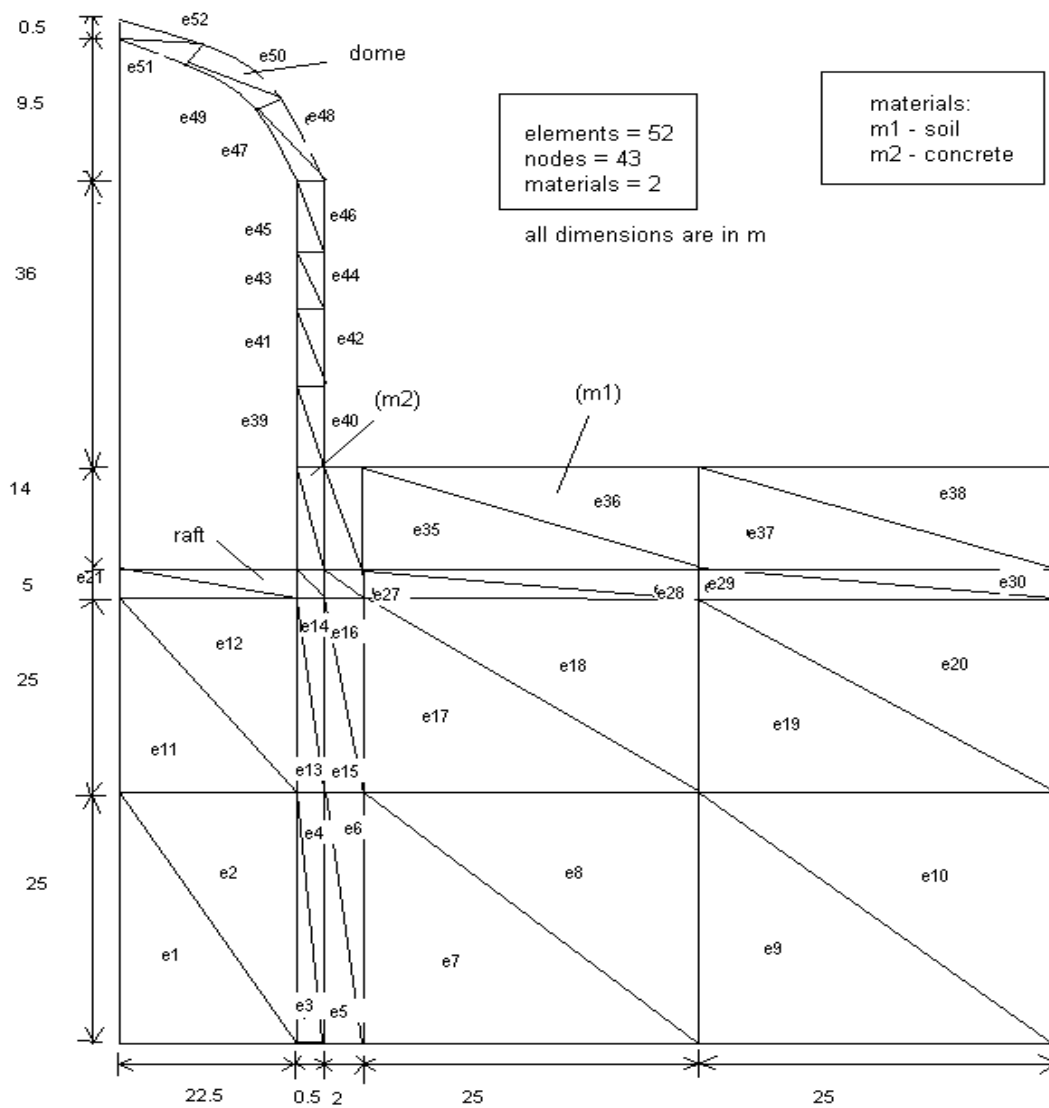


Figure 4: Finite element mesh of reactor building and founding soil

A reactor building along with foundation soil has been idealized by finite elements, consisting of three noded isoparametric elements shown in Fig 3. The dynamic response to horizontal earthquake ground motion is obtained by time wise mode superposition method. The time history analysis is carried out using Newmark's method (Anil k Chopra, 2007) where $\beta = \frac{1}{4}$ and $\gamma = \frac{1}{2}$ (the average acceleration method). The recorded El-centro

earthquake ground motion is selected for the analysis as given in Table 3. The soil boundary is taken as viscous media.

Table 3: Typical details of earthquake data considered in the analysis.

| Date of occurrence | PGA (g) | M(w) | Approximate duration (s) |
|---------------------------|---------|------|--------------------------|
| EL-Centro May 18, 1940 | 0.33 | 7.1 | 30.0 |

In this study only horizontal earthquake motions are considered because there is insignificant effect of vertical ground motion on overall seismic response of reactor.

All the lumped parameter models take advantage of simplicity of using spring dashpot and added mass have been popular in time history analysis of soil structure interaction problems.

The static stiffness of the embedded foundations increases by increasing the depth of the foundation (Kramer, 1996). Embedment can increase the radiation damping considerably. Wolf (1994) developed a series of cone models in which stiffness of the foundation is similar to the stiffness proposed by Gazetas (1983) though it is represented in a different format. The spring stiffness is considered as shown in Eq.8.

$$K=8Ga/(2-u) \quad (8)$$

Where A is Area of the foundation $A= \pi a^2$, G is the Shear modulus of the soil, u is the Poisson's ratio of the soil. However, the viscous damping coefficient was assumed to be proportional to the wave velocity in the soil and the foundation area and is shown below in Eq.9.

$$C=\rho c A_0 \quad (9)$$

where C is viscous damping coefficient taking into account the the radiation damping of the soil and foundation, ρ is soil density, c is wave velocity (600 m/s) in the soil and A_0 is foundation area (Wolf, 1987). It should be mentioned that the soil has been assumed to behave as an elastic material, and therefore there was no material damping added to the models. The finite element model is analyzed using the El-centro earthquake data and the displacement time history results for the

external nodes of the concrete nuclear reactor building are shown in Fig. 6 (a, b, c, d, e and f).

RESULTS AND DISCUSSIONS

The detailed procedure to estimate the free field response at the site, using this data and the analysis of a Nuclear Reactor constructed on thick soft soils and also the effect of soil structure interaction of embedded nuclear reactor building has been presented in this research paper. The dynamic analysis of a Nuclear reactor building resting on thick soft soil strata is performed initially. For the analysis purpose a Pressurized heavy water reactor is considered. Free field response of the soil strata considered is analyzed using DEEPSOIL. Analysis of the Nuclear reactor building is performed using SAP 2000. From the displacement time history of the joints at the three floors it can be seen that there is quite a reduction in the lateral displacements of the structure subjected to an earthquake excitation of a moment magnitude 6. The results are shown in Fig. 5 (a, b, c, d, e and f). Secondly soil structure interaction analysis is performed using three noded finite element model. A Nuclear reactor building with dome shaped concrete container is considered for the analysis purpose. A simple spring dashpot model is considered representing the soil structure interaction.

Structural engineers and designers should make every effort to obtain as much information as possible describing the properties of the site upon which a proposed structure is to be located. Dynamic analysis of pressurized Heavy water reactors has been performed using the data obtained from ground response. In this site specific geophysical, geological and geotechnical characteristics of the substrata below the structure is very crucial for the seismic design.

Considering fixed base

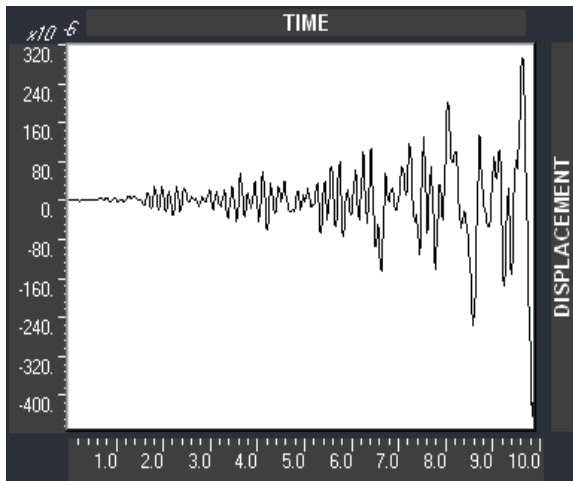


Figure 5 (a): Displacement time history of joint at the 3rd floor

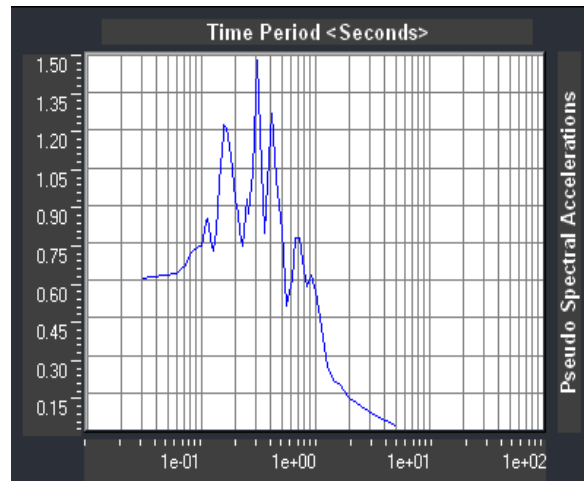


Figure 5 (b): Response spectrum of the joint at the 3rd floor

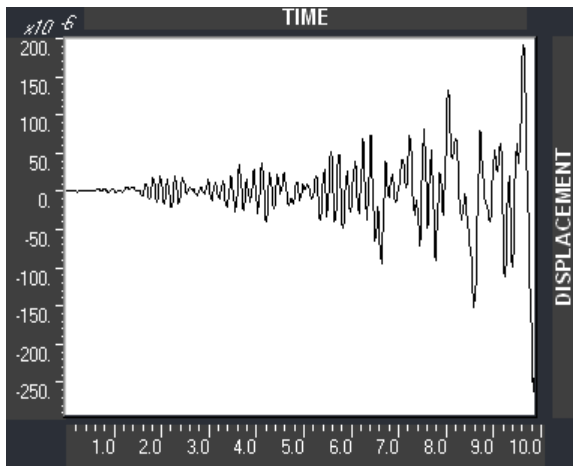


Figure 5 (c): Displacement time history of the joint at 2nd floor

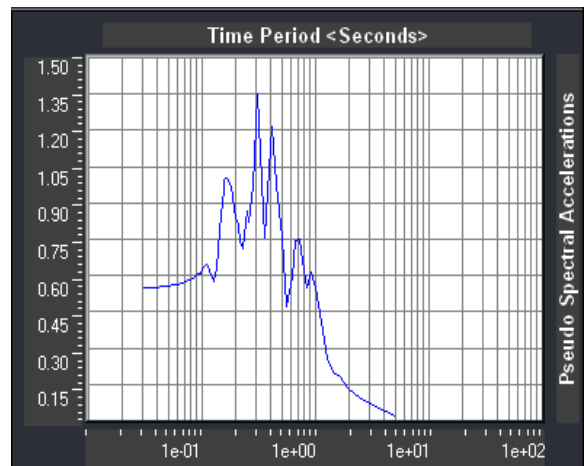


Figure 5 (d): Response spectrum of the joint at the 2nd floor

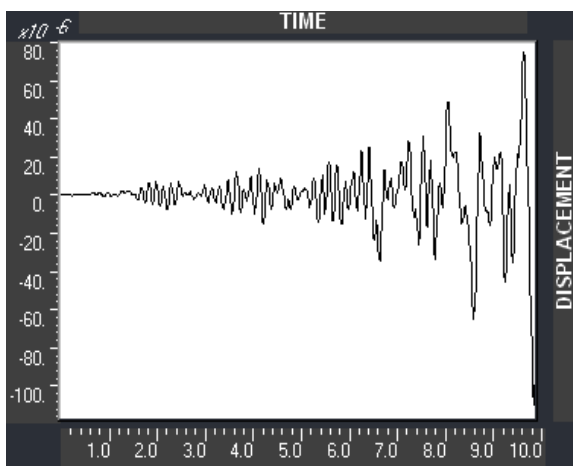


Figure 5 (e): Displacement time history of the joint at 1st floor

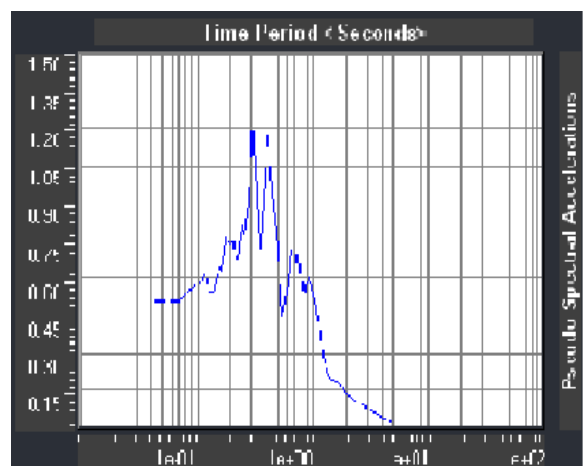


Figure 5 (f): Response spectrum of the joint at the 1st floor

Considering Soil Structure Interaction effect

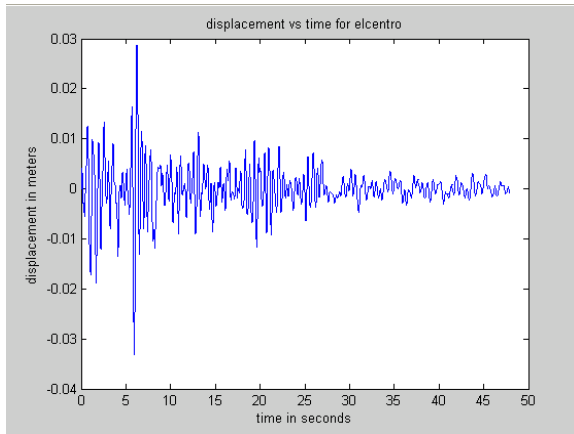


Figure 6 (a): Displacement time history for node 43

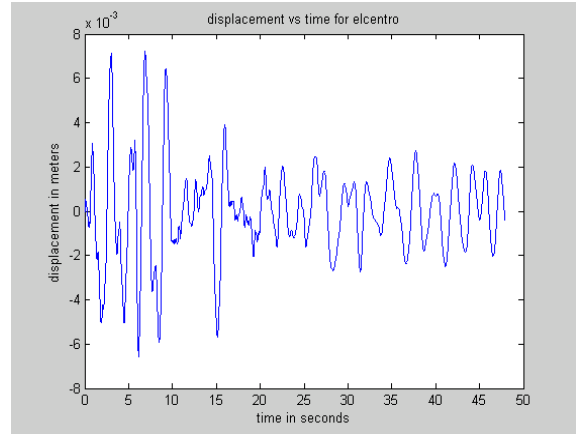


Figure 6 (b): Displacement time history for node 37

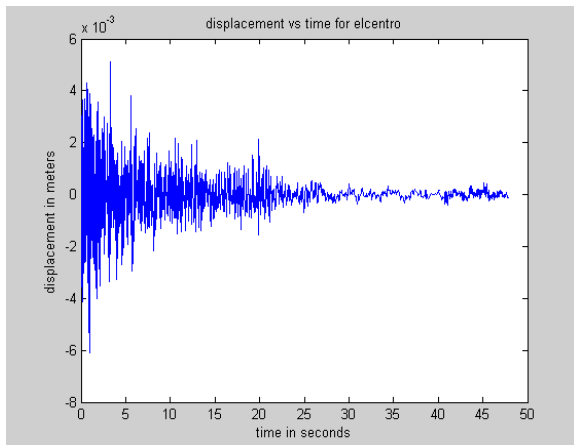


Figure 6 (c): Displacement time history for node 35

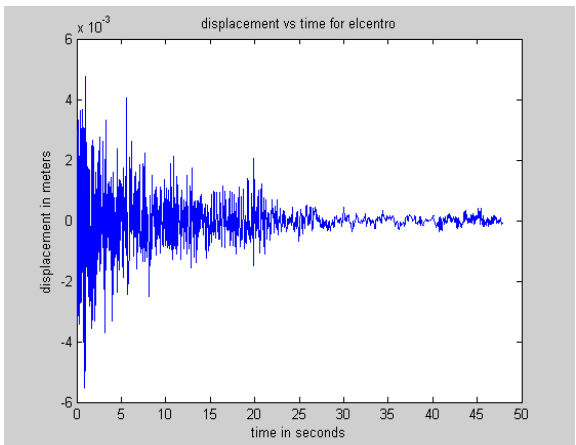


Figure 6 (d): Displacement time history for node 33

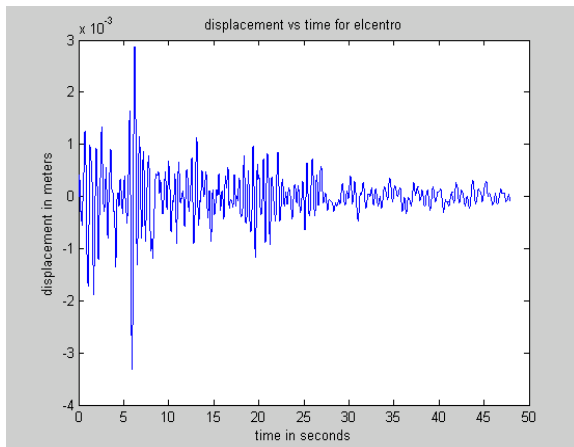


Figure 6 (e): Displacement time history for node 31

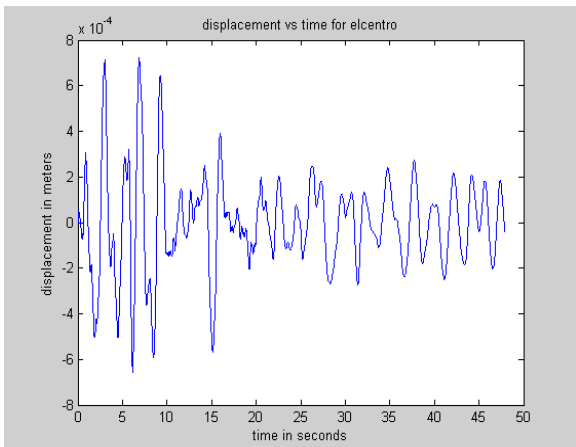


Figure 6 (f): Displacement time history for node 26

The maximum displacements occurring for the fixed base reactor at the three floors are 2.974×10^{-4} m, 1.925×10^{-4} m and 7.533×10^{-5} m. From these values it is clearly observed that the reduction in displacements moving from third floor to first floor.

Site specific response analysis for such important buildings is very necessary. For complicated and important structures such as reactor building, finite element method is well suited for the detailed assessment of stress and displacements. This paper also presents the numerical results of seismic analysis of Nuclear reactor building constructed on thick soft soil strata. When analyzing a structure founded on a soil site due to an earthquake there are changes in motion at foundation level leading to changes in the dynamic response of the structure. These changes are all effects of dynamic soil structure interaction. Modelling the foundation soil and base raft mat with finite elements gives more realistic results but it is too complicated for everyday engineering applications. Total displacements of the structure are larger in flexibly based structure and can be quite important for pounding of buildings.

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