EQUIVALENT LINEAR SPRING-DASHPOT MODEL FOR EMBEDDED FOUNDATIONS OF NPP

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Abstract

One of the significant factors which affect the response of a structure founded on soft soil is the yielding of soil which is generally ignored in the dynamic analysis of NPP structures. However, it is essential to consider the nonlinearity of soil in the dynamic soil-structure-interaction of NPP, especially for the strong ground motion. Furthermore, during dynamic loading, damping plays a vital role; therefore, this is also considered in the present analysis. To take into account the nonlinearity of soil, equivalent linear model of soil can be used for small strain range. In the present study, the same is considered while evaluating the spring and dashpot coefficients.

The equivalent linear method is proposed to account for the soil nonlinearity in the dynamic analysis of NPP structures in time domain. The spring and dashpot coefficients are obtained by iterating over the initial shear modulus ratio and damping of soil up to the converged strain level thus finding the updated values of stiffness and damping for spring and dashpot at each iteration. For this purpose, modulus reduction and damping curves are used for the layered soil mass. For the dynamic analysis, stiffness of spring and damping coefficients are calculated based on the frequency-dependent dynamic impedance functions. To verify the validity of the proposed spring-dashpot model, a simplified model of NPP structure with embedded foundation under the dynamic loading is analyzed and response is calculated at the top of the structure considering equivalent spring and dashpot model for soil as well as by three-dimensional finite element model. The response for both cases is compared. It is examined in three modes of vibration i.e., vertical, horizontal and rocking. The effect of embedment is investigated by comparing the results without and with embedment. The proposed method has the advantage over the finite element method because it is very simple and it reduces the computation time.

Keywords: Spring Constant, Damping Coefficient, Nuclear Power Plant, Embedded Foundation, Finite Element Analysis

1. Introduction

In the seismic analysis of the structure founded on the layered soil mass the motion experienced at the base of the foundation is determined from the two cases; (a) to free field motion at the site in the absence of structure; (b) the presence of the structure change the dynamic system from the fixed based system. Due to the interaction of the soil and structure, the motion is changed at the base of the foundation. The effect of the seismic soil-structure interaction becomes essential and cannot be neglected in case of designing of critical facilities like Nuclear Power Plants (NPP), Thermal Power Plant, Dam etc. The interaction effect becomes nonlinear when the massive and stiff structures are founded on the relatively soft soil. The analysis of these structure is very complex and time-consuming which required high efficient and powerful computing system. Various interaction models of foundation and structures are varying from elastic half-space to finite element models. The dynamic analysis of these interaction models could produce significantly different results. Therefore, the selection of the model becomes a crucial choice.

During the last five decades' considerable attention is received on the dynamic analysis of structure resting on the surface foundation. Some of these studies have become standard references e.g. Veletsos and Wei [1], Veletsos and Verbic [2], Veletsos [3], Richart et al. [4], Parmelee [5], Bielak [6], Luco and Westmann [7], Wong and Luco [8, 9], Gazetas [10], Novak [11] and Wolf [12]. It is well established that the SSI effect changes the dynamic properties of the system as compared to fixed base model i.e. time period and damping increases and stiffness decreases in the fundamental mode [12]. Dobry and Gazetas [13] developed expressions for calculating the stiffness and damping of arbitrarily shape embedded foundations. Mulliken and Karabalis [14] give the discrete model for the 3D analysis of foundation-structure system. Raychowdhury and Hutchinson [15] used the Winkler based shallow foundation model using the centrifuge test result for the performance evaluation of structure and foundation. The Winkler approach is based on the p-y curves obtained from the different types of soil. Kitiyodom and Matsumoto [16] give the spring constant for the piled raft foundation under static horizontal and vertical loading. Mylonakis and Gazetaas [17] used the frequency dependent axially and laterally loaded piles group in the inhomogeneous soil mass. The limitations of this model were soil linearity and prefect bond between the soil and foundation. Maravas et al. [18] studied the simplified model to calculate the natural time period and damping of the massless raft foundation on the linear elastic soil model, and also concluded that embedded foundation could simplify by the rocking impedance. Varma et al, [19] studied the linear and nonlinear soil structure interaction effect on the Fukushima Daichii nuclear power plant. Kumar et al. [20] studied the nonlinear soil structure interaction behavior of NPP structure by applying the bi-directional ground motion.

In India, NPPs are constructed on various types of foundations depending on the soil classification and geological conditions. Recently many NPPs will be coming on alluvium soil which is considered as a soft soil and required intensive dynamic analysis. In the western region where the basaltic formation exist the structure are founded on basalt. In the Indo genetic plain where alluvium extends to depth in excess of 200 to 300 m, nuclear structures are required to be especially designed to take into account the poor ground condition.

From the above literature review, it is found that all the spring-dashpot models are for linear elastic soil modelling. At present there is no strain dependent spring-dashpot model available. Therefore, in this paper, the emphasis is made to develop a strain dependent equivalent linear spring-dashpot model, which is time dependent and also consider the damping and stiffness of the inhomogeneous soil layers.

2. Problem Identification and Solution

In this study, two techniques are used to calculate the response of a NPP structure subjected to seismic loading and results are compared. In the first technique, finite element modelling is employed to model the soil. In the second technique, spring-dashpot model is used by replacing the soil with the equivalent stiffness and damping.

2.1 Finite Element Model

With the advancement of computers, Finite Element modelling of NPP structure is becoming popular for studying the complex and complicated interactive behaviour of structure and soil. Fig. 1(a) shows the generalized form of NPP structure which is converted into a lumped mass structure over the raft foundation as shown in Fig. 1(b). In this lumped mass model raft and soil are modeled using the 3D finite element formulation. The soil domain was chosen 200 m in the exited direction based on the size convergence study. In this model, soil was modelled using the 8 noded solid linear brick element (C3D8R) and 20 noded quadratic brick element (C3D20R) was used for the raft foundation. All the outer nodes are attached with the viscous dashpot in vertical and horizontal direction so as to absorb the incoming waves. All the base nodes are fixed and earthquake motion was applied in the in the X direction.

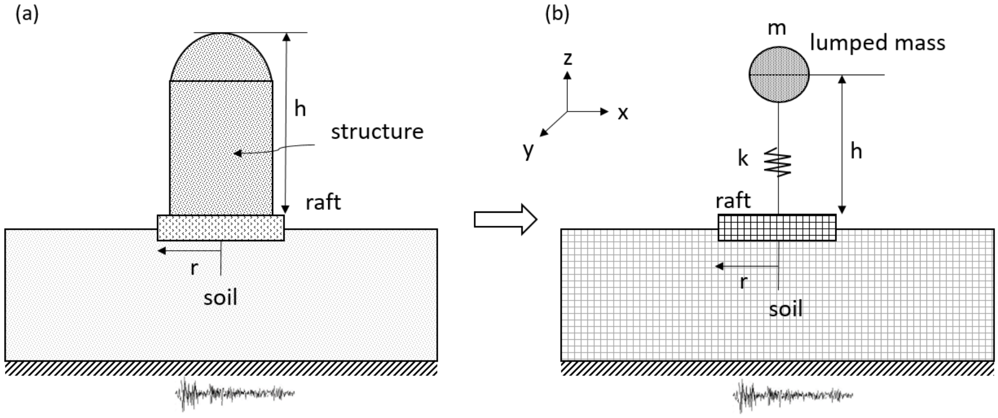

Fig. 1 – (a) Generalized NPP structure (b) Idealized finite element model of raft and soil with lumped mass model of structure

2.2 Spring-Dashpot Model

In this method of analysis, soil below the raft is replaced by the series of spring-dashpot (Voigt model) as shown in Fig. 2. The springs were applied in all 3 translations and 3 rotational directions. The spring and dashpot is calculated as the solution given by the Veletsos and Verbic [2] as

$$Q_j = K_j[k_j(a_o,\nu) + i a_o c_j(a_o,\nu)] \quad (1)$$

Where, Q_j is the complex valued stuffiness. In equation (1) real part is corresponding to dynamic stiffness and imaginary part represent the viscous dashpot. a_o is the dimensionless frequency parameter given by $\omega r/V_s$. k_j and c_j are the dimensionless functions of a_o and Poisson's ratio (ν), respectively for the soil medium. r is the radius of the raft foundation and V_s is the shear wave velocity of soil. In Eq. 1, K_j represents the static stiffness of soil in the j^{th} direction defined as

$$K_x = \frac{8Gr}{2-\nu} \quad (2)$$

$$K_\theta = \frac{8Gr^3}{3(1-\nu)} \quad (3)$$

$$K_z = \frac{4Gr}{1-\nu} \quad (4)$$

Where, G is the shear modulus of soil. The dimensionless functions k_j and c_j are calculated from the procedure given in reference [2]. For the constant hysteretic model, the dimensionless measure of damping capacity of half space material is defined by tanδ as

$$\tan\delta = \zeta \tag{5}$$

Where, ζ is the damping ratio. In the present analysis, it is assumed that $\tan\delta$ is constant, not a function of frequency. For the Voigt model, the dimensionless measure of damping capacity of half space material is defined by ξ as

$$\xi = \tan\delta/a_o = \zeta/\, a_o \tag{6}$$

In the last iteration, the damping ζ was found 10% and the average shear wave velocity in the upper two layer is 150 m/s. Therefore, dimensionless measure of damping capacity ξ is found 0.183. There is only small difference in ζ and ξ at the low frequency. For this, a MATLAB code is developed and found the exact same results as that reported by Veletsos and Verbic [2]. Fig. 3 indicates that the dimensionless stiffness and damping coefficient in x direction. Similarly, the dimensionless stiffness and damping coefficient in z and rocking direction can be found. These spring–dashpot coefficients are further used in the dynamic analysis of NPP structure. The stiffness of spring and viscous dashpot coefficients are frequency dependent of the forcing function. In the time domain dynamic analysis of NPP structure only the predominate frequency of earthquake motion is considered to make the calculation simple.

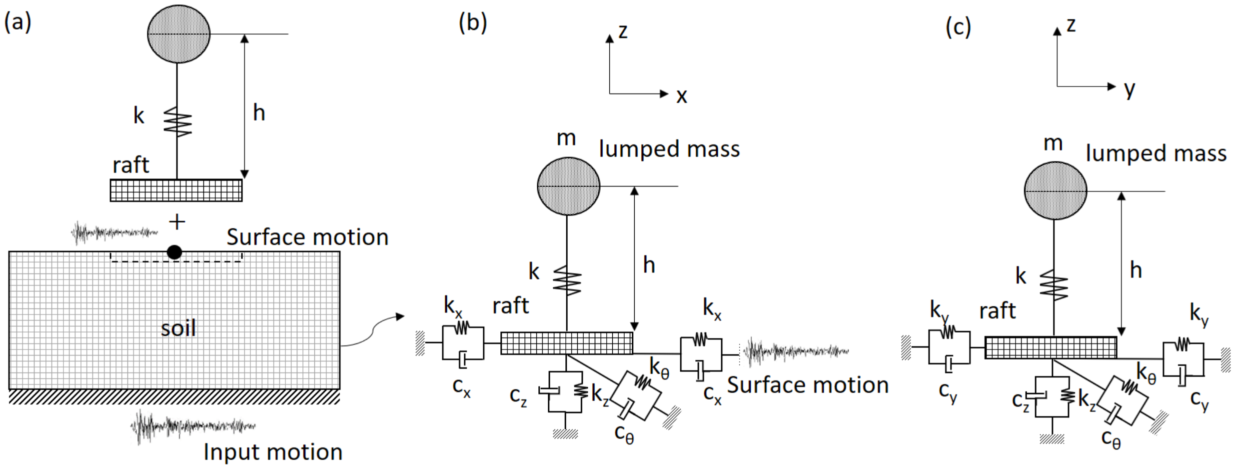

Fig. 2 – (a) Free field response, (b) Spring-dashpot model (x-z plan) and (c) Spring-dashpot model (y-z plan)

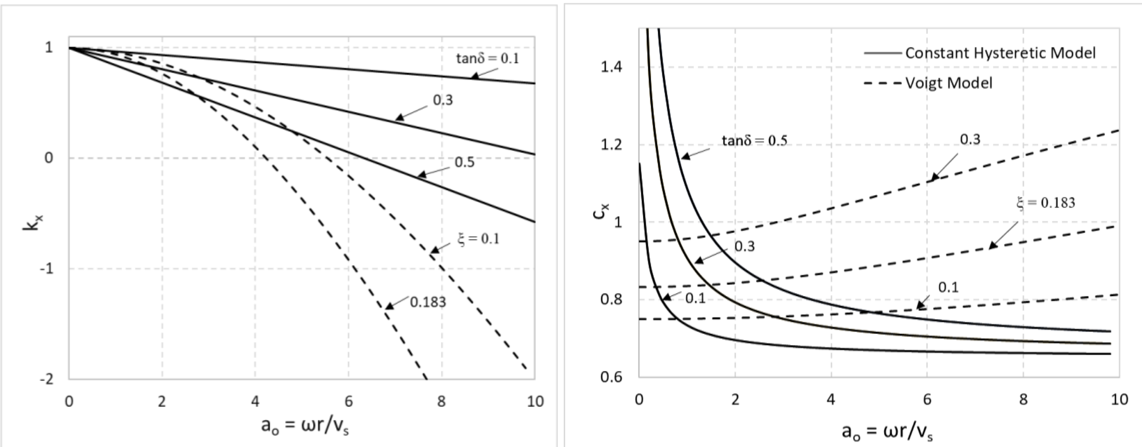

Fig. 3 – Dimensionless spring and damping coefficient in Horizontal direction, with ν =1/3

3. Model Description and Material Properties

The nuclear structure considered in this present study is a lumped model of a typical Indian nuclear reactor building reported in Paul and Saxena [21]. The raft foundation is circular having 22.5 m radius and 4 m depth with 2m embedment in the soil as shown in Fig. 4. The soil below the raft is heterogeneous having 3 m depth of each layer. Total depth of soil domain considered is 33 m and width is 200 m. The shear wave velocity (V_s) of the soil layer is calculated using the correlation given by Imai [22] as reported by Hasancebi and Ulusay [23]

$$V_s = 91N^{0.340} \tag{7}$$

The calculated maximum shear modulus and other material properties are shown in Table 1. The site was reported clayey silt with SPT value varying from 7 to 70. At the bottom layer SPT value is more than 50 which is considered as refusal. Therefore, fixed base condition is used in free field and finite element analysis. The modulus reduction and damping curve [24] are selected based on the PI value as shown in Fig. 5.

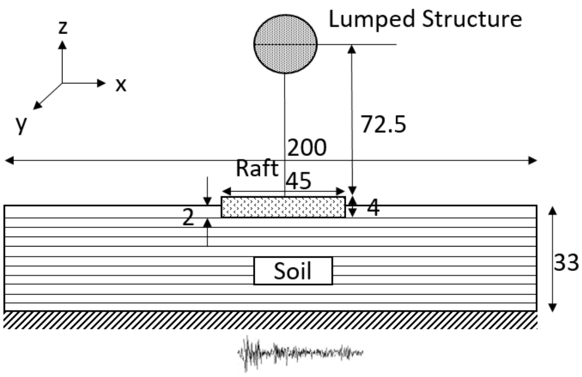

Fig. 4 – Schematic view of raft, soil and lumped structure

Table 1 – Index Properties and shear wave velocity

Depth (m)	SPT (N)	Density (kN/m^3)	Type of Soil	PI	Shear Wave Velocity (m/s)	G_{max} (MPa)
3	7	18.2	Clayey Silt	2	176	56.60
6	23	18.3		4	264	127.79
9	39	18.2		12	316	182.00
12	45	18.3		13	332	201.71
15	22	18.5		5	260	125.34
18	34	18.6		9	302	169.43
21	31	18.9		8	292	161.69
24	27	18.0		7	279	140.18
27	43	18.2		14	327	194.50
30	17	17.9		3	238	101.77
33	70	17.9		15	386	266.44

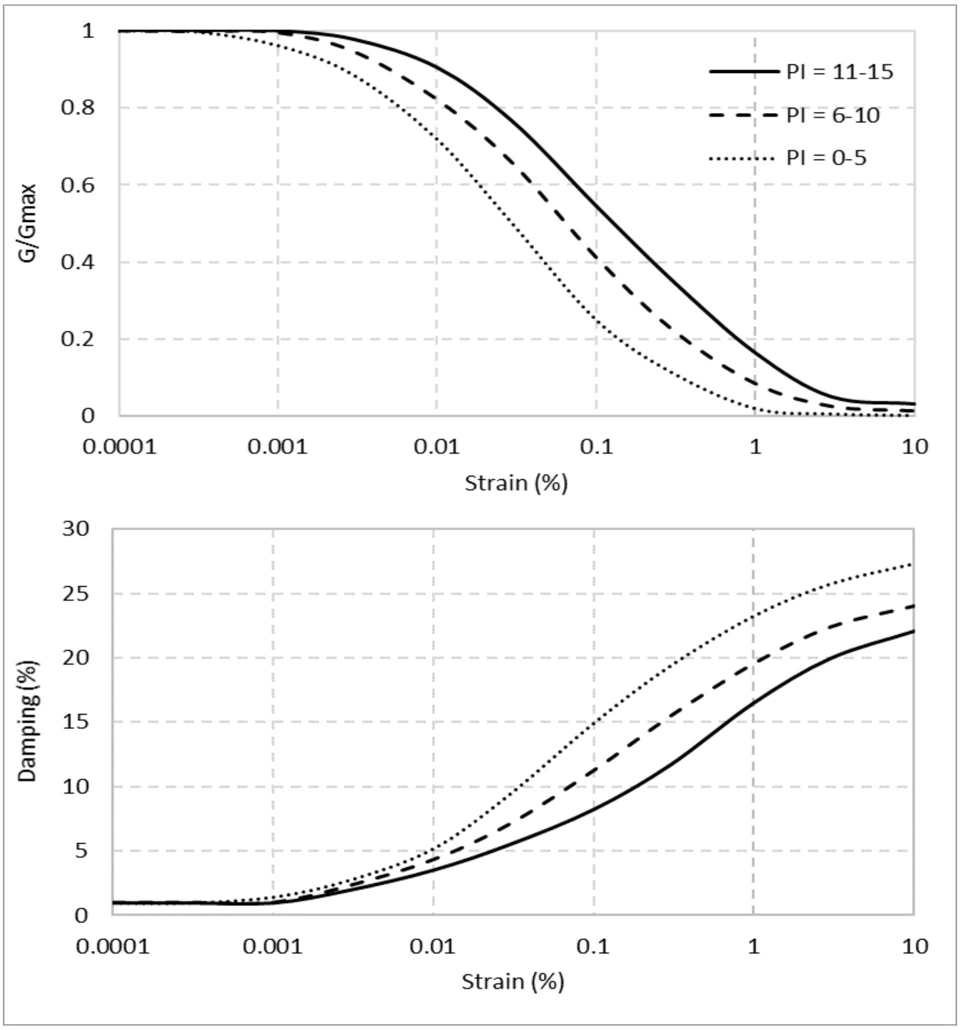

Fig. 5 – Modulus reduction and damping curves of soil (After Vucetic and Dobry, [24])

4. Procedure for Equivalent Linear Spring-Dashpot calculation

The procedure for calculating the response at the top of structure and corresponding equivalent strain dependent spring and dashpot coefficients in the proposed spring-dashpot model of NPP structure are as follows:

a) Select the modulus reduction and damping curve to be used in the dynamic analysis and identify the threshold strain i.e. strain upto which the G/G_{max} is 1 and after that shear modulus start reducing.

b) Estimate the spring and dashpot coefficients corresponding to predominant frequency of excitation and given Poisson's ratio by substituting the G value in Eqs (1-4). Use maximum shear modulus (G_{max}) in the first iteration.

c) Determine the free field response at the soil surface

d) Calculate the response of NPP structure by applying the surface motion from the step (c). The stiffness and damping coefficients shall be used from the step (b).

e) Calculate the maximum strain at the top layer using the free field response analysis.

f) Estimate the reduced value of *G* and increased value of damping corresponding to the strain obtained from the step (e). Using these value determine the spring and dashpot coefficient again

g) Repeat steps (b) to (f) until the value of strain is converged within a certain tolerance limit. For this strain, find the spring and damping coefficient for further computations.

5. Results and Discussions

In this section, a comparative study is carried out between the finite element model and spring dashpot model. The response is calculated at the top of structure.

5.1 Input Time History

Fig. 6 shows the input earthquake motion due to 1995 Kobe earthquake for the seismic analysis of NPP structure. The maximum PGA of the input motion is 0.344g having 0.58 Hz predominant frequency. This motion is used as a bedrock motion for finite element analysis and free filed analysis. The input motion used for the spring-dashpot model is determined by the free field analysis of layered soil mass. This motion is recorded at the top of soil. Fig. 7 shows the input time history for the spring-dashpot model in the last iteration. The maximum PGA of this motion is 0.421g having 1.70 Hz predominate frequency. It is observed that the both PGA and predominant frequency of surface motion is changed due to the presence of clayey-silt mixture.

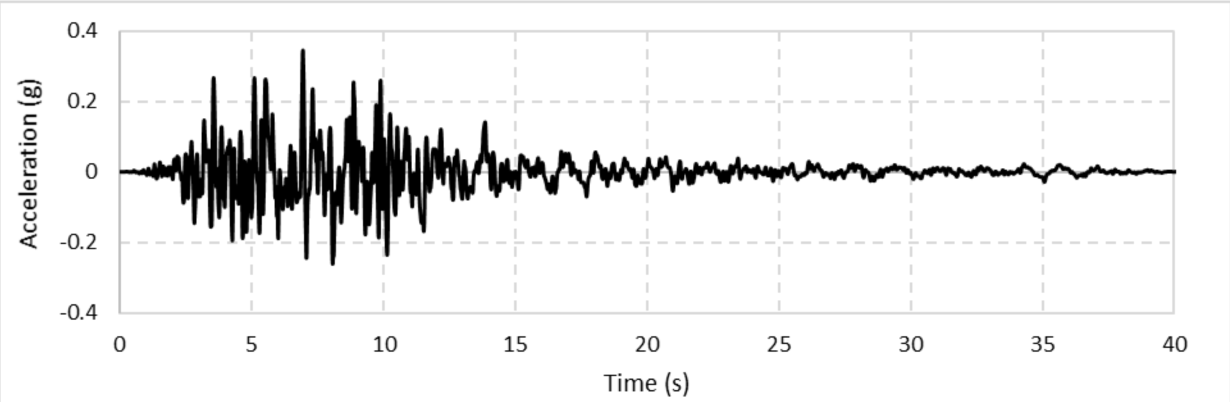

Fig. 6 – Input bedrock acceleration time history of Kobe earthquake (1995)

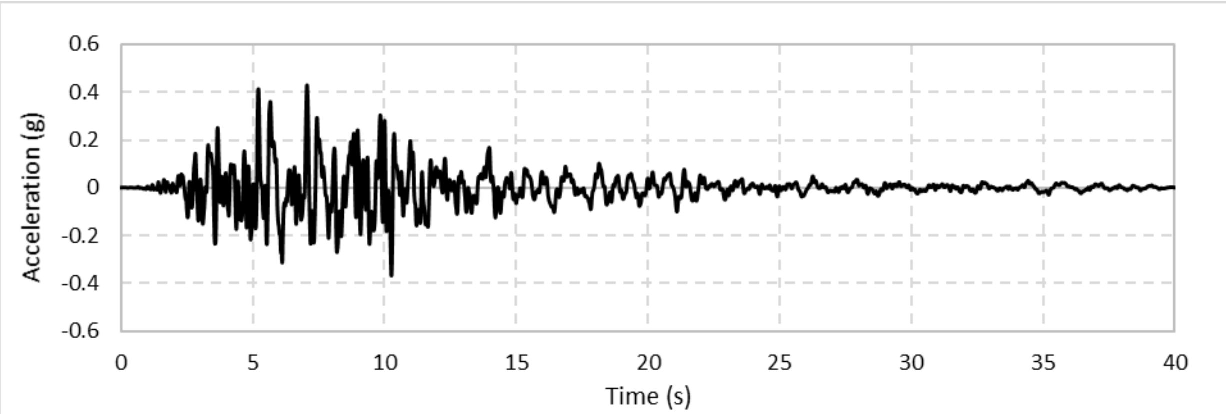

Fig. 7 – Acceleration time history at the base of raft for spring-dashpot model

5.2 Seismic Response of NPP Structure

The seismic response of NPP structure is calculated in terms of horizontal displacement, acceleration and response spectra. The seismic response of the NPP structure is calculated without and with embedment of raft foundation and results are compared with the finite element modelling. When the embedment is considered, 2 m depth of raft foundation is kept into the soil and lateral stiffness was provided by attaching the outer node of foundation with the spring-dashpot series. Fig. 8 (a) and Fig. 8 (b) show the horizontal displacement time history without embedment and with embedment respectively and results of spring-dashpot model are in good agreement with finite element modelling. The maximum displacement observed in the spring-dashpot and finite element model is shown in Table 2. In the spring dashpot model maximum displacement of NPP structure is increased by 7.08 % and 12.63 % without embedment and with embedment respectively with respect to finite element model. Therefore, it can be inferred that there is significant difference in results of spring-dashpot model with respect to FEM. This difference was expected which is still less than 13 %. In the finite element modelling, when the embedment is considered the displacement is reduced by 15.92 % while in spring dashpot model it is reduced by 11.57 %. Since due to the embedment, the stiffness, damping and natural frequency of foundation increases. Therefore, it reduced the horizontal displacement of NPP structure.

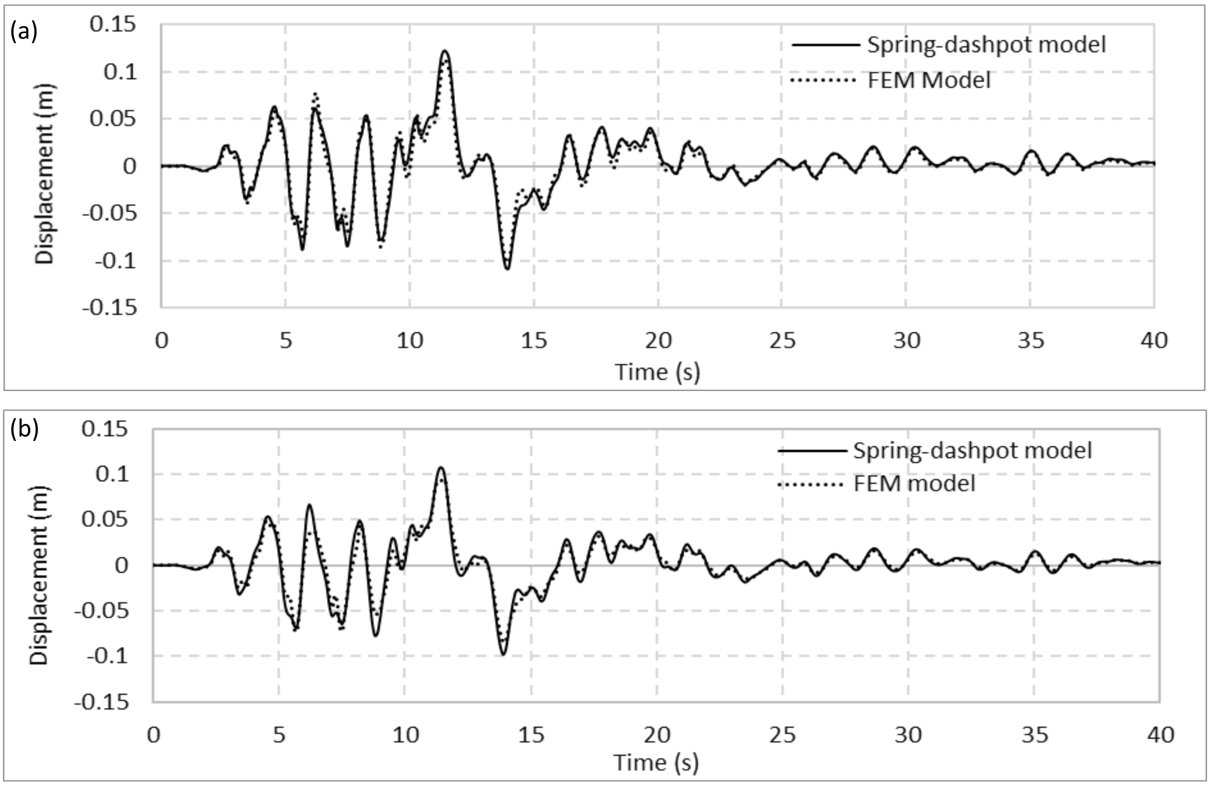

Fig. 8 – Displacement time history at the top of structure (a) Without Embedment (b) With Embedment

Table 2. Maximum Horizontal Displacement

	Maximum Displacement (m)		
Methodology	Finite Element Modelling	Spring-dashpot Modelling	% change
Without Embedment	0.113	0.121	7.08
With Embedment	0.095	0.107	12.63
% change	15.92	11.57	

Fig. 9 (a) and Fig. 9 (b) shows the horizontal acceleration time history without and with embedment respectively and results of spring-dashpot model are reasonably matching good with finite element modelling. The peak acceleration observed in the spring-dashpot and finite element model is shown in Table 3. In the spring dashpot model peak acceleration of NPP structure is increased by 16.43% and 15.18% without embedment and with embedment respectively with respect to finite element model. It was found that spring dashpot model underestimate the stiffness of soil. Without considering embedment, the peak acceleration at the top of structure is amplify by 1.27 and 1.48 times in the finite element and spring-dashpot model, respectively while by considering the embedment it amplified by 1.11 and 1.28 times in finite element and spring-dashpot model. In the finite element modelling, when the embedment is considered the peak acceleration is reduced by 12.78 % while in spring-dashpot model it reduced by 13.72 %.

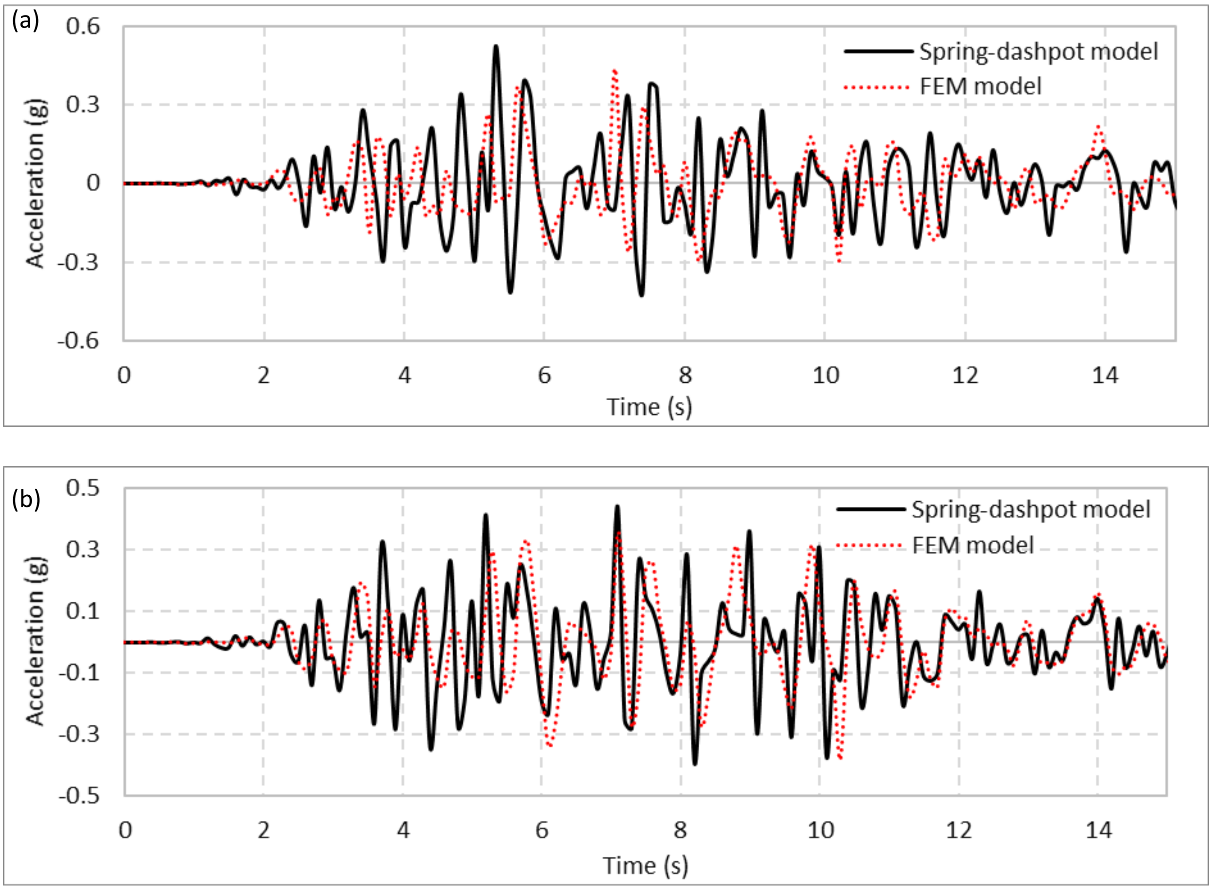

Fig. 9 – Acceleration time history at the top of structure (a) Without Embedment (b) With Embedment

Table 3. Maximum Horizontal Acceleration

	Peak Acceleration (g)		
Methodology	Finite Element Modelling	Spring-dashpot Modelling	% change
Without Embedment	0.438 (1.27)*	0.510 (1.48)*	16.43
With Embedment	0.382 (1.11)*	0.440 (1.28)*	15.18
Input Acceleration	0.344	0.427	
% change	12.78	13.72	

*Amplification ratio

Fig. 10 (a) and Fig. 10 (b) show the response spectrum at the top of structure without and with embedment respectively and results of spring-dashpot model are in same trend as of finite element model. However, the deviation is found between the finite element and spring-dashpot model. The time period of structure in the spring dashpot model is reduced as compared to finite element model. The peak spectral acceleration observed in the spring-dashpot and finite element model is shown in Table 4. In the spring dashpot model, the maximum spectral acceleration of NPP structure is increased by 8.08 and 4.86% without embedment and with embedment respectively with respect to finite element model i.e. means results are in good agreement and difference is about 10%. In the finite element modelling, when the embedment is considered the peak spectral acceleration is reduced by 27.27 % while in spring-dashpot model it reduced by 29.43 %. Means the effect of embedment is quite significant on spectral acceleration.

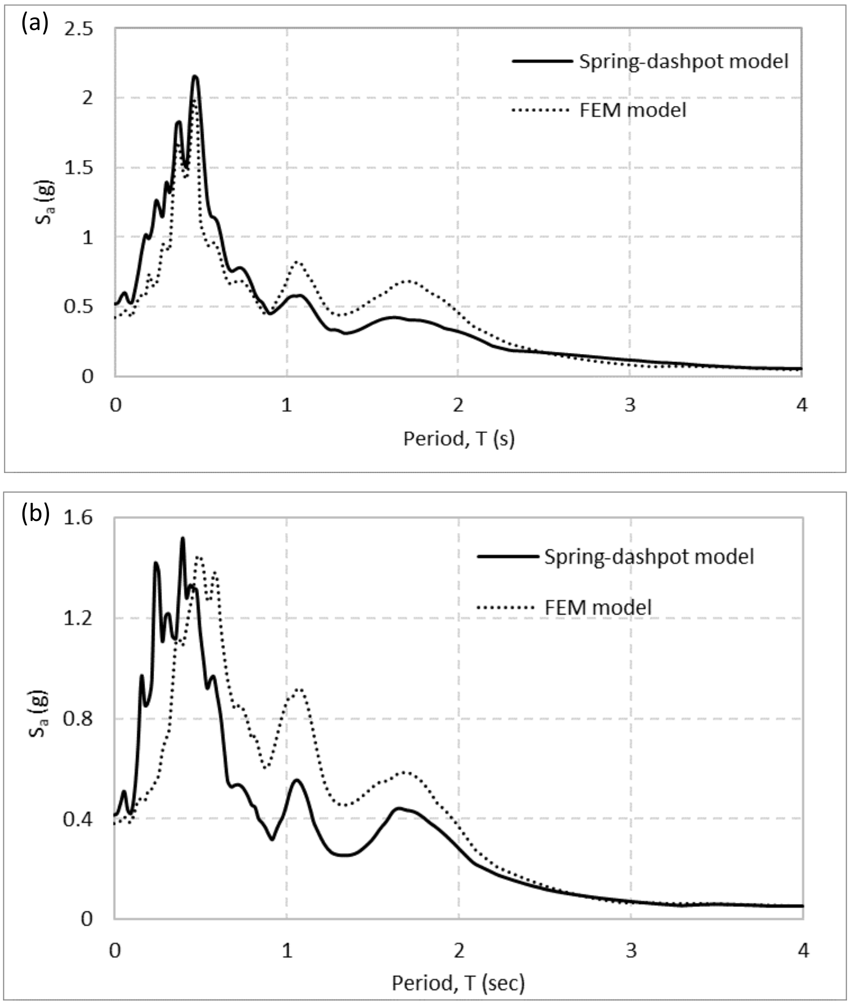

Fig. 10 – Response spectrum at the top of structure (a) Without Embedment (b) With Embedment

Table 4. Maximum Spectral Acceleration

	Maximum Spectral Acceleration, S_a (g)		
Methodology	Finite Element Modelling	Spring-dashpot Modelling	% change
Without Embedment	1.98	2.14	8.08
With Embedment	1.44	1.51	4.86
% change	27.27	29.43	

6. Conclusions

In this paper, an equivalent linear spring-dashpot model of embedded foundation of NPP structure is proposed to calculate the seismic response of lumped structure on the layered soil mass. A comparison of results obtained by the proposed method with those provided by the finite element method shows that method can calculate the horizontal displacement, acceleration time history and response spectrum for the seismic design of NPP structure. The proposed method has the advantage over the finite element method. First, it is very simple and second it reduces the computation time period. Furthermore, it is observed that proposed model is applicable for embedded foundation. Following conclusions can be drawn from the present study:

a) In the spring-dashpot model, the displacement of NPP structure is increased by 7.08 and 12.63% without embedment and with embedment respectively with respect to finite element model. In the finite element modelling, when the embedment is considered the maximum displacement is reduced by 15.92 % while in spring dashpot model it is reduced by 11.57 %. This is due to the increase in stiffness of foundation.

b) In the finite element modelling, when the embedment is considered the peak acceleration is reduced by 12.78 % while in spring-dashpot model it reduced by 13.72 %. In the spring-dashpot model peak acceleration of NPP structure is increased by 16.43 and 15.18 % without embedment and with embedment respectively with respect to finite element model. It can be concluded that spring-dashpot model underestimate the stiffness of soil.

c) In the finite element modelling, when the embedment is considered the peak spectral acceleration is reduced by 27.27 % while in spring-dashpot model it reduced by 29.43 %. In the spring-dashpot model, the maximum spectral acceleration of NPP structure is increased by 8.08 % and 4.86 % without embedment and with embedment respectively with respect to finite element model.

Thus results of spring-dashpot model are very close to finite element model and moreover effect of embedment is significant. The results presented in this paper can be used for the seismic design of NPP structure on the layered soil mass. Moreover, embedment should be taken into consideration while design the nuclear power plants.

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