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Wavelet Analysis of the Seismic Response of a Base-Isolated Nuclear Power Plant Structure Considering Soil-Structure Interaction

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ABSTRACT

Wavelet analysis has been proved to be a powerful tool in analysing non-stationary signals. The present study applies the wavelet analysis to assess the seismic response of a base-isolated nuclear power plant (NPP) structure considering the soil-structure interaction (SSI). Seismic isolation is widely used structural design technique to protect important civil infrastructure against earthquake forces. However, the application of base isolation to NPP structure is quite limited due to lack of information and experimental data about the behaviour of such devices. The soil-structure interaction (SSI) may have significant effect to alter the seismic responses of such large isolated structures. In this study, to investigate this effect, a base isolated NPP structure is considered as a lumped mass stick model and combined with a SSI model using the concept of cone models. The lead rubber bearing (LRB) isolator is used for seismic isolation of the structure. Moreover, the shear wave velocity of the soil is varied to represent the real site conditions of the structure. Furthermore, the seismic performance of the base-isolated structure is compared that of non-isolated structure. The results show that the wavelet analysis proves to be an efficient tool to investigate the effect of SSI on the frequency content of the acceleration response of base isolated NPP structure.

INTRODUCTION

The dynamic behaviour of inelastic structure subjected to seismic ground excitation is a complex non-stationary process. The conventional Fourier analysis has been considered as a primary tool to obtain the frequency content of the signal, which gives no information about the location of these frequencies in the time domain. To overcome this problem scientists have developed a method called wavelet analysis, which can provide both time and frequency localization information simultaneously. Recently, wavelets have been implemented in geotechnical earthquake engineering to analyse the non-stationary seismic response of dynamic system (Iyama and Kuwamura, 1999, Chatterjee and Basu, 2004). Therefore, in the present study, wavelet analysis is used to identify the time frequency characteristics of acceleration response of base-isolated NPP structure considering SSI effect.

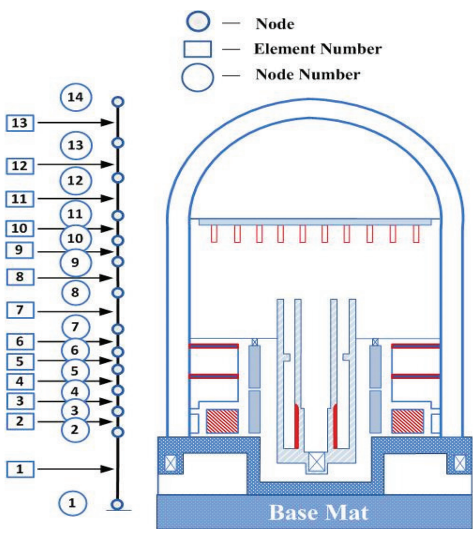
Seismic base isolation is a well-known flexible approach to reduce the potential damage caused by seismic ground motions. Recently seismic base isolation has become a widely used structural design technique for conventional structures, bridges, and infrastructures. Nowadays, only six nuclear reactors in two nuclear power plants have been isolated in France and South Africa (Huang et al. 2010). In addition, many studies have been conducted to investigate the seismic responses of NPP using base isolation system (Micheli et al. 2004, Zhao and Chen, 2013). Forni et al. (2012) provided the state-of-the-art of the application of seismic base isolation to NPPs. Up to date, no specific standards are available for the application of base isolation to NPPs.

The Soil-structure interaction may play a significant role to change the seismic responses of superstructure. The common practice usually neglects the SSI effects on seismic response of base isolated structure. In recent years several studies have been shown the effectiveness of considering SSI effect in the design of base-isolated structure. Novak and Henderson (1989) investigated the effect of SSI on the modal properties of base-isolated structures. Tongaonkar and Jangid (2003) assessed the effect of SSI phenomena on a three-span bridge with LRBs and concluded that SSI cause an increase in the seismic

displacements. Spyrakos et al. (2009) presented the importance of SSI on the seismic response of base-isolated buildings and shown that the SSI effects are more pronounced on the modal properties of the system.
The primary objective of this paper is to evaluate the effects of SSI on base-isolated NPP rested on the different rock site conditions. In that regard, a wavelet-based technique is applied to analyse the acceleration response of structures. Finally, the wavelet analysis is used to evaluate the degree of correlation between the input ground motion and the seismic responses of the structures.

NUCLEAR POWER PLANT (NPP) MODEL

In the present study, a simplified model of Advanced Power Reactor (APR1000) is used for numerical analysis. The structural model of base-isolated NPP established with a lumped mass stick model, base mat and base isolation devices. The total height of NPP stick model is 65.8m with fourteen nodes and thirteen three dimensional beam elements. The total dimensions of base mat are 100 x 80 x 4 m. However, the base mat dimensions under the stick model are 20 x 16 x 12 m. Total 121 LRB isolators are used for adopting base isolation system. The BI-NPP model is constructed by OpenSees Navigator (Schellenberg et al. 2013). The structural model of BI-NPP model is shown in Figure 1.



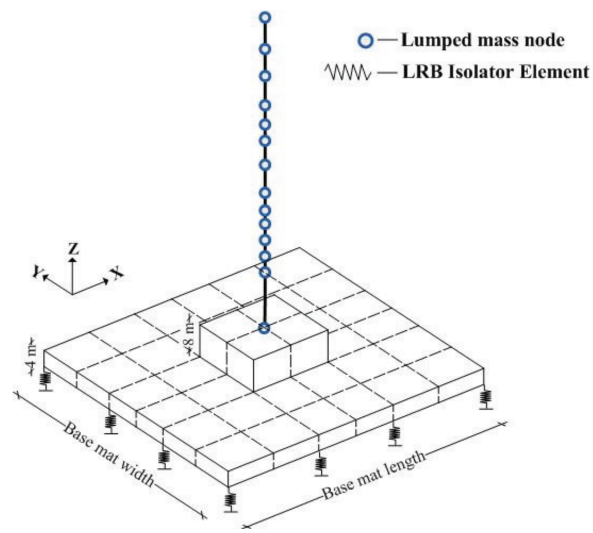


Figure 1. NPP containment building sectional elevation and stick model (left), Nuclear island base mat dimensions (right).

DESIGN OF LRB ISOLATORS

In this study, Lead rubber bearing (LRB) isolator is used which consists of low damping natural rubber, steel plates and a lead plug damper. The rubber is an elastic material and the lead plug damper acts as a plastic material at low levels of stresses, therefore, as a whole, the LRB device shows nonlinear dynamic properties. In this study, the international Organization for Standardization (ISO) specification (2010) are followed to design the LRB isolator. The equivalent linear properties are also used for isolation device analysis which is shown in Figure 2. In Figure 2 K_u is the linear horizontal tangential stiffness and K_d is the post-yield horizontal stiffness. K_H represents the effective horizontal stiffness of the isolator. Moreover, Q_d and F_y denote the characteristic strength and yield strength respectively. δ_{max} is the maximum horizontal displacement and δ_{min} is the minimum horizontal displacement of the isolator. Furthermore, F_{max} and F_{min} are the maximum and minimum horizontal forces corresponding to the maximum and minimum horizontal displacements of the isolator, respectively. Table 1 illustrates the dynamic properties of LRB isolator.

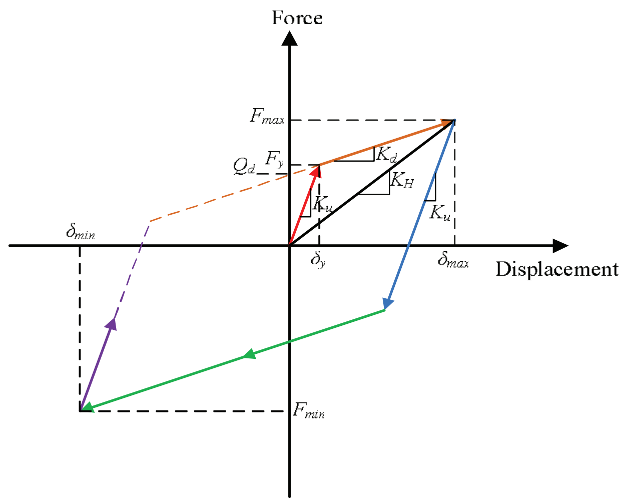


Figure 2. Linearization of the force-displacement relationship of LRB isolator (ISO, 2010).

Table 1: Properties of LRB isolator.

Horizontal Stiffness	Post-yielding Stiffness	Yield Strength	Characteristic Strength	Yield Displacement	Hardening ratio
K_H (KN/m)	K_d (KN/m)	F_y (KN)	Q_d (KN)	δ_y (mm)	α
8436.10	7089.55	303.73	269.31	4.85	0.113

WAVELET ANALYSIS

There are mainly two types of wavelet transform that is, the continuous wavelet transform and the discrete wavelet transform. Iyama and Kuwamura (1999) illustrated that discrete wavelet transform is more useful because it represents a signal characteristics as well. Therefore, the discrete wavelet transform is used in this paper and simply referred as wavelet transform.

Wavelet decomposition

The wavelet decomposition process starts with splitting the acceleration signal into two parts, the approximation and the detail, by passing through two complementary filters. The approximations are the high scale and contain the low frequency component of the signal. However, the details are the low scale and contain the high frequency component. The decomposition process is presented by the Equation 1.

$$A_j(t) = a_{j+1}(t) + d_{j+1}(t) \tag{1}$$

Where A(t) is the original acceleration signal, a(t) is the approximations component, d(t) is the details component, and j is the level number representing the particular range of frequency content of the signal. The frequency range of each decomposition level is expressed by Equation 2.

$$\omega_j = \left[\frac{1}{2^{j+1}\Delta t}, \frac{1}{2^j \Delta t} \right] \tag{2}$$

Where Δt is the time step of discretized signal. Sarica and Rahman (2003) illustrated that, the original signal can be reconstructed from details without losing any information and can be written by Equation 3.

$$A_o(t) = \sum_{j=1}^{n} d_j(t) \tag{3}$$

Where n represents the total number of decomposition levels. Using linear combination of wavelet basis function the details components of the original signal can be represented by Equation 4.

$$d_j(t) = \sum_{-\infty}^{\infty} c_{j,k} \psi_{j,k} \tag{4}$$

Where k is an index of time scale, $\psi_{j,k}$ are the basis wavelet function and $c_{j,k}$ are corresponding wavelet coefficients. The basis wavelet function can be written by following Equation.

$$\psi_{j,k} = 2^{\frac{j}{k}} \psi(2^j t - k) \tag{5}$$

In this study, 4th-order Daubechies mother wavelet is used as a basis wavelet function.

Energy Calculation

Walker (1999) illustrated that the total energy of a discrete signal can be expressed by the sum of the squares of its values.

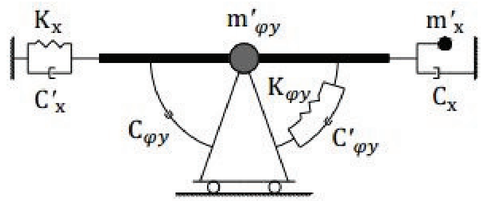
$$E = \Delta t \sum_{t=0}^{t} A_o^{\,2}(t) \tag{6}$$

Moreover, the total energy can be represented in the form of details only at each decomposition level. In this study, this concept is used to determine the cumulative energy of signals which is expressed by the Equation 7.

$$E = \sum_{j=1}^{n} \sum_{k=0}^{t} d_j^{\,2}(t) \tag{7}$$

SOIL-STRUCTURE SYSTEM IDEALISATION

In this study, the sub-structure methodology is used to adopt the SSI model. The infinite soil medium beneath structure is assumed as a homogeneous half-space and modelled by the concept of Voigt viscoelastic Cone Models. Five degree of freedoms are considered for sway and rocking motions about x and y axis and rotation about z axis. In addition, a set of frequency-independent springs and dashpots are used to consider the inertial interaction between structure and soil (Ghaffar-Zade and Cahpel, 1983). The soil model is represented in Figure 3.



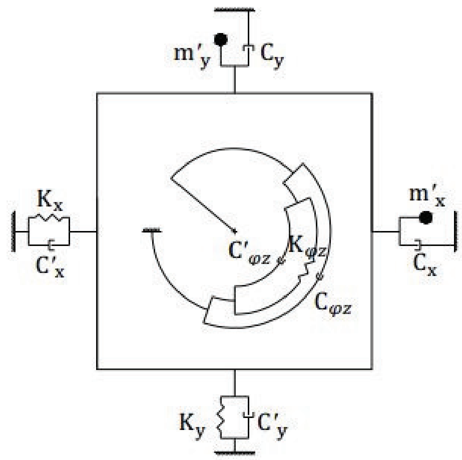


Figure 3. Soil model (Kenarangi and Rofooei, 2010).

The soil related parameters are presented by Equation 8 and 9.

$$K = \frac{\rho V^2 A}{z}, \quad C = \rho VA, \quad C' = 2\frac{\zeta}{\omega}K, \quad m' = \frac{\zeta}{\omega}C \tag{8}$$

$$K_\varphi = \frac{3\rho V^2 I}{z}, \quad C_\varphi = \rho VI, \quad C'_\varphi = 2\frac{\zeta}{\omega}K_\varphi, \quad m'_\varphi = \frac{\zeta}{\omega}C_\varphi \tag{9}$$

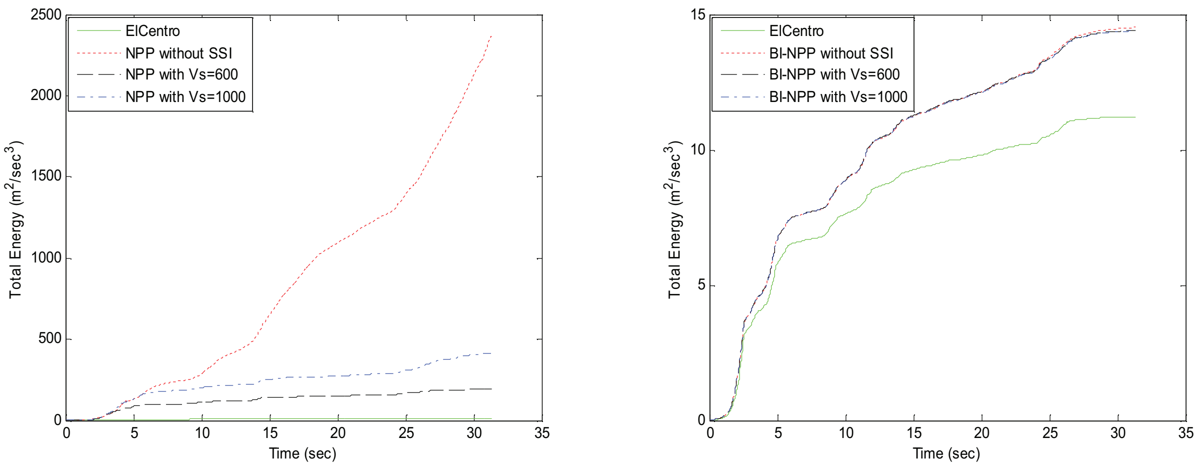
Where V is the shear wave velocity for sway and torsional motions and the dilatational wave velocity for rocking motions, ρ is the specific mass of soil and z is the apex height of the cone model. A and I denote the area of foundation and the area moment of inertia about the axes of rotation respectively. Furthermore, ζ and ω represent the damping ratio of soil and fundamental frequency of the soil-structure system respectively.

RESULTS AND DISCUSSIONS

In this study, depending on the consideration of base isolation system two types of structure is used, i.e., NPP (without considering base isolators) and BI-NPP (with considering base isolators). A discrete cone model based on the concept of voigt viscoelastic cone models is used to consider the soil properties beneath the structures. In addition, two shear wave velocities are used in the SSI model for considering soft rock (Vs=600 m/s) and rock (Vs=1000 m/s) sites. Moreover, the time history analysis is performed by applying 1940 El Centro ground motion. Finally, the wavelet transform is used to analysis the acceleration responses of the structures in conjunction with SSI.

Total energy

Figure 4 shows the total energy of acceleration responses of the top node of NPP and BI-NPP models. As seen in Figure 4 (a), for NPP structure the total energy of response increased greatly then the applied ground motion. However, when the SSI effect is considered the total energy reduced dramatically. The amount is 92% and 83%, for soft and rock site conditions respectively. Moreover, the rate of decrement is greater, which is more than 50% for soft rock site. Furthermore, Figure 4 (b) shows that, after implementing the base isolation device to NPP structure the increase of total energy is relatively low than the input record, whereas, the consideration of SSI effect is negligible which is less than 1% to alter the energy. It can be concluded that, SSI has great effect to decrease the total energy of response of NPP structure, whereas, the effect is negligible for BI-NPP structure. Moreover, the rate of change of the total energy is prominent for NPP rested on soft rock site.



(a) NPP model

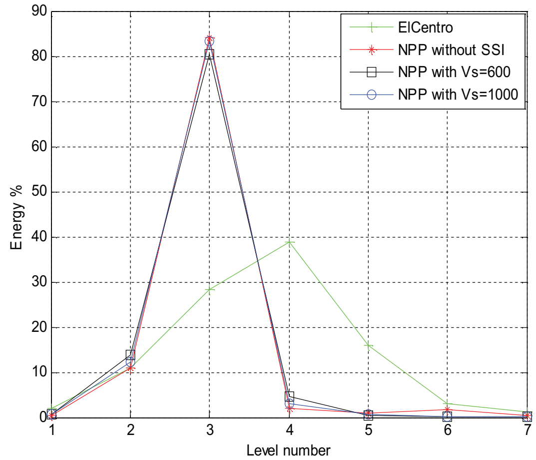
(b) BI-NPP model

Figure 4. Total energy of acceleration responses of nuclear power plant models.

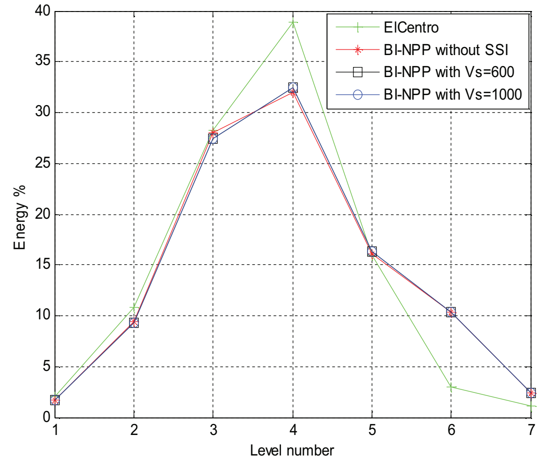
Energy distribution

The energy distribution at each decomposition level of top node acceleration responses of NPP and BI-NPP models with considering SSI effect is shown in Figure 5. It is observed that, the energy contribution of El-Centro earthquake record is distributed over wide level of frequencies. However, more than 90% of energy is contained in 0.39 to 12.5 Hz, which lies in levels 2-6. The fundamental frequencies of NPP models with SSI are found to vary from 4.1 to 4.6 Hz, which hold in level 3. As seen in Figure 5 (a), at level 3, total energy of input ground motion is 28% which increased to more than 80% for NPP model. Moreover, when the SSI effect is considered with two rock site conditions, the decrease of energy ratio is less than 5% at all frequency levels. Therefore, it can be concluded that fundamental frequency of NPP model dominates the energy distribution of acceleration response of the structure, whereas, SSI has negligible effect to change the energy portion at each decomposition level.

It can be seen from Figure 5 (b), for BI-NPP structure the energy contribution of each decomposition level follows the similar way of energy distribution of applied ground motion, except the level that contains fundamental frequency of the structure which is around 0.5 Hz. At levels 1-5 and 7 the energy ratios of input motion and response of BI-NPP are almost similar, whereas, at level 6 (contains the fundamental frequency of structure) it jumped from 3% to 10%. However, the decrease of energy portion at each level is negligible (less than 2%) when SSI effect is considered. It indicates that, after implementing the base isolation system to NPP structure the energy ratio at each level of response is spread over a wide band of frequencies, while, SSI dose not add any significant effect to alter it.



(a) NPP model

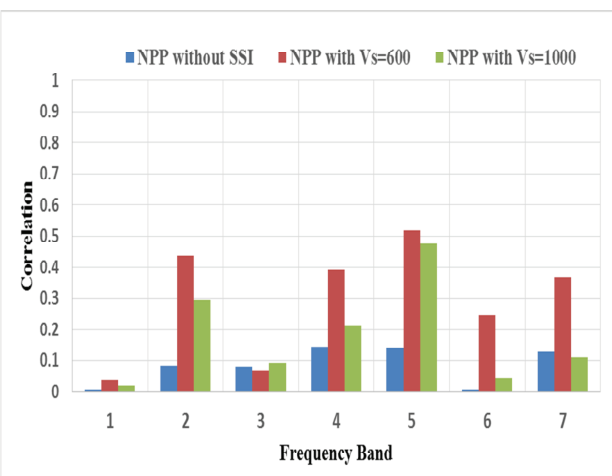


(b) BI-NPP model

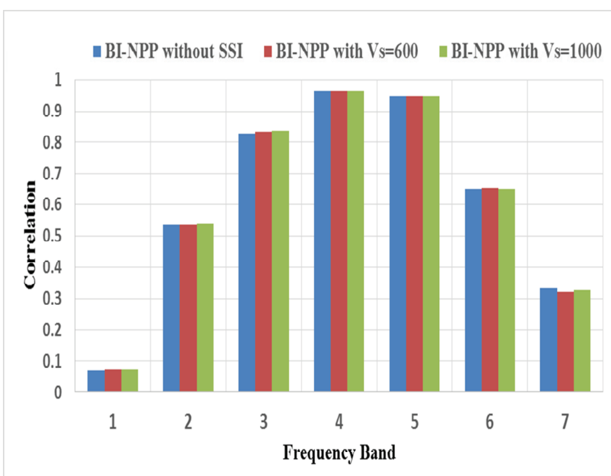
Figure 5. Energy distribution at each decomposition level of acceleration responses of nuclear power plant models.

Comparison of input motion and structural response

Wavelet analysis can be applied to identify short-term changes in the frequency content of a signal which can be used to detect the change of dynamic characteristics of structure, such as the initiation sign of stiffness degradation or the sudden occurrence of non-ductile events (Goggins et al. 2006). The change of wavelet coefficients can be identified by determining the degree of correlation between two signals, which is expressed by Equation 10,



(a) NPP model



(b) BI-NPP model

Figure 6. Degree of correlation between ground motion and acceleration response of nuclear power plant models.

$$\rho_{xyj} = \frac{\sum_i w_{xj} w_{yj}}{\sqrt{\sum_i w_{xj}^2} \sqrt{\sum_i w_{yj}^2}} \tag{10}$$

Where ρ_{xyj} is the correlation coefficient. w_{xj} and w_{yj} are the details of input ground motion and the acceleration response of structure at level j.

The variation of degree of correlation between input ground motion and acceleration response of NPP and BI-NPP models in conjunction with SSI are shown in Figure 6. It is observed from Figure 6(a) that, for NPP structure poor correlation exists for all decomposition levels. The level 3 contains the fundamental frequency of NPP model with highest energy portion, shows lowest correlation. However, after adding SSI effect correlation coefficients improved somewhat. Relatively better correlation exists when soft rock site is considered for NPP structure. On the other hand, it can be noticed from Figure 6 (b), good agreement occurs between BI-NPP response and input ground motion. Nearly perfect relation observes at levels 3-5 where most of the energy of the response lies. Moreover, better relationship displays at level 6 which contains the fundamental frequency of BI-NPP structure. Furthermore, correlation coefficients do not suffer much change when SSI effect is adopted. It can be concluded that, frequency content of NPP response is not related with input ground excitation, whereas, soft rock site relatively increases the relation. However, BI-NPP response directly correlates with ground motion and the relation does not change much when SSI effect is considered.

CONCLUSIONS

The present study evaluated the effect of SSI on a base-isolated NPP structure and compared with rigidly fixed NPP structure to the ground by using the wavelet analysis. The summary of this study are as follow:

- The energy calculation process based on wavelet transform is a good tool to investigate the effect of SSI on frequency content of the acceleration responses of nuclear power plant structures.
- The consideration of SSI effect causes significant decrease of accumulative total energy of the acceleration response of NPP structure, especially for soft rock site. This indicates that, NPP structure suffers less acceleration when SSI effect is adopted. Whereas, the effect is negligible for BI-NPP structure.
- The energy distribution of NPP structure is dominated by the fundamental frequency and demands more high frequency content than the input ground motions, while, SSI has negligible effect to change it. However, for BI-NPP structure the energy ratio at each level of response is spread over a wide band of frequencies, dose not suffer much change due to SSI effect.
- Poor correlation exists between acceleration response of NPP structure and input ground excitation, whereas, for soft rock site the relation increases significantly. Conversely, the frequency content of the response of BI-NPP is directly related to the input motions at the levels where most of the energy lie, however, SSI has negligible contribution to change the relation.

ACKNOWLEDGEMENT

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