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SEISMIC ANALYSIS OF BASE ISOLATED NUCLEAR POWER PLANT CONSIDERING NONLINEAR PILE-SOIL INTERACTION

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ABSTRACT

The seismic performance study of the base isolated nuclear power plants (NPP) has gained importance after the recent devastating earthquake events. For past few decades, the soil structure interaction (SSI) approach has been applied to structures to investigate the effects on the nonlinear response of the structure. The present work focuses on the performance of the rigidly fixed base isolated NPP reactor building compared to the one considering nonlinear pile-soil interaction. The NPP model is supported by deep pile foundation with 20m depth. Free site response analysis of two soil sites are considered to evaluate the dynamic behavior of the NPP models due to different geotechnical characteristics of stiff and soft soil strata. Two sets of Tohoku earthquake ground motions of short- and long-period; are selected and applied to the NPP model as input motions. The selected ground motions are spectrally compatible based on the guidelines provided by U.S Nuclear regulatory commission (USNRC). The numerical results of the seismic analysis are presented in terms of the lateral nodal displacement, the shear forces and the spectral acceleration of the NPP stick model. The obtained results indicate under the short-period inputs that the base isolated NPP model considering pile foundation show higher responses than the rigidly fixed base isolated NPP, while they are less under the long-period ground motions.

INTRODUCTION

Soil-pile-structure interaction can be an important consideration in evaluating the seismic response of pile-supported structure, particularly in soft and liquefying soil, Boulanger et al. (1999). The dynamic nonlinear p-y analyses have a long history of development and application to seismic and offshore problems [e.g., Matlock et al. (1978), Kagawa and Kraft (1980) and Nogami et al. (1992)]. Wang et al. (1998) compared several implementations of the dynamic nonlinear p-y method and showed that the calculation can be sensitive to the detailed of the nonlinear springs and dashpots. Evaluation of the pile-soil-structure interaction due to earthquake induced ground accelerations is an important step in seismic design of both the structures and piles. Free field site response analysis of two soil profiles; a clayey site and a sandy site with depth 30m are considered. The response of the soil profiles was analyzed using a 1D equivalent-linear site response program. In this study, a simplified Beam on Nonlinear Winkler Foundation (BNWF) model which can be used for the dynamic response analysis is introduced. The purpose of this study is to evaluate the seismic responses of the pile-supported base isolated NPP stick model considering nonlinear pile-soil interaction under two sets of ground motions compared with the rigidly fixed base isolated NPP stick model. The Tohoku earthquake was primarily considered because of its lengthy time history and better demonstration of the long-period component in the recorded spectra. Furthermore, the input ground motions for the two groups of motions i.e. short- and long-period; are selected compatible to the target design spectrum; specified in the performance based regularity guide of the USNRC, R.G. 1.60 (1973). Nonlinear p-y elements were implemented in the finite element program for the dynamic p-y analysis. Details of NPP structural model, the free-field site response analyses, and the nonlinear p-y elements are described.

NPP MODEL & GROUND MOTIONS SELECTION

The structural stick model of the NPP containment reactor building, Lee and Song (1999) was modeled using the OpenSees software framework, McKenna and Fenves (2001). The stick model height is 65.837m, which contains 13 elements and 14 nodes as shown in Figure 1. The actual masses of the NPP building are transferred as lumped masses to the corresponding nodes on each element edge. All the translational and rotational masses are defined at each node with total 2792.43 ton.sec^2/m and 637546.84 ton.m/sec^2 for the translational and rotational masses, respectively. The structural elements, which used to connect and join the different lumped masses in each node are used with average cross sectional area 168.7 m^2 and average moment of inertia 39803.4 m^4 for each element.

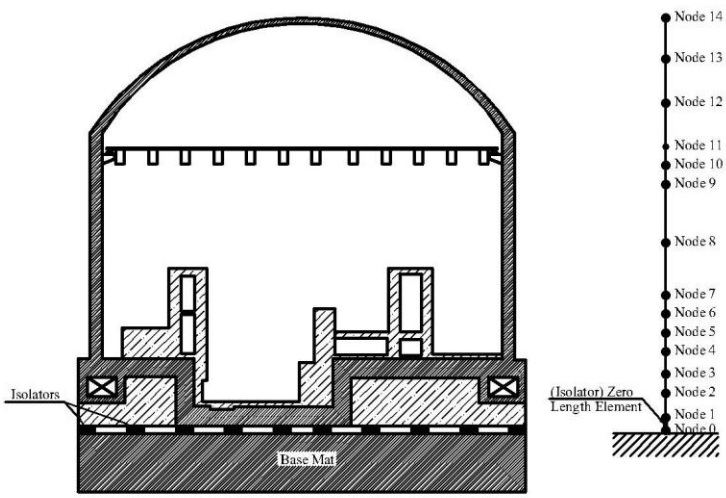
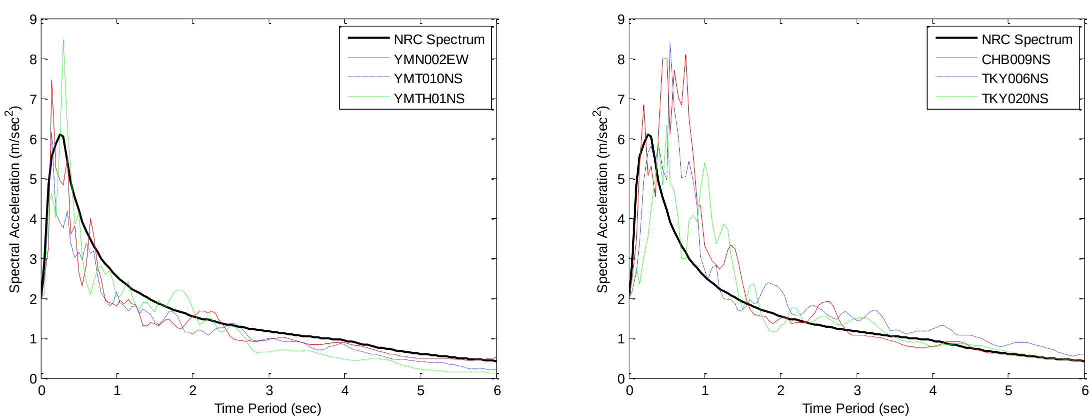


Figure 1. NPP containment building sectional elevation and structural stick model

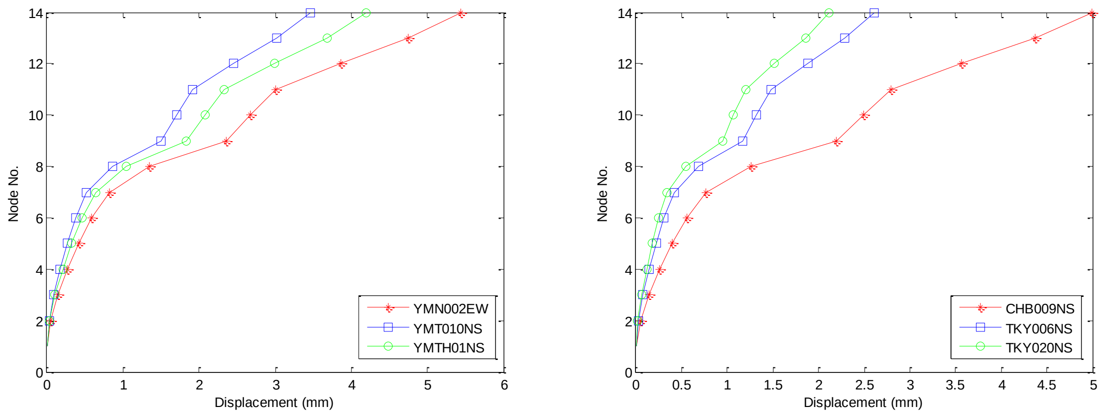
Tohoku earthquake is primarily considered because of its lengthy time history and better demonstration of the long period component in the recorded spectra. Two sets of ground motions i.e. short- and long-period are selected compatible to the target design spectrum which specified based on the regularity guide of the USNRC, Ali et al. (2012). The acceleration response spectra at 5% damping for the two sets of ground motions are presented as shown in Figure 2.



(a) (b)

Figure 2. Acceleration response spectra (5% damping) of short-period (panel a) and long-period (panel b) of selected Tohoku earthquake ground motions.

The two sets of the selected input ground motions were applied at the base of the fixed base NPP structural stick model. The fundamental time period of the fixed base NPP model is 0.168 second, while the responses of the model were recorded in terms of nodal lateral displacements as shown in Figure 3.



(a) (b)

Figure 3. Nodal lateral displacements of the fixed base NPP stick model under short-period (panel a) and long-period (panel b) of selected Tohoku earthquake ground motions.

BASE ISOLATOR

The idealization of the bilinear hysteretic model of the base isolator is shown in Figure 4. The yield force $F_{y=}$ 2.7x10^3 KN, elastic stiffness K_1=61x10^4 KN/m and post yield stiffness K_2=0.167*K_1. The lateral displacement (D_D) of the base isolator is calculated using the following formula which provided by Naeim and Kelly (1999):

$$D_D = \frac{(g/4\pi^2)C_{VD}T_D}{B_D} \tag{1}$$

Where D_D is the lateral displacement at the center of rigidity of the isolation system, g is the gravitational acceleration, C_{VD} is the seismic coefficient, T_D is the natural period of the isolator system, and B_D is the damping coefficient.

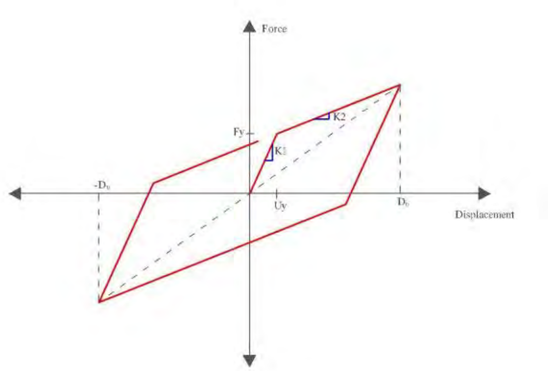
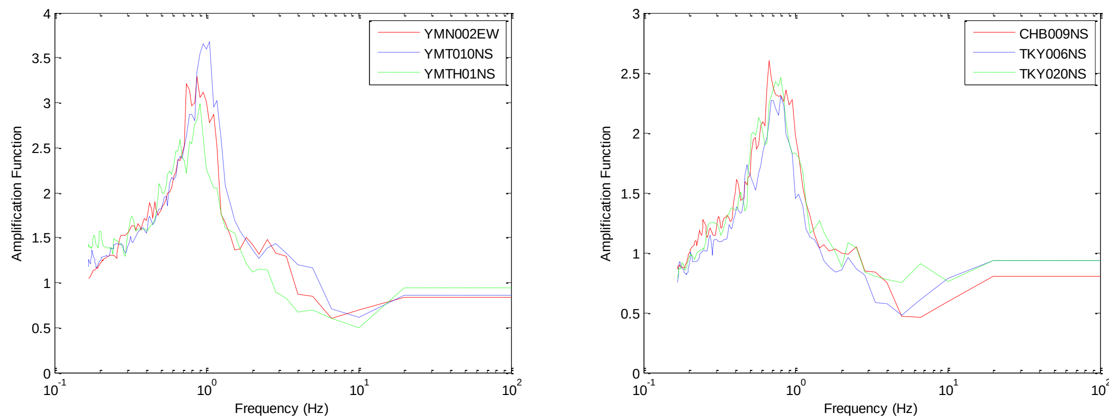


Figure 4. Parameters of basic hysteresis loop for the base isolator

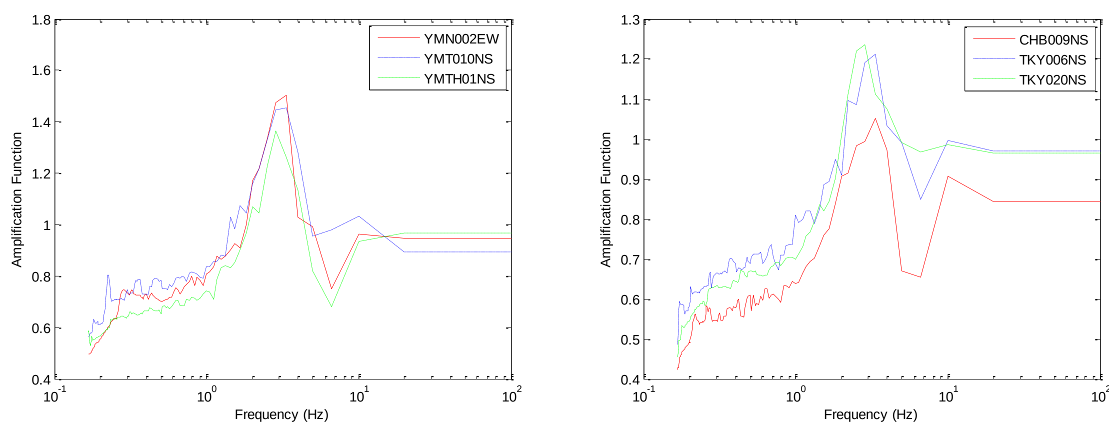
FREE SITE RESPONSE AND SOIL MODELLING

The free field site response analyses were performed using one-dimensional site response analysis based on the equivalent linear stress-strain model for the soil sites. Two soil sites are selected, a clayey site and a sandy site. The clayey site with depth 30 m and has an average shear wave velocity about 400 m/s which considered site (class C) according to the NEHRP site classification. While the sandy site with depth 30 m and shear wave velocity about 200 m/s which considered site (class D) according to NEHRP classification. The computer software DEEPSOIL, Hashash et al. (2011) is used for the free field site response analysis for the two soil sites. For each analysis, the amplification function at the site surface is computed by dividing the acceleration response spectrum ordinates of the motions at the site surface by the corresponding acceleration response spectrum ordinates the accelerogram applied at the soil column base, Bazzurro et al. (2004a) as shown in Figure 5&6. The amplification functions at the site surface of both site deposits under the short-period inputs are higher than that under the long-period as shown in Figure 5&6. Furthermore, it also shown that the sandy site deposit response is about twice the response of the clayey site deposit response. Hence, the sandy site will be only considered in the analysis of the base isolated NPP considering the pile foundation as shown in the next section.



(a) (b)

Figure 5. Amplification functions of the sandy site deposit under the short-period (panel a) and long-period (panel b) of selected Tohoku earthquake ground motions.



(a) (b)

Figure 6. Amplification functions of the clayey site deposit under the short-period (panel a) and long-period (panel b) of selected Tohoku earthquake ground motions.

PILE-SOIL INTERACTION

The NPP stick model is supported by deep pile foundation with 20m depth which was modeled considering a BNWF. The OpenSees software framework is used to model the elastic beam-column elements of the foundation. The beam-column element nodes of the pile are arranged in the vertical z-axis. The nonlinear p-y springs are used for modeling the soil nonlinear properties. One end of zero length spring nodes are tied together with pile nodes by equal degree of freedom techniques while the other end nodes are completely fixed. The numerical analysis is carried out for multi-support (non-uniform) ground motion excitations. From the previous free-field site response analysis of the sandy site deposit, the two sets of ground motions, i.e. the short- and long-period ground motions are applied to the sandy soil site bedrock. Therefore, the output accelerations from the free field analyses at different soil depths will be generated. Then, the computed acceleration ground motions at different level of the soil column are double integrated to get the displacement time histories. These output displacement time histories at different elevations of the pile depth are used as multi-support (non-uniform) ground motion excitations.

Pile BNWF Model

BNWF models should allow for the variation of soil properties with depth, nonlinear soil behavior, nonlinear behavior of pile-soil interfaces and energy dissipation through radiation, Kimiaei et al. (2004), which used to analyze the dynamic response of piles. When performing seismic response analysis of the pile foundation, the multi-support (non-uniform) ground motion excitations, which generated from the free field site response are computed in a separate site response analysis. Then, the computed acceleration ground motions at different level of the soil column are double integrated to get the displacement time histories for using as inputs for multi-support (non-uniform) excitations. Figure 7 shows the general view of the BNWF model and its main components in the nonlinear pile-soil interaction analysis.

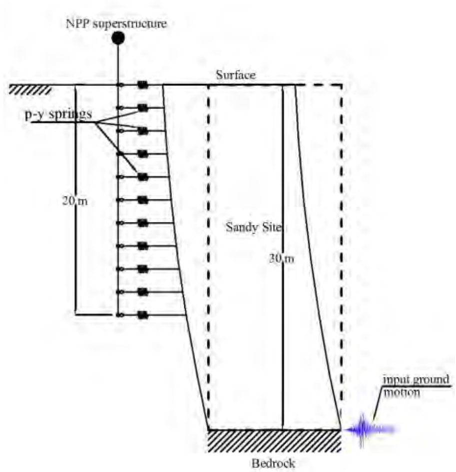


Figure 7. Main components of the nonlinear pile-soil interaction

Pile-Soil Interface

The soil stiffness is applied to the pile-soil interface using the p-y curve approach. The procedure of generating the p-y curves (lateral soil resistance versus lateral soil deflection) are recommended by the American Petroleum Institute, API (1987). El-Naggar and Bentley (2000) and Boulanger (1999) used the p-y curves to analyze the dynamic response of piles subjected to static and dynamic seismic excitations. In this study, the soil stiffness is modeled applying the static p-y curves recommended by API. Also, the soil springs are used to represent the lateral behavior of the soil only, no vertical constitutive behavior is assigned. Zero-length elements are used for the soil springs, and the lateral constitutive behavior is assigned using a uniaxial material objects. The input values for these objects are determined using ultimate lateral resistance values computed using the method of Brinch Hansen (1961) and initial stiffness values computed using the API recommendations modified for depth as discussed by Boulanger et al. (2003), Reese et al. (2001).

RESULTS AND DISCUSSIONS

1- Lateral Displacements:

Figure 8 shows the nodal lateral displacements of the rigidly fixed base isolated NPP stick model compared with the base isolated NPP considering nonlinear pile-soil interaction under the short- and long-period ground motions. It can be observed in both cases of the base isolated NPP stick model that the isolator displacement is quite large and predominant such that the relative displacement of the base isolated NPP stick model is smaller than the fixed base NPP stick model shown in Figure 3. In case of the short-period ground motions, the nodal lateral displacements of the base isolated NPP stick model considering nonlinear pile-soil interaction are higher than the rigidly fixed base isolated NPP model, while they are smaller in case of the long-period ground motions.

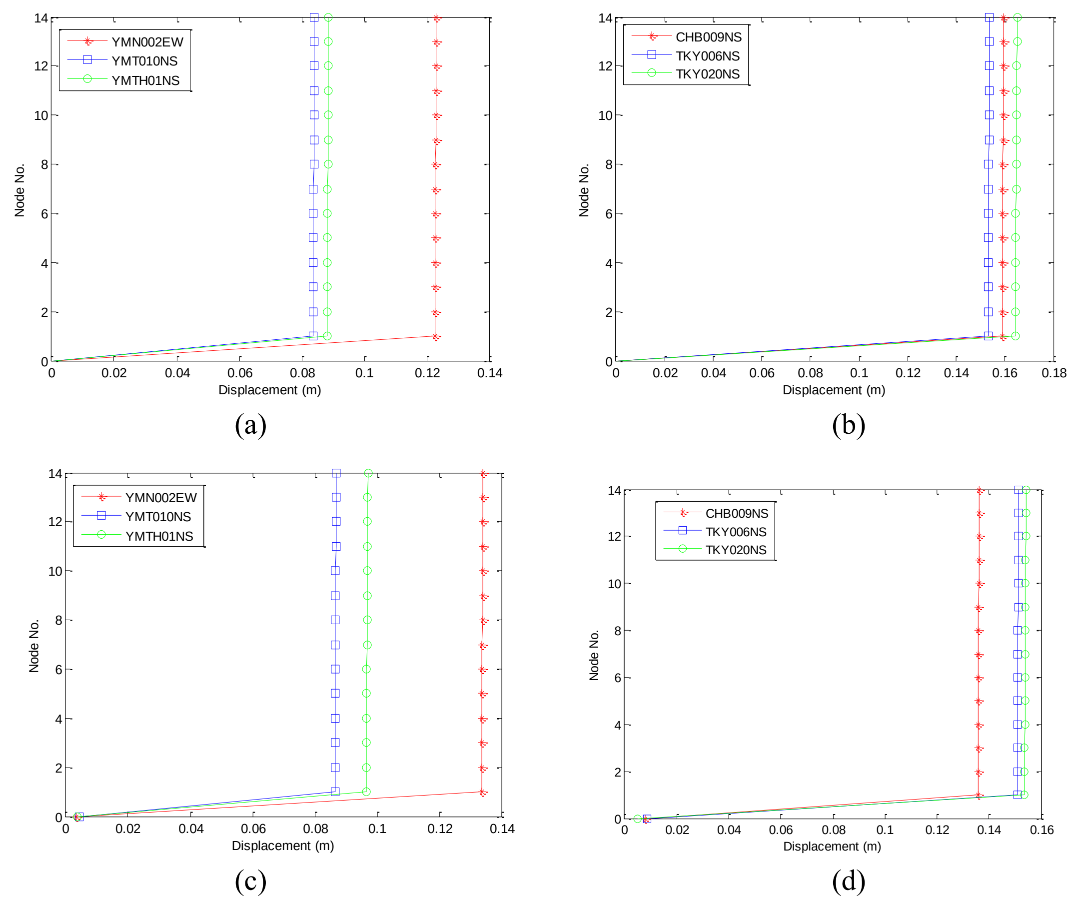
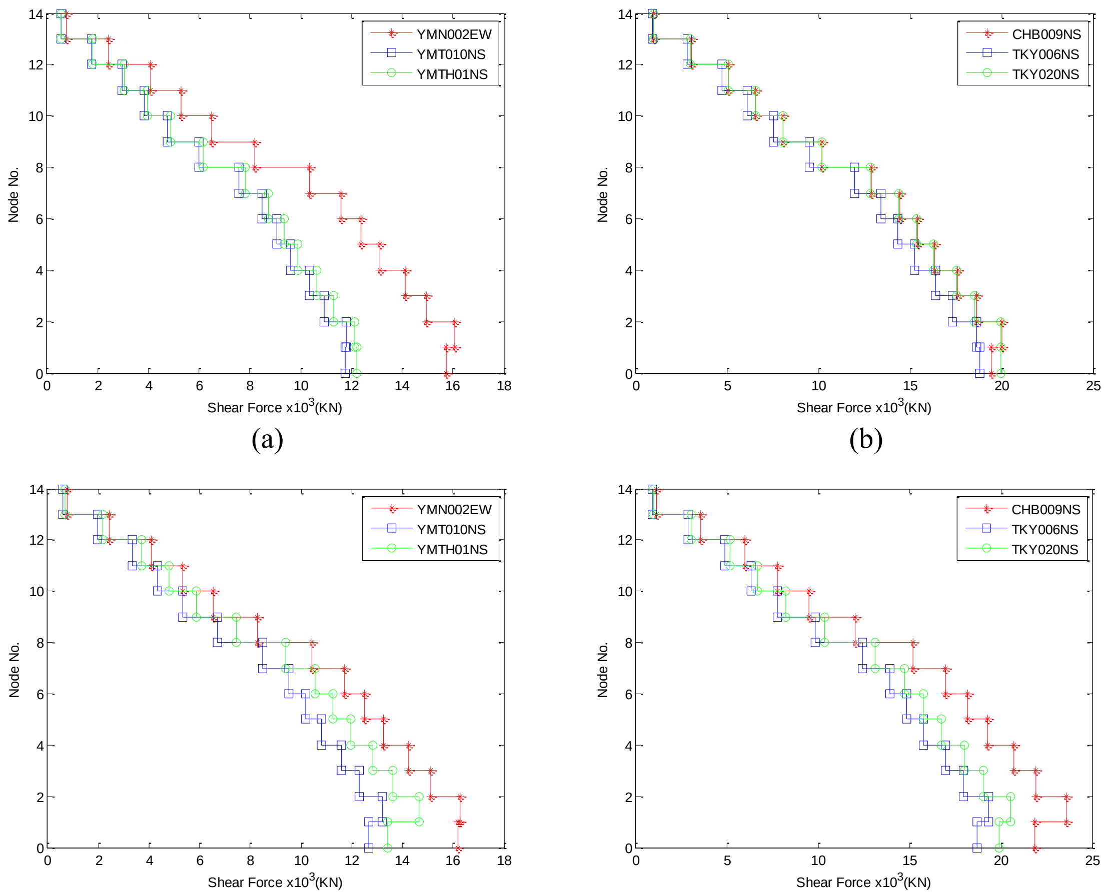


Figure 8. Nodal lateral displacements of the rigidly fixed base isolated NPP model under short-period (panel a) and long-period (panel b) and of the base isolated NPP model considering the pile foundation under short-period (panel c) and long-period (panel d) of selected Tohoku earthquake ground motions.

2- Shear Forces:

The shear forces along the base isolated NPP model of the rigidly fixed to the ground compared with considering nonlinear pile-soil interaction are shown in Figure 9. For the two sets of the ground motions, it can be seen that the maximum resistance is shown by the base of the model followed by a couple of nodes from the bottom. The shear forces after the two elements have shown a gradual descending trend which approaches to minimum at the top node of the model. Figure 9 credibly reflects the higher effect of long-period components as the response is fairly amplified in this case due to greater intensity when compared to the short-period excitation.



(a) (b)

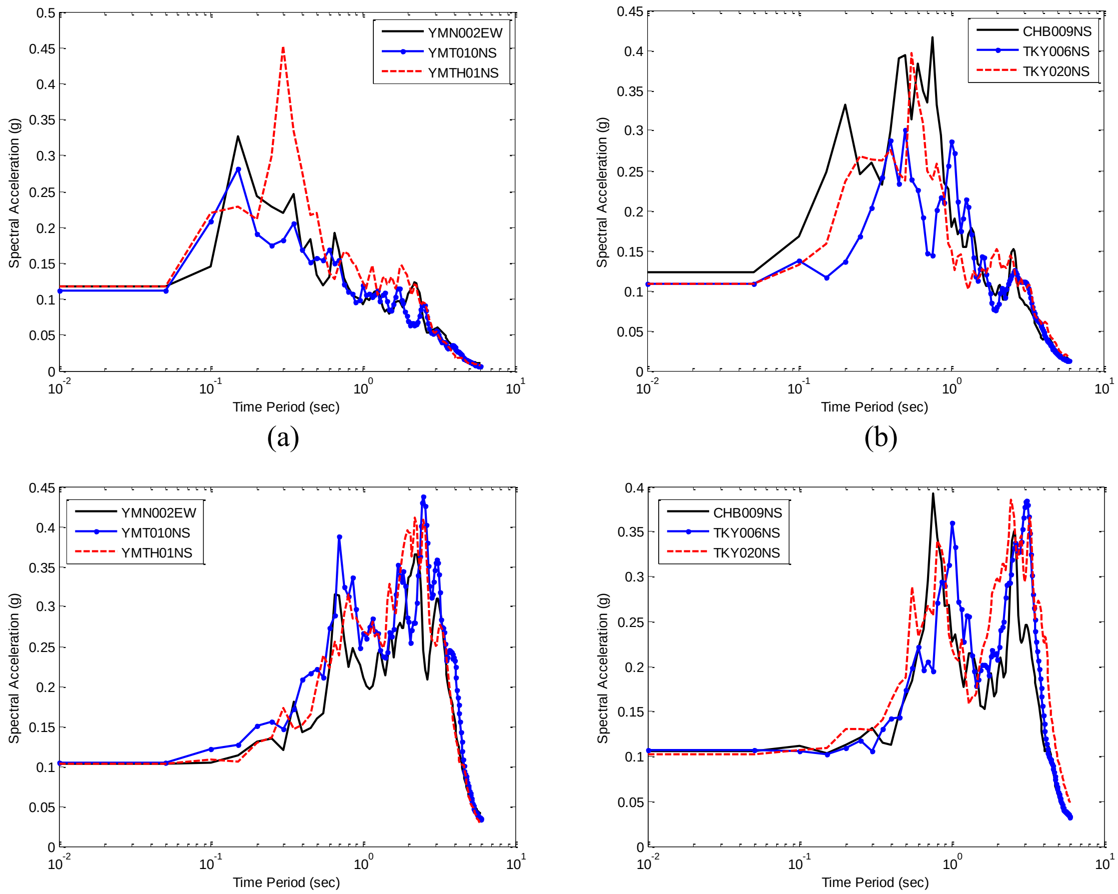
(c) (d)

Figure 9. Shear forces of the rigidly fixed base isolated NPP model under short-period (panel a) and long-period (panel b) and of the base isolated NPP model considering the pile foundation under short-period (panel c) and long-period (panel d) of selected Tohoku earthquake ground motions.

3- Spectral Acceleration:

Figure 10 shows the spectral acceleration at 5% damping on the top node of the base isolated NPP stick model in two cases: the rigidly fixed to the ground base isolated NPP compared with the base isolated NPP considering the nonlinear pile-soil interaction under the short- and long-period ground motions. From Figure 10 (panels a, b) for the rigidly fixed base isolated NPP, it can be show that under the long-period ground motions the peak spectral acceleration values at the top node are: 0.41g, 0.30g, and 0.39g while they are 0.32g, 0.28g, and 0.45g under the short-period ground motions. In case of the base isolated NPP considering the nonlinear pile-soil interaction, there are a slightly change in the peak ground acceleration values at the top node of the NPP model. Where the values are 0.39g, 0.38g and

0.38g under the long-period and 0.36g, 0.43g and 0.41g under the short-period ground motions as shown in Figure 10 (panels c, d).



(a) (b) (c) (d)

Figure 10. Spectral acceleration (at 5% damping) on the top node of the rigidly fixed base isolated NPP under short-period (panel a) and long-period (panel b) and of the base isolated NPP model considering the pile foundation under short-period (panel c) and long-period (panel d)

CONCLUSION

The present study reports the response of base-isolated NPP with two analysis cases; rigidly fixed to the ground and considering the pile foundation subjected to short-period and long-period ground motions. The fundamental time period of the NPP stick model is escalated from 0.168 second, for fixed base NPP, to 1.348 second due to considering the base isolation, and it increased to 1.388 second due to considering the pile foundation. A simplified BNWF model was introduced for the nonlinear response analysis NPP while the nonlinear p-y springs are used for modeling the soil nonlinear properties. For the pile foundation analysis case, free-field site response analyses were performed using one-dimensional site response analysis based on the equivalent linear stress-strain model for the soil sites. The conclusions drawn from this study are as follows:

The free-field site response analyses of the two soil site deposits show that the amplification at the surface of the soft site (sandy site) are higher than of the stiff site (clayey site) under the short- and long-period ground motions. Furthermore, the peak amplification values at the surface under the short-period ground motions are higher than under the long-period ground motion for both soil sites. While the resonant frequencies, at the peak amplification functions, are not that much different under the two sets of ground motions for the two soil sites.

The performance of the base isolated NPP for the two cases; rigidly fixed and considering the pile foundation subjected to short- and long-period ground motions is investigated. The lateral nodal displacements of the NPP under long-period inputs are fairly larger than that under short-period inputs for the both rigidly fixed and considering the pile foundation analysis cases. The results also show under the short-period inputs, that the lateral displacements in the case of the base isolated NPP considering the pile foundation are higher than that in the case of rigidly fixed base isolated NPP, while they show quite the opposite under the long-period ground motions.

The base isolated NPP stick model has shown great difference in the shear force resistance in the two cases of analysis; rigidly fixed and considering the pile foundation under the two set of ground motions. Generally, in both cases of analyses under the long-period inputs, the responses are higher than that under the short-period inputs but immense change in the difference of the force along the height is observed. In addition, there are slight differences in the resisting shear forces along the stick model height in the both cases of analyses; rigidly fixed and considering the pile foundation, which gives an indication that the vertical members resisting the shear forces will not suffer any severe change considering the soil structure interaction.

The responses of the base isolated NPP in the spectral acceleration term, shows that the peak spectral acceleration at the top node of the base isolated NPP under the short-period inputs are higher than under the long-period inputs for the two analyses cases. Where, in the rigidly fixed analysis case, the peak acceleration decreased from 0.45g to 0.41g, while it decreased form 0.41g to 0.39g in case of considering the pile foundation. Furthermore, the results show also that the peak spectral acceleration decreases by 8.8% and 4.8% due to considering the pile foundation under the short- and long- period inputs, respectively.

Finally, it can be concluded that considering the pile foundation for the base isolated NPP reflects the higher effect of short-period ground motions on the base isolated NPP responses, while the higher responses in case of the rigidly fixed base isolated NPP are under the long-period ground motions.

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