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# NONLINEAR RESPONSE ANALYSIS OF OFFSHORE PILES UNDER SEISMIC LOADS

**Mehrdad KIMIAEI[1], Mohsen Ali SHAYANFAR[2], M. Hesham El NAGGAR[3], Ali Akbar AGHAKOUCHAK[4]**

## SUMMARY

Nonlinear response of piles is the most important source of potentially nonlinear behavior of offshore platforms due to earthquake excitations. It is often necessary to perform dynamic analysis of offshore platforms that accounts for soil nonlinearity, discontinuity condition at pile soil interfaces, energy dissipation through soil radiation damping and structural nonlinear behaviors of the piles.

In this paper, an attempt is made to introduce a practical BNWF (Beam on Nonlinear Winkler Foundation) model for estimating the lateral response of flexible piles embedded in layered soil deposits subjected to seismic loading. This model was incorporated into a Finite Element program (ANSYS), which was used to compute the response of laterally excited piles. Equivalent linear earthquake site response approach was used for seismic free field ground motion analysis. Quantitative and qualitative findings and conclusions, which are needed for the design of offshore piles, are discussed and addressed in detail.
Keywords: nonlinear, seismic, offshore, piles, BNWF

## INTRODUCTION

Earthquake design of offshore platforms in seismic active areas is one of the most important parts in offshore platforms design. Dynamic response of piles in offshore platforms is a function of the characteristics of the loading, dynamic pile-soil interaction behavior and dynamic characteristics of the piles structural system. The SSPSI (Seismic Soil-Pile- Structure Interaction) analysis is the main step in evaluation of seismic behavior of pile supported offshore platforms. The pile-soil interaction problem

[1] Ph.D. Candidate, Civil Eng. Dept., Iran Univ. of Science & Tech., Tehran, Iran. Email:kimiaei@sp68.com
[2] Associate Professor, Civil Eng. Dept., Iran Univ. of Science & Technology, Tehran, Iran. Email:shayanfar@iust.ac.ir
[3] Associate Professor and Research Director, Geotechnical Research Centre, Faculty of Engineering, The University of Western Ontario, London, Canada. Email:melnagga@uwo.ca
[4] Associate Professor, Civil Eng. Dept., Tarbiat Modarres University, Tehran, Iran. Email:a_agha@modares.ac.ir

during earthquake loading as one of the most important sources of nonlinear dynamic response analysis of offshore platforms has received considerable attention in recent years and several studies investigated the nature of input ground motion and the mechanism of pile-soil interaction to determine seismic design loads for pile-supported structures.

The Finite Element and Boundary Element methods are not commonly used in offshore design offices mainly due to their presumed excessive computational costs and their complexity for common pile dynamic response analysis. The Beam on Nonlinear Winkler Foundation (BNWF) method is a simplified approach that can account for nonlinear Soil-Pile-Structure Interaction analysis and is commonly used in professional engineering and research practices. Generally, BNWF models are versatile and economical methods that can account for various complicated conditions in a simple manner. Matlock [1], Novak [2], Nogami [3], El Naggar and Novak [4,5] and El Naggar and Bentley [6] used BNWF models for piles subjected to lateral dynamic loads. The p-y curves (unit load transfer curves) approach (Matlock [7]) is a widely accepted method for predicting pile response under static loads because of its simplicity and practical accuracy. In BNWF models that are based on the p-y curves approach, the stiffness of the soil is established using p-y curves and the damping is established from analytical and/or empirical solutions that account for energy dissipation through wave propagation and soil hysteretic behavior. Wang et al [8] compared several implementations of nonlinear springs based on p-y curves and dashpots in parallel and in serial to represent radiation damping in BNWF models of piles subjected to seismic loading. Boulanger et al. [9] developed a BNWF model utilizing springs in series with dashpots representing radiation damping and used the model to analyze experimental centrifuge tests carried out by Wilson et al [10] for seismic loading on piles. The response computed was in good agreement with the measured one. El-Naggar and Bentley [6] introduced dynamic p-y curves for dynamic lateral response analysis of piles.

In this paper the components of a simplified BNWF model (using the features of ANSYS program [11] ) which can be used for dynamic response analysis of offshore piles) are introduced. The main objective of this study is to compare the developed model and published centrifuge tests for the numerical results, which could be used for seismic design of offshore piles.

## PILE-SOIL INTERACTION ANALYSIS WITH BNWF MODELS

BNWF models used to analyze the dynamic response of piles should allow for the variation of soil properties with depth, nonlinear soil behavior, nonlinear behavior of pile-soil interfaces and energy dissipation through radiation and hysteretic damping. Therefore, proper analysis of the seismic response of piles involves modeling the pile and surrounding soil including damping considerations and discontinuity conditions at the pile-soil interface. In addition, special attention must be given to the evaluation of the free-field excitation. When performing seismic response analysis, “free field” ground motion time histories are usually computed in a separate site response analysis. The computed ground motion at different levels within the soil is then applied to the nodal boundary supports representing the support motions. Figure 1 shows the general view of a BNWF model and its main components in dynamic nonlinear response analysis of offshore piles.

### Pile Modeling

The pile and surrounding soil are subdivided into a number of discrete layers. Pile response is traced independently at nodal points of the pile segments within each layer. The dynamic characteristics (i.e. stiffness, damping and mass) of the pile segments are established at these nodes.

### Soil Stiffness Modeling

The soil reaction to pile movement during transient seismic loading comprises stiffness and damping components. In the present study, the soil stiffness is established using the p-y curve (lateral soil

resistance versus lateral soil deflection) approach. The procedures for generating p-y curves proposed by Matlock et al [7], Reese et al [12] and O'Neil [13] are recommended by the American Petroleum Institute and are widely used in both research and professional jobs (API-RP-2a)[14]. El Naggar and Bentley [6] and Boulanger [9] used p-y curves to analyze the dynamic response of piles subjected to statnamic and seismic loadings, respectively. In this study, the soil stiffness is modeled employing the static p-y curves recommended by API.

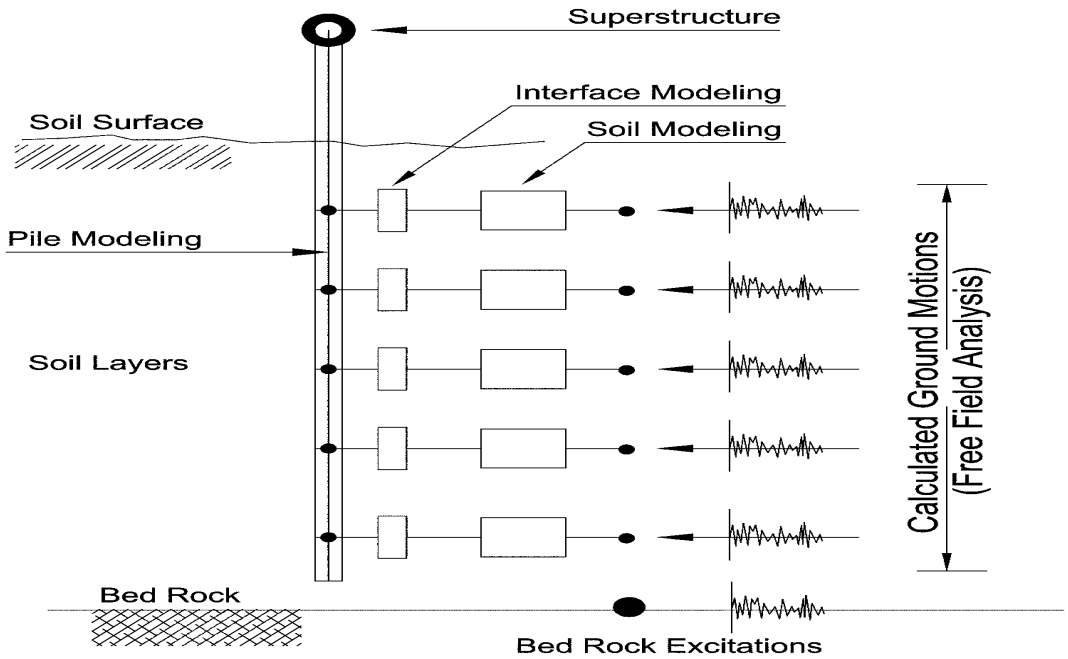


**Fig. 1- General view of BNWF models for nonlinear dynamic response analysis of offshore piles**

The soil damping provides a major source of energy dissipation in pile-soil systems subjected to dynamic loading. In the present study, the damping component of the soil resistance is represented by a dashpot whose coefficient is established based on the Berger et al model [15], i.e.,

$$c_L = 4B\rho v_S \quad [1]$$

where $B =$ pile diameter, $v_S =$ soil shear wave velocity and $\rho =$ soil unit density.

**Pile-Soil Interface**

To account for gapping and discontinuity conditions at the pile-soil interface, special interface elements are incorporated in the model to allow for relative movements of the pile and soil nodes. In clay soils, a gap develops when a tensile stress is detected in the soil spring, and the interface element disconnects the pile and soil nodes. The development of a gap between the pile and adjacent clay soil during earthquake excitations has been reported in the literature (Matlock [1], Nogami [3]). In cohesionless soils (sand), the soil caves in backfilling the gap created by the movement of the pile away from the soil and thus no permanent gaps will develop (El Naggar and Bentley [6]). Figures 2 and 3 show soil reactions versus pile deflections for typical cohesive and cohesionless soils (indicating "gapping" and "cave-in" behaviors), respectively.

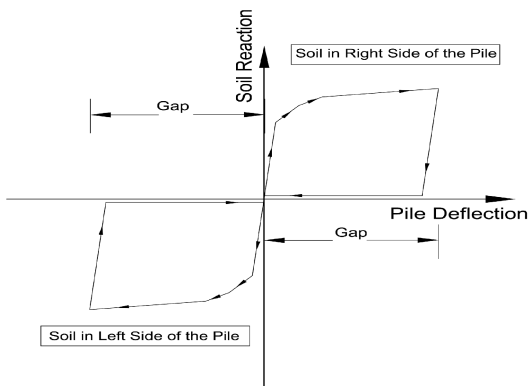


**Fig. 2- Typical Soil reaction- Pile deflection behavior for cohesive soils (Gapping)**

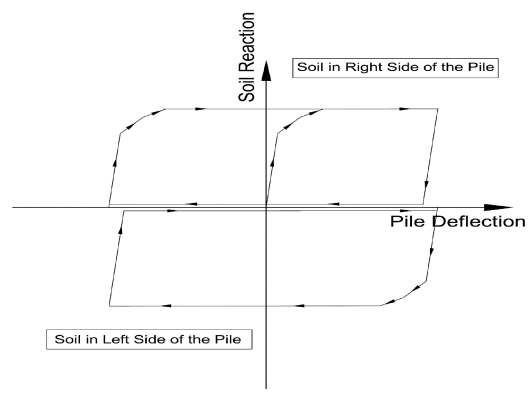


**Fig. 3- Typical Soil reaction- Pile deflection behavior for cohesionless soils (Cave-in)**

## FREE FIELD EXCITATIONS

Free field ground motion time histories are usually computed using common site response analysis techniques. In site response analysis, the ground motion of the soil layers is calculated due to earthquake excitations applied at bedrock. The results of such free field analysis (acceleration or displacement time histories at different soil layers) are then used as the input excitation at support nodes of the BNWF model.

In the present study the nonlinear stress-strain response of soil layers approximated by an equivalent linear approach using a modified Kelvin-Voigt model on which the nonlinear and hysteretic stress-strain behavior of soil is approximated (during cyclic loadings) by an equivalent linear shear modulus, $G$, taken as the secant shear modulus $G_s$, defined as follows:

[2] $$G_s = \frac{\tau_c}{\gamma_c}$$

where $\tau_c$ and $\gamma_c$ are the maximum stress and strain amplitudes respectively. The computer program EERA (Equivalent-linear Earthquake site Response Analysis) developed by Bardet et al [16] is used for free field ground motion analysis. In this computer program, one dimensional ground response analysis is performed based on the equivalent-linear stress-strain model for the soil.

## EXPERIMENTAL SEISMIC RESPONSE OF PILES

All experimental results presented herein are extracted from CSP-4 experimental centrifuge tests performed by Wilson et al [10] using the large servo-hydraulic shaking table at the University of California at Davis. The soil profile consisted of two horizontal soil layers. The lower layer was fine uniformly graded Nevada sand, 11.10 m thick with Cu=1.5 and D50=15 mm. The sand dry density was 1.66 Mg/m3 at a relative density of Dr = 75-80%. The upper layer was reconstituted Bay Mud 6.39 m thick. The liquid limit = 80% and the plasticity index = 48%. The mud was placed as a slurry (water content = 140%) in four equal layers. Each layer was individually pre-consolidated under an applied vertical stress. The single pile supported system (SP1) used in this test included a 670mm steel pipe with 19 mm wall thickness and total length of 20.57m, and a superstructure with the mass of 49100 kg attached to an extension of the pile of 3.81 m above ground surface. Figure 4 shows the soil profile, single pile, and superstructure systems.

This model was shaken by four simulated earthquakes and each event was a scaled version of a record prepared by filtering and integrating strong motion records from Port Island in the 1995 Hyogoken-Nambu (Kobe) earthquake. Simulated earthquake events with different Peak Base Accelerations (PBA) are presented in Table 1. Detailed documentation of the test and recorded time histories are available in Wilson et al [10].

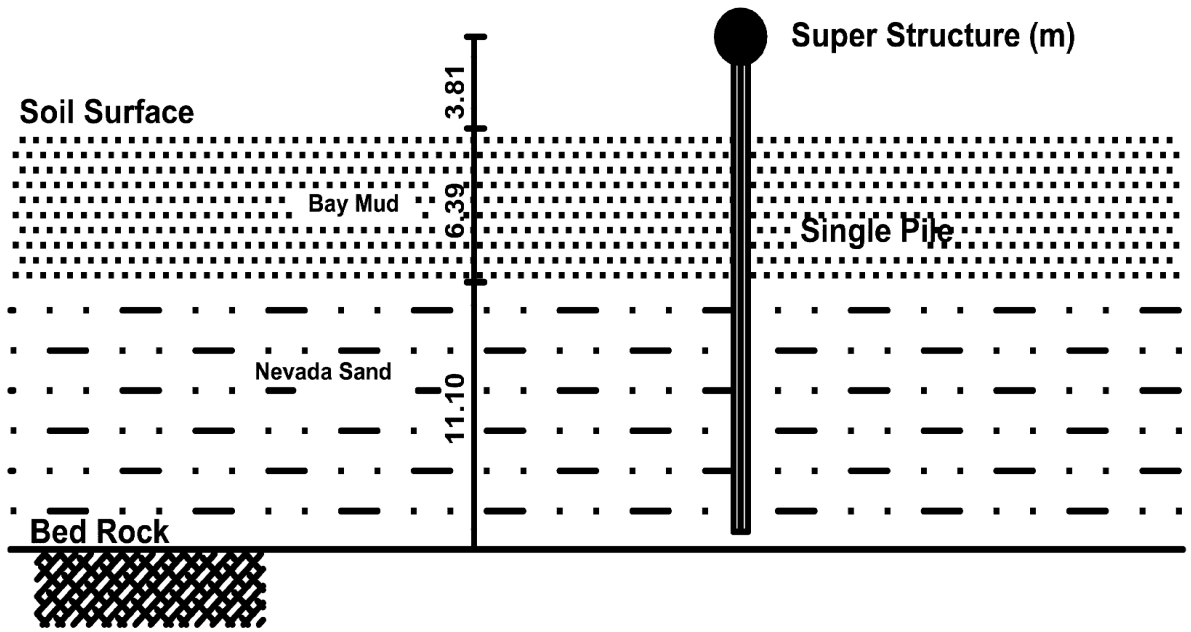


**Fig. 4- Single Pile Supported Structure in CSP-4 test**

**Table 1- Earthquake events for CSP-4 tests**

| Event | Motion | Peak Base Acceleration (g) |
|---|---|---|
| B | 1995 Hyogoken-Nambu (Kobe) | 0.055 |
| C | 1995 Hyogoken-Nambu (Kobe) | 0.016 |
| D | 1995 Hyogoken-Nambu (Kobe) | 0.200 |
| E | 1995 Hyogoken-Nambu (Kobe) | 0.580 |

## MODEL DESCRIPTION FOR DYNAMIC RESPONSE ANALYSIS OF PILES

In this study, the seismic pile-soil interaction analysis of the above mentioned experimental centrifuge tests was performed using the explained simplified BNWF model and the finite element analysis software ANSYS. The pile-structure was subdivided into 12 elasto-plastic pipe elements (11 elements below soil surface and 1 element above ground). Each pile node below the ground surface was connected to one set of a parallel nonlinear P-Y element and a linear dashpot element on each side of the pile. Interface elements were used to connect the pile and soil nodes at each level and on each side of the pile. Displacement time histories at different soil layers extracted from the free field site response analyses using EERA software were used as input motion to soil support nodes of the above mentioned BNWF model.

## COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

As it was described in previous sections, the displacement time history results of the free field analyses were used as the input excitations at support nodes of the BNWF model. The Acceleration Response Spectra (ARS) within different soil layers could be considered as the best indication for evaluation of the capability of the equivalent linear earthquake site response approach for free field ground motion analysis. Calculated and recorded horizontal ARS of the soil profile at different layers (considering 5% of damping) for all shaking events of B, C, D and E extracted from EERA free field ground motion analyses are shown in Figs. 5,6,7 and 8 respectively. In events B, C (with the lowest PBA in this study) an excellent agreement between recorded and calculated results is seen in Figs.5,6 respectively (mainly for deep soil layers,). For events D and E (with the highest PBA in this study) good agreement between calculated and recorded results are seen in Figs. 7, 8 respectively.

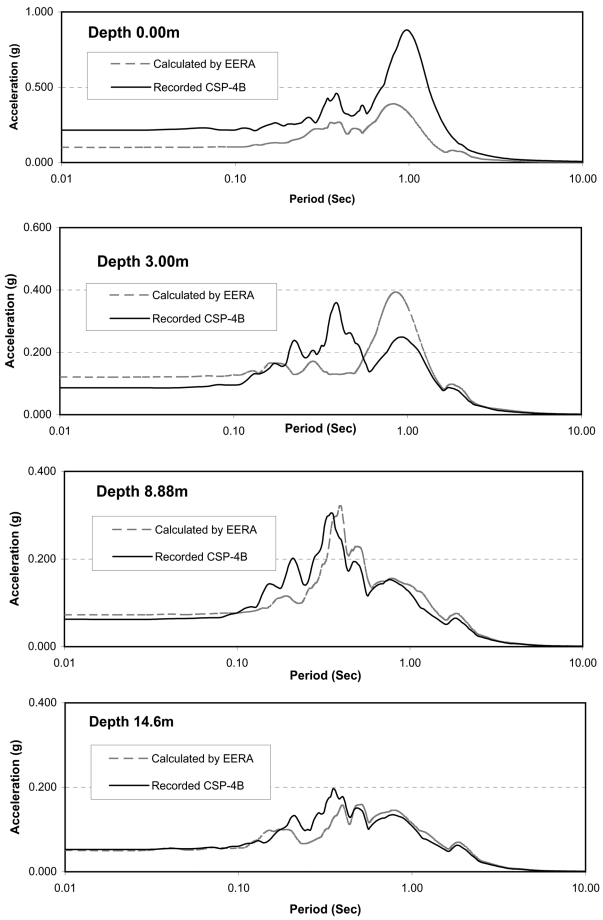


**Fig.5- ARS of the soil profile in Event B**

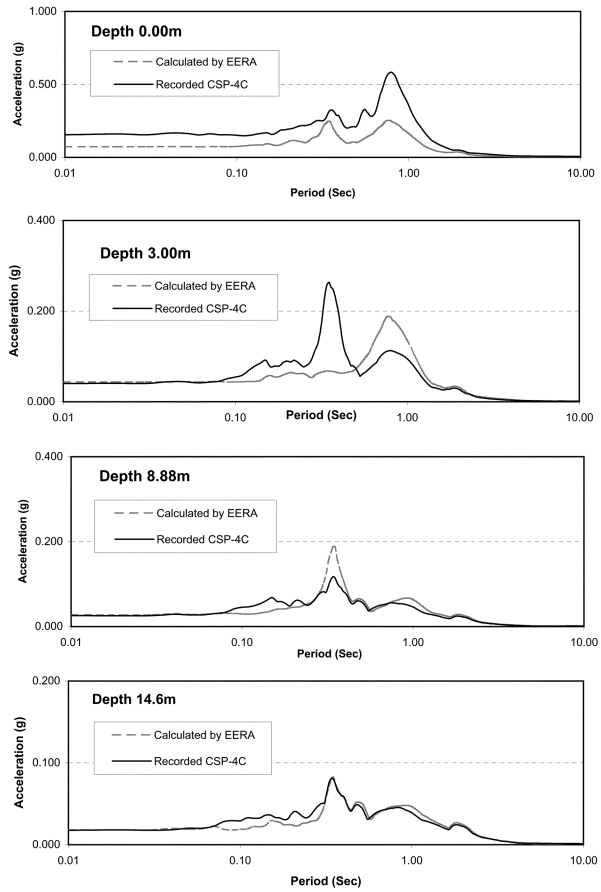


**Fig.6- ARS of the soil profile in Event C**

The ARS of the Superstructure, ARS of the Pile head, Superstructure maximum displacement and Pile Peak Bending Moments (PPBM) within the pile length could be considered as the main parameters to evaluate the capability of the proposed model in seismic design and response analysis of offshore piles.

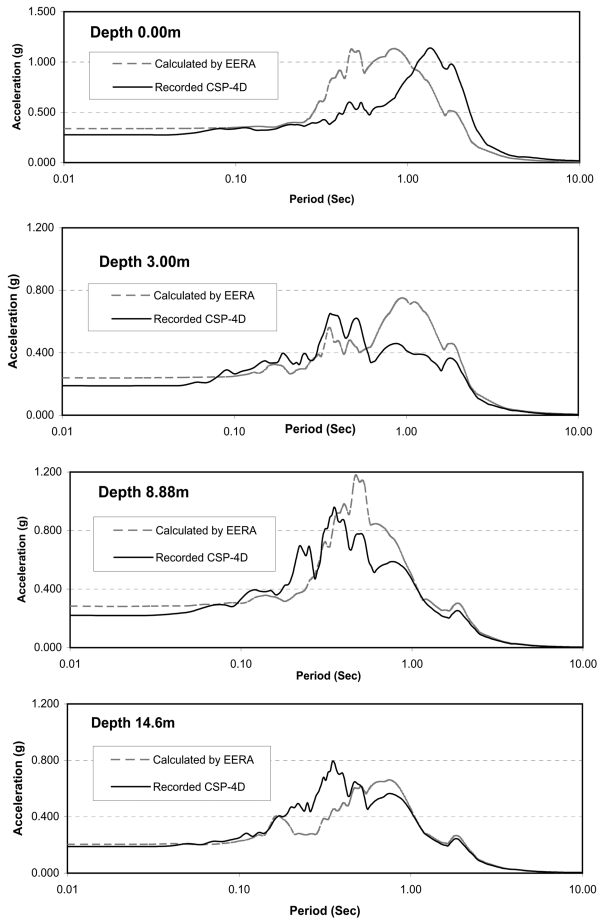


**Fig.7- ARS of the soil profile in Event D**

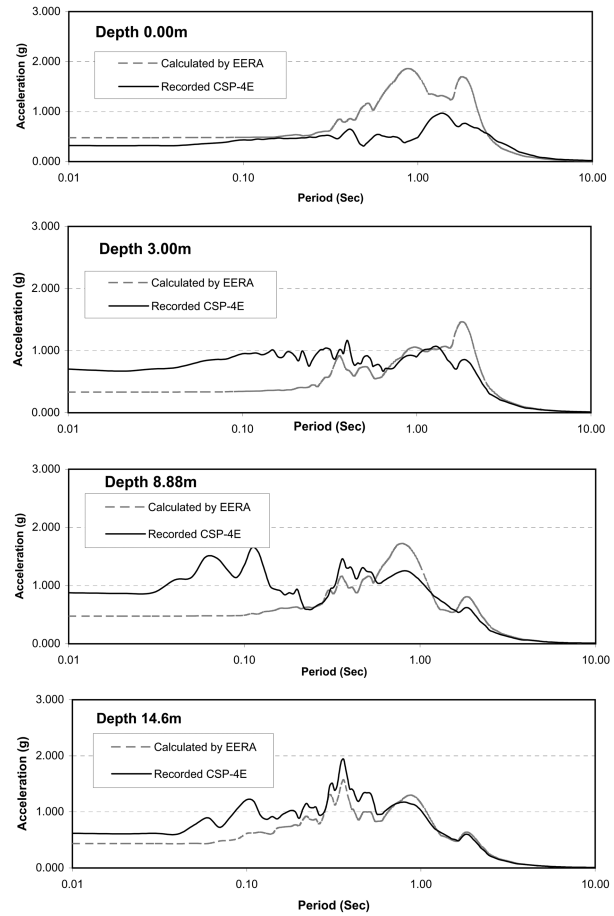


**Fig.8- ARS of the soil profile in Event E**

The maximum calculated and recorded ARS of the superstructure and pile head (considering 5% damping) for a PBA range of 0.016g to 0.580g and pile material damping ratios ( $\xi$ ) between 0% to 10% are shown in Figs. 9, 10 respectively. It can be seen that for moderate rates of PBA (Events B and D in this study) there is a good agreement between calculated and recorded results by using a reasonable rate of pile material damping ratio (between 1% to 3%). It is also observed that the ARS of pile head is less sensitive to the pile material damping ( $\xi$ ) than the ARS of the superstructure. In the other word, for low and moderate rates of PBA (less than 0.200g), the differences between ARS values of the pile head due to different values of pile material damping ratio is much less than the differences between ARS values of the superstructure.

The maximum calculated and recorded experimental PPBM along the pile shaft is shown in Fig. 11. It is seen that for a wide range of Peak Base Accelerations (between 0.016g to 0.58g) and by using pile material damping ratios between 0% to 10%, there would be an acceptable agreement between the calculated and recorded results. For moderate rates of PBA (Events B and D in this study) there is a good agreement between calculated and recorded results by using a reasonable rate of pile material damping (between 1% to 3%).

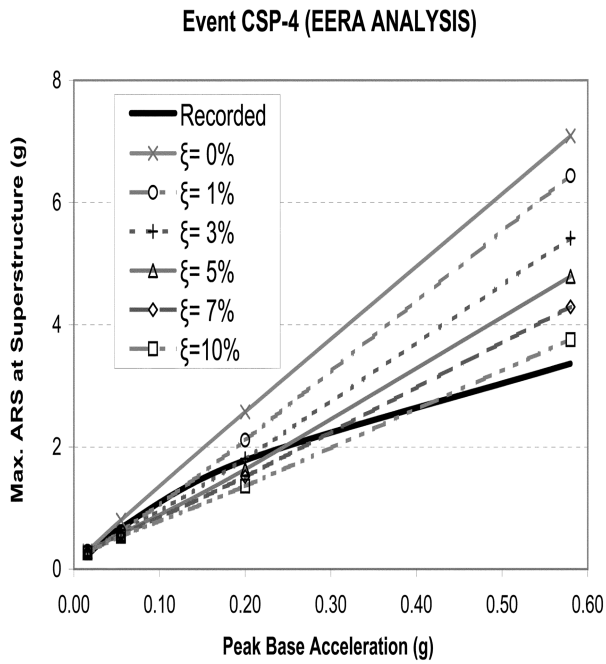


**Fig.9- ARS of the Superstructure**

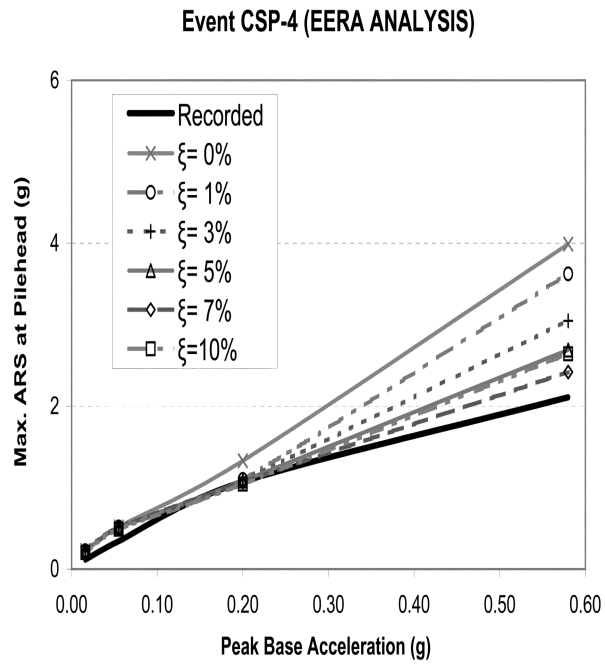


**Fig.10- ARS of the Pile head**

Figure 12 shows the maximum calculated and recorded experimental horizontal displacement of the superstructure versus the Peak Base Acceleration. It can be seen that the maximum-recorded displacements of the superstructure are in excellent agreement with the maximum calculated displacements for a reasonable rate of pile material damping ratio (between 1% to 3%).

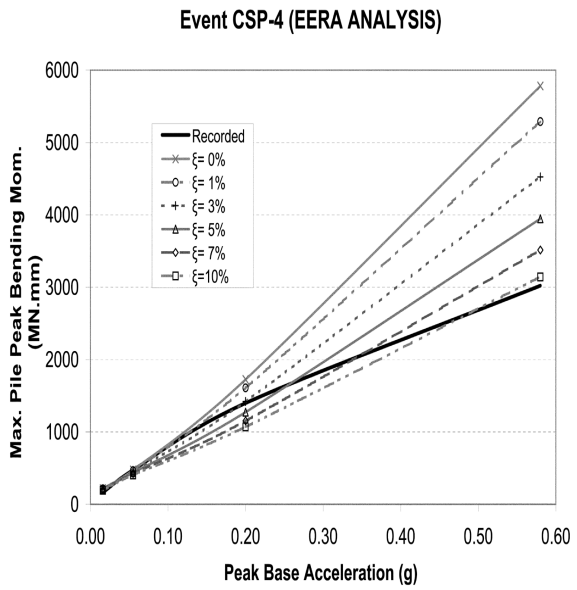


**Fig.11- Max. of PPBM Vs. PBA**

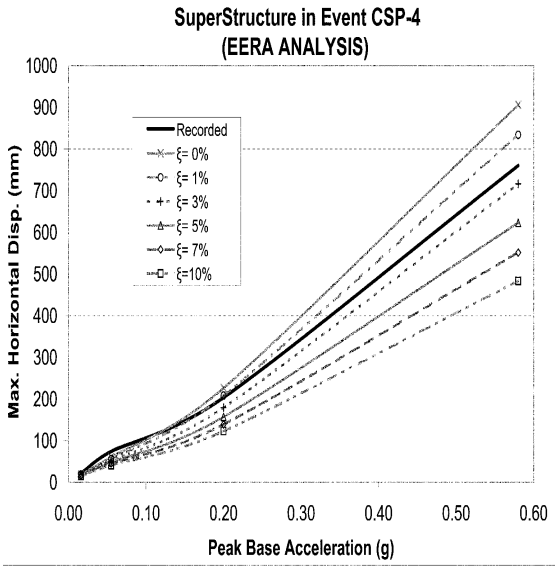


**Fig.12- Max. Displ. of Superstructure Vs. PBA**

## SUMMARY AND CONCLUSION

A simplified BNWF model was introduced for dynamic nonlinear response analysis of offshore piles. This model, together with an equivalent linear earthquake site response analysis for free field, was evaluated against a set of centrifuge model tests involving one single pile-supported structure in a profile of soft clay overlaying dense sand. Summary of the quantitative and qualitative comparison of the calculated and measured responses are as follows:

- The equivalent linear earthquake site response analysis is precise enough for free field ground motion analysis mainly for low rates of peak base accelerations.
- The proposed BNWF approach was reasonably able to model the recorded responses specifically for moderate rates of peak base accelerations.
- For cases of no material damping ( $\xi = 0$ ), all calculated results overestimates the recorded results.

The best results in this study are obtained for peak base accelerations between 0.05g and 0.20g, which covers the SLE (Strength Level Earthquake) and RIE (Rare Intense Earthquake) ranges for most of the offshore oil fields in the world.

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