Nonlinear seismic response analysis of single pile in sand

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ABSTRACT
Owing to their reasonable accuracy and relative simplicity, beam-on-nonlinear Winkler foundation (BNWF) models are widely used in the analysis of piles response to different loading conditions. For performance-based seismic design of piles-supported structures, it is essential to account for various variables that influence the piles behaviour. In this paper, a generalized BNWF model recently developed by Heidari and El Naggar (2016) is adopted for the seismic analysis of pile foundations. The nonlinear model is capable of accounting for important SSI features including soil nonlinearity, cyclic soil degradation/hardening, gap formation and soil-cave in, and energy dissipation due to radiation damping. Nonlinear behavior of pile material under seismic loading is also incorporated in the analysis by implementing a fiber technique. In this approach, the element behavior is derived by weighted integration of the section response while the nonlinearity can occur at any section along the pile element. Free-field motions obtained from linear and nonlinear time domain analyses are used to compute the response of excited pile. The accuracy of model predictions is verified by comparing the numerical results with full-scale test data. The comparisons show the capability of the method to predict deflection and internal forces of the piles.

1 INTRODUCTION

Performance-based design has been implemented progressively in geotechnical earthquake engineering to assess seismic response of pile-supported structures. This design approach relies on soil-structure interaction (SSI) and nonlinear behavior of the system to attain a reliable estimate of global displacement ductility. Nonlinear SSI of the supporting pile under earthquake loading involves different features such as soil and pile yielding, cyclic degradation of soil stiffness and strength under generalized loading, soil-pile gap formation with soil cave-in and recompression, and energy dissipation; as such, it is essential to utilize appropriate tool to predict the nonlinear dynamic response of the soil-pile system.

The common procedures often used for the analysis of seismic soil-pile-structure interaction include finite-element or boundary element methods, finite-difference methods and dynamic beam on a nonlinear Winkler foundation (BNWF) method. Although, finite element method potentially provides a powerful tool to incorporate important features of soil-pile interaction problem, however, dynamic BNWF models are the most popular due to their less computational efforts and yet offer potential advantages for detailed SSI and structural modeling with admissible accuracy (Heidari et al. 2014a, Boulanger et al. 1998).

Several researchers have developed enhanced BNWF models to account for various SSI response features for seismic applications (Matlock et al., 1978, Nogami et al., 1992; El Nagger and Novak, 1995 and 1996; Boulanger et al., 1999; El Naggar and Bentley, 2000; Brown et al., 2001; El Naggar et al., 2005; Gerolymos and Gazetas, 2005; and Allotey and El Naggar, 2008; Heidari et al., 2014b; Heidari and El Naggar, 2016). Boulanger et al. (1999) presented a BNWF model consisting of parallel and series springs as well as a dashpot to account for nonlinear soil behaviour, gap formation, drag force, and soil damping. They evaluated the accuracy of the model for analyzing seismic soil-pile-structure interaction against the responses attained from dynamic centrifuge tests. This model was implemented into OpenSees (Boulanger 2003), a software framework for simulating the seismic response of structural and geotechnical systems. Although, it has been extensively used to study the behavior of piles under different conditions, however, the model does not account for the effect of soil degradation and soil cave-in. A generalized dynamic BNWF model with defined rules for loading, reloading, and unloading was developed by Allotey and El Naggar (2008). The developed BNWF model was employed in software SeismoStruct. Although, the model accounted for various main response features, the model was backbone-curve independent that means the effect of pile characteristics on the lateral response was not incorporated in the analysis. Heidari et al. (2014a and b) extended the model to incorporate the 3-dimensional interaction response of laterally loaded pile in different types of soils.

The model is compression-dominant, requiring two spring elements at each depth for the modeling of soil-pile interaction. It is apparent that the combined response of the two springs should be the same as the original backbone curve; however, horizontal leftward shift of the force-displacement curve to model prestraining effect would lead to different response during the initial gap formation.

Recently, Heidari and El Naggar (2016) developed a robust and practical BNWF model by decomposing the total spring force into side shear and normal soil resistance components to simulate effectively the behavior of pile in the slack zone. A linearization technique was utilized to separate an original backbone curve into two separate springs at each side of the pile, and semi-empirical expressions were proposed for the model parameters. The developed model was implemented into a general software program for the nonlinear analysis of piles under static, cyclic and seismic loading. The software has the capability to incorporate complex interaction between pile and various types of surrounding soils as well as material nonlinearity of the pile using well-known fiber technique (Heidari and El Naggar, 2016).

The reliability of dynamic BNWF models (or any other method) should be evaluated employing available full-scale studies. Accordingly, this study evaluates the performance of the developed model by comparing its predictions to the results of a series of full-scale seismic tests on a driven pile installed in sandy soil. The experimental results used in the comparison herein were obtained by Elsawy et al. (2017) from seismic loading tests performed using NEES/UCSD Large High Performance Outdoor Shake Table (LLHPOST). The recorded responses of the single-pile supported under applied earthquake event were used to compare with those obtained from seismic analysis. During the experimental testing, there were no record of the ground response of the sand alone and the instrumented accelerometer's reading was affected due to the installation of the piles in the container that could not properly represent the response of free-field motion. As such, three different 1D linear, equivalent-linear and nonlinear ground response analyses were performed using site response program, DeepSoil, and then the free-field ground response were applied to the soil spring's support as input motions for the response analysis of the multi-support excitation problem.

Findings from the full-scale experiments and numerical analyses and their implications for design practice are discussed.

2 Model Description

2.1 Pile Model

The inelastic behavior of the pile element is modelled using the fiber technique. This model for beam-column elements can be formulated using stiffness-based or flexibility-based method, in which the pile is subdivided into sufficient number of elements, and the nonlinear behavior of each element is simulated by subdividing the element cross-section into longitudinal fibers. For each fiber along the axis of element, the response is determined at some controlling sections using appropriate material constitutive models representing the local behavior. For steel pipe pile studied in this paper, the constitutive relationship is an enhanced version of well-known Menegotto-Pinto model (1973), modified by Filippou et al. (1983) to incorporate isotropic strain hardening. Figure 1 includes a typical cyclic stress-strain curve based on this model.

As depicted in Figure 1, the element cross-section is subdivided into a number of fibers and the element behavior is characterized by some monitoring cross-sections along the element. The displacement field of each element is determined from the nodal displacements using linear and cubic interpolation functions along the element for the axial and transverse displacements, respectively (Heidari and El Naggar 2016).

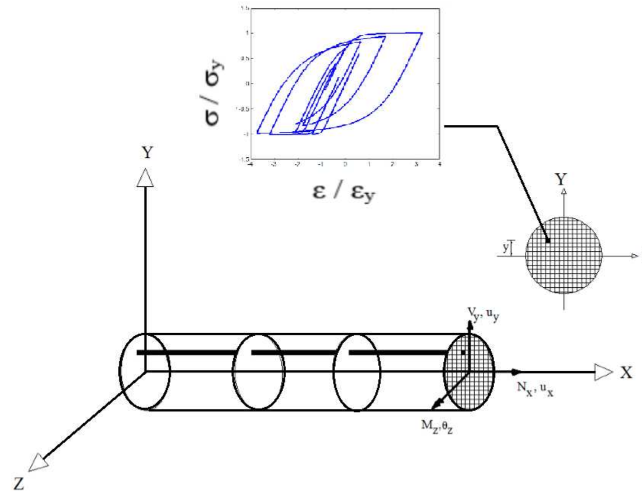


Figure 1. Fiber/layer element with control sections subdivided into fibers with the nonlinear hysteretic model for steel.

2.2. Dynamic BNWF Model

The response of a pile under earthquake loading is influenced by various factors including the soil and pile nonlinearity, gap formation and possible soil cave-in, cyclic degradation of soil stiffness and strength under generalized loading, and radiation damping. These complicated features of soil-pile interaction are incorporated in the seismic analysis of laterally loaded pile by implementing the robust BNWF model developed by Heidari and El Naggar (2016) into the nonlinear program software.

In this model, the API p-y curve formulations for cohesive and cohesionless soils were used to attain the backbone curves. Each nonlinear spring was decomposed into two no-tension springs at each side of the pile by linearizing the initial part of the curve and shifting the curve leftward based on the method proposed by Heidari and El Naggar (2016). Radiation damping was also modeled using a dashpot placed in parallel with the nonlinear spring, where the constant of the dashpots were calculated using the solution developed by Novak and Mitwally (1988).

Four controlling parameters enable the model to capture effectively oval-shape and inverted S-shape hysteretic loop. These parameters comprise load characteristic factor, α_l, limiting force factor, α_f, soil cave-in factor, α_c, and side-shear factor, α_s. The limiting parameters of α_f and α_l are employed to simulate different soil responses to a pile moving in the slack zone. Further details of the employed BNWF model were explained in Heidari and El Naggar (2016).

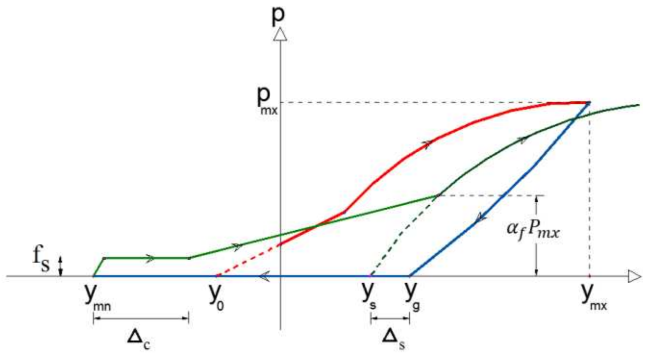


Figure 2. Schematic of the developed BNWF model

3. Experimental Setting

Elsawy et al. (2017) conducted a large scale seismic testing of helical and driven steel pipe piles. As part of this study, the dynamic response of a driven single steel pipe pile was investigated using the NEES/UCSD outdoor shake table (12.2 m x 7.6 m). The pile had an embedment depth of 3.36 m with a 0.3 m length above the ground surface. The diameter and wall thickness of pile were 8.81 cm and 5.3 mm, respectively. The shaker had two horizontal force actuators with a capacity of 6.8 MN that produces a peak acceleration of 4.2 g. Further details related to the testing program are provided in Elsawy et al. (2017).

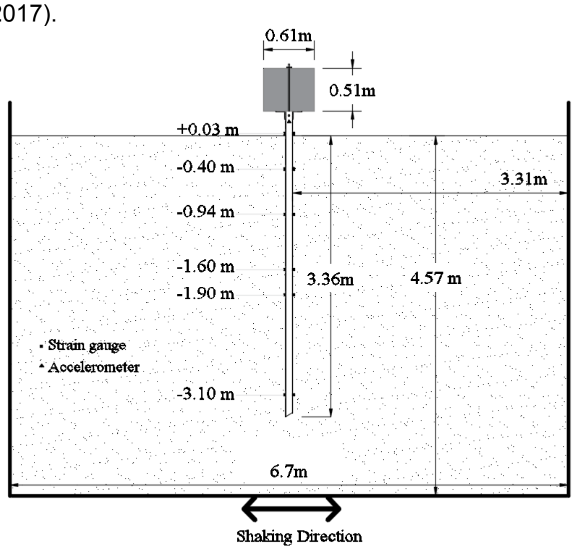


Figure 3. Instrumentation of pile in shaking table

The instrumented pile was installed in a full-scale laminar shear box (6.7 m x 3.0 m x 4.7 m) that has been filled with dry sand as shown in Figure 3. The laminar box consisted of laminar steel frames separated by rollers to simulate an absorbing boundary and reduce reflection of energy waves. A 317 kg mass attached to the pile head as depicted in Figure 3.

The sand was compacted to about 100% relative density classified as well-graded sand with a unit weight of 19.5 kN/m^3. The shear wave velocity of 250 m/s is determined based on results of SPT tests.

The Northridge 1994 earthquake was applied as the time history motion to base of the container. As shown in Figure 4, the peak acceleration of Northridge was 0.5g.

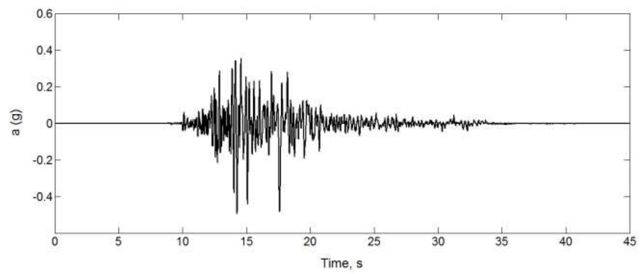


Figure 4. Acceleration-time history of Northridge earthquake

Since the bending moment values are known at certain depths along the pile at strain gauge locations, a curve fitting technique was implemented to fit an appropriate curve to the moment along the length of the pile. The obtained fitted curves for moment at each time step were then used to calculate the corresponding soil reaction and deflection of the pile by:

$$p(z) = \frac{d^2 M(z)}{dz^2} \quad [1]$$

$$y_{pile}(z) = \iint \frac{M(z)}{E_p I_p} dz \quad [2]$$

Where $M(z)$ represents the bending moment at depth z, E_p the pile material modulus and Ip the inertia of the pile.

4. Numerical And Experimental Responses

The developed dynamic BNWF model is implemented in the developed program, which was employed for the seismic analysis of the full-scale test. Each of the pile nodes below the ground surface is connected to one of the nonlinear BNWF elements described earlier. For a full substructure modeling, free-field ground response analyses are first performed using 1D Linear (L) and Equivalent Linear (EL) site response analyses in frequency domain.

Figure 5 presents the acceleration response spectrum of Northridge 1994 earthquake applied to the base of shear box in the experimental tests. This figure also includes the response spectrum of acceleration-time history of the ground at the surface that exhibits the natural frequency of the soil layer. It is evident that there is no difference between ground responses obtained from linear and equivalent linear analyses.

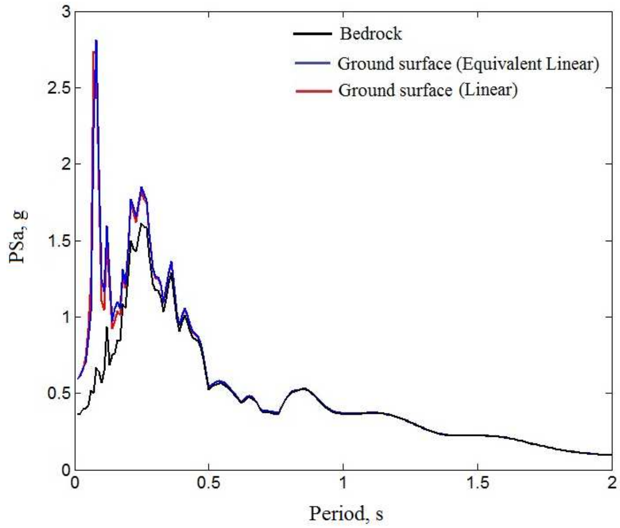


Figure 5. Response Spectrum of Northridge earthquake at bedrock and ground surface for 4.57 m of sand soil.

The time histories of the free-field ground motion at different elevations were then used as the input excitation of spring supports at each elevation along the pile to determine the pile response subjected to the earthquake as illustrated in Figure 5.

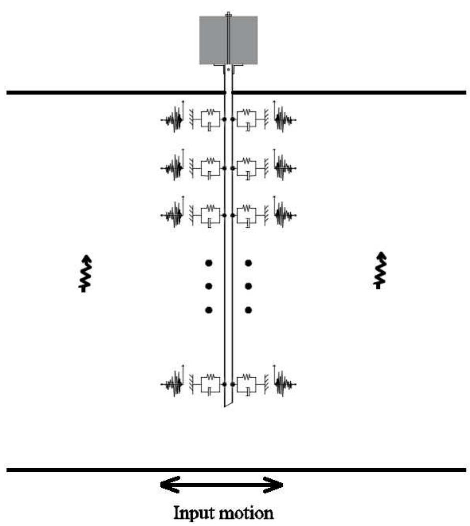


Figure 5. Schematic of full substructure analysis model

To demonstrate the capability of the BNWF model in incorporating various features of soil-pile-interaction, the calculated dynamic p-y curves at depths of 0.336, 0.504, 2.672 and 1.008 m are shown in Figure 6. As expected, soils near to the ground surface experienced higher nonlinearity and higher hysteretic damping behavior compared to the soil at lower depths that experienced almost linear-elastic behavior and stiffer response. It is also evident that the model could successfully simulate the soil cave-in and recompression in the slack zone as the limiting parameters of α_f and α_l were set to be 0.2 (Heidari and El Naggar 2016).

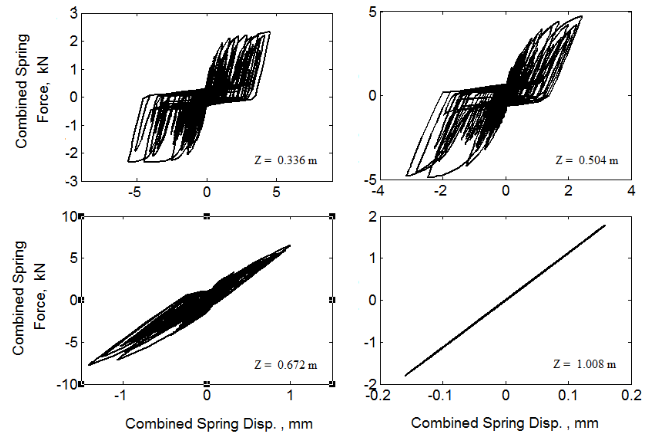


Figure 6. Dynamic p-y curves at different depths along the pile subjected to Northridge 1994 earthquake.

The calculated and measured time histories of the pile displacement at ground level are compared in Figure 6 to compare the response computed from numerical analyses with the measured data. As noted from Figure 6, the calculated displacement-time history from both multi-support excitation analyses (considering linear and equivalent-linear site response analyses) well predicted the observed response.

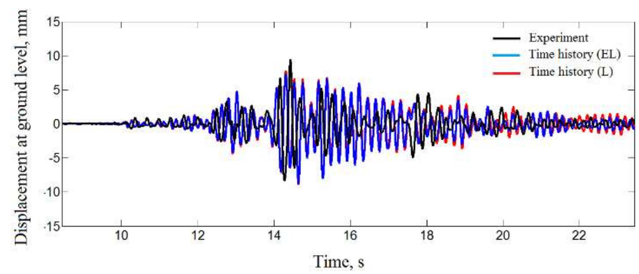
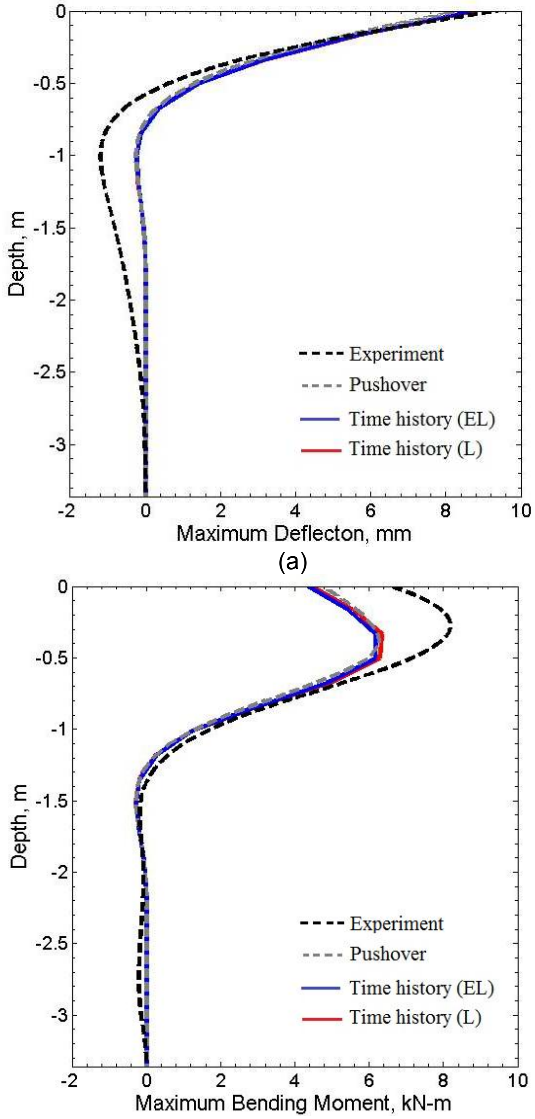


Figure 6. Comparison of computed and measured displacement-time history of pile at ground level

The comparisons of calculated and measured peak displacements and bending moments along the pile shaft are illustrated in Figure 7a and b, respectively. A static pushover analysis was also performed, which is a common alternative method for nonlinear analysis of structures. The obtained pile response from the pushover analysis corresponds to a lateral displacement of 27.74 mm applied at the pile-head. As expected, the pile undergoes significant displacement and flexural deformation closer to the surface.



(a)

(b)

Figure 7. Comparison of computed and recorded: a) peak deflection, b) maximum moment distribution with depth.

As shown in Figure 7, the computed responses obtained from the two seismic analyses are quite similar to that obtained from the pushover analysis. The main reason the different analyses yielded very close results is the low amplitudes of the applied earthquake, which resulted in approximately linear response of soil-pile system.

Although the predicted maximum moment is almost 20% lower than the measured value, the calculated and recorded structural responses of the pile under the shaking event are similar, especially the deflection profile along the pile shaft. Therefore, the seismic analyses based on the developed dynamic BNWF method are able to model reasonably the recorded responses despite the approximations in the implemented methods such as uncoupling of ground and structural responses, the equivalent-linear assumption for soil behavior in the free-field, and the uncertainties in soil properties and p-y characterizations. Additionally, the potential sources of errors in the full-scale test and interpretation of its results include the influences of soil-container interaction, difficulty in curve fitting due to the limited number of strain gauges, effect of the pile foundations on the surrounding soil profile motions and limitations in the signal processing.

Figure 8 displays the inertia forces plotted against pile-head displacements for pushover and dynamic analyses. As shown, the inertial load-lateral deflection curves attained from the two full models (i.e. linear and equivalent linear ground response analyses) are quite similar. This reveals that the induced shear strains within the 4.7 m depth soil layer due to the applied earthquake were within the linear range, which produced similar lateral ground excitations.

The pile-head lateral load-deflection curve obtained from the nonlinear static analysis correlates well with that of seismic analysis in the time domain. This also confirms the explanations provided earlier for the insignificant role of kinematic interaction effect related to the earthquake intensity and characteristics of the homogeneous soil layer. As such, it is concluded that the pushover analysis could be effectively employed to predict the nonlinear response of pile in similar soil conditions with reasonable accuracy.

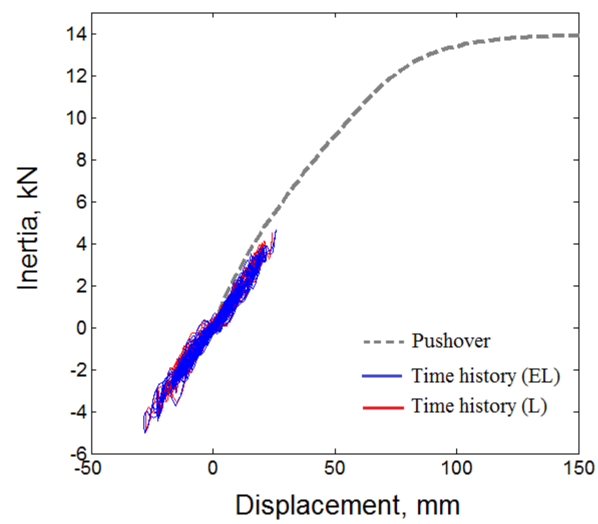


Figure 8. Lateral capacity of the pile through both pushover and seismic analyses

It is important to note that the lateral load corresponding to the pile-head deflection of 27.74 mm obtained from the pushover analysis is 5.87 kN, while an inertial force of 4.62 kN is determined form the dynamic analysis corresponding to the same pile-head deflection.

5. Conclusion

A dynamic beam on a nonlinear Winkler foundation (BNWF) analysis method was developed and verified against the measured response of a steel pipe pile subjected to seismic loading using the NEES/UCSD outdoor shake table. The pile was modeled employing the nonlinear fiber beam-column element and the different features of soil-structure-interaction is accounted for by using dynamic BNWF model developed Heidari and El Naggar (2016). The numerical analyses comprised linear and equivalent-linear site response analyses to calculate the dynamic response of the free-field soil profile and then applying the calculated site response as the input excitations to the end supports in the full substructure model to assess the dynamic response of the structural models. Despite the numerical approximations and potential experimental errors, reasonable agreement was observed between the seismic analyses and the full-scale test results. It was also found that the pushover analysis is able to replicate the results of the nonlinear dynamic analysis for within the range of demands considerate in the present study.

6. References

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