Analysis of Full-Scale Random Vibration Pile Tests in Soft and Improved Clays

Analyses à grande échelle de vibrations aléatoires sur pieux dans un sol argileux

Ashlock J.C., Fotouhi M.K.
Iowa State University, Ames, IA, USA

ABSTRACT: Full-scale pile vibration test results are analyzed for steel HP piles installed to a depth of 6 m in a soft clay profile, with one pile surrounded by a cement-deep-soil-mixed (CDSM) improved zone. Multi-modal tests with vertical and coupled lateral-rocking vibrations were conducted using a shaker mounted on a rigid pile cap. The improved soil zone significantly increased the stiffness of the measured vertical response, but had little effect on the lateral-rocking mode. Results of the forced vibration tests are analyzed using methods reported in the literature, including impedance functions and an approximate computational method which incorporates variation of soil properties with depth. The simplified model is able to capture the vertical response reasonably well in both the improved and native unimproved soil profiles, as well as the lateral response in unimproved soil. For the pile in improved soil, however, calibration of the model to the observed vertical mode results in a greatly stiffened lateral-rocking response which was not observed experimentally. To improve the simulation results, more sophisticated computational solutions are proposed for modeling the dynamic interaction of the pile and improved soil.

RÉSUMÉ : Les résultats d'essais de vibrations à grande échelle sur des pieux en acier (HP) et un pieu renforcé en tête par un mélange sol-ciment, installés sur 6 mètres de profondeur dans de l'argile, ont été analysés. Des tests multimodaux avec vibrations verticales et balancements latérales ont été réalisés à l'aide d'un actionneur monté en tête des pieux. Nous montrons que le renforcement du sol améliore la réponse verticale de manière significative mais n'a que peu d'effet sur la réponse latérale. Les résultats des essais ont été interprétés en utilisant des méthodes publiées dans la littérature, notamment une méthode qui prend en compte des fonctions d'impédance et une méthode numérique qui prend en compte les variations des propriétés du sol en fonction de la profondeur. Le modèle simplifié utilisé est capable de décrire correctement la réponse verticale pour les deux types du sol, avec ou sans renforcement, ainsi que la réponse latérale pour un sol non renforcé. Cependant, l'ajustement du model à partir de la réponse verticale rend compte d'une plus grande raideur latérale que celle observé expérimentalement. Ainsi, afin d'améliorer les résultats de nos simulations, nous proposons des modèles plus sophistiqués qui prennent en compte l'interaction dynamique des pieux avec le sol renforcé.

KEYWORDS: soil-pile interaction, soil dynamics, random vibration, pile, soil improvement, soft clay, impedance.

1 INTRODUCTION

Accurate characterization of the dynamic interaction between foundations and layered soils is an important issue for the design and analysis of foundations under seismic or vibratory loading. To date, several solutions ranging from simplified 2D approximations to 3D numerical models have been developed and employed to analyze soil-foundation interaction. However, validation and calibration of the various methods against full-scale field tests is essential for an understanding of their relative capabilities and limitations. While analytical and computational studies in the literature are numerous, the volume of full-scale field testing studies is comparatively limited. To help bridge the knowledge gap between theory and experimentation in soil-pile interaction problems, the current study investigates a series of full-scale dynamic field tests of two identical steel HP 250x63 (English HP 10x42) piles installed to a depth of 6 m in a soil profile featuring soft clay. The influence of local soil improvement on the dynamic pile response is also examined experimentally using a 1.2 m diameter, 4 m deep cement-deep-soil-mixed (CDSM) zone installed in the soft clay layer surrounding one of the piles. The piles were subsequently used for a reaction frame in a related study, which limited the pile spacing and diameter of the improved zone. The pile in the native unimproved soil profile is referred to as pile U, and the pile in the improved CDSM soil as pile I. The random vibration test procedures employed are described below, followed by analyses of the experiments via simplified 2D numerical models developed for dynamic interaction of piles with layered soils.

A newly developed servo-hydraulic shaker system was used to deliver three types and various levels of excitation. The excitation types used were chaotic impulse, random and swept-sine, denoted C, R and S, respectively. Theoretically, the broadband random (R) signal has a uniformly distributed energy over all frequencies while the swept-sine signals (S) concentrate the excitation's energy at a single frequency which is continually changing within a predefined interval. The chaotic impulse (C) excitation consists of a series of randomly timed impulses with randomly distributed amplitudes. In all tests, accelerations of the shaker and pile cap were measured in the horizontal (x) and vertical (z) directions in the plane of motion of the pile cap using six uniaxial accelerometers. Additionally, seven triaxial accelerometers were buried 6 inches below the soil surface at selected locations to record the near-surface vertical and horizontal motion. Figure 1 details the test setup including the soil profile, improved zone and sensor arrangement.

For data acquisition and real-time analysis in the time and frequency domains, a 20 channel dynamic signal analyzer was programmed in LabVIEW to record time histories and spectral quantities including FFTs, auto- and cross-spectral densities, transfer functions, and coherence functions. The stimulus for the transfer functions was taken as the force applied by the shaker's inertial mass in the direction of excitation, and all other accelerations of the pile cap and soil were treated as response quantities. Additionally, the full time histories of all sensors were simultaneously recorded on the nees@UCLA Kinemetrics Granite seismic recording systems to enable further interpretations such as time-domain analyses or different stimulus-response combinations.

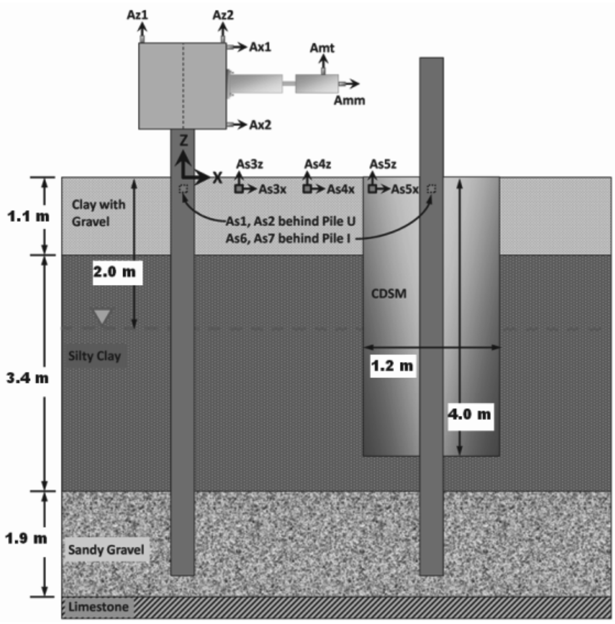

Figure 1. Soil profile, test set-up and sensor arrangement. Pile cap and shaker shown on pile U in native unimproved soil.

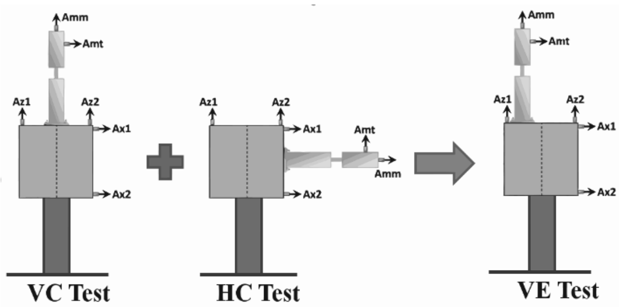

Figure 2. Inertial shaker configurations for the three test types.

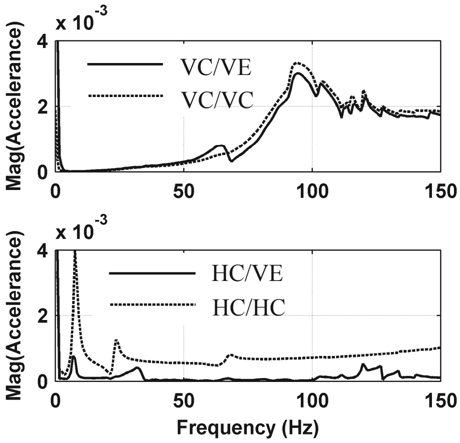

Figure 3. Comparison of VE test to combination of VC and HC tests for swept sine loading on pile I in improved soil. Top: VC response from VC and VE tests; Bottom: HC response from HC and VE tests.

For each combination of pile type (U or I), excitation type (C, R, or S) and intensity (1, 2, or 3), three separate tests were performed with the shaker mounted in the vertical-centric (VC), horizontal-central (HC), and vertically eccentric (VE) positions, shown schematically in Figure 2. The VC test primarily activates the vertical mode of vibration, while the HC test excites the coupled horizontal-rocking mode. These two tests have traditionally been performed independently, creating uncertainty as to the similarity of contact and soil conditions in the two separate tests. The VE tests were studied as a method to reduce such uncertainties and improve efficiency by activating the vertical and coupled horizontal-rocking modes simultaneously.

A total of 109 full-scale vibration tests were performed on the piles using the three excitation types and three shaker configurations described above, with a range of loading levels and excitation bandwidths. Typical experimental results are shown in Figure 3 for pile I. The results demonstrate that a single VE test can be used to characterize the vertical and horizontal-rocking modes normally obtained from separate VC and HC tests. Due to the difference in shaker orientation and location in the VE and HC tests, the HC response to HC excitation (HC/HC) differs from the HC response to VE loading (HC/VE). However, such differences are accounted for in the equations of motion of the shaker, pile cap, and un-embedded pile stem, and the HC and VE responses can be evaluated against their theoretical counterparts for both test types using a common set of soil-level impedance functions. A more detailed description of the test set up and experimental results can found in the Experimental Setup Report archived together with the data from all experiments described herein on the NEEShub at http://nees.org/warehouse/project/940.

To refer to the various tests, a naming convention of (Pile Type)-(Test Type)-(Excitation Type and Level) will be used. For example, U-HC-R3 refers to a test performed on pile U in unimproved soil with the shaker in the HC configuration, with random (R) excitation at the highest intensity level (3). In the naming convention, test types VC and HC can replace VE, and excitation types S (swept-sine) and C (chaotic impulse) can replace R. For any accelerometer, the accelerance is defined at each frequency as the ratio of the directional acceleration to the force applied by the moving mass of the shaker. Accelerance is used as the main frequency response function for comparing and analyzing experimental and analytical results. For example, VC/VE refers to the vertical-centric acceleration due to vertical-eccentric forcing. The pile-cap and stationary portion of the shaker are assumed to undergo rigid-body motion, and a set of vertical, horizontal and rotational accelerances at the centroid can therefore be easily calculated using acceleration measurements from three non-collinear points on the pile-cap.

2 THEORETICAL MODEL

The theoretical accelerance of the system is calculated using frequency-domain rigid-body equations of motion for the pile-cap and shaker, an Euler-Bernoulli beam-column formulation for the above-ground pile segment, and the aforementioned 2D approximate or 3D BEM formulations for impedance functions at the soil level to account for the dynamic pile-soil interaction (the BEM models are not discussed in this paper). The soil-pile impedance matrix relates the force and displacement of the pile cross-section at the soil surface elevation. Each component of the impedance matrix is frequency dependent and complex-valued, with the real part representing the dynamic stiffness of the pile-soil system and the imaginary part accounting for the material and geometric damping.

The 2D approximate pile-soil interaction model introduced by Novak and Aboul-Ella (1978) was used to calculate the soil impedances with account of the variation of soil parameters with depth. This model derives the soil reactions from a plane strain assumption and also incorporates the reaction of the soil at the pile tip. Upon constructing the stiffness matrices using the approach, the pile head impedances can be found by solving the global matrix equations for prescribed unit displacements and rotations of a pile section at the soil-surface. The model is limited to hysteretic damping behavior for the soil and a circular cross section for the pile. Circular sections with equivalent axial or bending stiffness as appropriate were therefore used to model the H-piles in this study. Additionally, the model requires that soil and pile properties are constant for each pile element.

The approach is fast compared to other numerical alternatives such as the finite element and boundary element methods, while offering good agreement with the more rigorous 3D computational methods for certain pile-soil configurations. However, the solution cannot easily model pile installation effects or soil-pile separation. Additionally, variation of the soil profile below the pile tip is not included in the formulation. The formulation was programmed in MATLAB for use in this study. More details on the theoretical approach can be found Novak and Aboul-Ella (1978).

3 PARAMETRIC STUDY AND RESULTS

The measured vibration data from full-scale tests were used in an inverse-analysis framework to calibrate the theoretical soil-pile model and identify the optimum values for each parameter in the solution. A sensitivity analysis was first conducted to determine the relative influence of the various parameters and estimate their possible range of variation for modeling the experimental observations. The properties of the pile-cap and shaker are known relatively accurately, and were therefore determined not to play a major role in the sensitivity analysis.

Attention was thus focused on the soil-pile interaction unknowns, including contact conditions and gapping near the surface, and profiles of soil shear modulus and damping. The parametric studies indicated that the un-embedded length of the pile can have a significant effect on the accelerance. Although the free un-embedded length of the pile can be measured accurately, slight gapping was observed in the field for pile U.

The sensitivity of accelerance to gapping effects was therefore examined by increasing the length of the free pile stem in the theoretical accelerance calculation, while decreasing the embedded pile length accordingly in the approximate 2D soil-pile impedance model. Figure 4 illustrates the effect of gapping on the theoretical accelerance, shown relative to the experimental HC/HC response for test U-HC-R4. As indicated in this figure, a 0.3 m soil-pile separation depth was found to produce an improved fit of the first experimental horizontal-rocking peak. Due to the non-destructive elastodynamic nature of the tests, the gapping depth was not observed to vary significantly between tests. Gapping was not observed for pile I in the field, likely due to its vibratory installation while the CDSM zone was still in a liquid state.

Figure 5 depicts the two shear modulus soil profiles that were used in the study of the unimproved soil-pile system. The profile labeled “CPT” was calculated from the CPT data using correlations to shear wave velocity presented in NCHRP Synthesis 368 (Mayne, 2007). Since correlations between CPT resistance and shear-wave velocity are not precise, the input values for the soil modulus are expected to incur some degree of error. Therefore, a second shear modulus profile based on Hardin and Drnevich (1972) was also examined, as shown in Figure 5. To model the soil damping profile, only three major layers corresponding to those shown in Figure 1 were distinguished along the length of the pile, compared to 38 finer layers used in shear modulus profiles.

Figure 6 demonstrates the effect of the two shear modulus profiles on the theoretical vertical and horizontal-rocking responses in VC and HC tests, respectively. The CPT profile generates a softer response in the vertical mode of vibration while yielding a slightly increased stiffness for the horizontal mode. This may be expected as the CPT-based modulus profile is softer overall, but is stiffer near the surface region which has a greater influence on the bending behavior.

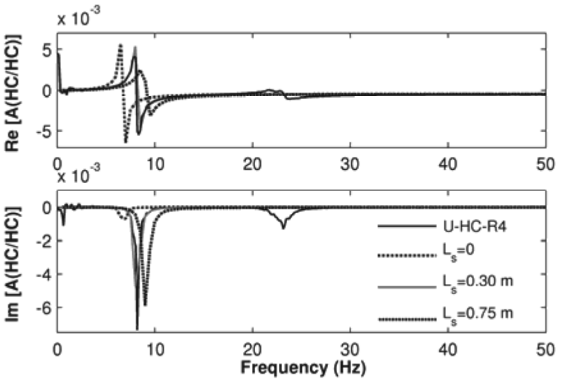

Figure 4. Effect of soil-pile separation depth on HC/HC response for pile U in native unimproved soil.

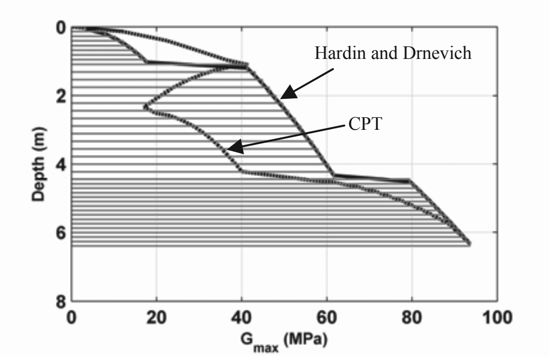

Figure 5. Two 38-layer shear modulus profiles used in the analyses based on interpretation of field CPT data and Hardin and Drnevich (1972).

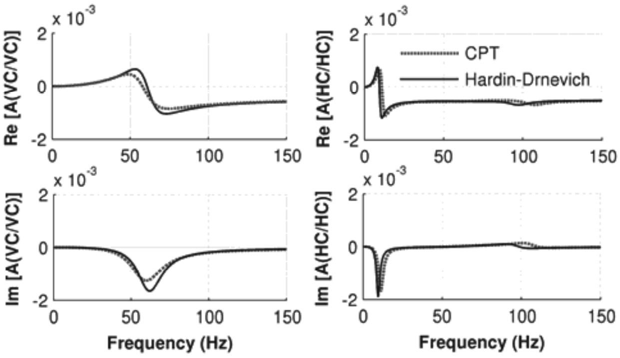

Figure 6. Effect of the two shear modulus profiles of Figure 5 on theoretical vertical response (left) and horizontal response (right).

Both the vertical and horizontal rocking modes of the pile in the native unimproved soft clay can be nearly captured using the Hardin & Drnevich shear modulus profile together with the 0.30 m separation zone, but require application of scale factors to the modulus and damping within the three major layers shown in Figure 1. Figure 7 illustrates such a comparison using modulus reduction factors of 0.8, 0.8 and 0.5 for the top, middle and bottom layers, respectively, while increasing the damping in all layers by a factor of 10. The peak frequency of the vertical mode is fit reasonably well, but the experimental vertical response exhibits some deviation from the theoretical solution at higher frequencies. This is assumed to be a relic of a higher mode of the shaker’s stationary base frame which does not behave as a perfectly rigid body. The first peak for the horizontal response matches very well, although this is difficult to see in Figure 7 as the experimental and theoretical curves are nearly coincident at this frequency.

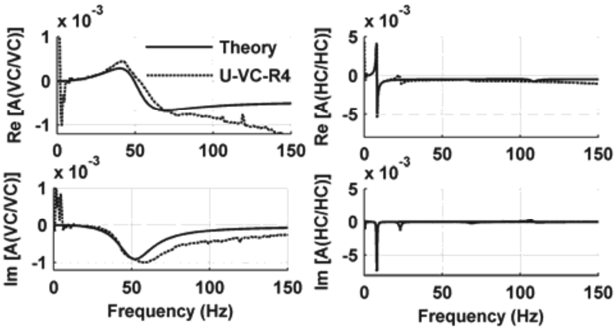

Figure 7. Comparison between experimental accelerance for pile in unimproved soil and theoretical model using the Hardin & Drnevich modulus profile with modification factors of (0.8 ,0.8, 0.5) for modulus and (10,10,10) for damping from top to bottom layers. Left: vertical response, Right: horizontal response.

Based on unconfined compression tests, the shear strength of the improved soil is more than 20 times greater than that of the unimproved soil. One approach for modeling pile I in the improved soil would therefore be to multiply the modulus values of Figure 5 by a factor of 20 for the first 4 m depth. On the other hand, the cement-like properties and mechanical mixing of the CDSM zone suggest the use of a more uniform modulus profile compared to the natural soil profile. These criteria may both be satisfied to some extent by using a modulus profile proportional to the fourth-root of depth (for curve fitting) and starting at 75 MPa at the soil surface. Such a profile will closely follow the natural soil profile below the improved zone. Although Figure 8 affirms that this modulus profile works very well for predicting the stiffened vertical mode for pile I in improved soil, Figure 9 illustrates that the corresponding experimental horizontal-rocking response was very similar for the native and improved soil profiles. Although a larger improved zone would likely be used in practice, the relatively unchanged dynamic lateral response in this study was unexpected considering the significant differences in native and improved soil properties. The similar lateral stiffness may be related to competing effects of a stiffer improved soil zone, but a relaxed state of stress in the surrounding soil due to installation of the CDSM zone, as well as separation between the CDSM region and surrounding soil from concrete shrinkage upon curing. The approximate 2D analytical model of Novak and Aboul-Ella (1978) is unable to incorporate such effects, and further study of more sophisticated 2-zone models may be necessary for modeling the observed behavior.

4 CONCLUSION

An experimental program was detailed for a series of full-scale pile vibration tests employing random vibration techniques. An approximate numerical elastodynamic model from the literature was employed to model the experimental results. Parametric studies revealed that an account of gapping between the pile and soil may be necessary to accurately model the observed behavior of the pile in unimproved native soft clay. However, the theoretical response was shown to be less sensitive to the modulus profile than to gapping, especially in the horizontal mode of vibration. The experimental response of the pile in soft clay was approximately fit by incorporating gapping over the first 0.3 m and scaling the modulus and damping in the three major soil layers. The vertical response of the pile in the improved cement deep soil mixed zone exhibited an increase in stiffness as expected. However, the horizontal response was relatively unchanged from that of the native soft clay profile. In practice, a larger lateral extent of soil improvement would be used, and a greater improvement in lateral stiffness expected. The numerical model can be fit to the stiffened vertical mode, but cannot simultaneously model the relatively unchanged horizontal stiffness encountered in this study. More sophisticated computational models will be examined to further model the latter behavior.

5 ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation under Grant No. 0936627. This support is gratefully acknowledged. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. This project was a payload to the NEESR-SG project 0830328. The assistance of the NEESR-SG project teams and the nees@UCLA team is appreciated.

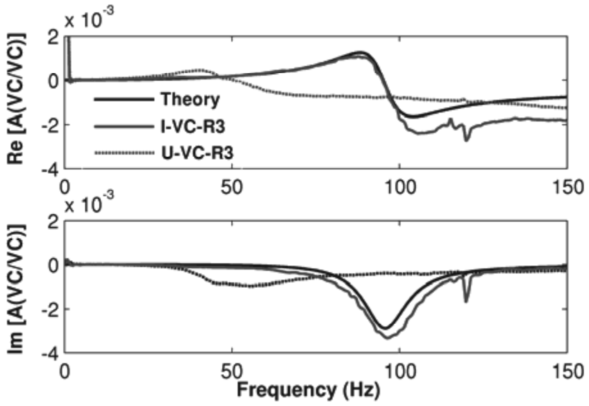

Figure 8. Experimental vertical response for pile in improved and unimproved soils with analytical model prediction for stiffened CDSM zone.

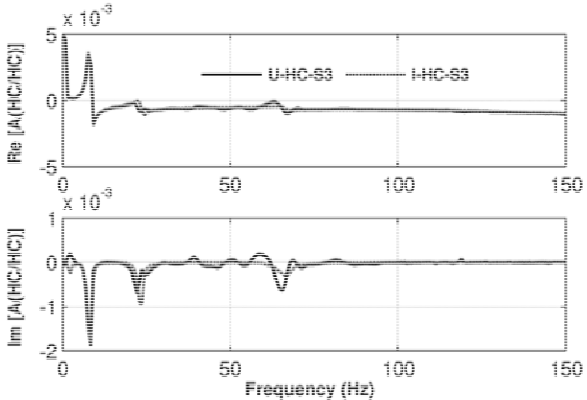

Figure 9. Representative experimental results for horizontal pile response in improved and unimproved soils exhibiting minimal difference.

6 REFERENCES

Ashlock, J.C. and Fotouhi, M.K. (2011). “Characterization of Dynamic Soil-Pile Interaction by Random Vibration Methods: Experimental Design and Preliminary Results”, Proceedings of 2011 NSF Engineering Research and Innovation Conference, Atlanta, Georgia (CMMI Grantee Conference), 11 pp. http://nees.org/warehouse/project/940

Fotouhi, M.K. and Ashlock, J.C. (2012). “Analysis of Experimental Dynamic Soil-Pile Interaction by Approximate Numerical Solutions ”, 15th WCEE, Lisbon , Portugal

Mayne, P. W. (2007). Cone Penetration Testing, NCHRP Synthesis 368. Transportation Research Board, Washington DC.

Novak, M. and Aboul-Ella, F. (1978). Impedance Functions of Piles in Layered Media. Journal of the Engineering Mechanics Division. 104:6, 643-661.

Hardin, B. O. & Drnevich, V. P. (1972). Shear modulus and damping in soils: design equation and curves. J. Soil Mech. Found. Engng. Div., ASCE 98, No. 7, 667–691