Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 178

ON PREDICTION OF DYNAMIC PILE BEHAVIOR

Shamsher Prakash[1] and Vijay K. Puri[2]

ABSTRACT

There are several models to predict response of single pile and pile groups. The lateral dynamic response of a single pile predicted by analytical models often yields higher natural frequencies and lower resonant amplitudes than those determined in field tests. This has been related to overestimated soil's shear modulus and radiation damping used in the calculations of the response. A simplified method was recently proposed to calculate strain dependent reduction factors for shear modulus and damping which were used for prediction of pile response. The reduction factors were developed based on reported pile test data at one site. The pile performance for another different site for which for which test results are available was calculated and compared with the observed pile response. In addition a comparison of the predicted pile response has been made with observed pile response during the full scale pile tests conducted by the authors. Results of these comparisons based on limited test results are presented.

Introduction

Piles have been used as foundations for high strain loading such as due to earthquake and in some cases for low strain loading such as due to machine foundations. The elastic solutions for determining response of piles subjected to dynamic loads have been presented by several investigators in the past. The pile response under dynamic loads is generally determined by making simplified spring-mass models. The soil springs are obtained from the shear modulus of the soil or from the modulus of sub-grade reaction. The seismic loading induces large displacements/strains in the soil. The shear modulus of the soil degrades and damping (material) increases with increasing strain. The stiffness of piles should be determined for these strain effects.

Prediction of pile behavior under dynamic loads depends upon pile dimensions, and soil properties, which include; soil shear modulus, material damping, and also on geometrical damping, and frequency of operation, and more importantly on strain level. Many investigators have attempted to bridge the gap between prediction and performance, by applying arbitrary correction factors to either soil stiffness or damping or to both, based on linear as well as non linear solutions.

[1] Professor Emeritus, Civil Engineering, Missouri University of Science and Technology, Rolla, Missouri, 65409; prakash@mst.edu
[2] Professor, Civil and Environment Engineering, SIU, Carbondale, IL 62901; puri@engr,siu.edu.

Prakash and Jadi (2001) reanalyzed the reported pile test data of Gle (1981) for the dynamic lateral loads and proposed reduction factors for the stiffness and radiation damping obtained by using the approach of Novak and El-Sharnouby (1983). Gle (1981) tested four different single steel pipe piles at two different sites in Southeastern Michigan. The soil profiles at these sites were predominantly composed of clayey soils. Each pile was tested at several vibrator-operating speeds. A total of eighteen dynamic lateral tests were conducted in clayey and silty sand media. The following approach was followed to analyze this data.

Method of Analysis

The method of analysis used in this study is as follows (Jadi (1999) and Prakash and Jadi (2001):

Step 1. Field data obtained from lateral dynamic tests performed by Gle (1981) on full-scale single piles embedded in clayey soils, were collected.

Step 2. Theoretical dynamic response was computed for the test piles, using Novak and El-Sharnouby's (1983) analytical solution for stiffness and damping constants, with no corrections.

Step 3. The soil's shear modulus and radiation damping used for the response calculations were arbitrarily reduced, such that measured and predicted natural frequencies and resonant amplitude matched.

Step 4. The reduction factors obtained from step 3 were plotted versus shear strain at resonance without corrected G and 'c'. Two quadratic equations given below were developed to determine the shear modulus reduction factors (λ_G) versus shear strain, (γ) and the radiation damping reduction factor (λ_C) versus shear strain (γ).

$$\lambda_G = -353500\,\gamma^2 - 0.00775\,\gamma + 0.3244 \qquad (1)$$

$$\lambda_c = 217600\,\gamma^2 - 1905.56\,\gamma + 0.6 \qquad (2)$$

where, λ_G and λ_c are the reduction factors for shear modulus and damping and γ is shear strain at computed peak amplitude, without any correction.

Step 5. For all the pile tests considered in this study, the empirical equations determined in step 4 were used to calculate shear modulus and radiation damping reduction factors. Predicted responses before and after applying the proposed reduction factors were then compared with the measured response.

Step 6. To validate this approach, the proposed equations were used to calculate shear modulus and radiation damping reduction factors for different sets of field pile tests. The new predicted response was then compared to the measured response, both for Gle (1981) tests and two other cases.

Comparison of Observed and Predicted Pile Response

Using the reduction factors (Eqs. 1 and 2) Jadi (1999) and Prakash and Jadi (2001) calculated the pile response for the same site and made a comparison of observed and predicted pile response. Figure 1 shows prediction and performance of Gle's pile. In Fig.1, it may be noted that the reduction factors for shear modulus and damping had been developed from tests by Gle.

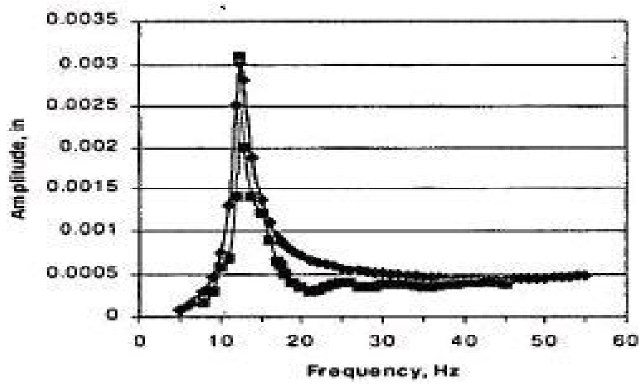

Fig. 1 Measured vs predicted lateral dynamic response for pile K16-7(ɵ=5°) at Belle River site. λ_G = 0.321, λ_c= 0.4 (Jadi, 1999) (■ measured, ♦ computed)

Therefore, this match is obvious. Figs. 2, 3 and 4 show plots of computed and measured response of several piles tested by Gle (1981). Plots of the measured resonant frequencies and amplitudes

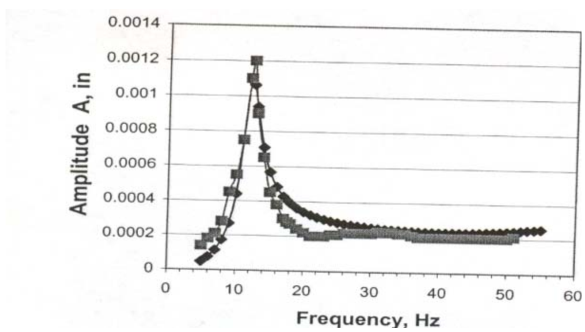

Fig 2. Measured and Reduced predicted lateral dynamic response for pile for lateral dynamic load test for pile L1810 θ=2.5^0 , Belle river site (Jadi, 1999) (■ measured, ♦ computed)

versus the corresponding predicted values determined with proposed reduction factors were constructed. Fig. 5 shows the measured natural frequencies of all test piles versus predicted natural frequencies. Fig. 6 shows measured resonant amplitudes for all test piles versus predicted resonant amplitudes. These figures show that all points fall into the zone of the 45 degree line, providing that predicted resonant frequencies and amplitudes are comparable to the measured values.

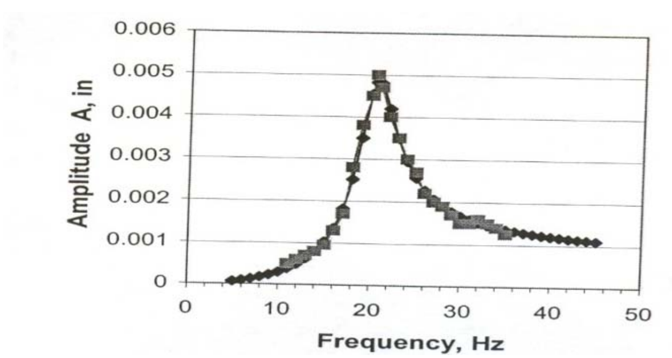

Fig 3. Measured and arbitrarily reduced predicted lateral dynamic response for pile LF16, θ=10^0, St. Clair Site (Jadi, 1999) (■ measured, ♦ computed)

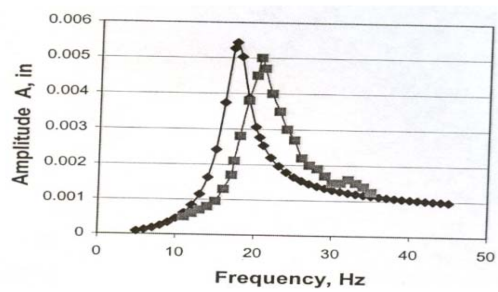

Fig 4. Measured and reduced predicted lateral dynamic response for pile LF16, θ=10^0, St. Clair Site λ_G = 0.321, λ_c= 0.4 (Jadi, 1999) (■ measured, ♦ computed)

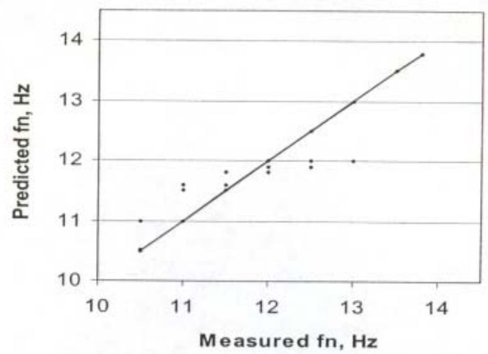

Fig 5. Measured natural frequency versus predicted natural frequency computed with proposed shear modulus reduction factor (Jadi, 1999)

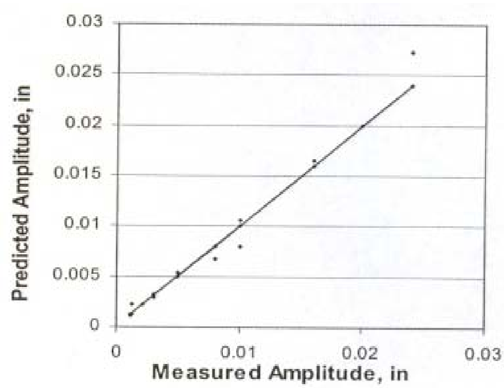

Fig 6. Measured resonant amplitude versus predicted resonant amplitude computed with proposed radiation damping reduction factor (Jadi, 1999)

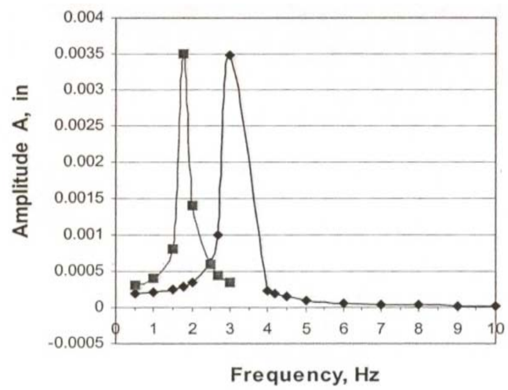

Fig7. Measured vs reduced predicted lateral dynamic response for pile 1 using proposed reduction factors, WES vibrator, $\lambda_G = 0.31$, $\lambda_c = 0.5$ (Jadi, 1999) (■ measured, ♦ computed)

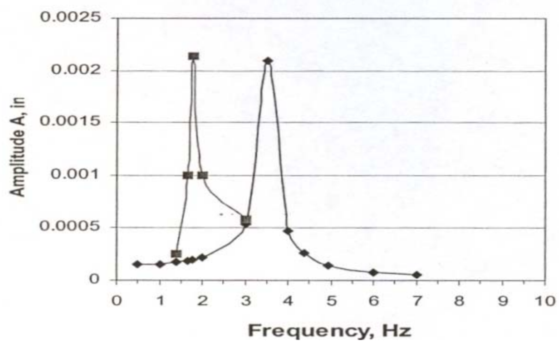

Fig 8. Measured vs reduced predicted lateral dynamic response for pile 1 using proposed reduction factors, FHWA vibrator, $\lambda_G = 0.32$, $\lambda_c = 0.54$ (Jadi, 1999) (■ measured, ♦ computed)

Comparison with Different Data

In order to confirm the validity of the proposed method, dynamic response of different sets of experimental data from other sites were also checked. Two series of experimental data were analyzed. Blaney (1983) carried out two lateral dynamic tests on the single pile, embedded in the clayey soils. The first test was performed with a 'WES' (Waterways Express Station) vibrator. For the second test an 'FHWA' (Federal Highway Administration) vibrator was used. Fig.7 and 8 represent the measured and computed response by applying suggested shear modulus and radiation damping reduction factors, for tests with WES, and FHWA vibrators respectively. The resonant amplitudes matched, but computed natural frequencies are about 40% different. However these figures show that the predicted response with proposed reduction factors compares much better to the measured response, as compared to the predictions by Blaney (Jadi, 1999).

The second experimental data considered for validation of the proposed method, consisted of Novak and Grigg's (1976) lateral dynamic test. This test was performed on a small single pile embedded in a very fine silty sand layer. Fig 9 shows measured and predicted lateral dynamic response for the 2.4 inch diameter pipe pile without corrections. Fig 10 shows the measured and predicted lateral dynamic response computed with proposed reduction factors for the same pile. As can be seen, the predicted response with proposed reduction factors becomes much closer to the measured response. The comparative analysis presented herein validates the effectiveness of the proposed reduction factors for piles embedded in clayey soils, to a degree.

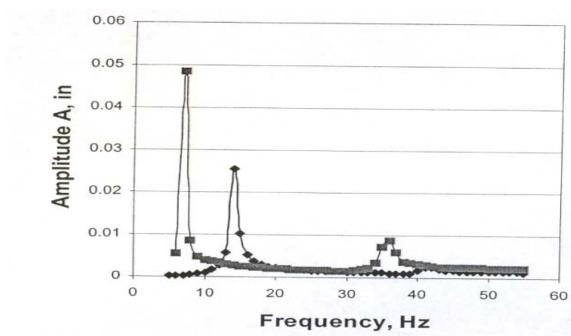

Fig 9. Measured vs predicted lateral dynamic response for the 2.4" pile without correction factors (Novak and Grigg, 1976, Prakash et. al 2009). (■ measured, ♦ computed)

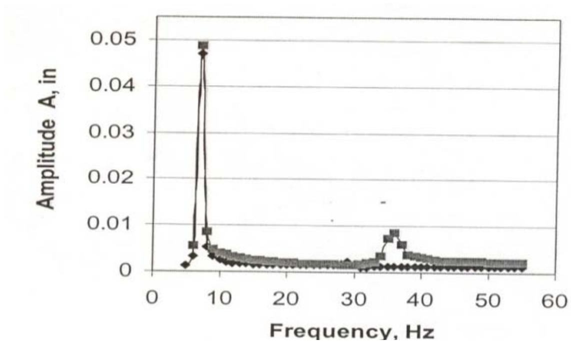

Fig 10. Measured vs predicted lateral dynamic response for the 2.4" test pile using proposed reduction factors λ_G = 0.044, λ_c= 0.34 (Jadi, 1999, Prakash et. al 2009). (■ measured, ♦ computed)

Comparison with Authors' Test Data

Free and forced vibration tests were conducted by authors on a 450-mm-diameter reinforced concrete pile driven 17 m into the deposit of silty sand. A reinforced concrete cap measuring 1.2m x 1.2m x 0.8m (high) was cast monolithically with the pile head for mounting the vibration-generating equipment. The frequencies and amplitudes of vibration were monitored. The dynamic soil properties were determined at the site by conducting wave propagation tests, block vibration tests and standard penetration tests. The data of these tests were interpreted following the approach suggested by Prakash and Puri (1988). The details of the tests for dynamic shear modulus determination are not discussed in this paper. The value of low strain dynamic shear modulus at the level of pile tip was determined to be 63.7 MPa (Prakash and Puri; 2004). The un-damped natural frequencies and damped vibration amplitudes for the case of horizontal vibrations of the soil-pile system were computed using the procedure of Prakash and Jadi (2001) and Prakash et.al (2009). The natural frequency for the case of free horizontal vibrations was also determined. The main difference between the free vibration case and forced vibration case is the order of strain induced by the pile vibrations.

The observed natural frequency of free horizontal vibrations was 11.5 Hz. The computed frequency of free horizontal vibrations by Prakash and Jadi's (2001) method was 15.2 Hz. The observed natural frequency of forced horizontal vibrations was 10.3 Hz and its calculated value was 13.7 Hz. The observed vibration amplitude was 0.44mm and the calculated amplitude was 0.225 mm. The computed values of natural frequency and the resonant amplitudes using Jadi,s method in this case are somewhat different compared to their observed values. However, the comparison seems reasonable keeping in view the fact that Jadi,s method provides a highly simplified method of calculating the pile response under lateral vibrations.

Comments on Predictions

Studies have been conducted in recent years to compare the observed pile performance under dynamic loads with the calculated values. Efforts have been made to match predicted values with computed data by making arbitrary modifications to stiffness and damping values (Novak and El Sharnouby, (1984)). No guidelines were provided as to how these values should be modified. Woods (1984) used PILAY program with modified stiffness to match prediction and performance. El Marasafawi et al (1990) used concept of a weakened zone surrounding the piles to match the observed pile test data with the computed values. In their studies the extent of the softened zone was arbitrarily assumed and the dynamic shear modulus and damping were also arbitrarily modified to match the computed and predicted pile response.

Jadi (1999) developed rational correction factors to both stiffness and damping to match the computed and predicted responses. She was reasonably successful in her efforts. Her approach is more scientific but based on a limited data. More studies are needed to develop relationships for the reduction factors for different modes of vibration, and different soils to further validate the concept.

Conclusions

Based on the observed data during the field tests on a single pile, and the results of analysis and reported data in literature , the following conclusions may be made.

1. Soil-pile behavior is strongly strain dependent. Many attempts have been made to obtain a match between observed and computed pile response.
2. The proposed concept of reduction factors for shear modulus and damping by Jadi (1999) appears reasonable. However , it is based on a limited data . More research is needed before this method can used in practice.

References

Blaney, G.W., (1983), "*Lateral Response of a Single Pile in Over Consolidated Clay to relatively Low Frequency Harmonic Pile –Head Loads and Harmonic Ground Surface Loads"*, University of Michigan, Ann Arbor, Michigan

El-Marsafawi, H, Han, Y. and Novak, M. (1990). "Dynamic experiments on two pile groups", *Research Report GEOT-20-90*, Dept. of Civil Engineering, Western Ontario, August.

Gle, D.R.(1981).“The dynamic lateral response of deep foundations.” *PhD dissertation*, University of Michigan, Ann Arbor.

Jadi, H. (1999), “*Predictions of Lateral Dynamic Response of Single Piles Embedded in Clay*”, MS Thesis, University of Missouri, Rolla.

Novak, M. and El Sharnouby, E.B. (1983). “Stiffness and damping constants for single piles.” *J. Geotechnical &Geoenvir. Engrg*., Vol. 109 (7): 961-974.

Novak, M. and El Sharnouby, E.B. [1984], “Evaluation of Dynamic Experiments on Pile Groups.” *J. Geotechnical &Geoenvir. Engrg*., Vol. 101(6): 737-756.

Novak, M. and Grig, R.F., (1976), “ Dynamic Experiments with Small Pile Foundations”, *Canadian Geotechnical journal*, Vol. 13, No 4, pp. 376-395.

Prakash, S. (1981).“*Soil Dynamics*.”McGraw Hill, New York. Reprinted SP foundation, Rolla, MO

Prakash, S. and Jadi, H. (2001). “Prediction of lateral dynamic response of single piles embedded in fine soils”, *Proc.* 4th *Int. Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics* , San Diego, CD ROM.

Prakash , S. Jadi, H. and Puri, V.K.(2009), “ Piles Under Dynamic Loads”, International Workshop on Soil-Foundation-Structure Interaction (SFSI 09) 26-27 November 2009,/ Auckland, New Zealand

Prakash , S. and Puri, V.K. (1988).“*Foundations for machines: analysis and design”,* John Wiley and Sons, New York.

Puri, V.K. and Prakash, S.,(2004), “Rational interpretation of typical pile load tests.” *Proc.13th World Conference on Earthquake Engineering*, Vancouver, , CD ROM.

Woods, R.D. (1984). “Lateral interaction between soil and pile.” *Proc. Int. Symposium on Dynamic Soil Structure Interaction*, Minneapolis: 47-54.