

ON PREDICTION OF DYNAMIC FOUNDATION BEHAVIOR

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ABSTRACT: Full scale dynamic pile load tests were conducted on a 450 mm diameter reinforced concrete pile that was driven 17m in a soil profile of uniform silty sand and the amplitude frequency response of the pile subjected to vertical and horizontal vibrations was observed. The natural frequency of free vibrations in the horizontal direction was also measured. The soil properties were determined by conducting in-situ and laboratory tests. A comparison of observed and predicted pile response is presented . A comparison of the computed and observed pile response based on the data reported in literature is also presented briefly.

INTRODUCTION

Piles have been used as foundations for high strain loading such as earthquake and in some cases for low strain loading such as 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.

A comparison of the observed and predicted response of a single pile for dynamic loading conditions based on the tests conducted by the authors is presented. In addition a comparison of the computed and observed pile response based on the data reported in literature is also presented briefly. The recent method of Prakash and Jadi

(2001) which seems to make better estimates of the predicted pile response is also presented.

TEST PROGRAM

Dynamic Pile Tests

Forced horizontal and vertical vibration tests were conducted on a 450-mm-diameter pile driven 17 m in a 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 vibrations were monitored with the help of acceleration transducers mounted on the pile at mud line. A typical amplitude-versus-frequency plot for one of these tests is shown in Fig. 1. Free horizontal vibration tests were also conducted on this pile by pulling and suddenly releasing it. A typical free vibration record is shown in Fig.2. The values of the observed natural frequencies are shown in Table 1.

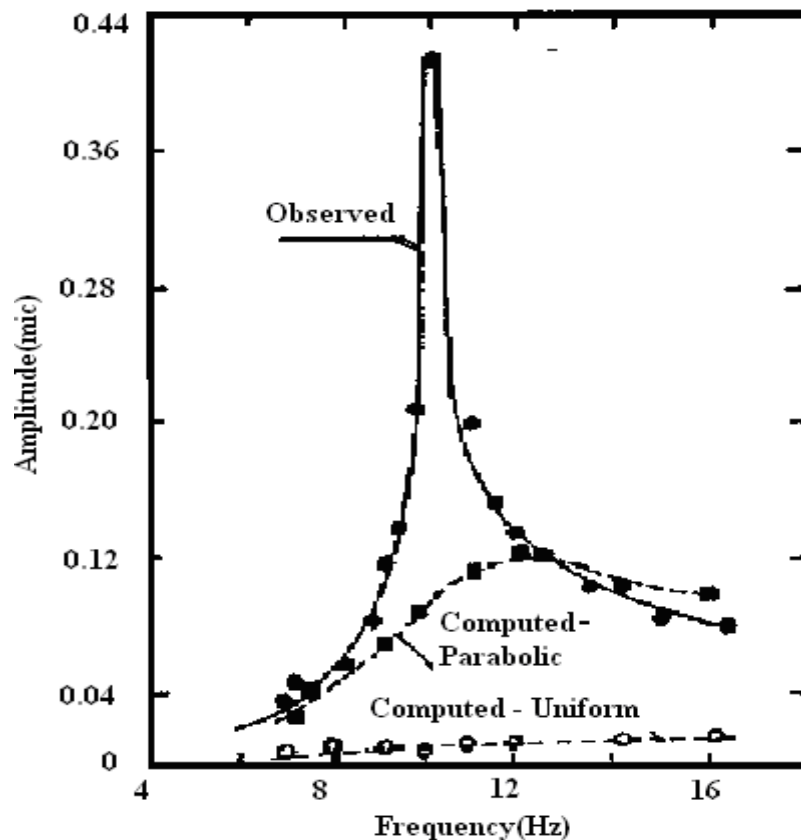


Figure 1. Typical amplitude-frequency plot

Determination of Dynamic Shear Modulus

The soil at the site was generally dense silty sand extending to a depth of about 22.5 m. It was generally non-plastic. The average value of the angle of friction for the soil as determined by conducting a number of tri-axial tests in the laboratory ranged from 36.2° to 38° . The values of the dynamic shear modulus at the site were determined by conducting block vibration, wave propagation 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 (Puri and Prakash; 2004).

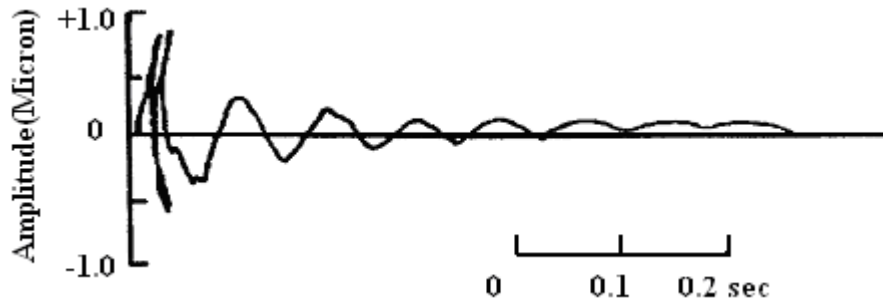


Figure2. Typical Free Horizontal Vibration Record

Table 1. Comparison of Observed and Computed Response

Vibration mode	Item	Observed values		Computed values		
				Uniform soil profile	Parabolic soil profile	
		Forced vibrations	Free vibrations	Forced vibrations	Forced vibrations	Free vibrations
Vertical	f_{nz} Hz	32.2	-	46.0	38.8	-
Horizontal	f_{n1} Hz	10.3	11.5	30.9	11.89	12.9
	f_{n2} Hz	-	-	77.6	45.7	-
	A_x mm	0.44	-	0.08745	0.116	-

COMPUTATION OF THE PILE RESPONSE

The natural frequencies of vertical vibration for the cases of uniform soil profile and parabolic soil profile were calculated using the concept of Novak and El-Sharnouby (1983) and Prakash and Puri(1988) The values of the natural frequency of vertical vibrations so calculated are shown in Table 1. The un-damped natural frequencies and damped vibration amplitudes for the case of horizontal vibrations of the soil-pile system were computed by treating it as a case of coupled rocking and sliding and using the appropriate spring stiffness and damping obtained from Novak and El-Sharnouby (1983) and Prakash and Puri (1988). The equations used for these calculations may be seen in any of these two references. In all cases the strain dependent values of soil spring stiffness were obtained for use in computation of the pile response. The calculated natural frequency of free horizontal vibrations is also shown in table 1(f_{n1} and f_{n2} in table 1 are the first (lower) and second (higher) natural frequencies in coupled rocking and sliding respectively). The calculated values of horizontal amplitudes at different frequencies are plotted in Fig. 1.

DISCUSSION ON COMPARISON OF OBSERVED AND COMPUTED RESPONSE

It may be noted from table 1 that:

1. The computed natural frequencies of vertical vibrations of the pile for the homogenous and parabolic soil profiles are 46.0 and 38.8 Hz respectively. The observed natural frequency of vertical vibrations is 32.2 Hz. The computed values of natural frequency for the homogenous soil profile are 43% higher than of the observed natural frequency in vertical vibrations. For the parabolic soil profile, the calculated natural frequency is about 20.5% larger than the observed natural frequency.
2. For the case of coupled rocking and sliding, the calculated values of smaller natural frequency f_{n1} are 30.9 and 11.89 Hz for the homogenous and parabolic soil profiles respectively. The observed natural frequency is 10.3 Hz. The calculated natural frequency for the uniform soil profile is substantially higher than the observed natural frequency of horizontal vibrations. For the case of parabolic soil profile, the calculated natural frequency is about 15% higher than the observed natural frequency.
3. The calculated natural frequency of horizontal free vibrations for the parabolic soil profile is 12.9 Hz and is 12% higher than the observed frequency of free vibrations (Table1). The observed value of the peak horizontal vibration amplitude is 0.44 mm, which is higher than the calculated amplitudes for the homogenous soil profile (0.08745 mm) and the parabolic soil profile (0.116 mm). In the frequency range considered (Fig. 1) the computed amplitudes of horizontal vibrations are generally smaller and near resonance they are substantially smaller than the observed values.
4. Because of the limited nature of the study, it is not possible to draw any general conclusions, but it seems that in this particular case the assumption of a parabolic soil profile has given reasonable values of natural frequencies both for vertical and horizontal vibrations.
5. Theoretical damping of the soil-pile system is substantially higher than the actual value, resulting in smaller resonant amplitudes.

The reasons for the differences between observed computed responses of the piles may be partly explained by the assumptions made in modeling the pile behavior. There are uncertainties in determination of the appropriate values of dynamic shear modulus and damping of the soil. The damping is generally overestimated in the method of Novak and El-Sharnouby (1983) which results in underestimation of vibration amplitudes, particularly close to resonance.. It is generally observed that a softened zone of soil develops surrounding the pile during pile installation which affects the estimated pile stiffness. This aspect is discussed below.

OTHER COMPARISONS OF PREDICTION AND PERFORMANCE

Several researchers have attempted to make a comparison of the observed and predicted pile response. Small scale pile tests, centrifuge tests and full pile tests have been conducted for this purpose (Gle, 1981; Novak and El-Sharnouby,1984; Woods,

1984). Woods (1984) reported results of 55 horizontal vibration tests on 11 end bearing piles 15 - 48 m long. The outer diameter of piles was 35.56 cm and the wall thickness varied from 0.47 cm to 0.94 cm. Woods (1984) also compared the observed and computed response of the piles. The stiffness and damping values were obtained using computer program PILAY which uses continuum model accommodating soil layers and assumes homogeneous soil in the layer with elastic behavior. A typical comparison of the pile response so computed with the observed response is shown in

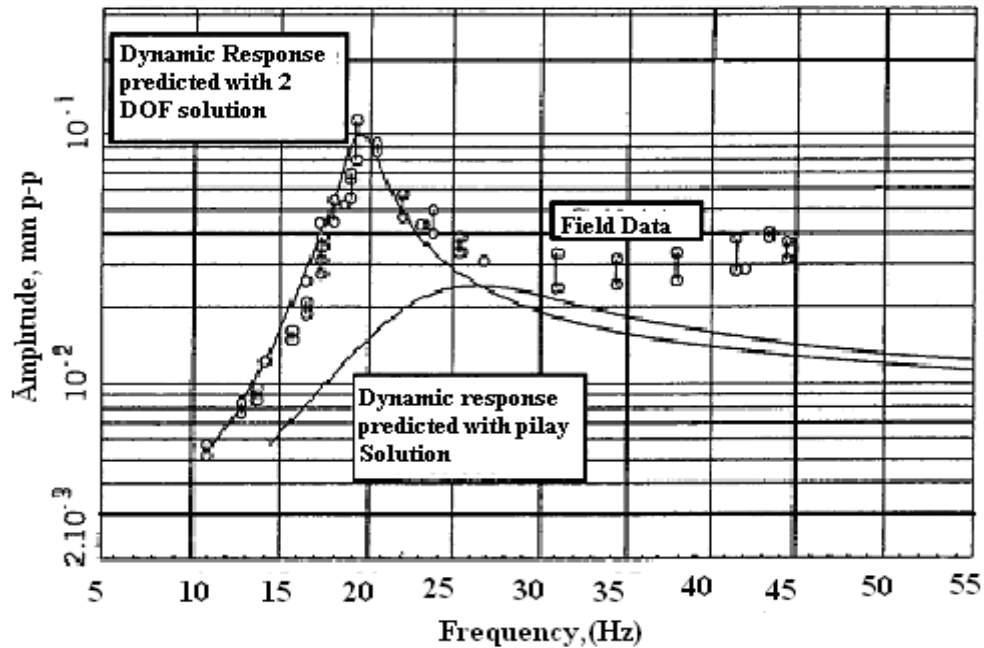


Figure3. Typical response curves predicted by PILAY superimposed on measured pile response (Woods, 1984)

Fig. 3. It may be observed from Fig. 3 that the calculated and computed responses do not match. Efforts were made to obtain a match between observed and predicted response by using reduced values of stiffness obtained from PILAY, which did not help much. A better match could, however, be obtained when a considerably softened or weakened zone was assumed surrounding the piles (program PILAY 2) simulating disturbance to soil during pile installation. A loss of contact of the soil with the pile for a short length close to the ground surface also improved the predicted response. El-Sharnouby and Novak (1984) performed tests on 102 model pile groups using steel pipe piles. It was observed by El- Sharnouby and Novak (1984) and Prakash and Sharma (1990) that the observed and predicted response for horizontal vibrations shows better agreement when a softened zone surrounding the piles and separation between pile and soil near the ground surface are accounted for in calculations.

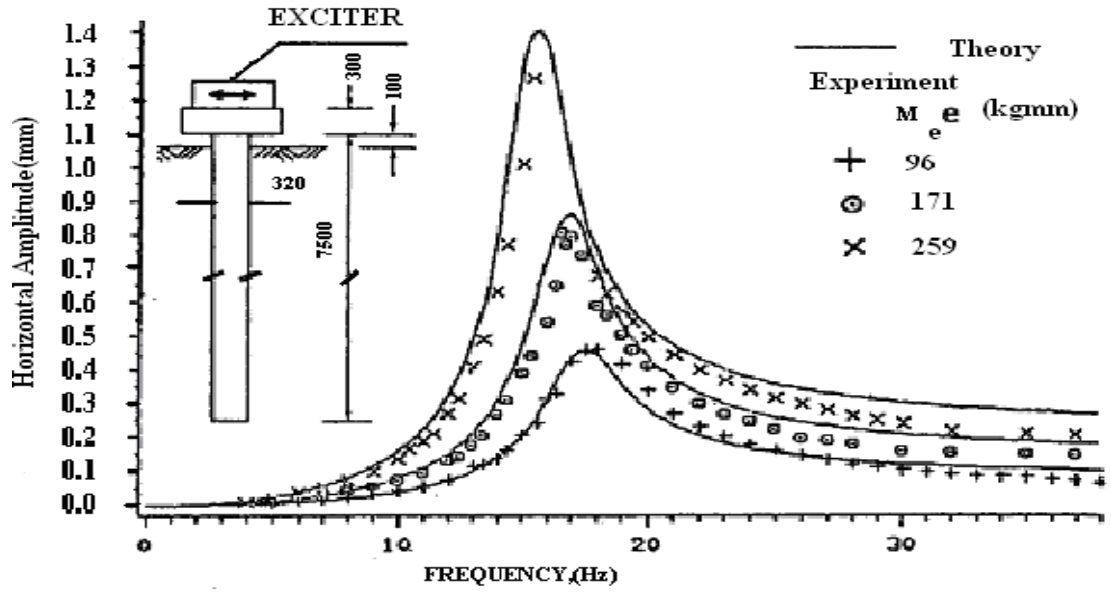


Figure 4. Theoretical and experimental horizontal response of concrete pile for three levels of harmonic excitation (El Marsafawi et al., 1990)

El Marasafawi et al (1990) conducted horizontal vibration tests on a 0.32 m diameter, 7.5 long piles and compared with the calculated theoretical response after accounting for the weak zone surrounding the piles. This comparison is shown in Fig. 4. Similar data for a six pile group is shown in Fig. 5. The comparison of the observed and computed response for these particular cases appears reasonable. In these 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

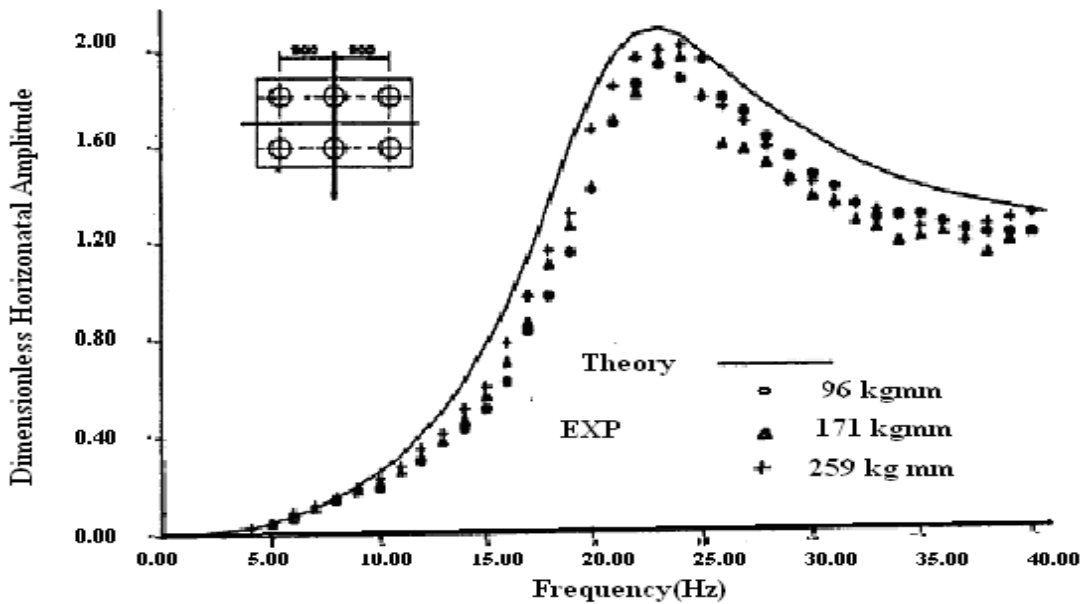


Figure 5: Horizontal theoretical and experimental response in Y-direction for group of six concrete piles 7.50 m long, 0.32 m in diameter (El Marsafawi et al., 1990)

Prakash and Jadi (2001) reanalyzed the reported pile test data of Gle (1981) for the lateral dynamic proposed reduction factors for the stiffness and radiation damping obtained by using the approach of Novak and El-Sharnouby (1983). The suggested equations for the reduction factors are:

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

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

where, λ_G and λ_c are the reduction factors for shear modulus and damping.

Using the proposed reduction factors the reported test data of Gle (1981) was reanalyzed by Prakash and Jadi (2001). A typical comparison of the observed and predicted pile response is shown in figure 6. The predicted values of natural frequency and amplitude of vibration at various frequencies show an excellent comparison with the observed data.

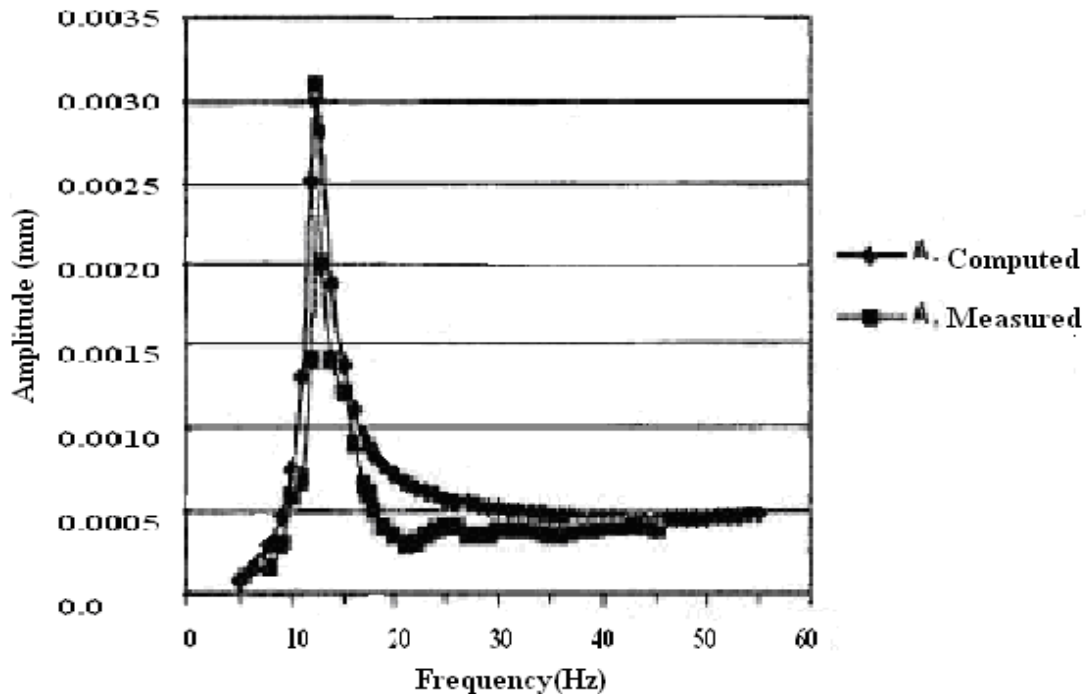


Figure 6. Comparison of Observed and Computed data of Gle (1981)

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. The comparison of observed and predicted dynamic pile response of the single test pile shows that assumption of a parabolic soil profile yields reasonable values of natural frequencies for the case of vertical as well as horizontal vibrations.

However, a general conclusion is not justified because of the limited nature of data.

2. It is necessary to account for the effect of softened soil zone in designing piles subjected to dynamic effects.
3. The concept using reduction factors for stiffness and damping appears promising. However, more research is needed before this approach can be used in practice.

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