TECHNICAL NOTE

On The Prediction of Experimental Results from Two Pile Tests, Case of Foundation Vibrations Due to Harmonic Loadings

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Dynamic response of pile foundations has been the subject of numerous research since early 1970's. While most of the work on this subject has focused on developing analytical solutions, some experimental work has been carried out in parallel to validate the theoretical results [1, 2, 3, 4, 6]. In general, the studies have shown that the pile-soil interaction is relatively complex and often requires the analytical methods to be validated against experimental data to provide reliable predictions.

The objective of this technical note is to investigate the pile group analysis procedure implemented in MTR/DYNA [5] to predict the experimental results of a single pile as well as a group of piles subjected to low amplitude forced harmonic loading from two available pile tests: one on model steel piles of intermediate size in non-cohesive soil and the other on full scale concrete piles in cohesive soil [6]. The experimental results provided in [6] are compared with analytical solutions obtained from MTR/DYNA to validate the accuracy of the new pile analysis procedure to predict vibration amplitude versus frequency response in both the linear and nonlinear range. The results of both linear elastic and nonlinear soil that consider the effects of confining pressure on soil/pile de-bonding as well as the soil nonlinearity due to deficiencies in the soil/pile interface and methods of pile installation are presented.

Method of Analytical Analysis

MTR/DYNA was used to predict dynamic response of the single pile and pile group. The program implements a new Pile element coupled with ring load solution in a layered system to solve for dynamic pile group interaction. A brief description of the methodology and validation of the elasto-dynamic results produced from the new pile analysis procedure are presented in Reference [7]. To account for the effects of local soil nonlinearity, a weak soil zone or weak soil layers may be included in the model, as described below. In addition, the program allows for modeling possible soil/pile de-bonding (gapping) due to low confining soil pressure in the uppermost layers. The soil/pile interaction modeling schemes used in the current study are described below.

Elastic Layers Model:

This is a linear visco-elastic model for pile group analysis in MTR/DYNA. In this model the piles are modeled using pile elements and the soil media consists of an elastic layered system over uniform halfspace, as shown in Figure 1(a). The elastic soil layer properties consist of the small-strain shear modulus and hysteretic damping measured from the field and/or laboratory tests.

Weak Layers Model:

The Weak Layers Model is shown in Figure 1(b). This model is the same as the Elastic Layers Model except that the soil shear modulus and damping can be adjusted for the soil layers within the effective length of the piles, L_r, to approximately account for soil nonlinearity. In general, the effective length of the piles is equal to 5 to 8 pile diameter for the horizontal excitation and full pile length for the vertical and rocking excitations.

Weak Zone Model:

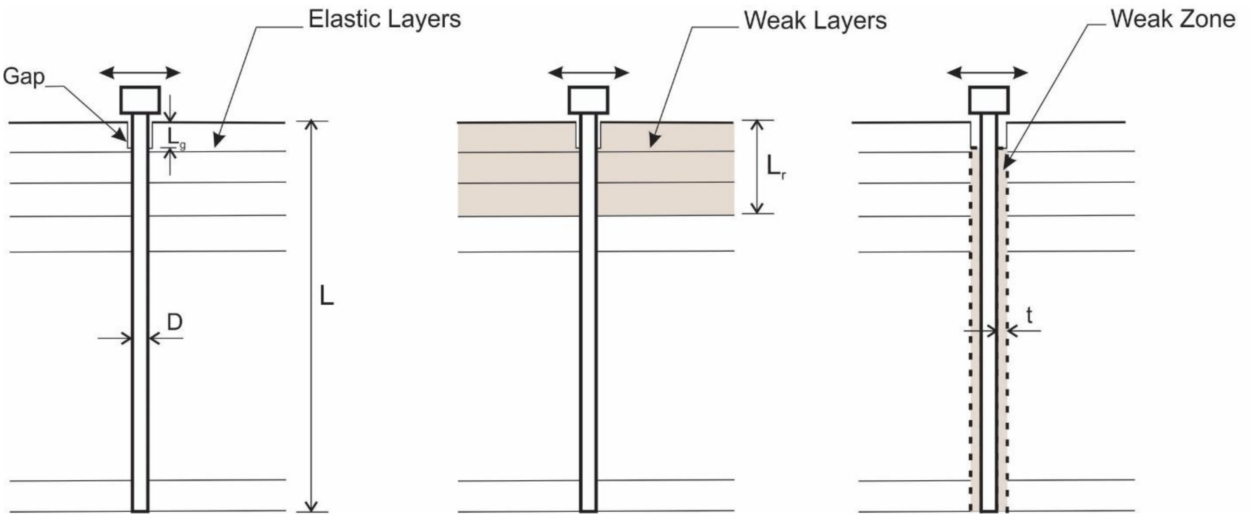
The Weak Zone Model for a single pile is shown in Figure 1(c). This model is the same as the Elastic Layers Model except that an annular weak zone of thickness, t, modeled by solid elements is incorporated between each pile and the surrounding soil. The thickness and properties of the weak zone are then set to account for the effects of local soil nonlinearity in the pile vicinity.

All three modeling schemes discussed above allow an optional gapping to be specified between the pile and soil from the ground surface to a depth of L_g (see Figure 1). Within the specified gap zone there is no transfer of stresses between the piles and surrounding soil.

The inclusion of a weak zone around the piles significantly increases the size of the analysis Model, which can make it computationally prohibitive for analysis of even a medium group of piles. The Weak Layers Model is a numerically efficient alternative to the Weak Zone Model for analysis of pile groups, and is found to provide equally accurate results as the Weak Zone Model.

The properties of the weak zone or weak layers are set through an iterative procedure in which the soil shear modulus and material damping are adjusted in each iteration for each frequency based on the calculated soil shear strains. However, in actual applications, the properties of the weak zone or weak layers may be set in advance based on the maximum foundation vibration amplitude to reduce the computer run time.

In the following sections, all three modeling schemes are used to predict the dynamic response of both the single pile and pile group tests. The nonlinear soil properties are selected to best match the test results, as appropriate, which, in turn, provide a guidance on how to set the weak layers or weak zone properties.



(a) Elastic Layers (b) Weak layers (c) Weak Zone

Figure 1 – MTR/DYNA Pile Modeling Schemes

Tests on Model Steel Piles in Non-Cohesive Soil

The first experimental results are from a group of model piles as well as a single pile subjected to low amplitude vertical and horizontal vibrations. The pile group consists of 6 hollow steel piles, 101.6 mm in outside diameter and 6.35 mm in wall thickness, connected at the top to a concrete cap. The piles are equipped with a conical plug and hydraulically driven 2.9 m below ground surface with a free length of 0.3 m. The piles are spaced 305 mm center-to-center (c/c) in the x-direction and 406 mm c/c in the y-direction giving a pile spacing to diameter ratio of s/d = 3 and 4, respectively. The single pile test was performed on pile No. 1 of the group prior to pouring the concrete cap. Figure 2 shows the layout of pile group and single pile test. Pile material damping ratio is assumed to be 0.25%. Other pile material properties correspond to typical steel material.

The soil consists of a layered stratum of silty fine sand and sandy silt with a gravel seam, overlying dense silty till at a depth of 2.9 m below ground surface. The measured small-strain soil shear wave velocity ranges from approximately 65 m/s at the ground surface to about 190 m/sec at a depth of about 3.5 m below grade. The ground water table is located at 16 m below grade.

The pile group is excited harmonically using a mechanical oscillator that produces forces proportional to the square of excitation frequency. The vertical response was measured at equidistant positions from the foundation center on the two axis of symmetry, and the results were averaged in order to eliminate the rocking mode. The horizontal and rocking responses due to a horizontal force applied in the x-direction are measured and reported at the level of foundation center of gravity (CG). The soil density is 1,780 kg/m^3 for the soil material above the till and 1,860 kg/m^3 for the till layer. The assumed soil Poisson's ratio and material damping are 0.3 and 2.5%, respectively for all layers.

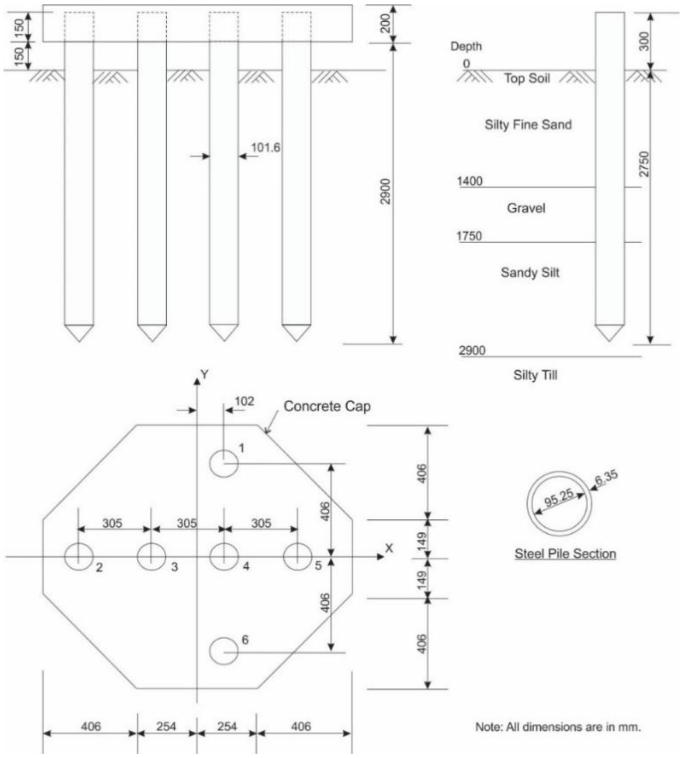


Figure 2 – Layout of Single Pile and Pile Group for Steel Pile Tests

Comparison of Theoretical versus Experimental Results

The steady-state responses of the pile foundation were measured with three levels of excitation intensities for different frequencies to establish the amplitude versus frequency response curves. The experimental results are presented for discrete frequencies and different excitation intensities, $m_e e$ where the excitation force is given by:

$$F(t) = (m_e e)\ \omega^2 \cos \omega t$$

And normalized response amplitudes are defined as:

$$A = (m / m_e e)\ u \qquad \text{for translation}$$

$$A' = [I / (m_e e.\ Z_e)]\ \psi \qquad \text{for rotation}$$

In the above equations, u and ψ are the measured translational and rotational response amplitudes, m is total mass, I is the mass moment of inertia and Z_e is the height of horizontal excitation above the CG. Similar normalization is applied to the calculated results. In examining the experimental results, it is noted that if the soil behaves in the linear range, the response is independent of the intensity of excitation and all normalized response curves should collapse on to a single curve.

Vertical Excitation, Single Pile

The normalized experimental vertical responses of the single pile due to three vertical excitation intensities ($m_e e$ = 2.45, 4.92 and 9.89 kg-mm) are shown in Figure 3. The results are for m = 941 kg and frequency range of 6 to 62 Hz. The maximum measured vertical displacement is 0.07mm. For this relatively large displacement (displacement to pile diameter ratio, $u/d = 6.9 \times 10^{-4}$), the measured response reveals some nonlinearity in the system, as shown in Figure 2 by a shift in the resonant frequency toward lower frequencies and an increase in the resonance amplitude with increasing intensity of loading. it is further noted that if the soil behaves in the linear range, the response would be independent of the intensity of excitation and all normalized response curves would then collapse on to a single curve.

The response of single pile calculated using the Elastic Layers model is shown as a solid black line in Figure 3. Comparison of the Elastic Layers results with the experimental results corresponding to the lowest amplitude vibration (i.e. $m_e e$ = 2.45 kg-mm having $u/d = 1.4 \times 10^{-4}$) shows reasonably good agreement in terms of the resonant frequency (52 versus 50 Hz) but the predicted response amplitude at resonance is lower than the measured data by a factor of about 1.6 indicating an overestimation of theoretical radiation damping.

To account for the effects of soil nonlinearity at higher excitation intensities, a weak zone was included around the pile. The shear modulus of the weak zone was reduced to 10 percent of the surrounding soil ($G_w = G_s / 10$). The results of the Weak Zone model shown as black long-dash line in Figure 3 show good agreement with the experimental results of higher intensity vibrations in terms of the resonant frequency but the resonant amplitudes are still lower by a factor of about 2, again indicating overestimation of theoretical radiation damping. Also, shown in Figure 3 are the results of the Weak Layers model with $G_w = G_s / 1.5$ shown as black short dash line in Figure 3. Again, the resonant frequency shows good agreement with the results of higher intensity excitations but the resonant amplitude is lower than the measured values by a factor of about 2.5 indicating overestimation of radiation damping. The results of Elastic Layers and Weak Zone models with 50% cap on the radiation damping applied to all frequency responses are shown as blue solid and blue long dash line, respectively, in Figure 3. As shown in Figure 3, by capping the theoretical radiation damping at 50%, satisfactory agreement between the predicted and measured response curves are obtained.

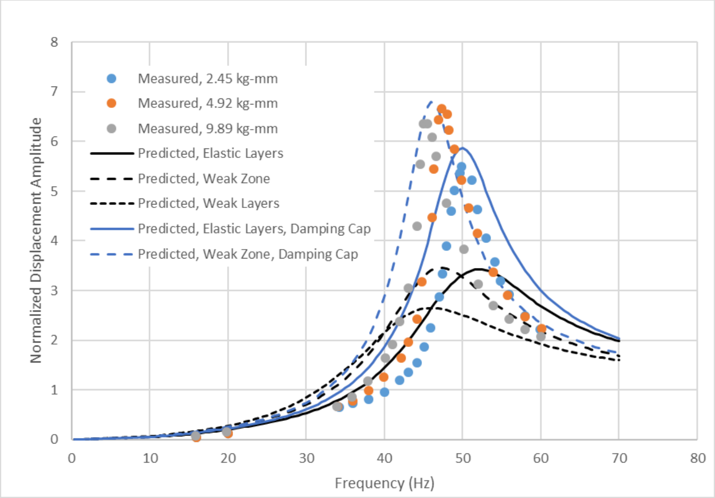


Figure 3 – Comparison of Predicted vs. Measured Foundation Vertical Response due to Vertical Excitation, Steel Single Pile

Vertical Excitation, Pile Group

The normalized experimental vertical response of the pile group for the three excitation intensities above are shown in Figure 4. The results are for m = 1,874 kg. The maximum measured vertical displacement is 0.028 mm. For such a small displacement ($u/d = 2.8 \times 10^{-4}$), all three response curves, as shown in Figure 4 are very similar indicating that the soil behavior is in the linear range. The vertical response of pile group calculated using the Elastic Layers model is shown as a solid line and compared with the measured data in Figure 4. As seen in Figure 4, although the resonant peak was not reached, there is reasonably good agreement in the overall trend of the predicted and measured responses except that the predicted peak response appear to be somewhat lower than the experimental results indicating moderate overestimation of radiation damping. Applying 70% cap on the radiation damping, the predicted vertical response curve shows improved agreement with the measured resonant amplitude and frequency (see dash line in Figure 4).

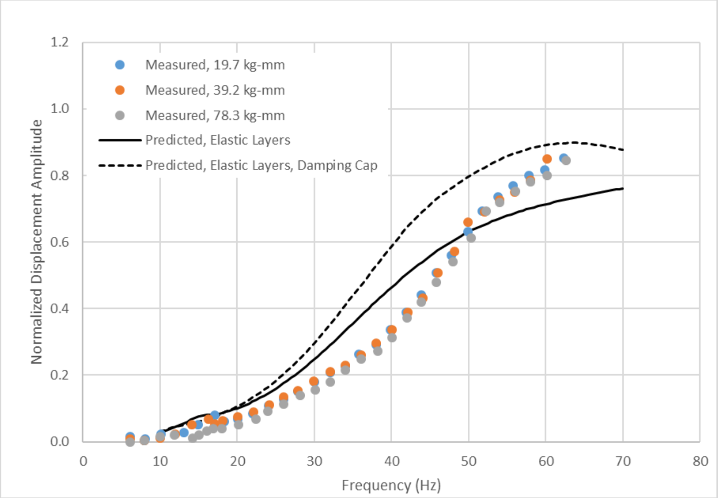


Figure 4 – Comparison of Predicted vs. Measured Foundation Vertical Response due to Vertical Excitation, Steel Pile Group

Horizontal Excitation

The experimental normalized horizontal and rocking responses of the pile group due to horizontal vibration with three levels of excitation intensities above are shown in Figure 5 and 6, respectively. The maximum horizontal displacement is 0.18 mm (u/d = 1.8 x 10^{-3}). This indicates minor nonlinearity as evidenced by small scattering of the data points at the same frequency. The predicted horizontal and rocking responses calculated using the Elastic Layers model are shown as a solid line and compared with the measured data in Figure 5 and 6, respectively. Comparison of the measured versus calculated results show excellent agreement in terms of the resonant frequency as well as the shape of the response curves except for the predicted amplitude at resonance, which for the primary horizontal response is lower than the measured amplitude by a factor of about 2, again indicating an overestimation of theoretical radiation damping.

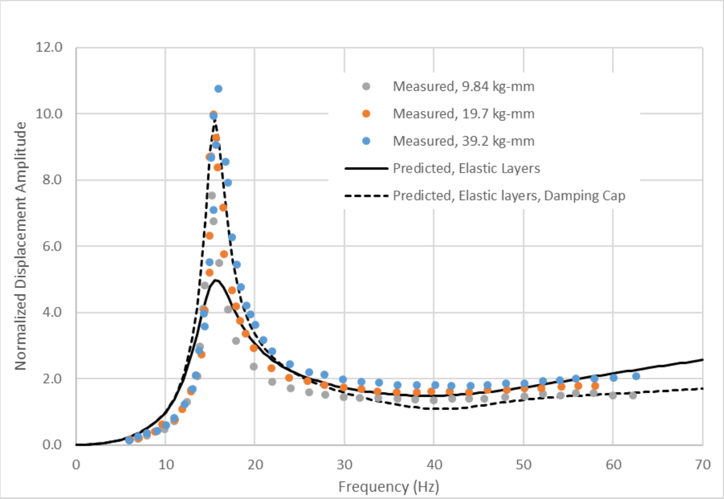


Figure 5 – Comparison of Predicted vs. Measured Foundation Horizontal Response due to Horizontal Excitation, Steel Pile Group

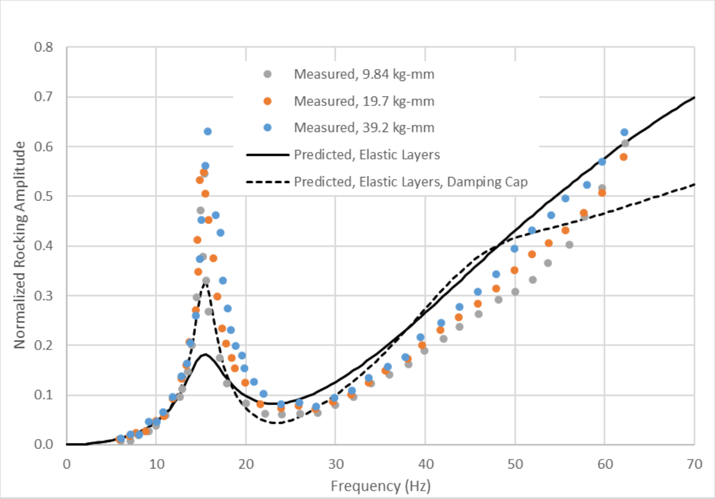


Figure 6 – Comparison of Predicted vs. Measured Foundation Rocking Response due to Horizontal Excitation, Steel Pile Group

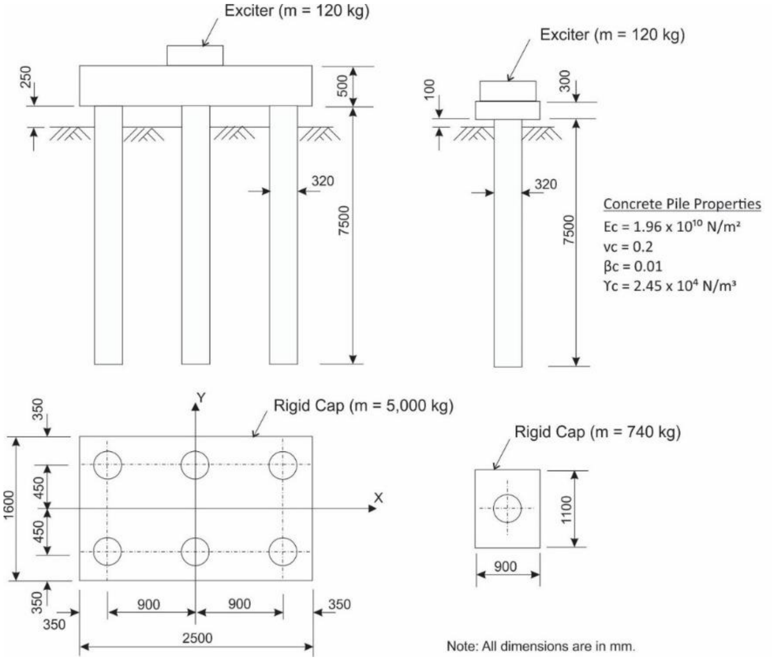
Applying 50% cap on the radiation damping, the predicted horizontal response curve shows excellent agreement with the measured data (see dash line in Figure 5). The rocking response curve due to horizontal excitation also show improved agreement with the measured data at frequencies below 50 Hz (see dash line in Figure 6).

Tests on Full-Scale Reinforced Concrete Piles in Cohesive Soil

The second experimental data are from a full scale test on a group of concrete piles subjected to small amplitude horizontal vibrations as well as a single pile undergoing large amplitude vibrations. Full scale tests provide valuable information because the soil-pile interaction is greatly influenced by the method of pile installation and confining pressure. The pile group consists of 6 cast-in-place reinforced concrete piles, 0.32m in diameter and 7.5 meter in length and extending 0.25m above grade, connected at the top to a rigid concrete pile cap. The piles are spaced 0.9 m center-to-center (s/d = 2.8). Figure 7 shows the layout of pile group and single pile test and pile properties assumed in the analysis.

The soil profile consists of relatively homogeneous sandy clay to a depth of 30m below grade. The measured low-strain, shear wave velocity ranges from about 130 m/s at the ground surface to 280 m/s at a depth of 7m below grade. The water table is reported at 20 m below ground surface.

Both the pile group and single pile are subjected to horizontal harmonic excitation having force amplitude proportional to the square of frequency produced by an exciter fixed to the top of pile caps (see Figure 7). The center of gravity of cap-exciter system was 0.24 and 0.1 m below the cap surface for the pile group and single pile, respectively. The exciting force acted 0.2 m above the cap surface in the y-direction. Both steady state horizontal displacement and rotation about x-axis were measured at the foundation surface with increasing excitation frequencies to establish the response curves.



(a) Pile Group **(b) Single Pile**

Figure 7 – Layout of Single Pile and Pile Group for Concrete Pile Tests

Comparison of Theoretical versus Experimental Results

The measured normalized horizontal responses of the single pile for three excitation intensities ($m_e e$ = 96, 171 and 259 kg-mm) are shown in Figure 8. The results are provided for m = 800 kg, I = 95 kg.m^2, Z_e = 0.3, CG height above pile head = 0.2 m and response at 0.1 m above CG, and for frequency range 4 to 40 Hz. The maximum measured horizontal displacement is 1.0, 1.7 and 2.7 mm for three excitation intensities, respectively. These are relatively large displacements ($u/d = 3.1 \times 10^{-3}$, 5.3×10^{-3} and 8.5×10^{-3}) for which appreciable change in the resonant frequency and amplitude of resonance with exceeding excitation intensities can be observed (see Figure 8). This implies that for all three excitation intensities, the soil behavior is in the nonlinear range.

The predicted results using the Elastic Layers model are shown by a solid line and compared with the measured data in Figure 8. As shown in Figure 8, the amplitude of the peak response is slightly higher than the measured value but the resonant frequency is grossly overestimated (25Hz vs 17Hz). Because of relatively large pile displacement, softening of the soil stiffness along the effective length of the pile as well as possible separation of the pile from soil due to low confining pressure near grade (gapping) can be expected. To approximately accommodate for the above effects, both a Weak Zone model and Weak Layers model were introduced to match the measured data. For the weak zone the shear modulus was reduced by a factor of 10, as compared to the surrounding soil ($G_w = G_s / 10$) and soil damping was increased by a factor of 2. In addition, a small soil-pile separation of 0.3 m was used at the top. The results of the Weak Zone model show significant improvement over the Elastic Layers model results in terms of the overall shape of the response curve and resonant frequency but the amplitude of resonance is overestimated by a factor of about 1.5 (see long dash line in Figure 8). For the Weak Layers model, the shear modulus of soil layers along the effective length of the pile was reduced by a factor of

2 ($G_w = G_s / 2$) and a small soil-pile separation of 0.2 m was used at the top. With the above set properties, the Weak Layers model show very good agreement with the measured response curves (see short dash line in Figure 8).

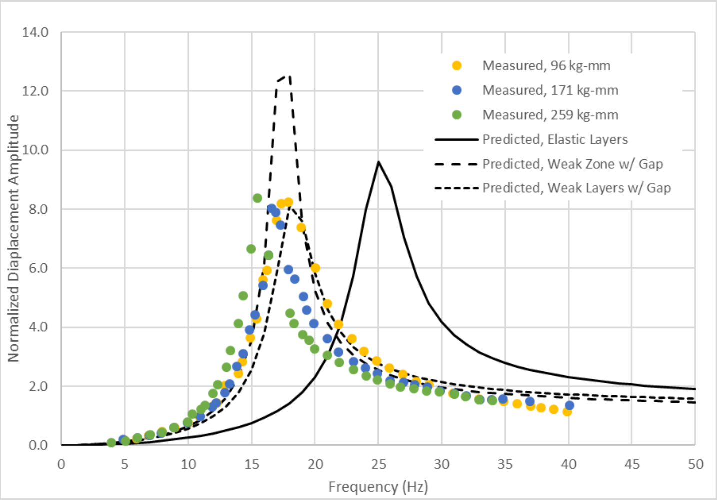


Figure 8 – Comparison of Predicted vs. Measured Foundation Horizontal Response due to Horizontal Excitation, Single Concrete Pile

The experimental normalized horizontal and rotational responses of the pile group subjected to three horizontal excitation intensities above are shown in Figure 9 and 10, respectively. The results are provided for m = 5,120 kg, I = 1,200 kg.m^2, Z_e = 0.44, CG height above pile head = 0.26 m and response at 0.24 m above CG. The maximum measured horizontal displacement is 0.1 mm. At such small displacement ($u/d = 3.1 \times 10^{-4}$), no appreciable change in the resonant frequency and resonance amplitude from different excitation intensities is observed, as shown in Figure 9 and 10.

The predicted response of the pile group using the Elastic Layers model are shown by a solid line in Figure 9 for the horizontal response and in Figure 10 for the rotational response. As shown in Figure 9 and 10, the amplitude of the peak response is comparable to the measured value of the first mode but the resonant frequency is grossly overestimated (50Hz vs 24Hz), which in turn implies over-estimation of soil stiffness.

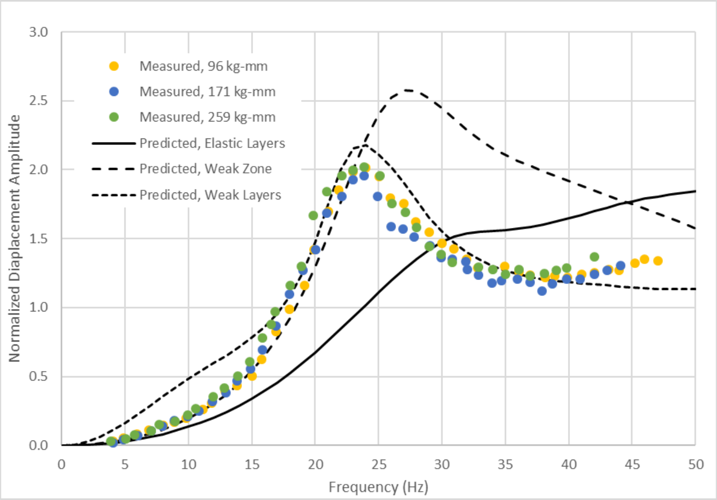


Figure 9 – Comparison of Predicted vs. Measured Foundation Horizontal Response due to Horizontal Excitation, Concrete Pile Group

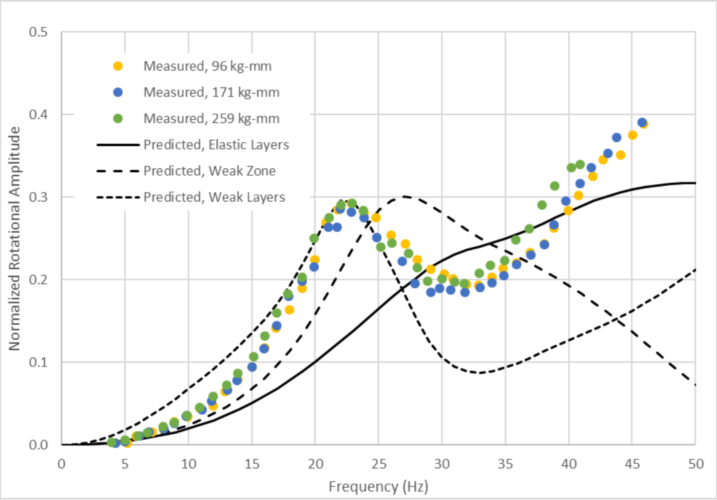


Figure 10 – Comparison of Predicted vs. Measured Foundation Rocking Response due to Horizontal Excitation, Concrete Pile Group

Because of the relatively small soil response (about 3.1 x 10^{-4} of pile radius), soil-pile separation or soil stiffness softening due to nonlinear soil response is not expected. Nonetheless, the method of pile installation where the concrete piles are cast in predrilled holes as compared to driven piles is likely to result in deficiencies at soil/pile interface that can affect the bonding between the soil and pile. In order to better match the observed results, the soil shear modulus had to be reduced by a factor 10 using the Weak Layers model and Weak Zone model. With this reduced stiffness, a significant improvement in the predicted results in terms of the frequency and amplitude of first mode as well as overall trend of the response curves are obtained by using the Weak Layers model (see short dash lines in Figure 9 and 10). The weak zone model also shows significant improvement of the results over the Elastic Layers model but the match with the measured response curves are not as good as that of the Weak Layers model.

Conclusions

The following summarizes the conclusions of this study:

1. In general, the use of linear analysis procedure to predict the vibration response of machine foundations supported on pile group appears to be adequate. This is mainly due to the tight vibration tolerance requirement for machine-induced vibrations and the fact that the group response is less dependent on the soil properties of topmost layer. This however, does not negate the fact that even small foundation vibration amplitudes can cause soil shear strains that may exceed the linear range of foundation stiffness and damping.

2. In using the linear elastic model that adopts soil properties derived from the measured shear wave velocities to predict the foundation response, the foundation radiation damping may be significantly overestimated for the case of driven piles while the soil stiffness may be grossly overestimated for the case of cast-in-drilled-hole concrete piles. In the former case, capping the radiation damping at 50% and in the latter case, incorporating a weak soil zone around the piles or weak soil layers along effective length of the piles with a shear modules equal to 1/10th of the surrounding soil will result in much better match with the measured test data.

3. If the foundation displacement to pile diameter ratio exceeds 10^{-3}, the foundation stiffness and damping may no longer be in the linear range. In such cases, provisions for accommodating the nonlinear soil effects as well as potential for pile/soil de-bonding must be considered in the analysis.

4. Both the Weak Zone and Weak Layers schemes are capable of modeling nonlinear soil effects in the pile group analysis. However, the Weak Zone model may become computationally prohibitive for analysis of even small group of piles due to significant increase in the size of finite element model. The Weak Layers model provides an effective alternative to the Weak Zone model and can provide comparable and in some cases even better results to those of the Weak Zone model.

References

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