PREDICTED VERSUS OBSERVED DYNAMIC LATERAL RESPONSE OF PIPE PILES

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SUMMARY

A procedure for conducting steady-state dynamic lateral load tests on full-scale pipe piles was developed and the field test results compared with analytical predictions for the dynamic lateral response. A total of 55 steady-state vibration tests were conducted on eleven piles at three sites. The dynamic lateral response was predicted analytically using a two degree-of-freedom solution. Dynamic stiffness and damping parameters were obtained from the computer program PILAY developed by Novak et al. (Ref. 1). Significant variation was found between the stiffness and damping parameters derived from the field steady-state vibration testing and those predicted analytically.

INTRODUCTION

Confidence in any analytical procedure used for the design of pile-supported foundations and equipment subjected to dynamic lateral loading is based on how well the analytical solution predicts the measured dynamic response of a full-scale pile-supported foundation. The art of pile driving is not conducive to readily predictable soil-pile boundary conditions for all piles driven at a particular site. Some variation in the soil-pile contact condition can be expected, even for uniform subsurface soil conditions.

The soil-pile boundary conditions assumed for analytical models, and subsequently used to generate the dynamic stiffness and damping parameters for foundation design, may have little resemblance to the actual soil-pile boundary conditions encountered in practice. It is necessary to recognize these differences and account for them properly to develop a satisfactory level of confidence in the final dynamic design of a pile-supported foundation.

Previous field testing of reduced scale-model piles by Novak and Grigg (Ref. 2) indicated that although the theory predicts the general character of the response reasonably well, agreement between the predicted dynamic response and the measured dynamic response was not acceptable when field-measured dynamic soil properties were used in the analytical

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prediction of the dynamic response. To evaluate the magnitude of the effect of soil-pile boundary conditions, a field dynamic lateral load testing procedure was developed (Ref. 3) and the dynamic lateral response of a soil-pile-mass system obtained experimentally. The dynamic lateral response was also predicted analytically and the two results compared.

SITE CONDITIONS AND PILE DATA

The eleven piles selected for steady-state vibration testing were located at three sites in southeastern Michigan; designated Monroe, Belle River, and St. Clair. The piles were embedded in cohesive and cohesionless soils with both soil types occurring within the upper few pile diameters which control the dynamic lateral response. A few of the piles selected for testing had been in place for up to 10 years while others were driven just prior to testing. The piles tested ranged in length from 50 to 160 feet long and had outside diameters of either 12.75 or 14 inches. Wall thickness was either 0.188 or 0.375 inches thick. Some piles were tested hollow while others were concrete filled. The surficial soils around two of the piles were removed, replaced with backfill, and retested.

To predict the dynamic response of the soil-pile-mass system analytically, it is necessary to determine the dynamic shear modulus distribution with depth next to the tested piles. This was accomplished using the seismic cross-hole technique proposed by Stokoe and Woods (Ref. 4). This method is thought to be appropriate for the amplitude levels generated during the steady-state response testing. Static soil properties were obtained by conventional boring and sampling methods.

FIELD TESTING PROCEDURE

The steady-state vibration testing procedure consisted of attaching steel plates to the head of a pile and vibrating the soil-pile-mass system with a Lazan oscillator, recording the dynamic lateral response at selected Lazan oscillator force levels.

The steel plates and Lazan oscillator, together weighing from 2200 to 2900 lbs (depending on the number of steel plates used), were welded and bolted to the head of the piles to be tested as shown in Figure 1. The Lazan oscillator is a rotating-mass oscillator capable of producing a harmonic forcing function of variable magnitude and frequency. Lazan oscillator force levels are selected by setting the eccentricity between the rotating masses of the Lazan oscillator. A variable speed electric motor was used to drive the soil-pile-mass system through a frequency spectrum from about 5 to 55 Hertz, stopping long enough at selected frequencies to record the steady-state response of the soil-pile-mass system. The dynamic lateral response was measured with two velocity transducers. When the maximum output of the Lazan oscillator at any eccentricity was reached, additional response data was obtained as the frequency was reduced, particularly for frequencies around resonance.

Using the method proposed by Richart et al. (Ref. 5), the amplitude of motion at each selected frequency was calculated from the voltage output from two calibrated velocity transducers attached at the same elevation on the steel-plate mass. Because each velocity transducer has different calibration characteristics, use of two velocity transducers mounted at the same elevation on opposing sides of the steel-plate mass provided an independent check on the calculated displacement amplitude.

At the conclusion of the first steady-state vibration test, the mass eccentricity on the Lazan oscillator was increased and the test repeated. Usually four to five steady-state tests are sufficient to bracket the displacement amplitudes encountered in the dynamic design of equipment foundations. Descriptions of the testing equipment and procedures are presented in references 3 and 6.

Typical data for a single steady-state vibration test are shown in Figure 2. The frequency-amplitude data from each velocity transducer is plotted and the corresponding amplitude from both transducers at each frequency connected with a vertical line.

ANALYTICAL SOLUTION

To predict the dynamic response of a pile-supported foundation system correctly, it is necessary to evaluate the dynamic pile stiffness and damping for all modes of pile vibration (vertical, horizontal translation, and rocking). This study concentrated only on evaluation of the dynamic lateral response of the soil-pile-mass system.

Because the Lazan oscillator produces only horizontal forces, the motion of the mass attached to the head of the pile is a coupled horizontal translation and rocking motion. In addition, since there are no restraints at the pile head, the measured dynamic response is that of a pile with a pinned head. Thus, the analytical stiffness and damping values for lateral translation and rotation must be appropriate for this boundary condition.

Several analytical techniques have been proposed in the literature for modeling dynamic soil-pile interaction to obtain the dynamic stiffness and damping values. Dynamic soil-pile interaction solutions based on discrete models (with lumped masses, springs, and dashpots), continuum theory, and the finite element method have been advocated. Of the theoretical soil-pile interaction solutions available, the continuum model accomodating soil layering proposed by Novak and Aboul-Ella (PILAY) was selected for use. This solution was selected because it has the capability to model the variation of soil properties with depth easily, is economical to use, and is available in the public domain.

The soil-pile-mass system behaves as a two degree-of-freedom system with lateral translation and rocking degrees of freedom. Thus, a two degree-of-freedom solution with viscous damping was used to evaluate the dynamic lateral response at each transducer location. Introduction of the dynamic stiffness and damping values at each selected frequency, along with the physical parameters of the soil-pile-mass system, enable prediction of the dynamic response at the center of mass of the soil-pile-mass system.

The predicted dynamic response can be influenced significantly by the distance the velocity transducer is away from the center of mass and whether or not the mass is in or out of phase with the head of the pile. In general, the phase angle for horizontal translation will be different from the phase angle for rocking and the maximum translation and rotation will not occur at the same time. Thus, the predicted transducer response is dependent not only upon the translation and rotation stiffness and damping values at each frequency but also the physical location of the transducer with respect to the center of mass. These corrections are described in reference 3.

A typical dynamic lateral response curve using the stiffness and damping values predicted with the PILAY program (with field measured values for the soil parameters) is shown superimposed on the recorded field data in Figure 2. The value $m_e\bar{e}/M$ is the theoretical dynamic response of a single degree-of-freedom system for a rotating mass excitation (Ref. 5).

COMPARISON OF PREDICTED AND OBSERVED DYNAMIC LATERAL RESPONSE

Comparison of the predicted and observed dynamic lateral response of the soil-pile-mass system can be based entirely upon the dynamic stiffness and damping values at the lateral translation resonance since all other parameters are the same. The horizontal translation and rocking stiffness and damping values are obtained directly from the computer program PILAY for the analytical prediction of the dynamic response. Equivalent values can also be evaluated for the field-observed dynamic lateral response. By introducing back-calculated single degree-of-freedom horizontal translation stiffness and damping values and assumed stiffness and damping values for rocking into the same two degree-of-freedom equations, a dynamic response curve reasonably matching the field-obtained dynamic response data at resonance can be obtained. The "best fit" stiffness and damping values for the steady-state vibration test can then be compared with the PILAY predicted stiffness and damping values.

As shown in Figure 2, only the lateral translation resonance was well defined for the steady-state vibration testing. However, the steady increase in amplitude at the higher frequencies likely indicates the beginning of the rocking resonance. The rocking resonance for the soil-pile-mass systems tested was apparently beyond the power capability of the Lazan oscillator and could not be obtained. Thus, PILAY rocking values were used initially with the back-calculated lateral translation stiffness and damping values from the single degree-of-freedom equations to obtain the "best fit" curve at resonance for the field data.

The predicted dynamic response matched the field test data up to and slightly above the lateral translation resonance using the back-calculated and assumed stiffness and damping values as shown in Figure 2. Beyond this point, the field test data had consistently higher amplitudes than the dynamic response predicted with the two degree-of-freedom solution.

Parametric variation of the rocking stiffness and damping values could not match the observed test results at the higher frequency range. Generally, the measured dynamic response amplitude was 1.5 to 2 times greater than the predicted amplitude at frequencies above the lateral translation resonance if the "best fit" curve through the lateral translation resonance was held fixed.

The resonant frequency and damping values predicted using the PILAY stiffness and damping values were consistently higher than the data evaluated from the steady-state vibration testing. Reduction of the PILAY stiffness and damping values and introduction of these values into the two degree-of-freedom equations gave a reasonably good approximation to the field data over the range of frequencies shown, realizing the measured amplitude will be slightly higher than the amplitude predicted for frequencies above the lateral translation resonance.

Table 1 gives an overall summary of the reduction in PILAY predicted lateral translation stiffness and damping values which were required to match the field data. As expected, the PILAY values are closer to the field data for the granular soils than for the cohesive soils. This illustrates the importance of development of the soil-pile boundary condition. In some cases, the stiffness and damping values predicted analytically were an order of magnitude lower than the observed dynamic field test results.

Although at times there were relatively wide ranges in the reduction of PILAY stiffness and damping values necessary to match each field test result for a series of tests conducted on the same pile, the stiffness values for the granular soils were typically in the range of 40 to 75 percent of the PILAY predicted stiffness values. This compares with about 5 to 10 percent of the PILAY predicted values for the soft to medium stiff clays. Other soil types were between these two ranges. The reduction necessary for damping was unusually low compared to the reduction necessary for stiffness and generally was in the range of 5 to 25 percent of the PILAY predicted damping values.

In general, the higher the percentage of PILAY stiffness required to match the field data, the higher the corresponding percentage of PILAY damping, although because of the very low damping percentages, much of this trend was masked by the variability of the data. Thus, the greater the ability of the soil to maintain contact with the pile, the closer the PILAY predicted stiffness and damping are to the evaluated steady-state vibration testing values which matched the measured field test results.

CONCLUSIONS

The objective of the dynamic design of a pile-supported foundation is to be able to reliably predict the dynamic stiffness and damping values for the piles and have some confidence that the field behavior will match the prediction. Dynamic response curves predicted using the PILAY stiffness and damping values (using field-obtained dynamic soil properties) were found to significantly overestimate the resonant frequency and damping observed during field steady-state vibration testing. Engineering judgment, based on dynamic field testing at each site, will be required to predict the dynamic lateral response under field conditions adequately until significantly more field test data becomes available for evaluation.

Because of the nature of pile driving operations, the variability found in this study will likely not be reduced without special effort. The range of variability in the soil-pile contact condition can be reduced to acceptable limits for the lateral translation and rocking modes by modifying the soil within the effective depth of soil-pile interaction. This can be done either by placing a controlled granular backfill within the effective depth of the soil-pile interaction or possibly isolation of the pile, depending upon the other constraints of the dynamic design. Replacement of the upper 4 feet of cohesive soil around pile L1810 with a compacted granular backfill was found to significantly increase the stiffness, although the damping remained about the same.

Dynamic steady-state vibration field testing, along with obtaining the corresponding dynamic soil properties, is recommended to verify the stiffness and damping values predicted analytically. This test is non-destructive, inexpensive compared to static pile tests, and can be conducted virtually any time there is no external vibratory influence to affect the recorded data.

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Table 1 Steady-State Vibration Pile Testing Data and Results

Site	Pile Designation	Cross-Section (Inches)	Length (Feet)	Near Surface Soil Type	PILAY Reduction Ratios[4] Stiffness k_x (%)	Damping c_x (%)
Monroe	FAN	14.00x0.375	54	Hydraulically filled Sand over Silt & Clay	40 - 50	10 - 50
	BM	12.75x0.375	50	Limestone, Gravel and Fly Ash Fill	70 - 100	10 - 25
	2PG[1]	14.00x0.375	51	Sand Fill[2]	50 - 70	15 - 20
	3PGE[1]	14.00x0.375	51	Sand Fill[2]	50 - 75	15 - 20
	3PGW[1]	14.00x0.375	50	Sand Fill[2]	65 - 100	20 - 35
Belle River	L1810	14.00x0.188	158	Insitu Soft Clay	5 - 10	10 - 15
	L1810S[3]	14.00x0.188	158	4.6 Ft. Sand & Gravel Backfill Over Insitu Clay	35 - 40	5 - 15
	GP13-7	14.00x0.188	157	Insitu Soft Clay	5 - 10	10 - 15
	GP13-7K[3]	14.00x0.188	157	4.0 Ft. Cement Stabilized Sand Over Insitu Clay	10 - 20	5 - 10
	K16.7	14.00x0.188	160	Insitu Soft Clay	5 - 10	2 - 5
St Clair	LF16	12.75x0.375	127	Granular Backfill	30 - 35	3 - 10

[1]Pile Filled with Concrete Prior to Testing.
[2]Sand Backfill Vibrofloted Prior to Driving Piles.
[3]Pile Backfilled as Indicated and Retested.
[4]PILAY Stiffness and Damping Values Multiplied by this Percentage to Match Field Testing Data.

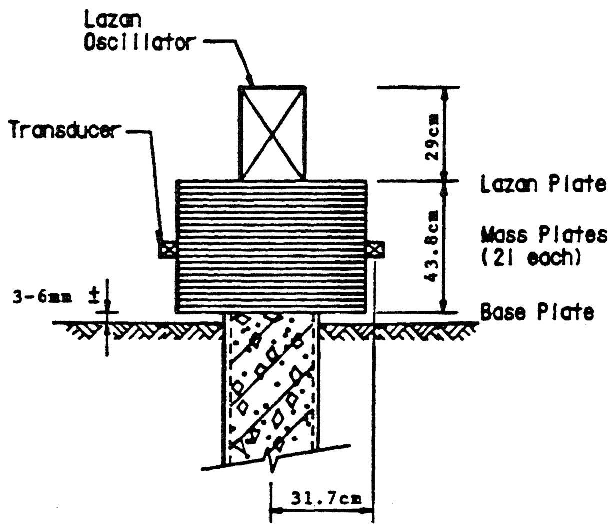

Figure 1 Typical Cross-Section of Dynamic Lateral Pile Test

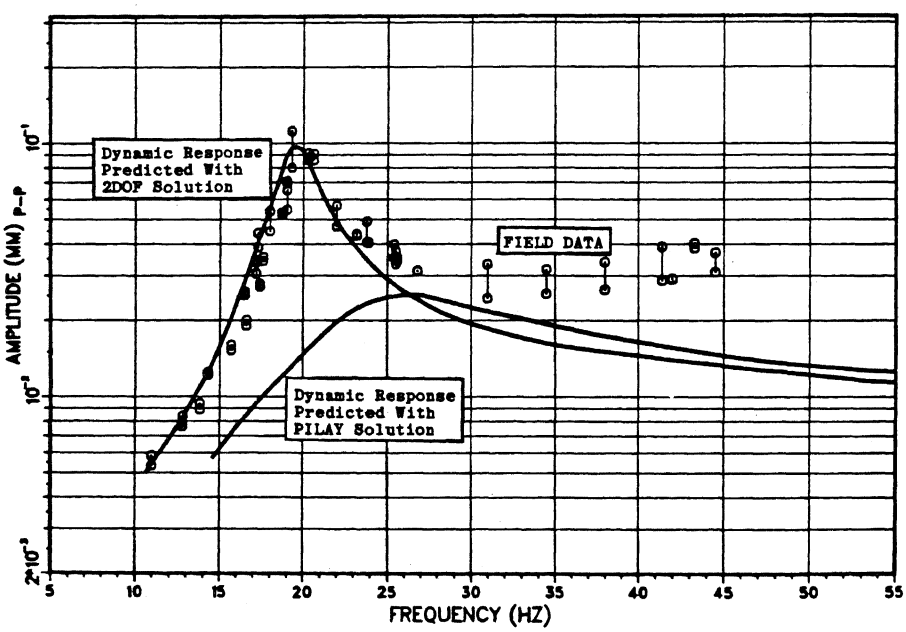

Figure 2 Typical Response Curves Predicted Analytically Superimposed on Field Response Data