DYNAMIC PILE TESTS BY CENTRIFUGE MODELLING

by

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SYNOPSIS

The scaling relations for performing dynamic model tests in a centrifuge are summarized. A description is given of centrifugal experiments (at 100 g) in the lateral vibrations of somewhat flexible model piles with attached masses embedded in dry sand. The results of simplified analyses of the results are presented. Model pile lateral frequencies of 115 to 160 Hertz, for embedment depths of 7.1 cm to 15 cm were observed. These correspond to prototype pile vibration frequencies of 1.15 to 1.6 Hertz for depths of 7.1 meters to 15 meters. Damping was calculated to be in the range 7 to 2% of critical for the smaller to the greater embedded lengths. Subgrade reaction coefficients for an equivalent Winkler soil model were found to be in the order of 5,000 MN/m^3 in the model (50 MN/m^3 in prototype).

INTRODUCTION

The scaling relations for geotechnical model tests in a centrifuge have been discussed [4, 5]. Briefly, if a soil model whose linear dimensions are n times smaller than those of the prototype at earth gravity, is subjected to an acceleration of n times gravity (ng), then the model behavior will correctly represent that of the prototype in a number of important aspects. The soil in the model is the same as that in the prototype. Velocities remain unchanged. Moduli, stresses, and strains are the same in model and full-scale specimens; Poisson's ratio, of course, is dimensionless. Structural components are thus required to be made of the same material (steel, aluminum, concrete) in model and prototype, for similarity to hold. In this paper prototype quantities appear in parentheses following model quantities, and are expressed in the same units.

Centrifugal testing appears to show promise in the study of some aspects of soil behavior during earthquakes, but only a few dynamic tests have been reported [1, 4]. This may be due to a number of difficulties associated with performing dynamic soil tests in a centrifuge. It is generally convenient to carry out tests at scales of about 1/100, so that the model must be subjected to 100 g centrifugal acceleration. At this scale the natural frequencies of the model, and the simulated earthquake vibration frequencies which must be applied to it, are 100 times those of the prototype. Model earthquake durations are 100 times shorter than those in the real world, and accelerations, of course, are 100 times larger. Thus, for example, at this scale, a model vibration analogous to one of the

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components of the well-known 1940 El Centro record would have a duration of a few tenths of a second and would involve a peak acceleration of about 35 g. If, for structural analysis purposes, real earthquake frequencies up to 10 Hertz are to be taken into account, then the model earthquake should include frequencies up to a kilohertz, i. e., in the audio range. However, a number of dynamic tests of interest in earthquake engineering applications can be performed without simulating an earthquake. One of these is an examination of modal frequencies in situations where soil-structure interaction is important.

A small centrifuge has been acquired by the California Institute of Technology and it has been used in an exploratory study of dynamic problems. The vibration behavior of embedded piles appears to have received only limited attention at essentially full scale [2]; this problem was selected for centrifuge model tests. Although a single embedded prototype pile represents perhaps the smallest size of full-scale interaction problem, it is still a formidable task in the field to generate in such a pile vibrations of large enough amplitude to reach a non-linear range of soil behavior. At 1/100 scale in the centrifuge model 10 or 20 Newtons of lateral force are sufficient to develop non-linear strains in the soil. A description of the experiments follows:

Experimental Arrangement: The working space at the end of the centrifuge arm is approximately 50 x 50 x 25 cm in size. A very stiff box, 37.5 x 30 x 25 cm deep was bolted in this space to contain the experiment. A uniform Ottawa Sand of mean grain size 0.2 mm was placed in the box to a depth of 20 cm, (20 m) in a medium-dense state. In the sand a model pile was inserted to varying depths in different experiments. The total pile length was 20 cm, (20 m) and it was 4.23 mm wide by 6.21 mm deep. The product of the modulus and the moment of inertia of the pile about the axis of interest in the tests (EI) was 41 MN/m^2 . The pile was intended to represent, at 100 g, the behavior of a full-scale steel pile at various embedded lengths up to 15 meters. Under these conditions the pile is relatively stiff, but not rigid, compared to the soil employed. The model pile was instrumented with strain gages at different points along its length; the gages were placed closer together in the region expected to experience the highest bending moments.

The weight of the pile was 0.4 N and a small mass of weight 0.9 N was attached to the top of the pile in such a manner that it could be moved along the pile and clamped at a required position. To this mass was connected a wire which generated the pile vibrations; it was pulled to deflect the pile laterally and then released suddenly to let the pile ring. Both the static and dynamic strains in the pile were indicated by the strain gages and recorded.

The wire was attached to a lever actuated by a cam which was rotated by an electric motor. As the cam rotated the pile was deflected until a step in the cam came opposite the lever and the pile was released. The cam operation was monitored by observing its rotation through a closed-circuit television system while the centrifuge was in motion.

Experimental Results: A typical oscillographic record of a test is shown in Fig. 1 and it can be seen that the strain gages indicate large strain oscillations when the pile is released. These decay fairly rapidly to a lower level of strain which damps out somewhat more slowly. The larger initial oscillations are in the non-linear area of soil behavior; the smaller oscillations are in the linear range. If the frequency of the oscillations is measured immediately after they begin, at an intermediate time, and then towards the end of the vibration, it is found that it increases. This is to be expected from the softening shear stress-strain behavior of soil, and the effect is illustrated in Fig. 2 for a range of depths of embedment.

Analysis: Since the pile is embedded in sand, the correct model of the soil's response to pile deflection would require a soil resistance increasing with depth, perhaps linearly. Even when the Winkler model for soil behavior is employed, however, the analytical results for the case where the lateral coefficient of subgrade reaction varies linearly with depth are complicated [3]. Consequently the first static analyses employed the Winkler model with lateral subgrade coefficient k constant with depth.

In this case, it was found that the experimental results could best be fitted when the analysis incorporated a value of $\lambda = 0.6$, where $\lambda = \sqrt[4]{k/4EI}$, and E and I are the Young's modulus and inertia of the pile respectively. The dimensionless product of λ and the length ℓ of the pile, for ℓ in the range of 10 to 20 cm is about 2 to 4, so that the pile can be considered to have some flexibility. It cannot be considered to be infinitely long.

With the above λ, substitution of the beam properties gives a value for the static subgrade coefficient k_o (=k/b, where b is the pile width) of about 5,160 MN/m^3. The coefficient in the centrifuge model is larger than in the prototype by a factor equal to the scaling ratio, so this corresponds to a prototype subgrade reaction coefficient of about 51.6 MN/m^3. If it is assumed that this coefficient effectively represents the equivalent uniform material properties at a depth of 1/4 to 1/3 of the pile length, a substitution of the values in Terzaghi's equations [6] for lateral subgrade reaction constant give a constant corresponding to the properties of a loose to medium-dense sand, which is appropriate.

These analyses corresponded to pile horizontal deflections of about 0.381 mm in the centrifuge model or 3.81 cm in the prototype at ground surface. The surface horizontal load required to accomplish this was about 4.5 N in the model, or equivalently 45 kN at full-scale. Lateral forces of up to 45 N in the model (450 kN in prototype) were applied to cause static deflections of 5 to 7 mm (0.5 to 0.7 meters). At these levels the force-displacement relation for the pile was extremely non-linear.

When the load was suddenly released the pile-mass system was set in vibration, as shown by the strain-gage records of Fig. 1. Since the pile was fairly stiff, in the first analyses of this motion, it was assumed to be rigid and embedded in a linear Winkler material whose lateral subgrade reaction coefficient increased linearly with depth from zero at the surface. The problem was solved to obtain the subgrade reaction coefficient at the pile tip required to give the observed frequency. For the pile embedded to a depth of 15 cm, for example, it was found that the required coefficient at the tip was 5,100 MN/m^3 (51 MN/m^3 in prototype) at the sixth cycle of oscillation (top curve of Fig. 2). This is close to the average value calculated from the equivalent static test above.

When the same method and soil model is applied to calculate the soil subgrade reaction coefficient required to explain the frequencies observed at the shallower pile embedments, it is found that a higher coefficient is needed. For the pile with 7.1 cm embedment, the apparent subgrade reaction coefficient is approximately 3 times higher than for the pile with 15 cm embedded length, to account for the observed frequencies. These results indicate that the model is not consistent with the observed results, although the assumption of rigidity should be a better one at shallower embedments. Other models are being examined.

From recorded vibrations in the form of Fig. 1 values of damping have been calculated. It was found that the pile embedded to 15 cm exhibited damping of about 2 to 3% of critical as an average over the first 6 cycles of vibration. For the piles embedded to 7.1 cm, the damping was higher, in the range of 5 to 7% of critical. These values of damping were indicated at peak displacements of the attached mass of about 1.3 mm in the model (13 cm). Since this description of damping is dimensionless, it would be expected to apply to the prototype piles.

For the pile embedded to the 15 cm depth, the peak acceleration at the location of the fixed mass above the ground surface was about 9 g in the model (0.09g prototype) at the lower levels of excitation and about 90 g (0.9 g) at the higher levels.

CONCLUSIONS

The feasibility of vibrating single piles with attached masses in soil in a centrifuge has been demonstrated. Forces, displacements and strains in the vibrating system have been measured for comparison with analyses. From the test results, the parallel quantities for prototype piles in the same soil can be obtained from the relevant scaling relations. Methods of analysis can be identified in this way for direct application to full-scale pile foundations subjected to earthquake ground motions. Tests on pile groups are currently being conducted.

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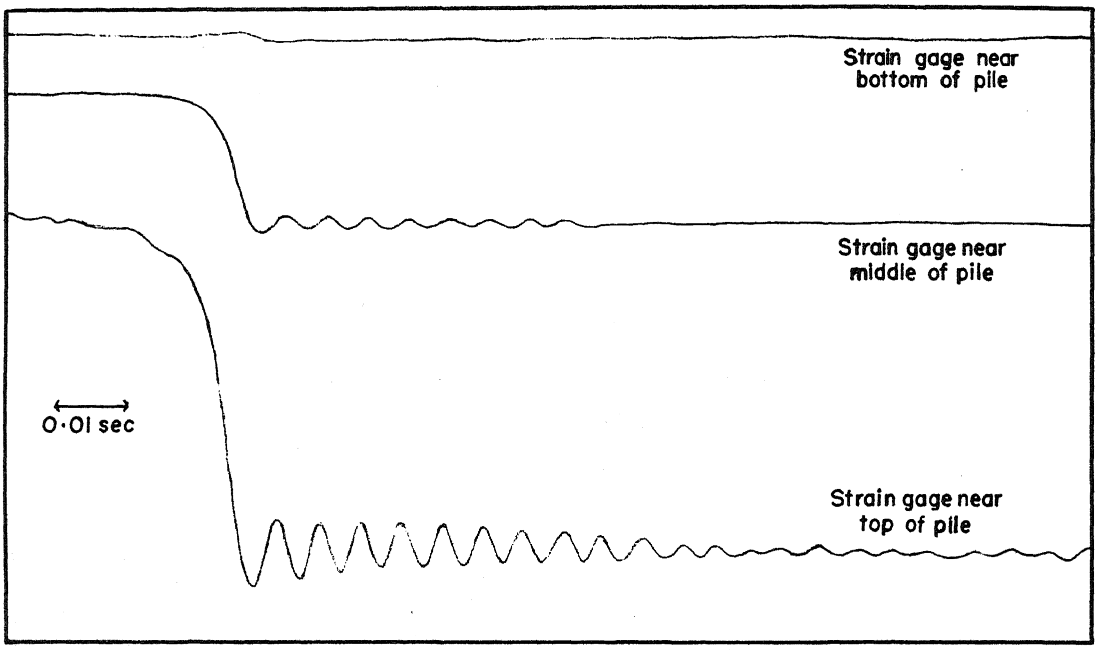

FIGURE 1 - TYPICAL GAGE OUTPUT DURING PILE UNLOADING

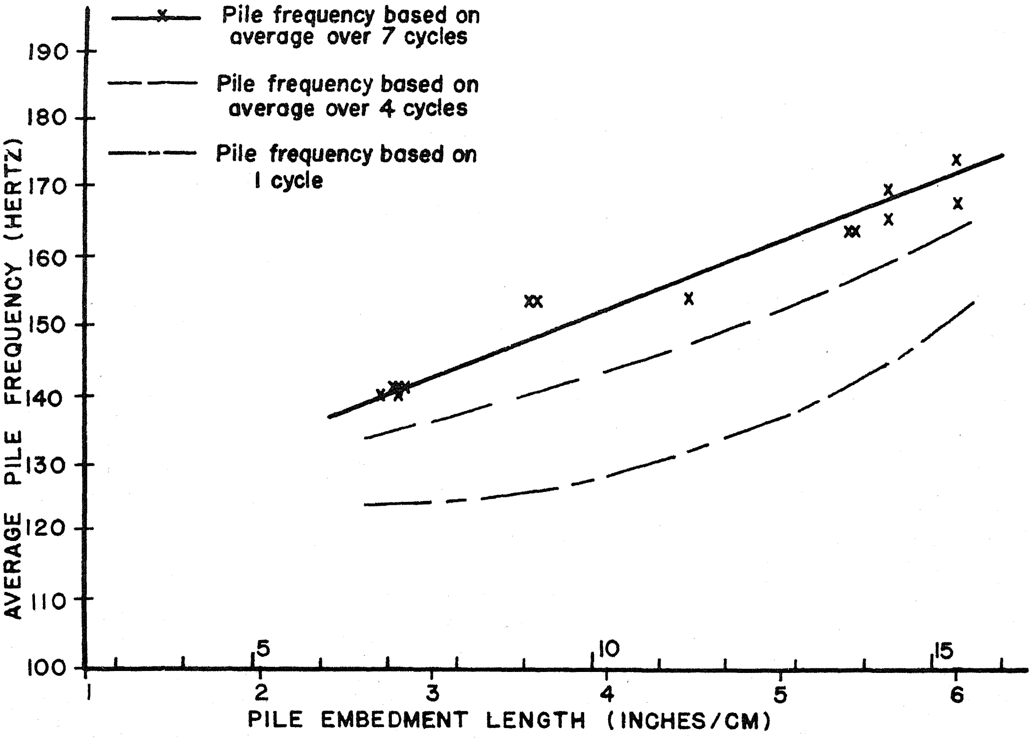

FIGURE 2