STATIC AND DYNAMIC LATERAL PILE GROUP ACTION

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SUMMARY

A centrifuge model study is presented on static cyclic and dynamic lateral loading of one, two and four pile groups embedded in saturated sand. Comparison of static and dynamic results indicate that the dynamic secant moduli are lower than the static moduli at lower deflection levels, but are greater at larger deflections. Evaluation of static lateral pile interaction formulae indicates that analytical methods based on linear elasticity are reasonable. Comparison of full scale and centrifuge single pile dynamic results confirm the validity of the centrifuge modelling technique.

INTRODUCTION

Pile groups are commonly employed to resist lateral static, cyclic and seismic loads. Due to the tremendous oil-related offshore development, it is now particularly important that lateral pile group behavior, in particular dynamic group action, be understood. While analytical techniques and full scale, ambient gravity (1-g) model and centrifuge model data exist for static and dynamic lateral loading of a single pile (Refs. 2,3,6,9), little has been done to assess the relation between dynamic and static pile response. For group behavior, analyses and data are limited primarily to static loading (4,5,7), with no truly comprehensive full scale or centrifuge model data available for static or dynamic group action.

To fill this gap, a limited experimental program was conducted on a single pile and two and 4 pile groups embedded in saturated sand, loaded laterally static cyclically and dynamically. This paper presents the results of this study and compares static and dynamic behaviors, full scale and centrifuge model one pile response, and observed and theoretical group action.

EXPERIMENTAL SETUP

For granular materials, it is generally recognized that a small scale 1-g model test does not correctly reproduce the stress conditions in the full scale prototype system at similar locations, resulting in dissimilar observed response. However, if the body force in the model were increased by an amount

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equal to the length scale reduction, then stresses at similar points in the model and prototype would be identical, and proper full scale response would be replicated, with some limitations. For this reason, centrifuge modelling is becoming increasingly popular for geotechnical purposes.

The experimental program was conducted on the California Institute of Technology 1 m radius, 5 g-tonnes capacity geotechnical research centrifuge. The model piles were made from stainless steel tubing 13 mm (0.5 in) in diameter with 0.25 mm (0.010 in) thick walls. At centrifuge accelerations of 48g, this corresponded almost precisely to the pile used in the full scale dynamic lateral load tests at Seal Beach, California sponsored by the United States National Science Foundation. The soil used in the centrifuge tests, a silty beach sand, was obtained from the site of the prototype tests and was prepared to a dry density similar to that at the site, about 1680 kg/m^3 (105 pcf), by mixing, reworking and then consolidating prior to each test. As in the full scale tests, a mass was mounted on the pile top to simulate a realistic structural load. At 48 g, this represented a prototype mass of about 24 tonnes per pile.

Each pile system was inserted into the soil to a depth at least 250 mm (10 in) at 1 g, probably resulting in near field stress conditions different from the full scale. Due to the duration and cyclic nature of the static cyclic and dynamic tests, the initial detailed soil structure in the vicinity of the pile should be eliminated during the test, and hence the effect of placement at 1 g should not result in significant differences in observed behavior. For the combination of soil, pile and pile embedment used, this pile is considered to be "flexible", or semi-infinite.

One of the piles was instrumented internally with 9 pairs of strain gauges along the pile length to measure flexural stains. Pile top deflections were monitored with a non-contact photovoltaic transducer, and static loads with a sensitive inline load cell. Static cyclic loads were applied at the pile top with a double acting pneumatic piston at rates between 1 and 4 cycles per second, while dynamic loads were applied with a specially built compressed air driven miniature eccentric mass shaker, described elsewhere (9). The rotation rate of the dynamic shaker could be varied up to 500 Hz, which at 48 g corresponds to about 10 Hz prototype scale.

The single pile and two pile "offline" group were loaded freeheaded, with the "offline" group loaded in a direction normal to the line connecting the two piles. The 2-pile "inline" and 4 pile groups were fixed at pile top with a steel pile cap and were loaded along their major axes. For each group, center to center pile spacings were varied from two through seven pile diameters. For the dynamic tests, a frequency sweep was conducted for each pile group configuration, with data acquired at discrete frequencies to locate the fundamental and higher modes of vibration. For the static tests, each configuration was subjected to cyclic loading at various peak force levels, with data taken during initial loading as well as after numerous cycles.

The data for each test were brought out from the centrifuge in electrical sliprings, then digitized and recorded automatically in a state-of-the-art high speed digital data acquisition system capable of 100,000 twelve-bit data scans per second for later reduction. To compute deflections in the pile at locations other than at the displacement transducer, the strain data were double integrated numerically.

TEST RESULTS

Results from static cyclic and dynamic model tests on a single pile are plotted in Figure 1 in prototype units, together with full scale dynamic data from (8). For the static results, each point represents the steady-state peak amplitude of force and displacement at the point of force application with the curve ("A") through these points being the best fit hyperbola. This backbone curve is symmetrical about the origin, extending back into the third quadrant. The dynamic data ("B") were obtained by computing the peak force at resonance using $u_d m \omega_1^2$, where u_d is the plotted dynamic peak deflection at the center of mass, m is the mass of the system at pile top, and ω_1 is the observed natural angular frequency of the system. For the static and dynamic model data, the point of load application in each case is about the same, about 2.4 m (8 ft) prototype scale above ground surface. However, since the height of center of mass for the full scale tests was only 1.5 m (5 ft) above ground surface, the full scale dynamic data (Curve C) and the model data should not be directly compared. Also, note that the full scale data plotted are only those tests which did not exhibit a large excess pore pressure during testing. Nevertheless, Fig. 1 indicates that while all of the data are similar in magnitude, the static and dynamic data exhibit marked differences.

Similarly, Figure 2 shows the results for the 2 pile offline, 2 pile inline and 4 pile group static cyclic and dynamic tests. Each curve for the static data represents a best fit hyperbola of load per pile versus deflection at the point of load application for each spacing, while the curve for the dynamic data is based on an average secant modulus for all spacings. Since the dynamic pile groups had a center of mass about 1.2 m (4 ft) prototype above ground surface, compared with a load application point of 2.4 m (8 ft) for the static tests, the static secant moduli should be even higher than indicated in these Figures, relative to the dynamic data. Regardless, one would still expect that the dynamic secant moduli to be lower at lower displacement levels, and higher at higher displacements, than the static secant moduli.

The effect of pile spacing on effective static pile stiffness is shown in Figure 3, together with predictions from several analytical (4,7) and empirical (5) methods. The stiffness in each case is the observed system stiffness at the point of load application, <u>not</u> at the ground surface as for the predictions. For the two pile offline case, the reference stiffness K_1 is from the single pile data, while the reference stiffness for the 2 pile inline and 4 pile groups was back calculated using the single pile data and a constant soil stiffness "Winkler" analysis. As a result, the actual values of the pile group efficiencies may deviate somewhat from those shown, but the relative values should remain as plotted. For each case, the initial tangent modulus, and the secant modulus at a specified displacement are plotted. Comparison of the observed and predicted pile efficiencies indicate that the methods by Poulos (4) and Scott (7) are reasonably accurate, with the latter being simpler to apply, while the empirical method presented tends to overestimate the interaction for the inline fixed head conditions.

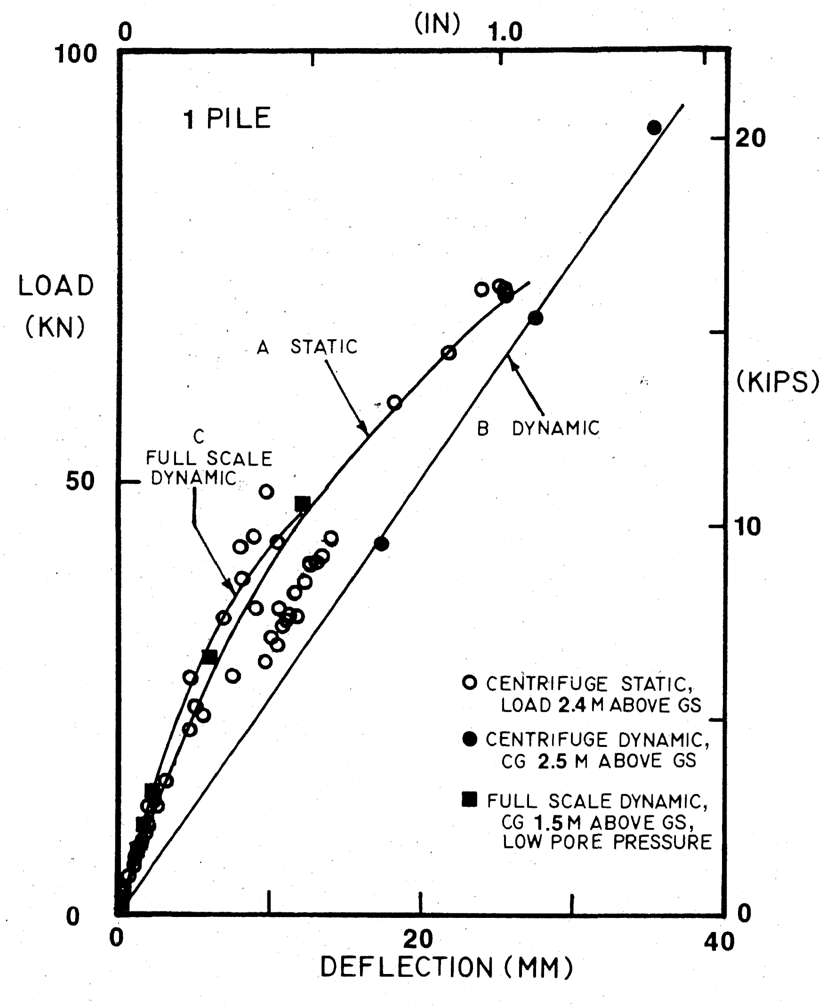
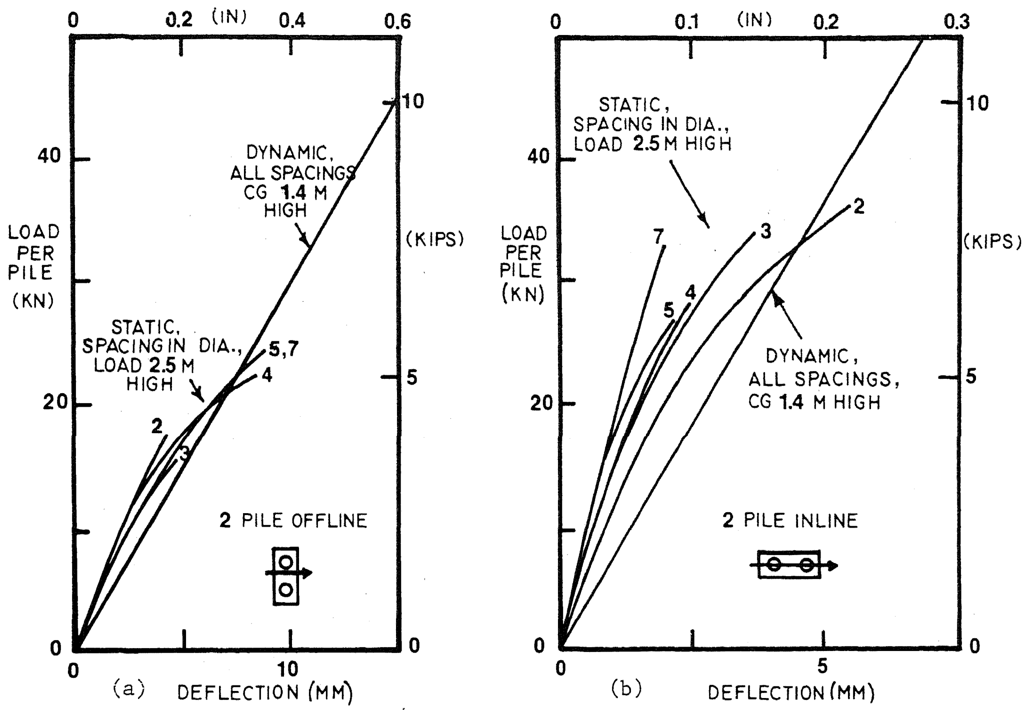


FIGURE 1. Prototype scale peak lateral load versus lateral deflection at point of load application (static) or center of mass (dynamic) for freeheaded lateral loading of a single pile.



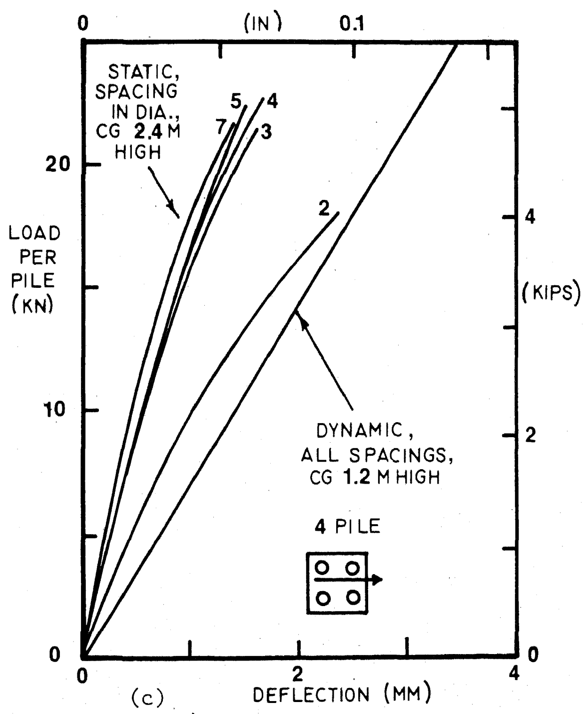


FIGURE 2. Prototype scale peak lateral load per pile versus lateral deflection at point of load application (static) or center of mass (dynamic).

(a) freeheaded 2 pile group offline
(b) fixheaded 2 pile group inline
(c) fixheaded 4 pile group

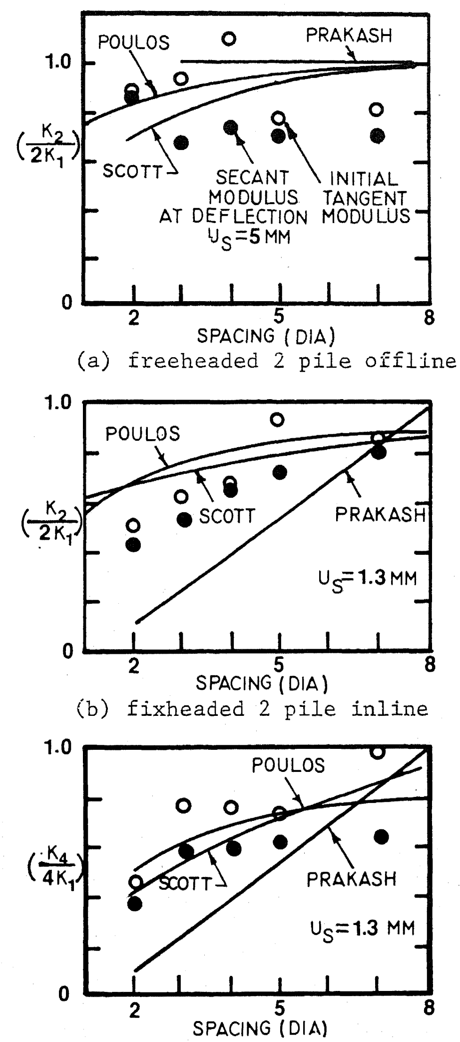
For the dynamic data, the system stiffness at the center of mass is plotted against pile spacing for each case in Figure 4. Note that the effective stiffness for the two pile offline system is essentially invariant, as expected. This provides a measure of the reproducibility of the soil and test conditions for the dynamic tests. For the fixed head groups, however, marked scatter is observed. This is due at least in part to the competing modes of vibration in the offline directions observed near resonance, which may have influenced the observed deflections in the primary directions. As plotted, it is difficult to discern any noticeable variation of group efficiency with spacing for the dynamic data. Better estimates of force and deflection levels are necessary for this data set before dynamic group interaction can be properly evaluated.

DISCUSSION

Figures 1 and 2 indicate dynamic secant moduli less than the static moduli at small deformations. Two phenomena could contribute to this. Lateral loading of piles often results in the formation of a gap between the soil and pile behind the loaded pile. Indeed, the static cyclic hysteresis loops from the centrifuge tests indicated that such gapping did occur in many cases. For a cohesionless material, one would expect soil grains to drop down and partially fill the gap during each cycle, given enough time. For the dynamic tests, the time allowed may have been insufficient for such an infilling, with a resulting lower overall observed system stiffness.

In addition, for the silty sand used in these tests, pore pressure generation during cyclic loading should be present, as observed in the full scale tests (8). Curve C in Fig. 1 plots only data from full scale tests where the initial pore pressure was low. For full scale tests carried out when the excess pore pressure was high, a system response up to 60% softer was observed. This suggests that for the centrifuge tests, the level of excess pore pressure during loading was higher for the dynamic tests than the static tests. Is such an observed difference in stiffness realistic? Since diffusion processes scale with the g-level squared, the excess pore pressures dissipate too quickly in the centrifuge relative to the applied dynamic stresses, which scale linearly with the g-level. It is possible that for the static cylic tests, dissipation occurred which would not have occurred in a prototype test. However, preliminary static cyclic data on the full scale pile also indicate an effective stiffness much higher than the dynamic, suggesting that such a dichotomy did not occur. Since no direct pore pressure measurements were taken during centrifuge testing, this cannot be shown conclusively.

Finally, Figures 1 and 2 indicate that the dynamic stiffness increases relative to the static, even exceeding it at larger deformations. At these higher levels, a larger quantity of soil near the surface must move in concert with the pile, resulting in an increased effective mass. It may be this increased effective mass which increases the observed dynamic system stiffness.

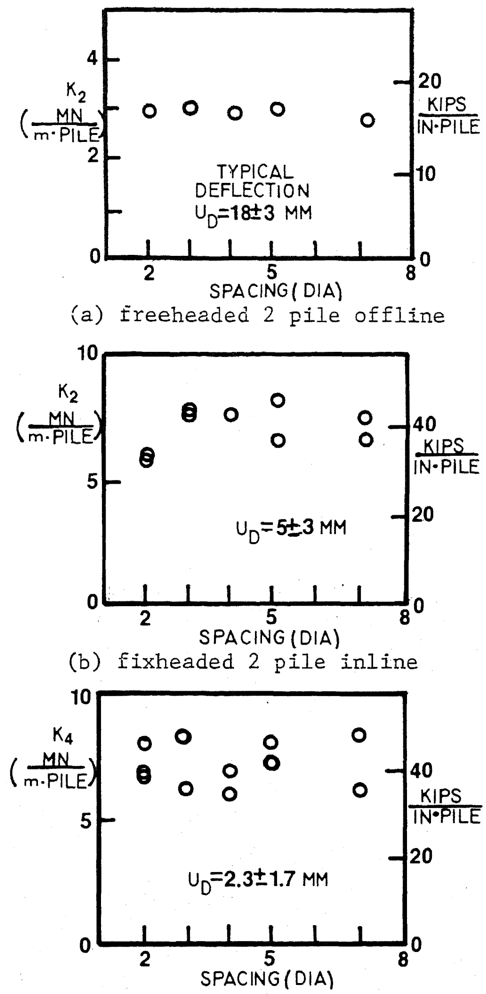


(a) freeheaded 2 pile offline

(b) fixheaded 2 pile inline

(c) fixheaded 4 pile group

FIGURE 3. Static cyclic pile group efficiency.



(a) freeheaded 2 pile offline

(b) fixheaded 2 pile inline

(c) fixheaded 4 pile group

FIGURE 4. Dynamic pile modulus at resonance.

CONCLUSIONS

The results of this centrifuge model study indicate that for small deflections, the dynamic secant modulus for single and multiple pile groups is lower than the static secant modulus, but is greater at large deflections. The former trend may be due to a higher excess pore pressure and less time for infilling of the soil-pile gap in the dynamic tests, while the latter may be caused by an increased effective soil mass moving with the pile at the larger deformation levels.

Comparison of full scale and centrifuge single pile dynamic data confirm the validity of the centrifuge modelling technique. Evaluation of static lateral pile group interaction formulae show that analytical techniques based on linear elasticity yield reasonable results, while additional reduction and analysis are necessary before the dynamic interaction can be analyzed using the existing data set.

ACKNOWLEDGEMENTS

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