SEISMIC RESPONSE OF OFFSHORE PILE FOUNDATIONS: CENTRIFUGE DATA AND ANALYSIS

by

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ABSTRACT

Site specific lateral resistance-deflection, p-y, curves were obtained from shaking tests conducted on model piles in a centrifuge with accelerations of 50 g. These p-y curves were incorporated in the dynamic beam-column program, SPASM, which was then used to compute the responses of the model piles to the loading conditions in the centrifuge tests. Comparison with the test data indicated that analysis by SPASM gave results adequate for design. Cyclic loading p-y curves recommended by the American Petroleum Institute were also used to predict the response of the model piles and gave results comparable to those obtained using the experimental p-y curves. The preliminary results provide the first quantitative verification of the SPASM type of analysis. More detailed studies of the centrifuge data are continuing and also of data from recent shaking tests in the field on prototype piles which mobilise significant non-linear response.

INTRODUCTION

Piles undergo both vertical and lateral displacements during earthquakes and both modes of displacement are usually modelled separately during the analysis of seismic response. In this paper only lateral displacements are considered.

The most important factor controlling the lateral response of piles under earthquake loading is the interaction between soil and pile. A schematic representation of an interaction model is shown in Fig. 1. The piles are modelled by an appropriate discrete-element mechanical analogue. The free field motions are best determined by a dynamic effective stress method of analysis in the case of sands or cohesionless silts (1) or by a total stress method of analysis including strength and stiffness degradation in the case of clays and plastic silts (2). The free field motions are applied to the pile through interaction elements, which may range from simple Kelvin-Voigt models through non-linear hysteretic elements capable of allowing gaps to open between soil and pile.

The interaction between pile and soil may be considered in three zones. Near the surface, the interaction exhibits highly non-linear and inelastic response due to the relative displacements between pile and soil, generated by inertia forces. At much greater depths, the pile deflections will follow the ground deformations because of the typically higher stiffnesses of the interaction elements. Between these two zones is a zone of gradual transition from one kind of interaction to the other (3).

A major difficulty in seismic response analyses of pile foundations is the selection of parameters to define the interaction elements. The variation in lateral resistance with deflection at any depth is usually represented by a curve giving the lateral resistances, p, per unit length for deflections, y, ranging from very small values up to and including deflections sufficient to cause yield in the soil. Such curves are referred to as p-y curves. The American Petroleum Institute (API) has published and recommended for use a non-dimensional set of p-y curves (4). These curves are based on very limited test data from quasi-static cyclic loading and there has been no verification of their applicability in the analysis of seismic response.

Recently, data has become available from shaking tests on a prototype pile in the field (5) and from dynamic tests on model piles in a centrifuge (6) which afford the opportunity to verify the applicability of the API p-y curves for seismic response analysis. Only the centrifuge data will be considered here.

Typical of the state-of-the-art for analysing the seismic response of pile foundations using p-y curves is the method of analysis incorporated in the computer program, SPASM (7,8). This program will be used to analyse the response of the model piles in the centrifuge tests.

CENTRIFUGE TESTS

The centrifuge tests were conducted by Scott et al (6) at the California Institute of Technology. The model pile was a stainless steel tube 0.5 in (13 mm) in diameter with a wall thickness of 0.010 in (0.25 mm). Centrifugal acceleration of 50 g was employed so that the model pile would scale up to the prototype size used by Scott et al (5) in the field tests. The pile was instrumented by 9 pairs of strain gauges mounted on the inside of the tube at opposite ends of a diameter at stations distributed along the pile. The pile was placed in position for testing by pushing it into the soil at 1 g.

The test soil was a silty sand with a dry unit weight, γ_d = 103 pcf (16.2 kN/m^3), a saturated unit weight, γ_s = 127 pcf (19.9 kN/m^3) and a void ratio, e = 0.61. Shaking tests were conducted on both dry and saturated sands; only tests on saturated sands are analysed in this paper.

The test pile was vibrated by a miniature shaking device driven by compressed air and mounted on the pile head at various heights above the sand surface. The exciting force was generated by an eccentric mass which could rotate at speeds up to 500 Hz (30,000 rpm). This speed was high enough to allow definition of the fundamental or first mode frequency of the system but was not sufficient to mobilise higher modes.

Data signals were recorded by a data acquisition system which converted the analog outputs from the strain gauges to digital form. Digitised data were transferred to tape for subsequent computer analysis. A summary of data from some of the tests analysed here is given in Table 1 at prototype scale.

INTERPRETATION OF TEST DATA

The distribution of bending moments along the pile is derived from the strain gauge data and is shown in Fig. 3a for a test in which the pile is vibrating at the first resonant frequency. The deflection, y, may be obtained by double integration of the moment distribution and the resistance, p, by a double differentiation according to the equations

$$y = \iint \frac{M}{EI}\,dz; \qquad p = \frac{d^2M}{dz^2} \tag{1}$$

where E = modulus of elasticity of the pile, I = moment of inertia, and z = distance along the pile.

The integration is a very stable procedure and reliable estimates of deflection are easy to obtain. The double differentiation is very dependent on minor details of the moment distribution curve and is difficult to carry out with sufficient accuracy (9). On the basis of extensive experience with the analysis of data from slow cyclic loading tests on piles in the Cambridge geotechnical centrifuge (10), the authors have developed a procedure that appears to give consistently reliable results (11). In this procedure, the moment distribution is simulated by a collection of cubic splines, one between each two data points. Continuity of slope is assured at each point. The spline is then differentiated to give the distribution of shear (Fig. 2b) and resistance, p (Fig. 2c), along the pile. The deflections (Fig. 2d) are obtained by integration.

The experimental p-y curve for any given depth may be obtained by plotting corresponding values of p and y at various levels of shaking. Data points from all tests run at the first resonant frequency are shown in Fig. 3. Interpolated p-y curves at various depths are also given. Although it is possible to put smooth curves through the data, the simple elastic plastic interpretation seems adequate in view of the limited range of deformation achieved at depths below 2 diameters.

Below about 3-4 diameters, the deflections are so small that experimental errors become significant and it is impossible to differentiate between the p-y curves at depths of 3 and 4 diameters. Before determining the p-y curves the data were corrected for inertia effects.

SPASM ANALYSES

SPASM (Seismic Pile Analysis with Support Motion) is a dynamic beam-column program using lateral p-y curves to simulate pile-soil interaction. It was developed by Matlock and Foo (7) for the analysis of the lateral response of piles to strong earthquake shaking.

The experimental p-y curves in Fig. 3 were incorporated in the SPASM program and SPASM was used to generate the dynamic response of the model piles. The computed responses were then compared with the experimental data to provide a measure of the applicability of the SPASM type of analysis.

The moment diagram computed by the SPASM analysis for a test case when the pile is vibrating at the first resonant frequency is shown by the continuous curve in Fig. 4a. The maximum moment is underestimated by about 15% and the moment at the mudline by about 30%. The corresponding shears, lateral resistances and deflections are shown in Figs. 4b,c, and d. Similar results are given in Fig. 5 for a case when the pile is vibrating at a frequency higher than the first resonant frequency. In this case, the agreement between the experimental and computed results is very good.

Finally, Matlock's version of the cyclic API p-y curves (12) was incorporated in SPASM and the response of the pile to vibration in the first mode was computed again. The results are shown in Fig. 6. The agreement between computed and measured response is adequate for design purposes. The API p-y curves have a higher initial stiffness than the experimental curves but a smaller ultimate resistance. These differences were also noted by Barton et al (10) in the case of slow cyclic loading.

CONCLUSION

It appears that the SPASM program incorporating the API p-y curves for cyclic loading gives adequate information on pile moments and lateral deflections for the purposes of design for seismic loads. This finding must be considered preliminary because only a few centrifuge tests have been analysed.

To put the agreement between computed and measured response in the proper perspective requires a detailed discussion of the quality and limitations of the data base. Editorial restrictions here preclude such a discussion but it will be presented in a later paper which will consider data from other centrifuge tests and from the field tests by Scott et al (5). One limitation of the data that should be noted is that porewater pressures were not measured. The effects of porewater pressures can be included in SPASM analyses in the manner outlined by Finn and Martin (3).

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TABLE 1

MODEL PERFORMANCE

All data given in prototype dimensions.

TEST NO.	M2-2	M2-3	M2-4
Soil	Wet	Wet	Wet
Shaking Level	Med.	High	High
First Mode Freq., f_1, Hz	1.65	1.64	1.67
Peak Displ., A_1, in.	0.34	0.50	0.71
Damping, % Critical	4.2	4.9	3.0
Shaker force, lb at 1 Hz	369	686	686
Max. moment, 10^5 lb-in.	20.1	35.6	42.6
Max. moment, depth, ft.	5	5	5
Height of force, above ground, ft.	8.8	8.7	8.1

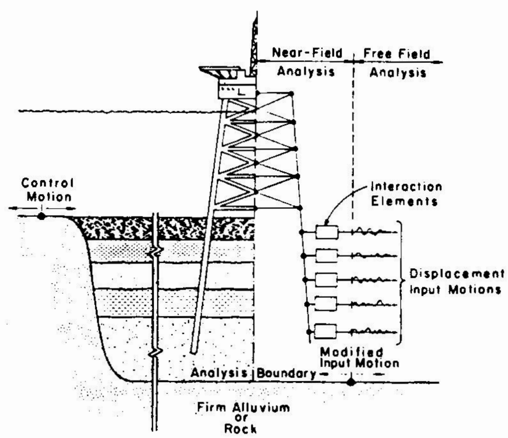

FIG. 1 Soil-pile-platform interaction model for earthquake loading.

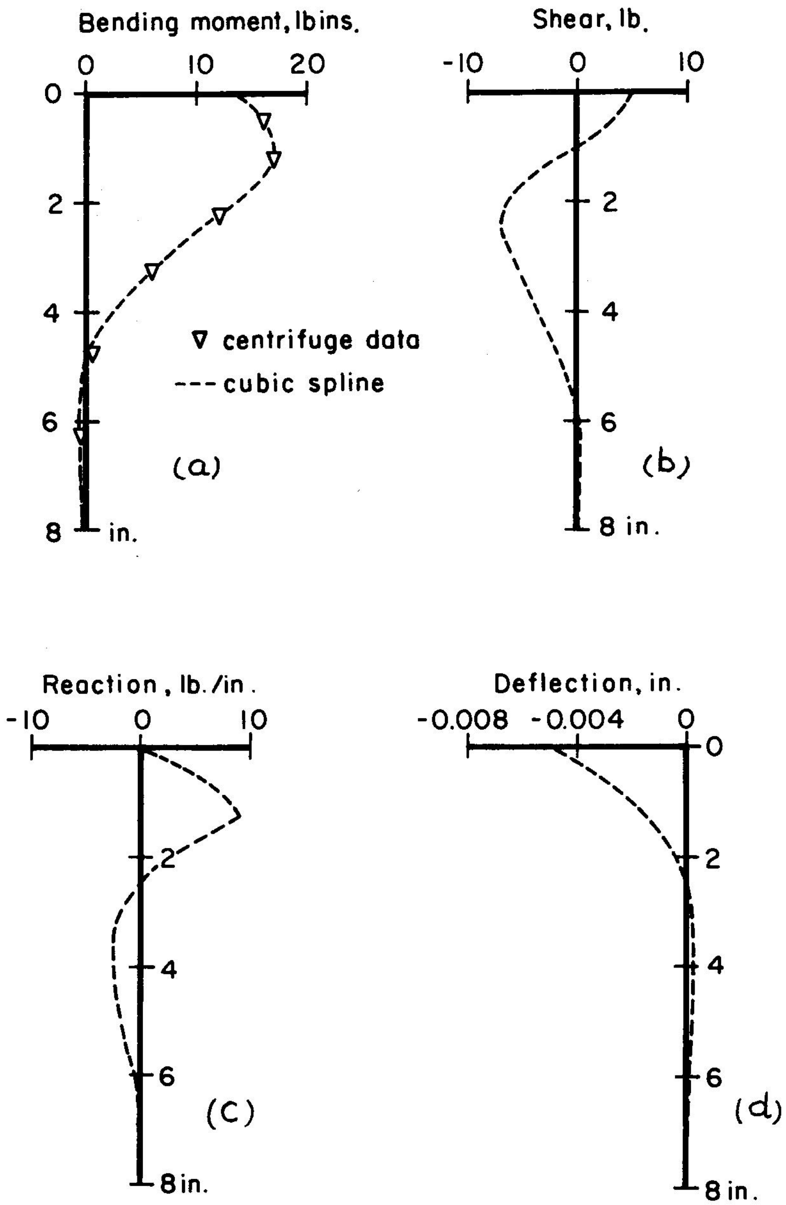

FIG. 2 Presentation of test data by cubic spline.

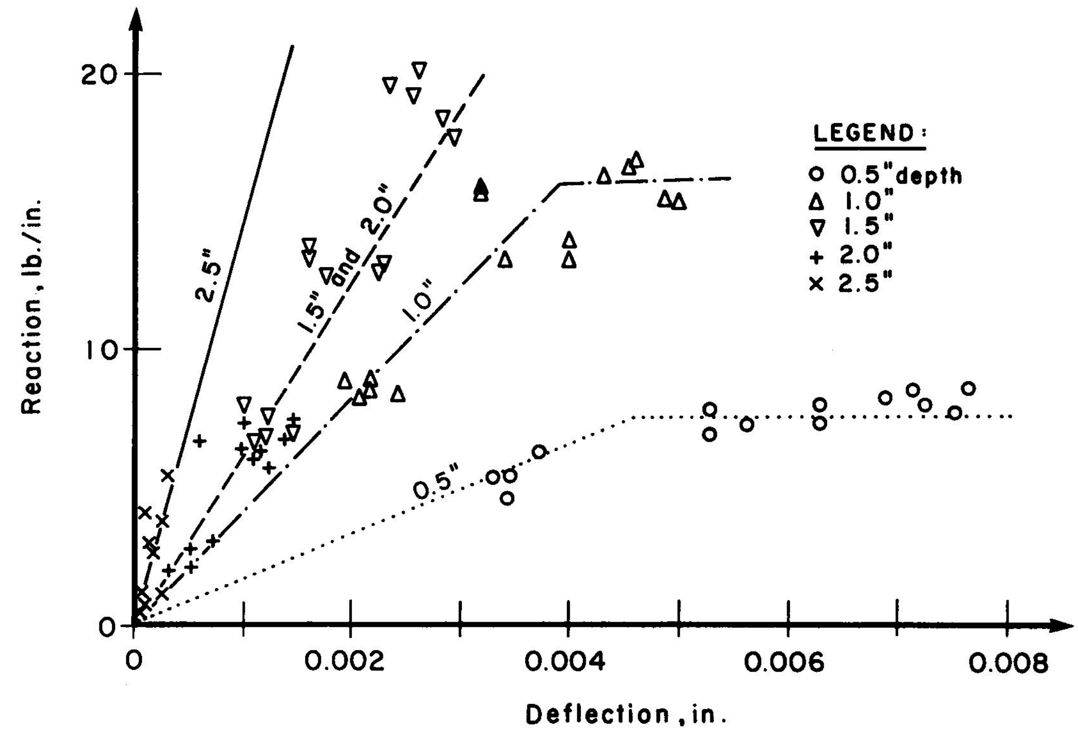

FIG. 3 Experimental p-y curves.

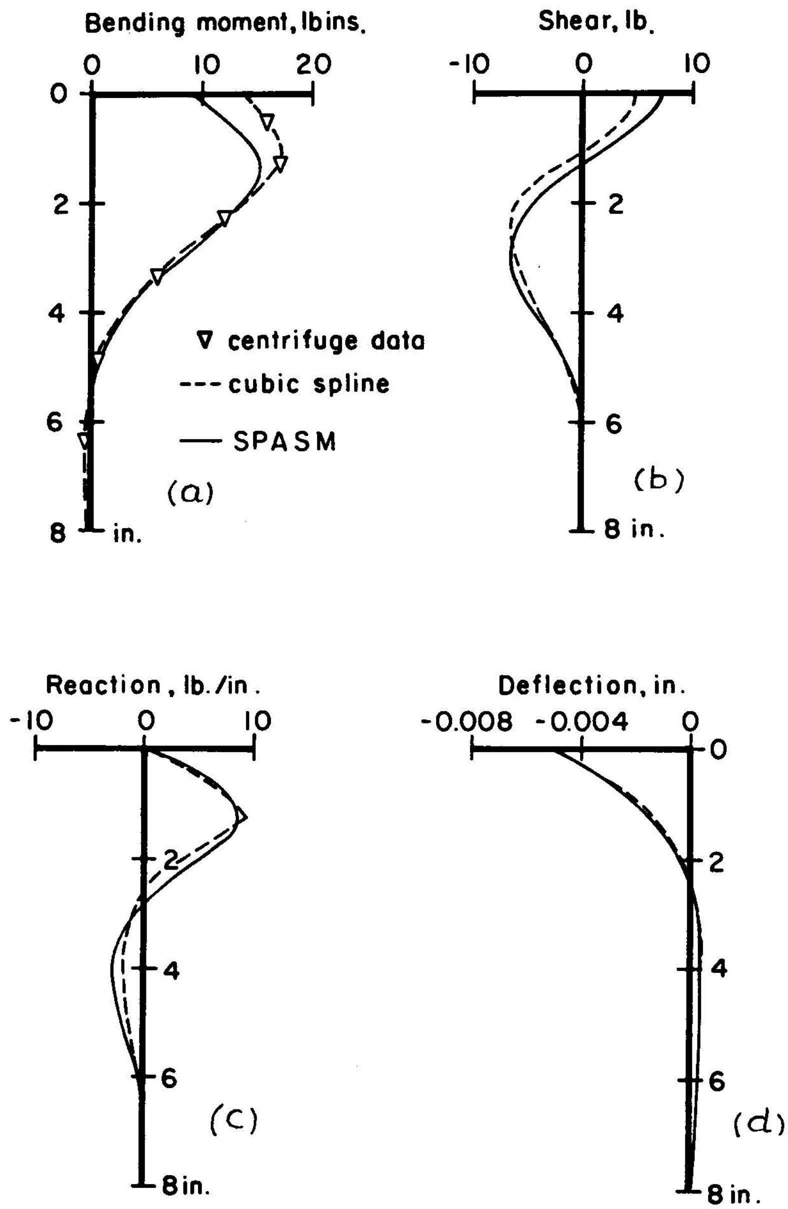

FIG. 4 Results of SPASM analysis of resonant vibration using experimental p-y curves.

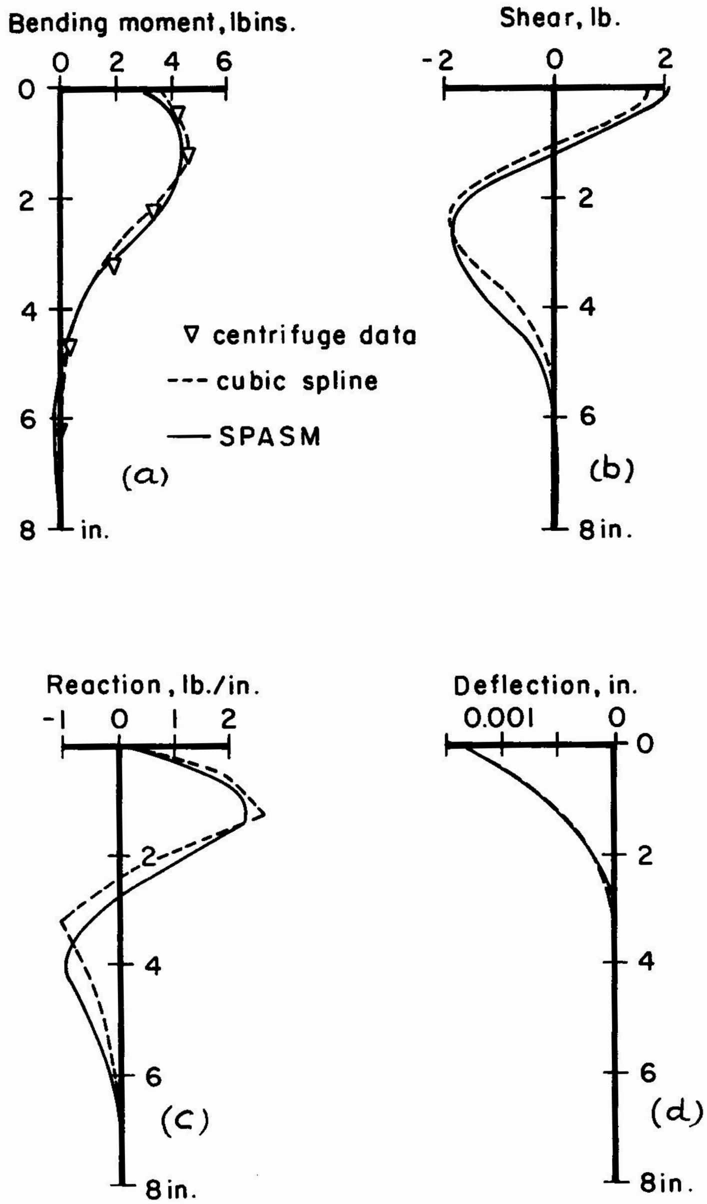

FIG. 5 Results of SPASM analysis of non-resonant vibration using experimental p-y curves.

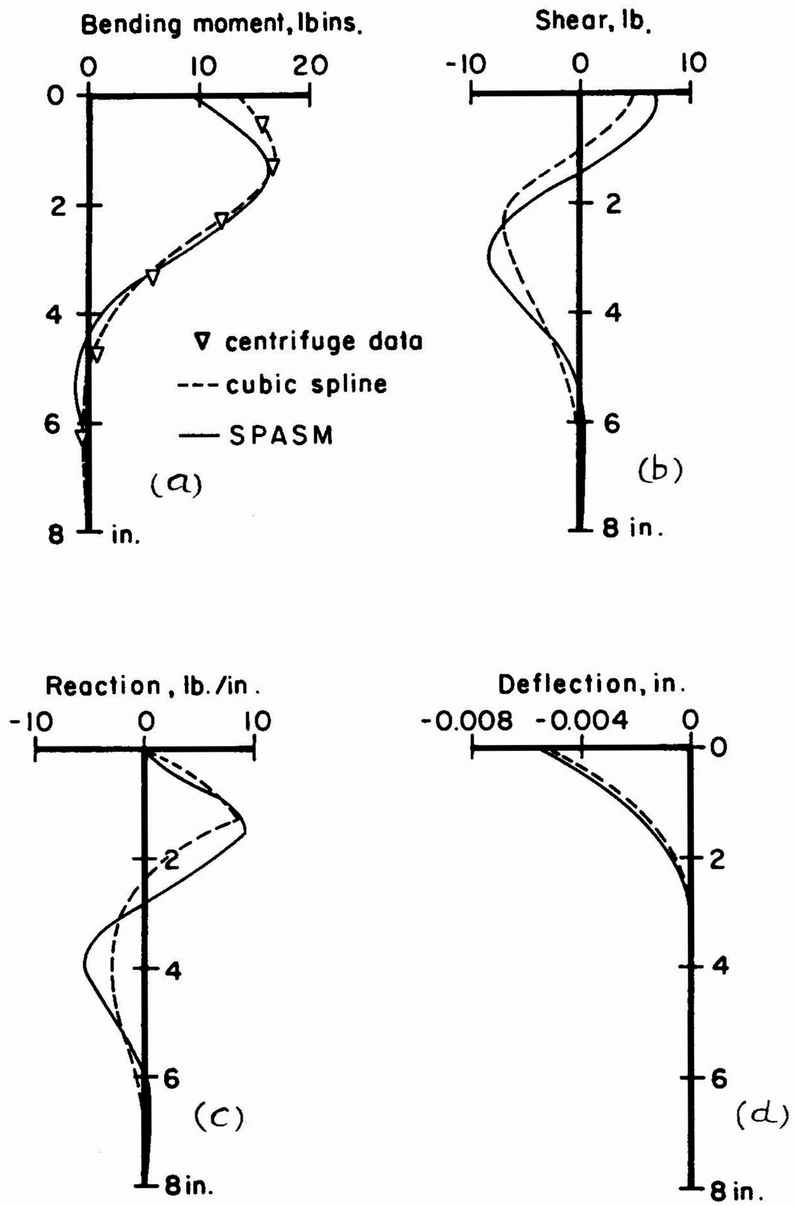

FIG. 6 Results of SPASM analysis of resonant vibration using Matlock's version of API p-y curves.