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Centrifugal Modeling of a Pile Under Vertical Random Excitation

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SYNOPSIS: Data from the experimental modeling of a pile in a geotechnical centrifuge are compared with analytical results. The model pile was subjected to vertical random excitation with subsequent determination of the compliance function in the frequency domain. This compliance function was found to be consistent with theory. An absorbing boundary was used to minimize reflected wave energy from the centrifuge container boundaries.

INTRODUCTION

The dynamic response of piles is of increasing interest to the earthquake engineer and soil dynamicist. Gazetas (1983), in a state of the art paper, indicates that early work in the soil-structure interaction field emphasized solutions for surface foundations on half space or layered soil media. However, in recent years research efforts have been directed more at other complicated problems such as dynamic soil-pile interaction problems. Novak (1977) and Kuhlemeyer (1979) have provided theoretical solutions for a pile subjected to vertical excitation at ground level. More recently, Pak and Jennings (1987) have presented a mathematical solution for the lateral response of a pile under transverse excitation.

This paper presents results of model experiments conducted in a geotechnical centrifuge. In the work subsequently described, the response of a model pile under vertical excitation was evaluated. Random vibration techniques and spectral methods were used to determine the dynamic compliance of the soil-pile system.

EXPERIMENTAL APPARATUS

The centrifuge, soil and boundary material, foundation model, exciter system, and instrumentation are described in the following paragraphs.

Centrifuge

The model experiments were conducted using the 15 g-ton centrifuge at the University of Colorado centrifuge facility. This machine can perform to 100 g. The radius to the base of the swing-up platform is 1.36 m during operation, while the platform area is 0.41 m by 0.43 m. This centrifuge has been described by Ko (1988).

Test materials

The test soil is a U.S. Silica Company F-75 dry uniform silica sand. This sand has a mean grain size of 0.19 mm per U.S. Silica specifications. This sand is also known as "banding" sand, and is used in liquefaction studies. For these experiments the sand was rained into a rigid metal container yielding a uniform soil profile with a relatively high mass density of approximately 1734 kg/m^3. This corresponds to a void ratio of 0.528 and a relative density of 87%.

Research has suggested, in order to obtain proper modeling of the wave propagation phenomena for prototype situations, that an energy absorbing material be placed at the model boundary to alleviate reflected energy from returning to the vibrating source. This approach was shown to be beneficial by Coe, Prevost & Scanlan (1985), Weissman (1989), Cheney, et al (1990) and Lenke, Pak & Ko (1991) in their respective dynamic centrifuge experiments. The material that they found to be particularly useful is called Duxseal, a Manville Corporation product. This material is a non-toxic sealing material with an oily-putty texture reinforced with small inert fibers. The mass density of Duxseal is 1.57 gm/cm^3. Its excellent adhesion allows for easy application to the boundary of a centrifuge container. The Duxseal was applied in a uniform thickness of approximately 35 mm to all internal surfaces of a rigid cylindrical container 0.38 m in diameter and 0.30 m in depth.

Model foundation

The model pile was made from stock-drawn aluminum (6061-T6) tubing of 6.35 mm outside diameter, 4.57 mm inside diameter and 0.89 mm wall thickness. The length of pile embedded in the soil is 127.0 mm which results in an embedded length to diameter ratio (L/D) of 20. The unembedded length of the pile is

15.3 mm. At the top of the tubing is press-fit an aluminum disk to which a truncated conical shaped cap is attached. This shape was used to accommodate the piezoelectric load washer. The load cell was clamped between this cone and a cable clamping block above. The clamping block serves to isolate and minimize any possible vibration of the high insulation resistance cable connecting the load cell with the load cell charge amplifier. Attached to the top of the cable clamping block is an accelerometer housing. All the above components were fabricated from aluminum. This entire pile assembly is attached to the exciter armature by a quick setting epoxy. Figure 1 depicts this entire assembly after post-test withdrawal. The model pile test described here was conducted in a centrifuge environment of 60 g.

Fig. 1 Experimental Setup

Exciter System

The exciter system is composed of an electromagnetic shaker, power amplifier, and random noise generator. A B&K 4809 permanent magnet shaker was used. This shaker has a low armature weight (60 gm), low total weight (8.3 kg), and can provide the necessary linear acceleration, velocity and displacement over the required frequency band. Scaling relations require that the frequency spectrum of the model be N times greater than that of the prototype, where N is the model scale. Most machine vibrations occur below 5000 cycles per minute (cpm); thus a model frequency spectrum would extend to 5000 Hz for N=60. Richart, Hall and Woods (1970) discussion of design procedures for dynamically loaded foundations suggest upper limits of displacement, velocity, acceleration and frequency for satisfactory operation. The B&K 4809 easily satisfies these criteria when scaled for centrifuge tests at 60 g.

The random noise signal was supplied by the output channel of a Tektronix 2630 Fourier analyzer. This random signal is uniform in the frequency domain over the specified frequency range with an adjustable root mean square (rms) voltage level to 1.81 V rms.

The random noise signal is passed through a Techron 5375 power amplifier prior to passing through the centrifuge slip rings to the exciter. The power amplifier gain used was two.

Instrumentation

Two force and two acceleration measurements were obtained from the pile shown in Figure 1. A Kistler 9001 load cell is mounted at the top of the conical shaped pile cap (note that this load cell cannot be seen in Fig. 1, but is concealed by the cable clamping block). This load cell has a low mass (3 gm) and good sensitivity and resolution (able to resolve to 0.01 N force). Two bondable Micro Measurement strain gages were attached at ground level on opposite sides of the pile. These gages (model N3K-06-S022H 50C) were placed in a full bridge configuration to compensate for any bending stresses in the pile. These gages are 5000 ohm gages which allow for a high excitation voltage of 30 V providing a very high sensitivity yet stable output. Acceleration was monitored on the pile cap and in the accelerometer housing via PCB 309A and PCB 303A11 accelerometers, respectively. The latter provided a consistency check for the results obtained from the pile cap. These units weigh 1 gm and 2 gm, respectively, with corresponding sensitivities of 5 and 100 mV/g. One will note the presence of an additional accelerometer mounted on the pile in Fig. 1; this unit was not used for the experiment described herein.

After passing through a programmable signal conditioner on board the centrifuge, all data signals are passed through slip rings to the Tektronix 2630 Fourier analyzer. The 2630 is a high performance analog data acquisition and signal processing unit which interfaces with an IBM PC. This data acquisition unit provides for the estimation of frequency response functions (FRF) and coherence functions using the built-in windowing and averaging features. The data presented has been windowed with a Hanning window and the FRFs were found to be nicely estimated using 50 averages in the frequency domain. The bandwidth was from 0-5 kHz with a frequency resolution of 3.125 Hz.

MEASUREMENT APPROACH

A linear dynamic system can be conveniently characterized by its frequency response function, $H(f)$, which describes the response of the system to time-harmonic excitation of arbitrary frequency, f. It is defined through

$$Y(f) = H(f)X(f) \tag{1}$$

where $X(f)$ and $Y(f)$ are the Fourier transforms of the input and output, $x(t)$ and $y(t)$, respectively. For the case at hand, the time and frequency representations are in terms of seconds and Hertz. As measurement noise is always present in the data acquisition system, a more appropriate method for determining the frequency response function is to employ the following relation (Bendat & Piersol, 1986)

$$H(f)=\frac{G_{xy}(f)}{G_{xx}(f)} \tag{2}$$

where $G_{xy}(f)$ is the cross-spectral density function of the input and output and $G_{xx}(f)$ is the autospectral density function of the input. Equation 2 is used in the determination of all FRFs using the Tektronix Fourier analyzer.

For the experiment described, the force is taken as the input and the acceleration response is taken as the output. Keeping the notation of the ideal system without noise of Equation 1 for simplicity, the frequency response function obtained from these two measurements is termed accelerance, $A(f)$, and is defined as

$$A(f)=\frac{\ddot{X}(f)}{F(f)} \tag{3}$$

where $\ddot{X}(f)$ is the acceleration output response in the frequency domain and $F(f)$ is the frequency domain representation of the force input. This equation has units of acceleration per unit force (for example $m/s^2/N$) and is a complex-valued function composed of both real and imaginary components.

The desired FRF is that of compliance (inverse of dynamic stiffness) which relates the displacement output to the unit force input (for example m/N). This compliance, $C(f)$, can be easily obtained by operating directly on Equation 3, by performing double integration in the frequency domain. Mathematically, this is represented as

$$C(f)=\frac{X(f)}{F(f)}=\frac{-\ddot{X}(f)}{4\pi^2 f^2 F(f)} \tag{4}$$

where $X(f)$ is the frequency domain representation of the displacement and f is the frequency in Hz.

Kuhlemeyer (1979) presents his results from a finite element analysis of a vertically excited pile as a complex displacement function which is the ratio of the compliance at frequency f to the compliance at zero frequency, i.e., the static case. This will be referred to as "normalized compliance" for the remainder of this paper and is defined as follows

$$\mathrm{C(f)}=\frac{C(f)}{C_{st}} \tag{5}$$

where **C(f)** is this normalized compliance and C_{st} is the static compliance. The results will be presented in the form of Equation 5.

RESULTS

Figure 2 presents the normalized compliance obtained from the acceleration measured by the PCB 309A on the pile cap and the force measurement of the strain gage bridge at ground level. The measured random force input was 1.65 N rms, while the measured response was 1.5 g rms. The real part and the negative of the imaginary part are depicted and are compared with Kuhlemeyer's analysis (1979). The analytical results are for a length to radius ratio (L/a) equal to 40 with the modulus ratio of the pile to the soil (E_p/E_s) as 400. The frequency band presented corresponds to a dimensionless frequency, $2\pi f a/\beta$, equal to 0.5, where β is the shear wave speed of the soil. The experimental data of Fig. 2 was normalized using a soil modulus (E_s) of 95 MPa, a Poisson's ratio of 0.25 and a shear wave speed (β) of 145.6 m/s. It is evident that the experimental data are generally in line with Kuhlemeyer's results.

One will note that the experimental data exhibits noticeable regular oscillations which diminish in amplitude with increasing frequency. This can be attributed to the existence of some standing wave energy despite the use of the special Duxseal boundary. Moreover, it is also found that the cylindrical container tends to focus this energy even with the presence of the absorbing boundary. A detailed discussion of various boundary effects can be found in Lenke et al (1991).

CONCLUSIONS

The vertical compliance of a model pile has been successfully obtained using random force excitation and, for the force range employed, was found to agree reasonably well with existing numerical results. With some further improvements, this experimental modeling method can be extended to more complex soil-structure interaction problems such as the compliance of pile groups.

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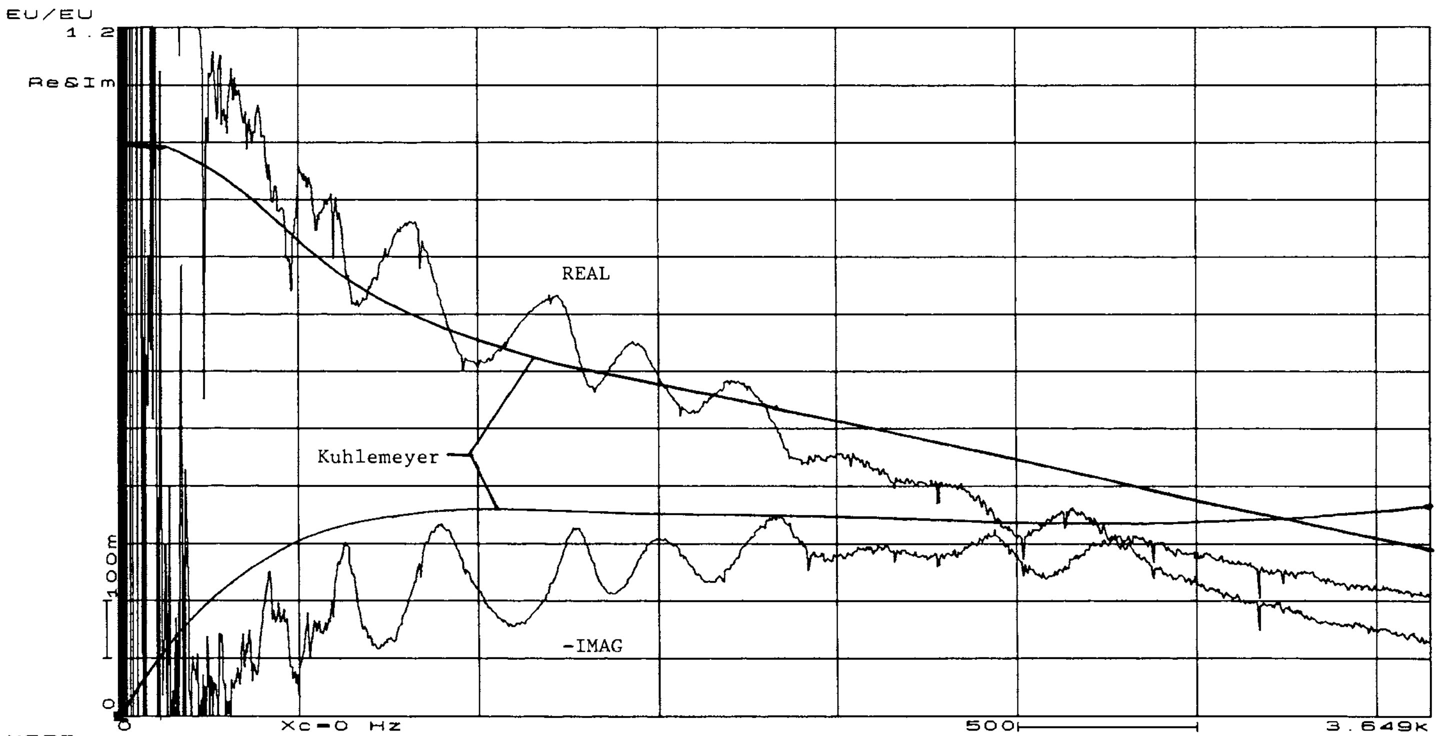

Fig. 2 Normalized Compliance of Model Pile

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