In situ determination of dynamic impedance functions of shallow foundations

In situ, la détermination des fonctions d'impédance dynamique de fondations

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ABSTRACT
Two square and embedded shallow foundations have been dynamically loaded at the National Geotechnical Experiment Site (NGES) on the campus of Texas A&M University (TAMU) via four dynamic loading devices implemented in several configurations. The dynamic load and vibration responses of the foundations were measured via appropriate electronic instrumentation. Utilizing appropriate equations of motion and system parameters, and the measured load and vibration responses, dynamic impedance functions were backcalculated for the vertical, horizontal sliding, and rocking modes of vibration.

RÉSUMÉ
Deux carrés et embarqués fondations ont été chargés dynamiquement à la National Geotechnical Experiment Site (NGES) sur le campus de Texas A & M University (TAMU) à travers quatre dispositifs de chargement dynamique de mise en œuvre dans plusieurs configurations. La charge dynamique et les vibrations des réponses des fondations ont été mesurées par des instruments électroniques appropriés. Utilisation appropriée des équations du mouvement et des paramètres du système, et la mesure de la charge des réponses et des vibrations, dynamique des fonctions backcalculated impédance pour la verticale, horizontale de glissement, et en balançant les modes de vibration.

Keywords: dynamic impedance functions, in situ, shallow foundations, vibration shaker

1 INTRODUCTION

Recent decades of research have produced significant advancements in both laboratory and in situ characterization of geotechnical sites, and in methodologies for the prediction of dynamic foundation behavior. Many numerical methods have been compared to the few exact solutions available and to each other, but virtually none have been compared with carefully performed, full-scale tests of dynamically loaded footings on well characterized soils. Yet, these methods are the starting points for virtually all calculations of dynamic foundation response, from sensitive instrument bases to earthquake shaking analyses. In part, these comparisons have not been conducted because equipment to dynamically load full-scale foundations has not been easily available.

2 DYNAMIC IMPEDANCE FUNCTIONS

Dynamic impedance functions are employed in soil-foundation interaction problems to describe an assumed linear relationship between interaction forces and interaction displacements (Gazetas [1991]). This assumed relationship allows for the solution of dynamic displacement from the differential equations of motion. Dynamic impedances are typically described via a complex number, and the coefficients for soil-foundation problems are dependent on the frequency of the excitation force. There are a very small number of studies documented in the literature in which dynamic impedance functions for shallow foundations have been determined in situ at sites in which the soil conditions and properties are well characterized. These studies include Crouse, et al. (1990); De Barros and Luco (1995); Luco, Trifunac, and Wong (1988); Luco and Wong (1990); and Wong, Trifunac, and Luco (1988). DeBarros and Luco (1995) provide detailed procedures and appropriate equations of motion for impedance function determination. In general, the process entails measuring the dynamic response of a foundation of known characteristics (e.g., geometry, mass, moment of inertia) and subjecting it to a measurable dynamic loading over a range of frequencies. The response, loading, and foundation characteristics are then used to backcalculate impedance functions using an appropriate set of dynamic equations of motion.

3 EXPERIMENT DESCRIPTION

Two shallow foundations, the first 1 m x 1m in plan and embedded 0.9 m, and the second 3 m x 3 m in plan and embedded 0.9 m, have been dynamically loaded at the National Geotechnical Experiment Site (NGES) on the campus of Texas A&M University (TAMU). The TAMU NGES site has been extensively characterized via both in situ and laboratory soil testing techniques, including shear wave velocity via both borehole and surface wave methods. Four dynamic loading devices implemented in several configurations have been used to excite each footing in vertical, horizontal sliding, and rocking vibration modes.

The complete experimental program produced impedance functions for the vertical, horizontal sliding, rocking, and coupled sliding/rocking vibration modes and for each of the two embedded foundations. For some vibration modes, independent experiments were conducted using more than one of the available vibration shakers. The purpose of this paper is to provide a summary or preliminary review of this work. By way of example, experimental results are presented herein for two loading configurations of the 1 m x 1 m footing.

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4 TEST RESULTS

4.1 *Vertical Load Experiment*

Figure 1 presents an experiment for the vertical loading of the 1 m x 1 m footing using an ANCO Model MK-12 rotating mass shaker mounted flush to the footing surface (Figure 1a). The shaker was configured to load in the vertical direction. The magnitude of the load was determined by the speed and eccentricity settings of the rotating masses. The photograph also displays the velocity transducers deployed at each of the four corners of the footing surface for measurement of the footing response to load.

Figures 1b to 1d present measurements of foundation load and vertical displacement. Figure 1b displays continuously increasing amplitude of vertical load as frequency increases, which is characteristic behavior for a rotating-mass-type shaker. The resulting vertical displacement response of the foundation is displayed in Figures 1c and 1d. The complex number (real and imaginary) format implicitly contains both the amplitude of the sinusoidal displacement response, as well as the phase lag of the displacement from the applied sinusoidal loading. In operation, the loading was conducted in a steady-state mode wherein several cycles of load were applied at a constant frequency, beginning at the lowest frequency. The dynamic response of the foundation was measured simultaneously via the velocity transducers, and recorded via a dynamic signal analyzer capable of characterizing the signals in complex number format. The displacement response was determined by integration of the velocity transducer measurements, and the loading was repeated at small increments of frequency through the frequency range noted in Figures 1c and 1d. Finally, it is noted that the displacement responses are displayed for each of the four corners of the foundation. The four responses are indeed very similar, which in part indicates that the foundation is moving vertically in a rigid-body-like fashion.

Figures 1e and 1f present the real and imaginary components, respectively, of the dynamic impedance function computed from the vertical load and response measurements and the foundation characteristics. The numerical values appear comparable in magnitude to impedance functions reported elsewhere (Crouse, et al. [1990]), but further work is ongoing to provide a better assessment.

4.2 *Horizontal Load Experiment*

Figure 2 presents an experiment for horizontal loading of the 1 m x 1 m footing using an APS Dynamics Model 400 Electro-Seis shaker suspended from a tripod and configured to load in the horizontal direction (Figure 2a). The horizontal load was applied to a steel frame attached to the footing surface, and the magnitude of the applied load was measured via a load cell attached between the shaker and frame connection. The photograph also displays the velocity transducers deployed at each of the four corners of the footing surface for measurement of the footing response to load.

Figures 2b to 2f present measurements of foundation load, horizontal displacement, and vertical displacement. The loading and measurement process was very similar to that described above for Figure 1, and the results displayed in Figure 2 are in the same complex number (real and imaginary) format. The responses at each of the foundation corners are displayed individually in the figures. It is noted that the four horizontal responses are indeed very similar, which in part indicates that the foundation is moving horizontally in a rigid-body-like fashion. The vertical displacements are due to the rocking motion of the foundation. Here, it is observed that there are two pairs of similar data. The similar responses are for the two corners along a foundation edge that is parallel to the axis of rocking. Of course, there are two such edges, and they are each on opposite sides of the axis of rocking. These responses should be at similar amplitude, but 180 degrees out of phase if the rocking axis is contained in the same vertical plane as the center of the foundation. Indeed, the data possess this symmetry: the real and imaginary pairs are both of similar magnitude, but opposite in sign (i.e., 180 degrees out of phase). This behavior also suggests a rigid-body-like rocking motion, and with this as an assumption, the rotation of the foundation can be calculated from the geometry and the vertical displacement responses.

Finally, figures 2g to 2j present the real and imaginary components of the horizontal and rocking dynamic impedance functions computed from the horizontal load and response measurements and the foundation characteristics. Further work is ongoing to provide a better assessment of the quality of these results.

5 CONCLUSIONS

There is little experimental data available in the literature that documents the in situ dynamic impedance functions of full-scale shallow foundations at well-characterized sites. Thus, models for the dynamic behavior of shallow foundations that have developed over the past several decades largely remain uncalibrated. It is anticipated that the results described in the paper can be an important contribution toward this calibration. Also, the description and publication of the procedures employed in this experimental program should be useful for the professional community. Hopefully, results from this work can help improve the implementation of appropriate soil-structure interaction principles into safer and more economical design of infrastructure facilities subjected to dynamic loads.

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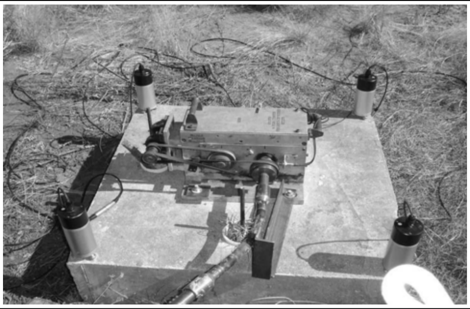
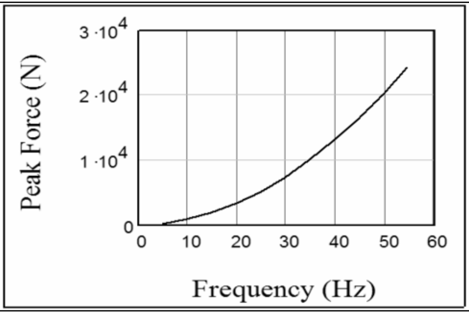
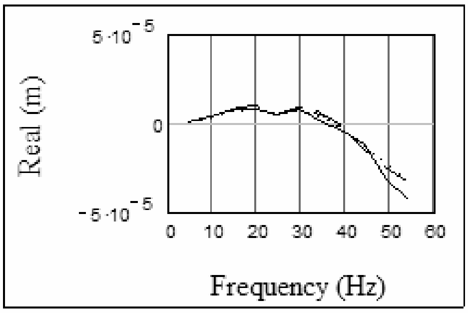


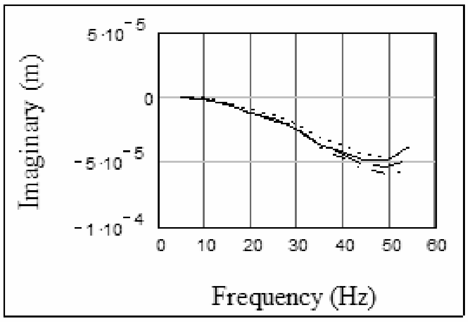
(a) Experiment Photograph



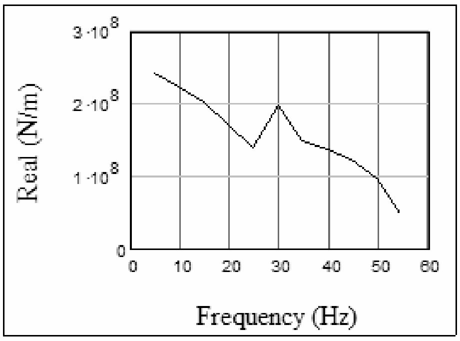
(b) Vertical Load



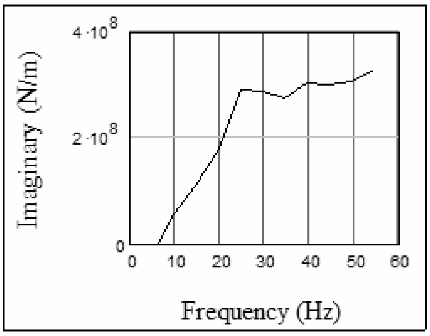
(c) Vertical Displacement, Real Component



(d) Vertical Displacement, Imaginary Component



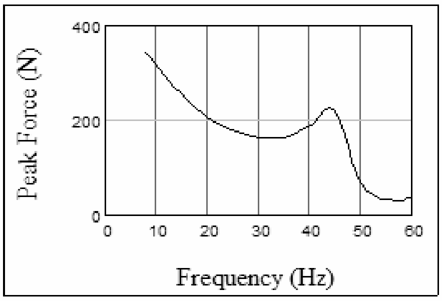
(e) Vertical Impedance, Real Component



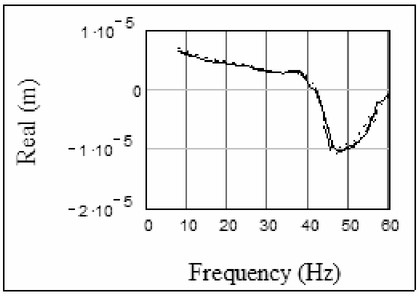
(f) Vertical Impedance, Imaginary Component

Figure 1. Vertical Loading Experiment for 1 m x 1 m Embedded Footing

(a) Experiment Photograph



(b) Horizontal Load



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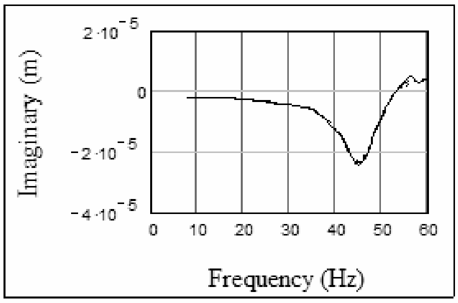

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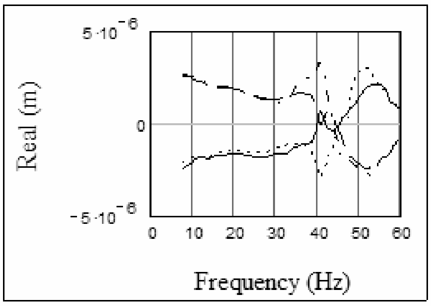
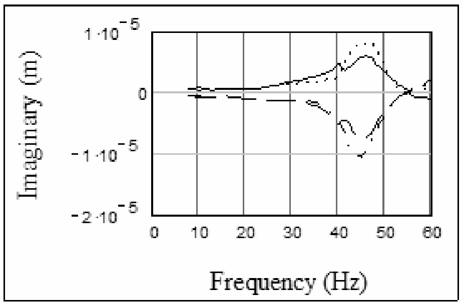
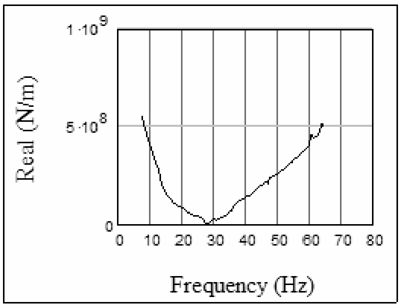


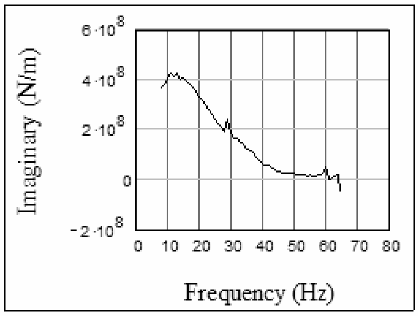
(e) Vertical Displacement, Real Component



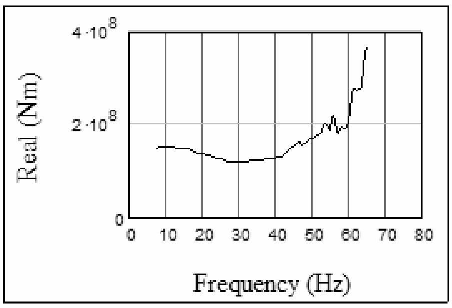
(f) Vertical Displacement, Imaginary Component



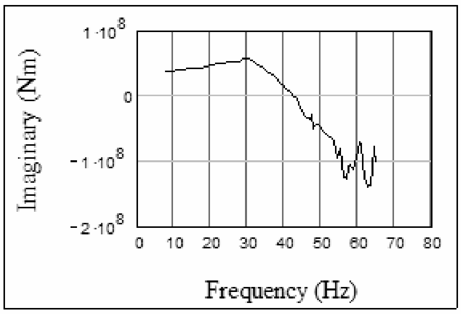
(g) Horizontal Impedance, Real Component



(h) Horizontal Impedance, Imaginary Component



(i) Rocking Impedance, Real Component



(j) Rocking Impedance, Imaginary Component

Figure 2. Horizontal Loading Experiment for 1 m x 1 m Embedded Footing