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Force-Displacement and Moment-Rotation Relationships in the Context of Dynamic Soil-Structure Interaction

Lisa M. Star[1], Michael J. Givens[2] and Salih Tileylioglu[3]
[1]*(Department of Civil Engineering and Construction Management, California State University, Long Beach, U.S.A)*
[2]*(Arup, Los Angeles, U.S.A)*
[3]*(Department of Civil Engineering, Cankaya University, Ankara, Turkey)*
Corresponding Author: Lisa M. Star

Abstract:*In this paper, we evaluate force-displacement and moment-rotation relationships to characterize dynamic soil stiffness and damping properties of structures subject to forced vibration loading. We first introduce a procedure to extract the necessary data to develop such relationships from forced vibration testing data. This procedure is then applied to data collected from forced vibration tests on a portable test structure at two different soil sites in California. The results show that the outlined procedure is useful in identifying soil-structure interaction characteristics and is a convenient way of presenting field performance data from forced vibration testing. For the data from the two sites collected, the derived relationships infer that rotational stiffness is more frequency dependent than the translational stiffness. Furthermore, the results suggest that the translational mode was more efficient in dissipating energy compared to the rotational mode.*

Keywords –*civilengineering,earthquake engineering,geotechnical engineering, seismic,soil-structure interaction*

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I. INTRODUCTION

Whether it is for the design of new structures in seismic regions, structural health monitoring of structures through vibration data, or seismic retrofitting of existing structures, soil-structure interaction plays an important role on the response of structures to dynamic loading. The loading may be a result of earthquakes or simply vibration generating devices near (or within) the structure itself. The response of the structure to excitation will be a function of how the foundation and the surrounding soil interact with each other. The interaction will have an impact on the design and as a result the construction of the project. Hence, developing a model for the soil-structure interface is as important as building a model for the superstructure itself.

Dynamic soil-structure interaction (SSI) effects are more pronounced in stiff structures that are overlying or within soft soils. The effects can result in an increase of the structural period (due to soil flexibility) as well a reduction in the acceleration within the structure (due to soil damping)[1]. One way of incorporating soil-structure interaction effects to a structural model is by modeling the soil with springs and dashpots at the foundation level. The springs model the soil stiffness while the dashpots model the soil damping. Theoretical derivations of soil stiffness and damping parameters during dynamic soil-structure interaction evaluation have been developed in the literature (e.g. [2],[3],[4]), and measured in the field [5], but it is difficult for engineers without a strong background in free-vibration theory to visualize and interpret the impact of the values. In this paper we show a practical way of evaluating and visualizing the flexibility and damping associated with dynamic soil-structure interaction by utilizing force-displacement and moment-rotation relationships. The relationships provided herein are inspired by stress-strain relationships and the results in this study are evaluated in a similar way to such relationships. We first show how to obtain the ordinates and abscissa terms for the plots from forced vibration test data. We then apply the procedure to field performance data collected from forced vibration tests applied to a portable test structure at two different sites. We conclude the paper by comparing the results of these tests and commenting on the effectiveness of the relationships presented.

II. STRUCTURE AND SOIL SITES

In this study we use data collected from forced vibration tests on a portable test structure at two locations. The first testing location was at the Wildlife Refuge Liquefaction Array (WLA) site. This site is located in California, 13 km north of Brawley and 160 km east of San Diego. The site consists of an approximately 3 m thick clay layer on top of a 3-4 m loose sand layer, which is susceptible to liquefaction [6]. The average shear wave velocity in the upper 5 m of the site is113 m/s. The second testing location was at the

Garner Valley Downhole Array (GVDA) site. The site consists mainly of silty sand materials up to a depth of 18 m below ground surface. The average shear wave velocity near the surface is reported as 187 m/s. The soil conditions at these sites are quite different from one another and hence allowed us to compare the effect of site differences on the dynamic behavior of the structure.

The portable test structure has a height of 2.88 m with plan dimensions of 4.26 m X 2.13 m. The base slab and top slabs have thicknesses of 0.61 m and 0.25 m respectively.Steel columns support the reinforced concrete top slab. A rigid base slab serves as the foundation of the structure, and was cast in-situ at both sites. The structure is equipped with removable cross-bracings. This allows for modifying the structural stiffness. [7] reports fixed-base frequency (frequency of structure excluding the soil) of 11.8 Hz and 11.6 Hz in the longitudinal and transverse directions respectively for the structure without the braces, and 32.5 Hz and 24.1Hz for the structure with braces. The structure was subjected to steady state forced vibration frequencies in both horizontal directions by a relatively small shaker that operates over a wide frequency range (4 – 54 Hz). The shaker is located at the top slab of the structure. During these tests, the structure was monitored by accelerometers, pressure cells, and displacement transducers. Fig. 1 shows a schematic of the structure and the accelerometer sensor locations. The sensor identification numbers are given.

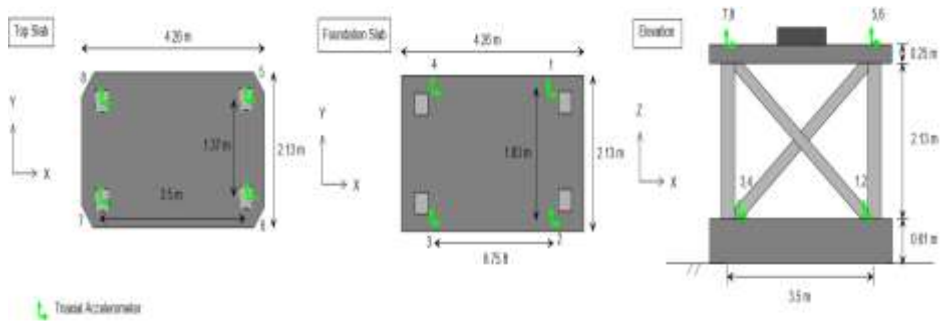

Figure 1. Schematic of portable test structure with accelerometer sensor layout

The sensor locations are used in developing the relationships in the following section. Further information regarding the structure and the instrumentation are provided in [6].

III. FORCE DISPLACEMENT AND MOMENT ROTATION RELATIONSHIPS FROM TEST DATA

In this section we present the procedure to develop the force-displacement and moment -rotation relationships via force vibration tests on the aforementioned test structure. We first develop a model of the soil-structure system. The model as depicted in Fig. 2, is essentially a 3-degree of freedom system. The degrees of freedom included are structural translation and foundational translational and rocking. The model is sufficient for the portable structure used in this study, but can easily be extended to structures having multiple stories as shown in [8].Structural information needed includes the foundation mass, m_f, the structural mass, m_s, the thickness of the foundation, H_f, and the overall height of the structure, H. In the model, structural translation is described byu_{st}, the total structural displacement andu_{sr}, the relative displacement between the top and bottom of the structure. The foundational degrees of freedom are described byu_f, the foundation displacement, and θ_f, the foundation rotation. Below we show how to determine these displacements using acceleration sensor data.

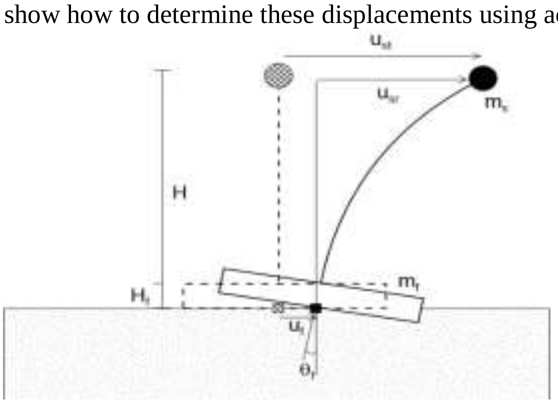

Figure 2. Schematic of the test structuremodel

We first calculate the foundation rotation by extracting time histories recorded at the vertical sensors at the corners of the bottom slab. Referring to the sensor locations in Figure 1, for forced vibration testing in the longitudinal ('x' direction in the figure) and with the assumption of a rigid foundation, the rotational acceleration can be calculated as:

$$\ddot{\theta}_f = \frac{(\ddot{u}_4 - \ddot{u}_1)}{d} \quad (1)$$

where,

$\ddot{\theta}_f$ is the rotational acceleration

$\ddot{u}_4$ and $\ddot{u}_1$ are the measured vertical accelerations on sensor 4 (or sensor 3) and sensor 1 (or sensor 2) respectively

d is the horizontal distance between sensors 4 and 1

For forced vibration loading in the transverse or 'y' direction, the vertical accelerations should be measured using sensor 2 (or sensor 3) and sensor 1 (or sensor 4) respectively.

To capture SSI effects the sliding displacement must be determined at the base of the foundation. As depicted in Fig. 1 and as is the case for most instrumented structures, the sensors are located at the top of the foundation slab. Using the model in Fig. 2, we convert these measured motions to bottom-of-foundation motions by subtracting the acceleration caused by the foundation rotation:

$$\ddot{u}_f = \ddot{u}_{\text{top of foundation}} - H_f \times \ddot{\theta}_f \quad (2)$$

where,

$\ddot{u}_f$ is the horizontal (sliding) acceleration at the base of the foundation

$\ddot{u}_{\text{top of foundation}}$ is the measured horizontal acceleration at the top of the foundation

Thehorizontal sliding acceleration from (1) and rotation acceleration from (2) are then converted to displacements by double integration.

The calculations of base shear and moment are once again based on the model presented in Fig. 2. The total shear force at the base of the foundation is calculated by adding all the forces generated in the model due to the vibration. From Fig. 2, and as derived in [5],[8],and [9] the equation of motion for the foundation translation degreeoffreedom can be written as:

$$F_{\text{shaker}} = m_s\ddot{u}_{st} + m_f\ddot{u}_f + c_f\dot{u}_f + k_f u_f \quad (3)$$

where,

F_{shaker} is the shaker force

$\ddot{u}_{st}$ is the horizontal acceleration at the roof

$\dot{u}_f$ is the measured horizontal velocity at the top of the foundation

c_f and k_f are the foundation translational damping and stiffness

Rearranging (3) we get:

$$F_{\text{shaker}} - m_s\ddot{u}_{st} - m_f\ddot{u}_f = c_f\dot{u}_f + k_f u_f \quad (4)$$

The left side of (4) is the total force acting at the base of the foundation level, i.e. the total base shear. The right-hand side of the equation is termed the foundation translational impedance; i.e. the translational foundation stiffness and damping.

Similarly, the equation of motion at the foundation rotational degree of freedom can be written as:

$$HF_{\text{shaker}} = m_s H\ddot{u}_{st} + I_f\ddot{\theta}_f + c_\theta\dot{\theta}_f + k_\theta\theta_f \quad (5)$$

where,

I_f is the mass moment of inertia of the foundation

c_θ and k_θ are the foundation rotational damping and stiffness

Rearranging (5), we get:

$$HF_{\text{shaker}} - m_s H\ddot{u}_{st} + I_f\ddot{\theta}_f = c_\theta\dot{\theta}_f + k_\theta\theta_f \quad (6)$$

The left side of (6) is the total moment acting at the base of the foundation level, i.e. the total overturning moment. The right-hand side of the equation is the termed as the foundation rotational impedance; i.e. rotational foundation stiffness and damping.

IV. RESULTS

The base shear from (4) and the moment from (6) as well as the horizontal sliding and rotationfrom double-integrating (1) and (2) can be used to plot shear-sliding and moment-rotation relationships.

Low-amplitude forced-vibration tests were carried out at 5 Hz, 7 Hz and 11 Hz. These tests were harmonic tests involving shaking the structure at a single frequency until a steady state response was reached. We first present the results obtained from tests carried out in the longitudinal direction performed at the WLA site (Fig. 3).

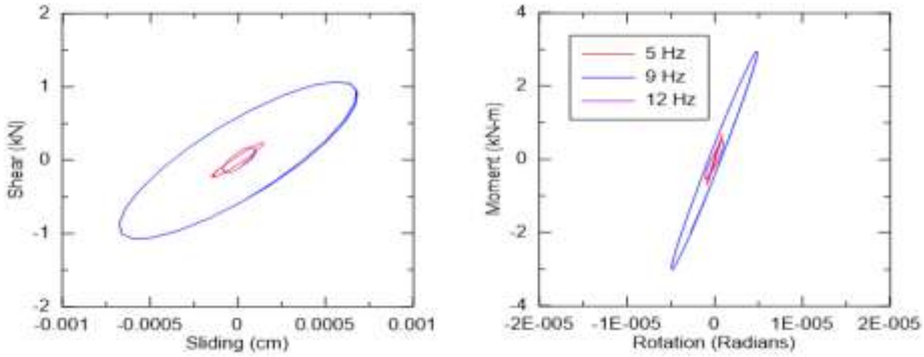

Figure 3. Shear versus base-sliding-displacement and moment versus base-rotation response of unbraced structure with shaking in longitudinal direction at WLA site.

The secant moduli of the shear-sliding which is an indicator of the foundation soil's stiffness, does not change much with frequency. It can be inferred that the stiffness is almost frequency independent. The secant moduli of the moment-rotation loops however decrease with frequency, indicating foundation rocking stiffness is frequency dependent. Furthermore, the "fatness" of the hysteresis loops is greater for shear sliding when compared to moment-rotation. This indicates that the shear-sliding deformation is more effective in dissipating energy.

For the testing along the transverse direction, similar results are obtained (Fig. 4). The shear-sliding deformation is once again less frequency dependent than moment-rotation. Also, the shear-sliding deformation is more efficient in energy dissipation. Comparing the longitudinal response results to the transverse results it can be seen that the secant moduli of the shear-sliding figure is very similar in both shaking directions. However, the secant moduli of the moment-rotation response is larger in the longitudinal direction compared to the transverse direction. This indicates that the rotational soil response is stiffer for longitudinal loading compared to transverse.

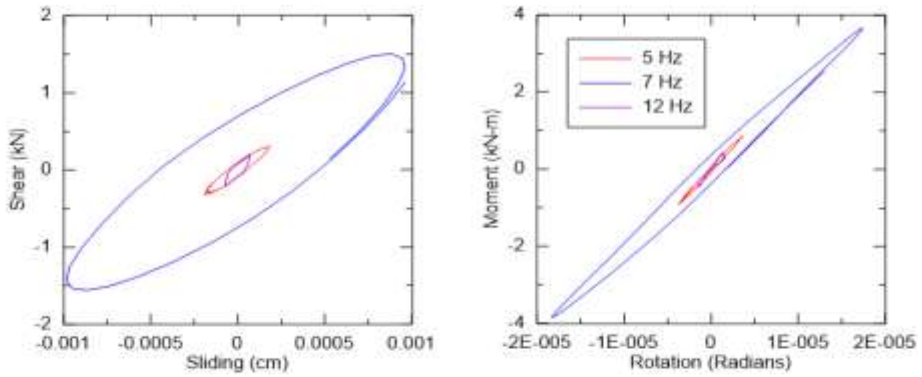

Figure 4. Shear versus base-sliding-displacement and moment versus base-rotation response of unbraced structure with shaking in transverse direction at WLA site

In both the transverse and longitudinal directions the amplitude of the shaker force is nearly constant, but the amplitude of the loops varies substantially between frequencies. The variation can be attributed to the inertial response of the structure, particularly near the resonant frequency of the soil-structure system. As noted in the Sites and Testing Structure section of the paper, the first mode fixed-base frequency of the structure is between 11 and 12 Hz, so if the structure were tested independently, we might expect the largest loops near that frequency. However, the soil compliance reduces the stiffness of the soil-structure system and causes the resonant frequency to drop to near 7 Hz.

Forced vibration tests were also performed on the structure with the bracing installed. As noted above, the bracing will make the structure stiffer, and tends to increase the response frequency. Fig. 5 shows the shear - sliding and moment-rotation loops for the braced structure with loading in the longitudinal direction. This is directly comparable to the loading shown in Fig. 3. Fig. 6 shows the loops for the braced structure with loading in the translational direction, and is directly comparable to Fig. 4. The peak response frequency increases from about 9 Hz to about 10 Hz for the longitudinal direction, and from about 7 Hz to about 8 Hz in the transverse direction. Although the structure has changed, the soil site is unchanged, so the stiffness of the soil, as evidenced by the secant-modulus, is basically identical between the braced and the unbraced cases.

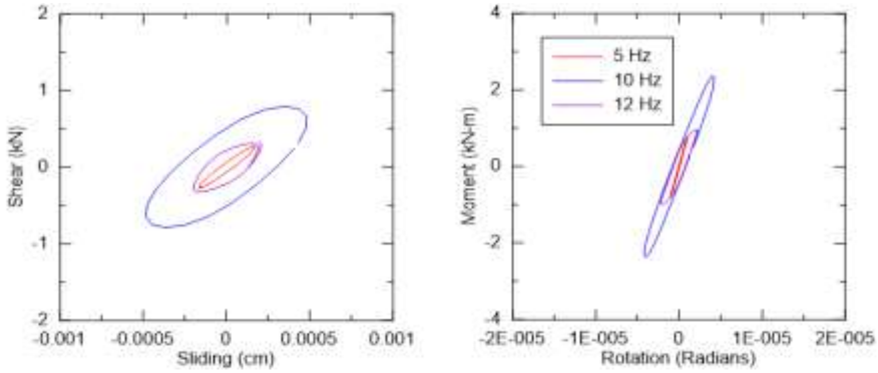

Figure 5. Shear versus base-sliding-displacement and moment versus base-rotation response of braced structure with shaking in longitudinal direction at WLA site

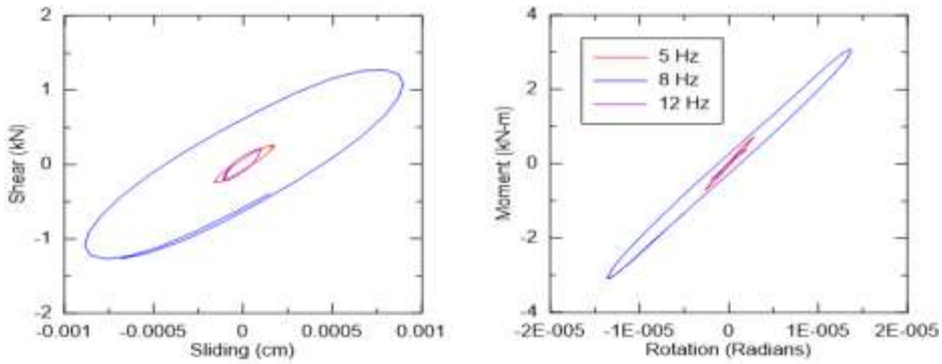

Figure 6. Shear versus base-sliding-displacement and moment versus base-rotation response of braced structure with shaking in translational direction at WLA site

Similar forced vibration tests were performed on the same structure at the GVDA site ([6] and [10]). The structure and forced vibration loading are basically unchanged, so any changes in the response of the soil-structure system will be due to changes in the soil. Fig.7 presents the shear versus translation and moment versus rotation for tests carried out in the transverse direction. The loops for this site produce consistent inclination across the frequencies. This suggests that the translational and rocking are nearly frequency independent. The loops are once again fatter for the shear sliding case indicating that the shear-sliding deformation mode is more effective in foundation-soil energy dissipation. The structure and loading are comparable to that in Fig 4.for the WLA site; the only change is in the soil conditions. The figures show that the secant modulus is larger, and the fatness of the loops is decreased in Fig. 7 compared to Fig 4.

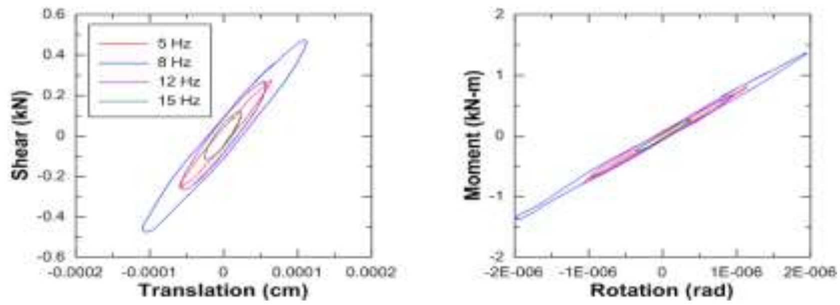

Figure 7: Shear versus base-sliding-displacement and moment versus base-rotation response of unbraced structure with shaking in transverse direction at GVDA site.

V. DISCUSSION AND CONCLUSIONS

We present a practical method that can be applied to forced vibration tests to visualize important SSI characteristics. The procedure enables plotting base-shear against sliding and moment versus rotation, which provides information on foundation soil stiffness and foundation soil energy dissipation capabilities. This method utilizes the measured response of an experimental model test structure subjected to forced vibration loading. The calculation of required structural response values from commonly measured structural acceleration data is shown. The effectiveness of the procedure is then demonstrated by applying it to forced vibration tests carried out on a portable test structure on two sites having different soil characteristics. Information about the stiffness, damping and peak response characteristics of the SSI system can be gleaned from the visualized data. The results show that the translational stiffness was nearly frequency independent. The rotational stiffness was found to have strong frequency dependency. The plots also revealed that the shear-sliding deformation is more effective in energy dissipation. It can also be seen that, the energy dissipation characteristics of the WLA site was higher to that of the GVDA site. This can be explained by the fact that the structure-to-soil-stiffness ratio at the GVDA site is higher than that for the WLA site and hence soil-structure interaction effects are less pronounced. In summary, the force-displacement and moment-rotation relationships presented in this study prove to be effective in describing soil-structure interaction characteristics of sites.

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