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System Identification Analysis on Soil-Structure Interaction Using Field Data

현장자료를 사용한 지반-구조물 상호작용에 대한 경험적 연구

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요 지

최근 지진공학 제반분야의 연구동향은 지진발생시 구조물의 거동을 보다 합리적/경제적으로 고려하는 내진성능 목표 개념에 입각하여 많은 향상을 성취하고 있다. 특히, 실제 지진에서 관측된 자료를 사용하여 시방기준과 해석기법에 많은 보완이 이루어지고 있는 실정이다. 그러나, 지반-구조물 상호작용에 대한 연구는 경험적으로 입증된 해석방법의 정립이 아직까지 과제로 남아있는 분야이다. 이러한 취지에서, 본 연구에서는 구조물과 지표면 자유장 운동의 강진기록이 잘 관측되어 있는 2개 사이트를 선택하여, 입/출력 자료를 가지고 시스템 특성치를 추정할 수 있는 System Identification 기법을 이용하여 지반-구조물 상호작용의 해석기법 중 가장 보편적이며 비교적 간단한 주파수 영역의 Impedance 함수를 계산하고 그 결과를 바탕으로 관성력에 의한 지반-구조물 상호작용에 대한 고찰을 수행한다.

Abstract

In the field of earthquake engineering, recent improvements in many areas, such as seismological source modeling, analysis of travel path effects, and characterization of local site effects on strong shaking, have led to significant advances in both code-based and more advanced procedures for evaluating earthquake ground motions. A missing link, however, is empirically verified design procedures for assessing the effects of soil-structure interaction (SSI). Available Soil-Structure Interaction (SSI) analysis techniques range from simple substructure-type procedures to relatively sophisticated finite element procedures. The most common substructure approach for foundation-soil interaction is to use a frequency-dependent and complex-valued impedance function. This study uniquely evaluates impedance functions for two well-instrumented sites with significant inertial SSI effects using a system identification technique. The system identification analysis results are then compared to predictions from a simple theoretical model to gain insight into the intertial interaction effect in the subject sites.

Keywords : Empirical study, Inertial interaction, Lotung nuclear containment model, Newport beach hoag hospital, Soil-structure interaction (SSI)

1. Introduction

It is common in seismic structural design practice to assume that the motion at the base of a structure is identical to the free-field motion, and that the structure is fixed at its base. However, this assumption is true only for the hypothetical case of structures supported on rigid ground. In reality, inertial forces developed in the

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superstructure lead to base moment and shear, which introduce rocking and translation of the foundation relative to the free-field. Structural response can be significantly influenced by the flexibility of foundation support and by the dissipation of vibrational energy through radiation and hysteretic damping in the foundation. This phenomenon is commonly termed as "Inertial Interaction" and quantified by a frequency-dependant and complex-valued impedance function. Further, the presence of stiff foundation elements in soil makes the foundation motion differ from the free-field motion in the presence of inclined or incoherent waves. This phenomenon is termed as "Kinematic Interaction" and quantified by a frequency-dependant transfer function. These various effects are collectively termed as Soil-Structure Interaction (SSI) and can significantly influence the seismic response of structures.

This paper focuses on empirical study of the inertial interaction, which is usually the most significant factor in SSI effects, with well-instrumented sites. First, closed-form solutions of the impedance function utilizing motion recordings are introduced. Then, impedance functions with different approaches are compared to gain insights into the SSI problems.

2. Dynamic Response of Elastic Structure on Compliant Base

2.1 System Considered

The problem considered in this paper is related to the response of a multi-degree of freedom structure founded on a compliant base. A simple representation of such a system is illustrated in Figure 1. The solution of the dynamic response of this system incorporates the effects of inertial soil-structure interaction, which is associated with foundation rocking (θ_f) and displacement (u_f) arising from base shear and moment.

The structure in Fig. 1 consists of a multi degree of freedom system with height H, floor masses m_i, stiffnesses k_i, and damping coefficients c_i. Foundation-soil interaction is represented by an impedance function (i.e., $\bar{k}_u$ and $\bar{k}_\theta$ for the horizontal and rocking complex-valued spring stiffnesses). Displacement, u_g, represents the free-field ground motion, u_i is the distortion of the structure at mass i, and u_f and θ_f represent the translational and rocking deformations at the foundation level, respectively.

2.2 Solution of Equation of Motion for Impedance Function

Kim (2001) solved the equation of motion for a five-degree of freedom (dof) system that includes two dof associated with foundation compliance (translation and rocking), and three translational dof associated with the structure. Kim (2001) also derived the impedance function out of the equation of motion for a multi-degree of freedom system utilizing actual motion recordings and the empirical impedance function is as follows:

$$\bar{k}_u = \frac{(\bar{u}_{ft} + H\bar{\theta}_f + \frac{\bar{u}_{s,N}}{\Gamma_1})\omega^2 M_{13} + \omega^2 m_f \bar{u}_{ft} - \omega^2 M^{*1}\bar{\theta}_f}{(\bar{u}_f + \frac{\bar{k}_{u\theta}}{\bar{k}_u}\bar{\theta}_f)}$$

$$= \frac{\ddot{u}_{t1}}{\bar{u}_f} \cdot \frac{\omega^2 M_{13}(1+A)}{(1+B)}$$

$$\bar{k}_\theta = \frac{(\bar{u}_{ft} + H\bar{\theta}_f + \frac{\bar{u}_{s,N}}{\Gamma_1^2})\omega^2 M_{13} H + \bar{u}_{ft}\omega^2 (m_f h_f - M^{*1}) + \bar{\theta}_f \omega^2 M^{*2}}{(\bar{\theta}_f + \frac{\bar{k}_{\theta u}}{\bar{k}_\theta}\bar{u}_f)}$$

$$= \frac{\ddot{u}_{t2}}{\bar{\theta}_f} \cdot \frac{\omega^2 M_{13} H(1+C)}{(1+D)} \qquad (1)$$

where, Γ : modal participation factor
M : mass of structure
H : height of structure
u_{ft} : total foundation horizontal translation
u_f : foundation horizontal translation relative to free field motion (u_g)
θ_f : foundation rocking
u_s : translation of roof relative to rotated foundation

Among the above motions, only u_{ft} is directly recorded, the others being inferred as follows:

$$u_f = u_{ft} - u_g$$

$$\theta_f = (u_{fv1} - u_{fv2})/2r_f$$

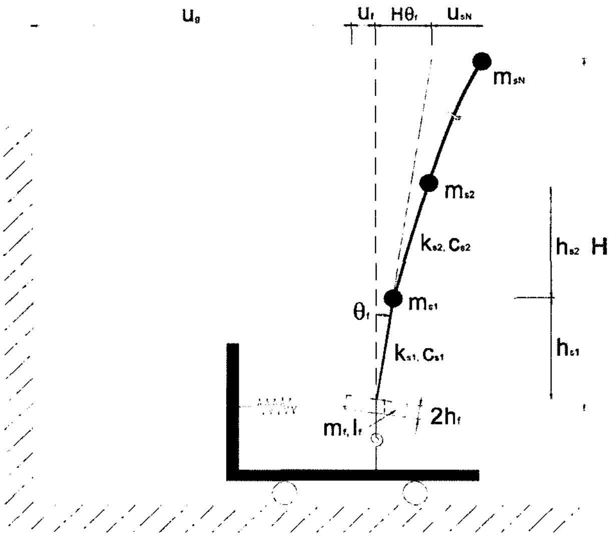

Fig. 1. Simplified model for analysis of inertial interaction

where, u_{fv1} and u_{fv2} are vertical motions recorded on opposite sides of the foundation, and r_f = foundation radius

$u_s = u_t - u_{ft} - H\theta_f$

where, u_t is the total roof horizontal translation

$$\bar{u}_{t1} = \bar{u}_{ft} + H\bar{\theta}_f + \frac{u_{sN}}{\Gamma_1}, \quad \bar{u}_{t2} = \bar{u}_{ft} + H\bar{\theta}_f + \frac{u_{sN}}{\Gamma_1^2}$$

$$A = \frac{m_f u_{ft} - M^{*1}\theta_f}{M_{13} u_{t1}}$$

$$B = \frac{k_{u\theta}}{\bar{k}_u} \cdot \frac{\theta_f}{\bar{u}_f}$$

$$C = \frac{(m_f h_f - M^{*1})\bar{u}_{ft} + M^{*2}\theta_f}{M_{13} H \bar{u}_{t2}}$$

$$D = \frac{k_{\theta u}}{\bar{k}_\theta} \cdot \frac{u_f}{\bar{\theta}_f}$$

The details of derivation of these equations will be omitted herein. However, it should be noted that the equations enable us to evaluate impedance functions from actual motion recordings at structure, foundation, and free-field. In the following section, two well-instrumented sites are utilized to obtain insights into the inertial interaction with the aforementioned unique way of empirical approach.

3. Analysis of Impedance Fuctions from Seismic Recordings

3.1 Lotung Site

3.1.1 Site Description

The structure is a reinforced concrete ¼ scale model of a nuclear containment facility as shown in Figure 2. The ¼ scale structure is part of the Lotung large-scale seismic test (LSST) facility in Taiwan. This facility also has a 1/12 scale containment structure and a free-field array of 15 ground surface instruments (FA1-1～5, FA2-1～5, & FA3-1～5) spaced 5 to 100 feet (1.5 to 30 m) from the ¼ scale model and two downhole arrays (DHA & DHB) to depths of about 150 feet (45 m). As shown in Fig. 2, accelerographs are present on four sides of the structure at the base level and about 8.5 feet (2.6 m) below the roof level. Three free-field instruments were used in the analysis, each located 100 feet (30 m) from the structure.

The site is located on level terrain near the southern end of the Lanyang River plain. Soil conditions encountered at the site consists of about 10 feet (3 m) of silty sand and sandy silt with some gravels, about 100 feet (30 m) of silty sand, sandy siltand clayey sand, and about 90 feet (27 m) of silty clay and clayey silt. Based on depth-to-groundwater measurements, the soils are assumed to be saturated below a depth of 3 feet (1 m).

3.1.2 Estimation of Impedance Functions from System Identification Analysis

Strong motion recordings at the Lotung site were obtained for event LSST07, an m_L=6.5 event that occurred approximately 66.2 km from the Lotung site. The mathematical formulation for deriving impedance functions from strong motion data was presented previously.

The actual calculation of impedance functions can be performed in two ways. First, Eq. 1 is invoked exactly as written, by using the Fourier transforms of the respective time histories to calculate the ratios. While this provides a simple and direct means of calculation, no insight is gained into the effects of noise on the identification. Accordingly, a second method of analysis is performed

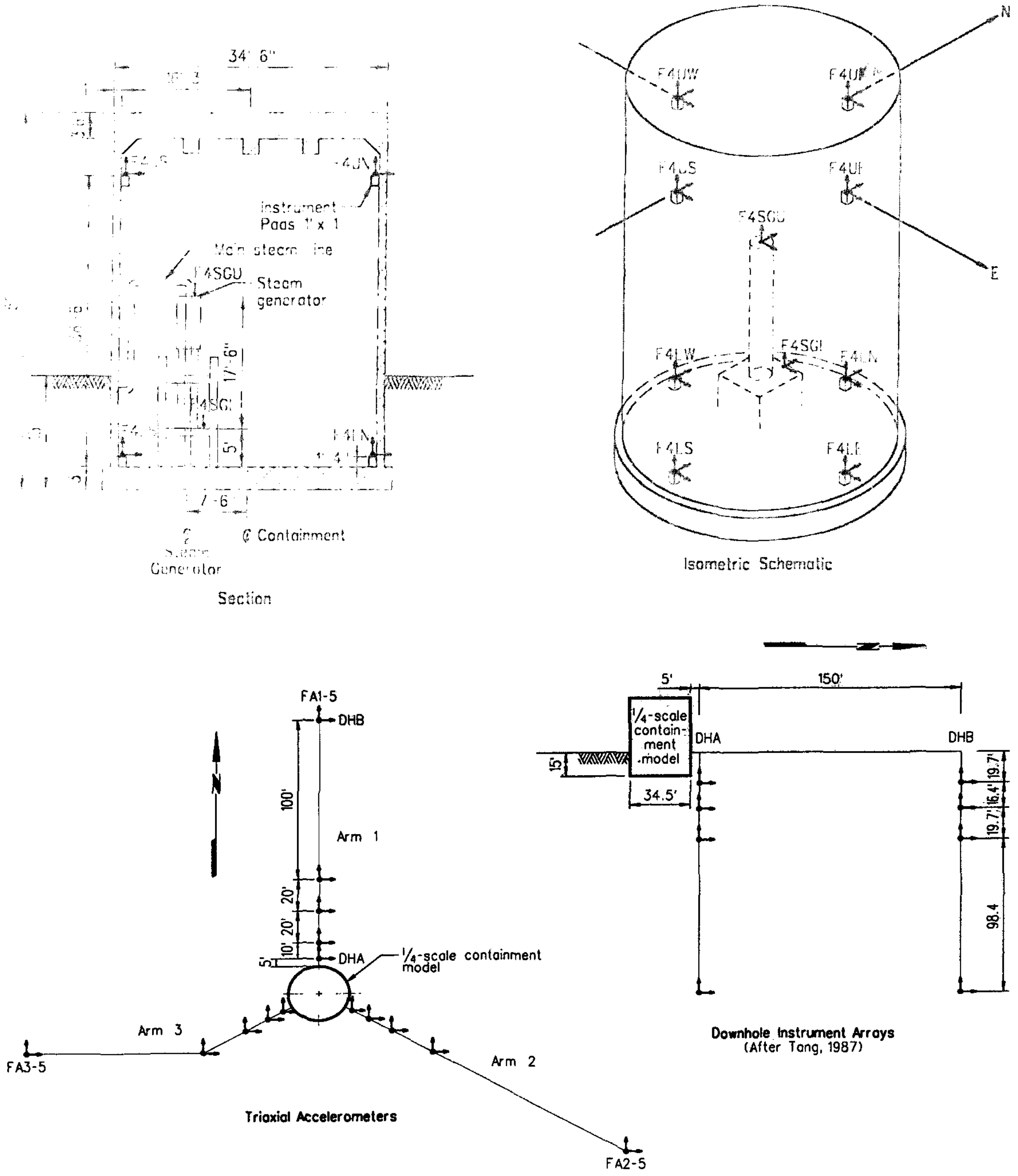

Fig. 2. ¼ scale nuclear containment model at Lotung, Taiwan

in which transfer functions are estimated using transmissibility functions, which are combinations of power spectral density functions (S_{xx}, S_{yy}) and cross spectral density functions (S_{xy}) of input (denominator) signal x(t) and output (numerator) signal y(t). For the analysis of transmissibility functions, the input and output time series were evaluated by summing the appropriate motions in the time domain.

Two estimates of complex-valued transmissibility functions are possible from an input and output time signal,

$$H_1(i\omega) = S_{xy}(\omega)/S_{xx}(\omega)$$
$$H_2(i\omega) = S_{yy}(\omega)/S_{xy}(\omega) \qquad (2)$$

where, ω = angular frequency and $i = \sqrt{-1}$.

The quality of the transmissibility function in the presence of noise and nonlinearities can be assessed using the coherence function, which is defined as the ratio of the first two estimates of H(i) [Pandit (1991); Johansson

(1993)]:

$$\gamma^2(i\omega) = \frac{H_1(i\omega)}{H_2(i\omega)} = \frac{|S_{xy}(\omega)|^2}{S_{xx}(\omega)S_{yy}(\omega)} \tag{3}$$

If the coherence is close to one, it may be inferred that the noise level is low and that there is a nearly linear response between input and output. Estimates of H(iω) with coherencies less than one are common in practice, indicating that the magnitude of $H_2(i\omega)$ exceeds that of $H_1(i\omega)$.

Results of the system identification studies are presented in Figure 3. Figure 3 presents the impedance functions, with the complex part re-expressed as a dashpot coefficient by taking the absolute value of the imaginary part and dividing by angular frequency ω. The respective coherence functions are also shown with each impedance function.

According to Kim (2001), the referenced motions and modifiers for the translational vibration mode are out of phase at some frequencies. This can result in negative calculated foundation stiffnesses. This obviously erroneous result occurs because relative translational motions are small and may be significantly affected by noise or other

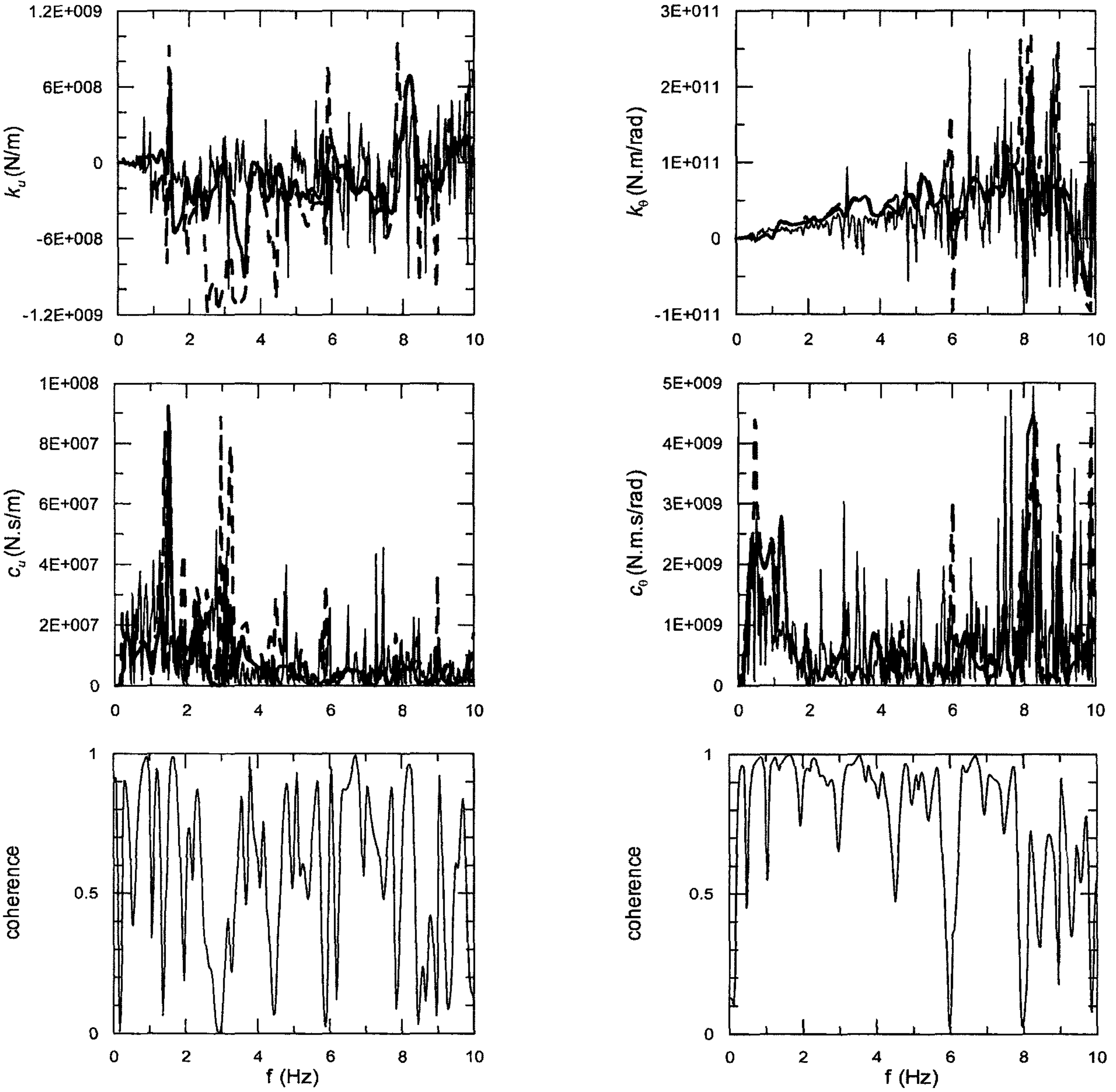

Fig. 3. Identified impedance functions for the EW direction of Lotung site (dashed bold line by using Fourier transform; solid line by using Transmissibility function)

identification errors. Moreover, coherence estimates for translational vibration are low. Accordingly, the impedance estimates for the translational vibration mode are not considered reliable.

For the rocking vibration mode, impedance estimates over a frequency range of f~1-2.5 Hz are reasonably coherent, indicating that the identification may be reliable. Not surprisingly, where the coherence is high, impedance estimates derived from direct use of Fourier Transform and from the H_1 and H_2 transmissibility functions are nearly identical.

3.1.3 Comparison with Elastic Half Space Solution

Apsel and Luco (1987) provided a rigorous solution for impedance functions for circular foundations embedded in a visco-elastic halfspace. The analytical formulation is based on a foundation that is rigid, massless, and perfectly bonded to the soil.

Figure 4 compares the identified rocking impedance for the Lotung site to the elastic solution by Apsel and Luco (1987). Evaluation of the theoretical impedance function requires the selection of a representative V_s for the site. In Fig. 4 (a), I show the degraded Vs profile by the equivalent linear procedure in SHAKE for the three estimates of the Vs profile (i.e., best estimate and upper/lower bounds). Figs. 4 (b) and (c) show the identified impedance function compared to Apsel and Luco predictions. The identified impedances are shown as solid lines at the frequency range with high coherence (f~1-2.5 Hz) and as dashed lines for other frequencies. These predictions were prepared so that the uniform halfspace shear wave velocity matches the system identification results at ~2 Hz (near the fundamental-mode flexible-base frequency only, A/L-A) and from approximately 1-2.5 Hz (over the full range of impedance where the coherence is high, A/L-B). The velocities were found to be Vs = 70 m/s (A) and 75 m/s (B), which as shown in Fig. 4 (a) are near the lower bound velocity for the soil immediately beneath the base slab.

3.1.4 Findings

The system identification analysis results using actual motion recordings at Lotung site were compared to an analytical solution. The comparison may result in the

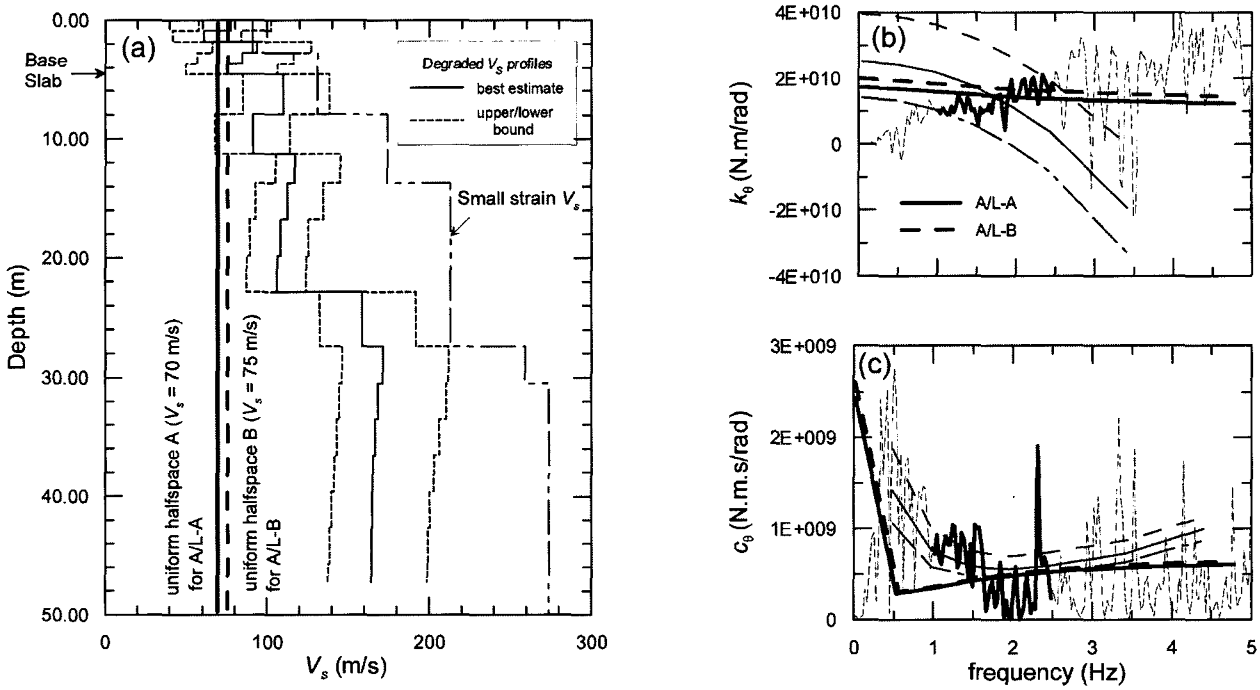

Fig. 4. Comparison of impedance function with an elastic solution by Apsel and Luco (1987) for the Lotung site. Impedance ordinates shown with a heavy line have high coherence and are considered reliable; ordinates shown with a dashed line have low coherence and are considered unreliable

following conclusions:

(1) only soil within close proximity of the base of the foundation significantly contributes to rocking impedance function and

(2) it appears that shear strains beyond those occurring in the free-field may contribute additional modulus reduction, but such effects appear to be "second" order relative to modulus reduction associated with free-field ground strains.

3.2 Newport Beach Site

3.2.1 Site Description

The structure is an 11-story hospital building with no basement, and is rectangular in plan (154 by 77 feet / 47 by 23.5 m). Located adjacent to the structure on the northeast side is a 12-story elevator tower, and several large two-story buildings are present along the entire north and east sides of the structure. The lateral load resisting system consists of perimeter concrete shear walls in both directions. A concrete frame in the building's interior was designed to only carry vertical loads. The foundation consists of shallow footings and has an approximate mass of m_f=66×10^4 kg and a mass moment of inertia in the EW direction of I_f=57×10^6 kg-m^2 (based on a concrete density of ρ=2400 kg/m^3). The superstructure has an estimated mass of M_{13}=600×104 kg, and the mass moment of inertia is 152×10^7 kg-m^2. As shown in Fig. 5, accelerographs are present at the service level, 3rd floor and roof of the structure. The free-field instrument is located about 650 feet (198 m) southwest of the structure in a landscaped area below a parking lot.

The site is on the Newport Mesa near the Pacific Ocean. A south sloping coastal bluff up to about 50 feet (15.2 m) high is present below the hospital and free-field instrument. The hospital structure is on relatively flat terrain, while the free-field instrument is on moderately sloping ground (1H:10V slopes) near the bluffs. The soil conditions consist of about 50 feet (15.2 m) of sandy terrace deposits, which are underlain by Monterey Formation siltstone and shale bedrock. The free-field instrument is located near the geologic contact between the

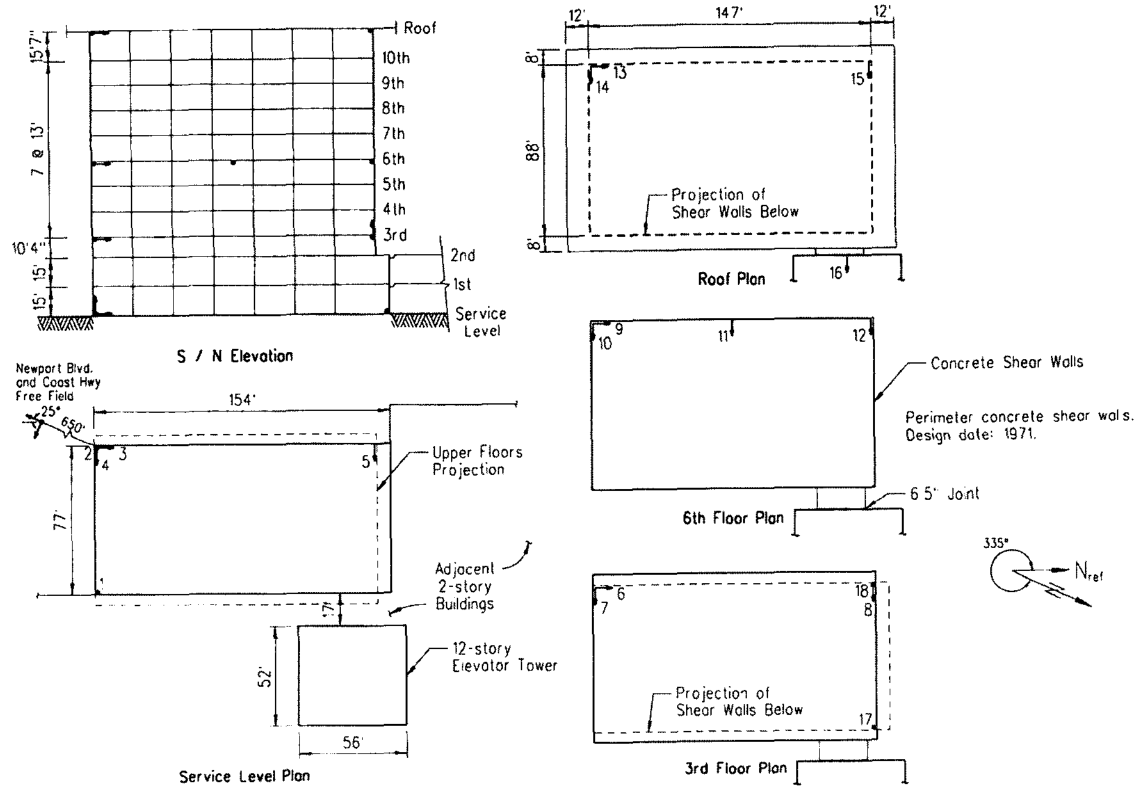

Fig. 5. Newport Beach Hoag Hospital

Terrace deposits and bedrock and is believed to be founded on rock.

3.2.2 Estimation of Impedance Functions from System Identification Analysis

Strong motion recordings at the Newport Beach site were obtained for the 1994 Northridge Earthquake, an m_w=6.7 event that occurred approximately 84.6 km from the site (measured as closest distance to fault plane). The accelerometers used herein are located on the north wall for resisting EW (transverse) motions, which is assumed to resist one-half of the structure's inertial forces.

From Fig. 6, the translation results show low coherence at all frequencies, and hence it is not possible to identify reliable translational impedance functions. However, the rocking results show high coherence for f ~ 0.9-1.3 Hz, and these are the only results that are considered reliable.

3.2.3 Comparison with Elastic Half Space Solution

Fig. 3.7 shows analysis results for the Newport Beach site. The format is similar to that presented above for the Lotung site. This site has perimeter walls around the foundation, and hence use of a rigid circular foundation model is reasonable. A major distinction between this site

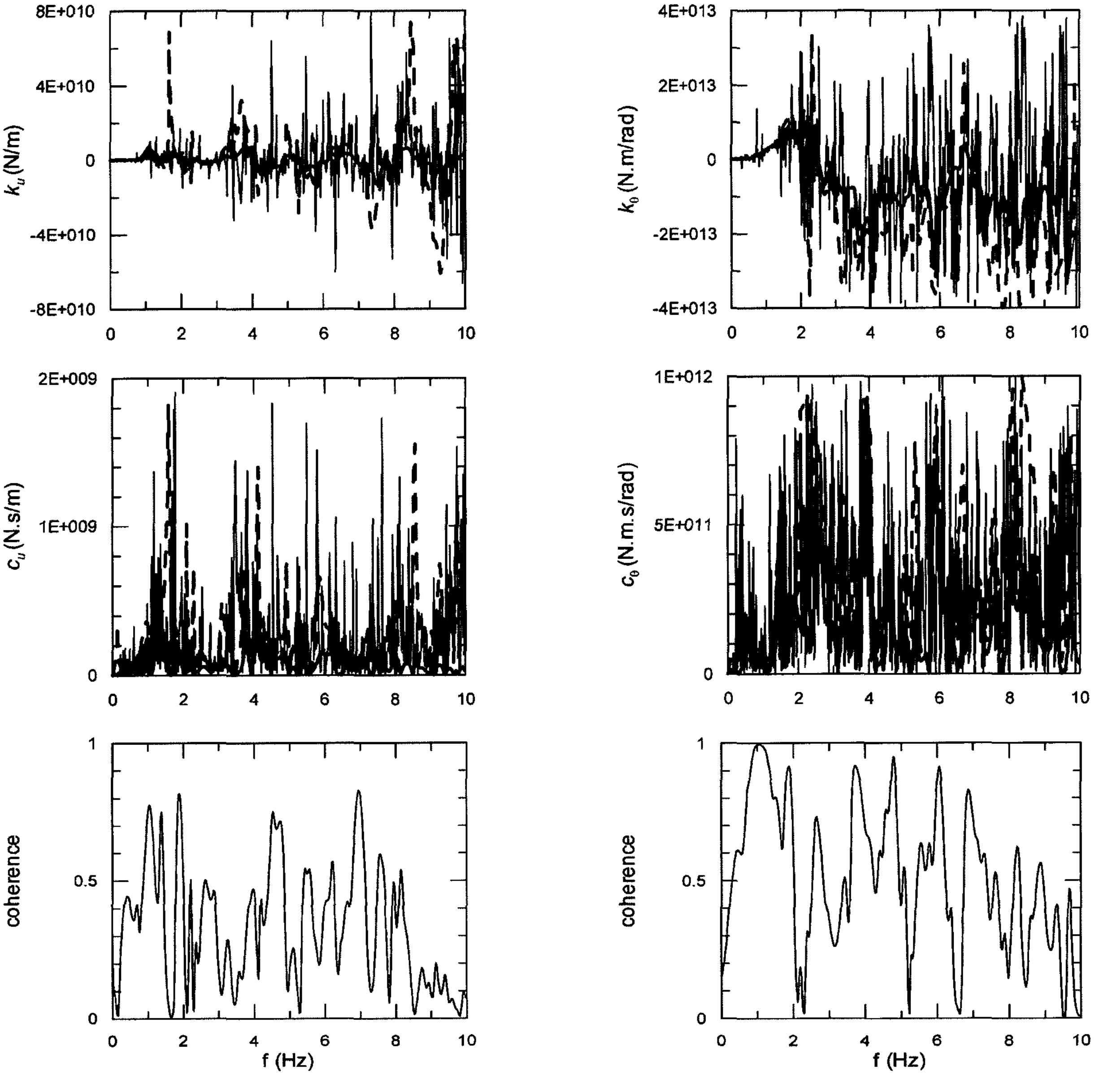

Fig. 6. Identified impedance functions for the EW direction of Newport Beach site

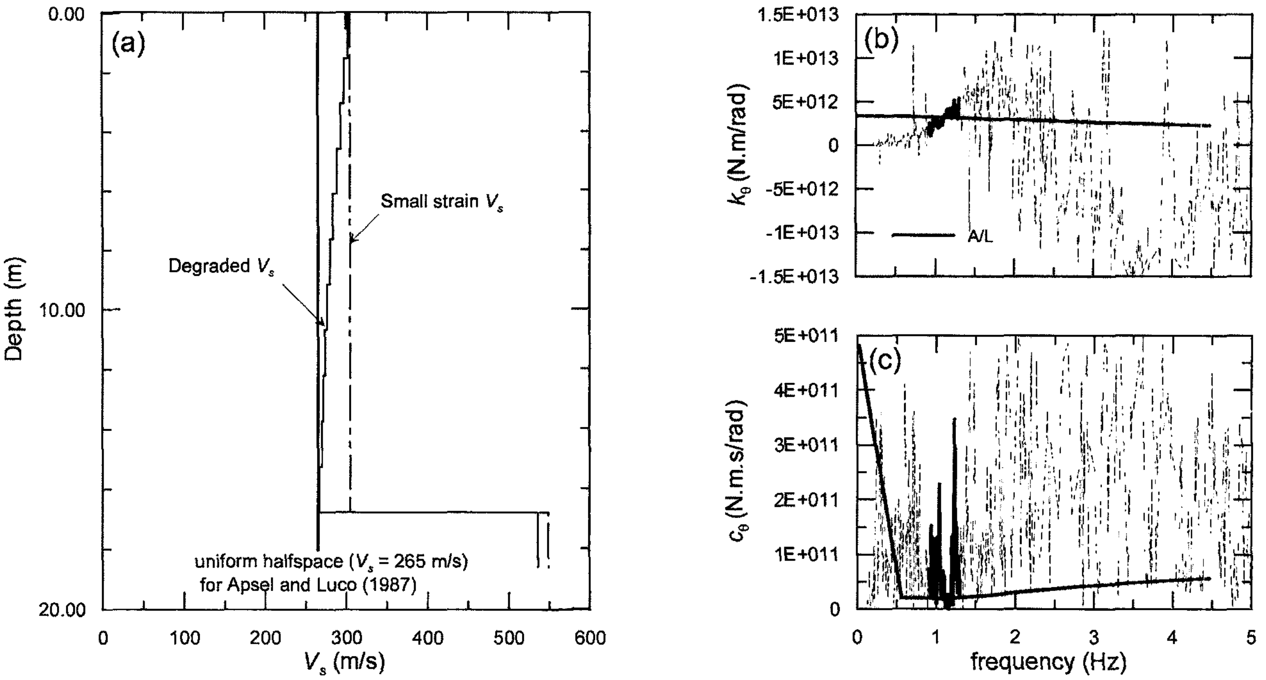

Fig. 7. Comparison of impedance function with an elastic solution by Apsel and Luco (1987) for the Newport Beach site. Impedance ordinates shown with a heavy line have high coherence and are considered reliable; ordinates shown with a dashed line have low coherence and are considered unreliable

and Lotung, however, is the relatively low quality of the V_s data. The V_s value that causes the A/L model to match the identified impedance is identified in Part (a) of the figure, and the A/L prediction is compared to observation in Parts (b)-(c) of the figure. The V_s value identified in this way is reasonably close to the previously published V_s estimate for the site (Stewart and Stewart, 1997).

3.2.4 Findings

The system identification analysis results using actual motion recordings at Newport Beach site were compared to an analytical solution. The comparison may result in the following conclusions similar to those of the Lotung site:

(1) only soil within close proximity of the base of the foundation significantly contributes to rocking impedance function and

(2) unlike the Lotung site, it does not show additional modulus reduction due to relatively small inertial effect of this particular site

4. Conclusions

The objective of this paper is to gain insights on inertial soil-structure interaction based on system identification analysis using field data. For this purpose, two well-instrumented sites were chosen and results from the system identification analysis were compared with an available elastic half space solution. Based on this empirical study, our findings can be summarized as followings;

(1) Impedance functions were successfully inferred for the rocking deformation mode from strong motion data at the ¼ scale containment structure at Lotung, Taiwan and the Hoag hospital at Newport Beach, USA. The results are considered reliable for both the real and complex parts over a frequency range of 1-5 Hz. Impedance functions could not be identified for the translational deformation mode, possibly due to measurement noise and an apparently small foundation flexibility in this mode.

(2) Only soil within close proximity of the base of the foundation significantly contributes to rocking impedance function.

(3) A comparison of rocking impedance functions to the Apsel and Luco model reveals that additional shear

strain induced by SSI (i.e., beyond that occurring in the free-field) is potentially significant when the inertial interaction is very significant.

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