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System Identification of Buildings with Considering of Soil-Foundation-Structure Interaction

考慮土壤—基礎—結構互制下建築物之系統識別

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Abstract

The main purpose of this research is to develop a system identification method which could identify the dynamic characteristics of the structure with embedded foundation. The interaction between the embedded foundation and the soil is first considered and a soil-foundation-structure interaction model is built to simulate the dynamic behavior. The mechanical characteristics of the embedded foundation is modeled by considering the dynamic embedded foundation stiffness and the damping force which is composed of radiation damping and material damping while. All models used in this research are treated as linear models. The proposed method can get real physical parameters from each floor and the embedded foundation. All the parameters here could provide helpful information about structure safety assessment, structure health monitoring and site investigation. Finally, the feasibility and accuracy of the proposed identification method for structures with embedded foundations is verified by the numerical analysis.

Key Words: System identification, Soil-foundation-structure interaction, Embedded foundation.

摘要

本研究旨在開發一系統識別方法，以識別埋置基礎之結構動態特性。首先考慮埋置基礎與土壤間之相互作用，並建立土壤—基礎—結構之相互作用模型來模擬其動態行為。埋置基礎之力學行為乃以考慮動態基礎勁度和由輻射阻尼與材料阻尼所組成之阻尼力來共同模擬之。建築物與埋置基礎皆視為線性模型，本研究所建議之方法可識別出各樓層與埋置基礎的真實物理參數，這些物理參數將可提供結構安全性評估與健康監測相當有用之訊息。最後，本文藉由數值範例，驗證本文所建議之識別方法運用於具埋置基礎建築物之可行性與準確性。

關鍵詞：系統識別、土壤—基礎—結構互制、埋置基礎

1. Introduction

The traditional seismic design is from a simplified analysis based on the assumption that the building is on the fixed-base. However, the soil, which supports a building, can be deformed and cause certain degrees of movement of a building. This phenomenon can reduce the stiffness of a whole structure system and increase the natural periods. The semi-rigid connection between a structure base and soil caused by soil-flexibility will change the reaction of a structure, and this interactive behavior between structures and soils is so-called Soil-Structure Interaction (SSI). From the study of critical response spectrum, the change of natural periods will cause the obvious change in the acceleration spectrum, so the fierce difference in the structure response will come from the change of natural periods in lateral direction [1,2,3,4,5]. The Soil-flexibility effect is recommended that it evaluate by specific stiffness spring, and prescribed in details in reference [6]. For high-rise structures, it is expectative that the lateral natural period will extend to the long period range in the response spectrum, and the increment of the lateral natural period will decrease the structure responses. So, it is reliable and acceptable that the traditional seismic design ignores the effect of soil-flexibility and is conservative. However, for low-rise structures, usually the natural periods are rather small, and it could be happened in the range where the response spectrum increasing dramatically. Therefore, the phenomena of the extension of the lateral periods caused by SSI will possibly increase the acceleration in the acceleration spectrum. So in the recent studies, the effect of soil-flexibility is strongly recommended not to be ignored [4,7,8].

Due to the larger size of the real structure, it is not simple to assess the benefits of seismic control by experiments. But for better understanding of the dynamic behavior of a structure under earthquakes, it is appropriate to do the field test and the results can be references for future design and construction. Generally, the contents of field tests include Microseism Test, Force Vibration Test and Free Vibration Test. Microseism Test can test the structural behavior under low loading effects (ex. wind load); the result of Force Vibration Test can be considered as structural dynamic behavior under earthquakes with the smaller magnitude; and Free Vibration Test is used for assessing the structural behavior under middle or small magnitude. However, field tests cannot simulate the dynamic behavior under strong earthquakes, which is the most important consideration in structure design. If the monitoring system can be installed on the structure, then the structural dynamic responses can be measured. Based on these data, the dynamic parameters of a building can be evaluated by System Identification Techniques, and the accuracy of a structure model and design can be further clarified.

An identification procedure is developed in the present study in order to figure out the dynamic characteristics of structures with embedded foundations. The active interaction of embedded foundations and surrounding soils are considered in the present study, and the force characteristics of embedded foundations are simulated by dynamic stiffness and damping forces including radius damping and material damping. All the structures and embedded foundations are considered as linear. In the present study, a physical-parameters identification procedure is developed to identify the relevant parameters of each floor and embedded foundation, which can provide useful information for structure safety detection and field investigation.

2. Motion Equation

Considering a linear shear frame with N-th floors and embedded foundation underneath, as shown in Fig. 1, and the wall of the foundation is connected with the soil as Fig. 2. The motion equation is derived as below,

$$m_j \ddot{x}_j + R_j(\dot{x}_j - \dot{x}_{j-1}, x_j - x_{j-1}) = -m_j \ddot{x}_g \quad (1)$$

$$\begin{aligned} & m_{j-1}\ddot{x}_{j-1} + R_{j-1}(\dot{x}_{j-1} - \dot{x}_{j-2}, x_{j-1} - x_{j-2}) \\ & - R_j(\dot{x}_j - \dot{x}_{j-1}, x_j - x_{j-1}) = -m_{j-1}\ddot{x}_g \end{aligned}$$

$$j = 3 \sim N \quad (2)$$

$$\begin{aligned} & m_1\ddot{x}_1 + R_1(\dot{x}_1 - \dot{x}_f, x_1 - x_f) \\ & - R_2(\dot{x}_2 - \dot{x}_1, x_2 - x_1) = -m_1\ddot{x}_g \end{aligned} \quad (3)$$

$$\begin{aligned} & m_f\ddot{x}_f + R_f(\dot{x}_f, x_f) - R_1(\dot{x}_1 - \dot{x}_f, x_1 - x_f) \\ & = -m_f\ddot{x}_g \end{aligned} \quad (4)$$

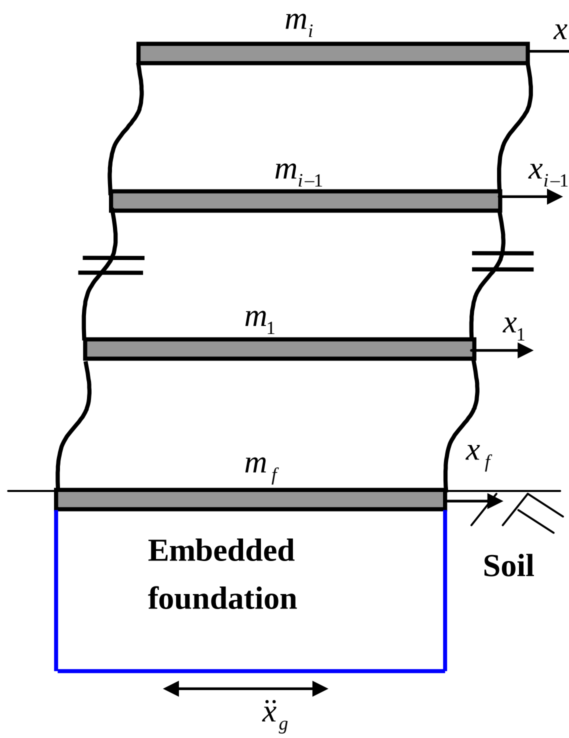

Fig. 1 Structure with embedded foundation

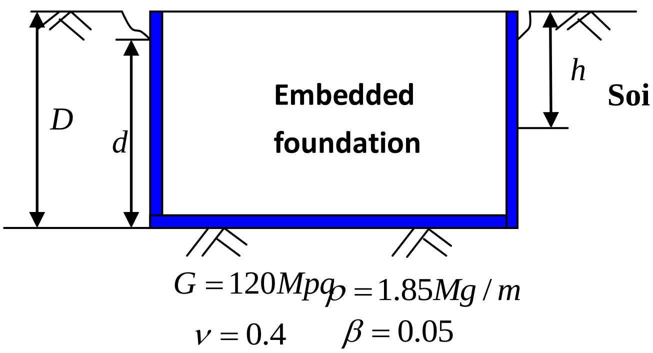

Fig. 2 Embedded foundation and soil profiles

The mass, displacement and restoring force of j-th floor are expressed by m_j, x_j and R_j; the mass, displacement and restoring force at the top of the embedded foundation are expressed by m_f, x_f and R_f; and the ground acceleration is expressed as $\ddot{x}_g$. Based on these notations, the equation (1) to (3) can be rearranged as below,

$$R_j\left(\dot{x}_j - \dot{x}_{j-1}, x_j - x_{j-1}\right) = C_j(\dot{x}_j - \dot{x}_{j-1}) + K_j(x_j - x_{j-1}) \quad (5)$$

$$R_1(\dot{x}_1 - \dot{x}_f, x_1 - x_f) = C_1(\dot{x}_1 - \dot{x}_f) + K_1(x_1 - x_f) \quad (6)$$

$$R_f(\dot{x}_f, x_f) = C_f\dot{x}_f + K_f x_f \quad (7)$$

In which, the damping coefficient and stiffness of *j*-th floor are expressed by C_j and K_j; The damping coefficient and dynamic stiffness of embedded foundation are expressed by C_f and K_f. The dynamic stiffness and damping coefficient of embedded foundation in the horizontal direction will be derived in the next section.

3. Dynamic Stiffness and Damping Coefficients of the Embedded Foundation

Based on Gazetas's research [6], the dynamic behavior of embedded foundation is simulated by the dynamic stiffness and damping in homogeneous half-space. The damping value is combined by the effects of radiation dashpot and material dashpot. When the embedded foundation is in homogeneous half-space as shown in Fig. 2, the dynamic stiffness of embedded foundation in the horizontal direction can be represented as below

$$\tilde{K}_{x,emb} = k_{x,emb} K_{x,emb} \quad (8)$$

In which, the dynamic parameter is expressed by $k_{x,emb}$, and its relevant charts is referred to Gazetas[6]. The dynamic stiffness of embedded foundation $\tilde{K}_{x,emb}$ is the same as K_f in Eq. (7). The damping of embedded foundation is as below

$$totalC_{x,emb} = C_{x,emb} + \frac{2\tilde{K}_{x,emb}}{\omega}\beta \quad (9)$$

The $totalC_{x,emb}$ is the same as C_f in Eq. (7).

4. System Identification

Identification of the system parameters can be conducted once the dynamic responses of the structure subjected to the input excitation are available. Based on an output-error concept [9,10], the system parameters are obtained by minimizing the discrepancy between the recorded and predicted responses of the system. The system parameters so evaluated are considered optimal. The equation for identifying the damping coefficient and stiffness of the foundation by using Eqs. (4), (6), (7) is derived as

$$e_f = \sum_{i=1} \begin{bmatrix} \ddot{x}_f + \frac{C_f}{m_f}\dot{x}_f + \frac{K_f}{m_f}x_f - \frac{C_1}{m_f}(\dot{x}_1 - \dot{x}_f) \\ -\frac{K_f}{m_f}(x_1 - x_f) + \ddot{x}_g \end{bmatrix}^2 \quad (10)$$

The values of C_f and K_f are obtained by simultaneously solving

$$\frac{\partial e_f}{\partial (C_f / m_f)} = 0 \qquad \frac{\partial e_f}{\partial (K_f / m_f)} = 0 \quad (11)$$

The equation for identifying the damping coefficient and stiffness of the second floor by using Eq. (3) is derived as

$$e_{f2} = \sum_{i=1} \begin{bmatrix} \ddot{x}_1 + \frac{C_1}{m_1}(\dot{x}_1 - \dot{x}_f) + \frac{K_1}{m_1}(x_1 - x_f) \\ -\frac{C_2}{m_1}(\dot{x}_2 - \dot{x}_1) - \frac{K_2}{m_1}(x_2 - x_1) + \ddot{x}_g \end{bmatrix}^2 \quad (12)$$

in which the updated values of C_1 and K_1 are adopted, Then, the values of C_2 and K_2 are obtained by simultaneously solving

$$\frac{\partial e_{f2}}{\partial (C_2 / m_1)} = 0 \qquad \frac{\partial e_{f2}}{\partial (K_2 / m_1)} = 0 \quad (13)$$

Finally, we obtain the equation for identifying the system parameters of the j-th floor by Eq. (2) as

$$\ddot{x}_{j-1} + \frac{C_{j-1}}{m_{j-1}}(\dot{x}_{j-1} - \dot{x}_{j-2}) + \frac{K_{j-1}}{m_{j-1}}(x_{j-1} - x_{j-2}) - \frac{C_j}{m_{j-1}}(\dot{x}_j - \dot{x}_{j-1}) - \frac{K_{j-1}}{m_{j-1}}(x_j - x_{j-1}) = -\ddot{x}_g \quad (14)$$

Similarly, application of the data set for Eq. (14) produces error function for j-th floor as

$$e_{fj} = \sum_{i=1} \begin{bmatrix} \ddot{x}_{j-1} + \frac{C_{j-1}}{m_{j-1}}(\dot{x}_{j-1} - \dot{x}_{j-2}) + \\ \frac{K_{j-1}}{m_{j-1}}(x_{j-1} - x_{j-2}) - \\ \frac{C_j}{m_{j-1}}(\dot{x}_j - \dot{x}_{j-1}) \\ -\frac{K_j}{m_{j-1}}(x_j - x_{j-1}) + \ddot{x}_g \end{bmatrix}^2 \quad (15)$$

extremization of Eq.(15) with respect to the unknowns yields

$$\frac{\partial e_{fj}}{\partial (C_j / m_{j-1})} = 0 \qquad \frac{\partial e_{fj}}{\partial (K_j / m_{j-1})} = 0 \quad (16)$$

from which the values of C_j and K_j are obtained, and C_{j-1} and K_{j-1} are derived from the previous step, e.g. $j = 3$; $C_{j-1} = C_2$,

$K_{j-1} = K_2$. This constitutes one cycle of the identification process until all the system parameters are identified. A few cycles may be needed.

Moreover, to assess the accuracy of the identification process as a whole, an error index is defined as

$$EI = \left\{ \frac{\int_0^t \left[\left(\ddot{x}_f \right)_r - \left(\ddot{x}_f \right)_t \right]^2 dt}{\int_0^t \left[\left(\ddot{x}_f \right)_r \right]^2 dt} \right\}^{1/2} \tag{17}$$

where $(\ddot{x}_f)_r$ is the recorded or measured acceleration response of the foundation and $(\ddot{x}_f)_t$ the corresponding theoretical or predicted response. The latter is calculated from the identified system parameters with the recorded input excitation. When f is replaced by fj, Eq.(17) represents the error index for the j-th floor.

5. Numerical Example

In the present study, the shear frame with three floors is considered, and the area and height of each floor are $10m \times 10m$ and $3m$. The damping ratio of reinforced concrete structures is 0.05, and other calculation is listed below: (1) the mass, stiffness and damping of the superstructure are $m_1 = m_2 = m_3 = 58.32 \times 10^3 kg$, $K_1 = K_2 = K_3 = 168.06 MN/m$ and $C_1 = C_2 = C_3 = 324 kN.s/m$. (2) the mass, dynamic horizontal stiffness and damping coefficient of the embedded foundation are $m_f = 68.04 \times 10^3 kg$, $K_f = 306.65 MN/m$ and $C_f = 215 kN.s/mc$.

Calculate the structural responses under N-S direction El Centro earthquake in 1940 by Newmark linear acceleration method, and take the result as measured data.

In the first cycle of the identification, the initial value of C_1 is set to be zero arbitrarily. The global measure-of-fit as a function of K_1 is presented in Fig. 3, which reveals that the least squares estimate of K_1 is $170.0 MN/m$. Then K_1 is fixed as this value and the minimization process is performed. As illustrated in Fig. 4, the optimal estimate of C_1 is $340 kN.s/m$. In the meantime, the identified parameter values of the embedded foundation $K_f = 309.44 MN/m$ and $C_f = 217 kN.s/m$. Then, substituting $C_1 = 340 KN.s/m$ and $K_1 = 170.0 MN/m$ into Eq. (12) through the minimization process, the identified parameter values of floor2 are $C_2 = 317 KN.s/m$ and $K_2 = 169.26 MN/m$. Finally, the parameters of the 3-th floor are obtained in a similar manner by Eq. (15) as $C_3 = 320 KN.s/m$ and $K_3 = 170.09 MN/m$, respectively. This constitutes one cycle of the identification.

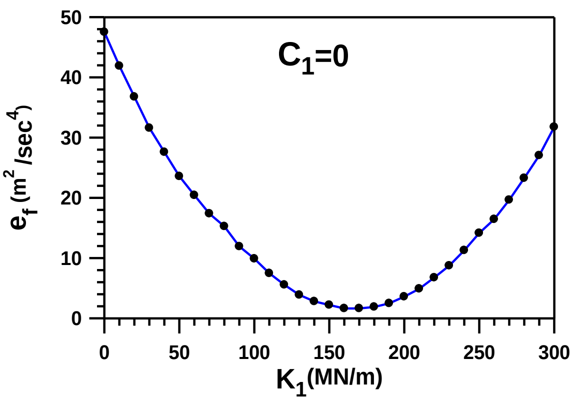

Fig. 3 Global measure-of-fit in the first cycle setting $C_1 = 0kN.s/m$

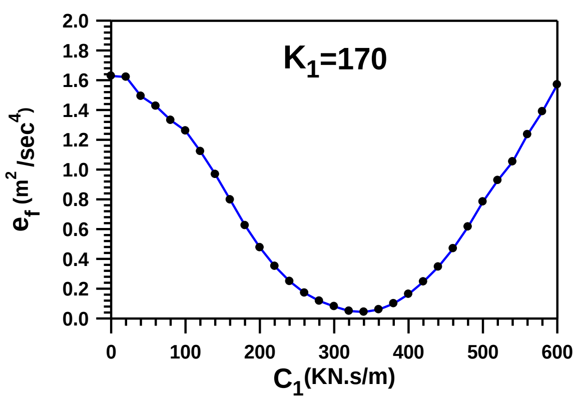

Fig. 4 Global measure-of-fit in the first cycle setting $K_1 = 170MN/m$

The second iterative cycle is next proceeded by considering the initial value of C_1 as $340kN.s/m$ derived from the previous cycle. Minimizing the global measure-of-fit, we have $K_1 = 168.0MN/m$, as shown in Fig. 5. Table 1 summarizes the system parameters of the embedded foundation and first floor identified respectively in three iterative cycles, while Table 2 summarizes the parameters of floor2 and floor3. Numerical results in this example suggest that three iterative cycles of identification are enough for sufficient accuracy.

Table 1 Identified parameters of embedded foundation and floor1

1	2	3
Number of cycle	C_f $kN.s/m$	K_f MN/m
1	217	309.44
2	215	306.56
3	215	306.71
True Value	215	306.65
Error Index	3.5458E-3	
1	4	5
Number of cycle	C_1 $kN.s/m$	K_1 MN/m
1	340	170.00
2	324	168.00
3	324	168.10
True Value	324	168.06
Error Index	3.8541E-3	

Table 2 Identified parameters of floor2 and floor3

1	2	3
Number of cycle	C_2 $kN.s/m$	K_2 MN/m
1	317	169.26
2	324	167.09
3	324	168.09
True Value	324	168.06
Error Index	3.9131E-3	
1	4	5
Number of cycle	C_3 $kN.s/m$	K_3 MN/m
1	320	170.09
2	324	168.01
3	324	168.08
True Value	324	168.06
Error Index	3.8852E-3	

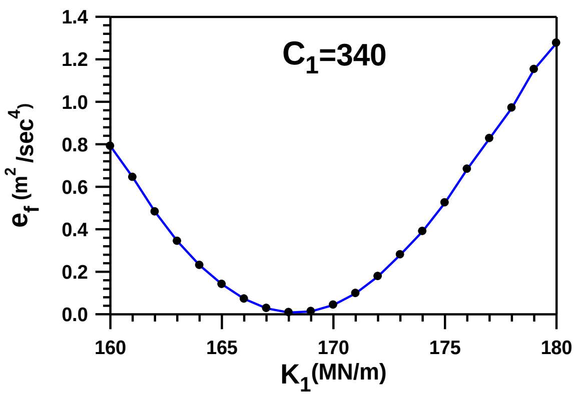

Fig. 5 Global measure-of-fit in the second cycle setting $C_1 = 340kN.s/m$

Further, the reliability of the present identification method can be proven by comparing the identified responses with the measured one. The comparison chart of acceleration and displacement at the top of embedded foundation from identification and measure are shown in Figs. 6 and 7., in which the solid and dotted lines indicate the measured data and the identified response, respectively. Both the values are almost the same. The identified acceleration responses of the third floor are also very closed to the measured one as shown in Figs. 8 and 9. As a result, the accuracy of the present identification method is testified.

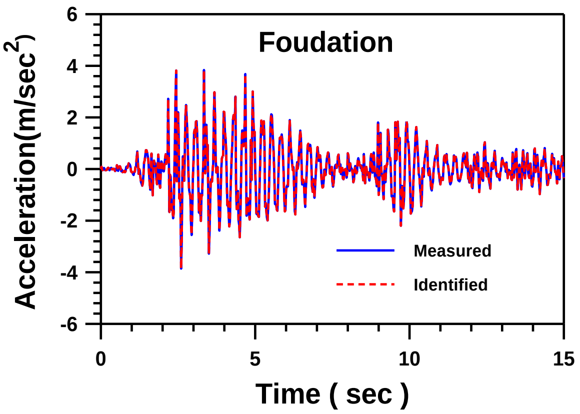

Fig. 6 Comparison between identified and measured accelerations of foundation

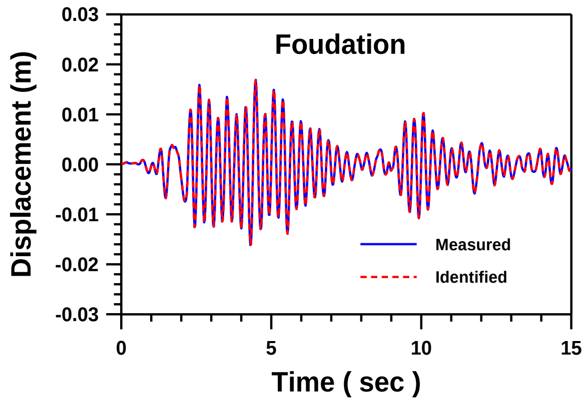

Fig. 7 Comparison between identified and measured displacements of foundation

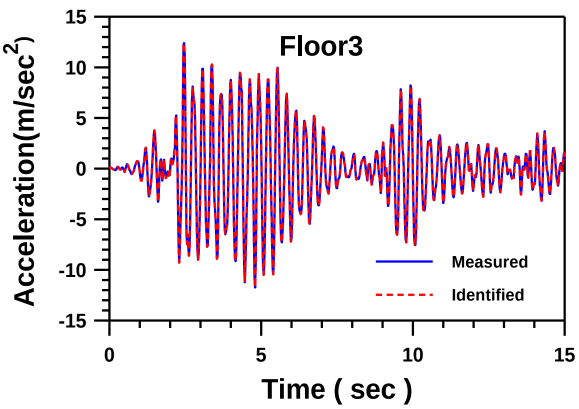

Fig. 8 Comparison between identified and measured accelerations of floor 3

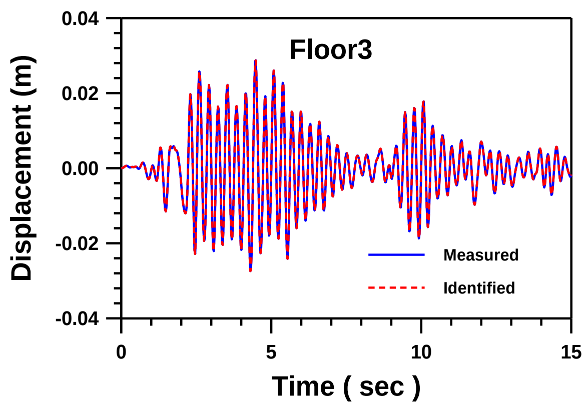

Fig. 9 Comparison between identified and measured displacements of floor 3

6. Conclusions

The purpose of this study is to develop an identification procedure for finding the dynamic characteristics of structures with embedded foundation. The interactive effect between structures and soil are considered in order to reflect the real dynamic behavior of structures under earthquakes. It is assumed that the embedded foundation is in Homogeneous half-space, and the force characteristics of embedded foundation are simulated by dynamic stiffness and damping force combined with radiation dashpot and material dashpot. The real situation of structures and the surrounding soil can be figured out by the parameters of each floor and embedded foundation identified by the developed physical identification theory. From the numerical analysis results, the identified responses of the structure with embedded foundation are closed to the measure responses, and the feasibility and accuracy of the proposed identification method for structures with embedded foundation are proven.

The major contribution of the proposed identification method is to approach the systematic parameters with physical meanings, for example, the stiffness and damping of each floor and embedded foundation. In fact, the transition level of structures after earthquakes can be found through identifying measured data by the proposed identification method, and the condition of the surrounding soil can also be detected. It is considered that the parameters identified by the proposed method can provide useful information for structure safety detection and field investigation.

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