Identification of SSI Damping System Based on Large-Scale Shaking Table Test

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Abstract. Damping system represents the pattern and characteristics of energy dissipation in a dynamical system. The correct identification of a damping system is not only the premise of selecting dynamical analysis method but also the foundation of obtaining accurate results in seismic analysis. Traditionally, the identification of a damping system under seismic waves is based on material properties. However, this method is the lack of theoretical and experimental research. Based on the most fundamental identification method, the paper presents the study on the consistency of dynamic characteristics between different parts and continuity of motion states at the interfaces of the SSI (Soil-Structure Interaction) system by shaking table test. The changing law of SSI damping system in different dynamic processes is investigated. The experimental results indicate that the SSI system manifests obviously classical energy dissipation characteristics under certain conditions and can be considered as an approximate classical damping system.

1. Introduction

In the dynamic structural analysis, the damping system represents the overall energy consumption characteristics of the structural system [1]. In the multi-degree of freedom equivalent viscous damping model, the damping system can be divided into classical damping system and non-classical damping system. The so-called classical damping system, under this energy dissipation characteristic, the movement of the whole system is consistent, its equation of motion can be decoupled in the chief model space, the system has the regular classical mode, the so-called "mode of vibration", the equation of motion can be solved by the mode decomposition method, but not the classical damping system, its energy dissipation characteristic cannot make the movement of the whole structure system consistent. The dynamic equation cannot be decoupled in the chief model space, the system does not have regular classical mode, there is no traditional concept of the so-called "mode of vibration", the solution of the motion equation is complex [2], usually using direct integration method, forced decoupling method, equivalent damping method and complicated mode analysis method to solve [3-5], this kind of solution method is complicated. Moreover, engineering application is difficult.

SSI system (Soil-Structure Interaction System) is a system considering the interaction between superstructure and foundation. SSI damping system represents the whole energy dissipation property of the interaction system of foundation and structure under dynamic load. In the traditional concept, the system composed of two or more materials, especially the SSI system with a vast difference in material properties is usually determined as a non-classical damping system [6]. However, the shaking table test of SSI system in Tongji University shows that the non-classical damping characteristics of SSI system will gradually disappear after the initial vibration of a small magnitude. Moreover, the classical damping
characteristics will gradually become evident within a specific load range [7]. This shows that the
cognition of the shallow judgment of damping system based on materials is the lack of in-depth and
practical basic research, which is different from reality.

SSI effect is universal, but there is little research on the classification of SSI damping system alone
with its discrimination method. Different types of damping system not only have vast differences in the
dynamic calculation methods but also in the calculation results. In the aseismic analysis of building
structures, it is not only the premise of choosing structural dynamic analysis method, but also the
foundation of ensuring the accuracy of structural aseismic analysis results to distinguish the types of
foundation structure damping system correctly. Therefore, it is necessary to carry out substantial basic
theoretical research together with large-scale experimental research on SSI damping system.

In order to study the behavior of SSI damping system under dynamic action and the existing condition
of SSI approximate classical damping system in the scope of engineering application, this paper, starting
from the fundamental analysis method of structural dynamics [8], discusses the preliminary judgment
idea of the damping system. Through the large-scale shaking table test of SSI damping system, through
the consistency of dynamic characteristics of different parts of the system and the continuity of interface
motion state. The damping characteristics of the SSI system are investigated. In the experiment, the
system was loaded by bedrock wave, Jiangyou wave, El Centro wave plus sine wave step by step. Under
the action of small earthquake, medium earthquake furthermore large earthquake, the acceleration and
displacement responses of different parts of the measuring system, as well as the dynamic characteristics
of different parts of the system between different levels of dynamic loads are measured. The consistency
of dynamic characteristics of different parts of SSI system under dynamic action and the continuity of
motion state at the interface are studied by using the methods of acceleration self-power spectral density
together with phase plane analysis.

2. The judgmental idea of SSI damping system
Under the assumption of viscous damping model, the motion of a system can be described by the
dynamic equation as [9]:

\[ \begin{bmatrix} M \end{bmatrix} \ddot{\mathbf{u}}(x,t) + \begin{bmatrix} C \end{bmatrix} \dot{\mathbf{u}}(x,t) + \begin{bmatrix} K \end{bmatrix} \mathbf{u}(x,t) = \{ p(t) \} \]  
(1)

Whether the above dynamic equations can be solved by vibration mode decomposition method, that
is, whether the dynamic equations can be decoupled, is the crucial difference between classical and
non-classical damping systems. If the dynamic equation can be decoupled, the modal displacement, velocity
and acceleration of any order decoupled can be expressed by shape function together with generalized
coordinates as follows [10-12]:

\[ \begin{align*}
\mathbf{u}_n(x,t) &= \phi_n(x) q_n(t) \\
\dot{\mathbf{u}}_n(x,t) &= \phi_n(x) \dot{q}_n(t) \\
\ddot{\mathbf{u}}_n(x,t) &= \phi_n(x) \ddot{q}_n(t)
\end{align*} \]

(2)

In the formula, \( \phi_n(x) \) is the shape function of the \( n^{th} \) mode, only related to the position coordinate
\( x \); \( q_n(t) \), \( \dot{q}_n(t) \), \( \ddot{q}_n(t) \) is the \( n^{th} \) order generalized coordinate displacement, velocity and
acceleration, only related to time \( t \).

The displacement, velocity and acceleration response of any measuring point of the classical
damping system will be the superposition of the modal response of each order:
\[ \{u(t)\} = \sum_{n=1}^{N} \{\phi_n\} q_n(t) \]
\[ \{\ddot{u}(t)\} = \sum_{n=1}^{N} \{\phi_n\} \ddot{q}_n(t) \]
\[ \{\dddot{u}(t)\} = \sum_{n=1}^{N} \{\phi_n\} \dddot{q}_n(t) \]

(3)

According to the method of dynamic structural analysis, the necessary conditions of classical damping system are as follows: The shape function \( \phi_n(x) \) of each mode is continuous. Moreover, the acceleration function \( \ddot{q}_n(t) \) of the reference point exists. The necessary conditions can also be expressed as follows:

\[
\begin{align*}
\phi_n(x) \text{ continuity} &\iff \phi_n(x) \text{ continuity} \\
\ddot{q}_n(t) \text{ existence} &\iff \ddot{q}_n(t) \text{ derivable} \\
\dddot{q}_n(t) \text{ smoothness and continuity} &\iff \dddot{q}_n(t) \text{ smoothness and continuity}
\end{align*}
\]

That is to say, if the shape function \( \phi_n(x) \) of each order is continuous alone with the reference point velocity function \( \ddot{q}_n(t) \) is smooth also continuous, then every point of the system is continuous by the superposition of the mode superposition, therefore the system is a classical damping system. If the motion state of any mode does not satisfy the above conditions, it will inevitably lead to the discontinuity of the motion state, therefore the system becomes a non-classical damping system. The continuous smoothness of the composite motion state can also reflect the modal motion state. Therefore, we can judge whether the damping system is classical or not by examining the motion state of the adjacent measuring points.

3. Vibrating table test of SSI damping system

The SSI test system is based on an 8-story frame with pile foundation as the test object, the typical loess in Xi'an area as the corresponding foundation, the foundation as the pile foundation, the elastic modulus, size and acceleration as 1/4, 1/10 alone with 2.5/1 of the prototype respectively as the basic similar parameter design model [13-14].

The test takes simultaneous interpreting as the primary vibration direction. In the test model, different sensors are set up according to the content of the test, including acceleration sensors, displacement sensors, strain sensors, earth pressure sensors, dynamic pore water pressure sensors, etc. The physical diagram of the test model as well as the layout of acceleration and displacement measuring points in different parts of the model are shown in Figure 1.

The large-scale shaking table test was carried out in the Key Laboratory of structural engineering and Earthquake Resistance Education Ministry of Xi'an University of Architecture and Technology. The test simulated a frequent earthquake, basic intensity earthquake furthermore rare earthquake. The simulated earthquake intensity of the shaking table was increased by a small magnitude. The horizontal X direction was used as the loading direction for the test. The input waves under the simulated earthquake intensity of each magnitude were bedrock wave, Jiangyou wave, El Centro wave as well as sine wave. A white noise scanning with a peak acceleration of 0.05g was carried out before the input of each magnitude of the simulated earthquake to measure the macro change of dynamic characteristics of the system. For the test, loading system, refer to Table 1.
Table 1. Test Program of the Shaking Table Tests.

| number | working condition | Peak acceleration(g) | remark column |
|--------|------------------|----------------------|---------------|
| S1     | WN1              | 0.05                 |               |
| S2(2),S3,S4 | SEISMIC WAVE | 0.125                | six perfections |
| S5(2)  | SINE WAVE        | 0.03/0.125           | S5-1,5.5Hz,0.03g |
| S6     | WN2              | 0.05                 |               |
| S7–S9  | SEISMIC WAVE     | 0.175                |               |
| S10    | SINE WAVE        | 0.175                | 7.3Hz         |
| S11    | WN3              | 0.05                 |               |
| S12–S14| SEISMIC WAVE     | 0.25                 | seven perfections |
| S15    | WN4              | 0.05                 |               |
| S16–S18| SEISMIC WAVE     | 0.375                |               |
| S19    | WN5              | 0.05                 |               |
| S20–S22| SEISMIC WAVE     | 0.5                  | eight perfections |
| S23    | WN6              | 0.05                 |               |
| S24–S26| SEISMIC WAVE     | 0.75                 |               |
| S27    | WN7              | 0.05                 |               |
| S28–S30| SEISMIC WAVE     | 1.0                  | nine perfections |
| S31    | WN8              | 0.05                 |               |
| S32–S34| SEISMIC WAVE     | 1.2                  |               |
| S35    | SINE WAVE        | 0.1/0.3              | S35-1,4.3Hz,0.1g |
| S36    | WN9              | 0.05                 | S35-2,8.3Hz,0.3g |

*Seismic wave include bedrock wave, jiangyou wave and EI Centro wave.

4. Research on the continuity of interface motion state of the SSI system

Due to the uncertainty of load intensity and frequency in the process of seismic loading, its motion state is difficult to form a rule in the phase plane. In order to understand the change rule of the applicable motion state of the internal contact surface of the system in the process of seismic loading, this paper will investigate the motion state of the contact surface under the same strength level.

Fig 2 shows the absolute phase plan of the bottom of bearing platform and the "adjacent" foundation soil measuring points composed of absolute velocity as well as absolute displacement under the same small magnitude earthquake of 0.125g together with the same different seismic wave inputs. Fig 2.a is a plan view of the movement phase of the contact surface between the foundation and bearing platform under the same magnitude earthquake. It can be seen that the movement state of the two "adjacent" measuring points on the contact surface is not the same when the first load is applied. Moreover, the velocity displacement trace of the "adjacent" measuring points on the contact surface is quite different. However, with the development of the same magnitude working condition as well as the increase of vibration time, when the same magnitude of basic rock wave, Jiangyou wave alone with EI Centro wave are input again according to the working order, as shown in Fig 2.b-d, it can be found that the speed as
well as displacement of the "adjacent" measuring points at the bottom of bearing platform and foundation soil tend to coincide gradually. Moreover, the difference between the movement tracks gradually decreases. That is, under the same magnitude of a small earthquake, the original movement state of the foundation is inconsistent. After experiencing an initial vibration, with the emergence of the internal interaction mechanism of the system, the interface movement state tends to be consistent, therefore the classical damping characteristics gradually appear.

Under sinusoidal excitation, the dynamic response of the measuring point is generally composed of two parts [11]: one is the damped free vibration response with the natural frequency as the vibration frequency, including the influence of initial conditions; the other is the simple harmonic vibration response with the excitation frequency as the vibration frequency. Due to the damping, the first dynamic response is the transient vibration response whose amplitude decays with time, while the second is the response under sinusoidal excitation, which is the steady-state vibration response whose amplitude does not change with time, and the steady-state response of classical damping system under sinusoidal excitation will be the same frequency sinusoidal response. Although the sinusoidal excitation as a single frequency function can’t reflect all the dynamic characteristics of the system, the consistency of the motion state in the system, especially between the contact surfaces, can be simply examined by the sinusoidal excitation with different frequencies.

Figure 3 shows the phase plan of "adjacent" measuring points on the contact surface between the foundation and bearing platform under the high sinusoidal excitation. Moreover, shows the corresponding measured acceleration self-power spectral density curves.

In the sinusoidal excitation of Figure 3 (a) S5-1, the input frequency is corresponding to the fundamental natural frequency of the structure. From the phase plane track of Figure 5.a, it can be seen that the motion law of the "adjacent" measuring points of the foundation–the base interface is not entirely
harmonic vibration response, which is reflected by the corresponding acceleration spectrum density curve of Figure 3 (d). At this time, there is a frequency different from the sinusoidal frequency, corresponding to the above. It can be seen from the analysis that the response at this time is not entirely a steady-state vibration response. Under this condition, there is a transient response of damped free vibration at the same time at the measuring point. Moreover, the amplitude of the transient vibration response is attenuated with time. In addition to the figure 3 (b) is a sequential condition, its sinusoidal input frequency is corresponding to the fundamental natural frequency of the foundation, the curve initially presents an elliptical phase trajectory. According to figure 3 (e), its corresponding acceleration self-power spectral density curve shows that at this time, the transient response of the free vibration is obviously attenuated, and the steady-state vibration response is forming. Figure 3 (c) is the post-interval condition. Its sinusoidal input frequency corresponds to the natural frequency of the system. At this time, the phase plane has basically presented as a group of sinusoidal ellipses around the origin. Figure 3 (c) and figure 3 (f) show that the transient response disappears as well as the system is in the steady-state vibration response stage.

The results from Figure 3 (a)-(c) can also be seen that, after experiencing the small-scale vibration action of the previous working conditions, to the sine excitation working condition of S5-1, the movement state of the "adjacent" two measuring points of the contact surface between the foundation and the bearing platform has basically coordinated. That is, whether the transient vibration response with time exists or not as well as whether the steady-state response is wholly formed, after the small-scale vibration in the early stage, the motion coordination mechanism is generated. Moreover, the motion state of the foundation bearing platform interface tends to be consistent. After the small-scale dynamic load, the motion characteristics of SSI classical damping system can be formed at the foundation bearing platform interface.

In addition to the figure 4 further investigates the movement track of the "adjacent" measuring points of the pile foundation contact surface in the phase plane under sinusoidal excitation, shows the corresponding measured acceleration self-power spectral density curve.

![Figure 4. Phase-Plane Curves and Auto-power Spectrum Density curves of "Adjacent" Measuring Points at Soil-Pile Interface under Sine Excitation](image)

It can also be seen from the motion track in Figure 4(a) together with the spectral density curve in Figure 4 (c) that the response of pile foundation interface is not entirely steady-state vibration under the sine excitation of S5-1. Moreover, there is a transient response of damped free vibration at the same time. At S10 sinusoidal excitation condition, figure 4(b) as well as (d) shows that the transient response disappears and the system is basically in the steady-state vibration response stage.

Different from the foundation-base interface, the movement of the "adjacent" measuring points of pile foundation under the sine excitation condition of S5-1 is not coordinated. It can be seen that there is still an absolute relative displacement as well as relative speed between the contact surfaces, as shown in Figure 4(a). However, after several small-scale vibration conditions, the movement state between the "adjacent" measuring points of pile-foundation is basically consistent when the S10 sinusoidal excitation condition is reached. Moreover, the movement characteristics corresponding to the SSI classical damping system are also formed at the pile-foundation interface.

5. Conclusion

In this paper, according to the fundamental judgment idea in the damping system analysis method, through the investigation of the dynamic characteristics consistency of different parts of the large-scale
shaking table model test of SSI system alone with the continuity of the motion state at the interface, the change law of SSI damping system in a specific range of dynamic process is studied. The results show that the dynamic characteristics of different parts of SSI system are not harmonious, the movement state of foundation cap as well as pile-soil interface is not continuous. Moreover, the nonclassical damping characteristics of SSI system are apparent. However, with the development of vibration together with the continuous strengthening of vibration, it is found that the mechanism of motion coordination between different parts of the foundation and structure is improved in the increasing load, the consistent trend of the central frequency of measured vibration in different parts is gradually improved in the increasing load, the motion coordination between the foundation bearing platform and the pile-soil interface is gradually improved as well as the classical damping characteristics of SSI system are gradually improved.

Reference
[1] SF Ghahari, MA, Ghannad, E Taciroglu. (2013) Blind identification of soil-structure systems. Soil Dynamics and Earthquake Engineering, 45(45): 56-69.
[2] CT, Sun, JM Bai. (1995) Vibration of multi-degree-of-freedom systems with non-proportional viscous damping. International Journal of Mechanical Sciences, 37 (37): 441-455.
[3] Wang H F, Lou M L, Chen X, et al. (2013) Structure-soil-structure interaction between underground structure and ground structure. Soil Dynamics and Earthquake Engineering, 54(11): 31-38.
[4] Celebi E, Goktepe F, Karahan N. (2012) Non-linear finite element analysis for prediction of seismic response of buildings considering soil-structure interaction. Natural Hazards and Earth System Sciences, 12(11): 3495–3505.
[5] Lamb H. (1904) On the propagations of tremor over the surface an elastic solid. Philos. Trans. Roy Soc Ser. A, 203(359-371): 1-42.
[6] Huang D M, Li C D, Chen J.Z. (2006) Earthquake act ion calculation of structure-soil interaction system—according to complex mode method in time domain based on the earthquake model about seismic code. Journal of Vibration Engineering, 19(4): 571-577.
[7] Zhang Z Y, Chou Zh D, Lv X L. (2010) Shaking table tests of the damping behaviour of SSI systems. China Civil Engineering Journal, 2(2): 100-104.
[8] Zhang Z Y, Gao Z C, Li Y. (2011) SSI Damping System Research Based on the Discontinuity of the Motion. Advanced Materials Research, 287-290: 2144-2147.
[9] Dong J, Deng H Z, Wang Z M. (2000) Studies on the damping models for structural dynamic time history analysis. World Information on Earthquake Engineering, 16(4):63-69.
[10] Li Y, Zhang Z Y. (2012) An Analytical Expression of Motion Equations of SSI System. Advanced Materials Research, 374-377:2180-2183.
[11] R. W. Clough, J Penzien. (2006) Dynamics of Structures. Beijing: Higher Education Press.
[12] Zhang Z Y, Wei H Y, Qin X. (2017) Experimental study on damping characteristics of soil-structure interaction system based on shaking table test. Soil Dynamics and Earthquake Engineering, 98: 183-190.
[13] Kagawa T, Sato M, Minowa C, et al. (2004) Centrifuge simulations of large-scale shaking table tests: case studies. Journal of Geotechnical and Geo-environmental Engineering, 130(7): 663-672.
[14] CHI S C, LAM S. (2004) Validation of similitude laws for dynamic structural model test. World Earthquake Engineering, 20(4): 11-20.