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Experimental Study on Damping Ratios of in-situ Buildings

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***Abstract*—**Accurate evaluation of damping ratios involving soil-structure interaction (SSI) effects is the prerequisite for seismic design of in-situ buildings. This study proposes a combined approach to identify damping ratios of SSI systems based on ambient excitation technique. The proposed approach is illustrated with main test process, sampling principle and algorithm steps through an engineering example, as along with its feasibility and validity. The proposed approach is employed for damping ratio identification of 82 buildings in Xi'an, China. Based on the experimental data, the variation range and tendency of damping ratios of these SSI systems, along with the preliminary influence factor, are shown and discussed. In addition, a fitting curve indicates the relation between the damping ratio and fundamental natural period of SSI system.

***Keyword*—**Damping ratio, seismic design, soil-structure interaction, system parameter identification.

I. Introduction

DAMPING level of a system is essential to in dynamic response analysis. In civil engineering, damping ratio is commonly employed in characterizing the damping level of structure and is of great importance in seismic design [1]. But for most conventional building seismic designs, the influence of the soil- foundation under the structures is disregarded. The damping ratio adopted in current design is based on the experiments that carried out on rigid soil-foundation. Since the SSI effect is universal, it is practical to involve SSI effect for an in-situ building dynamic response analysis. For seismic design of structures involving SSI effect, accurate experimental evaluation of damping ratios of SSI system is a necessary prerequisite.

To assess damping ratio of the system, many identification methods have been proposed and developed. But so far, most of them cannot achieve success in identifying accurate damping ratios of in-situ buildings, i.e. SSI systems mainly due to the fact that the responses are significantly influenced by noise. The peak-peaking (PP) method [2] is one of the most widely used ambient modal analysis method for its reliable results for extraction of natural frequencies. The utilization of PP method is still limited due to inaccurate estimation on damping ratios [3]. The Random Decrement technique [4] provides a simple and fast approach in either time or frequency domain for modal parameter analysis. Its drawbacks are related to the influence of applied forcing function [5] and argument in the free decay responses of system [6]. The Ibrahim Time Domain (ITD) [7] method is generally employed to solve noise contamination problems by using the RD technique. However, it is only applicable to free response data [8], [9]. The stochastic subspace identification algorithm [10], which shares the advantages of both ARMAV and ARV models [11], [12], is regarded as a solution technique to estimate the damping level of structures. In this algorithm, however, undesirable illusive modes are observed among real modes, and should be distinguished and removed from the identification results.

The general tests to determine the damping ratio of a system require both known input and output signals of the system. In practice, it is different to apply artificial excitation to actual SSI system and there always exist the non-controlled external excitations like passing vehicles or winds to excite the structures and their soil-foundations. Hence there is a growing interest in using ambient excitation technique [13] which requires no input excitation and measure only the output to predict the dynamic behavior of the structure.

To accurately evaluate the damping ratio of structure involving SSI effect, a combined identification method using ambient excitation technique is proposed in this contribution, along with the detailed description on its main test process, sampling principle and algorithm steps via an engineering example.

Based on this method, the damping ratios of 82 in-situ buildings located in Xi'an, China are investigated. The numerical range of damping ratios of the actual SSI systems in Xi'an, China is shown as well as their distribution pattern. And by means of a fitting curve, the variation tendency of damping ratios of in-situ buildings is revealed. In the end, this paper also briefly analyzed the influence factor of the damping ratios of actual buildings.

II. Identification Method of Damping Ratios of In-situ Building

A. Testing & Signal Processing

This experimental investigation is primarily concerned with the low order mode of in-situ SSI system. To avoid the errors

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induced by the mixing of high frequency, the vibration responses of the structures need to be anti-filtered and the bandwidth is selected to range over 0.25 ~ 22 Hz in the tests.

The sampling frequency f_s and sampling time plays a key role in discretizing continuous analog signals during sampling. In terms of Shannon sampling theorem [14] that states a band-limited continuous signal can be reconstructed fully if it is sampled at a rate $f_s \geq 2 f_c$, where f_c represents the maximum value of continuous frequency spectrum. In order to avoid the mixture between high and low frequency spectrum, the sampling frequency f_s usually ranges over $2.56 f_c \sim 4 f_c$. The sampling frequency f_s in the test is chosen as 102.4Hz. At the same time to improve the accuracy of the results, long sampling time is recommended in the tests. Considering the efficiency and the capacity of test equipment, the sampling time is set as 600s in the tests.

In the test, one segment of continuous signals is discretized by 1024 points during FFT and 512 points among them are shared by another segment of signals. Since the sampling time is 600s, the data are totally averaged 119 times in the test correspondingly.

B. *Identification algorithm of damping ratios*

In order to achieve high accuracy damping ratios of in-situ SSI system subjected to ambient excitation, this study proposes a new identification algorithm which adopts a combination of frequency domain method and time domain method. PP method is one of widely used modal analysis method in frequency domain. The PP method has an accuracy advantage in identifying natural frequency of SSI system, but has low accuracy in estimating the damping ratio. Stochastic subspace method which is based on time domain identification shares the advantages of both autoregressive moving average vector (ARMAV) and autoregressive vector (ARV) models but judging true or false mode is often a difficult point.

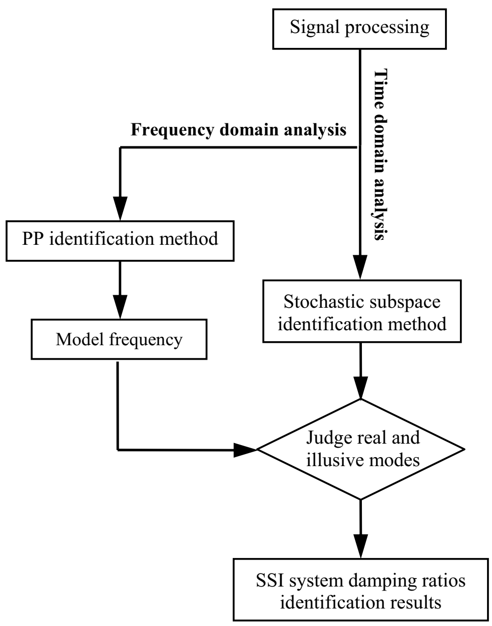


Fig. 1 SSI system damping ratio identification algorithm

The proposed algorithm employs both PP method and stochastic subspace method to identify accuracy modal damping ratios. PP method is used to contribute the natural frequencies for comparison. The modes obtained from stochastic subspace identification method, corresponding to similar frequencies derived from PP method, are considered as the real ones. In terms of these modes, the damping ratios of soil-structure system are achieved. The flowchart of proposed identification algorithm for identification of natural frequencies and damping ratios of SSI system is shown in Fig. 1.

III. Application Example

A. *Measurement*

To illustrate the proposed algorithm, An engineering example of a 9 stories frame-shear wall structure is raised to demonstrate the application.

The test is performed with 941 ultra-low frequency vibration gauge made by Institute of Engineering Mechanics of China Earthquake Administration. The received signal is magnified and filtered by anti-mix filtering amplifier, and then acquired and recorded by 16-channel INV303/306 data acquisition and signal processing system. The flow chart of experiment process is schematically shown in Fig. 2.

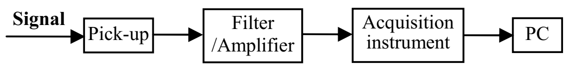


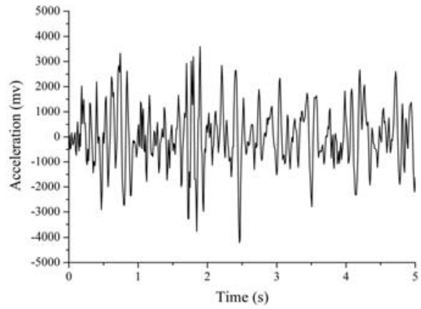
Fig. 2 Flow chart of experiment process

Sensors should be distributed according to the configuration of structures and experimental purpose. Four horizontal vibration sensors are utilized in the test to gain the acceleration response in both lateral and longitudinal directions. Sensors 1, 2, 3 and 4 are fixed on the 3rd, 5th, 7th and 9th stories, respectively. Aiming to observe the dynamic properties of the first mode, the test points are placed near the geometry center at every other story. In order to obtain robust data for easy analysis, the locations of these points are placed at positions having obvious structural mode response and away from the vibration nodes of shape modes.

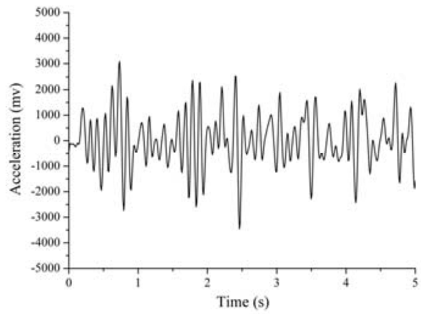
B. *Damping ratios extraction*

The acceleration self-power spectrums of the test points are derived via frequency domain analysis of the discrete acceleration responses. One can obtain natural frequencies and damping ratios by PP method. All test points have the same and high accurate first natural frequency of 1.80 Hz. Nevertheless, the accuracy of extracted damping ratios is unsatisfactory.

To achieve accurate damping ratios, stochastic subspace identification method is used to analyze the testing response data in time domain. Prior to the analysis, the signals are de-noised by virtue of 5 points cubic smoothing method. The smoothing effects are schematically shown in Figs. 3 and 4 respectively. Fig. 3 shows the acceleration time history responses at the first 10s before and after smoothing. Fig. 4 shows an example of frequency spectrum of testing signal before and after smoothing. In comparison with Fig. 4 (a), a significant smooth curve is observed in Fig. 4 (b), in which high frequency noise signals above 22 Hz are eliminated from the spectrum. After removing the higher frequencies, the frequency response signals are utilized to identify the damping ratios of SSI system via stochastic subspace method. The corresponding results, including extracted natural frequencies and damping ratios, are show in Tables 1 and 2.

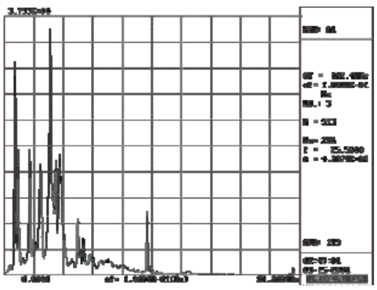


(a) Before smoothing

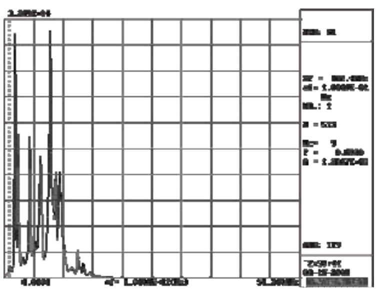


(b) After smoothing

Fig. 3 Comparison of acceleration responses at first 10s



(a) Before smoothing



(b) After smoothing

Fig. 4 Comparison of frequency spectrums

As it is mentioned above, the results obtained from stochastic subspace method usually involve illusive modes. This can be observed by the irregular data in Tables 1 and 2. Since the natural frequency of the frame-shear wall structure has been determined by PP method as 1.80 Hz, the data which are closed to this value (adopted as 1.78-1.83 Hz) in Table 1 is recognized as the results extracted from real modes. Consequently, the modal damping ratios corresponding to these frequencies in Table 2 are addressed as the correct results. Taking advantage of equal average algorithm, the damping ratio of the frame-shear wall SSI system is determined as $\xi = 2.64$, which is in good agreement with previous experimental results [15].

TABLE I
FREQUENCIES DERIVED FROM STOCHASTIC SUBSPACE METHOD

Natural frequencies											
2.691	0.000	0.968	0.000	3.640	0.000	1.408	0.000		0.000		0.000
2.432	6.827	2.307	6.734	2.156	6.042	1.985	6.221		3.540	3.004	4.072
2.165	6.647	2.346	6.669	3.041	6.902	1.980	6.248	2.282	6.560	3.280	6.885
	4.929	1.931	4.670		4.571	3.040	6.836	1.836	4.344	1.787	4.139
1.548	3.887		4.556	1.148	3.745	1.733	4.111	1.773	4.128	1.786	4.125
1.817	4.079	1.803	4.166	1.640	4.060	1.791	4.122	1.790	4.132	1.805	4.118
1.789	4.192	1.783	4.318	1.795	4.109	1.787	4.113	1.795	4.119	1.795	4.118
1.781	4.163	1.793	4.166	1.799	4.117	1.798	4.103	1.794	4.122	1.795	4.123
1.790	4.167	1.786	4.144	1.794	4.105	1.793	4.125	1.793	4.122	1.793	3.353
1.792	4.158	1.787	4.125	1.792	4.123	1.794	3.489	1.793	2.587	1.793	4.122
1.792	4.158	1.785	3.916	1.784	2.169	1.796	2.607	1.795	3.631	1.793	3.149
1.792	4.159	1.786	4.121	1.791	3.351	1.792	3.280	1.793	3.072	1.792	3.083
1.790	4.160	1.788	3.905	1.791	3.238	1.785		1.794	3.120	1.676	1.792
1.787	4.159	1.788	4.167	1.791	3.163	1.786	2.072	1.793	3.129	1.792	3.205
1.787	4.161	1.785	4.134	1.789	3.332	1.789	3.225	1.792	3.126	1.791	3.017

TABLE II
DAMPING RATIOS DERIVED FROM STOCHASTIC SUBSPACE METHOD

Damping ratios											
23.924	0.000	65.590	0.000	8.002	0.000	41.072	0.000	14.386	0.000	14.386	0.000
27.207	3.298	6.570	3.031	14.282	4.317	8.603	2.208	31.423	27.833	6.196	13.215
13.007	3.281	7.566	4.523	7.878	1.637	8.552	1.987	26.666	45.486	12.325	2.857
33.869	18.435	18.447	20.235	13.243	8.009	7.139	1.543	6.418	2.545	3.964	1.243
6.295	-8.617	10.743	3.411	5.862	13.867	1.562	1.397	3.628	0.992	3.434	1.513
3.590	0.655	3.398	4.592	8.154	7.071	2.097	1.483	3.802	0.815	3.275	0.478
3.503	-0.546	1.821	3.169	2.598	0.879	2.873	0.648	3.162	0.453	2.432	0.132
2.243	-0.323	2.903	0.223	2.669	0.485	3.087	-0.243	2.805	0.237	2.690	0.278
2.318	0.081	2.757	0.469	2.247	0.697	2.634	0.249	2.680	0.227	2.642	71.893
2.442	0.199	2.662	-0.089	2.515	0.217	2.732	-9.429	2.777	44.080	2.648	0.266
2.420	0.195	2.668	36.229	2.394	83.782	1.470	8.333	2.726	21.930	2.653	-1.413
2.411	0.164	2.688	0.048	2.207	-3.029	2.696	-46.22	2.674	6.578	2.637	-1.454
2.398	0.122	2.350	-4.979	2.313	1.498	2.143	-94.46	2.677	3.546	76.996	2.650
2.390	0.040	2.462	-1.265	2.205	8.960	2.258	-90.40	2.690	2.539	2.664	1.711
2.340	0.058	2.476	-0.419	2.215	11.097	2.224	14.741	2.753	2.240	2.699	36.713

IV. RESULTS OF DAMPING RATIOS IN-SITU BUILDING

A. The investigated buildings

Based on the Testing techniques and identification algorithm proposed above, the damping ratios of 82 in-situ buildings located in Xi'an, Shaanxi, P.R. China are experimentally determined in the year of 2007. These buildings serve as office, apartment, shop, school, hospital etc. The structures of most buildings are made of reinforced concrete and can be categorized into frame, shear wall, frame-shear wall structures. The others are made of masonry and steel. The site soil classifications of all structures are either type II or type III, which are commonly used local standard. The building foundations include types of piled raft, raft and strip, in which the piled raft is most popular one among high-rise buildings. All buildings measured in the tests include not only low-rise buildings but also middle- and high-rise ones. The number of buildings as well as their structural systems and heights are summarized in Table 1.

The aforementioned description implies that the in-situ buildings investigated in the present study cover most types of existing buildings with various usages, structural systems, site classifications and types of foundation. Therefore, they can be considered as representative models for exploratory research on damping ratios of SSI systems.

B. Distribution of damping ratios

An investigation into the relationship between the damping ratio of SSI system and its natural period is necessary.

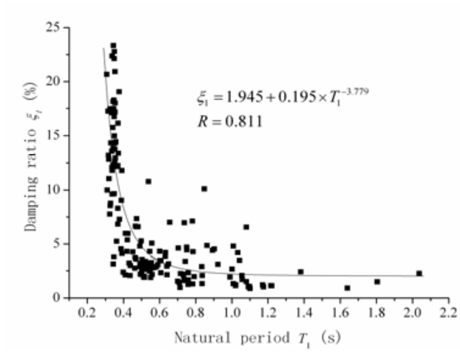


Fig. 5 Damping ratio versus fundamental period

Fig.5 presents the relation between natural period T_1 and damping ratio ξ_1 of the SSI system in fundamental mode. It is evident in the figure that the damping ratios are closely related to the fundamental periods of SSI systems. For SSI systems with natural period $T_1 < 0.4$ s, the damping ratio varies in the range of 2-24%, which significantly exceeds the limit of 2-5% provided in the design standard. In other cases, the damping ratios are observed within the range 2-7.5% for period 0.4 s < T_1 < 0.75 s and 1-5% for period $T_1 > 0.75$ s, respectively. The latter is close to the value range of design standard.

Due to its various configurations and complicated energy dissipation mechanism, establishing a complete mathematical damping model for SSI system is quite challenging. In order to preliminarily grasp the empirical regularity of damping effect, a nonlinear curve fitting analysis was applied by using least square method. As shown in Fig.5, this fitting curve characterizes the distribution of damping ratios under various natural periods of actual SSI system. The formula for fitting curve is expressed as

$$\xi_1 = 1.945 + 0.195 \times T_1^{-3.779} \qquad (1)$$

Fig.5 also indicates the correlation factor of fitting curve *R*. It is clarified that the *R* value reaches 0.81, which is high in comparison with the correlation factors obtained from experimental data of Japan [15].

With regard to the fitting curve shown in Fig.5, two things are clear: (a) the damping ratio of the SSI system decrease with increasing fundamental period, but in a nonlinear manner, and (b) the damping ratios with small periods have a steep change and maybe much larger than the evaluated value in the design code. For long natural period, the damping ratio becomes stable and is close to the design value.

The relationship between damping ratio and natural period of SSI system indicates that the soil and structure dynamic inter- action has a significant effect on the system damping ratio, especially for low-period SSI system. Since it is possible to have a strong dynamic interaction between soil and structure during low period, the energy dissipation due to the interaction accounts for a large proportion of the total energy dissipation, and their damping ratios are probably much larger than the values of high-period SSI system.

V. CONCLUSION

A new identification algorithm of damping ratios of SSI system subjected to ambient excitation is proposed in this study. The proposed algorithm relies on PP method to identify natural frequencies of SSI system and extracts damping ratios from stochastic subspace method. This approach combining both methods may greatly increase accuracy of identified damping ratios of the system taking SSI effect into account.

As an example of the identification approach performed, a 9 stories frame-shear wall structure considering SSI effect is presented to illuminate the test process, sampling principle and algorithm steps.

The proposed approach is employed to extract the damping ratios of 82 in-situ buildings located in Xi'an, China. Based on the experimental data, the variation range and tendency of damping ratios of these SSI systems are discussed. At lower periods the measured damping ratios vary over a wide range indicating larger values than evaluated ones in traditional seismic design. The higher periods in contrast fall within a narrow range and are close to the design values. The non-linear statistical analysis shows damping ratios of in-situ buildings is not holding constant. The higher the fundamental period of SSI system, the lower the damping level.

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