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TEST ERRORS OF THE DYNAMIC SHEAR MODULUS RATIOS AND DAMPING RATIOS OF SAND IN THE RESONANT COLUMN

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ABSTRACT

In this study, we created common and professional groups of representative testers and explored the distribution of the test errors of the dynamic shear modulus ratios and damping ratios of sand using a single resonant column device. We acquired the nonlinear test errors of the dynamic shear modulus ratios and damping ratios and the existing resonant column test level. The tests and analytic results show that the nonlinear test data of the dynamic shear modulus ratios and damping ratios at different shear strains from both test groups followed a normal distribution. The dispersion indicators of both groups exhibited consistent regularities. The mean values of the 2 test groups were similar, but the confidence interval of the common group was obviously larger; its coefficient of variation was 5 times that of the professional group. The coefficients of the variation of the modulus ratios were obviously smaller than those of the damping ratios in both test groups. We took into consideration the technical training for the resonant column test and recommended different numbers of parallel tests to ensure the reliability of the results for different seismic fortification intensities and types of buildings. One important cause of test errors is the difficulty with the existing resonance column test specifications; the specifications need to include more details.

Keywords: Keyword1; Resonant column device; Dynamic shear modulus ratio; Damping ratio; Test error; Ground motion

1. INTRODUCTION

Design philosophy is based on the reliability of the seismic design of engineering structures and engineering security design(Ou et al., 1995；Jian et al., 2015；Bertero et al., 2002；Fan et al., 2016). Currently, the soil parameters of geomaterials are acquired by test methods, and their uncertainties are mainly approached in 2 ways. The first approach is to use internal factors, which are the effects of the variability inherent in soils. The other approach is to use external factors, such as test techniques and analytical methods. Some research (Li et al., 2001；Ni et al., 2001；Hardin et al., 1972) has been performed on the uncertainties of the soil static parameters. However, a little research has been conducted on the uncertainties of the soil dynamic parameters.

Research on soil dynamics as a medium of earthquake wave transmission has shown that the dynamic performance of soil directly affects the safety of structures. The estimation of the dynamic parameters directly affects project costs, as well(Wen., 1994). The 2 main parameters of the soil dynamic characteristics are the dynamic shear modulus and damping ratio. They are indispensable analytic parameters for seismic microzonation, the earthquake-resistant design of large engineering structures, and seismic safety evaluations(Boulanger et al., 2007；Sun et al., 2004；Chen et al., 2007；Hardin et al., 1968；Zhang et al., 2005). The resonant column is based on reliable principles and simple analytical methods. It is an ideal device for the acquisition of the dynamic shear modulus ratios and damping ratios of soil, and it is recommended in the national standards (GB17741-2005). Resonant

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column test devices have been widely used since the Engineering Mechanics Institute, National Seismological Bureau, invented the first resonance column device in 1984. The Nanjing Institute of Automation, Department of Energy, and Zhejiang University successfully developed resonance column devices, while some devices were imported into China. The error level and confidence interval are essential and must be considered for any scientific data that can be measured repeatedly. Little research has been conducted on the test errors of resonance column devices. Zhu et al. (1990) compared the test data of different types of resonance column devices using unified standard sand. Their results showed that a certain dispersion existed among the dynamic shear modulus values from different types of resonance column devices. While there were discrepancies between the values given by different types of resonance column devices, there were also test errors for the same type of resonance column devices. However, there are currently no studies that address this issue. Some research（Aguirre et al., 1997；Sun et al., 2009；Martin et al., 1982) is available that examines the effects of the dynamic shear modulus ratios and damping ratios of soil on the design of ground motions. These research results showed that the dynamic shear modulus ratios are more sensitive parameters than the shear wave velocities in terms of the calculation results for the ground motions. The effect of the variability of the dynamic shear modulus ratios is obvious for zone 3 or 4 sites in seismic hazard regions. However, since the measurement errors of the dynamic shear modulus ratios and damping ratios are unknown, previous researchers had to adopt an assumed parameter dispersion, so their analytical results may be unreliable. The accuracy and technical level of those performing the resonant column tests cannot be assessed from the perspective of their effects on the ground motion, which has resulted in debates on the test accuracy of the dynamic shear modulus ratios and damping ratios. Some experts doubt the reliability of these test results (Xia et al., 2015；Xia et al., 2016；Huang et al., 2015). The formulation of relevant specifications and the improvement of test techniques are necessary.

Geotechnical tests are an important method for identifying the mechanical properties of soil. Compared to the testing of other civil engineering materials, such as rock, concrete, and steel, laboratory tests of soil are more susceptible to errors in sampling, sample preparation, sample loading methods, test operation, and other human factors (Shang, et al., 2008；Xu et al., 2016；Zhang et al., 2014). Therefore, it is important to research the factors affecting the laboratory tests of soil, analyze the reasons for the test errors, and determine the appropriate solutions.

We designed 2 representative test groups using a single resonant column device. This work addresses the test errors of the dynamic shear modulus ratios and damping ratios of sand, discusses the distribution of the test errors, derives the probability of the statistical indicators, and analyzes the differences and connections of the extent of the dispersion between the test groups and between the modulus ratios and damping ratios. We also examine the effects of the test errors on the calculation of the ground motions. The final purpose of the paper is to provide evidence for the current understanding of resonant column test techniques to help improve these tests.

2. TEST DESIGN

2.1 Device and Samples

Our tests used the first improved device with independent intellectual property rights (GZ-1) developed by the Institute of Engineering Mechanics, China Earthquake Administration. This device is a fix-free type, and its reliability has been verified (Sun, 2004). The test adopted the natural-vibration mode. Performing the test in the natural-vibration mode was more appropriate than performing resonance tests for the dynamic performance tests of soil under seismic loads. The size of the soil sample was Φ39.1 mm × 80 mm. The consolidation pressure of the soil samples was 100 kPa. Reconstituted sand samples were used as the standard. Table 1 shows their basic physical properties.

Table 1. Basic Physical Indicators of the Remolding Sand

Material	**Granule gravity**	**Maximum dry density (gr/cm^3)**	**Minimum dry density (gr/cm^3)**	**Uniformity coefficient**	**Curvature coefficient**
Standard sand	2.644	1.679	1.464	1.44	0.92

2.2 Test Program

The test was divided into 2 groups, common and professional, to reflect the 2 typical types of staff members who perform research on the test errors of the dynamic shear modulus ratios and damping ratios of soil in resonant column devices.

The common group test was completed by 10 trained technical staff members (master's students). The professional group test was completed by an experienced professional staff member. The testers in both groups rigorously followed the test specifications. The researchers in both groups had practical engineering backgrounds. The common and professional groups represented two typical cases, with maximum and minimum dispersions. While there are other groupings found in practical engineering work, such as a comparison between 10 common technical staff members and 10 professional staff members, or between 1 common technical staff member and 1 professional staff member, these cannot represent the extreme cases. The dispersions of their comparative results are expected to be between the 2 extreme cases.

Each member of the common group conducted 4 tests. Forty groups of test results were obtained. Each member in the professional group conducted 40 tests. The sand samples were re-prepared in each test according to the Geotechnical Test Procedures (GB/SL237-1999).

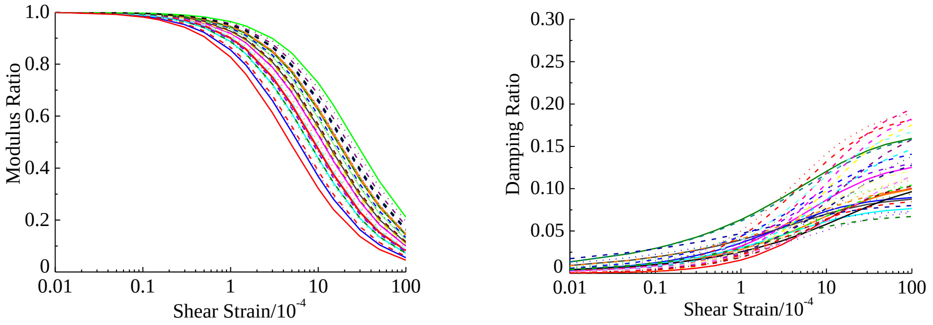
The relationships between the dynamic shear modulus ratios, damping ratios, and shear strains were nonlinear. The resonant column tests focused on the results for medium and small shear strains. The commonly accepted hyperbolic model was used to create the resulting curves for the medium and large strains. The parameters of the hyperbolic model were determined with test point regressions. The dynamic shear modulus ratios and damping ratios were determined for 8 typical shear strains, which were 5×10^{-6}, 10^{-5}, 5×10^{-5}, 10^{-4}, 5×10^{-4}, 10^{-3}, 5×10^{-3}, and 10^{-2}.

2.3 Test Results and Reliability

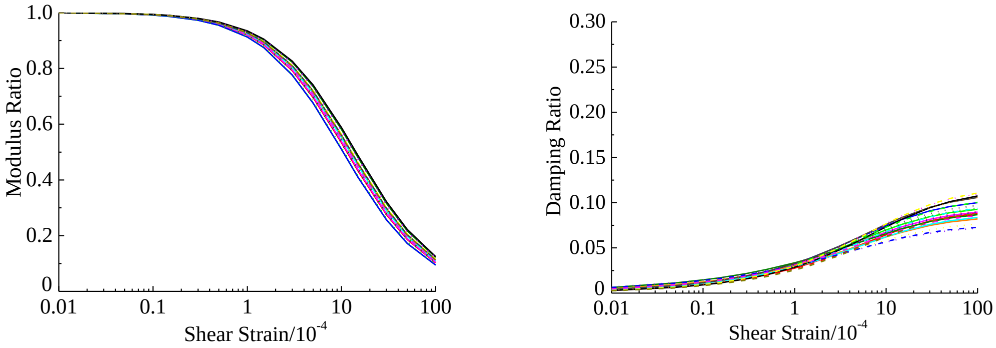
Figure 1 shows the dynamic shear modulus ratio and damping ratio results of the common and professional groups.

The test results show that the results from the professional group are normal. Some curve dispersions in the common group are larger, especially in terms of the damping ratios. Since the damping ratio tests are generally less stable than the modulus ratio tests, we did not remove the test points with larger dispersions for the damping ratios; we included them in the statistical data.

Empirical methods of abnormal value verification (Liang et al., 2014) indicated that more than 97% of the test results in the above curves were within the 2 standard deviations of the means range. This value is greater than the benchmark, 95%. Therefore, the test results are reliable and useful.



(a) Common group



(b) Professional group

Figure 1. Test Results of the Dynamic Shear Modulus Ratios and Damping Ratios

3. DISPERSION INDICATORS OF THE TEST RESULTS

We adopted statistical analysis methods and used the maximum, minimum, mean, standard deviation, standard deviations and coefficient of variation to describe the dispersions of the dynamic shear modulus ratios and damping ratios of samples for 8 shear strains. Tables 2 and 3 show the calculation results.

As shown in Tables 2 and 3, both the dynamic shear modulus ratio and damping ratio tests exhibit dispersions. However, the dispersion indicators of the common group are much greater than those of the professional group.

Table 2. Analytic Results of the Errors of the Modulus Ratios

Test	**Statistical indicator**	**Shear strain**							
		5×10^{-6}	**1×10^{-5}**	**5×10^{-5}**	**1×10^{-4}**	**5×10^{-4}**	**1×10^{-3}**	**5×10^{-3}**	**1×10^{-2}**
Common group	Maximum	0.9985	0.9967	0.9820	0.9643	0.8429	0.7282	0.3487	0.2112
	Minimum	0.9916	0.9813	0.9062	0.8271	0.4869	0.3215	0.0865	0.0452
	Mean	0.9964	0.9920	0.9583	0.9198	0.7030	0.5485	0.2045	0.1153
	S	0.0016	0.0036	0.0178	0.0325	0.0878	0.1019	0.0655	0.0411
	CV (%)	0.16	0.36	1.86	3.53	12.49	18.57	32.02	35.62
Professional group	Maximum	0.9972	0.9937	0.9668	0.9350	0.7406	0.5878	0.2218	0.1247
	Minimum	0.9962	0.9914	0.9550	0.9130	0.6755	0.5098	0.1721	0.0941
	Mean	0.9967	0.9927	0.9613	0.9247	0.7094	0.5497	0.1965	0.1090
	S	0.0003	0.0006	0.0031	0.0058	0.0171	0.0205	0.0130	0.0080
	CV (%)	0.03	0.06	0.32	0.63	2.41	3.72	6.61	7.33

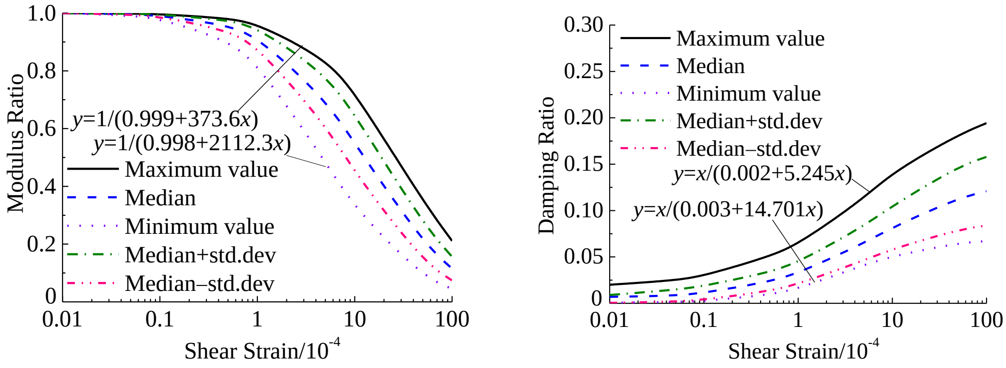
Table 3. Analytic Results of the Errors of the Damping Ratios

Test	**Statistical indicator**	**Shear strain**							
		5×10^{-6}	**1×10^{-5}**	**5×10^{-5}**	**1×10^{-4}**	**5×10^{-4}**	**1×10^{-3}**	**5×10^{-3}**	**1×10^{-2}**
Common group	Maximum	0.0247	0.0295	0.0506	0.0634	0.1130	0.1413	0.1818	0.1943
	Minimum	0.0013	0.0024	0.0091	0.0156	0.0415	0.0508	0.0652	0.0670
	Mean	0.0082	0.0111	0.0233	0.0323	0.0647	0.0819	0.1136	0.1209
	S	0.0063	0.0074	0.0102	0.0116	0.0184	0.0233	0.0341	0.0370
	CV (%)	77.32	66.43	43.55	36.01	28.47	28.43	30.02	30.59
Professional group	Maximum	0.0117	0.0169	0.0262	0.0335	0.0617	0.0770	0.1047	0.1107
	Minimum	0.0058	0.0101	0.0183	0.0254	0.0484	0.0563	0.0692	0.0718
	Mean	0.0084	0.0135	0.0228	0.0305	0.0556	0.0677	0.0878	0.0920
	S	0.0015	0.0017	0.0018	0.0019	0.0043	0.0061	0.0099	0.0108
	CV (%)	18.00	12.58	7.81	6.32	7.64	9.04	11.26	11.72

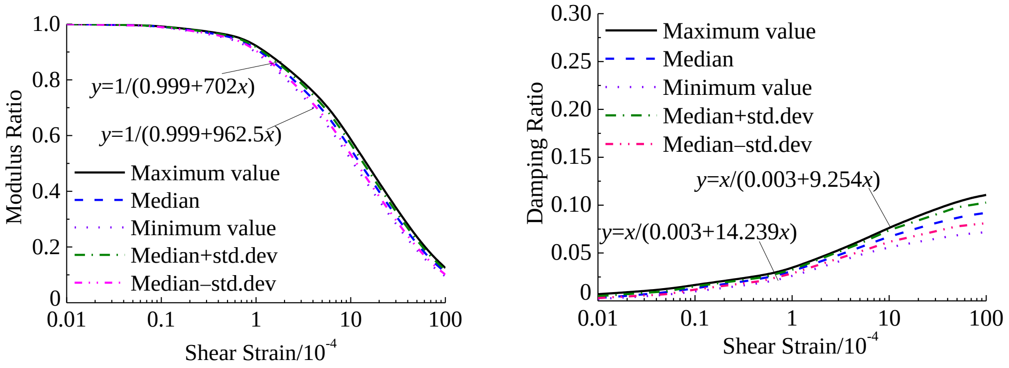
4. DISPERSION ANALYSIS OF THE TEST RESULTS

4.1 Standard Deviations and the Envelope Lines

Figure 2 graphically shows the standard deviations, enveloping curves (the maximum and minimum), equations, and means of the dynamic shear modulus ratios and damping ratios from Tables 2 and 3.



(a) Common group



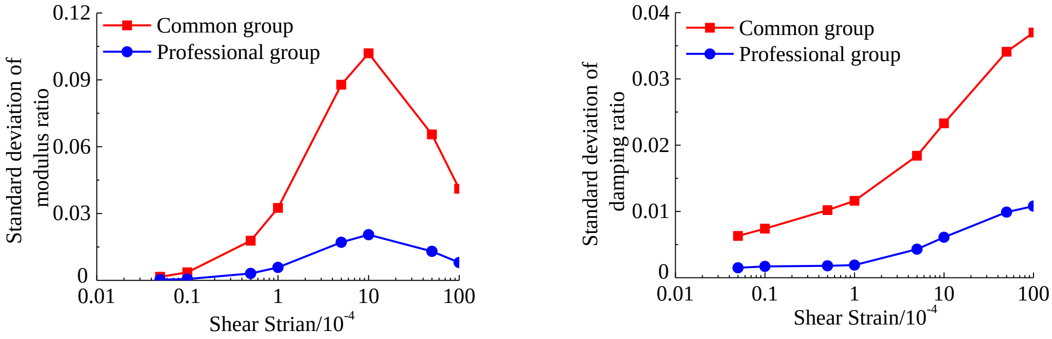
(b) Professional group

Figure 2. Means of the Dynamic Shear Modulus Ratios, Damping Ratios, 2 Standard Deviations, and Envelop Lines

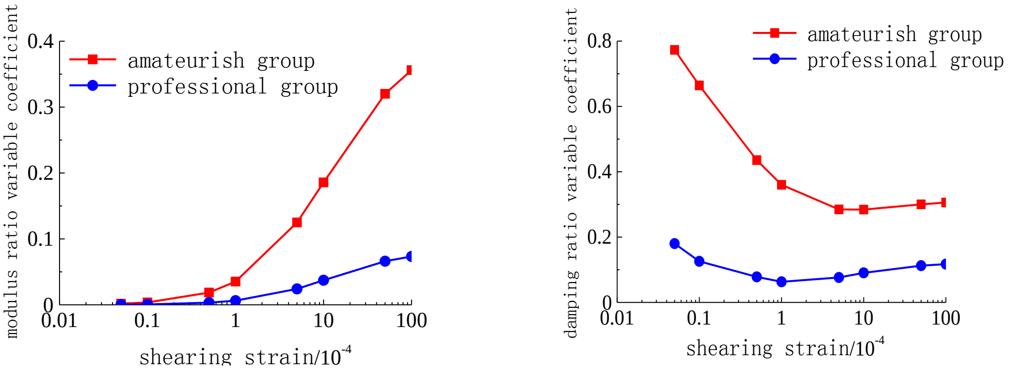
Figure 2 shows the differences in the enveloping curve equations are large between the dynamic shear modulus ratio and damping ratio in the common group; the differences between the enveloping curve equations in the professional group are small. Large differences exist among the one standard deviations, envelop lines, and means in the common group, while the differences in these values from the professional group are small. The results show that the test dispersion of the common group is obviously larger than that of the professional group. The test errors of the professional group are tiny, which indicates that the technical staff and test technique level have a large effect on the reliability of the test results.

4.2 Standard Deviations and Coefficients of the Variation

Figure 3 graphically shows the standard deviations of the dynamic shear modulus ratios and damping ratios and the relationships between the coefficients of the variation and shear strains.



(a) Dynamic shear modulus ratio standard deviation (b) Damping ratio standard deviation



(c) Dynamic shear modulus ratio coefficient of variation (d) Damping ratio coefficient of variation

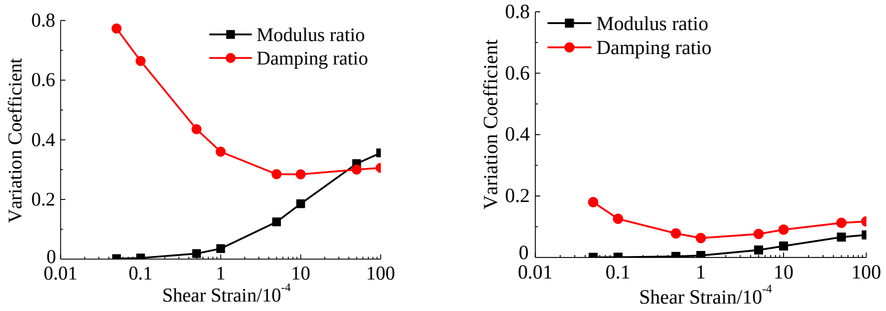
Figure 3. Relationships Among the Standard Deviations and Coefficients of the Variation of the Dynamic Shear Modulus Ratios, Damping Ratios, and Shear Strains

Figure 3 shows some regularities of the statistical indicators in the dispersion exist between the dynamic shear modulus ratios and damping ratios. The trends of the common and professional group are consistent, although they contain different values. The maximum values of the standard deviations of the modulus ratios are in a shear strain range between 10^{-4} and 10^{-3}, which is the most common range of the dynamic shear modulus ratios in the analysis and calculation of soil earthquake responses. The coefficients of the variation of the modulus ratios tend to increase with the increase of the shear strain. This result indicates that the dispersion of the dynamic shear modulus ratios is small in smaller shear strains, and the dispersion of the dynamic shear modulus ratios obviously increases for large shear strains. The coefficients of the variation of the damping ratios tend to decrease with the increase of the shear strains. This result indicates that the dispersion of the damping ratios is large in small shear strains, and the dispersion of the dynamic shear modulus ratios is small in large shear strains.

4.3 Comparison of the Variability of the Dynamic Shear Modulus Ratios and Damping Ratios

Figure 4 shows a comparison of the coefficients of the variation in the dynamic shear modulus ratios and damping ratios. This figure also shows the coefficients of the variation of the dynamic shear modulus ratios are obviously smaller than those of the damping ratios.

This result indicates that the extent of the test deviation of the dynamic shear modulus ratios is smaller than that of the damping ratios. It should be noted that the fitting of the dynamic shear modulus ratios from the resonant column test results was conducted first and then the fitting of damping ratios was conducted based on the results from the first step and λ_{max} determined from the test data. Therefore, the dispersion of the damping ratios involves 2 parts: the test errors of the dynamic shear modulus ratios and errors from the determination of λ_{max}. This may be the reason why the coefficients of the variation of the damping ratios are larger than those of the dynamic shear modulus ratios. In addition, Figure 4 shows there are large differences between the dynamic shear modulus ratios and damping ratios of the common and professional groups.



(a) Common group (b) Professional group

Figure 4. Comparison of the Coefficients of the Variation of the Dynamic Shear Modulus Ratios and Damping Ratios

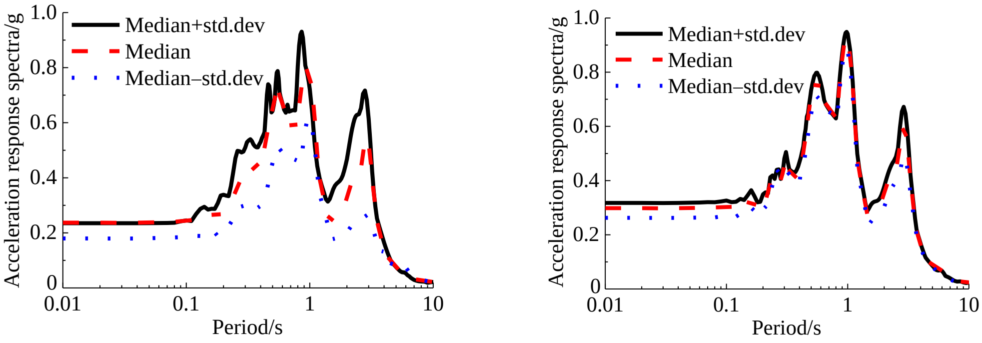
4.4 Preliminary Assessment of the Effects of the Test Errors on the Analysis of the Earthquake Responses

One important application of the dynamic shear modulus ratios and damping ratios is as calculation parameters for the analysis of a soil's earthquake response. Previous calculations and analyses [28] indicated that a 6% variation in the dynamic shear modulus ratios in medium and strong earthquakes at a 5×10^{-4} shear strain have a significant effect on the calculation of the ground motions. Figure 4 and Table 1 show that when a shear strain is greater than 5×10^{-4}, the coefficients of the variation of the dynamic shear modulus ratios in the common group are above 12%, which is beyond the negligible error range and cannot be ignored. For the professional group, the coefficients of the variation of the dynamic shear modulus ratios at a shear strain greater than 5×10^{-3} are between 6% and 8%. Based on these results, the test errors of the common group cannot be ignored in strong earthquakes and the test errors of the professional group might also have an effect in strong earthquakes.

The effect of the variability of the dynamic shear modulus ratios and damping ratios on the calculation of the ground motions is a complex nonlinear issue. This paper provides 2 typical calculation examples. The effects of the top and bottom values of 2 standard deviations of the dynamic shear modulus ratios and damping ratios on the response spectrum were calculated using the 1-dimensional soil-equivalent linearization program (SHAKE2000), with a focus on a zone 3 site; we used the El

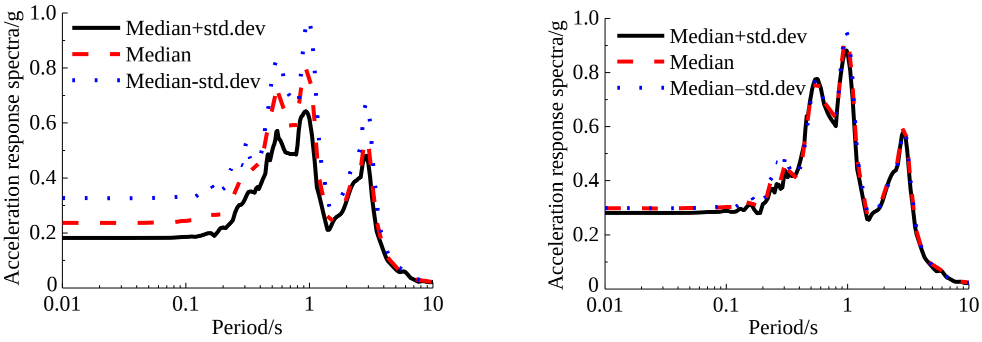
Centro waves with an acceleration peak of 0.4 g as the input waves, and the means of the dynamic shear modulus ratios and damping ratios in the common and professional groups served as the benchmarks. Figures 7 and 8 show the calculation results.

Figures 5 and 6 show that the effects of the test errors of the common group on the response spectrum of the ground acceleration cannot be ignored. The effects of the test errors of the professional group are negligible. In addition, although both groups' test errors of the damping ratios are larger than that of the dynamic shear modulus ratios (shown in our analytic results in terms of the analysis of the test errors of earthquake responses), the test errors of the dynamic shear modulus ratios in fact have a larger effect on the response spectrum of the ground acceleration. Of course, there is a significant difference between the situations described in this paper and reality. The test errors of other types of soil, different zone sites, and input from other types of earthquake waves all need to be explored in detail.



(a) Common group (b) Professional group

Figure 5. Effects of the Test Errors of the Dynamic Shear Modulus Ratios on the Response Spectrum of the Ground Acceleration



(a) Common group (b) Professional group

Figure 6. Effects of the Test Errors of the Damping Ratios on the Response Spectrum of the Ground Acceleration

4.5 Analysis of the Error Reasons

The above test results and analysis all show that the dispersion of the tests of the common group is obviously larger than that of the professional group. These results indicate that the effects of the different staff members and technical levels on the test errors of the dynamic shear modulus ratios and damping ratios of soil are significant. In summary, the test errors of the dynamic shear modulus ratios and damping ratios in resonant column devices are derived from the following:

1) Sample preparation differences, including the sample quality and density control differences, cause problems; this is consistent with the viewpoint of Zhu et al. (1990) and the theoretical inferences of Sun et al. (2007) . These differences may be due to the non-vertical dropping of hammers, uneven sample densities resulting from reading errors of the measurement of each layer of soil, sample surface roughness differences, and different overall heights of samples that result from reading errors. The common group members easily made mistakes in these areas.

2) Different staff technical levels, including the proficiencies in sample loading, the extent of disturbing the soil samples, and the determination of the depths of the blades in the soils, have an impact on measurement. The common group members were not proficient in these areas.

3) The effects of rubber membranes may cause errors in the results. New rubber membranes will increase the heights of samples and reduce the sizes of the diameters.

5. CONCLUSIONS

We designed 2 representative groups to highlight the test errors of resonant columns. The distribution of the test errors of the dynamic shear modulus ratios and damping ratios were derived using standard sand as the unified samples. Our conclusions are as follows:

1) We used empirical methods of abnormal value verification in statistics and found that all results with test curves of more than 97% are within a range of 2 standard deviations of the means. These results are beyond the 95% benchmark requirement, and therefore can be used for probability analysis.

2) The means of the dynamic shear modulus ratios and damping ratios are similar. The confidence intervals of the means are stable and reliable. These results indicate that the tests of both the common and professional groups are close to real values. The confidence interval of the common group is larger than that of the professional group, which indicates that the test results of the proficient technical staff are much closer to real values that those of the common group.

3) The differences in the envelop lines, 2 standard deviations, and means between the common and professional groups indicate that the dispersion of the common group is larger. The ratios of the coefficients of the variation of the dynamic shear modulus ratios and damping ratios of the common and professional groups are around 5. This result shows that the effects of the testing staff and technique levels have a significant effect on the reliability of the test results.

4) The effects of the test errors of the common group on the calculation of the ground motions cannot be ignored. The test errors of the professionals are negligible. However, the results for other types of soil, sites, and different types of earthquake waves require further exploration.

5) An effective way to ensure reliable results is to increase the number of parallel tests. In general, 2 parallel tests are recommended for common technical staff and 1 test is required for professional staff. For sites with a high seismic fortification intensity (greater than or equal to 8) and important engineering sites, 4 parallel tests are recommended for common technical staff and 2 tests for professional staff.

6) Although the tests were completed by rigorously following the test specifications, the dispersion of the test results of the common technical staff is large and beyond expectations. The main reason is that the existing test specifications are too dogmatic and brief. Therefore, a refinement of the existing technical specifications of the resonant column tests and addition of operational provisions are urgent and important.

6. ACKNOWLEDGMENTS

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