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Study on the Test Error of Silt Dynamic Characteristic and Its Influence on the Peak Ground Acceleration

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Abstract

In order to grasp the nonlinear experimental errors of dynamic shear modulus ratio (DSMR) and damping ratio (DR), as well as the current level of resonant column testing, the GZ-1 resonant column instrument was used to study the probability statistical indicators, basic laws, and the impact of experimental errors on peak acceleration of DSMR and DR of silt under 8 typical shear strains. The results show that, firstly, the DSMR and DR of silt under different shear strains obey normal distributions. Secondly, there is no significant difference between the reference range of the standard deviation of the DSMR and DR of silt and the outer envelope line. This result indicates that the dispersion of experimental errors for the same person is very small. Thirdly, in medium to hard sites, the influence of experimental errors in DSMR and DR on peak acceleration can be ignored. And the impact of DR test errors on peak acceleration should not be ignored on soft ground with a probability range exceeding 95%. Overall, the testing accuracy of the testing personnel proved to generally meet the requirements, while in other special cases, it is necessary to increase the number of parallel tests and improve the testing technology. Otherwise, it will cause certain risks to the estimation of seismic input for engineering structures.

Keywords: Dynamic Shear Modulus Ratio; Damping Ratio; Test Error; Probability; Peak Ground Acceleration.

1. Introduction

The reliability of geotechnical engineering is based on the probability and statistical analysis of soil parameters. The results of the probability statistical analysis of soil parameters directly affect the results of reliability indexes. As a complex medium, soil has great variability. The variability of geotechnical parameters includes the inherent properties of the soil itself and the influence caused by external factors such as calculation methods, testing of technical problems, and so on. Therefore, the accuracy of reliability analysis depends largely on the test results of soil parameters. In addition, the uncertainty influence of soil characteristic parameters tested with the calculation method is far less than that in the probability method. Therefore, it is of great engineering value and theoretical significance to study the dispersion of soil property indexes.

At present, some achievements have been published in the uncertainty analysis of static parameters of soil [1, 2]. There are few studies on the uncertainty of soil dynamic parameters. The DSMR and DR of soil are two important parameters for soil dynamic characteristics and are essential calculation parameters in soil seismic response analysis [3–9]. Due to their reliable principle and relatively simple analysis method, resonant columns are currently an ideal instrument for obtaining the DSMR and DR of soil. How the error level of any scientific data that can be repeatedly measured must be answered. But so far, there are few research results on the error of resonance column experiments. Sun et al. [10] gave the uncertainty analysis results of DSMR and DR of five conventional soil types in China through a

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resonant column experiment, including recommended values of the outer envelope, mean value, standard deviation, coefficient of variation, and so on. The variation range of DSMR and DR under different probability levels is also studied. An et al. [11] studied the effects of dry density and consolidation pressure on the DSMR and DR of Guyuan loess remolded soil using a GCTS resonant column tester, as well as the basic laws of experimental data errors. The results indicate that the DSMR and DR test data at different shear strain characteristic points exhibit a certain degree of discreteness. And the degree of discreteness of DR is significantly higher than that of DSMR.

Dong et al. [12] conducted resonance column tests on liquefied sand in Songyuan, exploring the dispersion degree of DSMR and DR for liquefied sand under different conditions. The results indicate that there is little difference between the DSMR and DR of liquefied sand. And the degree of dispersion of DR is higher than that of DSMR. Wang et al. [13] determined the distribution pattern and reference value range of DSMR and DR under 8 typical strains based on soil dynamic parameter data from resonance column tests in the Nantong area. Recommended values for local common soil types were provided and compared with the recommended values in the specifications. Zhu et al. [14] analyzed the experimental data obtained from different types of resonance column instruments for standard sand samples. The results show that the shear modulus values obtained from different types of resonant column tests have a certain degree of dispersion. In addition to the above research results, differences in experimental personnel can also lead to discreteness in resonance column test results. Currently, there is no published research on this aspect. Therefore, determining the impact of personnel factors on soil properties is an important task in reliability analysis.

There have been some research results on the influence of soil DSMR and DR on design seismic motion [15–17]. Guo et al. [18] conducted seismic response analysis and calculation of soil layers for deep soft sites in the coastal waters of Laizhou Bay. The results indicate that for soil layers at the same depth, the DSMR increases or decreases equally. As the input bedrock ground motion increases, the impact of PGA on the peak ground acceleration increases. Wei et al. [19] conducted triaxial tests on unsaturated loess with different moisture contents in the Xiji region of Ningxia and studied the impact of changes in surface loess layer moisture content on the ground motion intensity and characteristics of loess sites. Research has shown that with the increase in input ground motion intensity and water content, the PGA and response spectrum values of surface ground motion in loess sites show an increasing trend. Qiao et al. [20] analyzed the dynamic characteristics and seismic response characteristics of laterite in the Liuzhou area through SOILQUAKE program analysis. The results show that the characteristic period is inversely proportional to the DSMR and is not sensitive to changes in DR. The platform value is directly proportional to the DSMR and inversely proportional to the DR.

Sun et al. [21] analyzed the relationship curve between DSMR and shear strain through the one-dimensional equivalent linearization method, as well as the influence of maximum DSMR on the response spectrum characteristic period and surface acceleration peak value. The results indicate that for small and moderate earthquakes, the DSMR and maximum dynamic shear modulus of soil have a slight impact on the characteristic period of the response spectrum, with no significant impact on the peak ground acceleration. For large earthquakes, however, it has a significant impact on the characteristic period of the response spectrum and the peak ground acceleration. As the DSMR and maximum dynamic shear modulus increase, the characteristic period of the response spectrum decreases, and the peak ground acceleration increases. The thicker the soil layer, the greater its impact. The above results all indicate that the DSMR is a more sensitive parameter than the shear wave velocity for seismic calculation results. Especially for Class III and IV sites located in strong earthquake regions, its impact is very significant. However, due to the unknown testing errors of the dynamic shear modulus ratio and damping ratio, previous studies on their impact on seismic motion could only rely on the assumption of parameter dispersion, resulting in a lack of basis for the analysis results. On the contrary, it is also impossible to evaluate the accuracy and technical level of existing resonant column tests from the perspective of their impact on seismic motion, leading to disputes over the accuracy of DSMR and DR tests.

This study focuses on the influence of personnel factors on the DSMR and DR of silt. A single resonant column instrument was used to conduct a probability analysis of the experimental error dispersion of the DSMR and DR of soil under 8 typical shear strains. The distribution patterns of the DSMR and DR of soil, probability statistical indicators, and the influence of the discreteness of the DSMR and DR of silt on peak acceleration at different probability levels were given. The research results not only provide support for the theory of reliability design but also provide a reference for improving the understanding of soil dynamic performance.

2. Resonant Column Test

2.1. Soil Sample and Test Instrument

The GZ-1 resonant column instrument of fixed free end type and its improved instrument were used in the test. The reliability of the instrument has been verified [22]. Remolded silt was used in the test. The basic properties of remolded silt are shown in Table 1.

Table 1. The basic properties of silt

Material	Specific gravity of particles	Plastic limit /%	Liquid limit /%	Plasticity index
Silty soil	2.65	25.3	32.5	7.2

2.2. Test Method

The test parameters are determined according to the basic physical indexes of soil. The moisture content of remolded silt is 27%. The density is 1.77 g/cm^3. In order to ensure the comparability and accuracy of the test, 25 groups of remolded silt tests were conducted by the same person. The sample size is $\phi\, 39.1 \times 80\ mm$. The method of equal consolidation was adopted in the test, and the effective consolidation stress is 100 kPa.

The test process was divided into two parts: sample preparation and sample loading, as shown in Figure 1. The test operation steps are as follows.

(1) Step 1: Sample preparation

The water content and density were selected according to the measured liquid plastic limit index and test volume. The soil samples used are dried and crushed, and the mass of dry soil and water required for each soil sample was calculated. The dry soil shall be evenly watered and mixed, and the prepared soil bag shall be put into the moisturizing container for one day and night. Finally, according to the quality, it is evenly loaded into the three pieces mold in four layers. To ensure that the sample is well formed, oil shall be applied to each film, and the height of each layer of soil shall be 20mm by hammering. Each layer shall be roughened when hammered to the specified height.

(2) Step 2: Sample installation, consolidation, and vibration

The prepared soil sample shall first be removed from the three pieces of mold and covered with rubber film. Then the specimen was mounted on the resonant column. The upper and lower ends of the sample shall be firmly bound to the instrument through rubber sleeves to ensure no air leakage. After the cover was closed, an effective confining pressure of 100kPa was applied, and the consolidation time is 8 hours. It should be noted that one sample can only be tested once, and 25 samples shall be prepared for 25 groups of tests.

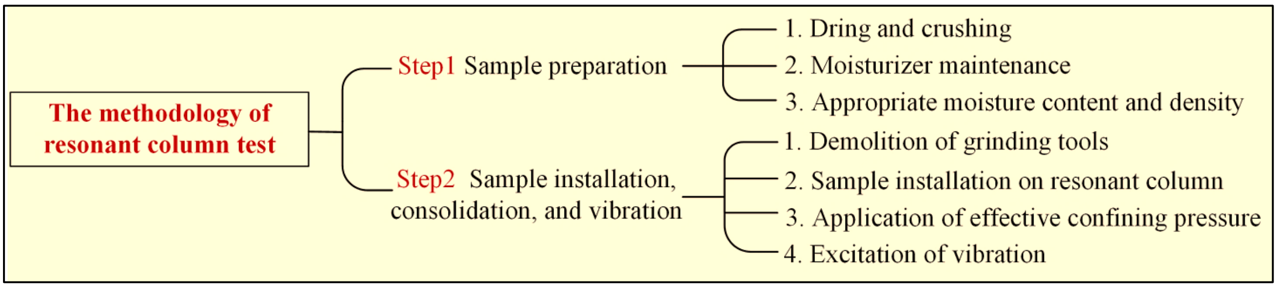

Figure 1. The process of the methodology

This research mainly studies the influence of the same tester on the discreteness of soil DSMR and DR. Therefore, the test shall be completed by professional test personnel with rich experience. Since the nonlinear relationship between DSMR and DR and shear strain is a curve, this study analyzes the error dispersion of DSMR and DR caused by testers for eight typical shear strains.

3. Test Results

The test results of DSMR and DR of silt are shown in Figure 2.

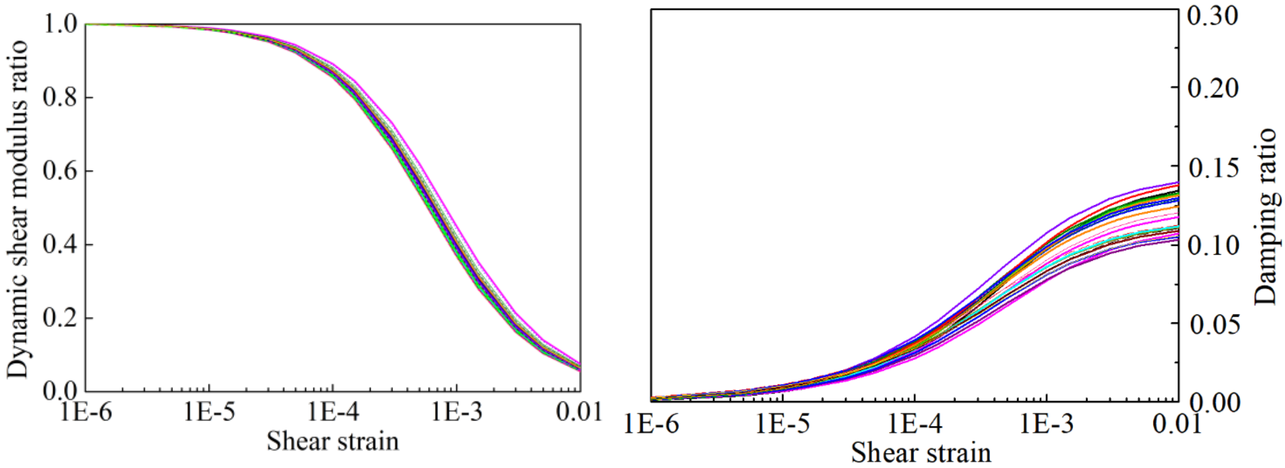

Figure 2. DSMR and DR of silt

The silt test results have a certain degree of dispersion, especially the DR. According to the outlier test method in statistics, the test results of DSMR and DR exceeding 99% fall within the range of 2 times the standard deviation of the mean value, exceeding the requirement of 95%. So, the silt test results are reliable.

4. Analytical Methods

4.1. Distribution

In order to obtain the reference value range under different probability levels, the distribution of DSMR and DR under eight typical shear strains must be determined first. The calculation method is determined according to the distribution. In order to give quantitative results, SAS software is used for quantitative analysis of data [23]. The results are shown in Table 2. In statistics, if the test result p is greater than or equal to 0.05, the data obey normal distribution. It can be found from Table 2 that the DSMR and DR of silt under different shear strains obey normal distribution.

Table 2. Normality test of p value

Soil types	Parameters	Shear strain							
		5E-6	1E-5	5E-5	1E-4	5E-4	1E-3	5E-3	1E-2
Silt (Professional group)	p value of modulus ratio	0.568	0.786	0.204	0.582	0.460	0.465	0.883	0.941
	p value of DR	0.815	0.288	0.806	0.926	0.952	0.432	0.144	0.103

4.2. Calculation Method of Probability Reference Value

In this study, statistical analysis method was used to analyze the error dispersion of silt DSMR and DR [24]. The maximum, minimum, mean, standard deviation, one-time standard deviation, coefficient of variation and different probability levels were used to describe the dispersion of silt DSMR and DR under eight typical shear strains, namely 5×10^{-6}, 1×10^{-5}, 5×10^{-5}, 1×10^{-4}, 5×10^{-4}, 1×10^{-3}, 5×10^{-3}, and 1×10^{-2}.

5. Analysis Results

5.1. Indicator of Divergence

For eight typical shear strains, the envelope, mean value, standard deviation, double standard deviation, variation coefficient, and 95% reference value range of silt DSMR and DR are calculated. The results are shown in Tables 3 and 4.

Table 3. Error analysis results of DSMR

Soil types	Statistical indicators	Shear strain							
		5E-6	1E-5	5E-5	1E-4	5E-4	1E-3	5E-3	1E-2
Remolded silt (One person)	maximum	0.995	0.989	0.943	0.892	0.621	0.449	0.140	0.075
	minimum	0.993	0.985	0.922	0.854	0.536	0.366	0.103	0.055
	mean	0.994	0.986	0.930	0.868	0.568	0.397	0.116	0.062
	standard deviation	0.001	0.001	0.006	0.011	0.024	0.023	0.010	0.006
	coefficient of variation	0.001	0.001	0.007	0.013	0.042	0.059	0.087	0.093
	95% lower limit of reference value	0.993	0.984	0.921	0.853	0.536	0.366	0.103	0.054
	95% upper limit of reference value	0.995	0.989	0.943	0.891	0.620	0.449	0.140	0.075
	Lower limit of one-time standard deviation	0.993	0.985	0.924	0.858	0.544	0.373	0.106	0.056
	Upper limit of one-time standard deviation	0.994	0.988	0.936	0.879	0.591	0.420	0.126	0.067

Table 4. Error analysis results of DR

Soil types	Statistical indicators	Shear strain							
		5E-6	1E-5	5E-5	1E-4	5E-4	1E-3	5E-3	1E-2
Remolded silt (One person)	maximum	0.009	0.013	0.033	0.050	0.105	0.129	0.162	0.167
	minimum	0.005	0.008	0.022	0.033	0.073	0.092	0.119	0.123
	mean	0.006	0.010	0.028	0.041	0.088	0.109	0.139	0.145
	standard deviation	0.001	0.001	0.002	0.003	0.008	0.010	0.013	0.014
	coefficient of variation	0.171	0.144	0.098	0.090	0.090	0.092	0.096	0.097
	95% lower limit of reference value	0.004	0.008	0.022	0.033	0.073	0.092	0.119	0.123
	95% upper limit of reference value	0.009	0.013	0.033	0.050	0.105	0.129	0.162	0.167
	Lower limit of one-time standard deviation	0.005	0.009	0.025	0.038	0.080	0.099	0.126	0.131
	Upper limit of one-time standard deviation	0.007	0.012	0.030	0.045	0.096	0.119	0.153	0.159

5.2. Standard Deviation and Coefficient of Variation

The standard deviation, variation coefficient and shear strain relation curve of DSMR and DR of silt are shown in Figure 3.

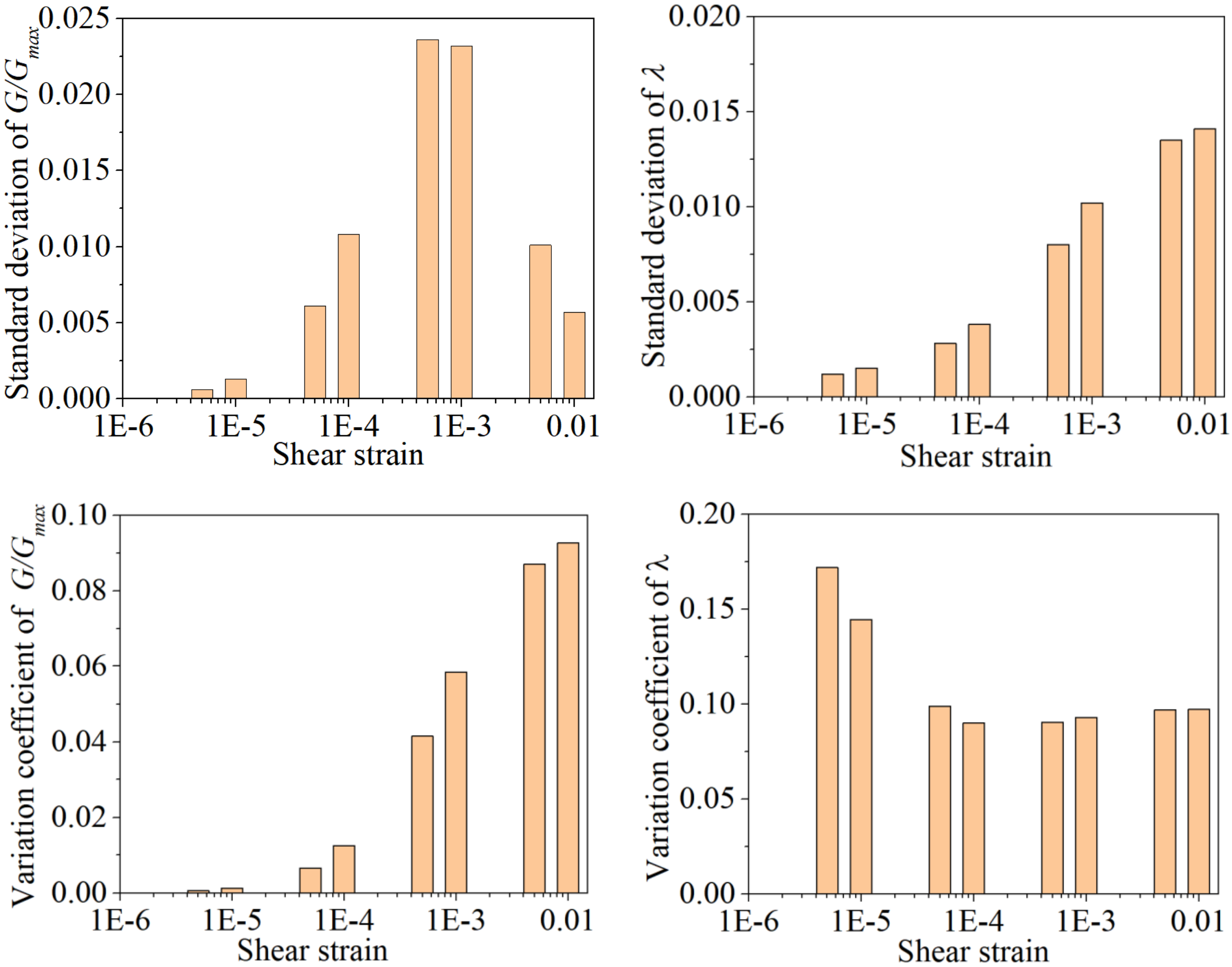

Figure 3. Relationships of standard deviation and variation coefficient of DSMR and DR with shear strain

It can be seen from Figure 3 that the statistical indicators of the dispersion of silt DSMR and DR under typical shear strain show good regularity.

(1) The maximum standard deviation of modulus ratio occurs in the range of shear strain 10^{-4}-10^{-3}, which is the range where the DSMR most often occurs in the analysis and calculation of seismic response of soil layers. The variation coefficient of modulus ratio also shows an increasing trend with the increase of shear strain. It shows that the discreteness of DSMR is small when the strain is small, and it is obviously increased when the strain is large.

(2) The variation coefficient of DR decreases with the increase of shear strain. It shows that the discreteness of DR is large when the strain is small, and vice versa.

(3) The average variation coefficient of modulus ratio is obviously smaller than that of DR, indicating that the variability of DSMR is smaller than that of DR.

In summary, the standard deviation and coefficient of variation of silt are very small, indicating that the dispersion of test error of the same person is very small.

5.3. Envelope Curve

The envelope, mean value and one-time standard deviation of silt DSMR and DR are shown in Figure 4.

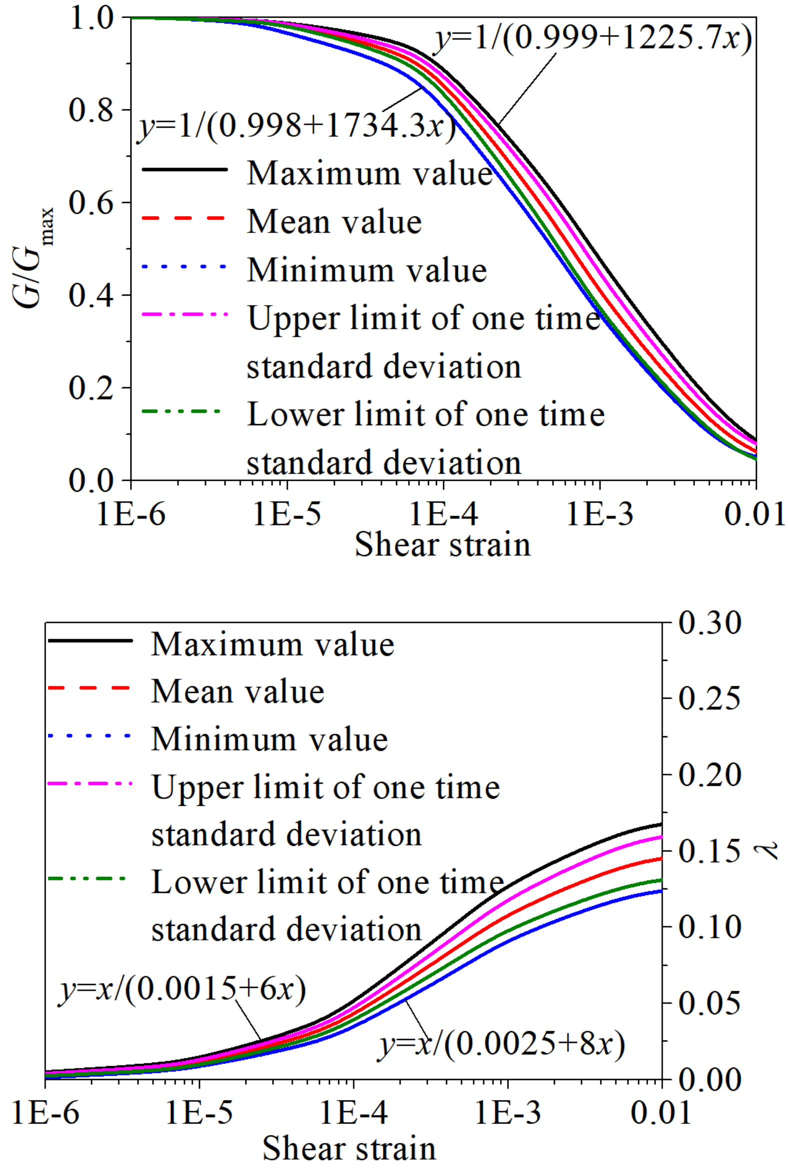

Figure 4. Mean values, standard deviation and envelopes for DSMR and DR versus strain

It can be seen from the figure that the reference value range of one-time standard deviation of silt DSMR and DR is not significantly different from the envelope, indicating that the same tester has little dispersion. It should be noted that one time of standard deviation is equivalent to about 68% probability level.

5.4. Comparison of Variation Coefficients of DSMR and DR

Figure 5 shows the comparison about variation coefficients of DSMR and DR. It can be seen that the variation coefficient of silt DSMR is obviously smaller than that of DR, especially when the strain is small. It shows that the deviation degree of DSMR test is smaller than the result of DR. Because the fitting of DR experimental data is based on the fitting of DSMR data. Therefore, the author believes that there may be two reasons why the error of DSMR test is less than that of DR. One is the test error of modulus ratio, and the other is the test error of DR calculation. The two cases together make the DR test error greater than the DSMR test error.

6. Probability Analysis of Influence on Soil Layer Response

6.1. Calculation Condition

The upper and lower limits of reference values under different probability levels were calculated. The influence of test error of DSMR and DR on peak acceleration under different probability levels was studied [25]. The research results provide support for probabilistic seismic design. Site class Ⅰ, class Ⅱ and class III are selected as the research object, and one-dimensional equivalent linearization program SHAKE2000 was used for calculation. The site profile information is shown in Table 5.

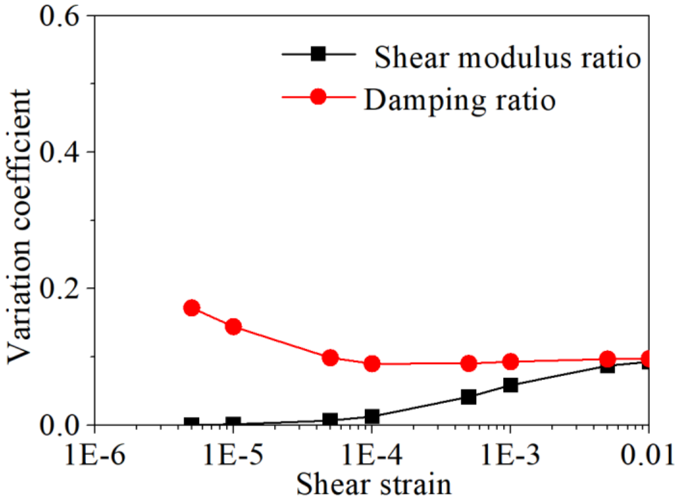

Figure 5. Comparison of variation coefficients of DSMR and DR

Table 5. Physical and mechanical properties of the site profile

Site classes	Number	Soil types	Density（kg/m³）	Wave velocity（m/s）	Thickness (m)	Predominant period(s)
I	1	Clay	1640	350	3	0.034
	2	Bedrock	2200	800		
II	1	Clay	1640	200	24	0.48
	2	Bedrock	2200	800		
III	1	Clay	1640	200	80	1.6
	2	Bedrock	2200	800		

6.2. Input Ground Motion

El Centro ground motion was adopted as the input ground motion. The input peak ground motion acceleration is 0.1g, 0.2g and 0.4g. The time history of input acceleration is shown in Figure 6. Seven groups of nonlinear indicators were selected, namely 95% upper limit, 65% upper limit, 30% upper limit, mean value, 30% lower limit, 65% lower limit and 95% lower limit.

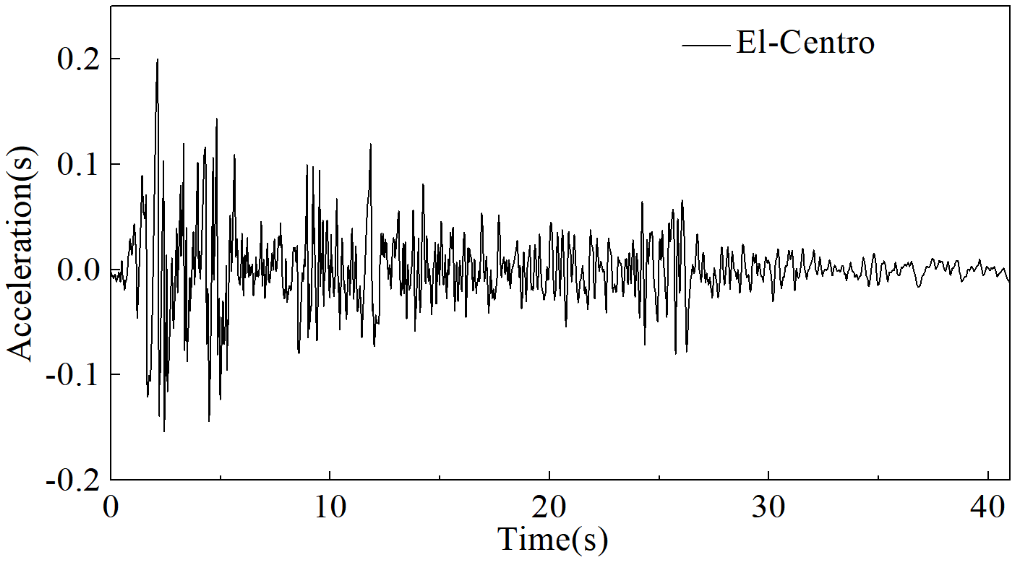

Figure 6. Acceleration time histories for input (PGA=0.2g)

6.3. Probabilistic Analysis of the Effect of Test Error Dispersion on PGA

6.3.1. Probability Analysis of the Influence of DSMR Error on PGA

This study took the peak ground acceleration calculated by SHAKE2000 when the DSMR was taken as the mean value as the standard, and calculated the relative error between the peak acceleration under different probability levels of DSMR. So as to analyze the influence of DSMR test error on ground motion. In this study, when the relative error of acceleration peak value is less than 20%, it is acceptable in engineering, and the impact on ground motion can be ignored, otherwise it cannot be ignored. The most unfavourable principle is adopted to analyze the results, that is, the lower upper limit and lower limit parameters of the same probability level are calculated, and the maximum relative error is selected. The relative error between the peak acceleration of silt under the condition of different probability level DSMR and the peak acceleration under the condition of nonlinear mean value is shown in Table 6.

Table 6. Relative error of PGA under different probability level DSMR of silt (%)

Site classes	Nonlinear combination	0.1g	0.2g	0.4g
I	Upper limit of 95%	0.30	0.69	1.38
	Upper limit of 65%	0.10	0.23	0.48
	Upper limit of 30%	0.05	0.13	0.27
	Lower limit of 30%	0.07	0.17	0.35
	Lower limit of 65%	0.16	0.36	0.76
	Lower limit of 95%	0.20	0.47	1.00
II	Upper limit of 95%	8.42	16.95	16.37
	Upper limit of 65%	3.19	10.04	7.64
	Upper limit of 30%	1.82	6.10	2.87
	Lower limit of 30%	3.03	11.08	2.89
	Lower limit of 65%	6.37	14.49	12.04
	Lower limit of 95%	8.40	15.45	11.66
III	Upper limit of 95%	1.19	1.84	18.83
	Upper limit of 65%	0.42	3.70	6.08
	Upper limit of 30%	0.05	2.00	3.08
	Lower limit of 30%	1.08	1.80	2.26
	Lower limit of 65%	3.09	3.31	3.98
	Lower limit of 95%	5.94	3.50	4.94

6.3.2. Probability Analysis of the Influence of DR Error on Peak

In this study, the peak ground acceleration calculated by SHAKE2000 when the DR was taken as the mean value was used as the standard to calculate the relative error between the peak acceleration and its corresponding value under different probability level DR. So as to analyze the influence of DR test error on ground motion. The relative error between the peak acceleration of silt under different probability level DR and the peak acceleration under the condition of nonlinear mean value is shown in Table 7.

Table 7. Relative error of PGA under different probability level DR of silt (%)

Site classes	Nonlinear combination	0.1g	0.2g	0.4g
I	Upper limit of 95%	0.02	0.08	0.25
	Upper limit of 65%	0.01	0.03	0.09
	Upper limit of 30%	0.00	0.01	0.03
	Lower limit of 30%	0.00	0.01	0.02
	Lower limit of 65%	0.00	0.03	0.10
	Lower limit of 95%	0.01	0.05	0.19
II	Upper limit of 95%	2.30	9.31	4.69
	Upper limit of 65%	0.83	6.91	3.10
	Upper limit of 30%	0.60	6.08	2.22
	Lower limit of 30%	0.26	7.30	1.29
	Lower limit of 65%	0.62	8.47	2.14
	Lower limit of 95%	0.54	3.24	3.13
III	Upper limit of 95%	7.39	13.88	5.95
	Upper limit of 65%	3.33	7.26	2.77
	Upper limit of 30%	2.67	5.87	2.04
	Lower limit of 30%	1.81	4.91	3.96
	Lower limit of 65%	4.24	9.80	7.26
	Lower limit of 95%	8.24	17.98	13.06

It can be seen from Table 7 that the influence of the test error of silt DR on the peak acceleration in site class Ⅰ and class Ⅱ can be ignored. In the site class III, the influence of DR test error on peak acceleration within 95% probability range can be ignored. The influence of DR test error on peak acceleration beyond 95% probability range cannot be ignored.

7. Conclusions

In this study, experimental data were used to study the influence of tester factors on the dispersion of soil DSMR and DR. The distribution form of DSMR and DR, probability statistical index, variation range under different probability levels, and influence of test error of DSMR and DR of silt on peak acceleration were given. The risk assessment results about the impact of the DSMR and DR test results on the seismic calculation results were proposed. The results consist of the following five aspects:

(1) The DSMR and DR of silt under different shear strains obey normal distributions.

(2) The statistical indexes of the discreteness of silt DSMR and DR under typical shear strain show good regularity. The maximum standard deviation of modulus ratio occurs in the sensitive area of soil layer seismic response analysis and calculation, which is consistent with existing conclusions.

(3) There is no significant difference between the reference range of the standard deviation of the DSMR and DR of silt and the outer envelope line. This result indicates that the dispersion of experimental errors for the same person is very small.

(4) Taking the non-negligible impact on seismic motion as the threshold, the impact of peak acceleration on DSMR and DR test errors in hard sites can be ignored. In medium to hard sites, the impact of DSMR test error on peak acceleration can be ignored, and the risk level of DR test error is close to 5%.

(5) In general, the impact of experimental errors on the ground motion calculation results of the testing personnel can be basically ignored. In special cases, the technical level of the testing personnel should be improved. Otherwise, it will cause significant risks to the estimation of the ground motion input of the engineering structure.

8. Declarations

8.1. Author Contributions

Conceptualization, B.L. and X.F.L.; methodology, B.L. and X.F.L.; software, X.F.L.; validation, B.L. and X.F.L.; formal analysis, B.L. and X.F.L.; investigation, B.L.; resources, B.L. and X.F.L.; data curation, B.L.; writing—original draft preparation, B.L.; writing—review and editing, B.L. and X.F.L.; visualization, B.L. and X.F.L.; supervision, X.F.L. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available in the article.

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8.4. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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