Variability of Nonlinear Dynamic Shear Modulus and Damping Ratio of Soils

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ABSTRACT :

The dynamic shear modulus and damping ratio of soils are two important parameters in soil property and affect earthquake ground motion greatly. The laboratory experimental results at present show a significant variation because of the soil complication. Studying the uncertainty of the dynamic shear modulus and damping ratio is quite helpful for understanding the nonlinear behavior of soils. Also, the quantitative results of the variability are one of basic elements of the reliability analysis for the ground motion and structure damage. However, the related research at present mostly concentrates on the static problem and the study on dynamics parameters especially nonlinear uncertainty problem is rare.

In this paper, the uncertainty of the nonlinear dynamic shear modulus and damping ratio is investigated and the quantitative results for five typical soils are presented. The original experiment data of dynamic shear modulus and damping ratio of 588 groups from 17 provinces, 42 cities in China are collected. The standard relation of dynamic shear modulus and damping ratio with the shear strain, i.e., $G/G_{\max}$-γ and λ-γ, fitted by the hyperbolic model are attained. For the eight typical shear strain points in the nonlinear scope, the uncertainty of dynamic shear modulus and damping ratio is conducted. The distribution characteristics of the dynamic shear modulus and damping ratio for the eight typical shear strain points is given, separately, and the normal distribution is verified by two methods. Based on these, the reference value range of 95% probability, the maximum value, the minimum value, the mean value, the standard deviation and the coefficient variation are presented finally.

KEYWORDS: Soils; Nonlinear; Dynamic Shear Modulus; Damping Ratio; Variability; Uncertainty

1. INTRUDUCTION

The dynamic modulus and damping ratio of soils are two important parameters in soil dynamics. They are indispensability for soil layer seismic response analysis and seismic safety evaluation of engineering sites. During the soil layer seismic response analysis, the difference of dynamic modulus and damping ratio will affect earthquake ground motion greatly.Due to anisotropy of soil itself, experiment error, testing model error, statistical error, etc., the uncertainty of the two soil dynamic parameters can be quite large. In this paper, the uncertainty for five typical soils have been investigated and presented quantitatively. On the one side, we can master the variety range of the two parameters for the five typical soils expansively at all-around. On the other side, it can provide references when there are no experiment conditions.

Currently, the dynamic modulus and damping ratio of soil have been investigated by some scholars. Series of achievements on the uncertainty analysis of the soil parameters have been published. Li Xiaoyong (2001) collected 100 drills of 10 building engineering sites in Taiyuan, and studied dynamic triaxial strength indexes and anti-shearing strength indexes ,such as the sample mean value μ, the sample coefficient of variation δ, the sample size N by statistic. It delt with the probabilistic characteristics of strength indexes of silty clay in Taiyuan, and studied more thoroughly the correlation between the strength indexes of different tests. The variability coefficients of strength indexes for Taiyuan silty clay were compiled statistic on, then some chang laws were drawn out. And also the paper built the distribution for strength indexes of Taiyuan silty clay, studied the correlation between physical and strength indexes, and got some empirical equations. There is higher variability for strength indexes of silty clay in Taiyuan. Lan Qinglong(1997) gives the results of dynamic behaviors and the mean values of volume-weight of the 8 types of soil in Taiyuan area using the results of dynamic triaxial test of the 142 soil samples in Taiyuan area. Chen Guoxing(2004) analyzed the test results of free vibration column apparatus on recently deposited soils in Nanjing and its neighboring areas. Based on the test results and theoretical analysis, the average curves, recommended values and envelopes of dynamic shear modulus ratio G/G_{max} and damping ratio λ versus dynamic strain γ for the 6 kinds of soils are presented. At present, all the achievements are only limitied in one or some areas.The full-scale statistical results of the soil dynamic parameters in China are not given. Further research and investigation will be carried out for the common dynamic properties of the soil in China.

Through testing and collecting the results of resonant column apparatus on differences of soils, the original experiment data of dynamic shear modulus and damping ratio of 588 groups including (mucky soil, clay, silty clay, silt, sand) in 17 provinces, 42 cities in China are studied. The standard relation of dynamic shear modulus and damping ratio with the shear strain, i.e., G/G_{max}-γ and λ-γ, is fitted by the hyperbolic model. For the eight typical shear strain points($5*10^{-6}$、$1*10^{-5}$、$5*10^{-5}$、$1*10^{-4}$、$5*10^{-4}$、$1*10^{-3}$、$5*10^{-3}$、$1*10^{-2}$) in the nonlinear scope, the uncertainty of dynamic shear modulus and damping ratio is conducted. The distribution characteristics of the dynamic shear modulus and damping ratio for the eight typical shear strain points is given, separately, and the normal distribution is verified by two methods. And the quantitative results for five typical soils are presented.

2. ANALYSIS METHOD

2.1 Distribution Characteristics

The normal distribution of the data is verified by two methods. At first, we draw the frequency distribution graph and probability paper testing plot，observe its distribution characteristics. Only the charts fit normal distribution obviously, the assumption of its according to normal distribution can be right. This method depends on human, so testing method must convert quantitatively. So, in this paper, the normal distribution is verified quantitatively by authority software SAS in the field of Statistics.

2.2 Uncertainty Analysis

To describe the uncertainty of dynamic shear modulus and damping ratio of soils better, the maximum value, the minimum value, the mean value, the standard deviation, the coefficient variation and the reference value range of 95% probability of the different soils at the eight typical shear strain points are presented finally.

3. UNCERTAINTY OF DYNAMIC SHEAR MODULUS AND DAMPING RATIO OF SOILS

In this paper, the original experiment data of dynamic shear modulus and damping ratio of 588 groups for five typical soils are collected, including 112 groups of clay, 209 groups of silty clay,95 groups of silt,138 groups of sand,34 groups of mucky soil. The uncertainty of the nonlinear dynamic shear modulus and damping ratio is investigated and the quantitative results for five typical soils are presented. The standard relation of dynamic shear modulus and damping ratio with the shear strain, i.e., G/G_{max}-γ and λ-γ fitted by the hyperbolic model are attained. For the eight typical shear strain points in the nonlinear scope, the uncertainty of dynamic shear modulus and damping ratio is conducted. The distribution characteristics of the dynamic shear modulus and damping ratio for the eight typical shear strain points is given, separately, and the normal distribution is verified by two methods. Based on these, the reference value range of 95% probability, the maximum value, the minimum value, the mean value, the standard deviation and the coefficient variation are presented in Table1 and Table 2.

The paper does not classify the soil data corresponding to different consolidation stress but lumps all the data of different consolidation stress for statistical analysis. Due to lack of sand samples and the existing samples have not been classified clearly, as well as a few documents of mucky soil, further investigation will be undertaken in the future research.

Table 1 Results of the uncertainty of dynamic shear modulus for five typical soils

Soils	Statistic	Shear Strain γ (10^{-4})							
		0.05	0.1	0.5	1	5	10	50	100
Clay	Maximum	0.9984	0.9965	0.9813	0.9630	0.8377	0.7205	0.3400	0.2048
	Minimum	0.9578	0.9093	0.6499	0.4788	0.1133	0.0600	0.0125	0.0063
	Mean	0.9936	0.9852	0.9265	0.8668	0.5863	0.4272	0.1415	0.0781
	Standard Deviation	0.0051	0.0123	0.0504	0.0764	0.1359	0.1303	0.0630	0.0370
	Coefficient of Variation (%)	0.5150	1.2479	5.4446	8.8115	23.1760	30.5029	44.5305	47.4190
	Lower Boundary	0.9780	0.9450	0.7760	0.6340	0.1980	0.1718	0.0240	0.0170
	Upper Boundary	0.9978	0.9951	0.9741	0.9490	0.7868	0.6827	0.2692	0.1555
Silty Clay	Maximum	0.9987	0.9970	0.9839	0.9679	0.8568	0.7493	0.3739	0.2299
	Minimum	0.9688	0.9325	0.7173	0.5567	0.1995	0.1107	0.0243	0.0123
	Mean	0.9933	0.9851	0.9250	0.8611	0.5662	0.4028	0.1253	0.0677
	Standard Deviation	0.0035	0.0076	0.0342	0.0568	0.1089	0.1070	0.0528	0.0314
	Coefficient of Variation (%)	0.3528	0.7757	3.7018	6.5919	19.2379	26.5651	42.1066	46.4225
	Lower Boundary	0.9845	0.9658	0.8383	0.7196	0.3527	0.1931	0.0484	0.0248
	Upper Boundary	0.9979	0.9952	0.9744	0.9495	0.7798	0.6125	0.2715	0.1571
Silt	Maximum	0.9990	0.9976	0.9873	0.9283	0.7199	0.5621	0.2041	0.1136
	Minimum	0.9230	0.8720	0.5770	0.4800	0.1300	0.0690	0.0038	0.0019
	Mean	0.9875	0.9746	0.8817	0.8025	0.4868	0.3345	0.0995	0.0529
	Standard Deviation	0.0128	0.0219	0.0816	0.1011	0.1339	0.1143	0.0444	0.0248
	Coefficient of Variation (%)	1.2973	2.2502	9.2603	12.5944	27.5056	34.1801	44.6071	46.8732
	Lower Boundary	0.9520	0.9220	0.6250	0.5300	0.2215	0.1104	0.0125	0.0043
	Upper Boundary	0.9967	0.9925	0.9607	0.9194	0.6936	0.5587	0.1864	0.1015
Sand	Maximum	0.9978	0.9952	0.9742	0.9492	0.7875	0.6493	0.2700	0.1561
	Minimum	0.9000	0.8370	0.6600	0.6449	0.1750	0.1031	0.0310	0.0108
	Mean	0.9760	0.9544	0.8389	0.8012	0.4003	0.2763	0.0868	0.0431
	Standard Deviation	0.0225	0.0364	0.0884	0.0815	0.1512	0.1257	0.0488	0.0283
	Coefficient of Variation (%)	2.3012	3.8115	10.5405	10.1676	37.7740	45.4735	56.1569	65.6607
	Lower Boundary	0.9120	0.8600	0.6853	0.6090	0.1761	0.1120	0.0312	0.0120
	Upper Boundary	0.9968	0.9929	0.9624	0.9282	0.7156	0.5616	0.2038	0.1135
Mucky Soil	Maximum	0.9984	0.9963	0.9803	0.9611	0.8304	0.7098	0.3283	0.1964
	Minimum	0.9000	0.8640	0.6300	0.4600	0.1000	0.0790	0.0170	0.0080
	Mean	0.9722	0.9526	0.8397	0.8041	0.4377	0.3099	0.1262	0.0659
	Standard Deviation	0.0247	0.0347	0.0892	0.1294	0.1841	0.1671	0.0822	0.0491
	Coefficient of Variation (%)	2.5395	3.6410	10.6254	17.4043	42.0616	53.9136	65.1199	74.5436
	Lower Boundary	0.9000	0.8640	0.6648	0.4898	0.1100	0.0890	0.0290	0.0150
	Upper Boundary	0.9984	0. 9963	0.9803	0.9611	0. 7986	0.6373	0.2872	0.1964

Table2 Results of the uncertainty of damping ratio for five typical soils

Soils	Statistic	Shear Strain γ (10^{-4})							
		0.05	0.1	0.5	1	5	10	50	100
Clay	Maximum	0.0669	0.0870	0.1280	0.1500	0.2272	0.2304	0.2667	0.2734
	Minimum	0.0020	0.0040	0.0110	0.0170	0.0440	0.0620	0.0906	0.0993
	Mean	0.0260	0.0313	0.0526	0.0637	0.1029	0.1174	0.1447	0.1504
	Standard Deviation	0.0155	0.0168	0.0268	0.0281	0.0389	0.0388	0.0455	0.0468
	Coefficient of Variation (%)	59.5347	53.6273	50.8928	44.1804	37.7509	33.0862	31.4489	31.0865
	Lower Boundary	0.0060	0.0090	0.0230	0.0290	0.0530	0.0700	0.0970	0.1020
	Upper Boundary	0.0650	0.0715	0.1180	0.1388	0.2057	0.2220	0.2578	0.2670
Silty Clay	Maximum	0.0620	0.0720	0.0990	0.1293	0.1980	0.2168	0.2643	0.2733
	Minimum	0.0020	0.0026	0.0097	0.0175	0.0505	0.0582	0.0748	0.0820
	Mean	0.0171	0.0215	0.0398	0.0532	0.1017	0.1149	0.1437	0.1493
	Standard Deviation	0.0102	0.0109	0.0141	0.0166	0.0262	0.0315	0.0402	0.0419
	Coefficient of Variation (%)	61.5925	52.3947	37.1154	32.2790	27.3823	27.4457	27.9543	28.0969
	Lower Boundary	0.0040	0.0067	0.0174	0.0251	0.0572	0.0700	0.0840	0.0860
	Upper Boundary	0.0410	0.0480	0.0770	0.0917	0.1597	0.1893	0.2370	0.2471
Silt	Maximum	0.0660	0.0700	0.0820	0.0926	0.1552	0.1852	0.2462	0.2570
	Minimum	0.0030	0.0060	0.0152	0.0192	0.0387	0.0506	0.0750	0.0770
	Mean	0.0170	0.0214	0.0394	0.0518	0.1012	0.1087	0.1337	0.1388
	Standard Deviation	0.0143	0.0137	0.0161	0.0199	0.0299	0.0370	0.0485	0.0513
	Coefficient of Variation (%)	74.0937	60.6748	40.2056	35.9555	29.5396	30.3990	32.1220	32.6170
	Lower Boundary	0.0050	0.0070	0.0170	0.0260	0.0530	0.0640	0.0806	0.0820
	Upper Boundary	0.0650	0.0680	0.0752	0.0924	0.1545	0.1848	0.2454	0.2556
Sand	Maximum	0.0520	0.0610	0.0860	0.0990	0.1613	0.1893	0.2539	0.2651
	Minimum	0.0010	0.0020	0.0100	0.0180	0.0390	0.0503	0.0590	0.0604
	Mean	0.0135	0.0176	0.0346	0.0467	0.0840	0.0982	0.1183	0.1222
	Standard Deviation	0.0089	0.0104	0.0156	0.0186	0.0253	0.0290	0.0395	0.0427
	Coefficient of Variation (%)	66.3817	59.1503	45.1798	39.8220	30.0686	29.5656	33.3848	34.9687
	Lower Boundary	0.0029	0.0040	0.0134	0.0189	0.0459	0.0540	0.0627	0.0639
	Upper Boundary	0.0370	0.0460	0.0710	0.0870	0.1380	0.1644	0.2314	0.2484
Mucky Soil	Maximum	0.0400	0.0470	0.1020	0.1300	0.1904	0.2141	0.2608	0.2793
	Minimum	0.0058	0.0085	0.0235	0.0305	0.0660	0.0830	0.1170	0.1260
	Mean	0.0162	0.0212	0.0429	0.0623	0.1270	0.1586	0.1919	0.2007
	Standard Deviation	0.0081	0.0097	0.0217	0.0272	0.0356	0.0407	0.0437	0.0459
	Coefficient of Variation (%)	49.9718	45.9983	50.6589	43.5714	28.0297	25.6808	22.7845	22.8586
	Lower Boundary	0.0058	0.0089	0.0238	0.0348	0.0676	0.0980	0.1410	0.1440
	Upper Boundary	0.0286	0.0370	0.0780	0.1040	0.1792	0.2140	0.2565	0.2776

Lower Boundary: Lower Boundary of Reference Value
Upper Boundary: Upper Boundary of Reference Value

Meanwhile, the envelopes, average fitting curves, reference range are presented in Figure1-5.

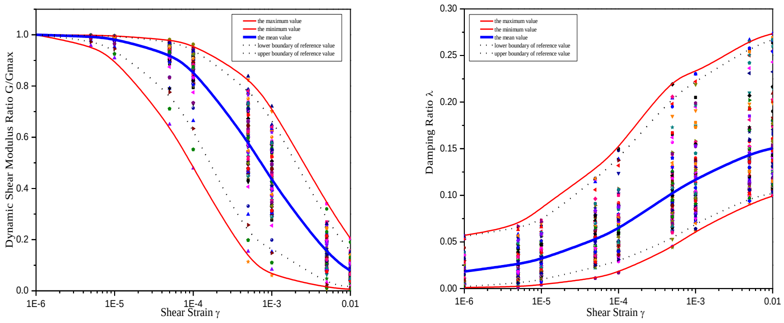

Figure1 Range and fitting curves of dynamic shear modulus and damping ratio for clay

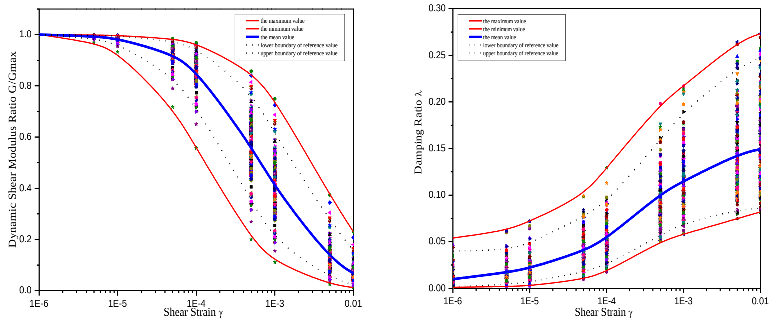

Figure2 Range and fitting curves of dynamic shear modulus and damping ratio for silty clay

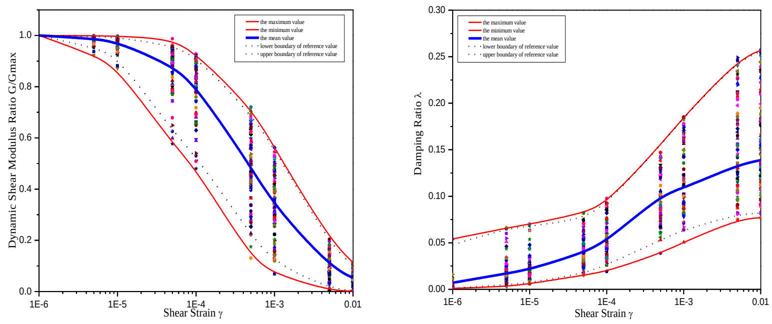

Figure3 Range and fitting curves of dynamic shear modulus and damping ratio for silt

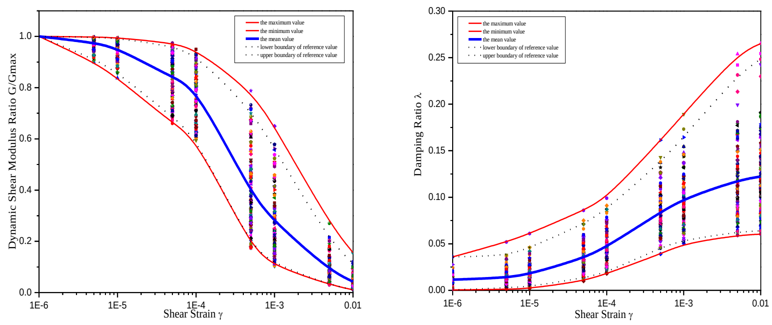

Figure4 Range and fitting curves of dynamic shear modulus and damping ratio for sand

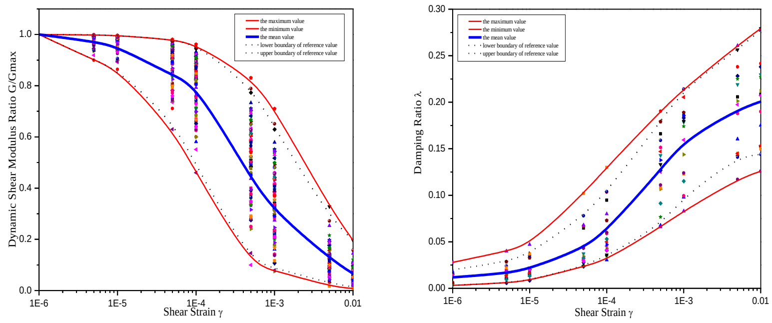

Figure 5 Range and fitting curves of dynamic shear modulus and damping ratio for mucky soil

From Table1-2 and Figure1-5, some points can be sum up:(1) The average value of the dynamic shear modulus and damping ratio of clay are larger than those of silty clay corresponding to different shear strains, and the average values of silty clay are larger than those of silt. (2) The changing range of the average values of clay, silty clay and mucky soil is relatively large while the changing rang of average values of silt and sand is relatively small. (3) From the Figure.1-5, the dispersion effects of clay, silty clay and mucky soil are large but the dispersion effects for silt and sand are small. (4) The variability of damping ratio is larger than that of shear modulus. (5) The variability of shear modulus increases with increasing shear strain while the variability of damping ratio decreases with increasing shear strain, but the variability of damping ratio is not large. (6) The reference value ranges of 95% probability are notably different from the envelopes, especially the upper boundary of reference values of the shear modulus and damping ratio.

4. CONCLUSION

In this paper, the original experiment data of dynamic shear modulus and damping ratio of 588 groups in 17 provinces, 42 cities in China are collected and investigated. The uncertainty of the nonlinear dynamic shear modulus and damping ratio for the eight typical shear strain points is investigated and the quantitative results (the reference value range of 95% probability, the maximum value, the minimum value, the mean value, the standard deviation and the coefficient variation) for five typical soils are presented. To conclude, some salient points can be outlined.

(1). All the average values of dynamic shear modulus for the five typical soils are larger than 0.8 at 1*10-4 shear strain point. The average values of different soils have some difference. The average values of clay and silty clay are relatively large, which are about 0.86. The average values of silt, sand and mucky soil are relatively small, which are about 0.8.

(2). The average values of damping ratio for the five typical soils have some difference, which decrease in the order of mucky soil, clay, silty clay, silt, sand. It accords with the cognition.

(3). The envelopes of dynamic shear modulus and damping ratio for the five typical soils are different, which are mucky soil, clay, silty clay , silt and sand from top to bottom respectively.

(4). The standard deviation and the coefficients of variation of shear modulus of the five typical soils increase with increasing shear strain. The relative and absolute dispersion effects for shear modulus increases with increasing shear strain.

(5). The standard deviation of damping ratio for the five typical soils increases with increasing shear strain, the absolute dispersion effects for damping ratio increases with increasing shear strain. But the coefficient variation decreases with increasing shear strain, the relative dispersion effects for damping ratio are larger when shear strain are small.

(6). For the five typical soils, the reference value range of 95% probability and envelope have distinguish difference, which demonstrates the dispersion of the testing results are relatively large.Therefore, the envelopes may be not quite applicable for general results of soils.

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