Experimental Research on Difference of Dynamic Modulus and Damping Characteristics of Loess in Shanxi Province

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Abstract. Dynamic triaxial tests are carried out on loess from different regions in Shanxi province. Based on the test results, dynamic constitutive relation, dynamic modulus and damping ratio behaviors of the loess are studied. Influence of regional distribution, physical indexes and ages on dynamic modulus and damping ratio of the loess are analyzed by comparing the model parameters. The results show that dynamic constitutive relation of Shanxi loess conforms to hyperbolic model. The relationship between the dynamic shear modulus ratio and the dynamic shear strain can be described as a negative exponential function. However, the relationship between the damping ratio and the dynamic strain obeys to a power function. The maximum dynamic shear modulus tends to increase from south to north. Moreover, there is a good correlation between dynamic shear modulus ratio and initial void ratio. The variation trend of dynamic modulus changing with dynamic shear strain is related to natural moisture content of the loess, and the value of dynamic shear strain in the central part of Shanxi province is bigger than that in south and north. While that in the north is the least. The increasing tendency of damping ratio has obvious regional differences which have been greatly affected by the natural moisture content and ages.

1. Introduction

Loess is characteristic of large pores, weak cementation and rich soluble salts. Under the impact of earthquakes, loess soils are prone to structural damages, resulting in serious geotechnical earthquake disasters, including earthquakes seismic subsidence and, landslides, etc. In China, loess is widely distributed and formed by diverse factors, which leads to significant regional differences in the physical and mechanical properties of loess [1, 2].

Located in the eastern part of the Loess Plateau, Shanxi Province covers a series of south-north fault basins distributed in Datong, Xinding, Taiyuan, Linfen and Yuncheng. There is a Fenwei earthquake belt in the region with strong neotectonic movements and complex geological conditions. Due to the water sensitivity and dynamic vulnerability of loess, the risk of loess earthquake disasters in Shanxi Province is high, which seriously threatens the safe use of construction projects.

Dynamic shear modulus and damping ratio are important parameters for describing the dynamic characteristics of soils. They are usually used as the basic data for analyzing the earthquake effects effect of engineering sites, and are also essential parameters for earthquake response analysis of soil layers layer [3].

S. Yamada et al. studied the seafloor clay through cyclic torsional shear test and found that its dynamic shear modulus increases and the damping ratio decreases with the increase of plasticity index, which provides data reference for port earthquake engineering in Japan [4]. Zhijie Wang et al. [5] measured the dynamic shear modulus and damping ratio of undisturbed loess in different regions by cyclic torsional shear test, and discussed the regional distribution characteristics of dynamic modulus and damping ratio of loess from the spatial plane. Xiaobing Li studied the dynamic modulus attenuation law of saturated soil from the perspective of stress path, and described the dynamic constitutive relationship of soil more comprehensively [6]. Xiaoyi Cao studied the shear strength of the loess in western Shanxi, and found that the internal friction angle of loess varies with water content [7]. Yan et al. compared and analyzed the differences in dynamic and static properties of Shanxi loess under different water contents, and established the relationship between the dynamic and static strength of Shanxi loess [8]. However, the above studies on the impacts of regional characteristics on the dynamic modulus and damping ratio of loess are mainly targeted at the Longxi loess, Shanbei loess and Guanzhong loess in Loess Plateau while there are few researches on Shanxi; the analysis of the dynamic modulus and damping ratio of loess in different regions of Shanxi is still insufficient.

Based on the results of dynamic triaxial tests, the dynamic constitutive relationship of Shanxi loess is obtained, and the variation law of dynamic modulus and damping characteristics with dynamic strain is analyzed. Then, the impacts of regional distribution, difference in physical index and forming time are studied on the dynamic modulus and damping characteristics are studied. The research results can provide a theoretical reference for the analysis of dynamic stability analysis of construction project foundation in Shanxi Province.

2. Test conditions

2.1. Samples

In the artificially excavated exploration wells of Changzhi, Linfen, Taiyuan and Xinzhou regions of Shanxi Province, undisturbed loess samples were taken. The soil density, natural water content and plasticity index are shown in Table 1, and the results of the particle analysis test are shown in Fig. 1. It can be seen from Table 1 and Fig. 1 that the initial porosity of Shanxi loess gradually decreases from east to west and from south to north. Besides, the natural water content gradually decreases from south to north, but due to the impact of precipitation on shallow soils, the water content of loess at different depths in the same region also differs. The particle size gradation of the soil generally tends to be more uniform from south to north and from east to west. LF-1 loess has the highest powdered content and low clayed content, while XZ-2 loess is Q_2 loess with high clayed content.

Table 1. Physical properties of loess in Shanxi province.

Sample	Depth /m	Density g/cm^3	Water content /%	Void ratio	Plastic index	Locating
CZ-1	4.5	1.40	16.77	1.25	12.31	Changzhi
CZ-2	3.0	1.47	20.20	1.21	12.52	
XZ-1	4.0	1.65	24.44	1.05	11.94	Xinzhou
XZ-2	15.0	1.62	10.24	0.84	15.03	
LF-1	7.0	1.47	15.69	1.12	14.17	Linfen
TY-1	3.5	1.36	9.81	1.18	13.49	Taiyuan

2.2. Test instrument and method

The instrument used in the test is a WF-12440 dynamic triaxial-torsional shear test system. The test method of dynamic elastic modulus and damping ratio is about the Geotechnical Test Procedure (SL237-032-1999).

The sample size is 50mm (D) × 100mm (H). The sample is subjected to biased cementation. To compare the samples in different regions is set as 100kPa and the side pressure coefficient K_0 is set as 0.59. During the test, the cyclic dynamic load is an equal-amplitude sine wave with a frequency of 1Hz. The sample is loaded step by step by increasing the dynamic load amplitude.

3. Dynamic modulus and damping characteristics of Shanxi loess

3.1. Test results

According to the results of the dynamic triaxial test, the $\sigma_d \sim \varepsilon_d$ curve of loess in different regions under cyclic loading is plotted as shown in Fig. 2.

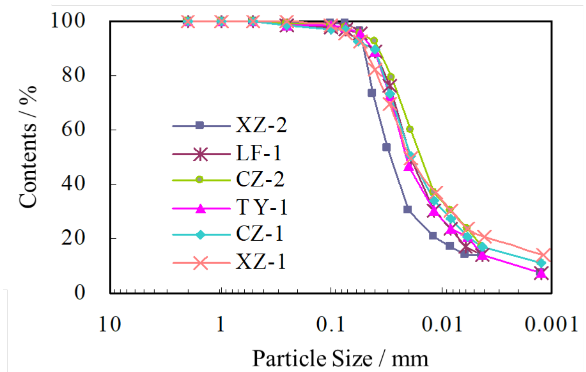

Figure 1. Particle size of the loess in Shanxi regions.

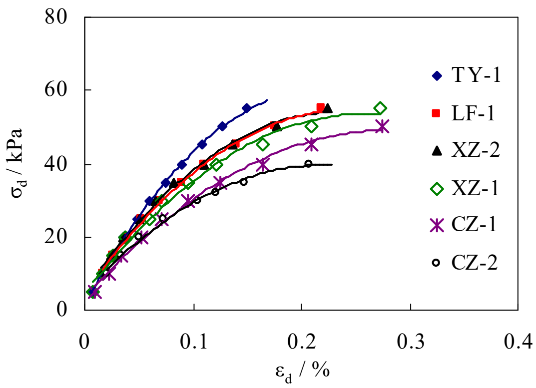

Figure 2. Curves of σd ~ εd of Shanxi loess.

It can be seen from the figure that with the increase of dynamic stress, the dynamic strain of loess in different regions shows a nonlinear characteristic, firstly increasing rapidly and then steadily. The difference in physical index caused by the different distribution of loess has a significant influence on the development of the $\sigma_d \sim \varepsilon_d$ relationship curve. When the strain is the same, the dynamic stress of TY-1 loess is the highest, and the dynamic stress of CZ-2 loess is the lowest. Combined with the physical properties of loess in different regions in Table 1, TY-1 loess has the lowest natural water content and a higher plasticity index; CZ-2 loess has a higher natural water content and a lower plasticity index, showing the difference in the natural water content and plasticity index caused by different distribution regions has obvious influence on the dynamic deformation characteristics of Shanxi loess; the loess with higher natural water content and lower plasticity index requires a lower dynamic stress to reach a certain strain. The analysis of the $\sigma_d \sim \varepsilon_d$ relationship curves of LF-1 and CZ-1 loess shows that when the natural water content is similar, the loess with a lower initial porosity requires a higher dynamic stress to reach a certain strain.

3.2. Change characteristics and attenuation model for dynamic elastic modulus of Shanxi loess

The dynamic elastic modulus of soil is an index to measure the difficulty of elastic deformation in soil. A higher dynamic elastic modulus indicates a lower elastic deformation of soil under the impact of a certain dynamic load. According to the dynamic stress and dynamic strain data of Shanxi loess recorded by the dynamic triaxial test, and the definition of dynamic elastic modulus, formula (1) can be used to calculate the dynamic elastic modulus of loess, and then the reciprocal of dynamic elastic modulus is shown as formula (2). The $1/E_d \sim \varepsilon_d$ relationship curve of loess in different regions of Shanxi is plotted as shown in Fig. 3.

$$E_d = \sigma_d / \varepsilon_d \tag{1}$$

$$1/E_d = \varepsilon_d / \sigma_d \tag{2}$$

It can be seen from the figure that the reciprocal of the dynamic elastic modulus $1/E_d$ increases with the increase of the dynamic strain ε_d, and the relationship between the two is linear, and the slope of the fitted curve demonstrates obvious regional characteristics. The slope of the $/E_d \sim \varepsilon_d$ curve of TY-1 loess is the smallest, and the slope of the $1/E_d \sim \varepsilon_d$ curve of CZ-2 loess is the largest. The slope of the $1/E_d \sim \varepsilon_d$ curve has the characteristics of Changzhi>Xinzhou>Linfen>Taiyuan. In addition, for the loess in the same area, the forming time and initial physical index have a certain influence on the slope of the $1/E_d \sim \varepsilon_d$ curve. The loess with an earlier forming time and a lower natural water content has a smaller slope of the $1/E_d \sim \varepsilon_d$ curve.

Based on the intercept and slope of ε_d curve, the relationship between $1/E_d$ and ε_d can be expressed as:

$$1/E_d = a + b\varepsilon_d \tag{3}$$

Then, formula (2) is substituted into formula (3), and we get:

$$\sigma_d = \frac{\varepsilon_d}{a + b\varepsilon_d} \tag{4}$$

According to formula (4), the dynamic constitutive relationship of loess in different regions of Shanxi obeys the Hardin-Dinevich hyperbolic model. The model parameters a, b and correlation coefficient R^2 are shown in Table 2.

Table 2. Dynamic constitutive relation parameters of Ed~εd of Shanxi loess.

Samples	Model parameters		R^2
	a（$\times 10^{-3}$）	b	
CZ-1	1.903	1.313	0.9993
CZ-2	1.849	1.319	0.9946
LF-1	1.517	1.134	0.9994
TY-1	1.526	0.802	0.9993
XZ-1	1.485	1.287	0.9978
XZ-2	1.367	1.223	0.9987

According to the definition of the dynamic shear modulus G_d of the soil, there is the following conversion relationship between G_d and the dynamic elastic modulus E_d:

$$G_d = E_d / [2(1+\upsilon)] \tag{5}$$

Correspondingly, the relationship between the dynamic shear strain γ_d and the axial dynamic strain εd is:

$$\gamma_d = \varepsilon_d (1+\upsilon) \tag{6}$$

In the study, the ratio of the final dynamic stress to the initial dynamic elastic modulus is defined as the reference strain. The reference shear strain γ_r is calculated according to formula (6), and the relationship between the dynamic shear modulus ratio G/G_0 and γ_r is used to perform nonlinear fitting calculation on the test results to obtain the $G/G_0 \sim \gamma_d$ relationship curve of Shanxi loess as shown in Fig. 4.

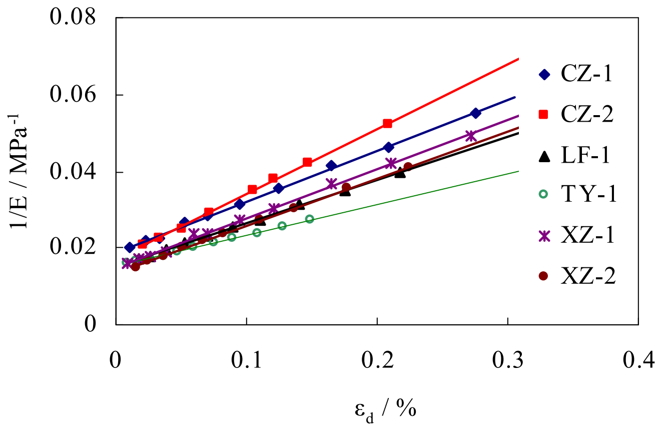

Figure 3. Curves of 1/Ed~εd of Shanxi loess.

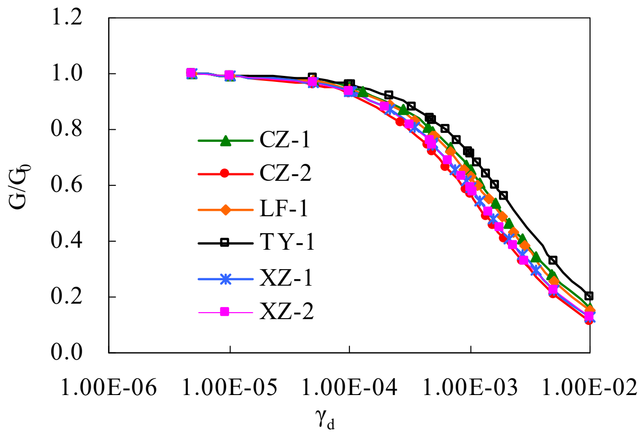

Figure 4. Normalized average curves of G/G0~γd of Shanxi loess.

It can be seen from the figure that the dynamic shear modulus ratio is gradually reduced with the increase of dynamic shear strain. The dynamic shear modulus ratio and the dynamic shear strain curve of loess samples in different regions demonstrate the same trend, which means that when the dynamic shear strain reaches 1×10^{-4}, the dynamic shear modulus ratio starts to decrease sharply, and the rate of decrease slows down when the dynamic shear strain reaches about 5×10^{-2}. The attenuation relationship of the dynamic shear modulus ratio with the increase of dynamic shear strain can be described by a negative exponential function in the semi-logarithmic coordinate system (Formula 7). The normalization coefficients m, n and correlation coefficients are shown in Table 3.

Table 3. Normalized parameters of G/G0~γd of Shanxi loess.

Samples	Model parameters		R^2
	m	n（$\times10^2$）	
CZ-1	0.8515	2.0059	0.9229
CZ-2	0.7883	2.2208	0.8956
LF-1	0.8343	1.9925	0.9125
TY-1	0.7462	1.6705	0.9437
XZ-1	0.8182	2.2001	0.9007
XZ-2	0.8084	2.1586	0.9003

$$G/G_0 = \mathrm{m}e^{-\mathrm{n}\gamma_d} \tag{7}$$

3.3. Damping characteristic and growth mode of Shanxi loess

The damping ratio of soil characterizes the influence of soil viscosity on its dynamic stress-dynamic strain relationship, which is the main cause for the relative hysteresis of soil nonlinearity and dynamic strain to dynamic stress. According to the ratio of the soil energy consumed in one cycle of the cyclic load to the energy corresponding to the maximum shear strain in the cycle, the damping ratio D of the soil is obtained, and then nonlinear fitting calculation is performed on the damping ratio through the multi-stage cyclic loading to get the $D \sim \gamma_d$ relationship curve of Shanxi loess as shown in Fig. 5.

It can be seen from the figure that with the increase of dynamic strain, the damping ratio shows a nonlinear characteristic of slow growth-rapid growth-slow growth, and the change trend and maximum of the damping ratio of loess in different regions are obviously different. The relationship between the damping ratio and the dynamic strain of loess in different regions of Shanxi is fitted. It is found that the relationship is in good agreement with the logarithmic function (Formula 8). The fitting parameters p, q and correlation coefficients are shown in Table 4.

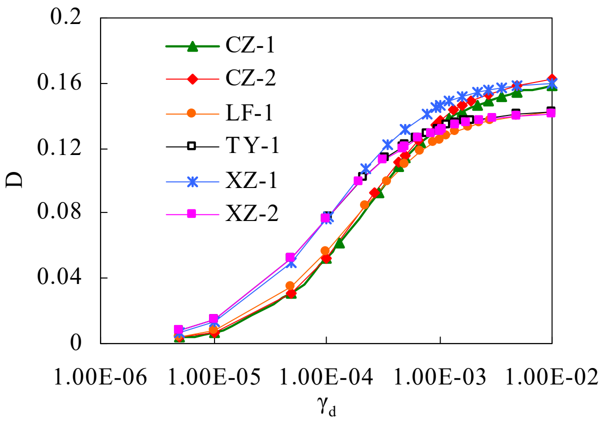

Figure 5. Curves of D~γd of Shanxi loess.

Table 4. Correlation coefficient of D~εd of Shanxi loess.

Samples	Model parameters		R^2
	p	q	
CZ-1	0.0243	0.2904	0.9590
CZ-2	0.0251	0.3005	0.9577
LF-1	0.0217	0.2664	0.9581
TY-1	0.0207	0.2686	0.9215
XZ-1	0.0236	0.2980	0.9398
XZ-2	0.0201	0.2608	0.9208

$$D = p \ln \gamma_d + q \tag{8}$$

4. Difference in dynamic modulus and damping ratio of Shanxi loess

4.1. Impact of regional distribution on dynamic modulus and damping ratio of Shanxi loess

Table 5 shows the typical dynamic shear modulus G_0, $G/G_0 \sim \gamma_d$ curves and $D \sim \gamma_d$ curves of loess in different regions of Shanxi. It can be seen from the table that the hyperbolic model parameters a, b and the initial dynamic shear modulus G_0 are more affected by the regional distribution. The initial dynamic shear modulus G_0 generally increases from south to north. The model parameter a represents the reciprocal of the initial dynamic elastic modulus E_{dmax}, and thus its change trend is opposite to the change trend of G_0; the model parameter b represents the attenuation rate of dynamic elastic modulus of soil with the increase of the dynamic strain, and does not show obvious regional distribution law. However, the distribution characteristics of the model parameter b of the loess in different regions are obvious: the parameter b of the

Changzhi loess is the highest, indicating that the attenuation rate of dynamic elastic modulus is the highest with the increase of the dynamic strain. Besides, the parameter b of Taiyuan loess is the lowest, indicating that the attenuation rate of dynamic elastic modulus is the lowest with the increase of the dynamic strain. The dynamic shear modulus ratio G/G_0 has the same regional distribution law under different shear strain amplitudes, which means that the G/G_0 of Taiyuan loess in the central region is the highest, followed by Linfen and Changzhi loess. The G/G_0 of Xinzhou loess in the north is the lowest. The damping ratio D of loess in different regions is similar under small strain amplitude, but with the increase of shear strain γ_d, the damping ratio D of Changzhi, Linfen and Taiyuan loess shows similar growth laws, which means that the damping ratio has a slow growth-rapid growth trend. The damping ratio of Xinzhou loess increases rapidly when the dynamic shear strain is between 5×10^{-6} and 1×10^{-4}, and its growth slows down with the increase of dynamic shear strain in the later stage.

4.2. Correlation of physical index with dynamic modulus and damping ratio

The correlation of the natural water content, initial porosity and plasticity index of the loess in different regions of Shanxi with the initial dynamic shear modulus, dynamic shear modulus ratio and damping ratio is analyzed in Table 1 and Table 5. There is a good negative correlation between the initial porosity and the initial dynamic shear modulus, which means that as the initial porosity increases, the initial dynamic shear modulus of loess decreases. Besides, there is a certain linear correlation between the plasticity index and the initial dynamic shear modulus, which means that as the plasticity index increases, the initial dynamic shear modulus shows an overall increasing trend. In addition, the initial dynamic shear modulus decreases with the increase of water content, but there is a poor linear correlation between the water content and the initial dynamic shear modulus due to the impacts of initial porosity and the plasticity index.

Table 5. G0 of loess in difference Shanxi area and physical value in curves of G/G0~γd and D~γd.

Samples	Model parameters		G_0 / MPa	Parameter	Shear strain γ_d							
	a（$\times10^{-3}$）	b			5×10^{-6}	1×10^{-5}	5×10^{-5}	1×10^{-4}	5×10^{-4}	1×10^{-3}	5×10^{-3}	1×10^{-2}
CZ-1	1.903	1.313	68.30	G/G_0	0.9974	0.9947	0.9741	0.9496	0.7903	0.6533	0.2737	0.1585
				D	0.0038	0.0073	0.0310	0.0521	0.1135	0.1332	0.1546	0.1577
CZ-2	1.849	1.319	76.42	G/G_0	0.9962	0.9924	0.9632	0.9290	0.7235	0.5667	0.2074	0.1157
				D	0.0038	0.0074	0.0312	0.0525	0.1158	0.1363	0.1588	0.1621
LF-1	1.517	1.134	85.70	G/G_0	0.9971	0.9943	0.9721	0.9456	0.7767	0.6349	0.2581	0.1481
				D	0.0044	0.0086	0.0346	0.0558	0.1097	0.1248	0.1402	0.1424
TY-1	1.526	0.802	85.18	G/G_0	0.9980	0.9960	0.9802	0.9611	0.8317	0.7119	0.3307	0.1981
				D	0.0079	0.0149	0.0527	0.0771	0.1224	0.1321	0.1411	0.1423
XZ-1	1.485	1.287	88.65	G/G_0	0.9966	0.9933	0.9672	0.9364	0.7466	0.5956	0.2276	0.1284
				D	0.0068	0.0131	0.0496	0.0760	0.1322	0.1457	0.1586	0.1604
XZ-2	1.367	1.223	95.08	G/G_0	0.9966	0.9932	0.9667	0.9356	0.7440	0.5923	0.2252	0.1269
				D	0.0079	0.0149	0.0525	0.0766	0.1211	0.1306	0.1394	0.1405

According to Table 1, Table 5, and Fig. 4, the correlation between the main physical indexes and the dynamic shear modulus ratio G/G_0 of Shanxi loess is analyzed. It is found that for Q_3 loess, the natural water content w has a significant impact on the attenuation trend of $G/G_0\sim\gamma_d$ curve. The larger w is, the faster the curve attenuates. Besides, there is no obvious correlation of the initial porosity e and the plasticity index Ip with the attenuation trend of the $G/G_0\sim\gamma_d$ curve. In addition, combined with Table 1, Table 5 and Figure 5, there is a good correlation between the natural water content and the maximum damping ratio of loess. The higher the water content, the higher the maximum damping ratio; the plasticity index has a certain impact on the increase trend of the $D\sim\gamma_d$ curve. The lower the plasticity index, the faster the $D\sim\gamma_d$ curve increases; additionally, the correlation between the initial porosity and the damping characteristics of loess is not obvious.

4.3. Impact of forming time on dynamic modulus and damping ratio

According to the test results of dynamic characteristics of Q_2 and Q_3 loess in Xinzhou, the correlation between the forming time of loess and the dynamic modulus and damping ratio is discussed. According to Table 5, the impact of forming time on the initial dynamic shear modulus and damping ratio of the Xinzhou loess is more obvious, and the Q_2 loess with an earlier forming time has a higher initial dynamic shear modulus, and its damping ratio increases slowly with the increase of the shear strain. The initial dynamic shear modulus of Q_3 loess is relatively lower, and the damping ratio increases rapidly with the increase of shear strain, and the difference in growth rate is obvious when the dynamic shear strain is between 1×10^{-4} and 1×10^{-2}. The forming time does not have an obvious impact on the dynamic shear modulus G/G_0 of Xinzhou loess.

5. Conclusion

(1) The dynamic constitutive relationship of Shanxi loess conforms to hyperbolic model. The dynamic elastic modulus decreases with the increase of dynamic strain, and the change rate demonstrates a regional characteristic, decreasing from Changzhi, to Xinzhou, to Linfen and to Taiyuan.

(2) The dynamic shear modulus ratio of Shanxi loess gradually decreases with the increase of the dynamic shear strain, and the change accords with the negative exponential function. The change trend of loess in different regions is consistent; the damping ratio demonstrates a slow growth-rapid growth-slow growth characteristic with the increase of dynamic strain. The change conforms to the power function model, and there are significant regional differences in the change trend.

(3) The initial dynamic shear modulus of Shanxi loess shows a good correlation with the initial porosity, increasing from south to north; the dynamic shear modulus ratio and the natural water content shows a good correlation.

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