THE EFFECT FO DENSITY ON SEISMIC SUBSIDENCE OF LOESS

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SUMMARY

Dry density is the most important and effective physical index to indicate the compactness of loess after it is treated with various methods of compaction. In this paper, based on the seismic subsidence test of compacted loess specimen with different dry densities, the quantitative relationship between dry density and seismic subsidence of compacted loess is revealed in expressions of equations for seismic subsidence curves. The authors also established the mathematical relationship between dry density and seismic subsidence coefficient under different cyclic times and proposed empirical formulas to estimate the seismic subsidence coefficient of compacted loess with dry density. Furthermore, for the application of this study in practice, the criteria in dry density and wave velocity for the seismic treatment of loess ground are provided.

INTRODUCTION

Loess is a kind of porous and weak cohered deposit formed in the Quaternary period. It occurs widely in the north China. Both field investigations and laboratory studies show that an earthquake with a certain magnitude can cause prominent collapse of loess ground [1]-[3]. This is called seismic subsidence, which can produce cracks and uneven subsidence of loess ground and cause the damage and collapse of buildings. Unfortunately, the related construction codes [4]-[5] in China gives no consideration on seismic subsidence of loess. At the same time, the study on the treatment of seismic subsidence of loess ground is rare.

The first author noticed that various treatments of compaction are widely used in treatment of collapsible loess ground and they are proved very effective in practice. Then, whether the seismic subsidence resistance of loess is improved at the same time in these treatment or not? In this paper, dry density of compacted loess is used as the index of compaction treatment. The seismic subsidence tests of unsaturated specimen of compacted loess were performed. The seismic subsidence of compacted loess at different dry density was studied. The technical criteria for the compaction treatment of seismic subsidence of loess ground were proposed.

SPECIMEN, APPARATUS AND METHODS USED IN THE TEST

The specimens used in the test were secured from the typical Malan loess deposit (Q3) at the depth of 5 meters in Lanzhou. Previous study [3] indicates that it can produce a seismic subsidence of 9 cm and 57 cm respectively under the effect of earthquakes with seismic intensities of 8 and 9 degree. The physical indexes and gradation of the loess specimens are listed in Table 1.

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Table 1: Physical indexes and gradation of the loess used in tests

Sample No.	Water content (%)	Dry density (kg/cm3)	Specific Gravity	Void ratio	Plastic limit	Liquid Limit	Gradation(%)		
							Clay	Silt	Sand
L97-1-x	10.25	1.40-1.43	2.7	0.888-	8.4	24	10	78	12

Since water content has obvious effects on the seismic subsidence of loess, it is necessary to make all the specimens in the uniform water content in the tests. On the other hand, the water content of all specimens should be the optimum water content of loess to get a wide range of dry density. In Fig 1, it is indicated that the optimum water content of loess is between 15.4 – 16.2%. In the tests, the uniform water content is taken as 16%.

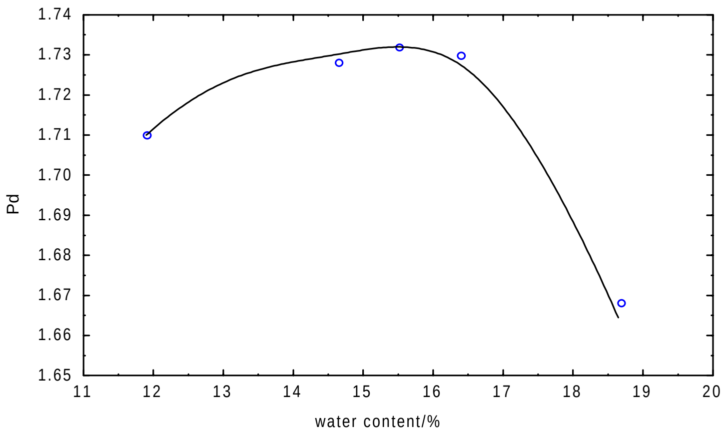


Figure 1: The relationship between water content and maximum compacting dry density.

Actually, the water content of specimens will somehow be less or more than 16% because of system error and the losing of water under available reservation condition. The real water content of specimens ranges from 15.2% to 16.99% with the group average from 15.78% to 16.66%.

The reconstituted specimens of compacted loess were prepared as follows: 1. dry the loose loess in the oven at the temperature of around 1000C; 2.add water to let its water content reach 16% and place it in an airtight container to let the loess have the same water content; 3.compact the loess with an 8 ton jack. The size of the samples got from the compacting apparatus is Φ7cm×14cm. 4. cut them to the specimens of Φ5cm×10cm used in the seismic subsidence test. The dry density of the 5 groups of specimens ranges from 1.497 to 1.684kg/cm3 (Table 2.), which basically covers the dry density range in compaction treatment of loess ground in engineering practice.

Table 2: The dry density and water content of specimens used in the seismic subsidence test

Group No.	Dry density (g/cm3)	Average dry density	Water content	Average water content
S1	1.497 – 1.528	1.513	16.22 – 16.56	16.45
S2	1.561 – 1.570	1.566	16.32 – 16.99	16.66
S3	1.581 – 1.600	1.589	16.04 – 16.99	16.57
S4	1.620 – 1.637	1.631	15.83 – 16.45	16.38
S5	1.648 – 1.684	1.662	15.20 – 16.05	15.78

A DSD – 160 electronic-magnetic dynamic triaxial apparatus was employed in the seismic subsidence tests. The dynamic load applied to the specimen is 1Hz sinusoid load and the consolidation ratio of specimen is 1.69 with the axial consolidation stress of 200kPa and lateral consolidation stress of 118kPa.

During the test, two levels of dynamic loading are applied after the consolidation of each specimen. The first level of dynamic loading with small amplitude only make the specimen to produce elastic deformation, which cycles for ten times. The second level of dynamic load with much large amplitude aims to produce residual deformation, which cycles for as much as 60 times. At least 4 or 5 specimens with the same dry density are used to perform the seismic subsidence test under different dynamic loads. The test results of these 4 or 5 specimens can be used to plot a curve indicating the development of residual strain with the increasing of dynamic stress, which is named a seismic subsidence curve. The detailed method for plotting the seismic subsidence curves is stated in reference [4].

INFLUENCE OF DRY DENSITY ON SEIEMIC SUBSIDENCE CURVES OF COMPACTED LOESS

Since seismic subsidence curves can be used to estimate the residual strain of loess under a certain dynamic stress, a seismic subsidence coefficient, it is a basis for the prediction of seismic subsidence amount of loess ground. Fig 2 and 3 are the seismic subsidence curves of compacted loess respectively under the cyclic times of 10 and 30.

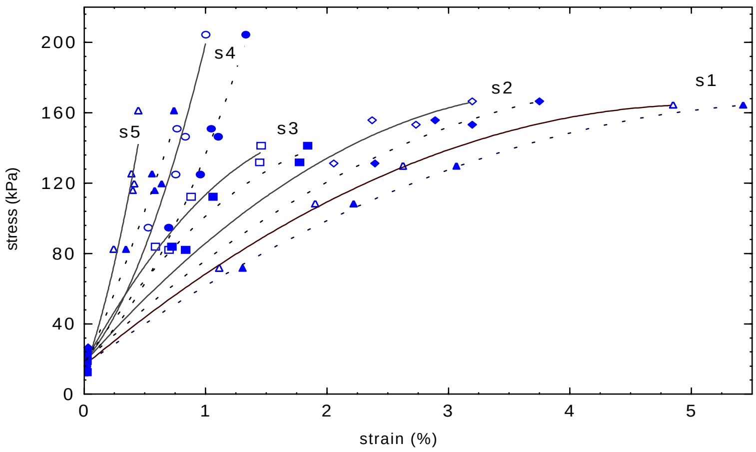


Figure 2: The seismic subsidence of compacted loess under the cyclic times of 10.

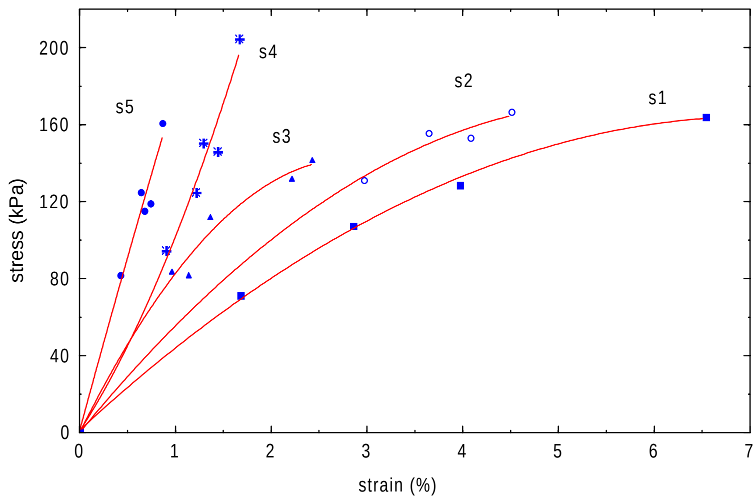


Figure 3: The seismic subsidence curve of compacted loess under the cyclic times of 30.

Obviously, under both circumstances the seismic subsidence curves close to the axis of dynamic stress with the increase of dry density, which means the seismic subsidence coefficient under the same dynamic stress becomes smaller with the increase of dry density. At the same time, the pattern of seismic subsidence curves changes from nonlinear curve to quasi-linear line. When the dry density increases from 1.513g/cm3 of group S1 to 1.631 g/cm3 of S4, the pattern of seismic subsidence curves turns into quasi-linear line. If the dynamic stress is less than 150kPa, the residual strains (or seismic subsidence coefficient) under the cyclic times of 10 and 30 are respectively less than 1.0% and 1.5%. According to the construction code for collapsible loess, the loess with a coefficient of collapsibility less than 1.5% is not considered as the collapsible loess. Accordingly, it may be regarded that when the dry density of compacted loess is above 1.63g/cm3, its property of seismic subsidence has been eliminated under the effect of earthquakes with a Chinese seismic intensity no more than 9 degree.

To estimate the amount of seismic subsidence of loess ground conveniently, the fitting formulas for curves in Fig. 2 and 3 are got. It is found that the seismic subsidence curve for compacted loess can be expressed as:

$$\sigma_d = a \cdot \varepsilon_r + b \cdot \varepsilon_r^2 \qquad (r=0.9586\sim0.9987) \qquad (1)$$

where a and b may be determined by dry density. The value of a is always positive while that of b varies with the dry density.

For the further study, a group of specimens subjected to almost the same dynamic stress (σd=125kPa~132kPa) were selected to analyze the development of residual strain with the variation of dry density under the same cyclic times. The analyzed result shows in Fig 4. In Fig 4, the cyclic times of the lines from the top to the bottom respectively are 60, 50, 40, 30, 20 and 10.

Table 3: The dry density of the specimens and dynamic stress applied

Specimen No.	S1.3	S2.2	S3.2	S4.2	S5.3
Dynamic stress(kPa)	128	131	132	125	125
Dry density(g/cm3)	**1.527**	**1.565**	**1.6091**	**1.632**	**1.680**

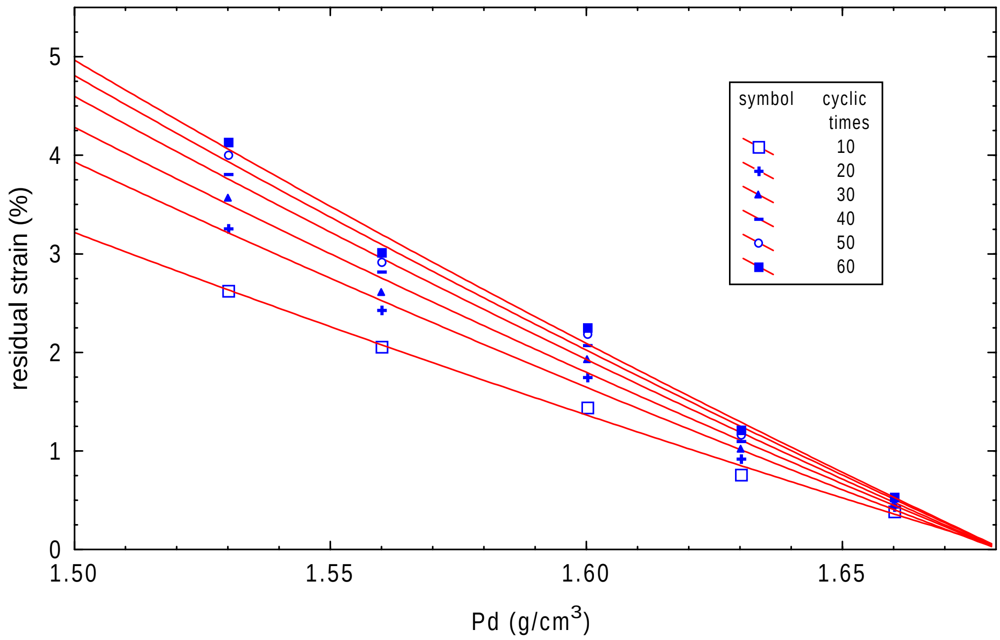


Figure 4: The effect of dry density on the coefficient of seismic subsidence.

Fig 4 indicates that seismic subsidence coefficient and dry density have a linear relationship under the same dynamic stress and cyclic times. That is:

$$\varepsilon r = a - b \cdot \rho d \qquad (r=0.994\sim0.996) \qquad (2)$$

where a and b are positive. They increase with the increase of cyclic times.

I t is necessary to be noted that the fitting curves in Fig 4 converge together at high dry density section., which means that the seismic subsidence of compacted loess will not change much under different cyclic times if its dry density is high enough. It can also be seen that the seismic subsidence coefficient of compacted loess remains less than 1.5% even under cyclic times of 60 when its dry density is above 1.63g/cm3. Thus, the residual strain of compacted loess does not increase any more under the cyclic dynamic loading.

INFLUENCE OF CYCLIC TIMES ON SEISMIC SUBSIDENCE OF COMPACTED LOESS UNDER DIFFERENT DRY DENSITY

To show the effects of cyclic times on seismic subsidence of compacted loess under different dry densities, the relationship between residual strain and the cyclic times of the group of specimens listed in Table 3 are shown in Fig 5.

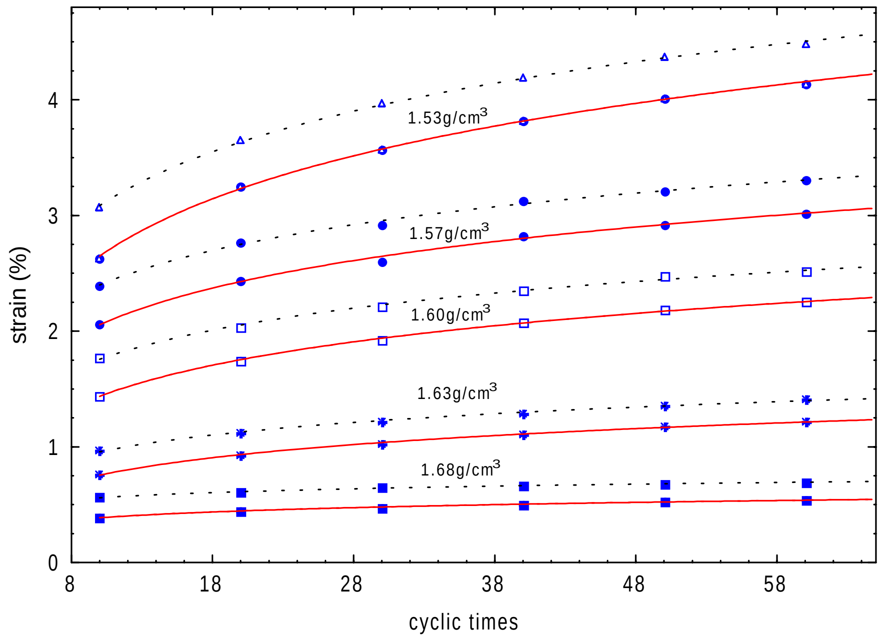


Figure 5: The relationship between seismic subsidence coefficient and cyclic times under different dry densities.

In Fig 5, the strain of the dashed lines includes both residual strain and elastic strain while the strain of the solid lines is residual strain only. These curves may be described by the following formula:

$$\varepsilon r = a + b \cdot \lg(N) \qquad (r=0.997\sim0.999) \qquad (3)$$

We can see from Fig.5 that the higher the dry density of compacted loess is, the less the increase of residual strain with the increase of cyclic times would be. When the dry density reaches as high as 1.63g/cm3, the residual strain under cyclic times of 60 is slightly larger than that under cyclic times of 10 by 0.4%. The total of residual strain is only 1.2%, which is smaller than 0.015, the criteria of collapsibility of loess. At higher dry density of 1.68g/cm3, there is hardly any increase of residual strain from the cyclic times of 10 to 60. This can be interpreted that when the dry density of compacted loess is above 1.63g/cm3, its microstructure has become stable and its potential of seismic subsidence disappears.

It can also be seen that with the increase of dry density the curves of total strain become closer to the corresponding residual-strain-only curves. This means that the ratio of elastic strain to residual strain changes regularly with the increase of dry density. For the further analysis, the ratio of elastic strain to residual strain under dynamic stress is briefly called ES-RS ratio. Even under different dynamic stress and cyclic times, the ES-

RS ratio seems to be well controlled by dry density (shown in Fig. 6). What's more, there is clearly a mathematical expression for the developing pattern of ES-RS ratio with the variation of dry density as follows:

$$\frac{\varepsilon_e}{\varepsilon_r} = 0.0948 + 0.3557 \cdot \exp(-200.7024 + 229.0647 \cdot \rho d - 64.4457 \cdot (\rho d\ 2)) \qquad (r=0.8332) \qquad (4)$$

This expression is shown by the dashed curve in Fig 6.

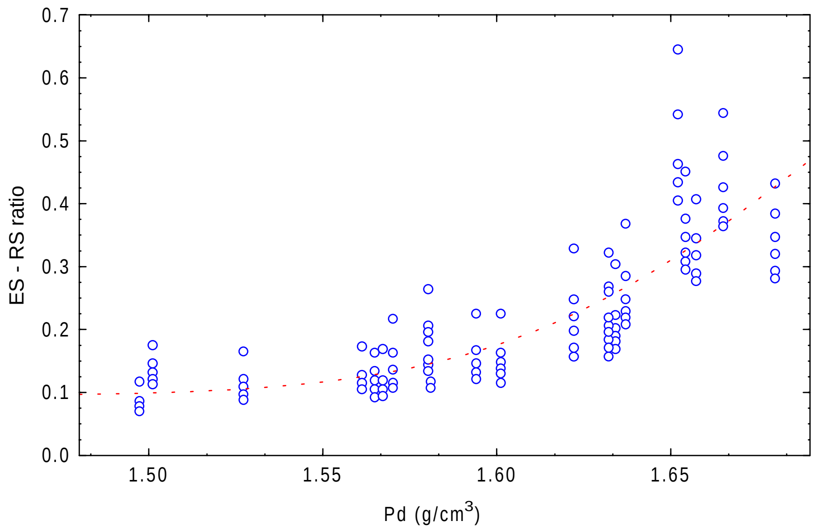


Figure 6: The influence of dry density on ES-RS ratio.

Generally, the ES-RS ratio increases with the increasing of dry density. However, if dry density is less than 1.60g/cm3, the increase is very limited and the value of ES-RS ratio is very small (ranges from 0.1 to 0.2), too. Only when dry density is above 1.60g/cm3, it increases dramatically, ranging from 0.1 to more than o.6. Therefore, with the increase of dry density, the residual strain contributes less and less to the total dynamic deformation under a certain dynamic load while the elastic strain does more. The capability of anti-seismic subsidence of loess ground becomes better in this process. This should be take into consideration in the dynamic response analysis of compacted loess ground.

INFLUENCE OF DRY DENSITYON THE WAVE VELOCITY OF COMPACTED LOESS

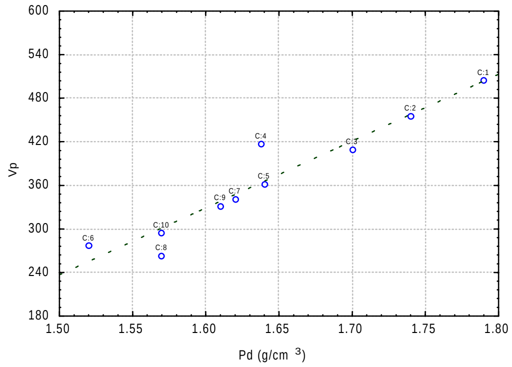
Wave velocity is often used as an index for evaluating seismic-resistance of site soil in situ test. In our study, the shear wave velocity (Vs) and compression wave velocity (Vp) of both specimen of compacted loess and compacted loess ground are measured respectively by using a SYC - III supersonic velocity meter and a INV-II seismometer.

Fig 7 and 8 respectively show the relationships between dry density of compacted loess and its Vp and Vs, which can be expressed by the following equations:

$$\begin{cases} V_p = -1144.5 + 920.9 \cdot \rho_d & (r = 0.955) \\ V_s = -371.2 + 340.3 \cdot \rho_d & (r = 0.886) \end{cases} \qquad (5)$$

It is worth to say that the wave velocity corresponding to the dry density criteria of 1.63g/cm^3 of eliminating seismic subsidence respectively are as follows:

$$Vp|_{\rho_d=1.63g/cm^3} = 356m/s$$
$$Vs|_{\rho_d=1.63g/cm^3} = 184m/s$$



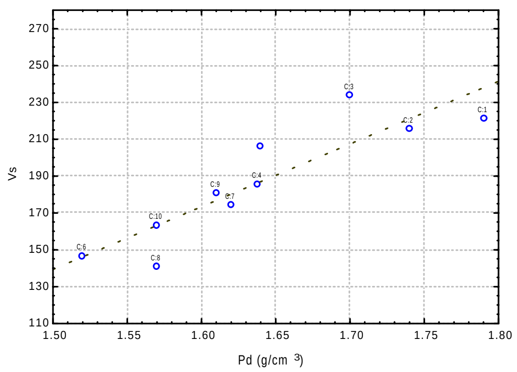


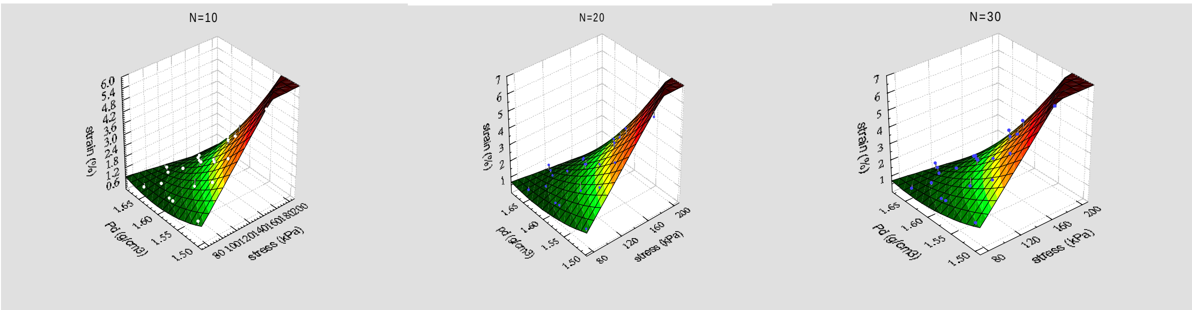
Figure 7: Vp versus dry density.

Figure 8: Vs versus dry density.

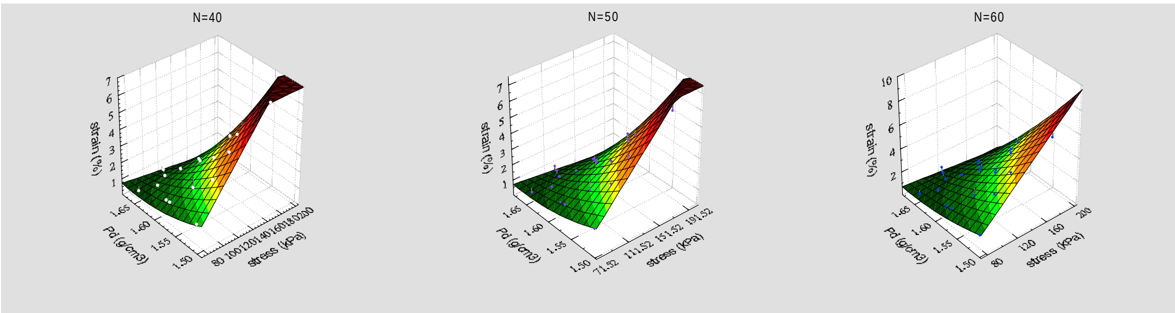
AN INTEGRATED EVALUATIONOF SEISMIC SUBSIDENCE OF COMPACTED LOESS

Though dry density is the most important interior factor that determines the seismic subsidence property of compacted loess, exterior factors such as dynamic stress and cyclic times play an important role in real case of seismic subsidence. How could we estimate the amount of seismic subsidence of compacted loess ground using all these factors?

Based on the test results, the influence of dry density and dynamic stress on seismic subsidence coefficient of compacted loess under different cyclic times is shown in Fig 9.



(a) N=10 **(b) N=20** **(c) N=30**



(d) N=40 **(e) N=50** **(f) N=60**

Figure 9: The influence of dry density and dynamic stress on seismic subsidence of compacted loess under different cyclic times

The general fitting formula for Fig 9 is:

$$\varepsilon_p = a - b\cdot(\rho_d\cdot\sigma_d) + c\cdot\sigma_d - d\cdot\rho_d + e\cdot\rho_d^2 \qquad (r > 0.9865) \qquad (6)$$

Where a, b, c, d and e are test constants. They may be determined by Table 4.

Table 4: The test constants under different cyclic times

Cyclic times	a	b	c	d	e	r
10	104.234	0.289	0.480	149.977	52.719	0.9867
20	90.126	0.328	0.536	133.449	47.894	0.9875
30	91.321	0.341	0.567	135.572	48.751	0.9873
40	87.969	0.354	0.588	131.599	47.588	0.9875
50	86.391	0.346	0.574	127.954	45.963	0.9866
60	83.920	0.354	0.589	125.231	45.219	0.9865

In formula (6), the second item represents the co-influence of dry density and dynamic stress. The third item represents the influence of dynamic stress, the larger the dynamic stress is, the bigger the seismic subsidence coefficient would be. The fourth item represents the influence of dry density, the higher the dry density of compacted loess is, the smaller the seismic subsidence coefficient would be. Under high dry density, however, seismic subsidence coefficient would decrease less significant than that under lower dry density. Therefore, the fifth item is a revision of the fourth item. Thus, given a dry density, dynamic stress and cyclic times, the amount of seismic subsidence of compacted loess ground can be well determined by formula (6).

CONCLUSIONS

The dry density has significant effect on the seismic subsidence of compacted loess. This is embodied in the pattern of seismic subsidence curves, the value of seismic subsidence coefficient, the development of seismic subsidence coefficient with cyclic times, the ES-RS ratio and wave velocity.

Seismic subsidence coefficient decreases monotonously with the increase of dry density. Under the condition of optimum water content (about 16%) and axial consolidation stress of 200kPa with consolidation ratio of 1.69, the critical dry density of eliminating seismic subsidence potential of compacted loess is 1.63g/cm3. Vp, Vs and void ratio corresponding to the critical dry density are respectively 356m/s, 184m/s and 0.8. These critical values given here, however, need to be verified by means of in situ test and case studies.

The estimation methods and values of seismic subsidence coefficient of compacted loess proposed in the paper can be used to evaluate the seismic subsidence coefficient and to predict the amount of seismic subsidence of loess ground treated with compaction.

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