THE DYNAMIC CONSTITUTIVE MODEL OF COMPACTED LOESS

Zhongxia YUAN[1] And Lanmin WANG[2]

SUMMARY

Compacted loess sites are widely used as construction ground in loess areas in Northwest China. Since these areas are of high seismic risk, it is necessary to determine the dynamic constitutive model and dynamic modulus of site soil for seismic safety evaluation. This paper describes the research achievements on the test method, test results and analysis on dynamic constitutive model of compacted loess and the influence of dry density on its parameters.

INTRODUCTION

In Northwest China, where the distribution of the porous loess is widespread, various methods of compacting are applied to improve its engineering performance. For these methods of loess treatment are economically cheaper and simpler than otherwise. They also can meet needs in many cases in civil engineering. Conventionally, the considerations involved in these compacting treatments are mainly focused on the bearing capacity and wet collapse of loess ground. Its dynamic characteristics after it is compacted, however, are seldom known. Most of the loess deposits are located in the area of high seismic risk. What is more, both researches and historical records make it clear that seismic disasters in loess grounds can be catastrophic. Therefore, it is necessary to determine or evaluate the dynamic characteristics of loess. This includes many aspects such as, types of load, damping, dynamic strength, dynamic deformation etc. Since the dynamic constitutive model (DCM) of soil is often a basic requirement to predict the dynamic response of ground, it is necessary that a reasonable DCM should be established for evaluating the seismic resistance capability of compacted loess. This paper represents an effort to accomplish the goal.

THE ARTS FOR RESEARCH

As far as the test standards on dynamic characteristics of compacted loess concerned, no widely accepted standards exist. As a results, many aspects of this research approach on the dynamic constitutive model need to be clarified before the research results are discussed. The main ideas that ran through this research is to get DCM for reconstituted specimens and make further analysis on relationship between parameters of DCM and dry density. With this research, it is expected to not only obtain a complete picture of DCM of Compacted loess, but also to determine the influence of dry density on the DCM of compacted loess can. These are very valuable for the evaluation of behavior of compacted loess under the effects of earthquakes.

Generally, the research approach can be divided into three parts: a. Preparing reconstituted specimens of compacted loess with different dry density; b. Performing dynamic test with a dynamic triaxial apparatus; c. Discovering relationship between dry density and parameters of DCM. In another words, make clear the influence of dry density on DCM of compacted loess. Each part will be discussed separately in following.

[1] *Lanzhou Institute of Seismology, 410 Donggangxilu, Lanzhou, 730000 P.R China, E-mail: wlmyj@public.lz.gs.cn*
[2] *Lanzhou Institute of Seismology, 410 Donggangxilu, Lanzhou, 730000 P.R China, E-mail: wlmyj@public.lz.gs.cn*

The Preparation of Specimens

Since the preparation of specimens is crucial to the rightness of the result, how to prepare specimens in a proper way for research of certain purpose is often brain consuming. Since it is unpractical to compact the loess ground with one type of compacting treatment (for example, dynamic compaction) and observe it's seismic capability, there are two choices left. One is to use undisturbed samples from the compacted loess ground, the other is to obtain loess from a site and make reconstituted specimens with it. The first bears the advantage of preserving some characters of in situ soil. But with the variable dry density and limited precision of standard penetration test (SPT), strokes of hammer, it is incapable of providing efficient description of dynamic characteristics of compacted loess.

Obviously, the reconstituted specimens are different from the undisturbed samples in the second way of preparing specimens. The high porosity, low water content (*w*) and weak cohesion of loess make it is sense that the test results of reconstituted specimens can suggest much on the dynamic modulus of compacted loess with the same density in situ. The advantages are obvious: a. Dry density (ρ_d) can be controlled freely. b. The control of other physical indexes of specimen is convenient so that we can make a group of specimens comparable.

The loess was got from Pengjiaping Q_3 stratum, which locates in west suburb of Lanzhou. The physical indexes for the undisturbed loess is listed in Table 1 and Table 2:

Table 1: Physical index of undisturbed loess used in research

No. of Samples	*W(%)*	ρ_d	W_l	I_p	Specific gravity
L97-1-x (x=1..20)	10.25	1.40-1.43	24	8.4	2.7

Table 2: Void ratio and gradation of undisturbed loess used in research

Void ratio	Gradation(%)		
	Clay	Silt	Sand
0.888-0.929	10	78	12

To make specimens typical, it is needed to choose water content carefully. There are two points for this: 1. In Lanzhou, experiences in civil engineering shows that the water content of loess ground on which the structures laid will usually increase by several percent because of the improving of water supply after they are inhabited. Therefore, the water content of these specimens should be higher than that of undisturbed loess. 2. To get a wider range of dry density, the water content for these specimens should near the optimum water content (OWC) so

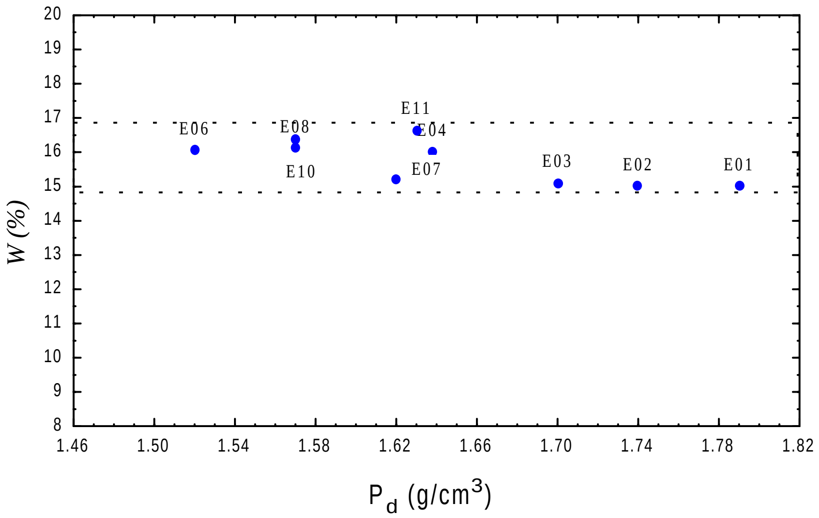

Fig 1: The *w* and ρ_d of specimens used in dynamic modulus test of compacted loess

that the highest dry density under laboratory condition can be got. Since the water content for undisturbed loess is around 10% and their OWC is found to be ranging from 15.4 to 16.2%, 16% is a value that satisfies the two demands. Actually, many factors in laboratory, which are out control of the technicians, will lead to the variation of water content. Thus, the water content for the specimens ranges from 15.2% to 16.4% (Fig1).

A hydraulic specimen maker is used to prepare specimen. It is composed with a frame, a specimen container and the compressing system, which has an 8ton hydraulic Jake on the bottom and a fix-removable iron hammer on the upper bar of frame. This apparatus can apply as far as 2000kPa stress on the loess specimens. In fact, the maximum ρ_d (1.79g/cm^3) attained in this way is higher than that attained through dynamic compaction on a natural loess ground. (1.70g/cm^3 or so). All the specimens obtained are shown in Fig1. The consolidation ratio (Kc) is 1.69 to simulate the natural ground footing condition in civil engineering.

Test of Dynamic Modulus Using the Dynamic Triaxial Apparatus

The main instrument used for the testing of dynamic modulus is DSD-160 electromagnetic exciting cyclic triaxial apparatus. It can provide data of strain that ranges from 10^{-4}□$10^{-□}$.The auxiliary equipment for it are: X□Y plotter, ultraviolet recorder. The former can plot hysteresis loop and the later record value of ε_d and σ_d.

In the test, each specimen was applied with 8 levels of 1 Hz sinusoidal loads, which increase step by step and strike 10 times with each. Through fitting with different mathematics expression, the most suitable model of σ_d—ε_d can be obtained. Under dynamic triaxial condition, shear stress, shear strain, G can be calculated with normal stress, normal strain and dynamic Young's modulus. Further calculation can get the relationship between τ_d—γ_d and.

The formulas involved in these calculations are as following:

$$E_d = \frac{\sigma_d}{\varepsilon_d} \quad (1)$$

$$G_d = \frac{E_d}{2(1+\mu)} \quad (2)$$

$$\tau_d = \frac{1}{2}\sigma_d \quad (3)$$

$$\gamma_d = \varepsilon_d \cdot (1+\mu) \quad (4)$$

The Influence of Dry Density on the Developing Pattern of DCM of Compacted Loess.

As water content of the specimens are relatively the same, we can regard that ρ_d determines the previous obtained results on DCM. To determine that mathematically, non-linear estimation of relationship between ρ_d and parameters of DCM of all specimens is performed. The result shows how the DCM changes in regard to $\rho_{d.}$ It can also be interpreted as how the ρ_d of compacted loess influence its DCM. Hence, ρ_d can be used directly to evaluate the dynamic characteristics of compacted loess.

THE DYNAMIC CONSTITUTIVE MODEL OF COMPACTED LOESS AND THE INFLUENCE OF DRY DENSITY ON IT

Based on the above-mentioned art of research, tests and analysis on the DCM of compacted loess were carried out. These show that DCM of compacted loess with different dry density obey the same pattern — hyperbolic model, and dry density of compacted loess influences the parameters of their DCM greatly while the DCM remains the same.

The Constitutive Model of Compacted Loess under Different Dry Density

The $\sigma_d \sim \varepsilon_d$ relationship is what is called DCM relationship. To find the fittest DCM, transferring of σ_d, ε_d into 1/E versus ε_d was done. Fitting results show that all the points are on or near a line (Fig2), that means,

$$\frac{1}{E} \propto \varepsilon_d \qquad (5)$$

In another way: $\frac{1}{E} = a + b\varepsilon_d$ (6)

Where a, b are constants. Other results for all specimens are shown in Table 3. Using formula (1), formula (6) can be transferred into another form,

$$\sigma_d = \frac{\varepsilon_d}{(a + b * \varepsilon_d)} \qquad (7)$$

This is just the hyperbolic model, which is the same dynamic constitutive model for undisturbed loess[2] (Lanmin WANG, 1992). Fig3 is the fitting curves for the specimens using hyperbolic model and Table 4 shows other results. With the relationship coefficient above 0.99 for all the specimens, this hyperbolic DCM fits the compacted loess very well so that it can be used to predict the dynamic deformation of loess ground confidently.

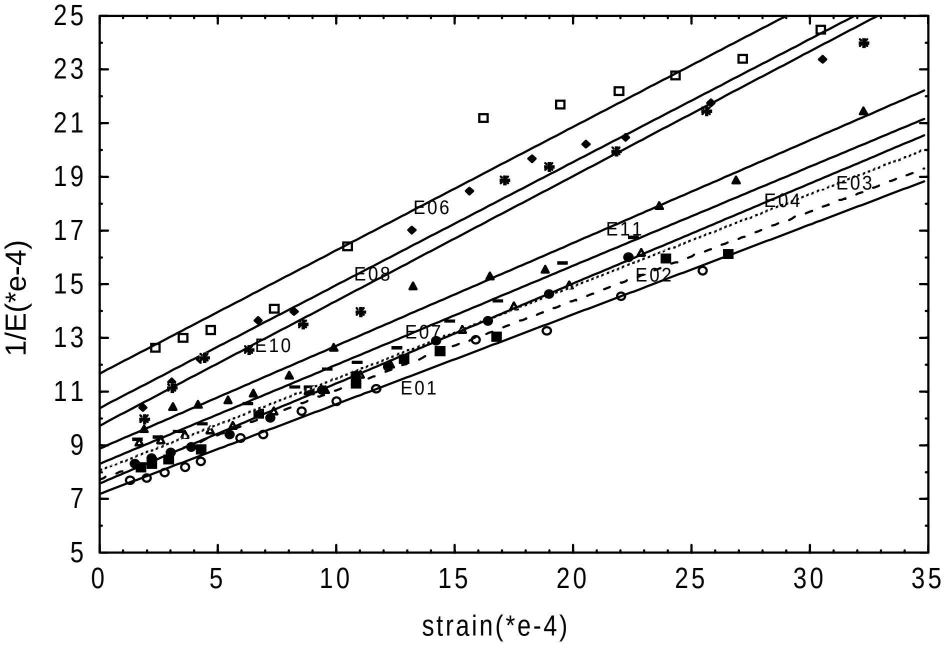

Fig 2: 1/E versus ε_d

(Notification: 1/E(*e4) and strain(*e-4) mean that the real values of 1/E are their axial value multiple 0.0001. This is to avoid the appearance of too many decimals in the figure. The same happens in the following figures.)

Table 3: Fitting results of 1/E versus ε_d relationship

Specimen	Fitting formula (y=10^4*(1/E), x=10^4*ε_d)	R
E01	y=7.188+0.334*x	0.9968
E02	y=7.23+0.333*x	0.9963
E03	y=8.067+0.343*x	0.9944
E04	y=7.577+0.372*x	0.9987
E06	y=11.856+0.441*x	0.9809
E07	y=8.307+0.369*x	0.9974
E08	y=10.536+0.444*x	0.9944
E10	y=10.066+0.432*x	0.9923
E11	y=8.888+0.382*x	0.9932

Table 4: Fitting formulas for the specimens

Specimen	Fitting formula (x=10^4*ε_d)	R
E01	σ_d = x/(0.072960+0.0032820*x)	0.9994
E02	σ_d = x/(0.079182+0.0032139*x)	0.9993
E03	σ_d = x/(0.077331+0.0036487*x)	0.9996
E04	σ_d = x/(0.074345+0.0038220*x)	0.9998
E06	σ_d = x/(0.12831+0.0040076*x)	0.9992
E07	σ_d = x/(0.08075+0.0038463*x)	0.9948
E08	σ_d = x/(0.11372+0.0040866*x)	0.9996
E10	σ_d = x/(0.10554+0.0041547*x)	0.9981
E11	σ_d = x/(0.08856+0.0038278*x)	0.9993

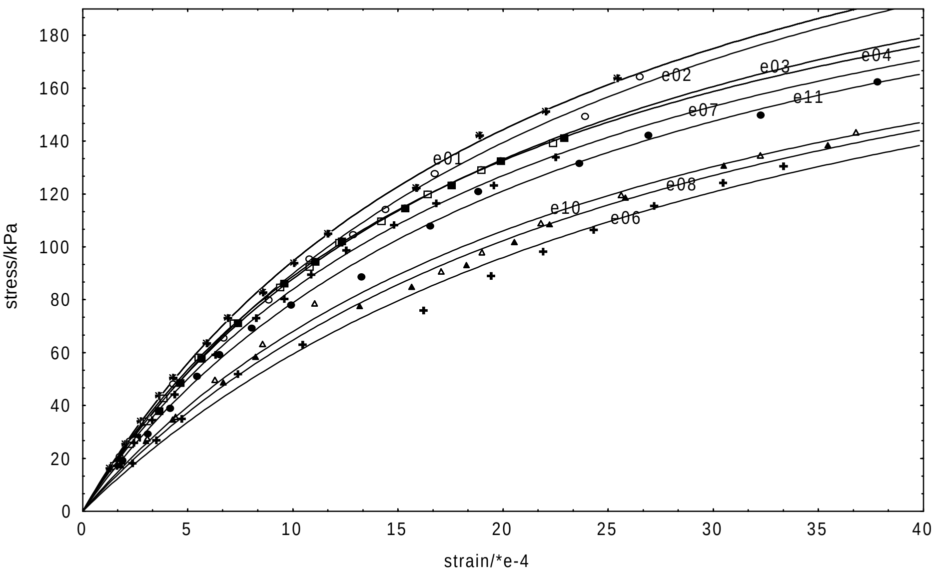

Fig 3: Fitting results using hyperbolic DCM

In some cases, engineers prefer to the τ_d~γ_d relationship to be used in design. In a similar way, using formula (3), (4), (7), formula (8) can be got.

$$\tau_d = \frac{\gamma_d}{(a + b * \gamma_d)} \quad (8).$$

Therefore, under condition of uniform moisture, DCM of compacted loess obeys a hyperbolic model, the same model for the undisturbed loess.

The Influence of Dry Density on Parameters Development of DCM

With the hyperbolic DCM in mind, there comes a new question: How to determine the parameters (a and b in formula (7) and (8)) of the DCM or, at least, what influences the parameters of DCM of compacted loess most. Because dry density is the most common used physical index to indicate the effect of compaction, it maybe a useful index to parameters development of DCM, too. In the research, with uniform water content, this influence can be got through the analysis on the relationship between dry density and parameters of DCM. In Fig 4, 5, 6, 7, the fitting results of ρ_d ~a and ρ_d ~b reveal that dry density determines the parameters of the hyperbolic DCM significantly under condition of uniform water content.

In fact, the parameters in the hyperbolic DCM have physical meanings. In formula (7) and (8), a is the reciprocal of initial G or E. It is an indication of seismic capability of compacted loess. Generally, the smaller a is, the better it earthquake resistance ability. Fig 4 indicates that ρ_d has a close relationship with a. b represents the reciprocal of ultimate normal stress or shear stress. Therefore, the results of Fig 4, 5, 6, 7 can be understood as not only the mathematical expression changes of the hyperbolic DCM of compacted loess but also as the variety

of dynamic characteristics of compacted loess with dry density.

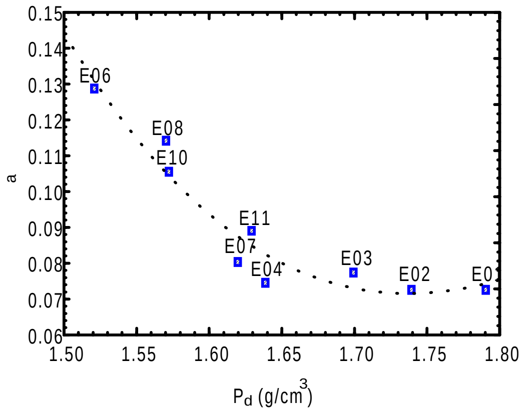

Fig 4: a~ρ_d in $\sigma_d \sim \varepsilon_d$ relationship DCM

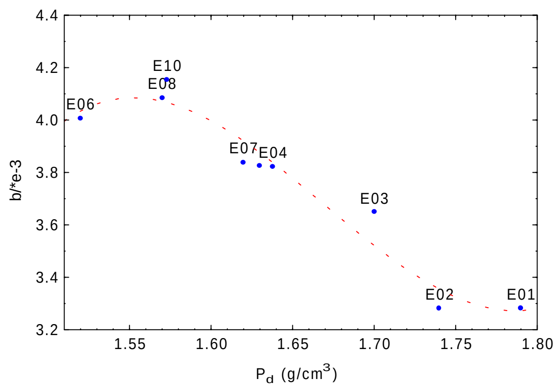

Fig 5: b~ρ_d in $\sigma_d \sim \varepsilon_d$ relationship DCM

$$\begin{cases} a = 9.2884 - 14.1530\rho_d + 7.1315\rho_d^2 - 1.1735\rho_d^3 & (r=0.964) \\ b' = -578.5295 + 1056.807\rho_d - 636.2444\rho_d^2 + 127.056\rho_d^3 & (b=b'*0.001,\ r=0.976) \end{cases}$$

$$\begin{cases} A = 45.8833 - 76.3966\rho_d + 42.52932\rho_d^2 - 7.8824\rho_d^3 & (r=0.957) \\ B' = -1353.52 + 2472.616\rho_d - 1490.688\rho_d^2 + 298.2166\rho_d^3 & (B=Bb'*0.001,\ r=0.971) \end{cases}$$

A Valuable Critical Point of Dry Density of Compacted Loess

From fig4, 5, it can be seen that for compacted loess with dry density between 1.62~1.63g/cm^3 its dynamic characteristics are at a critical state. The curves indicate that a or b will not change much if the dry density is above this critical point. This can be regarded as when the ρ_d is below this point, the improvement of its seismic resistance capability increases significantly with the increasing of dry density. But above this point, the improvement of its seismic resistance capability would diminish sharply. This means there is an economic choice for the compaction of loess. Further work of compaction above the critical point of dry density would gain very little.

CONCLUSION

1) The DCM of compacted loess obeys the hyperbolic model without concern of dry density.

2) The parameters of hyperbolic DCM of compacted loess change in a regular pattern with the change of dry density. This result is helpful to determine the dynamic characteristics of loess after it is compacted.

3) There is a critical value of dry density above which the seismic resistance capability increase of compacted loess with dry density will be fairly small. It maybe a good reference for an economic choice in compacting treatment of loess ground.

4) Since loess of different deposits or ages can be various in their dynamic characteristics, the mathematical expressions in the paper are rather used as examples for explaining than for practical use.

ACKNOWLEDGMENT

Special thanks should be given to the respected tutor of the first author, Prof. Chongshao SUN, whose valuable advice on the research and kindness are very helpful to the paper. We also feel grateful to Prof. Zhenzhong ZHANG, who shared his rich research experiences on loess dynamics with us.

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