Influence of stress ratio and moisture condition of loose deposit on dynamic parameters and ground response spectrum

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ABSTRACT

Coarse-grained loose deposit, distributed widely in earthquake-prone area in southwestern China, is one of the challenging problematic geomaterials. The dynamic shear modulus \( G_d \) and the damping ratio \( D \) are two main parameters in seismic-hazard analysis and one of the principal influencing factors affect the dynamic parameters is initial conditions. This paper presents a study of the effects of initial stress ratio and moisture condition on dynamic shear modulus \( G_d \) and damping ratio \( D \) of loose deposit with large-scale dynamic triaxial tests. The experimental results show that, in the considered ranges of confining pressure \( (\sigma_0=100\text{kPa}-1000\text{kPa}) \) and stress ratio \( (K_r=1-3) \), the dry densities of the same prepared specimens after consolidation are well normalized with the mean effective stress \( \sigma_m \). The maximum dynamic shear modulus \( G_{d_{\text{max}}} \) is calculated using \( \sigma_m \) and the influence of different consolidation stresses on initial void ratio has been considered. The test data demonstrate that the well-known Hardin’s equation underestimates the influence of stress ratio \( K_r \) on \( G_{d_{\text{max}}} \). An improved empirical relation in consideration of the effect of stress ratio based on Hardin’s equation is proposed in the paper. It is also concluded that the curve of the dynamic shear modulus ratio \( G_d/G_{d_{\text{max}}} \) versus the normalized shear strain \( \gamma_{tn} \) under air-dried condition shows more obvious nonlinearity than the one under saturated condition. In addition, a case study using the proposed improved equation of \( G_{d_{\text{max}}} \) and the nonlinear relationships of \( G_d/G_{d_{\text{max}}} \) versus \( \gamma_{tn} \) is provided to illustrate the importance of considering stress ratio and moisture condition in the response spectrum analysis of ground.

Keywords: loose deposit, dynamic shear modulus, stress ratio, moisture condition, response spectrum of ground

1 INTRODUCTION

Coarse-grained loose deposit distributed widely in earthquake-prone area in southwestern China, is one of the challenging problematic geomaterials. In May 12, 2008, the Wenchuan earthquake challenged engineers to enhance their understanding of the seismic behavior of loose deposit. The dynamic shear modulus \( G_d \) and damping ratio \( D \) are two fundamental parameters in dynamic response analysis. For loose deposit slope, the various initial static stress ratio and moisture conditions are two major factors affecting the seismic response. In the past five decades, the effects of initial static stress ratio on small strain shear modulus for soils have been investigated and some studies suggested that the stress ratio has minor influence on shear modulus(Hardin and Black 1966; Sully and Campanella 1995; Hoque and Tatsuoka 2004), others suggested that the stress ratio has significant influence on shear modulus(Yu and Richart 1984; Chien and Oh 2002;Sun and Yuan 2007). In moisture condition, Wu et al. (1984) reported that the small strain shear modulus rapidly increased from the value at dry condition to a peak value corresponding to an optimum degree of saturation, thereafter slowly decreased as the increase of degree of saturation. The peak value of shear modulus is almost 2 times that of saturated and dry condition. Similarly, Qian and Gray (1993) found that the existence of the capillarity can significantly increase the shear modulus at small strain of sands. Vassallo et al(2007) also found that the suction history of silt has great effect on the shear modulus at small strain. Nowadays, the effects of stress ratio and moisture condition on shear modulus at small-strain are far from the last word.

To study the influences of stress ratio and moisture state on dynamic shear modulus and damping ratio of loose deposits, large-scale dynamic triaxial tests were carried out and an improved empirical relation based on Hardin’s equation is proposed. A case study using the proposed improved equation of \( G_{d_{\text{max}}} \) and the nonlinear relations of \( G_d/G_{d_{\text{max}}} \) versus \( \gamma_{tn} \) is provided to illustrate the importance of considering stress ratio and moisture condition in the response spectrum analysis of ground.
2 LABORATORY TESTS

2.1 Materials

The loose deposit material obtained from a site of the Mianmao highway located in Mianzhu, Sichuan province, is mainly composed of limestone rubble and weathering products. Natural density is 1.98 g/cm³ and moisture content is about 3.0%. The site gradation of loose deposit is a coarse-grained material consisting of particles up to 600mm in size. The particle size of the in situ loose deposit is reduced by the parallel gradation technique, with a maximum particle size of 60mm, the grain size distribution of sample are shown in Fig.1.

![Fig.1. Particle size distribution of site material and tests material](image)

2.2 Specimen preparation and testing procedure

The tests were carried out with large-scale dynamic triaxial equipment TAJ-2000. The confining pressure was applied by the air-water pressure system, with a maximum pressure of 5MPa. The cyclic axial load was applied by the oil hydraulic system, with a maximum axial load of 1500kN. The specimen size in 300mm diameter and 600mm in length. Two kinds of samples, air-dried and saturated, were prepared with the controlled dry density \( \rho_d = 1.90 \) g/cm³.

![Fig.2. Relation of the dry density after consolidation and the effective stress](image)

After saturation, the specimen was loaded under confining pressure \( \sigma_c \) and stress ratio \( K_c \) (stress ratio \( K_c \) defined as the ratio of axial load and confining pressure) and the dry density of specimen before and after consolidation was given in Table 1.

Table 1. Dry density of specimens before and after consolidation

| \( \sigma_c \) (kPa) | Initial dry density \( \rho_d \) (g/cm³) | Dry density after consolidation \( \rho_d \) (g/cm³) |
|------------------|---------------------------------|---------------------------------|
|                  | \( K_c = 1 \) | \( K_c = 2 \) | \( K_c = 3 \) |
| 100              | 1.902  | 1.906  | 1.910  |
| 200              | 1.925  | 1.937  | 1.959  |
| 400              | 1.961  | 1.978  | 1.990  |
| 600              | 1.975  | 1.999  | 2.017  |
| 1000             | 2.002  | 2.010  | 2.031  |

![Fig.3. Typical test curves: (a) relation curves of \( \sigma_d \) and cyclic times; (b) relation curves of \( \varepsilon_d \) and cyclic times](image)
3 TESTS RESULTS

3.1 Effects of stress ratio and moisture condition on the maximum dynamic shear modulus $G_{d,max}$

The empirical formula for the small strain shear modulus proposed by Hardin is: $E_{d,max}=A'p_a(\sigma_m/p_a)^b$, where $A'$ is the dimensionless parameter, $p_a$ denotes the atmospheric pressure, set as 100 kPa, $\sigma_m$ the mean effective principal stress. The relationship between $\sigma_d$ and $\varepsilon_d$ can be expressed as a hyperbolic curve: $E_d=1/(a+b\varepsilon_d)$. Fig. 4 and Fig. 5 showed that the test data in $1/E_{d,\varepsilon_d}$ plane can be well fitted as lines, where $b$ is slope of the line and $1/E_{d,\varepsilon_d}$ is the intercept. In $\lg(E_{d,max})$ - $\lg(\sigma_m/p_a)$ plane, $E_{d,max}$ at different $K_c$ is not on the same line, as shown in Fig.6, which illustrated that the stress ratio $K_c$ has significant effect on $E_{d,max}$ and the Hardin’s equation may underestimate the influence of stress ratio $K_c$ on $E_{d,max}$. In order to calculate the effect of stress ratio on $E_{d,max}$, an improved empirical relation based on Hardin’s equation is proposed:

$$E_{d,max} = A'p_a(\sigma_m/p_a)^b(K_c)^m$$  (1)

![Fig.4. Relation curves of $1/E_d$ and $\varepsilon_d$ under saturated condition at various stress ratios: (a) $K_c=1$; (b) $K_c=2$; (c) $K_c=3$](image)

![Fig.5. Relation curves of $1/E_d$ and $\varepsilon_d$ under air-dried condition at various stress ratios: (a) $K_c=1$; (b) $K_c=2$; (c) $K_c=3$](image)

Fig.4. Relation curves of $1/E_d$ and $\varepsilon_d$ under saturated condition at various stress ratios: (a) $K_c=1$; (b) $K_c=2$; (c) $K_c=3$

Fig.5. Relation curves of $1/E_d$ and $\varepsilon_d$ under air-dried condition at various stress ratios: (a) $K_c=1$; (b) $K_c=2$; (c) $K_c=3$

The parameters of the equation (1) can be obtained from the fitting data of Fig. 6. Considering $\gamma_d=(1+\nu_d)$ $\varepsilon_d$, $G_d=E_d/2(1+\nu_d)$, $\nu_d$ is dynamic Poisson’s ratio of deposit soils, set $\nu_d=0.3$, then $G_{d,max}=A'p_a(\sigma_m/p_a)^b(K_c)^m$, in which $A'=A/2(1+\nu_d)$. For two different moisture conditions, parameters are listed in table 2.
Table 2. Parameters of the empirical equation

| Physical conditions | $A'$ | $A$ | n  | m  |
|---------------------|------|-----|----|----|
| Saturated condition | 1877 | 722 | 0.587 | 1.001 |
| Air-dried condition | 3182 | 1224 | 0.646 | 0.777 |

3.2 Effect of moisture conditions on $G_d/G_{dmax}$

To analyze the influence of different moisture conditions of deposit soils on $G_d/G_{dmax}$ a normalized shear strain $\gamma_{dn}$ is used to normalize the $G_d/G_{dmax}$ relationships. Substitution of Eq. (1) into the hyperbolic formulation $E_d=1/(a+b\gamma_d)$ gives

$$E_d = A'p(\sigma_m/p_g)^{n}(K_s)^{m}$$

The normalized strain $\epsilon_{dn}$ is defined as follows:

$$\epsilon_{dn} = \frac{e_d}{(\sigma_m/p_g)^{n}(K_s)^{m}}$$

Substituting Eq.(3) into Eq.(2) gives

$$\frac{E_d}{G_{max}} = \frac{1}{1+\frac{A'b\sigma_m(K_s)^{m}\epsilon_{dn}}{1}}$$

Converting the compression modulus and compression strain into shear modulus and shear strain using relationships $A=A'/2(1+\nu_d)$ and $\gamma_{dn}=(1+\nu_d)\epsilon_{dn}$, the Eq.(4) can be expressed as:

$$\frac{G_d}{G_{dmax}} = \frac{1}{1+k\gamma_{dn}}$$

where $k=2Ab\sigma_m(K_s)^m$. As shown in Fig.7, the parameter $k$ on saturation condition is 11.7 and air-dried condition is 25.8.

Fig.7. Normalized relation curves of $G_d/G_{dmax}$ and $\gamma_{dn}$ of loose deposits at various conditions

3.3 Effect of moisture conditions on $D$

The test data of damping ratio $D$ versus shear strain $\gamma_{dn}$ is scattered than that of $G/G_{dmax}$ versus $\gamma_{dn}$. According to Rollins’ (1998), the relation curve of $D$ and $\gamma$ of gravel can be expressed as:

$$D(\%) = 0.8 + 18(1 + 0.15\gamma_{dn})^{0.7}$$

The test data of loose deposit can be described as the Rollins' formulation with different parameters. The parameters of damping ratio versus shear strain under different moisture conditions can be obtained from the optimal fitting curves expressed as Rollins’ formulation, as shown in Eq.(7) and Eq.(8).

Saturated condition:

$$D(\%) = 1.2 + 17.9(1 + 0.20\gamma_{dn})^{0.65}$$

Air-dried condition:

$$D(\%) = 1.2 + 23.4(1 + 0.20\gamma_{dn})^{0.65}$$

As shown in Fig. (8), the damping ratio of air-dried condition loose deposit is slightly larger than that of saturated condition and the effect of moisture conditions on $D$ is not so significant. It is worth noting that at $\gamma_{dn}<10^{-1}$, the test data points are generally above the fitting curves, the main reason of this phenomenon may be that the friction caused by the instrumental axial dowel bar affected the test results.

Fig.8. Relation curves of $D$ and $\gamma_{dn}$ under different moisture conditions: (a) saturated condition; (b) air-dried condition

4 APPLICATION

To illustrate the influences of stress ratio and moisture condition on seismic response analysis of loose deposit, a 60m layered deposit model is considered, as shown in Fig.9. The equivalent linear method is used in the application (Zhang et al 2005). The calculating parameters of deposit layers model are listed in Table 3. Four situations of the model are considered: 1) without considering the difference of stress ratios ($K_s=2$), adopting the previous water level; 2) considering the difference of stress ratios, adopting the previous water level; 3) without considering the difference of stress ratios ($K_s=2$), adopting the current
water level; 4° considering the difference of stress ratios, adopting the current water level. Fig.10 shows four response spectra of acceleration for a single degree of freedom structure (λ=5%) at the ground surface determined using the input of the rock outcrop motion and the generalized $G_d/G_{dmax}$ and $D$ curves. The input of rock outcrop motion is El Centro wave and the peak acceleration is 0.34g. When considering the difference of water levels, response spectra under $1^\text{st}$ and $3^\text{rd}$ conditions are unimodal and the $1^\text{st}$ condition peak acceleration is 1.08g, smaller than that of 1.51g at the $3^\text{rd}$ condition. When considering the difference of stress ratios, as $2^\text{nd}$ and $4^\text{th}$ conditions, spectra are multimodal and the peaks are 1.0~1.15g at the $2^\text{nd}$ condition and 1.15~1.30g at the $4^\text{th}$ condition. These results illustrate that the moisture condition and stress ratio have significant influences on response spectra.

![Current water level](image1)

![Previous water level](image2)

![Bedrock](image3)

**Fig.9. Sketch of loose deposit layers model**

**Fig.10. Spectral acceleration under varies conditions**

### Table 3. Calculating parameters of deposit layers model

| Layer number | Thickness /m | Dry unit weight kN/m$^3$ | Total unit weight kN/m$^2$ | Stress ratio $K_c$ |
|--------------|---------------|------------------------|----------------------------|-------------------|
| 1            | 4             | 18.7                   | 20.6                       | 2.5               |
| 2            | 13            | 18.9                   | 21.4                       | 2.0               |
| 3            | 24            | 19.4                   | 21.7                       | 1.8               |
| 4            | 19            | 19.6                   | 22.0                       | 1.5               |

### 5 CONCLUSIONS

Based on the large scale dynamic triaxial test results, an empirical equation considering the effect of stress ratio $K_c$ based on Hardin’s formula have been developed, and the effects of moisture conditions of loose deposit on the relations of $G/G_{dmax}$ and $D$ were calculated.

In a certain range ($K_c=1$–3), the stress ratio is larger, the $G_{dmax}$ is greater. Comparing the two curves of the $G_d/G_{dmax}$ versus $\gamma_{air}$, it was found that the curve under air-dried condition was more nonlinear than in saturated condition. Moreover, the damping ratio under air-dried condition is slightly greater than saturated condition.

A case analysis showed that the stress ratio and moisture condition had significant influences on the response spectra of ground surface, the stress ratio affected the response spectra of acceleration and the peak acceleration in the saturated condition was larger than that in the air-dried condition. Therefore, moisture condition and stress ratio need to be considered when response spectra are selected for design.

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