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A modified dynamic shear modulus model for rockfill materials under a wide range of shear strain amplitudes

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ABSTRACT

High rockfill dams experience a wide range of shear strain amplitudes during earthquakes. To provide more reliable material property descriptions for earthquake response analysis of high rockfill dams, this study investigates the dynamic properties of rockfill materials in a wide strain range by large-scale cyclic triaxial testing with a high-sensitivity laser sensor. The results reveal the considerable increase of shear modulus and decrease of damping ratio with increasing confining pressure for a given initial stress ratio and the significant effect of the initial stress ratio on the small-strain shear modulus and normalized shear modulus. Previously proposed equations were found to imprecisely depict the variation of the dynamic shear modulus of rockfill materials for a wide strain range. Furthermore, the dynamic shear modulus is dependent on the Initial stress ratio in the anisotropic stress condition. Based on the existing hyperbolic model, a modified model for rockfill materials is suggested to accurately estimate the nonlinear behavior. The applicability of the modified model and previous studies for rockfill materials are assessed in the estimation of the normalized shear modulus. The results provide a reference for evaluating the accurate shear modulus in a wide strain range for strong earthquake motions.

1. Introduction

Many high rockfill dams are being built around the world, especially in China. According to statistics, 17 rockfill dams in western China exceed 200 m in height. These dams are mostly located in the earthquake-intense area of western China. If these high dams fail during an earthquake, not only would significant economic losses occur but also the life and property of the residents in the downstream area would be threatened. Therefore, evaluation of the dynamic response of high rockfill dams during earthquakes is of major importance. The small-strain shear modulus ($G_{\max}$), normalized shear modulus ($G/G_{\max}$) and damping ratio (D) are important parameters for seismic response analysis. These parameters are generally determined based on the equivalent linear viscosity–elasticity model, which utilizes iterative calculation to match the dynamic characteristics and computed strain with the modulus reduction and damping ratio increase curves—i.e., G and D versus shear strain amplitude γ measured in laboratory [1].

Extensive studies have been dedicated to the relationships between dynamic properties and shear strain amplitude for sandy soils and cohesive soils [2–13]. The experimental studies by Senetakis et al. [11–13] focused on the effect of the mineralogy of the particle form, particularly on the dynamic properties of granular soils. It was revealed that at small to medium shear strains the dynamic properties of the volcanic granular materials and pumice sands are remarkably more linear in comparison to the response of quartz sands. And for the volcanic and pumice sands, the elastic threshold and volumetric threshold are shifted to higher strain levels. However, the modulus reduction model for gravels and rockfills receives less attention than that for sandy and cohesive soils. In the past two decades, experimental results of gravels and rockfills have also been obtained using advanced devices [13–24]. Seed et al. [16] compared the dynamic behavior of gravels with that of sands and concluded that the normalized shear modulus reduction curve of gravels significantly diverges beneath the curve of sands. The damping ratio increasing curves of sands and gravels are roughly similar. Rollins et al. [18] reviewed extensive published experimental results of gravels and presented the range of dynamic behavior of gravels. The experimental study by Senetakis et al. [13] have shown that the curves by Rollins et al. described satisfactorily the dynamic properties data of quartzitic crushed rock in the range of small to medium shear strain amplitudes. In the literature, the dynamic behavior of gravels and rockfills within a range of shear strain amplitude from $5\times10^{-4}\%$ to about $5\times10^{-2}\%$ has been examined

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extensively [14,15,21]. Hardin and Kalinski [15] investigated the shear modulus reduction of gravelly soils at the shear strain level less than 0.05% and expanded the modulus reduction model originally developed for sands, silts and clays to include gravels. The experimental results of Xenaki [21] showed that the modulus curves proposed by Stokoe [17] and Hardin and Kalinski [15] are lower and higher than the measured data of gravels at the large strain level, respectively. However, for highly compacted rockfill materials, the shear strain level can reach up to 0.1% or higher in earthquakes [23]. The construction of high rockfill dams in high-intensity seismic regions raises the demand for a full description of the dynamic characteristics of rockfill materials corresponding to a wide range of shear strain levels.

Rollins et al. [18] analyzed the effect of gravel content, maximum grain size, relative density and confining pressure on the extensive dynamic nonlinear behavior of the gravels, which implies that both $G/G_{\max} - \log\gamma$ and $D - \log\gamma$ curves are less sensitive to these parameters except for confining pressure. The pre-earthquake static stresses in rockfill dams are simulated in cyclic triaxial test by consolidating specimens. It should be noted that most of the investigations have been conducted under isotropic compression conditions because it was commonly performed [14–18,27]; Several studies considered the significant influence of stress anisotropy on the dynamic characteristics of sands [26,45]. Yu and Richart [45] demonstrated the effect of stress ratio on the small-strain shear modulus for sands and found that the shear modulus decreased as the stress ratio increasing. The experimental results have shown that the normalized shear modulus in the same shear strain increased as the stress ratio decreased [26]. Less attention has been paid to the effect of the anisotropic stress state on the dynamic response of rockfill materials. Cyclic triaxial tests conducted by Araei et al. [23–25] demonstrated that both the confining pressure and anisotropic stress condition have significant influences on the dynamic properties of rockfill materials. The available experimental results on the dynamic properties of rockfill materials under anisotropic stress state are also limited.

The modulus reduction and damping increase characteristics are commonly obtained by cyclic triaxial tests [27–31], resonant column tests [31,32], and cyclic torsional shear tests [29,33–35]. Onsite and in-laboratory wave velocity testing can only determine $G_{\max}$ in the small strain on an order of magnitude of 10^{-6} [36–40]. However, the large-scale cyclic triaxial tests and the high-sensitivity laser tests enable measurement of the dynamic properties of rockfill materials from small strain to large strain levels [41–44].

This study presents the results of a series of large-scale cyclic triaxial tests for rockfill materials in a wide strain range from the orders of 10^{-6}–10^{-3}, and the effects of high confining pressure and initial stress ratio on the dynamic properties are evaluated. Based on the modulus reduction equations developed by Stokoe [27], a modified model is developed to accurately characterize the normalized shear modulus of rockfill materials. Using the experimental data, the applicability of the modified model is assessed in the estimation of the normalized shear modulus. The improved model is compared against previous studies, and the results provide a reference for estimating the dynamic properties of rockfill materials for a wide strain range.

2. Previous studies to estimate shear modulus

Many empirical equations have been developed to estimate the shear modulus. Considering the effects of void ratio e and anisotropic stress, the relationship between $G_{\max}$ and mean effective confining pressure is expressed in the form of [45–47]

$$G_{\max} = \frac{A}{F(e)} P_a \left(\frac{p}{P_a}\right)^n \tag{1}$$

where $p = (\sigma_1' + \sigma_2' + \sigma_3')/3$ is the mean effective confining pressure, P_a is the atmospheric pressure, $F(e)$ is a function of the void ratio, and A and n are material constants.

The hyperbolic model proposed by Hardin [32] is widely used in seismic analysis. To improve the fits to the test data, Stokoe et al. [27] introduced a curvature coefficient m. It has been demonstrated that the modified hyperbolic model can adequately describe the behavior of sandy gravel [21]. The model is expressed as

$$\frac{G}{G_{\max}} = \frac{1}{1 + (\gamma/\gamma_r)^m} \tag{2}$$

where γ_r is the reference shear strain used to normalize the shear strain amplitude, which is the shear strain when $G/G_{\max}$ is equal to 0.5. m is assumed to be a constant, which is suggested to be 0.92 by Darendeli [3]. The reference strain varies significantly with the mean effective stress p:

$$\gamma_r = \gamma_{r1}(p/P_a)^k \tag{3}$$

where γ_{r1} is the reference strain at an atmospheric pressure P_a, and k is an exponent that expresses the slope of the relation between γ_r and p in a log scale.

3. Test materials, specimen preparation and testing procedure

3.1. Material properties

The tested rockfills samples used in this study were obtained from the rockfill materials of the Houziyan concrete-faced rockfill dam (CFRD) and the Lianghekou core rockfill dam (CFD) in China. The limestone rockfills in the different parts of Houziyan CFRD—namely, HZY-1, HZY-2, and HZY-3—correspond to the main rockfill zone, the transition layer and the cushion layer, respectively. Additionally, rhyolite rockfills used in the main rockfill zone are named HZY-4. The natural sandy gravels located in the overburden layer of the two dams are named HZY-5 and LHK-2, respectively. The main rockfill zone of Lianghekou CFD is constructed with granite rock grain, which is named LHK-1. The main properties of the rockfill materials are listed in Table 1, the percentage of gravel size particle varied from 68% to 92%. The grain size distributions of the materials are shown in Fig. 1 with maximum particle sizes of 60 mm.

3.2. Specimen preparation and testing procedure

Cyclic tests were conducted on large scale specimens with 300 mm in diameter and 750 mm in height under different confining pressure and anisotropic state condition. The testing program was performed in the large scale trixial equipment, which is equipped with electro-hydraulic servo controller for vertical load. Static capacity of the equipment specification is 1000 kN and dynamic capacity of load is ± 500 kN. Lateral pressure for rockfill specimen is limited to 3.5 MPa. Waveforms are sinusoidal, triangle and rectangle. High sensitive laser transducer is equipped to obtain the dynamic stress-strain relations in the small strain level of 10^{-5} or less. Specimen was prepared by vibrating the dry rockfills in a split mold to the desired density. The

Table 1
Summary of the material properties of rockfill materials in cyclic triaxial tests.

Material symbol	ρ_d (g/cm^3)	e	C_u	$D_{\max}$ (mm)	D_{50} (mm)	Percent gravel (%)	Percent fine (%)
HZY-1	2.27	0.235	7.52	60	17.34	91.68	1.78
HZY-2	2.32	0.195	30.25	60	14.2	82.97	2.21
HZY-3	2.37	0.205	85.29	60	7.85	68.52	5.94
HZY-4	2.20	0.235	7.52	60	17.34	91.68	1.78
HZY-5	2.28	0.179	17.76	60	17.34	84.95	2.18
LHK-1	2.07	0.241	8.81	60	19.17	92.07	2.38
LHK-2	2.15	0.186	33.06	60	17.45	83.14	3.06