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Empirical Formulas of Shear Modulus and Damping Ratio for Geopolymer-Stabilized Coarse-Grained Soils

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The contribution of gravel fraction on the maximum shear modulus (G_{max}), dynamic shear modulus ratio (G/G_{max}), and damping ratio (λ) of cementitious coarse-grained soils has not been fully understood yet. Large-scale triaxial cyclic tests for geopolymer-stabilized coarse-grained soils (GSCGSs) were conducted with different volumetric block proportions (VBPs) under various confining pressures (CPs) for investigating their dynamic behaviors and energy dissipation mechanisms. Results indicate that the G_{max} of GSCGS increases linearly with VBPs but nonlinearly with CP. High VBPs will probably result in a gentle decrease in G/G_{max} and a rapid increase in normalized λ (λ_{nor}), while the opposite is the case for a high CP. With the shear strain amplitude being normalized, the G/G_{max} and λ_{nor} are distributed in a narrow band with low dispersion and thus can be well-described by empirical functions of the normalized shear strain amplitude.

Keywords: coarse-grained soils, geopolymer, shear modulus, damping ratio, empirical formulas

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INTRODUCTION

Cementitious coarse-grained soils (CCGSs) are widely used as filling materials in infrastructure projects such as high-speed railway subgrades, earth dams, and highways [1,2]. However, the design and construction of engineering structures on CCGS are always challenging for engineers due to parameter determination difficulties. Dynamic soil properties including the maximum shear modulus (G_{max}), dynamic shear modulus ratio (G/G_{max}), and damping ratio (λ) from small to large shear strain amplitude (γ) are crucial indices for the seismic design and stability evaluation of geotechnical structures subjected to periodic random loads. Previous studies showed that CCGS was inhomogeneous and heterogeneous geotechnical materials [1,2]. Their cyclic shear behaviors were affected by gravel fraction, cementation, interparticle contact stiffness, void ratio, curing period, and deformation within individual particles [3–6]. Of these factors, the gravel fraction and cementation played a particularly significant role in the shear behavior of CCGS. However, no consensus exists on their effects up to now. Geopolymer binders (GBs) are alkali-activated aluminosilicate gel materials with enormous advantages in high strength, fast hardness, weak shrinkage, *etc*. Their primary raw materials are solid wastes, such as fly ash, glass waste, red mud, metakaolin (MK), and combinations of two or more of these materials [7]. The coarse-grained soil stabilized with GBs (GSCGS) thus can also be a better choice for engineering practices, regardless of safety performance in seismic resistance and durability or feasibilities in resource acquisition and cost control. This study conducted large-scale undrained triaxial cyclic tests on GSCGS with different volumetric block

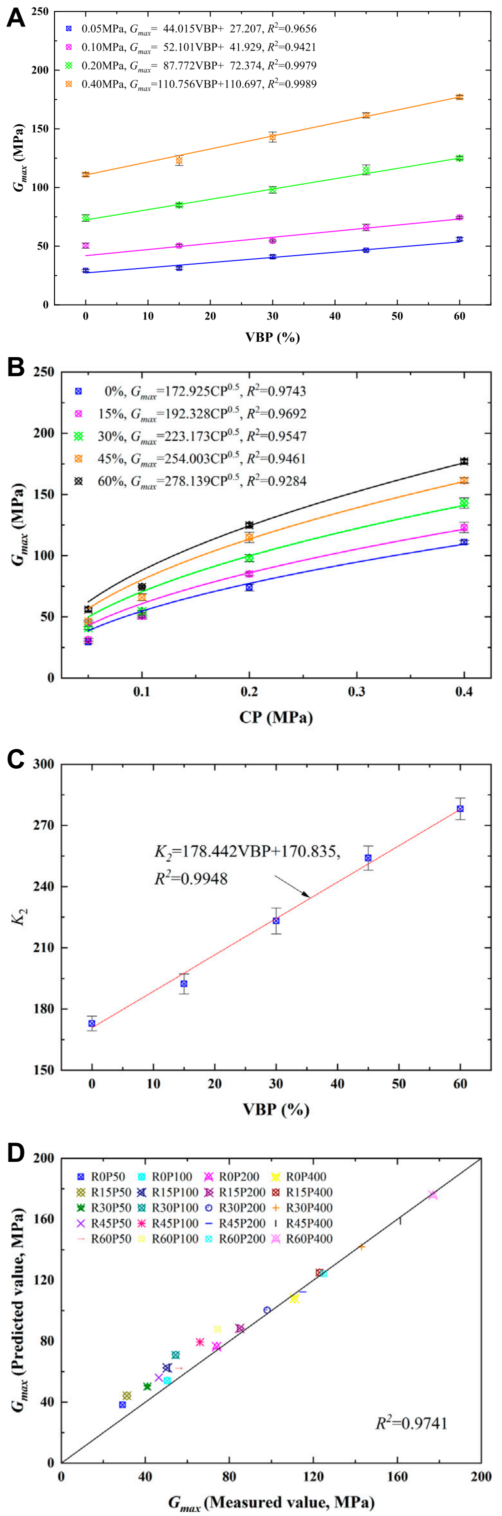

FIGURE 1 | Relationships of the G_{max} of GSCGS with the VBP and CP.

proportions (VBPs) under various confining pressures (CPs). The evolution of G_{max}, G/G_{max}, and λ was investigated, and their relationships with γ were discussed.

EXPERIMENTS

The dynamic behaviors of GSCGS in this study were investigated *via* a large-scale triaxial cyclic shear instrument (HCA300) developed by the American company GCTS. Each GSCGS cylindrical specimen was 100 mm in diameter and 200 mm in height. For the convenience of sample preparation, coarse-grained soils were considered a mixture of the soil matrix and rock blocks. The soil matrix was fine-grained residual soil, with a maximum grain size of 2 mm. The natural dry density was 1.64 g/cm^3. The maximum dry density and optimum water content were 1.72 g/cm^3 and 18.3%, respectively. The rock blocks mainly comprised crushed stones with a dry density of 2.42 g/cm^3. The maximum rock block size was limited to be 0.2 times the diameter of the specimen to avoid the grain size effect, namely, the rock block size used in sample preparation was 2–20 mm.

Considering that the VBP greater than 60% may result in considerable hollow phenomena among rock blocks and significant difficulties in packing GSCGS samples in the mold, only five VBPs (0/15/30/45/60, %) combined with four CPs (0.05/0.10/0.20/0.40, MPa) were considered in this study. The previous study showed that GBs could synthesize from MK, CaO, and $NaHCO_3$ with a mass ratio of 4:1:1, and their optimal mixing ratio in fine-grained soil was 15 wt% [7]. Therefore, the dosage of GBs in the coarse-grained soil samples was determined by the relative content of the soil matrix because of the cementation of GB functions primarily in the fine-grained soil. In other words, once the VBP is selected, the dosage of fine-grained soil in a GSCGS specimen is known, and the dosage of GBs can be determined. The water consumption for sample preparation was the sum of the amount of water required for the fine-grained soil to reach its maximum dry density and an extra water compensation of 5% for rock blocks' water absorption. All the specimens were cured in a humid environment at room temperature for 7 days and saturated by a vacuum extractor on GCTS until the B-value reached 0.95 at least before loading. The axial strain amplitude was increased from 1×10^{-5} to 1×10^{-2} in a level-by-level manner. The number of cyclic loadings for each strain amplitude was 5. The loading frequency was 0.5 Hz.

RESULTS AND DISCUSSION

Dynamic soil properties, including G and λ, were achieved by following the calculation methods for symmetrical and asymmetric hysteresis loops suggested by Kumar et al. [8]. **Figure 1A** presents the relationship between the G_{max} of GSCGS and the VBP. The G_{max} always increases linearly with the VBP, despite GSCGS being subjected to tensile or compressive stress. The increasing gradient of fitting curves suggests that there is a positive correlation between the G_{max} and CP. Hence, the relationship of the G_{max} and VBP can be described as follows:

$$G_{max} = k_p VBP + G_{matrix}, \tag{1}$$

where k_p is the gradient of fitting curves and G_{matrix} is the intercept denoting the fundamental stiffness of the soil matrix under a specified CP. The fitting results based on **Eq. 1** illustrate that the k_p

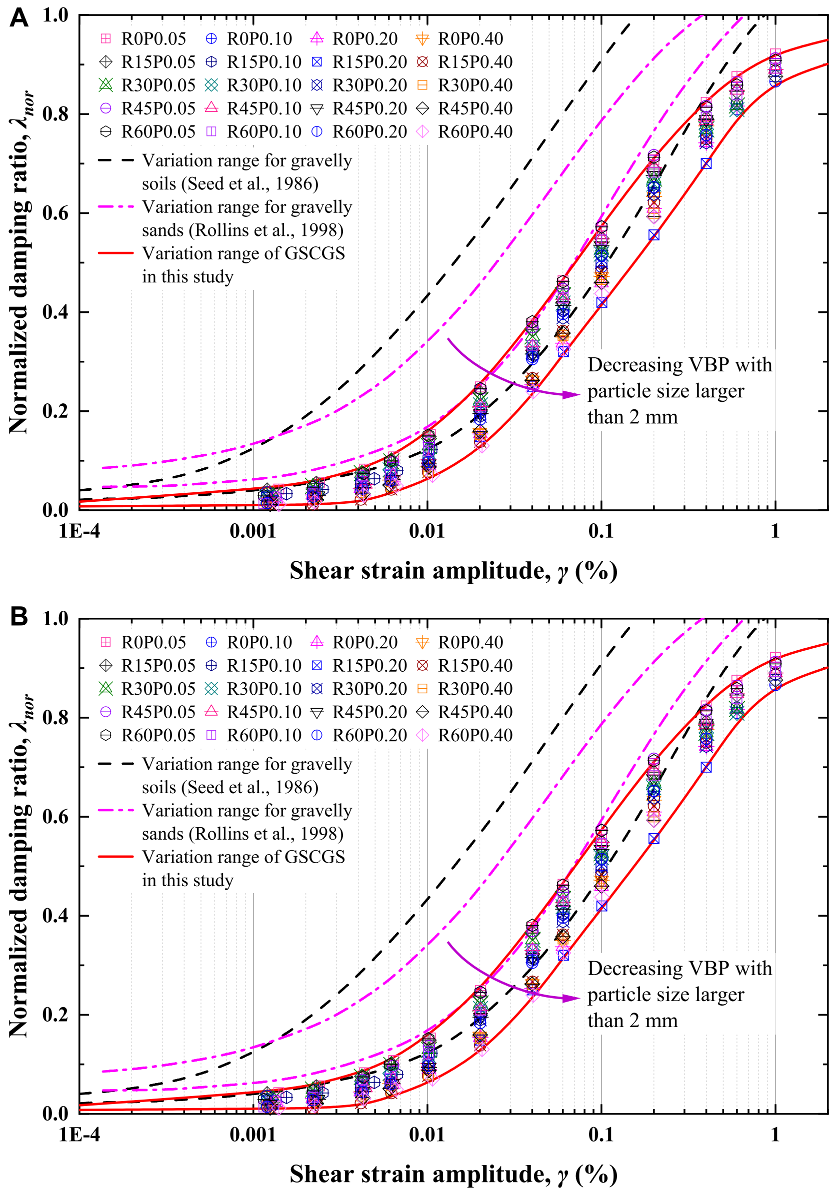

FIGURE 2 | G/G_{max} and λ envelope curves of GSCGS with different VBPs under various CPs.

increases with the CP, namely, high CP will result in larger values in G_{max}. **Figure 1B** presents the relationship between the G_{max} of GSCGS and the CP. The G_{max} increases nonlinearly with the CP at the same VBP. Seed et al. [9] proposed a simplified relationship between the G_{max} and CP for gravelly soil as follows:

$$G_{max} = K_2 (CP)^{0.5}, \tag{2}$$

where K_2 is a regression coefficient. Rollins et al. [10] reported that K_2 was a function of relative density for soils. Since the GSCGS is regarded as the soil matrix and rock blocks, the density of GSCGS can be summarized as a function of the VBP. Therefore, K_2 is related to the VBP of GSCGS. **Figure 1C** illustrates an excellent linear correlation between K_2 and VBP. Thus, a new empirical formula for the G_{max} of GSCGS is defined as follows:

$$G_{max} = (k_0 VBP + C)(CP)^{0.5}, \tag{3}$$

where k_0 and C are regression coefficients. **Figure 1D** presents the measured and predicted G_{max} of GSCGS. Both are close to the bisecting line with a high correlation coefficient (R^2) of 0.9741, which indicates that the proposed empirical formula can predict the G_{max} of GSCGS well.

Figure 2A presents the G/G_{max} envelope curves of GSCGS with different VBPs under various CPs. The G/G_{max} is distributed within a band on the whole. The shape of the curves is very close as γ is less than the order of 10^{-4}%. When γ lies between 10^{-4}% and 0.01%, the G/G_{max} is scattered. When γ lies between 0.01 and 1.0%, the G/G_{max} decreases significantly. The reduction rate of G/G_{max} slows down once γ is higher than 1.0%. As a whole, the $G/$

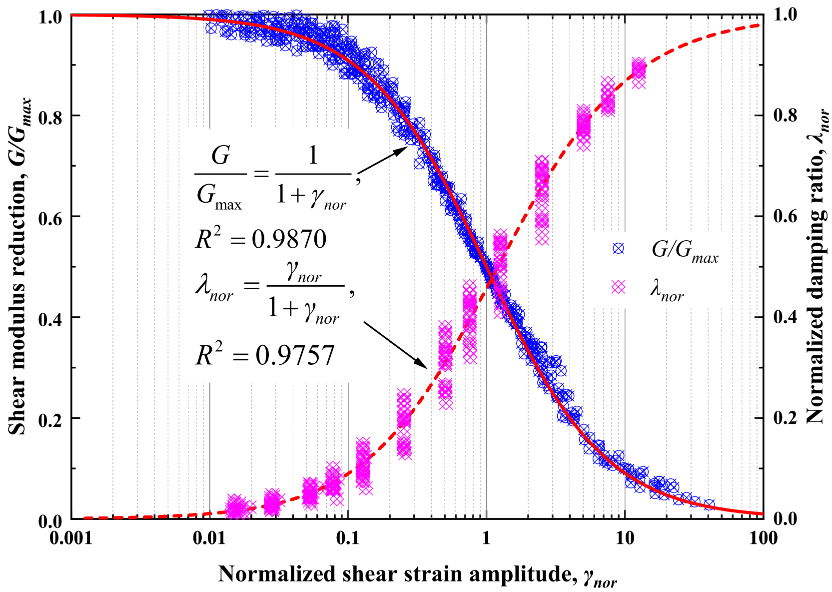

FIGURE 3 | Relationships of the G/G_{max} and λ_{nor} of GSCGS with γ_{nor}.

G_{max} of GSCGS is more likely to be characterized following a hyperbolic G/G_{max} function proposed by Hardin and Drnevich [11], which is given in the following equation:

$$G/G_{max} = 1/\left(1 + \gamma/\gamma_r\right)^n, \tag{4}$$

where γ_r is the reference shear strain and n is the curvature coefficient. It can be observed that the envelope region of G/G_{max} overlaps with the bounds proposed by Rollins et al. [10] when the VBP of GSCGS is higher than 45%. However, when the VBP is less than 45%, they have not overlapped anymore, especially when γ ranges between 0.01 and 1.0%. Seed et al. [9] pointed out that the G/G_{max} of sands always decreased faster than gravelly soils as γ increased, namely, high VBP would result in a gentle decrease in G/G_{max} of gravelly soils. This discovery explains why the G/G_{max} envelope curves of GSCGS are relatively higher than those of gravelly soils used in studies by Seed et al. [9] and Rollins et al. [10].

Figure 2B shows the normalized λ (λ_{nor}) envelope curves of GSCGS with different VBPs under various CPs, wherein the empirical model proposed by Chen et al. [12] is applied.

$$\lambda_{nor} = \lambda_0 \left(1 - G/G_{max}\right)^n / \left(\lambda_{\max} - \lambda_{\min}\right), \tag{5}$$

where $\lambda_{\min}$ and $\lambda_{\max}$ are the minimum and maximum λ, respectively, and λ_0 and n are regression parameters related to soil properties. It can be observed that λ_{nor} is distributed in a narrower band overall. The shape of the curves becomes unanimous when γ is less than the order of 10^{-3}%. This result implies that the VBP and CP might have a minimal impact on λ_{nor}. The reason why the λ_{nor} envelope curves of GSCGS are lower than those of gravelly soils examined by Seed et al. [9] and Rollins et al. [10] maybe that a high VBP is more likely to result in significant difficulties in compaction of coarse-grained soils, while cementation improves the integrity of CGS significantly, and thereby results in relatively low λ_{nor} when subjected to cyclic loadings.

Figure 3 presents the relationship of the G/G_{max} and λ_{nor} of GSCGS vs. normalized γ ($\gamma_{nor} = \gamma/\gamma_r$). It can be observed that both G/G_{max} and λ_{nor} are distributed within a narrow band, namely, both of them are insensitive to the VBP and CP *via* γ_{nor}. Martin and Seed [13] had summarized a nonlinear elastic model for gravel soils with γ_{nor}, which is

$$G/G_{max} = 1 - \left[\gamma_{nor}{}^{2\beta}/\left(1 + \gamma_{nor}{}^{2\beta}\right)\right]^{\alpha}, \tag{6}$$

where α and β are regression parameters. The fitting results of G/G_{max} show that this nonlinear model is also available to GSCGS with an excellent correlation coefficient of 0.9870 and can be simplified as follows:

$$G/G_{max} = 1/\left(1 + \gamma_{nor}\right). \tag{7}$$

Substituting **Eqs 4**, **6** into **Eq. 5** yields

$$\lambda_{nor} = \left[\gamma_{nor}{}^{2\beta}/\left(1 + \gamma_{nor}{}^{2\beta}\right)\right]^{\alpha n}. \tag{8}$$

The fitting results of λ_{nor} show a perfect correlation of 0.9757 with γ_{nor}, and can be rewritten as follows:

$$\lambda_{nor} = \gamma_{nor}/\left(1 + \gamma_{nor}\right). \tag{9}$$

This empirical formula thus can characterize λ of GSCGS under cyclic loadings.

CONCLUSION

The dynamic properties of GSCGS were investigated *via* large-scale triaxial cyclic tests in this study. Outcomes illustrate that the G_{max} of GSCGS increases linearly with the VBP but nonlinearly with CP. Thus, new empirical formulas of G_{max} referring to the VBP and CP are proposed. A high VBP may result in a gentle decrease in G/G_{max} and a rapid increase in λ_{nor}, while the opposite is the case for a high CP. G/G_{max} and λ_{nor} are insensitive to VBP and CP *via* γ_{nor} so that they can be described by empirical formulas of γ_{nor}. The proposed empirical formulas can provide a reference to understand the dynamic behaviors of GSCGS and other similar cementitious geomaterials.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Funding acquisition and formal writing of the work, SW; investigation and data analysis of the work, XG; review and editing of the work, WM, GL, CS, and PZ. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.