Physical Modelling in Geotechnics

Dynamic characterization of mine waste rock in centrifuge testing

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ABSTRACT: A series of centrifuge modelling tests were conducted at the University of South Carolina, to investigate the dynamic response of a saturated mine waste rock. The material consists of a gravel-sand mixture of 50% gravel and 50% sand by weight. Several models were tested under the centrifuge gravitational acceleration of 50 g to simulate a prototype soil profile height of 7.6 m and were shaken using 1-Hz sinusoidal shaking motions with the peak amplitude of 0.01, 0.05, 0.10, 0.19, 0.27, and 0.40 g (in prototype scale), covering a range of strains from 0.03 to about 3%. The shear wave velocity profile of the soil prior to shaking was measured using bender elements. Recorded accelerations were analyzed to generate shear stress-strain loops used to evaluate a variation of shear modulus and damping with shear strains. Results from the centrifuge tests were compared with resonant column tests. Comparison of results from the different test methods showed that shear modulus agreed reasonably well, while damping obtained from centrifuge tests was generally higher and more scattered. A significant reduction in shear modulus and a relatively large damping at high strains were found in the mine waste rock tested in this study.

Keywords: shear modulus, damping, liquefaction, mine waste, physical modelling.

1 INTRODUCTION

Measurements of dynamic soil properties, namely shear modulus and damping, are typically obtained using methods such as resonant column, torsional shear, and bender element tests. The measured shear modulus and damping using those methods are limited to a small to medium range of shear strains. In centrifuge modelling, the bender element is widely used to measure low strain shear modulus of soil models prior to or after a loading application. Limited centrifuge studies (e.g. Zeghal et al. 1999, Elgamal et al. 1996 and 2005, Brennan et al. 2005) utilized model response from dynamic centrifuge shaking tests to characterize dynamic soil properties for sand. Application of the similar approach to gravelly soils is very limited or non-existent due to the lack of research studies on the dynamic behaviour and liquefaction potential of gravelly soils. Gravelly soils are found in natural deposits as well as man-made deposits such as railroad embankments, riverbank slopes, and mining ponds. This paper presents the dynamic soil characterization of a mine waste rock composed of gravel and sand. Assessment of shear modulus and damping varying with shear strains was performed using an approach combining resonant column, bender element, and dynamic centrifuge modelling methods.

2 MATERIAL PROPERTIES

Mine waste rock tested in this study was obtained from a mine waste dump originally composed of gravel and sand particles with a small amount of fine content. Extensive experimental studies have been conducted on the waste rock to evaluate dynamic response and liquefaction behaviors (Rutthivaphanich and Sasanakul 2022a and 2022b, Rutthivaphanich 2022). This study focuses mainly on the dynamic characterization of the loose mine waste rock containing 50% by weight of gravel particles ranging from 4.76 to 19 mm and 50% by weight of sand particles ranging from 0.075 to 4.76 mm. The grain size distribution curve of the material is presented in Fig. 1.

3 METHODOLOGY

A series of dynamic centrifuge tests were performed at 50-g centrifuge gravitational acceleration by applying base shaking with a 1-Hz uniform sinusoidal motion for a range of amplitude between 0.01 and 0.4 g. The 50-g acceleration simulates a prototype soil profile height of 7.6 m. This paper includes results from a total of 4 centrifuge tests. For the first test, the same model was,

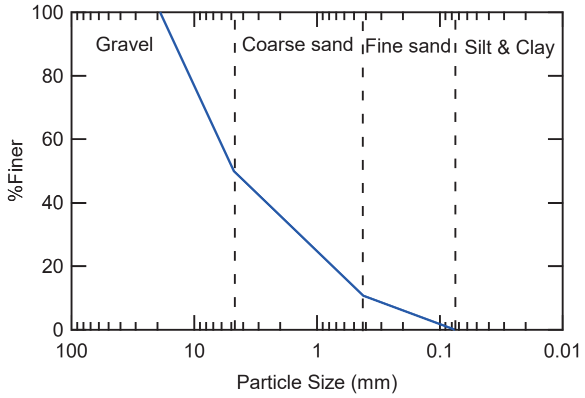

Fig. 1 Grain size distribution curve.

subjected to 3 levels of shaking amplitude: 0.01, 0.05 and 0.1 g, for 15 cycles each. For all other tests, three identical centrifuge models were prepared and subjected to a shaking amplitude of 0.19, 0.27, and 0.4 g for 40 cycles. All centrifuge models were prepared at the same initial condition. The material was placed in 4 layers in a laminar container shown in Fig. 2 using the moist tamping method with an initial moisture content of about 7% and a target dry density of 17 kN/m^3. Viscous fluid with the properties of 50 mPa·s at 20 °C was used for all models. Arrays of pore pressure sensors and accelerometers were placed in the model as shown in Fig. 2. The model was then saturated with the viscous fluid and placed on the centrifuge shaker. Additional sensors including accelerators and linear variable displacement transducers (LVDT) were installed outside of the model as shown in Fig. 2. All models were consolidated to a 50-g centrifuge gravitational acceleration measured at the mid depth of the model. Shaking was applied upon the completion of consolidation. The dynamic characterization of the waste rock model was focused at about 4.8 m depth in the model (shown at 95 mm in model scale in Fig. 2).

Additional centrifuge bender element test was performed to measure shear wave velocity of the centrifuge model prepared in dry condition. The model was prepared to achieve the same initial dry density and was consolidated at the 50-g centrifuge gravitational acceleration. Four pairs of bender elements located at 1.3, 2.6, 3.9, and 5.1 m (in prototype scale) were used to measure shear wave velocity after consolidation as shown in Fig. 3. Results were analyzed to develop the relationship between shear wave velocity and effective vertical stress of the material.

The same material was tested in a Stokoe-type resonant column device. Since the largest particle size is approximately 19 mm, a specific of top cap and bottom pedestal were developed for this material to achieve a ratio of 4 for the sample diameter to the largest soil particle size. The dry specimen with a diameter of 100 mm and a height of 200 mm was prepared at the same initial dry density and subjected to 3 levels of isotropic confining pressure equivalent to mean effective stress (σ_m') of 12, 23, and 47 kPa. The RC tests were performed until the G/G_{max} reached 0.8 for the σ_m' of 12 and 23 kPa, and 0.5 for the σ_m' of 47 kPa.

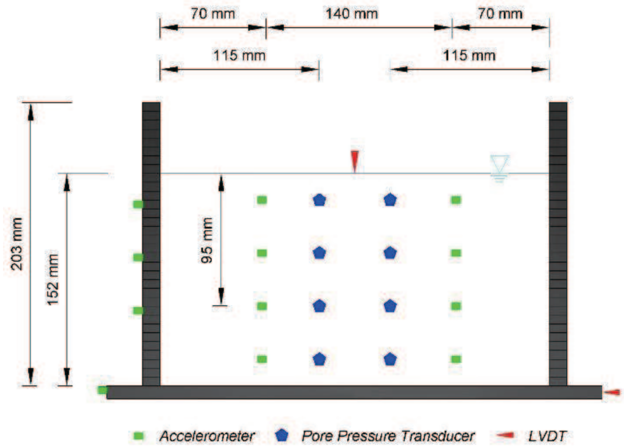

Fig. 2 Sensor setup in the dynamic centrifuge test

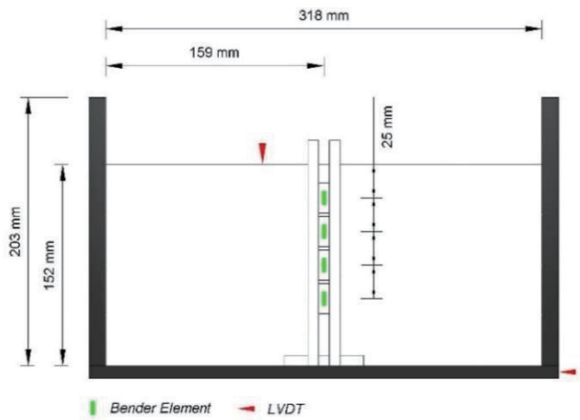

Fig. 3 Setup for the centrifuge bender element test

4 RESULTS

4.1 Centrifuge Bender Element Tests

At the end of the 50-g centrifuge consolidation and prior to performing bender element tests, very small settlement was observed in the model due to the consolidation despite the material initially being very loose. As a result, the change in the void ratio was minimal. Results from centrifuge bender element tests present a variation of shear wave velocity (V_s) with effective vertical stress (σ_v') in Fig. 4. The values of V_s for the material ranged from 107 to 132 m/s along the depth of the model. This is to be expected as the material is very loose. Curve fitting was performed to develop the expression for the V_s prediction. For the mine waste rock tested in this study, the V_s is expressed using the following equation:

$$V_s = 41.3\ (\sigma_v')^{0.25}$$

Based on this result, the low-strain shear modulus (G_{max}) at the σ_v' of 53 kPa was determined using the expression $G_{max} = \rho V_s^2$, where ρ is the saturated density of soil in the dynamic centrifuge shaking model. Consequently, the G_{max} value of 23.6 MPa is used as a representative value for all the models.

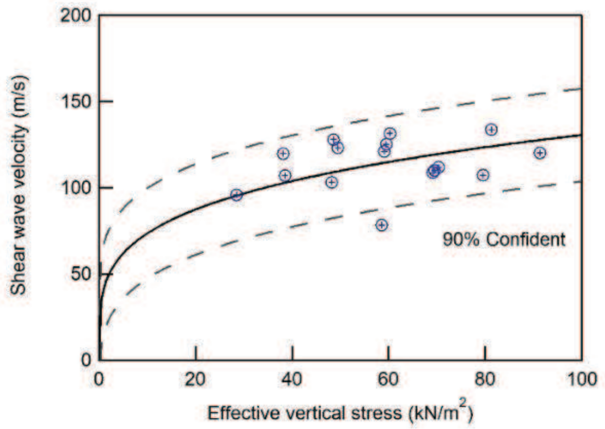

Fig. 4. Variation of shear wave velocity in the centrifuge model.

4.2 Dynamic Centrifuge Shaking Tests

Prior to shaking, and as mentioned previously, the change in the void ratio due to consolidation is minimal. The initial dry density was assumed to be 17 kN/m^3 for all of the centrifuge tests and is consistent with the centrifuge bender element and resonant column tests. This paper presents results from 6 centrifuge shaking tests conducted on 4 centrifuge models and mainly focuses on the dynamic characterization at a depth of 4.8 m corresponding to an effective vertical stress of 53 kPa. Acceleration time histories and pore water pressure development observed at this location for all models were recorded. Shear stresses and shear strains were calculated in accordance with the procedure suggested by Zeghal et al. (1995), Elgamal et al. (1996), Brennan et al. (2005), and among others. Effect of number of cycles is not focused on in the paper; therefore, the first stress-strain loops were considered as presented in Fig. 5. It is noted that for the large amplitude shaking, a change in the characteristics of the hysteretic loop with number of cycles was observed as a result of pore water pressure development (Δu). As a reference, Fig. 6 presents a plot of excess pore water pressure ratio (r_u, where $r_u = \Delta u / \sigma_v'$) with number of cycles for all 6 tests. Considering the first shaking cycle, a range of r_u values can be observed in the figure. In Fig. 5, effect of shaking amplitude (as well as pore pressure development) is clearly observed on the shear stress-strain loop. As the shaking amplitude increases, the shear stress and shear strain increase. The range of shear strains is between 0.03 to 1.09% for all amplitudes of shaking. Degradation of shear modulus (G) is also observed as the shaking amplitude increases. Based on these hysteretic loops, the shear modulus and damping were calculated and presented in Table 1. The area of the loop is also clearly observed to increase with the shaking amplitude. As shown in Table 1, the damping value for the 0.01-g test is 7%. Because of the degradation of shear modulus at higher strains, the damping values are relatively close for other shaking tests and with a range from 28 to 31% and an average of 29%.

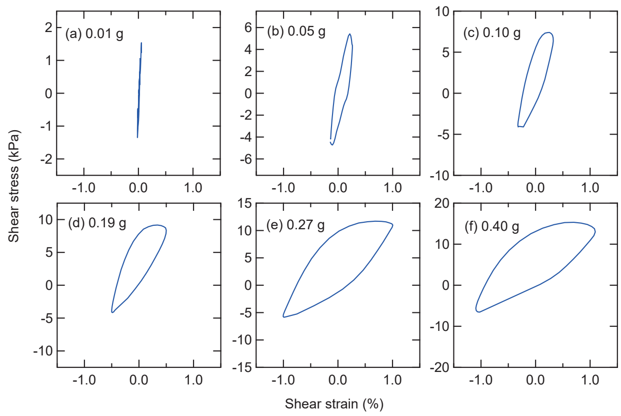

Fig. 5 Stress-strain loop at the first cycle (N=1).

Table 1 A summary of shear modulus and damping data for various G-levels for the first shaking cycle

Shaking Amplitude (g)	Shear Modulus (kPa)	Damping (%)
0.01	4549	7
0.05	2080	28
0.1	1525	31
0.19	1143	29
0.27	771	29
0.4	750	28

Fig. 6 shows that the development of pore water pressure at the shaking amplitude of 0.01 g was minimal. However, the maximum value of r_u was observed to be 0.36, 0.58, and 0.70 for the shaking amplitudes of 0.05, 0.10, and 0.19 g, respectively. The shaking amplitudes of 0.27 and 0.40 g caused the model to liquefy based on the observed r_u values of 0.92 and 0.95, respectively.

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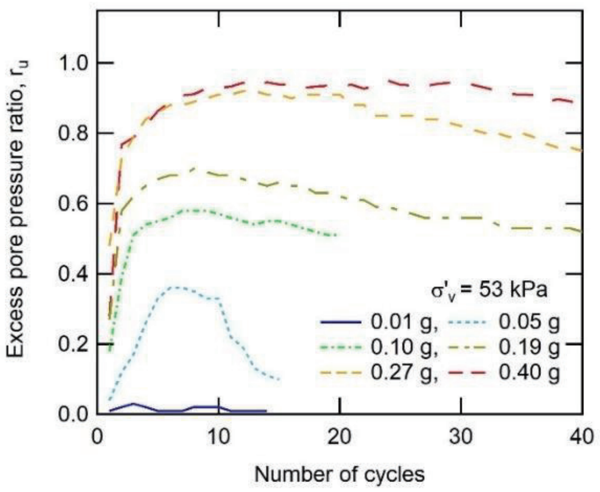

Fig. 6 Development of excess pore water pressure during shaking.

4.3 Resonant Column Tests

Variation of the normalized shear modulus (G/G_{max}) and damping curves for 3 mean effective confining stresses (σ_m') of 12, 23, and 47 kPa are presented in Fig. 7. Assuming the coefficient of lateral (k_o), these σ_m' values correspond to the effective vertical stress (σ_v') of 18, 35, and 70 kPa, respectively. It is noted that $\sigma_v'=1.5\ (\sigma_m')$. Effects of confining pressure were observed from both curves as shear modulus and damping behave more linearly as the confining pressure increases. The curves were also compared with empirical curves for sands by Seed and Idriss (1970) and gravel by Rollins et al. (1991). Seed and Idriss (1970) proposed G/G_{max} and damping curves for sand using data from numerous tests (e.g. torsional shear, hollow cylinder simple shear). Rollins et al. (1991) combined available data to create G/G_{max} and damping curve relationships for gravels. The percentage of gravel particles varied between 20 and 90%. The majority of the data available is the results of cyclic triaxial tests. It was found that both G/G_{max} and damping curves were within the lower bound of the empirical curves. The observation is expected because the confining pressures are relatively low.

To assess the G/G_{max} and damping behaviors at the depth of 4.8 m in centrifuge models, the curves at the effective vertical stress of 53 kPa are required and can be obtained using the following procedure proposed by Zhang et al. (2005).

Curve fitting was performed using the modified hyperbolic model (Stokoe et al. 1999) expressed as:

$$\frac{G}{G_{max}} = \frac{1}{\left[1+\left(\gamma/\gamma_r\right)^{\alpha}\right]}$$

The curve fitting parameters α and γ_r at σ_v' of 53 kPa were determined from the interpolation of the fitting parameters obtained from the other three σ_v'. The α and γ_r values are 1.13 and 0.014, respectively.

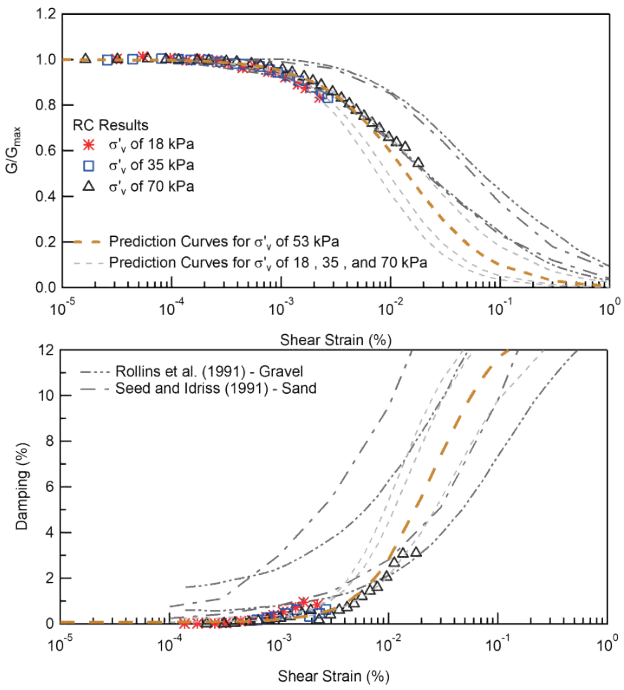

Fig. 7. Shear modulus and damping curves from resonant column test.

Damping (D) curves were modeled as a function of G/G_{max} using the following equation obtained from curve fitting of damping curves from the other three σ_v'.

$$D=12.265\left({}^{G}/_{G_{max}}\right)^{2}-26.311\left({}^{G}/_{G_{max}}\right)+14.103+D_{min}$$

where, D_{min} is small strain material damping. The D_{min} at σ_v' of 53 kPa was 0.0094% determined from the interpolation of the D_{min} for the other three σ_v'. Based on these procedures, the prediction curves for G/G_{max} and damping for σ_v' of 53 kPa were developed for the centrifuge models. These curves are shown in Fig. 7 and replotted in Fig. 8.

5 DISCUSSIONS

The values of G_{max} from the centrifuge bender element tests and the values of G and D from the dynamic centrifuge shaking tests were used to determine G/G_{max} and D with shear strains for the first 3 cycles of shaking. These data are compared with the prediction curves from the resonant column tests as presented in Fig. 8.

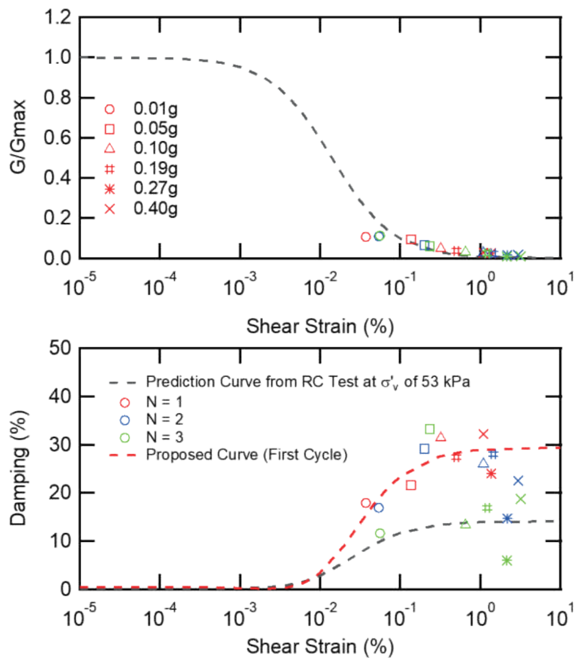

Fig. 8 Comparison between the prediction curves from RC tests and results from the first 3 cycles of centrifuge tests.

Overall, the G/G_{max} values obtained from centrifuge tests match very well with the predicted G/G_{max} curve from the resonant column tests. Results show that the shear modulus is significantly reduced at high strains. At the maximum strain of about 3%, the G/G_{max} value was nearly 0.01. For damping, it appears that the values estimated from centrifuge shaking tests are higher than the predicted curve. Curve fitting was performed to generate a new damping curve to match the centrifuge results obtained from the first number of cycles. It is noted that the pore pressure development is relatively low ($r_u \sim 0.01$ to 0.48) for the first cycle. Brennan et al. (2005) found that a significant reduction in damping of saturated sands was observed once the pore pressure ratio (r_u) was higher than 0.6. Similar damping behavior was observed for the waste rock, as shown in Fig. 8 where the reduction in damping was observed, when r_u was high for the second and third cycles especially for the shaking amplitude of 0.19 g and higher. These results are compiled and will be analyzed in future publications.

6 CONCLUSIONS

A series of dynamic centrifuge tests performed on mine waste rock are used to characterize dynamic soil behavior in terms of shear modulus and damping. In centrifuge tests, shear modulus and damping were obtained for shear strains ranging from 0.03 to 3%. Prediction curve for shear modulus obtained from resonant column tests performed at low shear strains compares reasonably well with the results from the centrifuge modeling tests. A significant reduction in shear modulus was found. However, the damping values at same range of strains from centrifuge tests are much higher than the predicted values. A new prediction curve was proposed. Preliminary observations found that the pore pressure development caused the damping to decrease.

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