Development of a new hollow cylinder apparatus for seismic torsional shearing in the laterally constrained condition

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1 Introduction

Taiwan lies in a seismically active region with a thick alluvial deposit. Dynamic soil properties, such as the modulus-reduction relationship, damping curves, and liquefaction resistance, have attracted significant attention for seismic geotechnical analyses and designs. Laboratory element testing is the essential approach for determining dynamic soil properties over broad strain ranges. In the geotechnical engineering field, a cyclic simple shearing mode with constrained lateral deformation is used to simulate field conditions for soil subjected to upward shear waves.

Element test systems capable of applying cyclic shearing include cyclic triaxial testing (CTX), cyclic direct simple shear testing (CDSS), cyclic torsional shear system (CTS), and hollow cylinder torsional apparatuses (HCA). The hollow cylinder apparatus is an advanced soil-testing system capable of simulating in-situ soil shearing conditions under seismic loading. The CDSS is a popular element testing technique for simulating in-situ stress/strain conditions under seismic loading. However, the uniformity of stress and strain at large strains, and the inability to apply multi-directional loading, are of concern. The HCA is superior to other shearing systems in inducing anisotropic stress states, applying uniform shearing stress and strain, capable of a wide strain range, and simulating different stress paths. However, promoting HCA is hindered by complex sample preparation, the need for local deformation measurement, and the accuracy of multi-axis control.

The noted references in the HCA systems literature include Hight et al., Ampadu and Tatsuoka, Huang et al., and Serra and Hooker [1-4]. These systems inherited the cylindrical sample dimensions under the torsional shear mode. The hollow specimen is used to alleviate nonuniform strain along the radial direction in the horizontal plane. However, the nonlinear deformation along the vertical direction underscores the need for local strain measurement and for limited strain levels.

In this consideration, the radial stress state of the inner and outer stress/strain conditions can be simplified by lateral constraints, thereby reducing the complexity of the testing system. Furthermore, the sample dimensions proposed for cyclic simple shear are adopted to reduce the need for local strain measurement and alleviate concerns about stress uniformity in solid torsional shearing. Compared with a simple shear apparatus, the torsional shearing device can avoid the need for correction for multi-directional loading and accommodate large strain ranges in the residual state. Consequently, a new HCA is designed and fabricated in NCKU (NCKU-HCA) with novel features to alleviate the difficulties in sample preparation and system integration while maintaining the field conditions and wide strain ranges.

The NCKU-HCA has been used to investigate the effects of strain rate on dynamic soil properties of sand. Typical results from strain-controlled cyclic tests are presented, showing that the new system shows promise for seismic soil testing.

2 Development of NCKU-HCA

The NCKU-HCA is a hybrid system combining the CDSS and HCA features. Figure 1 shows the schematic of the NCKU-HCA along with its assembly. The two major subsystems of the apparatus are the multi-axis loading and the shear box. To simplify the control of normal stress/strain, the NCKU-HCA uses two independent control systems for the torsional and normal modes at the top and bottom of the specimen, respectively. Torsional torque/rotational deformation is applied by a servo motor mounted on top of the specimen, and normal load/vertical deformation is applied by the hydraulic actuator described in Menzies [5]. The Proportional-Integral-Derivative (PID) Controller is used to establish a computer-automated closed-loop feedback system that provides accurate and independent control of load, torque, vertical displacement, rotation, pressure, and calculated stresses and strains.

A new torsional shear box capable of inducing torsional shearing while maintaining normal lateral boundary conditions has been developed, as shown in Figure 2. The hollow specimen is encapsulated by an inner membrane that clings to a solid rod and an outer membrane that is laterally constrained by a stacked-ring reinforced membrane [6]. The lateral confinements induced the K_0-condition that is generally used to mimic the in-situ stress before the seismic loading on level ground. The new shear box significantly simplifies sample preparation and eliminates the need for lateral boundary control.

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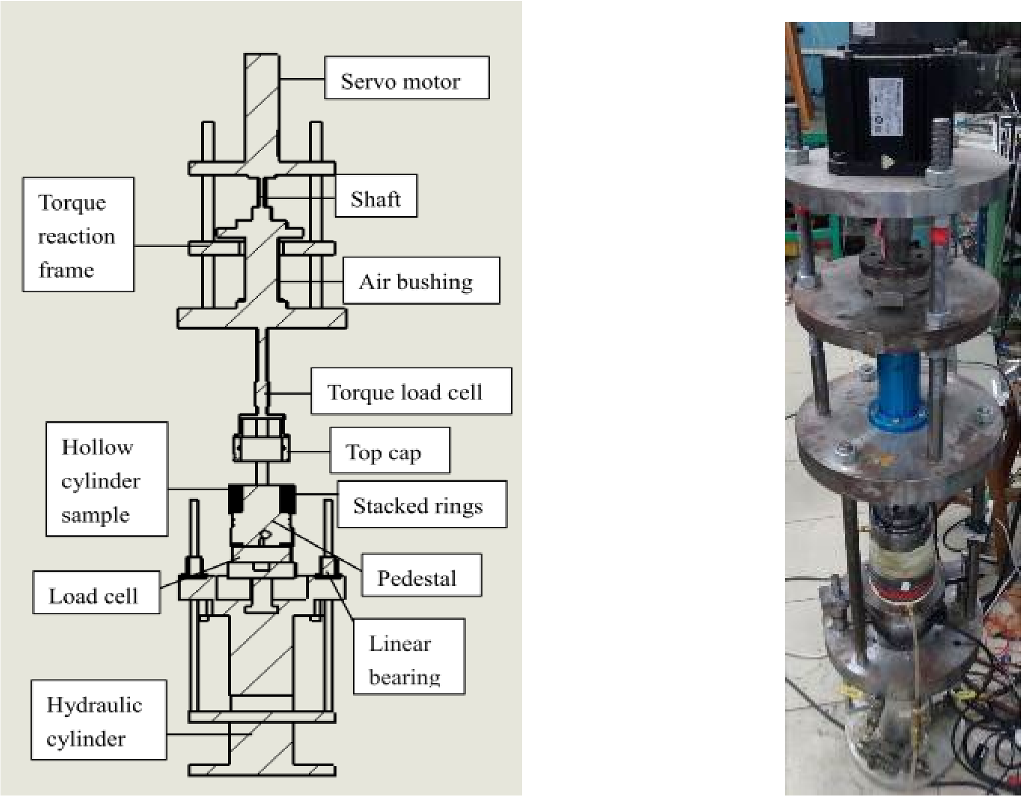

(a) (b)

Figure 1. NCKU-HCA System: Schematic drawing (a), and assembly of the system (b).

(a) (b)

Figure 1. Photos of Torsional shear box: (a) specimen with outer membrane, (b) and assembly of shear box.

The diameters of the inner rod and outer membrane, denoted as r_1 and r_2, are 70 and 100 mm, respectively, and the initial height of the specimen is 30 mm. To avoid slipping between the two caps and the specimen during shearing, the rough surface on the bottom of the pedestrian and fins, as designed by Tatsuoka et al. [7], is adopted for the top cap. Additionally, a low-friction Teflon spring seal is installed atop the inner rod to enable specimen consolidation while maintaining the seal integrity of the hollow specimen.

The shear stress is calculated by torque (T) following the derivation by Iwasaki et al. [8], which considered the average perfect elastic (τ_{ave}) and average perfect plastic (τ_{avp}) as:

$$\tau_{ave} = \frac{4}{3\pi} \frac{r_2^3 - r_1^3}{(r_2^2 - r_1^2)(r_2^4 - r_1^4)} T \tag{1a}$$

$$\tau_{avp} = \frac{S}{A} = \frac{3}{2\pi} \frac{1}{r_2^3 - r_1^3} T \tag{1b}$$

In the NCKU-HCA system, the average of the perfect-elastic and plastic shear stresses is used. The average shear strain (γ_{av}) is calculated by:

$$\gamma = \gamma_{av} = \frac{\theta}{H}\frac{r_1+r_2}{2} \tag{2}$$

where θ is the rotation angle on the horizontal plane, and H is the specimen height.

3 Testing results for the strain rate study

The NCKU-HCA has been used to study dynamic soil properties and liquefaction characteristics. The testing program covered liquefiable soils with various fines contents under vertical effective stresses less than 100 kPa. The Ottawa sand tests are batch tests used to study fines content and verify the system. To focus on the introduction of the new testing system, the strain-rate effects on modulus reduction and damping ratio are presented. The influence of shear strain rate on the dynamic characteristics of soil is relatively limited at large shear strain and high shearing frequency. The main reason is the lack of large-strain, high-speed shearing equipment. The purpose of this study is to develop a K_0-constrained hollow-cylinder torsional shear apparatus that can be used at high speed and with large strain. The system can be applied over the frequency range of 0.01~5 Hz, overcoming the frequency limitations of the existing single shear mode. This system was used to investigate the effect of shear strain rate on soil shear modulus and damping ratio of Ottawa sand.

Strain-controlled shearing tests are performed over 2 cycles, and the typical second hysteretic loops for different shear strain levels are shown in Figure 3, with a relative density of 70 % under a vertical effective stress of 100 kPa. The secant modulus, denoted G_{eq}, at various frequencies is normalized to the modulus at the shearing frequency of 1 Hz, denoted G*. To show the relative variations, the variations of G_{eq}/G^* at small, medium, and large shear strain levels, denoted as γ, are shown in Figure 4, in which strain levels range from 0.007 to 1.47 %. Variations in the damping ratio are shown in Figure 5.

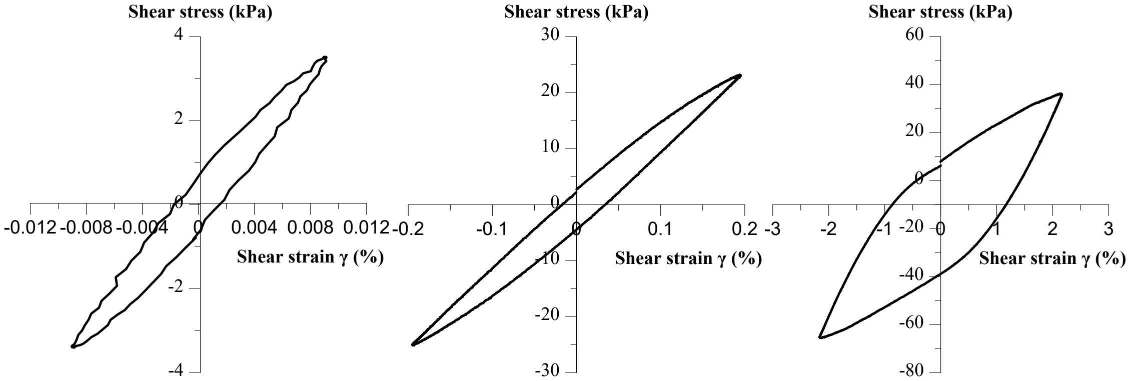

Figure 3. Hysteretic loops of strain-controlled Ottawa sand.

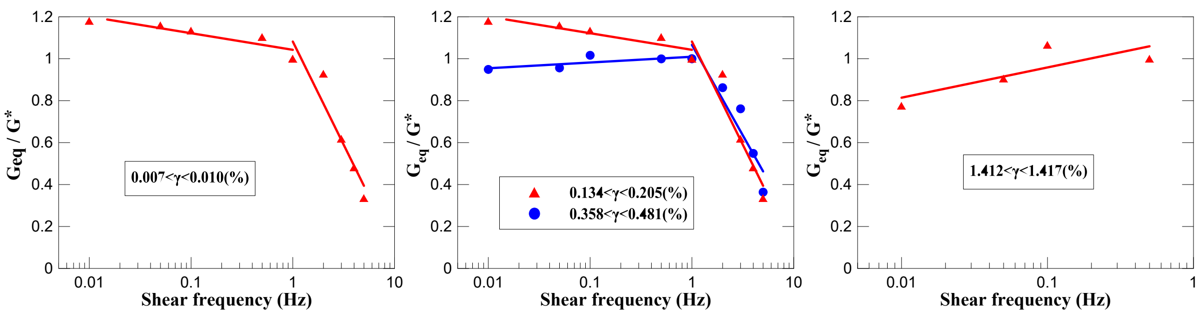

Figure 4. Variations of shear modulus in different strain levels and frequencies.

Results in Figure 4 show that the soil shear modulus of Ottawa sand varied by 20% at shearing frequencies below 1 Hz. Significant and consistent decrease in the shear modulus with increasing frequencies over 1 Hz. The data show a turning point at 1 Hz for strain levels below the medium range. A simplified linear regression could serve as a preliminary recommendation for assessing the frequency-rate effect. In Figure 5, the variations of damping ratios below medium shear strain levels are relatively small with frequencies below 1 Hz compared with the variations at frequencies over 1 Hz. The high damping ratio under high frequency is consistent with the effects of viscous damping. Nevertheless, the results reveal that loading frequency or strain rate shall be considered in both cyclic element tests and the dynamic analysis.

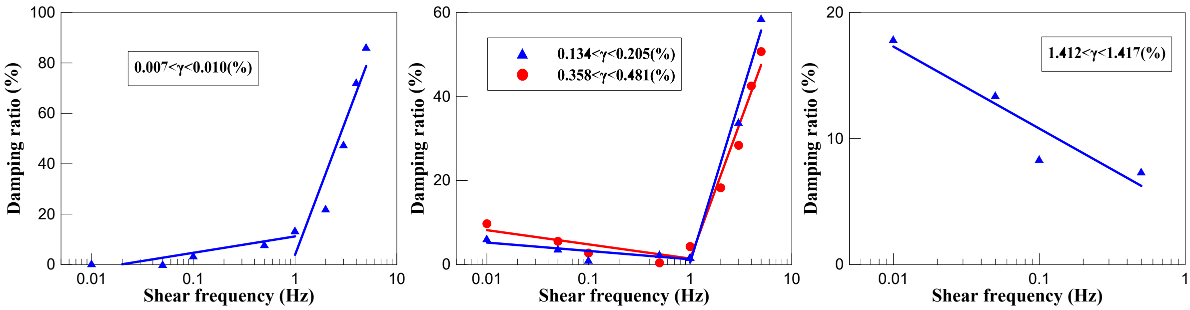

Figure 5. Variations of damping ratios in different strain levels and frequencies.

4 Summary and conclusions

A new hollow-cylinder torsional shear apparatus has been developed, which combines simple shear stress lateral boundaries and a hollow specimen feature to induce uniform stress/strain at multi-directional and large-strain levels. A new shear box is designed to provide lateral constraints and reduce the difficulties in sample preparation. The hollow-cylinder torsional shear apparatus developed in this study has high accuracy and repeatability and offers relatively simple operation.

Results for Ottawa sand subjected to different shear strain levels and loading frequencies reveal a clear turning point at 1 Hz. Below 1 Hz, the shear modulus varies within 20 % of the 1 Hz value, while a significant, linear decrease in shear modulus at frequencies over 1 Hz. Additionally, the damping ratio increases sharply above 1 Hz, consistent with the trends of viscous damping. Nevertheless, strain-rate effects shall be considered in both cyclic testing and seismic analysis of dynamic soil properties.

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