Upgrading a resonant column apparatus to reliably measure specimen void ratio

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ABSTRACT

The small strain shear modulus of soils is an important design geotechnical parameter for a wide range of civil infrastructure applications. The small strain shear modulus can be determined by using elastic theory as a relationship between the soil density, which is expressed as a function of void ratio, and the measured shear wave velocity. Thus, the void ratio has a fundamental impact on the accuracy of the result. Laboratory testing involving resonant column apparatus allows for determining the changes in stiffness of soils with varying void ratios. Standard of-the-shelf resonant column apparatus works well for clayey soils but presents a number of limitations for coarse soils that makes accurate and reliable void ratio measurement difficult due to both pore fluid and (often) sample loss during removal from the equipment. This paper presents the development of a modular set-up which allows for complete specimen sealing at the end of shear wave velocity testing. The modular set-up along with the specimen can be removed from the resonant column apparatus and the void ratio can be determined by means of end-of-test-freezing similar to triaxial testing. From this, reliable small strain stiffness at well-determined void ratio can be computed. The void ratio measurements using the new modular set-up were compared to those from triaxial tests performed on identically prepared specimens. The difference in void ratio at any given isotropic confining stress was between 0.001 and 0.011.

Keywords: resonant column apparatus; void ratio; shear modulus; sand; silt

1. Introduction

For structures designed to be far from failure, such as retaining walls, foundations and tunnels, strains in the ground are small and determining the small strain shear modulus of the soil, namely G_0, has been highlighted as an important parameter in design (Burland 1989). G_0 is also a very important parameter in the design of foundations for offshore wind turbines (Burd et al 2020). Additionally, a number of advanced constitutive models include the maximum small strain shear modulus, G_{max}, as an input parameter.

Shear waves tend to induce very small shear deformations. Their velocity, namely the shear wave velocity (V_s) represents an effective stress parameter. The shear wave velocity is a direct measurement of soil stiffness or shear modulus, G.

The shear wave velocity of soils and tailings (i.e., mine waste residue) is primarily influenced by their void ratio, e, and effective confining stress, p'. Additionally, fabric, degree of saturation, heterogeneity, particle size distribution and mineralogy have an influence on V_s.

The shear wave velocity can be measured both in situ and in laboratory, most commonly by means of seismic cone penetration testing (CPTs) for the former or bender elements or resonant column testing for the latter. Both in situ and laboratory shear wave velocity testing have advantages and disadvantages, which are very well summarised in Clayton (2011).

The shear modulus G of a material is related to V_s by:

$$G = \rho V_s^2 \quad (1)$$

where ρ is the material bulk density, which is expressed as a function of void ratio. Thus, apart from reliably measuring the shear wave velocity, in order to accurately determine G or G_0 a correct estimation of the void ratio is necessary.

Laboratory testing has the advantage of allowing for testing in a very well controlled environment, permitting to reliably replicate the same test result if near-identical reconstituted samples are tested under the same conditions.

Quality of-the-shelf geotechnical laboratory testing equipment is easily available nowadays. These pieces of equipment also provide the user the ability to upgrade and/or modify them in-house.

The current study shows how a modern of-the-shelf resonant column apparatus can be modified in order to permit users to accurately measure the void ratio of a coarse-grained soil specimen, and thus, reliably determine the small strain shear modulus under various confining stresses and soil densities.

2. New Resonant Column Apparatus modular set-up

2.1. The case for a modular set-up

This study involves a Stokoe-type fixed-free resonant column apparatus (RCA), manufactured by GDS Instruments UK, which has been commissioned at the University of Western Australia (UWA). The original equipment is manufactured with the base platen fully fixed to the RCA base by means of bolts screwed in from the underside of the equipment base. As such, the tested soil specimen cannot be easily removed and kept sealed at the end of the resonant column test. This is not an issue for clayey specimens which do not lose water or material during removal from the equipment due to their high cohesion and very low permeability. By contrast, removing coarse-grain soil specimens at the end of the testing represents a non-trivial task during which both pore fluid and specimen material are lost irrespective of the user's care in handling. Inadvertently, the specimen removal at the end of the test results in errors in determining the gravimetric water content (GWC), which in turns results in errors in determining the void ratio required for computing the bulk density, and by extension G_0 (see Eq. 1).

Sladen and Handford (1987) have proposed end-of-test freezing of specimens after triaxial testing for improving the end-of-test volume and GWC measurements. This method has been widely adapted both in academic research and industry consulting practice (Shuttle and Cunning 2007, Morgernstern et al 2016, Jefferies et al 2019). Reid et al. (2021a,b) have shown how a modular set-up for triaxial testing allowing for end-of-test freezing improves the accuracy and reliability of volume and void ratio measurements.

The ramped-up demand for small strain stiffness measurements for the design and management of tailings storage facilities and offshore wind farms introduces the challenge of accurately measuring the void ratio of loose sand and silt. Thus, a set-up similar to the one already widely used for triaxial testing could be employed for resonant column testing.

2.2. RCA system modifications

A modular set-up that permits specimen sealing and easy removal from the RCA was developed to enable placement of the end-of-test specimen into the freezer. The modular set-up was designed by the author and manufactured by an external contractor.

The rationale behind the design was:

- To manufacture a simple modular set-up that still maintains the fixed-free original design;
- The new modular set-up should not require any additional modifications of the original RCA system, especially the top part of the equipment;
- The new modular set-up should be sufficiently lightweight to be easily maneuvered by any user;
- The new modular set-up should accommodate soil specimens identical to those prepared for triaxial testing.

The last rationale provides the opportunity to test the ability of the new set-up to accurately and reliably measure the void ratio of the specimens.

The following modifications were performed to the original RCA system:

1. A new thin circular base plate fixed with bolts from the underside of the equipment base was manufactured. This base plate seals off the original base drainage channels and makes them redundant.
2. A new modular base platen (see **Figure 1**) which tightly mounts and screws onto the new base plate was manufactured. A new base drainage channel from the side of the base platen was introduced. This drainage channel is fitted with a quick-release connection that also seals off the specimen upon disconnection from the apparatus.
3. One of the drainage lines of the original top platen was sealed off and made redundant. The remaining drainage channel was fitted with a quick-release connection that also seals off the specimen upon disconnection from the apparatus.
4. Two of the four drainage channels on the RCA pedestal were sealed off and made redundant (see point 1.). The remaining two channels were connected to the modular base and top platens, respectively, making the RCA set-up similar to the triaxial counterpart.

Figure 1. New modular base platen for the RCA apparatus

3. Validation

The new RCA modular set-up was specifically developed to prepare identical specimens to those prepared for triaxial testing. A series of additional components, such as moist tamping mold and a tamping rod, were also designed and manufactured with the goal to prepare loose sand or silt samples by using the moist tamped technique (Ladd 1978). As such, loose moist tamped specimens will have (almost) identical initial densities whether prepared for resonant column or triaxial testing. This means that when the specimens are subjected to the same levels of isotropic consolidation (n.b., the Stokoe-type RCA permits only isotropic consolidation), they will densify to (almost) the same void ratio.

In order to validate whether the new RCA modular set-up can facilitate accurate and reliable void ratio measurements, two non-plastic coarse-grained soil samples were tested both in a triaxial apparatus and the resonant column apparatus. The testing procedure for resonant column testing and triaxial testing can be identical up to and including the consolidation stage.

Four tests on loose specimens were carried out, two using the resonant column apparatus and two using the triaxial apparatus. **Figure 2** shows the RCA loose specimen prepared by means of moist tamping using the undercompaction method (Ladd 1978).

Both the resonant column and triaxial tests were carried out as follows:

- Application of isotropic confining pressure of 50kPa and back-pressure of 20 kPa;
- Flushing de-aired de-ionised water through the specimen from base to top for about 60-80 minutes, until no air bubbles came out;
- Application of back-pressure saturation up to 1000 kPa, ramped in parallel with the confining pressure, while maintaining a 30kPa difference between the two;
- The B-value was checked and a minimum of 0.95 was obtained for all specimens;
- Isotropic consolidation was then carried out incrementally to reach target mean effective stress p' = [100,500] with increments of 100 kPa.

Although not part of this study, after each incremental consolidation stage was achieved, the shear wave velocity testing using only very low voltage was carried out in the RCA.

At the end of each test, the top and bottom drainage valves to the specimens were closed, stopping the flow of pore fluid to or from the specimen. After the cell pressure was lowered and the cell was lifted, the drainage lines were disconnected using the quick-release connections and the modular set-up along with the sealed specimen was manually removed from the RCA. **Figure 3** shows the fully liquefied (but perfectly sealed) specimen after testing in the RCA. Liquefaction of the fully-saturated loose coarse-grained specimens is often unavoidable and their removal from the original RCA set-up becomes a very challenging task. **Figure 4** shows the liquefied specimen sealed within the RCA modular set-up as placed in the freezer.

3.1. Soil samples

Two non-plastic soils, namely a silty-sand (Sample A) and a sandy-silt (Sample B), were used to validate the new RCA modular set-up. General geotechnical properties of both samples are given in Table 1.

Table 1. General geotechnical properties of tested soil

	Sample A	Sample B
Specific gravity	3.21	3.21
$\mathbf{M_{tc}}$	1.52	1.45
< 75 μm	55	35
$\mathbf{D_{50}}$ **(mm)**	0.07	0.1
$\mathbf{D_{60}/D_{10}}$	7.5	120

Figure 2. Soil sample prepared by moist tamping within the new RCA modular set-up

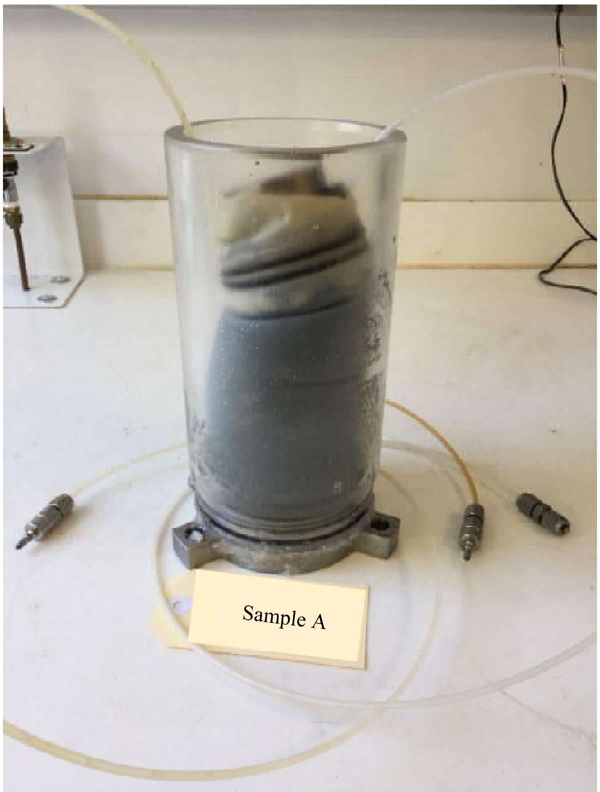

Figure 3 End of RCA test soil sample: fully liquefied, isolated with quick-release connection fittings

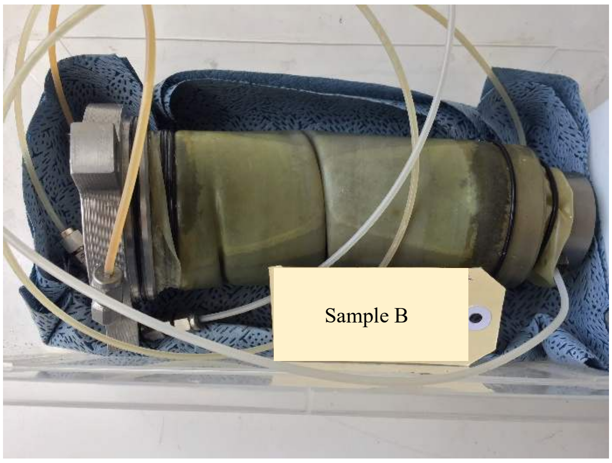

Figure 4. End of RCA test soil sample: as placed in the freezer

3.2. Results

Following end-of-test freezing, the specimens were removed from the top and base platens and the latex membrane was then peeled off from the frozen specimens before placing them in the oven. The GWC of the end-of-test specimens was then used to back-calculate the void ratios at each incremental isotropic consolidation stage for each of the triaxial and resonant column tests.

Table 2 summarises the measured void ratio, e, for Sample A as tested in the resonant column and triaxial apparatus under incrementally increased isotropic consolidation stress, p'. The void ratio difference, Δe, between the two tests varies between 0.004 and 0.011.

Table 2. Void ratio measurements for Sample A

	Triaxial test	**RCA test**	
p' (kPa)	**e (-)**	**e (-)**	**Δe**
100	1.023	1.034	-0.011
200	1.005	1.012	-0.007
300	0.993	0.997	-0.005
400	0.981	0.990	-0.009
500	0.972	0.976	-0.004

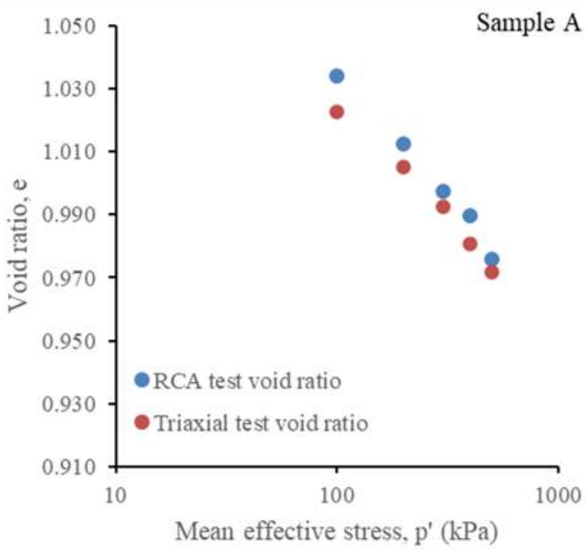

Figure 5. Void ratio results comparison between RCA and triaxial testing for Sample A

Table 3. Void ratio measurements for Sample B

	Triaxial test	**RCA test**	
p' (kPa)	**e (-)**	**e (-)**	**Δe**
100	0.961	0.967	-0.006
200	0.941	0.948	-0.006
300	0.926	0.935	-0.009
400	0.911	0.920	-0.009
500	0.903	0.905	-0.001

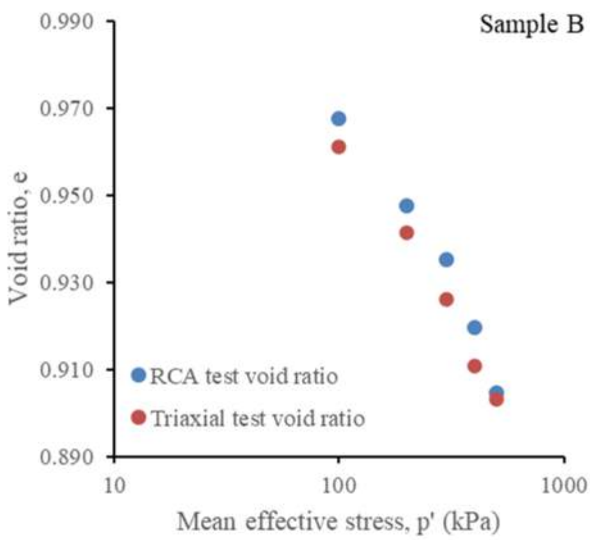

Figure 6. Void ratio results comparison between RCA and triaxial testing for Sample B

Figure 5 illustrates the evolving void ratio with mean effective stress, p', for Sample A. The subtle variable differences in void ratio between the two tests could potentially be attributed to non-perfect homogeneity of the specimens as well as the impossibility to create perfectly identical reconstituted specimen. Nonetheless, the difference in void ratio between the two specimens is trivial.

Table 3 and **Figure 6** summarise the measured void ratio for Sample B for both the triaxial and resonant column test. Sample B has a lower percentage of fines content (i.e., particles with size < 75 µm) than Sample A. The resulting minimum and maximum differences in void ratio between the two tests are 0.001 and 0.009, respectively.

4. Conclusions

The small strain shear modulus is an important parameter in the design and management of many types of civil infrastructure ranging from offshore wind turbines to facilities used to store mine waste residue into perpetuity. The accurate estimation of this parameter is essential in a wide range of geotechnical applications. Using elastic theory, the small strain shear modulus is a direct function of the material density (or void ratio) and its shear wave velocity. Thus, apart from reliably measuring the shear wave velocity, in order to accurately determine the shear modulus correct estimation of the void ratio is necessary.

The current study shows how a simple modification, in the form a modular set-up, to a modern of-the-shelf resonant column apparatus can permit users to accurately measure the void ratio of a coarse-grained soil specimen.

To validate the new modular set-up, resonant column tests using the new modular set-up were performed on non-plastic silty-sand and sandy-silt, respectively. Two triaxial tests were also performed on the same samples, using identical preparation technique, and under the same testing conditions.

The difference in void ratio between the two types of tests ranged from 0.001 to 0.01 across five different confining stresses, in effect validating the suitability of the new modular RCA set-up to accurately and reliably facilitate the measurement of void ratios on tested soil.

This type of modular set-up is particularly useful for coarse-grained soil samples with very high permeability and a tendency to liquefy either during testing or during manual handling at the end of test.

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