

Resonant column round-robin testing

Essais de résonance en torsion: comparaisons inter et intra-laboratoires

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ABSTRACT: Faced with seismic risk, to better understand and characterize the behaviour of soils, advanced geotechnical laboratory tests are necessary. These include, for example, torsional resonance tests. The American standard (ASTM D4015 – 15), which describes the process for carrying out these tests, points out the lack of interlaboratory tests to determine their accuracy. As part of the ASIRI+ project, a cross-test campaign was launched in France from the beginning of 2023 on two types of sandy materials (HN31 and a mixture of HN38, HN34, HN31, HN04). Three independent laboratories participated. The results of resonant column tests obtained are presented. The following evolutions are discussed: shear modulus vs distortion, damping vs distortion. Results are compared to empirical models.

RÉSUMÉ: Face au risque sismique, pour mieux comprendre et caractériser le comportement des sols, des essais géotechniques avancés en laboratoire sont nécessaires. Ceux-ci comprennent, par exemple, des essais de résonance en torsion. La norme américaine (ASTM D4015-15), décrivant le processus de réalisation de ces tests pointe le manque de tests interlaboratoires pour déterminer leur précision. Dans le cadre du projet ASIRI+, une campagne de tests croisés a été lancée en France à partir de début 2023 sur deux types de matériaux sableux (HN31 et un mélange de HN38, HN34, HN31, HN04). Trois laboratoires indépendants ont participé. Les résultats des essais de colonne résonante obtenus sont présentés. Les évolutions suivantes sont discutées : module de cisaillement vs distorsion, amortissement vs distorsion. Les résultats sont comparés à ceux issus de modèles empiriques.

Keywords: Resonant column apparatus; round-robin test; shear modulus; damping.

1 INTRODUCTION

Dynamic soil response is of considerable importance for loadings produced by earthquakes, machine foundations, wind, waves, and impacts. Two of the most important parameters in any dynamic analysis involving soils are the shear modulus and the damping ratio. Both the shear modulus, G , and damping, D , are dependent on the shear strain, γ . For earthquake problems, the variation of G and D with shear strain must be considered. In laboratory, the resonant column apparatus (RCA) constitutes a means of determining these parameters. Precision of these results depends of the nature of tested soils, specimen variation, operator or laboratory testing variation (ASTM, 2021).

In the 1970's, USA organized resonant column round robin testing program for determining the dynamic shear modulus and the damping ratio of Monterey sands (Chung, 1982). At the beginning of 2023, in France, three independent laboratories

decided to organize intercomparison testing on sandy reconstituted specimens.

For this study, the methodology was quite free: reconstitution method, apparatus, drainage conditions, method of determining depreciation are chosen by each operator according to their constraints and practices.

2 MATERIALS AND METHODS

2.1 Materials

The material used in this research work were two sands:

- Hostun HN31 sand whose properties have been extensively studied by many research laboratories (Baudouin, 2010).
- A mixture of Hostun sands composed of 25% in dry weight of the fraction HN38 HN34 HN32

and HN 04 (fraction HN 04 cut at 0.63 mm).

Particle size distributions of each material is shown in Figure 1. Their physical characteristics are given in Table 1. Different properties are presented: the effective Grain Size D_{10} , the median Grain Size D_{50} , the coefficient of uniformity $C_u = D_{60}/D_{10}$, the coefficient of curvature $C_c = D_{30}^2/D_{10}D_{60}$.

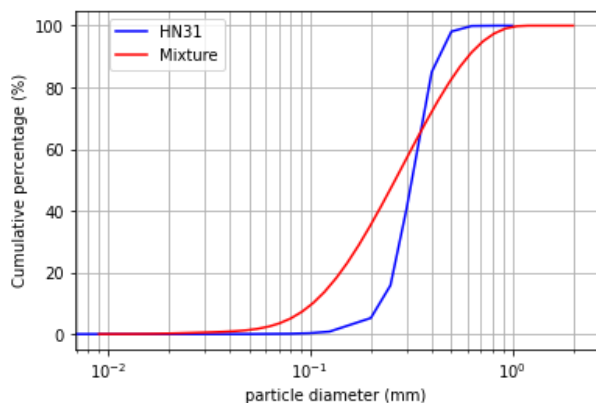


Figure 1. Particle-size size distribution (HN31 and mixture).

Table 1. Properties of HN31 and mixtures sands.

	HN31	Mixture
D_{10} (μm)	220	104
D_{50} (μm)	320	250
C_u	1.57	3.13
C_c	1.03	0.96

2.2 Specimen preparation

Three procedures of reconstitution of the samples were used: compaction, raining and compaction followed by freezing. Only the density was fixed. Grain bulk density was measured: 26.00 kN/m³.

8 HN31 specimens and 7 mixture specimens were reconstituted in laboratories (with a density objective of respectively, 19.22 and 20.21 kN/m³). The height of the samples was about 100mm and the diameter about 50mm.

Void ratio of specimens before testing are presented in Figure 3 and Figure 4. HN31 and mixture specimens presented respectively density between 18.96 and 19.30, and between 19.63 and 20.11 kN/m³.

2.3 Testing conditions

All specimens were saturated (Skempton coefficient $0.95 < B < 1.00$). They were consolidated at an isotropic pressure $\sigma'_0 = 100$ kPa (HN31) or 300 kPa (Mixture). Some specimens were drained at their top and their base, others only at their base. Intermediate reconsolidation phases were carried out when the overpressures were too high (threshold determined by each laboratory).

2.4 Resonant column apparatus tests

The evolution of the shear modulus and the damping of a soil as a function of the distortion can be obtained by torsional tests on the RCA (Figure 2).



Figure 2. RCA in the Cerema laboratory.

The RCA is well suited for accurate measurements of soil stiffness and damping at low to medium shear strain amplitudes, typically between 0.0001% and 0.1% (ASTM, 2021). An axially and radially confined cylindrical sample is sheared by applying a sinusoidal torsional moment of predefined amplitude and increasing frequency to its top end, while the base end is fixed. Once the resonant frequency has been identified, it is used to calculate the soil shear modulus using a theoretical elastic model, which correspond to the applied shear strain amplitude. Two different approaches are generally applied to determine the damping rate using a RC test: steady-state and free vibration decay methods (Semblat et al., 2011). Both were used in this study.

The reduction in shear modulus and evolution of damping is obtained by repeating the test with increasing amplitudes.

The G modulus measured at the smallest amplitudes and distortions is called G_{\max} .

3 RESULTS

3.1 Shear modulus as a function of distortion

Torsional RCA tests provide shear modulus decrease curves as a function of shear strain γ . The test results are presented for each type of specimens: HN31 (Figure 3) and mixture (Figure 4). Colors correspond to the initial void ratio of each specimen (from red to blue presented in the histogram).

Symbols correspond to different specimen preparation: ● is linked with compaction followed by freezing, + to raining and ★ to compaction.

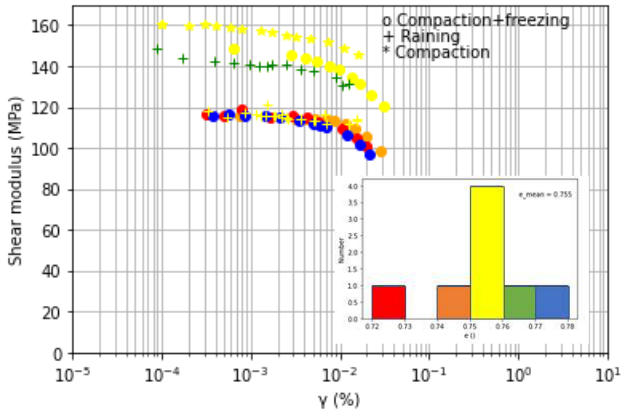


Figure 3. Shear modulus as function of distortion (HN31).

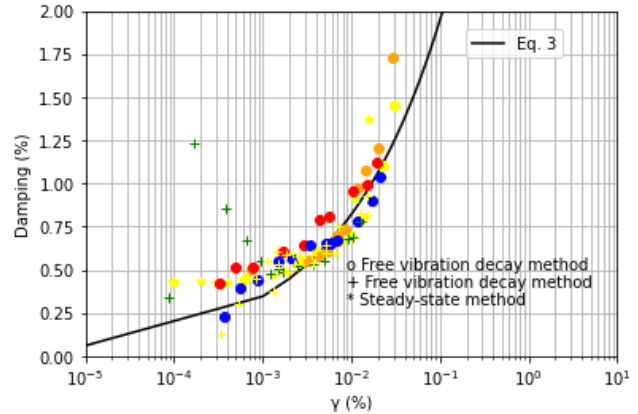


Figure 4. Soil damping as function of distortion (HN31).

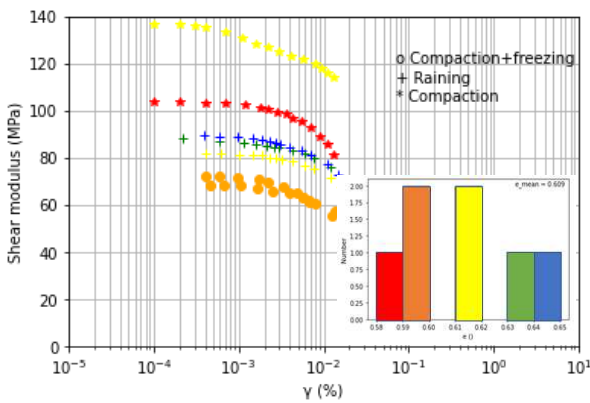


Figure 5. Shear modulus as function of distortion (Mixture).

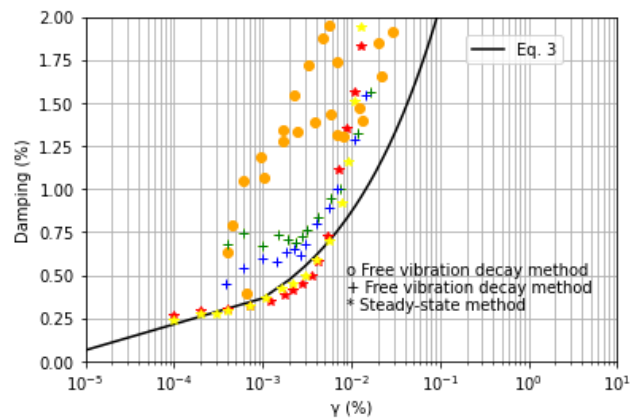


Figure 6. Soil damping as function of distortion (Mixture).

Two different apparatus were used (machine M1 ★ and machine M2 ● and +). Two different drainage conditions were used (drainage at the bottom of the specimen ★ and drainage at the top and the bottom of the specimen ● and +). The laboratories carried out several different tests on different specimens under the same drainage conditions and consolidation pressures.

The HN31 specimens present maximum shear modulus values varying between 120 and 160 MPa; those of the mixture, values between 65 and 140 MPa. The results of HN31 are less dispersed than those of the mixture. Results obtained with M1 (drainage only at the base of the specimen) are always higher than others. In Figure 3, yellow circle (●) and green plus (+) curves correspond to tests with technical problems (leak or inclination of the electro-magnets into the coils). Other curves are very closed but correspond to different initial void ratio. Void ratio after saturation and consolidation phases has to be considered, instead of initial one. In Figure 4, the yellow plus (+) curve corresponds to a laboratory test with a leak.

More generally, repeatability of tests for the same laboratory is observed.

3.2 Damping as a function of distortion

Torsional RCA tests also provide damping as a function of shear strain γ . The test results are presented for each type of specimens: HN31 (Figure 5) and mixture (Figure 6). Like for the previous figures, symbols are linked with specimen preparation and colors to the void ratio.

For both materials, the damping varies between 0 and 2%. The results of HN31 are less dispersed than those of the mixture. Steady-state and free vibration decay methods were used to determine the soil damping. The first one corresponds to ● and + symbols and the second one to ★ symbols. Figure 6 seems to show that steady-state method is more precise to determine the damping for very small distortions.

3.3 Discussion

Experimental results are compared to empirical relationships (solid and dotted black lines) that have been proposed in the literature for sandy soils in Figures 7, 8, 5 and 6. (Rollins et al., 2020) presented simplified equations for shear modulus degradation and damping of sandy soils in relation with confining

pressure and coefficient of uniformity (Equations. 1, 2 and 3):

$$\frac{G}{G_{max}} = \frac{1}{1 + \left(\frac{\gamma}{0.0063\sigma'_0} \right)^{0.87}} \quad (1)$$

$$\frac{G}{G_{max}} = \frac{1}{1 + \left(\frac{\gamma}{0.0046C_u} \sigma'_0 \right)^{0.84}} \quad (2)$$

$$D = 26,05 \left(\frac{\gamma}{1 + \gamma} \right)^{0.375} C_u^{0.08} \sigma'_0{}^{-0.07} \quad (3)$$

Normalized shear modulus is the current shear modulus G divided by G_{max} . In the Figure 7, measured values of G are above the empirical curves for HN31 specimens, whereas the empirical curves frame the measurements in the Figure 8 (mixture).

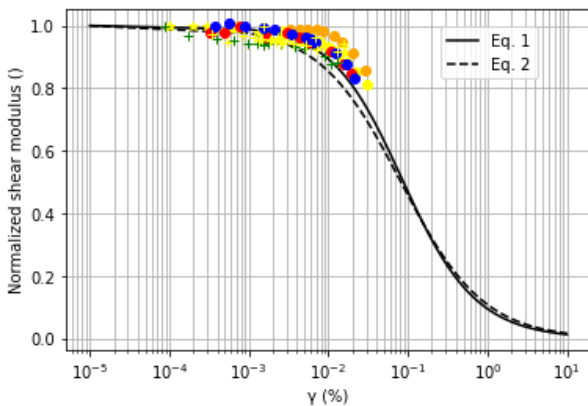


Figure 7. Normalized shear modulus as function of distortion (HN31).

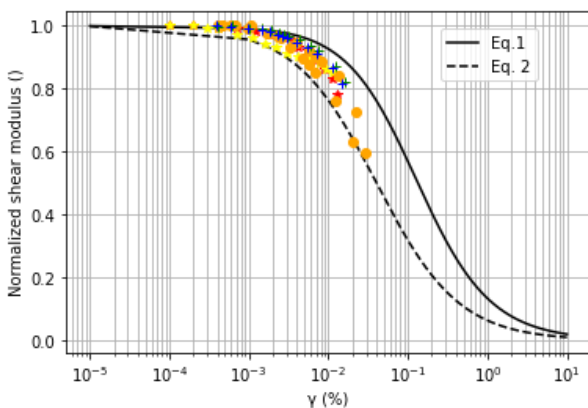


Figure 8. Normalized shear modulus as function of distortion (Mixture).

Regarding damping, the measured values coincide with the empirical curve proposed for the evolution of the damping of HN31 sand as a function of distortion (Figure 5). For the mixture, the empirical curve corresponds to the minimum of the measured values (Figure 6).

4 CONCLUSIONS

Finally, fifteen tests were carried out by three independent laboratories using a resonant column apparatus. Shear modulus and damping were determined on sandy specimens. In terms of shear modulus, the values are relatively dispersed explained by different sample preparation, different void ratio and hydromechanical problems during tests. However, the dimensionless modulus reduction curves are relatively close to each other and to the empirical curves in the literature. The HN31 sand damping values are also close to each other and are well reproduced by the empirical curves even though two different methods were used to determine them. An analysis of the test procedures and operating methods will be carried out to try to explain the dispersion of the curves. Other tests still need to be carried out.

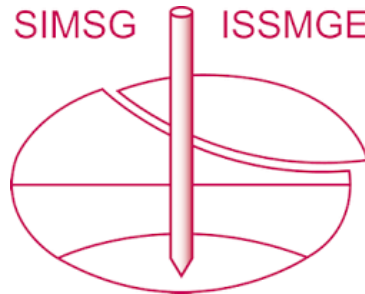
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