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Small strain damping ratio of sands and silty sands subjected to flexural and torsional resonant column excitation

Kostas Senetakis[a,*,1], Meghdad Payan[b,1]

[a] City University of Hong Kong, Hong Kong
[b] Faculty of Engineering, University of Guilan, Rasht, Iran

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ABSTRACT

Damping ratio is a critical soil property used for the geophysical characterization of sediments and the study of the behavior of geo-materials against wave propagation. Two types of damping ratios are examined and quantified in this study conducting small-strain resonant column tests in torsional and flexural modes of vibration. During the course of this study, a variety of non-plastic soils from clean sands to silt-sand mixtures with variable index properties are examined and the laboratory specimens are subjected to isotropic stress conditions. Measurements and comparisons are conducted between flexural (D_{fo}) and torsional (D_{so}) damping. For clean sands, based on the data analysis, an empirical equation for (D_{fo}) is derived which is given as a function of (D_{so}) and the characteristics of the sands. Flexural damping ratios for all the tested materials are observed to have fairly equal or greater values and lower rate of variation with isotropic confining pressure compared to their torsional counterparts (D_{so}). Furthermore, the proportions of small-strain flexural and torsional damping ratios (D_{fo}/D_{so}) are obtained for all the tested sands and silty sands and plotted against the isotropic confining pressure. The results highlight the important role of particle shape, grain size distribution and silt content on the behavior of non-plastic geo-materials in terms of the ratio (D_{fo}/D_{so}).

1. Introduction

It is well acknowledged in the literature that soil dynamic properties play important role in a variety of problems including seismic ground response analysis, soil-structure interaction problems, prediction of deformations for critical facilities and the design of geo-systems. With a focus on granular materials, previous literature has paid particular attention on soil stiffness, the different factors controlling modulus as well as the critical evaluation of different interpretation methods (e.g., [1-14], among others). Studies on small-strain and small-to-medium strain damping ratio have been relatively more limited compared to soil stiffness (e.g. [10,15-20], among others).

Material damping ratio or attenuation, typically denoted as D or ξ, is an important soil dynamic property used for the geophysical characterization of sediments, the seismic design of civil engineering facilities and the study of energy dissipation in geo-materials [21-25]. Damping ratio is defined as the energy absorption in a soil medium during wave propagation or cyclic loading which is heavily influenced by the induced strain level. Of particular interest in geotechnical engineering practice to characterize the behavior of geo-materials, is the value of damping ratio at very small strains (typically below $10^{-3}\%$ or $10^{-4}\%$). In this range of behavior, depending on the mode of vibration, damping ratio reaches a minimum value and it can be expressed for most practical purposes as a flexural damping (D_{fo}), longitudinal damping (D_{lo}) or torsional damping (D_{so}) against flexural, longitudinal or torsional dynamic excitation, respectively. Even though the importance of damping ratio in engineering practice is recognized, material damping has been mostly a topic researched in the discipline of geophysics rather than in soil mechanics/dynamics research by geotechnical engineers.

With respect to the different mechanisms that contribute to energy loss particularly at small strain levels, fundamental aspects have not been thoroughly discussed or understood throughout the literature. Santamarina & Cascante [26] reported that processes other than frictional losses are probably involved in the dissipation of energy at small strains. Due to the difficulties associated with the elimination of the background noise and equipment-generated damping, accurate measurement of material damping ratio in the range of small strains has been quite challenging in the past [27] in laboratory research works. With the advancement in the soil testing technology, it is now possible

* Corresponding author.
E-mail address: ksenetak@cityu.edu.hk (K. Senetakis).
[1] formerly UNSW Australia

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to obtain reasonably accurate measurements of small-strain damping ratio of geo-materials (e.g. [10,17,19,20,28]). In recent years, there has been a notable increase of research works investigating small-to-medium strain damping of geo-materials, along with soil stiffness, particularly using the resonant column, torsional shear and hollow cylinder configurations (e.g. [15,29-32], among others). These recent works have improved significantly our understanding of soil response and have contributed to the development of new empirical models with immediate interest in geotechnical earthquake engineering.

Using the results of a comprehensive set of torsional resonant column tests on solid and hollow specimens of dry sands having a relative density of 60% and under confining pressures ranging from 10 kPa to 300 kPa, Chung et al. [27] concluded that the damping ratio generally decreases with the increase in confining pressure. In their study, for the tested sands and the range of applied confining pressures, all damping ratios were observed to be less than 1% for small-strain measurements. In another study performed by Laird [33], several resonant column tests were conducted on different specimens of a specific type of sand. The results of that study indicated that at confining pressures below 20 kPa, damping ratio is quite high in magnitude, while it reduces to values less than 1% beyond 20 kPa of confining pressure and becomes rather constant at relatively higher confinements. Cascante et al. [21] conducted a set of torsional and flexural resonant column experiments on variably saturated uniform silica sands in a resonant column apparatus. From the results of their study, it was observed that while damping ratios of partly and fully saturated sands in flexural mode of excitation are higher than that in torsional mode, both the damping values were almost the same for dry sands. In their study, Cascante et al. [21] observed a significant increase in the proportion of flexural to torsional damping ratio (D_{fo}/D_{so}) from around 1 for air-dry condition to about 3.5 for partially and fully saturated states.

As discussed above, almost all the results of the previous studies suggest that the small-strain damping ratio in shear (or torsional excitation) decreases with increasing confining pressure, while no specific influence of void ratio was reported in most studies [10,17,19,20,33,34]. The effect of grain size characteristics on the small-strain damping ratio of granular soils has been investigated in the studies performed by Menq [10] and Senetakis et al. [19]. They correlated the small-strain torsional damping ratio (D_{so}) of sands to the mean effective confining pressure and gradation characteristics of the soil. As observed by Menq [10], the small-strain damping ratio of granular soils increases with the increase in the coefficient of uniformity (C_u) and decrease in mean grain size (d_{50}). However, no specific influence of the grain size characteristics on D_{so} was observed by Senetakis et al. [19], as they proposed empirical equations with constant fitting parameters for different types of sands. In another study, Senetakis et al. [30] discussed the influence of particle morphology on D_{so} showing that the small-strain damping ratios of pumice and quartz sands were generally different due to their variable mineralogies and particle morphologies. In a recent study performed by Payan et al. [17], the effect of particle shape on the damping properties of sands in shear was systematically incorporated into a general small-strain torsional damping ratio model. Simple expressions for the correlation of material damping with different important parameters, for example the confining pressure or the grain size characteristics of the material (e.g. studies by [10,17], among others) have important practical implications in seismic ground responses analyses.

In another study performed by Madhusudhan and Senetakis [35], the results of tests on a resonant column apparatus in flexural mode of vibration were implemented to characterize the small-strain Young's modulus and flexural damping ratio of a quartz sand. In their study, the small-stain flexural damping ratio was observed to decrease in all confining pressures as the material becomes stiffer, i.e. relative density increases. Madhusudhan and Senetakis [35] emphasized in their study that flexural damping was in general greater in magnitude than torsional damping and that the influence of the confining pressure to damping was more pronounced for the torsional mode of vibration in comparison to the flexural mode. Thus the ratio (D_{fo}/D_{zo}) increased for greater pressures. However it is needed to be noticed that their study focused on a given type of sand of given particle morphology and distribution. Payan et al. [17] noticed that there may be substantially different values of damping due to the effect of particle morphology and that the relationship damping – pressure is notably affected by the material characteristics in terms of grain shape and size distribution. Similar to damping, the effect of particle morphology (as well as distribution of sizes) on the stiffness of sands (e.g. [1,11]) and the liquefaction resistance of soils [36-38] has been well acknowledged by scholars.

The previous study by Payan et al. [17] had a focus solely on torsional damping for dry sands. In this study, several resonant column tests are performed in order to characterize the small-strain damping ratio of dry sands and sand-silt mixtures in both torsional and flexural modes of excitation. Sands with a variety of grain size characteristics and particle morphologies in terms of particle shape along with a silica non-plastic silt are used. The influence of different sand index properties along with the effect of the addition of fines content on the proportion of the small-strain flexural and torsional damping ratios are specifically highlighted (D_{fo}/D_{so}). An effort is attempted to correlate quantitatively the flexural and torsional damping of clean sands incorporating the possible role of particle shape and grading characteristics in this relationship.

Table 1
Properties of tested sands.

Soil name	Laboratory material	Particle size distribution		Particle shape descriptors		
		d_{50} (mm)	$C_u = d_{60} / d_{10}$	Roundness (R)	Sphericity (S)	Regularity (ρ)
S	Sydney Sand	0.31	1.95	0.61	0.76	0.69
Br	Bricky Sand	0.47	2.19	0.48	0.71	0.6
W	White (Blue circle) Sand	0.24	1.69	0.71	0.76	0.74
US	Uniform Sydney Sand	0.36	1.18	0.61	0.76	0.69
R	River (Nepean) Sand	0.59	4.15	0.55	0.77	0.66
N	Newcastle Sand	0.33	1.94	0.64	0.73	0.69
CBL	Crushed Blue Sand	1.88	4.11	0.24	0.51	0.38
UCBL1	Uniform Crushed Blue Sand 1	1.66	1.41	0.24	0.51	0.38
UCBL2	Uniform Crushed Blue Sand 2	0.69	2.00	0.24	0.51	0.38
50UBr-50UBL	50% Uniform Bricky, 50% Uniform Blue Sand	0.54	1.96	0.36	0.61	0.49
70UBr-30UBL	70% Uniform Bricky, 30% Uniform Blue Sand	0.49	2.01	0.41	0.65	0.53
30UBr-70UBL	30% Uniform Bricky, 70% Uniform Blue Sand	0.59	1.99	0.31	0.57	0.44