The effect of sample size on the measured V_s using the Piezoelectric Ring-Acturator Technique (P-RAT)

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ABSTRACT
Unlike most of the geotechnical parameters (e.g., N-SPT and q_c-CPT) which can be measured only in the field, shear wave velocity, V_s can be assessed by either in-situ or laboratory traditional techniques such as BE and RC. Such techniques may effectively be used to analyze and quantify the effects of various parameters on V_s, also their versatility, convenience, and usefulness, especially to augment limited field data, were proved. Also it is worthy to mention that several factors are involved may leads to increase the number of BE tests required, for this reason BE technique may not be standardized yet. Overviews of several previous explanations and hypotheses were presented, but only few works signaled that, the geometry of samples can affect the shear wave propagation. This paper focuses on an experimental investigation of sample size effect on the measured V_s using the piezoelectric ring-actuator technique (P-RAT). Such technique is incorporated into the traditional odometer apparatus to obtain V_s values of the same granular soil having different sample sizes. The experimental results show that the use of (P-RAT) in the determination of V_s may not be affected by samples sizes.

RÉSUMÉ
Contrairement à la plupart des paramètres géotechniques (N-SPT et qc-CPT) qui peuvent être mesurés que sur terrain, la vitesse des ondes de cisaillement, V_s peut être évaluée in situ ou en laboratoire en utilisant des techniques traditionnelles telles que bilames piezoelectrique (BE) et colonne de résonance (RC). Ces techniques peuvent être utilisés efficacement pour étudier et quantifier les effets de divers paramètres sur Vs. Ces essais au laboratoire ont prouvé leurs polyvalences,et leurs utilités en particulier pour enrichir les données de terrain qui sont relativement limitées. Cependant, le nombre de questions augmente de la même manière que le nombre des essais BE augmente et il pourrait être la raison pour laquelle BE n'est pas encore normalisé. De nombreuses explications et hypothèses ont été faites, mais peu ont signalé que la géométrie de l'échantillon peut affecter la propagation des ondes de cisaillement. Cet article porte sur une étude expérimentale sur l'effet de la taille de l'échantillon sur le V_s mesurée en utilisant la technique d'anneau actionneur piézo-électrique (P-RAT). Cette technique est incorporée dans l'appareil œdométrique pour obtenir des valeurs V_s sur des sols granulaires ayant différentes géométries. Les résultats expérimentaux montrent que l'utilisation du P-RAT dans la détermination de V_s peut minimiser l'effet d'échelle.

1 INTRODUCTION

Shear wave velocity, V_s has been used for many years in geotechnical engineering practice for the analysis and design of various geotechnical structures. Several investigations have been carried out using traditional techniques such as bender element (BE) and resonant column (RC) focusing on the parameters affecting the shear wave propagation such as confining pressures, void ratio, and particle characteristics (e.g., Hardin and Richart, 1963; Iwasaki and Tatsuoka, 1977; Yang and Gu 2012; Hussien and Karray 2013). Meanwhile, BE testing conditions and results are highly varying in accordance with many concerned and integrated factors, which may be the reason that BE is not standardized yet. Previous works show that many explanations and hypotheses were developed, but few works signaled that the geometry of sample can affect the shear wave propagation. For example Oztoprak and Bolton (2013) collected data from 62 experimental studies on measuring shear wave velocity in laboratory using Oedometer, tri-axial, BE as well as RC techniques for different soil types and draining conditions. Based on the collected database by Oztoprak and Bolton (2013) several detailed investigations on the effects of various parameters on V_s were carried out. Despite these valuable investigations, the effect of sample size on the wave propagation was not included.

This paper highlights the use of the piezoelectric ring-actuator (P-RAT) to study the effect of samples sizes on measuring the shear wave velocities for two different granular soils with different particles size distributions. Three different odometer cells having various heights and diameters were employed for this purpose. Also detailed explanation of the P-RAT apparatus, tested materials, experimental results, and brief review of the samples sizes for the studied soils on the investigated soil properties especially V_s will be presented.

2 SIZE SAMPLE EFFECT: A REVIEW

Specimens, six to ten times of the maximum particles size were considered as an approved assumption within the geotechnical community to have a representative elementary volume for laboratory testing devices (e.g. Holtz and Gibbs 1956). Table 1 summarize the habitual oedometer cells used in geotechnical laboratories.

With respecting the above condition and specifications given in Table 1, the sample size does not affect the physical and mechanical properties of the tested soil (Hu et al. 2011). This implies that V_s as an effective stress parameter for the soil (e.g. Richart et al. (1970), and Hussien and Karray (2015)), may not be affected by the size of the tested samples.

Table.1. The habitual oedometer cells used in geotechnical laboratories (Mokhtari et al. 2015).

Oedometer type	*Casagrande* ASTM D2435	*Casagrande* BS 1377 Part 5	*Hydraulic (Rowe cell)* ASTM D4186	*Hydraulic (Rowe cell)* BS 1377 Part 6
Minimum diameter (D)	50 mm	-	50 mm	-
Minimum height (H)	Greater than 12 mm and 10 times max particle diameter of specimen	Greater than 18 mm and 5 times mean diameter of largest particle of specimen	Greater than 20 mm and 10 times max particle diameter of specimen	6 times diameter of largest particle of specimen
Diameter to height ratio (D/H)	2.5 (minimum)	2.5 (minimum)	2.5 (minimum)	2.5-4
Reference	Nash et al. 1992	Pitts et al. 1984	Rowe and Barden 1966	ASTM D2435–02 2003

Sazzad et al. 2014, conducted a numerical simulations using discrete element method (DEM) to investigate the effect of sample size on both the macro- and micro-scale responses of granular materials and compared successfully their results with experimental data in term of stress-strain curves. The investigation was made on three different tested samples of different sizes in a true tri-axial device. Sazzad et al. 2014, also found that the dilatancy index behaviour as well as coordination number are almost independent on the sample size. Chan et al. 2010, worked on three different geometries of soil specimens; D = 33, 40 and 50 mm keeping the same height-to-diameter ratio (D/H) of 2. Chan et al. 2010, conducted their experiments on the same soil type through BE mounted by same sensors. The measured shear wave velocities were found to be in concordance with the above constitutions. In other words, the sample size does not affect the measured shear wave velocity. In contrast, Fener 2011, reported that dimensions of rock sample significantly affect the measured primary wave velocities (P-wave).

A comparison of one-dimensional consolidation characteristics of clays with two different specimens sizes tested in the traditional oedometer device carried out by Kongkitkul et al. 2014, showed that the effect of sample size on consolidation parameters, such as compression index, swelling index, coefficient of consolidation, pre-consolidation stress, and compression modulus is negligible.

Moreover, Yamashita et al. 2009, presented an international parallel tests on the measurement of G_{max} using BE techniques were organized by the technical committee (TC29) of the international society of soil mechanics and geotechnical engineering (ISSMGE) in 2003, on Toyoura sand. Different geometries of Toyoura sand specimens were used along these parallel tests and a D/H ratio varies from 0.53 to 2.18 on dry and saturated conditions. Analysis and evaluation of tests indicated a slight difference among all results.

The general conclusion from the above mentioned review, that the validity of the shear wave velocity values determined from representative, high-quality, laboratory test specimens representing the actual field response may not depend on the size of the tested specimens.

In fact, it's worthy to mention that, there is an acceptable range for the distance between sensors to allow wave traveling between sensors and to avoid reflection. Reflections of waves at boundaries could generate complex output signal that cannot be interpreted easily. More specifically, it can be said that the travel distance between sensors and boundaries as well as their locations with respect to each other's has a great importance in the acquisition and the interpretation of the output signals.

3 P-RAT TECHNIQUE

P-RAT is considered as a promising alternative for laboratory determination of shear wave velocity of soils as it minimize/eliminate some difficulties (i.e., the mixed radiation of both P- and S-waves, near field effects, boundary effects, and uncertain detection of first arrivals) which may be associated with other techniques.

The current experimental investigation was done using the piezoelectric ring-actuator technique (P-RAT) which developed by University of Sherbrooke geotechnical research team (e.g., Gamal El Dean, 2007; Ethier, 2009 and Karray et al. 2015). As shown in Fig. 1, also the P-RAT apparatus consists of two piezoelectric rings incorporated in the traditional oedometer cell, first ring transmits the shear wave after converting the electrical voltage input and a receiver diffuses data to acquisition card.

Three different oedometer cells were used in this study. Table 2 summarizes the dimensions of the used cells (a, b, and c). It's important to mention that the initial D/H ratio was constant (D/H ≈ 3) among all the tested samples. In addition, two different sensors were used.

Cells (a) and (b) were mounted with identical sensors with dimensions: diameter (d = 20 mm) and thickness (h = 5 mm), while cell (c) was mounted with a larger sensor: (d = 42 mm) and (h = 5 mm).

Table. 2: different cell dimensions

Cell	D (mm)	H (mm)
a	63.45	19.1
b	100	33.3
c	282	89.4

4 TRANSFER FUNCTION IN P-RAT

Soil deformations produced during P-RAT or BE tests are very low ($\gamma<10^{-3}\%$) hence linear behavior for the surface deformations can be assumed. Figure 2 illustrates that the whole test can be conceived as a system correlating between the input and output signals. This system may then be decomposed into several connected subsystems as presented by Arroyo et al., 2003a for the transducer operation and sample transmission. The purpose for such decomposition is performing instance separation for the transmission through the sample and the dissipation of reflections (Arroyo, 2001, Karray et al 2015).

Santamarina and Fratta, (1998) stated that any dynamic linear subsystem or combination may be characterised in time domain by its unit response function or in the frequency domain by its transfer function. Hence, theoretically the soil sample can be treated as a dynamic system that can be evaluated based on its transfer function (TF).

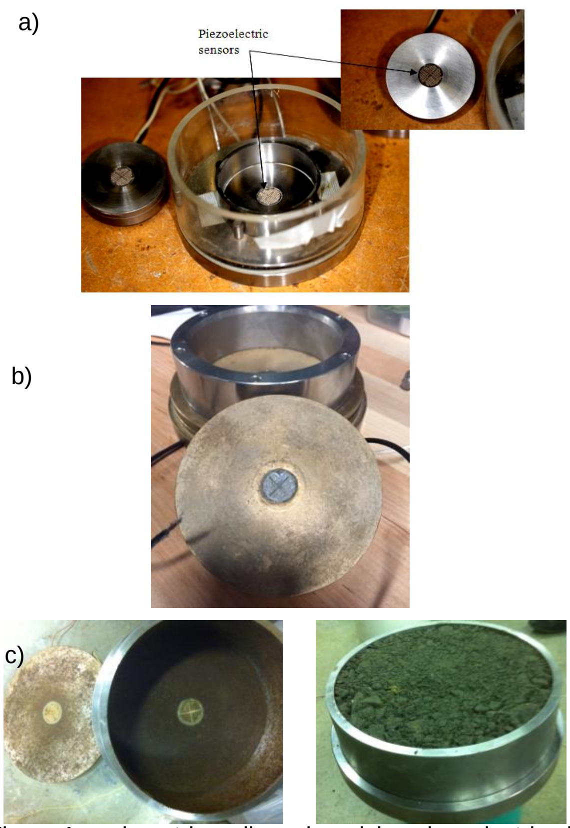

Figure.1 oedometric cell equipped by piezoelectric ring-actuator: a) Small cell, b) Medium cell, c) Large cell

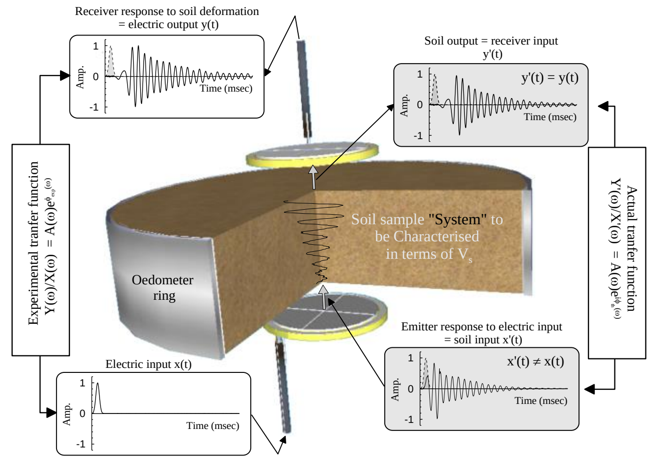

Figure 2. Schematic shape representing the experimental and actual transfer functions (Karray et al 2015).

TF in turn can be described in terms of amplitude $A(\omega)$ and phase $\theta(\omega)$; where ω is the angular frequency. To effectively evaluate TF of a certain system, it is necessary to compare the response of the system $Y(\omega)$ with respect to an input function $X(\omega)$. It is well known that for linear systems, TF will be independent of the input function $X(\omega)$.; therefore the TF of the soil would be independent on the adopted input function. In practice, TF ($A(\omega)$ and $\theta(\omega)$) of a soil sample is often evaluated based on the input signal $x(t)$ sent to the transmitter ($x(t)$ is different from the signal $x'(t)$ sent to the soil sample) and the output signal $y(t)$ from the receiver ($y(t)$ is different from the soil output signal $y'(t)$). The calculated TF ($Y(\omega)/X(\omega)$) therefor cannot be expected to account properly for the actual soil response as the experimental signal impregnates the responses of the transmitter and receiver dynamic systems.

To properly evaluate the actual TF ($Y'(\omega)/X'(\omega)$) of the tested soil, it is necessary either to have two perfect dynamic systems (emitter and receiver) that produce neither phase shift nor amplification (which is practically impossible except for a given frequency band) or to correct the TF with respect to the changes made by the sensors. In our case, we are interested in the velocity of shear waves, which can be estimated from the phase shift between the emitted and the received signals. It is therefore possible to determine a correction function of the phase shift caused by the transmitter-receiver system which allows for an evaluation of the true phase shift of the soil. The use of the P-RAT gives the opportunity to perform tests without soil sample (face-to-face) at different test conditions in order to determine the phase shift caused by the transmitter-receiver.

Technically, the sensors can be considered as a dynamic system that vibrates mainly in its own way so that the theoretical phase shift produced by one of the sensors pertain to a single degree of freedom (SDOF) system, and can be expressed by:

$$\phi = \tan^{-1}\frac{2\xi \omega/\omega_0}{1-\omega^2/\omega_0^2} \Leftrightarrow \phi = \tan^{-1}\frac{2\xi f/f_0}{1-f^2/f_0^2} \quad [1]$$

Where:

ϕ_i is the instrumental phase shift produced by the emitter or the receiver; ζ is damping ratio of the system; f_0 and ω_0 are respectively the fundamental and angular fundamental frequencies of the system.

With considering that the emitter-receiver system which used in the P-RAT is linear, the choice of the input signal may depend primarily on the frequency band to be generated. It would be necessary to use a signal whose frequency content is below f_0 in order to avoid the resonance of the sensors.

5 USED SOIL SAMPLES

To verify the assumption and reach the purpose of the present investigation, a series of tests was conducted on three sands: Péribonka sand (portion < 5 mm), the whole Péribonka sand and Champagne sand. The grain-size distribution curves of the tested soils are illustrated in Fig. 3.

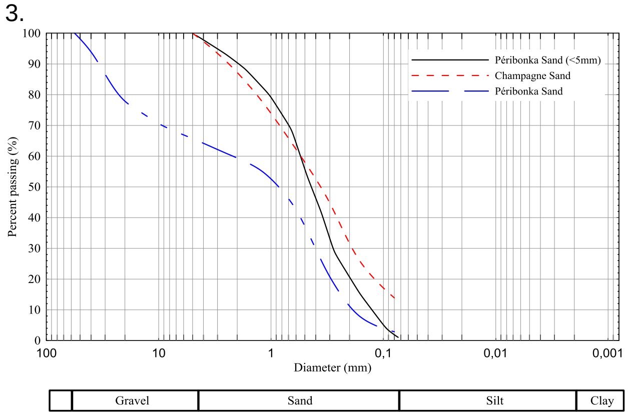

Figure 3. Grain-size distribution curves of the used soil samples

6 RESULTS AND DISCUTION

The experimental phase shifts of the emitter-receiver system obtained from the interpretation of signals were compared to the theoretical curves of 2 SDOF (emitter and receiver) systems in Figs. 4 and 5 for the small and large cells, respectively. Those Figures show that all instrumental phase shifts take the same trend with the theoretical curve for a resonant frequency of 40 kHz and damping ratio of 5% for the small cell and of 19 kHz and the same damping ratio for the large cell. The input signals were delivered to the transmitter elements generated by an arbitrary wave form generator card. Examples of the used input signals in both time and frequency domains are illustrated in Figs 4, respectively. These results confirm the assumption for the emitter-receiver system and prove that an increase of the diameter of piezoelectric ring produce a decrease of the resonant frequency of the sensor. An advantage of the P-RAT presented indirectly in Figs. 5 and 6, which is the high quality of the face-to-face test. These results prove also the ability of the P-RAT to evaluate characteristics of the used sensors with different geometries by conducting face-to-face tests. The latter conclusion makes the P-RAT works in different ranges of frequencies by simply adjusting sensors dimensions.

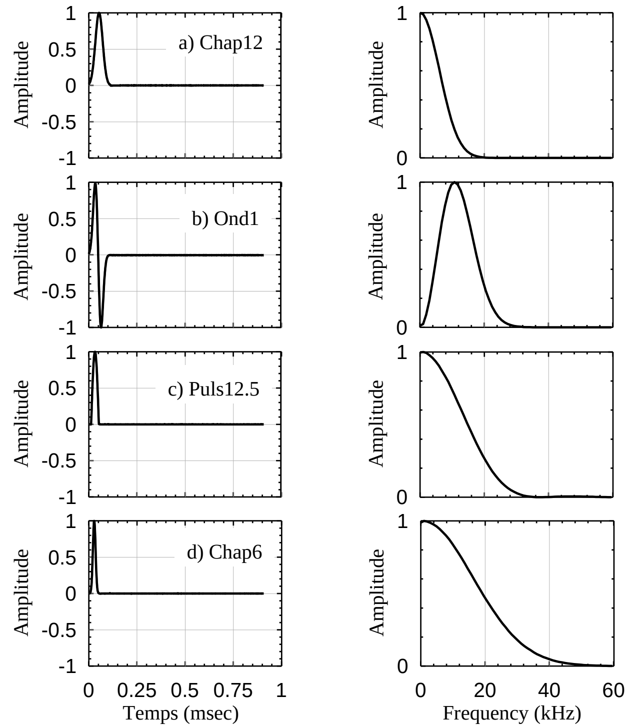

Figure 4. Examples of input signals: time and frequency domain.

Several investigations used the assumption of discretizing the soil-sensors to three subsystems and focused on evaluating a transfer function for each subsystem (e.g. Wang et al 2007). The results of their works have formed a considerable level of understanding the different transfer functions and also the effect of the distortion of emitter and receiver to the final output signals as well as their quality. Analytically (Cruse and Rizzo (1968), Sanchez-Salinero et al 1986) and experimentally (Wang et al 2007) investigated the attempt to define the transfer function of soil to assess the near field affects.

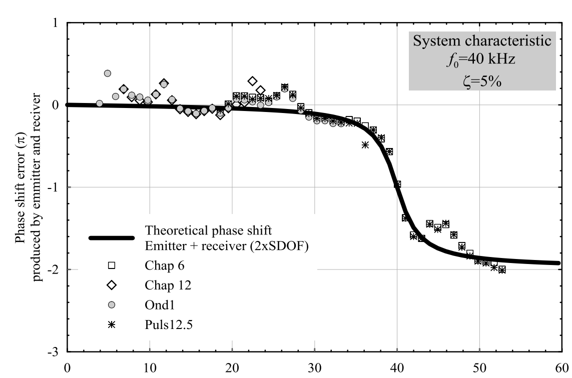

Figure 5. Comparison between the experimental phase shifts of the emitter-receiver system from a face-to-face test and the theoretical curve of 2 SDOF (emitter and receiver) systems for the small cell (no. a)

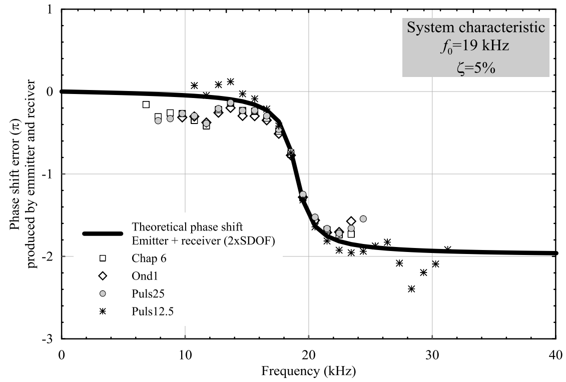

Figure 6. Comparison between the experimental phase shifts of the emitter-receiver system from a face-to-face test and the theoretical curve of 2 SDOF (emitter and receiver) systems for the large cell (no. c)

Figure 7 shows a comparison between normalized shear wave velocities of champagne sand in the small and medium cells. A slight difference between the V_{s1} values is observed. In discretizing the two systems, theoretically the same transfer function were used for all used sensors of the two cells (see figure 5). In other words, the two cells incorporated by the same sensors for the emitter and receiver. Same values of V_s prove that the transfer function didn't change in different sample size geometry. So it leads us to say that sample size does not affect the measures shear wave velocity.

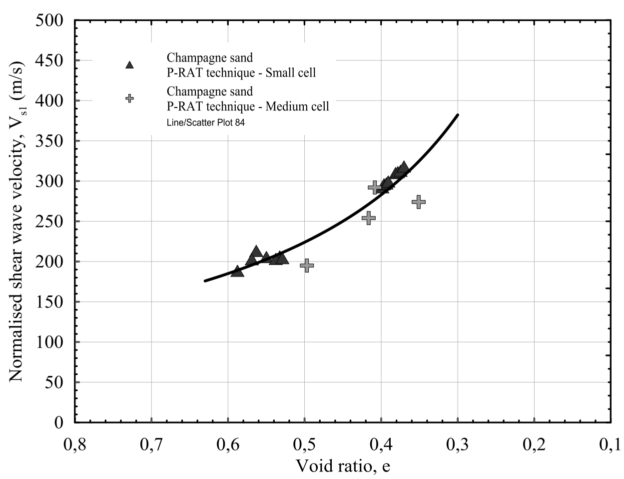

Figure 7. Normalized shear wave velocity as a function of void ratio of Champagne sand

Referring to the second group of tests on Péribonka sand, Fig. 8 illustrates that the measures normalized shear wave velocities, V_{s1} of specimens of the same soil (Péribonka sand) tested in different cells (small and large cells) at different initial void ratios (different tests) collapse onto the same trend. In these cases, different samples sizes were used but also different sensors geometries. In other words, two different dynamic systems are presented in Fig. 7 with different transfer functions. However, perfect matches between results have been achieved and this may attributed to the fact that the soil transfer function is unique even if tested in different cells in accordance with the assumption of soil linearity adopted in the development of P-RAT.

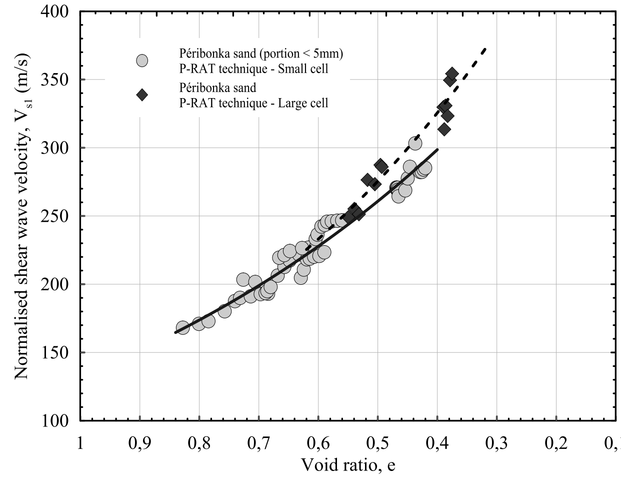

Figure 8. Normalized shear wave velocity as a function of void ratio of Péribonka sand.

It's also worth to mention that two different Péribonka samples were tested as illustrated in Figure 3. Cell (a) was used for portion (< 5 mm) while cell (b) for the whole granular fractions. Also 32 percent of granular curve of Péribonka sand is gravel so a correction should be done to the maximum and minimum void ratios. As a result of this correction, a shift were generated of the range of void ratio between the whole fractions of Péribonka sand and those < 5mm (from 0.35 - 0.85 to 0.26 - 0.56). An interesting conclusion could be made from the V_{S1}-e curve shown in Fig. 8 is that the normalized shear wave velocities for two samples has the same origin and particle shape are dependent on D_{50}, C_u and e_{min}-e_{max} range.

7 CONCLUSION

The effect of sample size on the measured shear wave velocity is investigated using the piezoelectric ring-actuator technique (P-RAT) developed at the geotechnical laboratory at Sherbrooke University. The P-RAT is a promising alternative for laboratory determination of shear wave velocity of soils as it minimize/eliminate the difficulties (i.e., the mixed radiation of both P- and S-waves, near field effects, boundary effects, and uncertain detection of first arrivals) associated with other techniques. The experimental results on different granular soils including Péribonka and Champagne sands tested in different odometer cells mounted with different sensor dimensions showed that the use of P-RAT in the determination of V_s could minimize the scaling effect. In other words, the transfer function of soil is found to be unique is a concordance with the assumption of soil linearity adopted in the development of P-RAT and other similar techniques such as BE.

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