ISSN 1644-0633
www.acta.media.pl

ACTA Acta Sci. Pol. Architectura 14 (1) 2015, 55–65

SMALL-STRAIN DYNAMIC CHARACTERIZATION OF CLAYEY SOIL

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Abstract. An appropriate evaluation of dynamic soil properties is important for proper seismic response analysis and soil modelling programs. The primary aim of this study was to investigate the dynamic properties of clayey soil from Warsaw area, taking into consideration some of the selected factors affecting the shear modulus (*G*) and the damping ratio (*D*) of examined samples. A series of resonant column tests were conducted to study the effect of applied pressure and shear strain amplitude on soil stiffness and its damping properties. These parameters were reviewed, investigated and discussed. On the basis of the results obtained from these tests as well as the theoretical analysis, it can be established that confining pressure and the range of considered strain had a significant influence on the dynamic shear modulus and on the dynamic damping ratio. The impact of stress level on *D* is also discussed.

Key words: small-strain stiffness, laboratory tests, resonant column apparatus

INTRODUCTION

Currently, there is a large number of tests in geotechnical engineering to classify soils dynamically. What distinguishes them are boundary conditions, the working strain amplitude and frequency [Brocanelli and Rinaldi 1998]. A comprehensive review with an emphasis on their applications and with comparison of their advantages and disadvantages is presented in Woods [1978] paper. Direct determination of seismic wave velocities in laboratory is becoming lately a common worldwide practice, given its great potential in determine soil's stiffness under small strains [Ferreira et al. 2013]. Although the small-strain shear modulus (G_0) can be determined under in-situ conditions from the shear wave velocity (V_S) measured in the field, it is rather difficult to obtain strain dependant curves of the shear modulus (*G*) and the damping ratio (*D*) directly on the basis of in-situ tests

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[Ishihara 1996]. At present, it is widely accepted by the engineers that the effects of various factors (e.g. confining pressure (σ_0) and shear strain (γ)) on *G* and *D* are primarily estimated through laboratory tests, such as resonant column (RC), cyclic triaxial (CTX), cyclic simple shear (CSS) or cyclic torsional shear (TS). These laboratory analyses not only provide the values of soil stiffness and damping properties, but also yield the variation of *G* and *D* with stress and strain [Liao et al. 2013]. One of the techniques for seismic wave measurement makes use of piezoelectric transducers, e.g. bender elements (BE).

The dynamically-measured shear modulus (G_0) is applicable to small strains ($<10^{-3}$%) and is believed to be an "elastic" soil property. It is widely used to evaluate the deformation of soil under dynamic loading arising from earthquakes or machine foundations. Burland [1989] in his work reported the importance of this parameter for static loading conditions. He observed that working strain levels in soils around well-designed structures are actually smaller than previously thought. Thereby, G_0 is recognized as the maximum shear stiffness, which applies to small strains within a complete stress-strain relation [Kim and Finno 2014].

Apart from the small-strain shear modulus, the damping ratio (*D*) is regarded as a key parameter for analysis of the dynamic behaviour of soil and rock subjected to various forms of vibrations and shaking. The damping ratio stands for the amount of energy lost in the cycle due to a hysteretic nature of the loop. In the area of small strains, where the shear modulus is practically constant and corresponds to its maximum value, the damping ratio responds to its minimum value, often expressed as the small-strain or the initial damping ratio (D_0) [Senetakis et al. 2012].

This paper contains the results of experiments received from resonant column tests on clayey soil from the area of Warsaw, the capital of Poland. The aim of this paper is to present dynamic properties in the wide range of strains, with a strong focus on small strains of the selected cohesive soils.

EXPERIMENTAL TECHNIQUE

The resonant column device is a laboratory apparatus, commonly used for the measurement of soils' dynamic properties. It provides a successful method of determining the shear modulus at small strain levels. Furthermore, this technique allows us to estimate the rate of stiffness degradation under increasing strain [Clayton 2011]. It can be applied at a wide range of strain levels ($10^{-5}\% < \gamma < 10^{0}\%$) and excitation frequencies ($30 \text{ Hz} < f <$ $< 300 \text{ Hz}$) [Khan et al. 2010]. There are different instrument configurations, including *RC*, which enable vibration of a soil specimen in torsion, in flexure and axially. In the case of torsional testing no bending effects have been observed. Therefore, it should be a preferred test method for stiffness evaluation [Clayton 2011].

Figure 1 shows a photograph of the resonant column device employed by the authors for the experiments discussed here. It is a Stokoe fixed-free type of resonant column, manufactured by British company GDS Instruments Ltd. An electromagnetic drive head, to which four magnets are attached, is bolted to the sample top cap. Magnets are held in place by a substantial support frame. Application of torsion takes place by electrically exciting the four coils with a driving voltage. Flexure is achieved by exciting only two

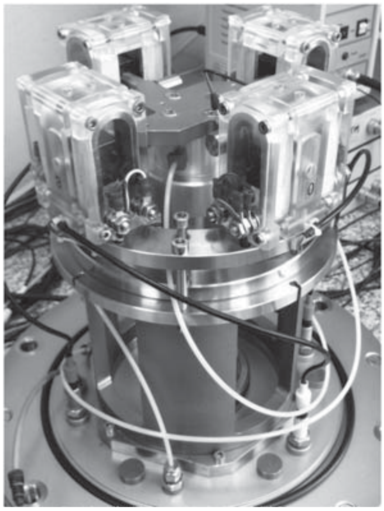

Fig. 1. Exemplary photograph of the resonant column device

diametrically opposed coils. At the start of the test a relatively low sinusoidal drive voltage is applied followed by a frequency sweep. In the following study, the corresponding coil voltage values began at 0.001 V and ended on the value of 1.0 V. It presents a maxima at certain frequencies (f_n), corresponding to the resonance frequencies of the soil. This procedure is shown in Figure 2. Initially, the peak amplitude, occurring during low levels of damping at the resonant frequency, is then being recorded. Knowing that the mass polar moment of inertia of the resonant column drive system was equal I_0 = 0.0035 during these tests, as well as the specimen's mass and its dimensions, while also assuming its linear elasticity, the small-strain shear modulus (G_0) of the examined soil can be calculated [Gabryś et al. 2013, Gabryś 2014].

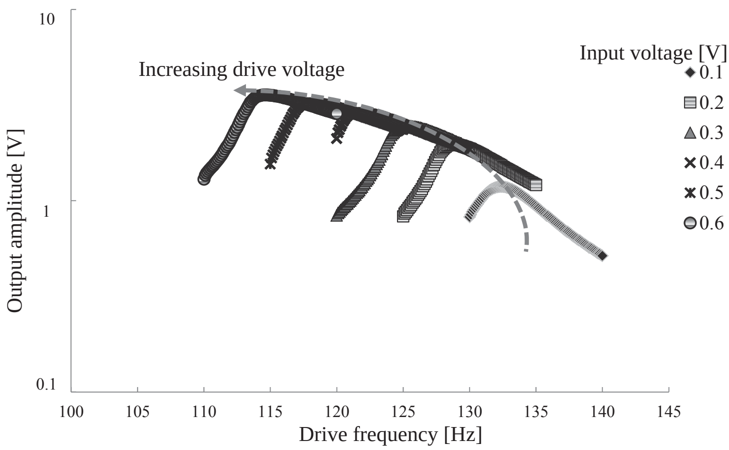

Fig. 2. Relationship between output amplitude and drive frequency by various values of input voltage

The measurement is then repeated for different driving voltages. Both, amplitude and strain, are increased. Primarily, at the lowest strain levels, which here were equal $\gamma \cong 10^{-5}$%, achieved by the small driving voltage, the resonant frequency is independent of the driving voltage. When shear strain (γ) increases, the soil stiffness decreases subsequently, entailing changes in the peak frequency of the system, which drops as a result (Fig 2). Based on the measurements, the shear modulus at small strains (G_0) and the stiffness degradation curve (Fig. 3) can be obtained.

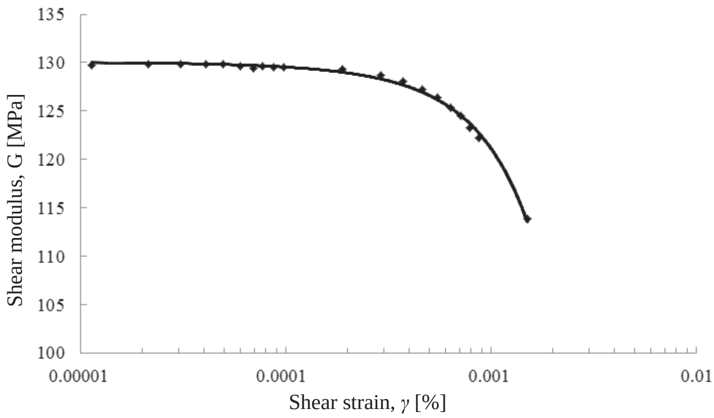

Fig. 3. An example of soil stiffness degradation curve

The conventional analysis of resonant column test results assumes an elastic system with zero damping for the evaluation of the shear modulus. The damping ratio (*D*) is computed independently from the shear modulus using the free vibration, half-power bandwidth method or transfer function technique. In the following work the authors employed the former method. More details of this technique are included in the references [ASTM–D 4015-92 2000, GDS 2010, Gabryś 2014]. The samples were excited between 2 and 10 seconds, after which the coils were switched off completely and the drive system was left to free vibrate. Each measurement was repeated between 10 and 50 cycles. The resulting in damping curves were calculated and the average result of all the damping ratios was estimated.

Tests in RC can be conducted under isotropic effective stress conditions (in the Stokoe type apparatus) or under anisotropic effective stress conditions (in the Hardin type). In this study, the soil was consolidated to predetermined isotropic stress. In every test, an isotropic effective confining pressure was applied in several separate steps (namely at 85, 170, 225 and 310 kPa). The maximum mean effective stress applied was equal to 310 kPa, due to the equipment's limitations. The advantages of the Stokoe apparatus include – the relatively simple piece of equipment and the possibility of the application of high levels of torque, thus exploring a greater torsional strain range [Clayton 2011]. Other details of the instrumentation used by the authors can be found in many sources e.g. in their publication [Sas and Gabryś 2012].

TEST RESULTS

Identification of research material

In this study, a type of silty clay from the Warsaw area was analysed. Samples in this research were obtained from the test site located at the streets Jana Pawła II and Grzybowska, exactly from the centre of Warsaw, district Śródmieście. Figure 4 shows the location of the study in Google Maps. The testing material was selected carefully considering the uniformity of the soil structure, its physical properties and its double-phase. High quality specimens were extracted from the depth approximately of 8.5 m with a thin-walled aluminium tube sampler. The grain-size distribution curve of the analysed samples is presented in Figure 5 and their basic soil properties are summarized in Table 1.

Fig. 4. Approximate sampling site location as seen in Google Maps

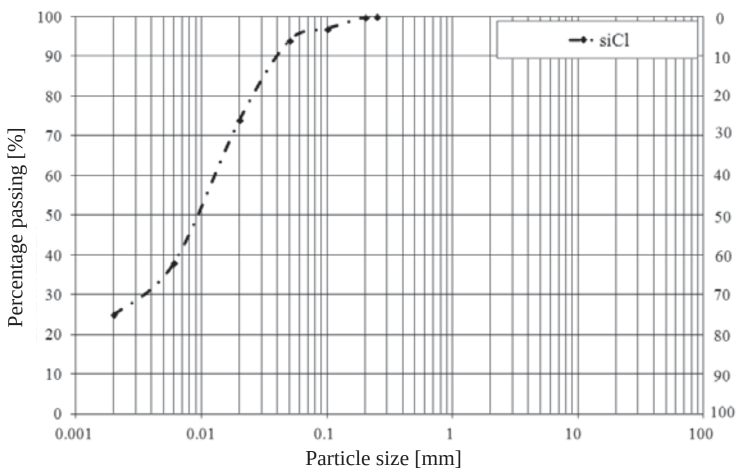

Fig. 5. Grain size distribution of tested specimens

Table 1. Initial physical properties of the soil specimen from Warsaw centre

Description	Unit	Value
Diameter	mm	70
Length	mm	140
Total mass	g	1096.2
Water content	%	20.68
Specific gravity of solids	$g\cdot cm^{-3}$	2.67
Bulk denisty	$g\cdot cm^{-3}$	2.06
Void ratio	–	0.57
Plasticity Index	–	0.12

Laboratory test results

Various laboratory analyses were conducted on the soil samples. In this article, however, the authors limit themselves to the discussion of the results from resonant column tests. To simplify the discussion, the experiments were divided into two groups, A and B. Group "A" corresponds to dynamic tests and torsional excitation. Group "B" concerns damping tests. Resonant frequencies at low shear strain ($\leq 10^{-3}$%) were measured at different confinement levels. The experiments at each confinement level were repeated until two consecutive measurements showed no change in the resonance frequency. The damping ratio was also studied with the torsional resonant frequency. A summary of results obtained from each type of tests is shown in Tables 2 and 3. All the formulas necessary to compute shear wave velocity (V_S), the shear modulus (G) and shear strain (γ) were thoroughly discussed in other publications [Sas and Gabryś 2012, Gabryś 2014].

Table 2. Selected results of torsional analysis of silty clay from Warsaw centre

Mean effective stress p' [kPa]	Input voltage – [Volt]	Resonant frequency f_r [Hz]	Shear wave velocity V_S [$m\cdot s^{-1}$]	Shear modulus G [MPa]	Accelerometer – [milivolt]	Shear strain γ [–]
1	2	3	4	5	6	7
85	0.001	89.6	187.08	71.04	18.09	0.000026
85	0.005	89.4	186.66	70.73	55.39	0.000079
85	0.01	89.2	186.24	70.41	107.58	0.000154
85	0.05	87.2	182.06	67.29	461.03	0.000692
85	0.1	82.8	172.88	60.67	747.69	0.001245
170	0.001	109.6	228.83	110.30	14.79	0.000014
170	0.005	109.3	228.21	109.72	63.10	0.000060
170	0.01	110.0	229.67	109.98	123.36	0.000116
170	0.05	110.4	230.50	107.86	567.99	0.000532
170	0.1	107.5	224.45	102.27	996.38	0.000984
255	0.001	119.5	249.50	129.77	14.22	0.000011
255	0.005	119.2	248.88	129.84	61.90	0.000050
255	0.01	121.0	256.35	129.56	124.76	0.000097

Table 2, cont.

1	2	3	4	5	6	7
255	0.05	119.9	250.34	127.22	582.55	0.000463
255	0.1	117.5	245.33	122.18	1050.85	0.000869
310	0.001	135.3	282.49	162.00	15.52	0.000010
310	0.005	135.2	282.28	161.76	67.56	0.000042
310	0.01	135.1	282.07	161.52	133.19	0.000083
310	0,05	134.3	280.40	159.61	637.11	0.000403
310	0.1	132.4	276.44	155.13	1184.43	0.000771
310	0.2	128.8	268.92	146.81	1967.09	0.001354
310	0.3	125.5	262.03	139.38	2451.13	0.001777
310	0.4	121.8	254.31	131.28	2893.55	0.002227
310	0.5	118.1	246.58	123.43	3257.28	0.002666
310	0.6	114.7	239.48	116.42	3571.97	0.003100
310	0.7	112.8	235.51	112.60	3807.44	0.003416
310	0.8	109.3	228.21	105.72	4037.13	0.003858
310	0.9	106.4	222.15	100.18	4242.83	0.004279
310	1	103.5	216.10	94.80	4439.29	0.004731

Table 3. Selected results of damping analysis of silty clay from Warsaw centre

Mean effective stress	Input voltage	Shear strain	Mean damping ratio
p' [kPa]	– [Volt]	γ [–]	*D* [%]
1	2	3	4
85	0.005	0.000079	1.70
85	0.01	0.000154	1.74
85	0.05	0.000692	2.14
85	0.1	0.001245	2.86
170	0.005	0.000060	1.54
170	0.01	0.000116	1.58
170	0.05	0.000532	1.81
170	0.1	0.000984	2.08
255	0.005	0.000050	1.50
255	0.01	0.000097	1.56
255	0.05	0.000463	1.80
255	0.1	0.000869	2.07
310	0.005	0.000042	1.35
310	0.01	0.000083	1.40
310	0,05	0.000403	1.59
310	0.1	0.000771	1.73
310	0.2	0.001354	2.03

Table 3, cont.

1	2	3	4
310	0.3	0.001777	2.33
310	0.4	0.002227	2.63
310	0.5	0.002666	3.12
310	0.6	0.003100	3.62
310	0.7	0.003416	3.86
310	0.8	0.003858	4.11
310	0.9	0.004279	4.39
310	1	0.004731	4.78

Results of the variation of soil stiffness at four different types of effective pressures are shown in Figure 6. It can be noticed on its basis that the shear modulus presents an overall growth with increasing confining pressure. Confining pressure, or differently mean effective stress (*p*'), is recognized as one of the most important factors influencing the shear modulus. The highest value of the shear modulus was obtained for the highest mean effective stress (i.e. equal to 310 kPa) and the smallest value for the smallest one (*p*' = 85 kPa). It can be observed that the shear modulus versus shear strain reduction curve plots higher with the increase in confining pressure. The difference in the values of *G*, at highest and lowest pressure states, was equal to 90 MPa at the smallest strain ($\gamma \cong 10^{-5}$%).

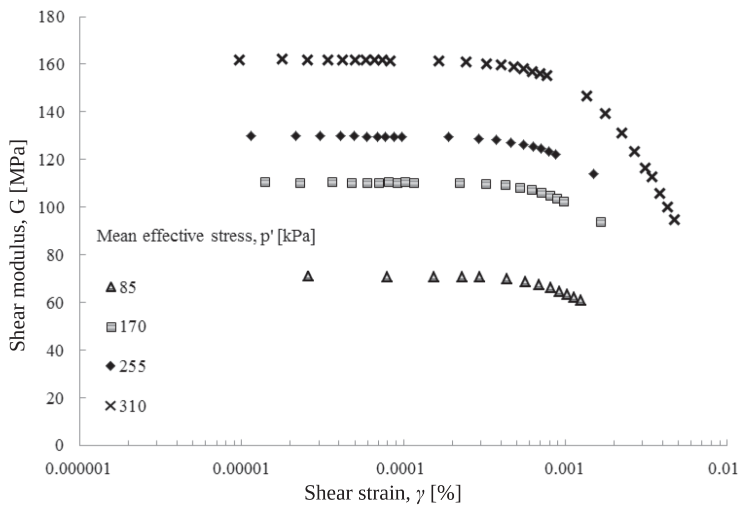

Fig. 6. Degradation of shear modulus with increasing shear strain

As it is already known, the shear modulus decreases as shear strain rises, which is confirmed by the illustration presenting the results in Figure 6. In this figure, an effect of strain range on the soil stiffness distribution is clearly noticeable.

The initial value of the shear modulus (G_0, measured at lowest shear strain) as presented in Figure 6, is its maximum value (G_{max}) and corresponds to the elastic soil behaviour. It is measured at strain levels of approximately 10^{-5}–10^{-3}%. For strains above $\gamma > 4.0 \cdot 10^{-4}$%, the value of the shear modulus begins to decline gradually. This mentioned value of γ will be the linear cyclic threshold shear strain (γ_{tl}). Below it soil behaves as a perfect linearly elastic material and the shear modulus remains constant with the increase in shear amplitude. According to the literature, for $\gamma < 10^{-5}$ the effect of shear strain on shear modulus is negligible.

After applying torsional resonance and conducting the resonant frequency for G_0 and G_{max}, damping tests were carried out to measure the damping ratio (D) corresponding to said resonant frequency. The damping ratio seems to be affected by fewer factors than the shear modulus [Kokusho et al. 1982]. The authors of the article, however, verified the impact of only two selected factors, namely of confining pressure and shear strain on the damping ratio (D) of the soil. Therefore, in Figure 7 the relationship between the damping ratio and shear strain is shown. From it, one can see that the damping ratio of the examined soils increases continuously with strain amplitude. The measured value of the damping ratio ranges from approximately 1.3% until nearly 5.0%. During the analysis of the data presented in this figure, some influence of mean effective stress on damping ratio can also be noticed. For the same level of strain, the damping ratio decreases monotonically with mean effective stress. This effect becomes more noticeable at higher values of strain. Yet, the observed changes in D are rather small, being in the range of 0.4–0.5% at $\gamma = 10^{-4}$%, and hence further studies of this topic are required. These differences in the damping ratio values increase with shear strain.

In Figure 7 the variation of the damping ratio for the wide range of strain is presented. In general, the damping ratio of the analysed soils increases continuously along with increasing strain amplitude.

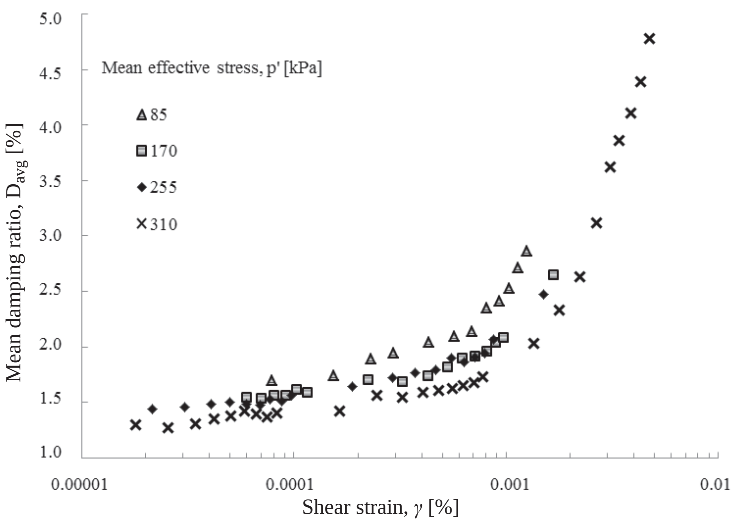

Fig. 7. Strain dependant damping ratio

CONCLUSIONS

In the presented work, the authors studied the behaviour of silty clay from the Warsaw area, under dynamic conditions. The results allowed for the following conclusions to be drawn:

1. The resonant frequency increases with the increase in mean effective stress. The rate of increase is higher at low stresses.

2. The increase of both, confining pressure and mean effective stress, causes the increase in the soil stiffness. As confining pressure increases, the modulus reduction curve shifts to a higher position.

3. The shear modulus dependence on stress levels is strongly non-linear.

4. The threshold level for strain effect is near $4.0 \cdot 10^{-4}$%. When the amplitude of motion is below this value, the shear modulus is independent of strain amplitude. A rapid decrease in shear modulus values occurs when strain exceeds $4.0 \cdot 10^{-4}$%.

5. The damping ratio for examined cohesive soil increases constantly with shear strain.

6. The damping ratio slightly decreases with the rise of confining pressure. This effect becomes more evident for higher strains .

The authors recognize that the conclusions drawn are limited to the type of soil and particular conditions of this experimental work. They expect that the effects reported in the following work will stimulate further research on the dynamic properties of clayey soil from Warsaw area.

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DYNAMICZNE WŁAŚCIWOŚCI GRUNTÓW SPOISTYCH W ZAKRESIE MAŁYCH ODKSZTAŁCEŃ

Streszczenie. Odpowiednia ocena dynamicznych właściwości gruntu jest niezwykle ważnym elementem przy analizie reakcji gruntu poddanego obciążeniom sejsmicznym, jak również z punktu widzenia różnych programów do modelowania zachowania się gruntu w złożonych warunkach obciążenia. Głównym celem tej pracy było zbadanie właściwości dynamicznych gruntów ilastych z okolic Warszawy, biorąc pod uwagę kilka wybranych czynników wpływających na wartość modułu sprężystości poprzecznej (G) i wskaźnik tłumienia (D) badanych próbek. Przeprowadzono wiele badań w kolumnie rezonansowej, aby sprawdzić wpływ zadanego ciśnienia w komorze i amplitudy odkształcenia postaciowego na sztywność badanych gruntów oraz ich właściwości tłumiące. Na podstawie uzyskanych wyników badań i przeprowadzonych analiz teoretycznych stwierdzono, że zarówno ciśnienie otaczające próbkę w komorze, jak i zakres rozpatrywanych odkształceń miały znaczący wpływ na dynamiczny moduł sprężystości poprzecznej i na dynamiczny wskaźnik tłumienia. Autorzy zalecają kontynuację badań wpływu średniego naprężenia efektywnego na wskaźnik tłumienia.

Słowa kluczowe: sztywność w zakresie małych odkształceń, grunty ilaste, badania laboratoryjne, kolumna rezonansowa

Accepted for print: 28.04.2015

For citation: Gabryś, K., Sas, W., Soból, E. (2015). Small-strain dynamic characterization of clayey soil. Acta Sci. Pol., Architectura, 14 (1), 55–65.