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Wojciech SAS*, Emil SOBÓL**, Katarzyna GABRYŚ*, Katarzyna MARKOWSKA-LECH*

Study of the cohesive soil stiffness in a modified resonant column

Abstract: The expansion of cities encourages designers and engineers to build increasingly sophisticated skyscrapers and underground structures. Such complicated projects require more reliable soils parameters. Dynamic parameters of the soils are commonly used for the purposes of civil engineering design. The resonant column is one of the most reliable devices allowing the above-mentioned soil properties to be obtained.

In this article, the authors studied a dynamic parameter shear modulus G of the cohesive soil clayey sand. Researchers conducted their own examination, using a modified resonant column, which is equipped with bender elements and a torsional shear device. The studied material was an undisturbed cylindrical sample of the cohesive soil clayey sand (clSa) from a depth of 6 m from the village of Kociszew. In order to calculate the maximum shear modulus, the authors have employed two types of time-domain techniques to measure shear wave velocities, namely the first peak to peak and start-to-start methods. In bender elements test authors investigate shear wave velocity in a range of period from 0.01 to 0.1 ms and 14 V amplitude, which gave a wave length from about 0.1 to 3.5 cm. In the case of torsional shear tests, researchers examined ten cycles of sinusoidal torsional excitation with 1 Hz frequencies and amplitude from 0.004 to 1 V. The research performed indicated that the results obtained by using the torsional shear and first peak to peak methods are in very good agreement, while the overestimation of the results obtained by using the start-to-start method reached up to 27%.

Keywords: resonant column, cohesive soil, shear modulus, torsional shear, bender elements

Badanie sztywności gruntu spoistego w zmodyfikowanej kolumnie rezonansowej

Streszczenie: Rozwój miast wymusza na projektantach i wykonawcach budowanie coraz wyższych wieżowców, a także coraz bardziej skomplikowanych konstrukcji podziemnych. Dla tak wyrafinowanych projektów potrzebne są jak najbardziej wiarygodne parametry gruntowe. W dzisiejszych czasach inżynierowie powszechnie korzystają

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* Ph.D., Department of Geotechnical Engineering, Water Centre Laboratory, WULS–SGGW, Warsaw; e-mail: emil_sobol@sggw.pl

** M.Sc., Department of Geotechnical Engineering, Faculty of Civil and Environmental Engineering, WULS–SGGW, Warsaw.

z dynamicznych parametrów gruntu. Jednym z najpopularniejszych i jedocześnie najbardziej wiarygodnych aparatów do uzyskiwania wspomnianych wyżej właściwości jest kolumna rezonansowa.

W tym artykule autorzy zbadali dynamiczny parametr jakim jest moduł ścinania. Badania zostały przeprowadzone na nienaruszonej cylindrycznej próbce piasku ilastego (clSa), która pochodziła z 6 m głębokości z miejscowości Kociszew. Autorzy prowadzili badania w zmodyfikowanej kolumnie rezonansowej, która wyposażona jest zarówno w piezoelementy rodzaju bender jak i urządzenie do ścinania skrętnego. Użyto dwóch metod do interpretacji sygnału w odbiorniku w testach piezoelementami rodzaju bender, mianowicie technikę „pierwszego szczytu" i metodę „od startu do startu". W testach elementami bender przebadano fale porzeczne o okresie około 0,01 do 0,1 ms i amplitudzie 14 V, co przełożyło się na długość fal od około 0,1 do 3,5 cm. W badaniu ścinania skrętnego użyto 10 cykli sinusoidalnego wzbudzania o częstotliwości 1 Hz i amplitudzie od 0,004 do 1 V. Z przeprowadzonych badań wynika, ze wyniki uzyskane metodą „pierwszego szczytu" pokrywały się z tymi uzyskanymi za pomocą ścinania skrętnego, natomiast metoda „od startu do startu" zawyżała wyniki nawet do 27%.

Słowa kluczowe: kolumna rezonansowa, grunt spoisty, moduł ścinania, ścinanie skrętne, piezoelementy rodzaju bender

Introduction

In geotechnics, several laboratory techniques have been developed throughout the years, in order to measure shear modulus or shear wave velocities. Such techniques include: the resonant column (RC) test (Gabryś et al. 2015), the quasi-static loading test with high resolution strain measurements (Głuchowski et al. 2015) and the bender elements (BE) test (Sas et al. 2016). Dyvik and Madshus (1985) proposed and reported the inclusion of the BE for measuring the propagation of shear waves in soil samples during geotechnical laboratory tests. By observing the input and output signals during the BE test, shear wave velocities V_s can be calculated on the basis of the following equation:

$$V_s = \frac{L_t}{\Delta t} \tag{1}$$

in which L_{tt} stands for the wave propagation distance, which is the distance between the source and the receiver, and Δt stands for the wave travel time (Gu et al. 2015). With the value of V_s being known, the G_0 can be evaluated as follows:

$$G_0 = \rho V_s^2 \tag{2}$$

With ρ being the volumetric density involved in the wave propagation.

The main reason behind many discussions concerning the BE tests is the attempt to establish which signal interpretation method provides the most reliable results and which test conditions should be taken into consideration during the result validation process. Lee and Santamarina (2005) showed that choosing is not only a proper method for interpreting the BE tests important, but also that various aspects of bender element installation, including: electromagnetic coupling, directivity, resonant frequency and near field effect, should also be taken into consideration. Other factors, such as signal-to-noise ratio, and a wave path length to wavelength ratio have been investigated by Leong, Yeo and Rahardjo (2005). They reported that for the signal and interpretation of the bender element test to improve, the signal-to-noise ratio should be at least 4 dB and the wave path length (L) to wavelength (λ) ratio should be at least 3.33. Godlewski and Sczepański (2015) confirmed Leong, Yeo and Rahardjo's research. Kumar and Madhusudhan (2010) measured the wave time travel by using three different methods, however the said methods, namely the first arrival time, the cross-correlation and the first peak to peak method, were related to the time domain. They reported that the main difficulty in correct result interpretation is caused by the near field effect, which can be reduced by increasing the frequency of the input signal. They generated a wave, L/λ ratio of which ranged from 2.44 to 4.10. Aside from the methods of interpretation and the L/λ ratio, Chan (2012) examined the impact of the input wave frequency, specimen geometry and the near field effect. He observed that the best quality signal occurred when the input frequency was kept high enough to achieve $\lambda/D_{50} \geq 5$ (D_{50} – grain diameter with 50% material passing on the particle size distribution curve). In order to ensure the accurate definition of the average shear wave velocity propagation through a soil specimen, he also recommended the sample height should to be equal at least 10 times the value of D_{50}. In additional, Chan proved that keeping the L/λ ratio between 2 and 4 reduces the near field effect.

Difficulty with the interpretation of the signal produced by the piezoelectric elements forced the scientists to compare shear wave velocities obtained from the BE test with those obtained by using a different laboratory technique, thus allowing the shear modulus to be acquired. Youn, Choo and Kim (2008) used a modified resonant column (RC) with BE and torsional shear (TS) equipment to compare the results of three different laboratory techniques using the same sand sample. Researchers used the time domain method to evaluate the V_s during the BE tests and calculated the $G_{\max}$ value witch was related to obtained $G_{\max}$ value from the RC and TS research. It turned out that in dry conditions values from all three tests were in good agreement, but upon the sample's saturation, more discrepancies appeared in the results. Gu and his research team (2015) researching the possible methods of interpretation and confirmation of the BE test results. In 2015, they examined dry and saturated sand specimens, by using four time domain methods, to determine wave velocities and compare the results of the RC and TS tests. It turned out that the first arrival time technique provided the best results from all the four time domain methods. The $G_{\max}$ values obtained from the BE, RC and TS tests are also consistent with each other under both dry and saturated conditions as long as the effective density (defined as related to the fraction of pore water that moves with the soil skeleton during shear wave propagation Qiu and Fox 2008) is used in BE tests.

In this article, the authors will present results of the shear wave velocity measurement by using a BE test. Moreover, the authors compared a designated $G_{\max}$ value obtained from the BE test to a small shear modulus obtained from the hysteresis loop during a TS test. Conclusions were drawn on the basis of the conducted research.

1. Test equipment, material and procedure

1.1. Test equipment

In this study, the authors used a modified Stokoe fixed-free type of resonant column. The scheme of the employed device can be seen in figure 1. The largest advantage of the described RC is that the BE and TS tests can be simultaneously carried out on identical specimens, which can surely improve the reliability of the test results. A detailed blueprint and description of this device can be found in the authors' other publication (Soból et al. 2015; Gabryś et al. 2015).

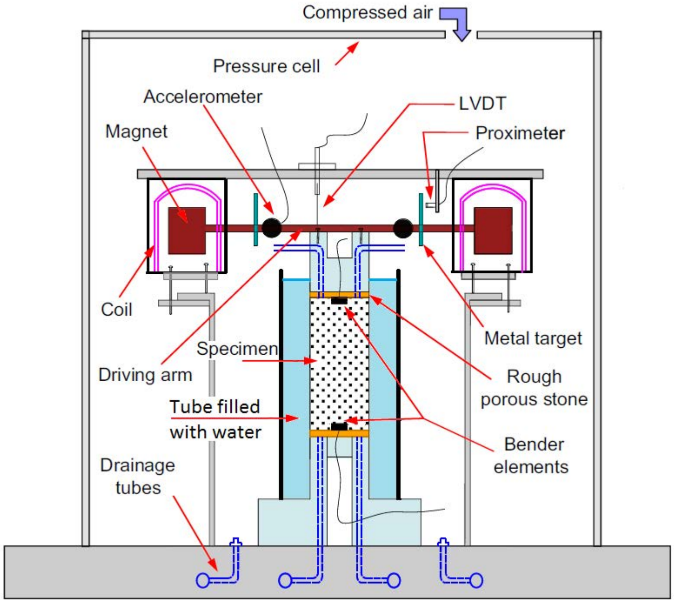

Fig. 1. Schematic illustration of the resonant column apparatus with bender elements and torsional shear device used in the study (not to scale), based on (Gu et al. 2015)

Rys. 1. Schemat kolumny rezonansowej wyposażonej w element bender i aparat ścinania skrętnego (nie w skali), na podstawie (Gu i in. 2015)

The BE, which have also been provided by GDS were installed in the said resonant column apparatus in the top cap and pedestal. Those bender elements are made from piezoelectric ceramic bimorphs. A sinusoidal shear wave is produced by a displacement in the top cap source transducer due to the applied excitation voltage from 1 to 14 V. Sending a shear wave creates a displacement in the pedestal receiver, which creates a voltage that can be measured. A detailed specification regarding the device and the generation of the shear wave and compression wave by the discussed bender elements can be found in (Sas et al. 2016).

During a torsional shear test, the sample is set in small cyclic torsional motion due to the coil-magnet system and shear stress is calculated from the torque generated by magnets. The shear strain level is determined from the sample twist angle, measured by a proximitor. The shear strain can be manipulated by applying voltage to the coil, ranging from 0.004 to 1 V, which generated a shear strain ranging from 0.0001% to 0.003%.

1.2. Test material

A cohesive soil sample was collected from a spot located at the depth of 6m, in the area of a village called Kociszew was used to examine wave velocities and the value of shear modulus. The soil used during tests, which is of Quaternary origin, was sampled in an undisturbed state using a standard Shelby tube. Next, a very carefully cylindrical specimen with 140 mm in height and 70 mm in diameter was cut from an undisturbed Shelby core. An aerometric analysis was performed in order to investigate the grain size distribution in the tested material. Figure 2 presents the results of said test.

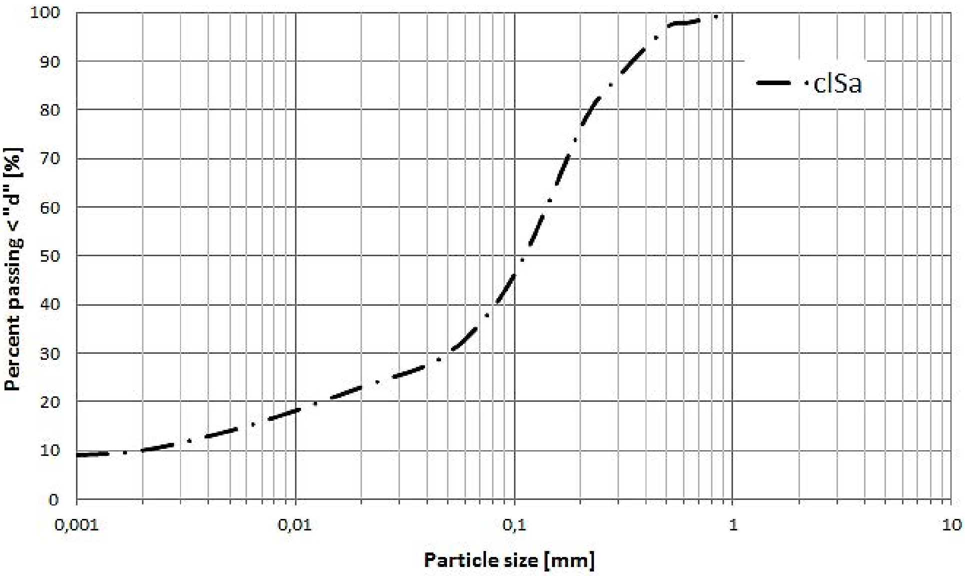

Fig. 2. Grain distribution curve of the tested soil

Rys. 2. Krzywa uziarnienia badanego gruntu

According to (PN-EN ISO 14688-1:2006), the soil examined by the authors was clayey sand (clSa). In order to estimate the basic physical properties of the tested soil, standard tests, such as a plastic limit and the fall cone liquid limit test were employed. The results of the physical properties study are presented in Table 1.

TABLE 1. Basic properties of the tested soils

TABELA 1. Podstawowe właściwości badanego gruntu

Parameter	clSa
	Value
w [%]	11.05
w_P [%]	11.10
w_L [%]	17.11
I_P [%]	6.01
I_L [–]	–0.01
I_C [–]	1.06
ρ [kg/m^3]	2 230

Explanations: w is the water content; w_P is the plastic limit; w_L is the liquid limit; I_P is the plastic index; I_L is the liquidity index; I_C is the consistency index; and ρ is the mass density.

1.2. Test procedure

After inserting the sample in the resonant column, the specimen was flushed with de-aired water. Back pressure was applied to ensure the saturation of the sample. When the Skempton parameter reached 0.90, the saturation process was considered to be completed. The soil sample prepared in such way was subjected to consolidation at isotropic effective confining pressures of: 60, 120, 240, 360 and 430 kPa. BE and TS tests were performed at each stage of the consolidation.

Two time domain methods were employed in order to designate wave velocities, namely the start to start (the first arrival time) and first peak to peak techniques. The interpretation technique used in this paper is presented in Figure 3.

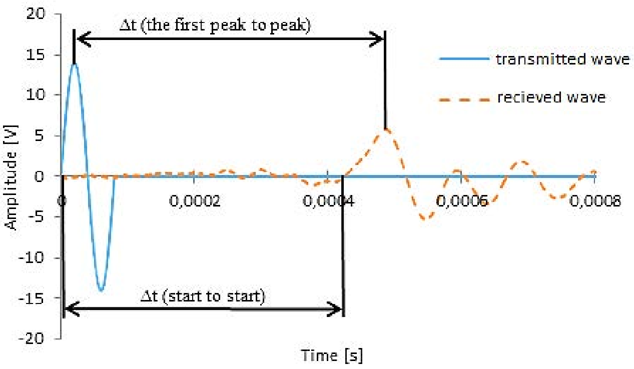

Fig. 3. Identification techniques of travel time in the time domain method used in the study

Rys. 3. Techniki identyfikacji czasu propagacji fali poprzecznej w dominie czasu użyte w badaniach

Researchers generated sine shear wave in range of period from 0.01 to 0.1 ms and 14 *V* amplitude. The wave periods used allowed the *L*/λ ratio ranging from 4 up to 70, to be achieved. The near field effect was greatly reduced by high input frequencies. Signal-to-noise ratio was kept by the authors above the level of 4 dB during bender element tests, which also improved the reliability of the results. In order to examine the stiffness of the clayey sand, the authors used the Equation 2.

To compare the shear modulus calculated on the basis of the bender element tests, torsional shear studies were performed by the authors on the same specimen. Ten cycles of the sinusoidal torsional excitations with 1 Hz frequency were applied to the sample. Shear modulus was calculated on the basis of the equation 3 (Kim 2015):

$$G = \tau / \gamma \tag{3}$$

in which τ stands for the maximum shear stress and γ stands for the maximum shear strain, registered during the tenth excitation cycle hysteresis loop (figure 4). To obtain the shear modulus degradation curve, the amplitude of applied excitation was manipulated from 0.004 to 1 V.

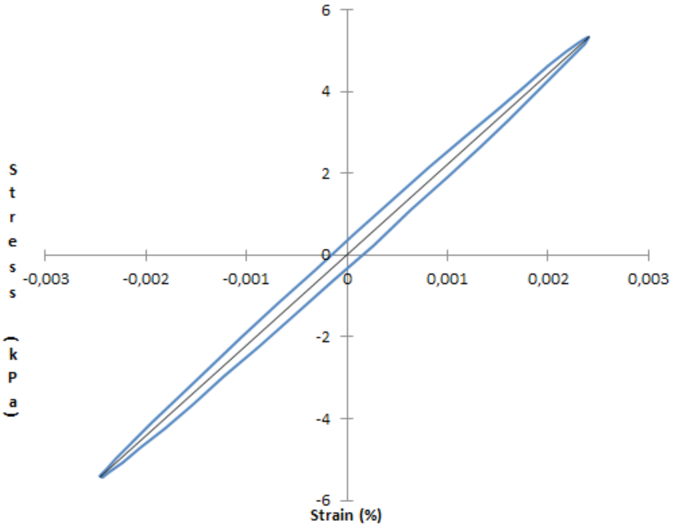

Fig. 4. Tenth excitation cycle hysteresis loop obtained from the torsional shear test

Rys. 4. Pętla histerezy otrzymana z dziesiątego cyklu badania ścinania skrętnego

2. Results

2.1. Bender element test results

In Figure 5, the variation of the measured shear wave velocity (V_S) with a predetermined period of propagation wave at different specified stress levels is shown. The first peak to peak method was used to designate the wave velocity.

Results of investigation presented in Figure 5 indicate that differences between the measured shear waves velocity values are not significant, but the wave velocities in the period between 0.01–0.02 (marked by rectangle) are slightly smaller and nearly identical at every effective stress level. The length of the waves passing through the sample, depending on the

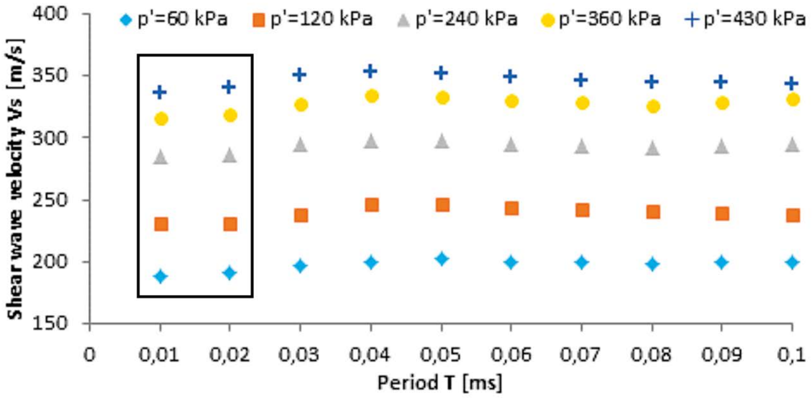

Fig. 5. Variation of the measured V_S with the period, the first peak to peak method

Rys. 5. Zmienność pomierzonej prędkości V_S w zależności od okresu fali, metoda pierwszego szczytu

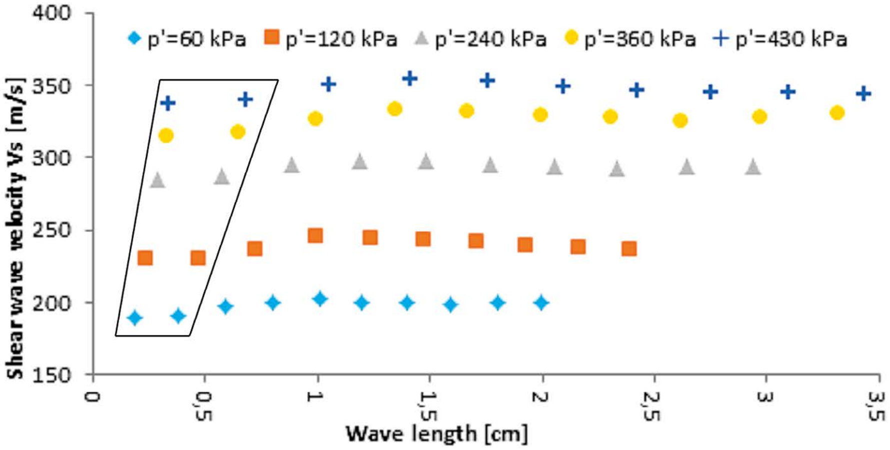

Fig. 6. Variation of the measured V_S with the wave length; the first peak to peak method

Rys. 6. Zmienność pomierzonej prędkości V_S w zależności od długości fali, metoda pierwszego szczytu wave's velocity at various effective stress levels can be observed in Figure 6. Points marked in Figure 6 presented the same waves as points selected in Figure 5. The period between 0.01 and 0.02 ms provided the shortest wave length.

Figures 7 and 8 present the same relationship as Figures 5 and 6, but for the start to start method. In contrast with the first peak to peak method, a disagreement between wave velocity values at different periods is more noticeable. Waves in the period between 0.01 and 0.02 ms are not in good agreement, as it was at first peak to peak technique. The smallest difference can be seen in the wave period between 0.03 and 0.04 ms.

Similarly to the first peak to peak method, the marked points in both figures referring to the start to start technique denote a single wave. No trend for changes in wave velocities presented in Figures 7 and 8 could be found, however the biggest disagreements occurred at the 430 kPa effective stress value. Moreover, each measured wave displayed a L/λ

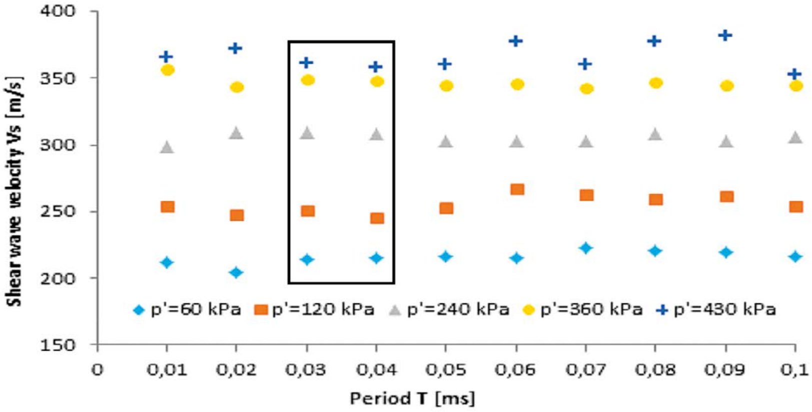

Fig. 7. Variation of the measured V_S with the period; the start to start method

Rys. 7. Zmienność pomierzonej prędkości V_S w zależności od okresu fali, metoda od startu do startu

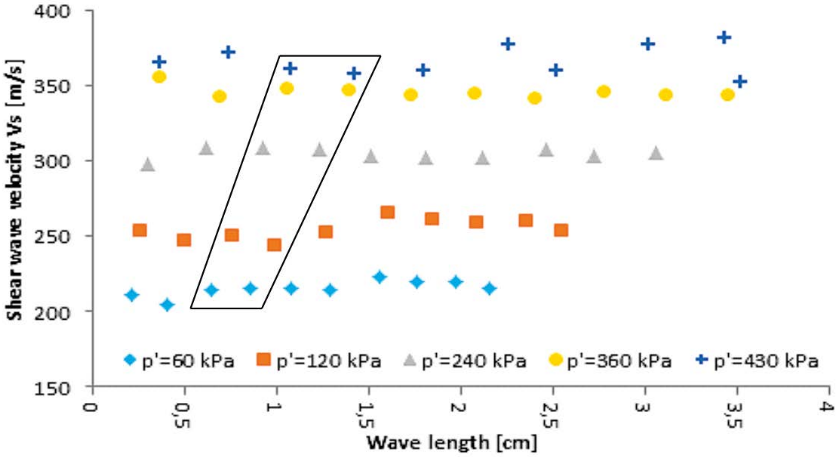

Fig. 8. Variation of the measured V_S with the wave length, the start to start method

Rys. 8. Zmienność pomierzonej prędkości V_S w zależności od długości fali, metoda od startu do startu ratio exceeding 3 (–), yet differences in shear wave velocity could still be found for both methods.

On the basis of Figures 5 to 8, the authors picked shear waves to calculate the maximum shear modulus. For the first peak to peak method, the average wave velocity at the period between 0.01 and 0.02 ms was selected, while for start to start technique, waves at the period between 0.03 and 0.04 ms were chosen. The smallest differences occurred between the shear wave velocities for the entire analyzed effective stress (Fig. 9).

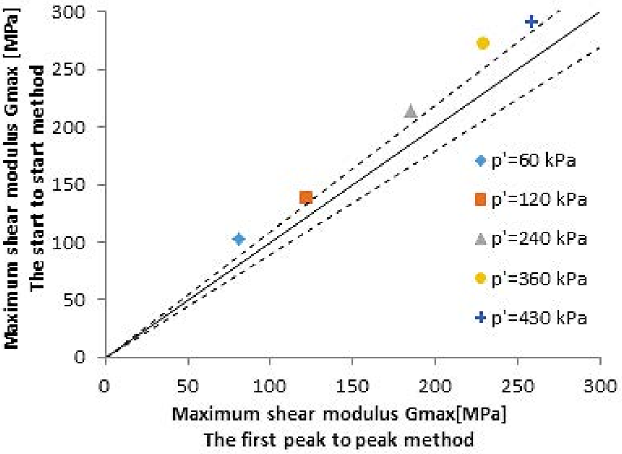

Fig. 9. Comparison of the maximum shear modulus (G_{max}) calculated from shear wave velocity measured by the first peak to peak method and start to start method

Rys. 9. Porównanie maksymalnych modułów ścinania (G_{max}) obliczonych na podstawie prędkości fali poprzecznej pomierzonej metodą pierwszego szczytu i metodą od startu do startu

In Figure 9, a difference between maximum shear moduli is presented. On the vertical axis, the G_{max} value is calculated by using the wave velocity obtained from the start to start method, while the shear modulus is presented on the horizontal axis, estimated on the basis of the first peak to peak method wave velocity measurement. The solid line shows the equal value of the maximum shear moduli, whereas the dashed lines present the ±10% error area. Each point is above the +10% error area, which means that the start to start method gives greater shear wave velocities and 12–26% greater G_{max} values than the first peak to peak method. The increase of the G_{max} value accompanying the effective stress increase can be observed. This phenomenon was confirmed in authors' other publication (Sas et al. 2015).

2.2. Torsional shear tests results

In Figure 10, a variation of shear modulus with shear strain is shown. Shear modulus increases along with the effective stress increase and decreases with the shear strain development. These trends were described more carefully in the work of Gabryś et al. (2015). The maximum shear modulus was obtained from the marked area in Figure 3.6 and compared to results of the bender element tests.

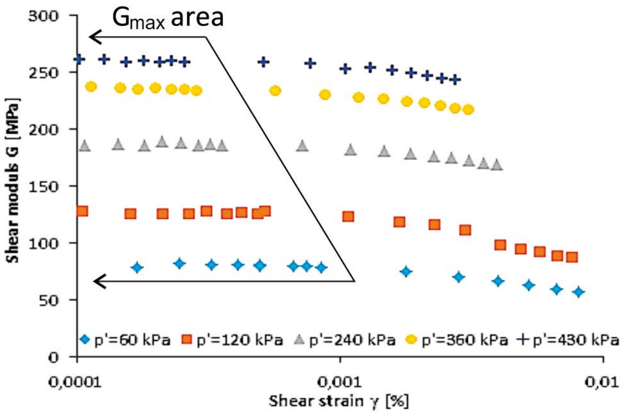

Fig. 10. Shear modulus G [MPa] depending on shear strain γ [%]

Rys. 10. Moduł ścinania G [MPa] w zależności od odkształcenia postaciowego γ [%]

2.3. Results comparison

In Figure 11, the maximum shear moduli were obtained by using three methods, namely the first peak to peak, the start to start and torsional shear, depending on the effective stress shown. The G_{max} value obtained by using the start to start technique adopts the highest value. The results of two other techniques are very similar.

In Table 2, the precise values of the maximum shear modulus for three techniques used in this article are presented. The difference between the first peak to peak and torsional shear

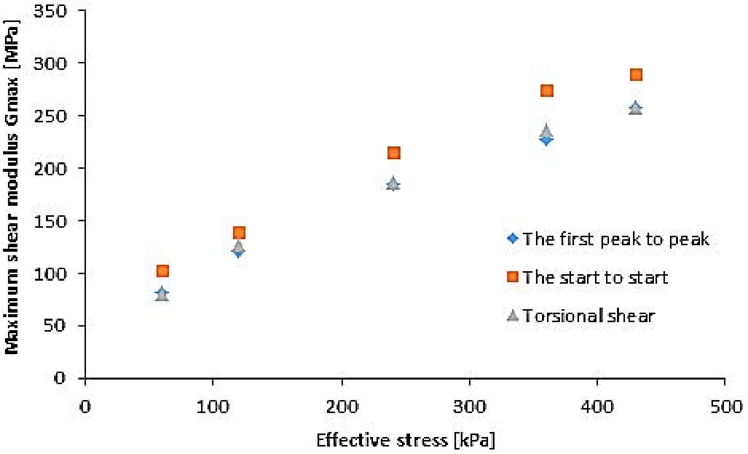

Fig. 11. Maximum shear modulus G_{max} depending on effective stress [kPa] for the three used methods

Rys. 11. Maksymalny moduł ścinania G_{max} w zależności od naprężenia efektywnego [kPa] dla trzech użytych metod test ranges from 2 to 8 MPa, meaning that the disagreement ratio ranges between 1 and 4%. Significantly higher discrepancies can be observed between the start to start method and the torsional shear tests, namely from 10 to 27%.

TABLE. 2. Maximum shear modulus G_{max} [MPa] for three used method

TABELA. 2. Maksymalny moduł ścinania G_{max} [MPa] dla trzech użytych metod

Effective stress [kPa]	Maximum shear modulus Gmax [MPa]		
	The first peak to peak	The start to start	Torsional shear
60	81	103	81
120	121	139	127
240	185	215	187
360	228	274	236
430	258	290	258

Conclusions

This paper presents studies on clayey sand stiffness conducted with the use of a modified resonant column apparatus, equipped with bender elements and torsional shear device. Two time domain methods were employed for the interpretation of the signal in bender elements test,. A carefully analysis of results obtained from the research performed enabled the authors to reach the following conclusions:

1. In studied soil, the examined periods of the shear waves did not have a significant influence on the wave velocity obtained by the first peak to peak method, however the smallest differences in wave velocities were noticed between wave period of 0.01 and 0.02 ms.
2. The start to start method provides much greater discrepancies in wave velocities at different shear wave periods, but any trend of these disagreements could not be observed in a tested specimen. The most reliable results were provided by waves with periods of 0.03 and 0.04 ms.
3. Adoption of the L/λ ratio above 3 allowed for a much more reliable interpretation of the received signal.
4. In order to reduce the near field effect, the authors suggest using a very high input signal frequency.
5. In the tested soil, the G_{max} calculated from the shear wave velocity, obtained from the start to start method overestimated the maximum shear modulus from 10 to 27%, compared to the two other methods which were used.
6. G_{max} obtained from the torsional shear test was in very good agreement with the maximum shear modulus from the first peak to peak method.
7. The correctness of the performed research proves the values of the maximum shear modulus , which increase along with the increase of effective stress in all three cases.

8. On basis of the performed research, the authors recommend the first peak to peak method for interpretation of the signal received in clayey sand.

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