S-wave velocity in samples of calcareous waste

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Abstract. The studies have been carried out in the calcareous waste area “White Seas” of the closed factory Solvay Sodium Plant in Krakow in southern Poland. The study was conducted to determine the S-wave velocity of samples of the anthropogenic subsoil. It was aimed at the possibility of using post-production waste for construction purposes. Due to the high humidity of the analysed samples, the tests were carried out on samples taken using Shelby type probes, from the 12m borehole. The saturation level of soil samples was estimated based on Skempton’s law (B>0.95). The S-wave velocity was determined depending on the different degree of saturation as well as the different degree of consolidation of the soil sample. Only S-wave velocity was analysed because properties of samples caused difficulties in determining of the first arrivals of P-wave. The measurements were carried out in the triaxial apparatus equipped with Bender element (BE). Finally, the shear modulus G of the samples were calculated. Results showed the effect of S-wave velocity increase with increase of degree of saturation and with the increase of effective stress in tested samples. The S-wave velocity significant increased up to about 100 kPa, and then this increase was smaller.

Keywords: Solvay plant, calcareous waste, bender element test, P- and S- wave velocity

1 Introduction

In recent years, numerous geotechnical studies have been carried out in the area of the factory Solvay Sodium Plant in Krakow (which is currently closed) [1–7]. The factory produced sodium carbonate (Na_2CO_3) since 1906. As a result of the production, the studied waste was produced [6]. This waste developed in the form of a slurry and it was entirely deposited in sedimentation tanks. These tanks occupied a total area of over 30 hectares. The stored waste formed heap of nearly 20 meters high. In the 1990s, on the basis of hydrogeological and hydrotechnical studies, the environmental effect of the waste from the Solvay Plants was analysed [8], and then the reclamation of this area was decided. The designated plan [9] and further development plans in this part of Krakow forced the necessity of analysing the soil substrate and evaluating its suitability for construction purposes. Currently, in the area of "White Seas" in Krakow two construction projects are realized. These are the construction of

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the Łagiewnicka Route by the enterprise "Trasa Łagiewnicka" [5] and the golf course implemented by the Golf & Spa Resort company. In both cases, post-production waste, which, as an anthropogenic soil occurs in the foundation level, was a problem related to the choice of the type of construction of future buildings.

The study was aimed at the possibility of using post-production waste for construction purposes. In addition, the Soil – Structure Interaction Division, Cracow University of Technology, also participated in research with the aim of determining the load capacity of piles [4] for future buildings included in the John Paul II Centre.

Due to the lack of data related to the deformation parameters of calcareous waste from the Solvay Sodium Plant in Krakow, the Soil – Structure Interaction Division, Cracow University of Technology, conducted research to determine the dynamic shear modulus G of the subsoil samples from the area of "White Seas" [6, 7]. Only dynamic shear modulus G was analysed because properties of samples caused difficulties in determining of the first arrivals of P-wave. The G modulus of the samples was calculated depending on the different degree of saturation as well as the different degree of consolidation of the soil sample. The tests were carried out on samples taken using Shelby type probes. In the study it was necessary to modify the probe to receive a sample with an undisturbed structure.

In the paper, a detailed modification of the sampler is presented. We also presented methodology of laboratory test and finally the results of the determination of the S-wave velocity and dynamic shear modulus G for the calcareous samples.

2 Undisturbed samples

In the study, for the P- and S- wave velocity determination by the laboratory method, the Shelby sampler was adapted to take samples with an undisturbed structure (Fig. 1).

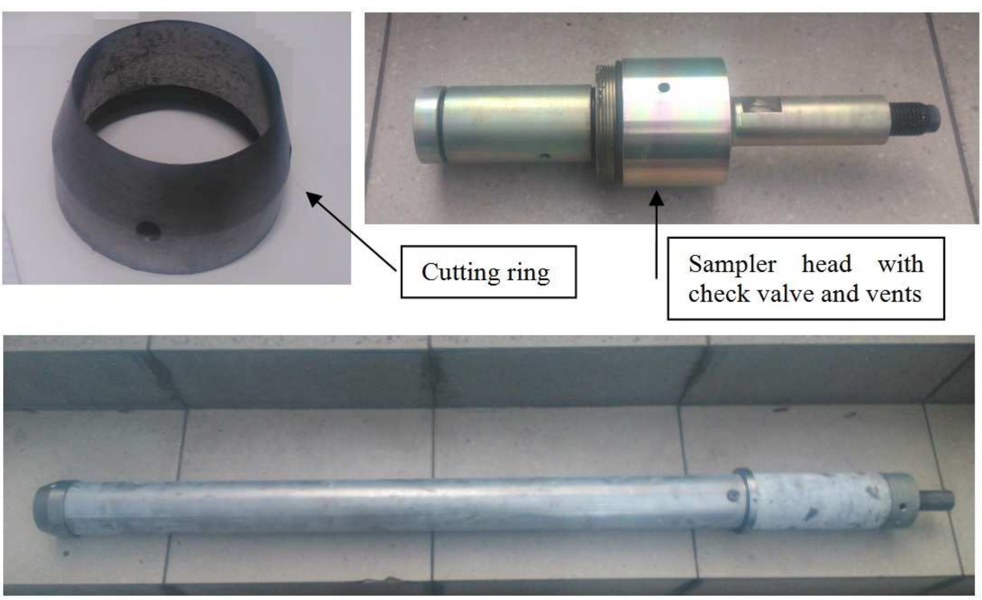

Fig. 1. Modified thin-wall open drive soil sampler.

Due to the high humidity of the analysed samples, i.e. around 200%, the soil exhibited large deformations even at low pressure. In addition, during the extrusion of the sample from the probe there was a significant consolidation of the soil sample and a significant loss of water from the tested soil. The possibility of receiving a sample with an undisturbed structure could therefore be achieved by matching the Shelby probe with a plastic insert, which could be cut in the laboratory as required.

Commercial solutions for probes with plastic inserts are mainly found for small diameters [10]. Finally, a probe with an exterior diameter of 80mm was chosen, which allowed for the installation of a plastic pipe with a diameter of 75mm. Therefore, the interior diameter of the probe was 71mm. The consequence of increasing the thickness of the sampler wall, consisting of a steel pipe and a PE pipe, was to adjust the cutting knife to avoid large deformations of the sample taken. The last modification of the sampler was to provide the probe with a cylinder, so that during the extraction of the probe from the borehole in the sampler a vacuum was created. Due to this modification, the probability of receiving the sample remaining undisturbed has been significantly increased. All modifications of the probe are shown in figure 1.

The probe is terminated with a screw, and because of this, it is possible to push the Pagani static probe (CPT) to a specific depth. Due to the anchoring of the probe, it is possible to take samples from depths of up to 20m. In the case of smaller sampling depths, it is possible to use a lightweight dynamic probe or impact hammer to drive the sampling probe into subsoil.

3 Materials and methodology

Samples for laboratory tests were taken from a borehole drilled to the layer at a depth of approximately 8 m up to around 12m with a high water content [4] (Fig. 2).

Fig. 2. The location of borehole on the research area of White seas.

Eight samples (S1 – S8) with dimensions of 50mm in diameter and an initial height of 75mm were cut from the probes discussed in chapter 2. The height before each test was determined individually [11]. The results of the particle size distribution and chemical composition of the tested samples did not differ from the samples taken from a depth of 1 to 5m, the results of which were previously presented by the authors [6]. The main element of the anthropogenic soil is calcium carbonate ($CaCO_3$), which occurs together with silicon oxides ($SiSO_2$) and other substances (i.e. P_2O_5, $CaSO_4$, $MgSO_4$, $BaSO_4$, NaCl, $CaCl_2$ [1]).

All tests were carried out in accordance with the European Standard [12], which also has the status of the Polish standard. The average physical parameters of soil from at a depth 8-12m are presented in table 1. It was also possible to calculate the following initial soil parameters, which are presented in table 2.

Tab. 1. The average physical parameters of the soil in the area of the "White Seas".

Sample number	**Water content [%]**	**Bulk density [kg/m^3]**	**Specific density [kg/m^3]**
S1÷S8	200	1210	2680

Tab.2. The calculated avarage physical parameters of the soil in the area of the "White Seas".

Sample number	**Dry mass density [kg/m3]**	**Porosity [-]**	**Total water content [%]**	**Degree of saturation [-]**
S1÷S8	400	0.85	210.5	0.95

The tests of determination of the P- and S-wave velocity were carried out using the VJ-Tech triaxial compression apparatus equipped with Bender element. The length of the piezo elements, i.e. the transmitter and receiver, is 6mm in total.

Shirley and Anderson [13] introduced bender ceramics in place of the shear plates for testing dry sand. Incorporation of bender elements in triaxial apparatus is arguably the most common practice, as demonstrated by Chan et al. [14].

The tests to determine the wave velocity were carried out for the following eight sample states:

- for undisturbed structure sample (sample S1),
- for samples fully saturated (sample S2),
- for samples fully saturated and then isotropically consolidated with the values of the effective stress being 50, 100, 150, 200, 250, 300kPa (samples S3 - S8).

All tests were performed using a sinusoidal wave, generated with time intervals of 15 seconds. This time was determined on the basis of the total time of signal suppression and the time necessary for registering the reply. The registered signal was filtered into a continuous function to better evaluate wave transition time. For this purpose, a moving average method was used with an eight-point window. For each sample, twenty designations were made on the basis of which the result was averaged. Filtering were performed in order to obtain the exact time of P- and S-wave arrivals.

By using the "back pressure" method [15] it was possible to fully saturate soil samples using a triaxial compression test apparatus. "Back pressure" was applied to the top of the sample. It is possible to determine the saturation level of a sample in the form of calculated Skempton parameter B:

$$B = \frac{\Delta\delta_1}{\Delta\delta_3} \tag{1}$$

where:
$\Delta\delta_1$ - change in pressure value in the triaxial cell [kPa],
$\Delta\delta_3$ - change in pressure in the soil sample [kPa].

Then a consolidation step was carried out by varying the pressure difference in the cell and in the sample. Six levels of consolidation were used, i.e. 50, 100, 150, 200, 250 and 300kPa. At each state of the sample, the determination of the P- and S-wave velocity was carried out. Finally, only S-wave velocity was analysed because properties of samples caused difficulties in determining of the P-wave first arrivals (Fig. 3).

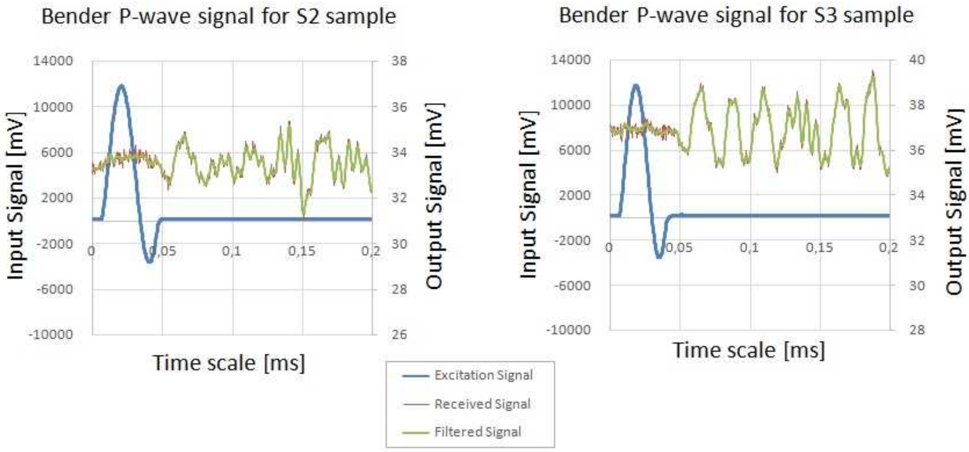

Fig. 3. The P-wave excitation and received signal for S2 and S3 sample.

In the study, an additional element the Local Strain Transducers LVDT (linear variable differential transformer) was applied which provided small strain measurements of axial and radial strain Fig. 4). Due to the use of sensors that were mounted directly on the ground sample, it was possible to control the change in sample height at each stage of the triaxial test [16, 17]. The sensitivity of the LVDT displacement transducers was 0.001mm and the measuring range of LVDT was 50mm.

The advantage of the small deformation sensors used was the precise determination of the height changes and then time of the wave propagation from the transmitter to the receiver.

4 Results and analysis

The waveforms of the input and output signal for S-wave are shown in figure 5. The S-wave velocity changes from 49.9 m/s for sample in undisturbed structure up to 86.9 m/s in fully saturated conditions. In conditions of effective stress increase, S-wave velocity increases from 94.1 m/s for 50 kPa to 168.2 for 300 kPa of fully saturated samples.

The results of the S-wave velocities for eight sample states are presented in table 3.

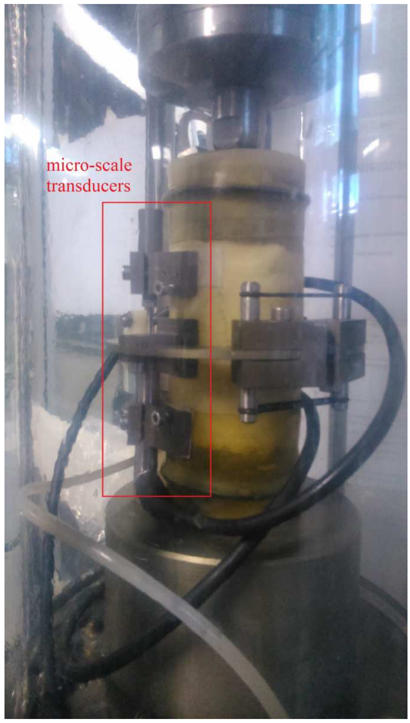

Fig. 4. A calcareous waste sample in the triaxial cell equipped with micro-scale transducers.

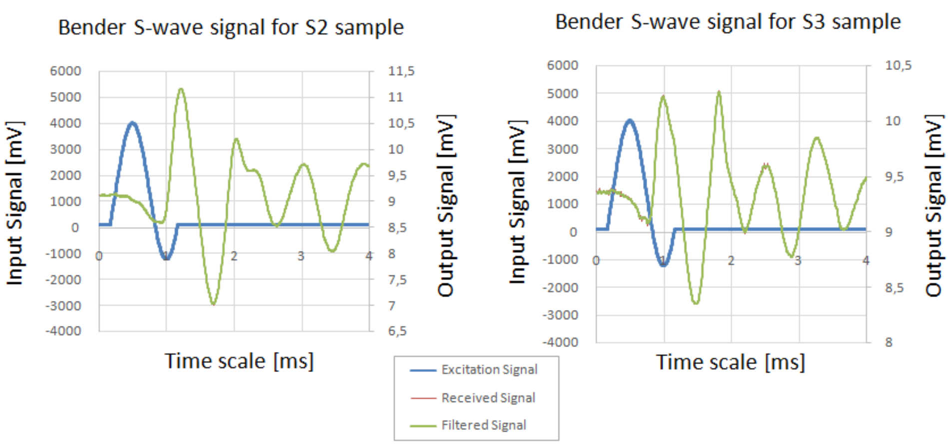

Fig. 5. The S-wave excitation and received signal for S2 and S3 sample. (Red line coincides with green line).

Tab. 3. The average values of the parameters of the tested samples for the S-wave test.

Sample states	Undisturbed structure (S1)	Fully saturated (S2)	Effective stress in consolidation [kPa] (fully saturated)					
			50 (S3)	100 (S4)	150 (S5)	200 (S6)	250 (S7)	300 (S8)
S-wave velocity [m/s]	49.9	86.9	94.1	132.9	142.0	154.8	151.9	168.2

As a result of analysing the wave velocity, it may be noticed that with the increase of effective stress in tested samples the S-wave velocity increases according to figure 6. The S-wave velocity significant increases up to about 100 kPa, and then this increase is smaller.

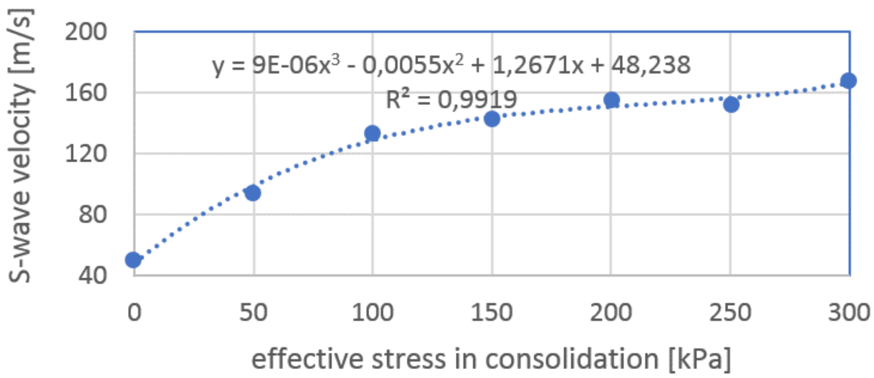

Fig. 6. S-wave velocity to effective stress in calcareous waste samples.

In addition, the measurements of deformation of the sample with LVDT sensors allowed for the determination of changes in the volume of the sample. In effect, it was possible to precisely determine the changes in the porosity of the tested sample. It is necessary to note the very large outflow of water at the consolidation stage. Volumetric distortions registered during the test for 50 kPa amounted to about 18.6%, while for the 300kPa test, volumetric strains reached a water pressure of above 32.8% at the time of full dissipation. Finally, the calculated dynamic G modulus was presented in table 4.

Tab. 4. The average values of the dynamic shear modulus G of the soil calcareous waste samples.

Sample states	Undisturbed structure (S1)	Fully saturated (S2)	Effective stress in consolidation [kPa] (fully saturated)					
			50 (S3)	100 (S4)	150 (S5)	200 (S6)	250 (S7)	300 (S8)
Dynamic modulus G [MPa]	2.92	9.07	10.63	21.19	24.21	27.69	28.76	33.94

5 Conclusions

The study presents the results of the determination of S-wave velocity and dynamic G-modulus conducted by the Soil – Structure Interaction Division, Cracow University of Technology in the area of " White Seas " in Krakow. The samples taken represented a subsoil of post-production waste of the Solvay Sodium Plant. The S-wave velocity of the samples was measured depending on the different degree of saturation as well as the consolidation of the soil sample. Using the triaxial apparatus, due to which the wave velocity was determined in the saturated and consolidated medium, it was possible to calculate the dynamic modulus.

In general, we may observe the effect of S-wave velocity increase with increase of degree of saturation of the tested samples. It may be noticed that with the increase of effective stress in tested samples the S-wave velocity significant increases up to about 100 kPa, and then this increase is smaller. The same effect was observed with modulus G changes.

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