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Experimental studies of dynamic properties of Quaternary clayey soils

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ABSTRACT

The recent significant development of technical infrastructures in Poland, along with the construction of tower blocks, roads, railways and underground rapid transit system, resulted in greater demands for investment projects as well as geotechnical data characterizing the variation of various soil parameters found in the subsoil. The most important parameter, which represents the stiffness of soil deposits, is the shear modulus G. Therefore, this study focused on determining the initial shear modulus of cohesive soils from the area of the capital of Poland. In this research, a set of the resonant column (RC) tests was performed and the influence of three selected factors, i.e. mean effective stress (p'), void ratio (e) and plasticity index (PI), on the low-amplitude shear modulus (G_O) was presented and discussed. The results obtained from laboratory tests indicated that the stress state plays an important role for the small-strain shear modulus values of the Polish Quaternary cohesive soils. In contrast, there was no clear trend observed for the significant effect of e or PI on G_O for the studied soils. Based on the performed tests, the authors proposed the power-law relations for G_O versus p' of the forms: $G_0=3.02p'^{0.68}$ and $G_0=0.82p'^{0.96}$.

1. Introduction

Over sixty years, a significant amount of research has been carried out in order to understand better the mechanical response of soils under dynamic excitations. A variety of laboratory techniques were used for these studies, e.g. cyclic torsional shear tests, cyclic direct simple shear tests, cyclic triaxial tests and resonant column tests. They allowed researchers to define the impact of many factors, most importantly of strain amplitude and frequency of excitation, on soil behaviour (Lai et al. [1]).

In 1937, two Japanese engineers, Ishimoto and Iida, developed the first resonant column test method [2]. Then, in the 1960's this equipment was popularised by such scientists as Hall and Richart in 1963 [3], Drnevich, Hall and Richart in 1967 [4] as well as Hardin and Black in 1968 [5]. In the last 40 years, some improvements and modifications of the design of the first resonant column testing device were made. Drnevich helped to standardize the whole test procedure and developed more complicated mathematical models to be used in these tests (Drnevich [6]).

For proper seismic response analysis, as well as for the development of soil modelling programme, an appropriate investigation of dynamic soils properties is essential (Rayhani and El-Naggar [7]). When describing the soil dynamic characteristic, the most important are two following characteristics: the dynamic shear modulus and the damping ratio (Senetakis et al. [8]). These parameters are required in order to build the Hardin-Drnevich [9] model, which describes the stress-strain relationship (Nie et al. [10]).

To investigate dynamic properties of soils, the resonant column test is applied. The basic principle of this kind of test is to vibrate a cylindrical soil sample in an elemental mode of vibration: torsion or flexure. Historically, it has been used to estimate the small-strain shear modulus G_{max} (frequently designated as G_O), the small-strain material damping D_{min} as well as the relationship between the shear modulus G, the material damping D and the shear strain γ in soils and soft rocks (Kalinski and Thummaluru [11], Yang and Yan [12]). The resonant column tests are performed in order to understand better the mechanisms affecting stiffness (Schneider et al. [13]).

According to the ASTM Standard (ASTM [14]), the vibration of the sample may be superposed on a controlled ambient state of stress in the specimen. The vibration apparatus and specimen are typically enclosed in a triaxial chamber and subject to an all-around pressure and an axial load. Additionally, the specimen may be subject to other controlled conditions, such as: pore-water pressure, degree of saturation or temperature. These test methods of the shear modulus and damping determination are considered non-destructive when the strain amplitudes of vibration are less than 10^{-4} rad (10^{-4} in./in.). Under such conditions, many measurements can be carried out on the same specimen and under various states of the ambient stress.

The series of experiments and analyses herein were performed to study dynamic properties of normally consolidated soils from Warsaw,

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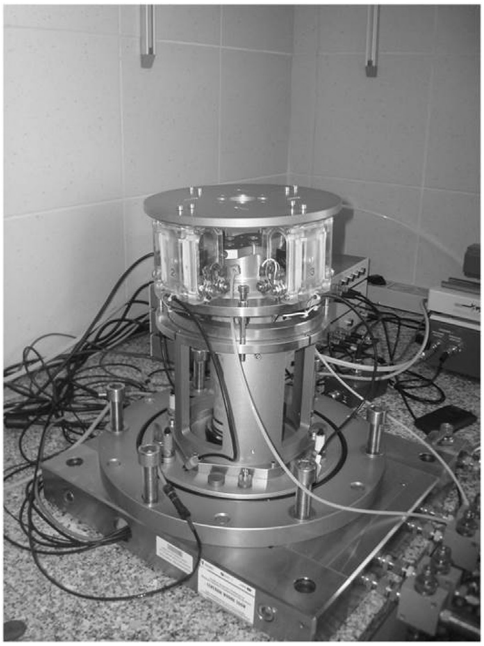

Fig. 1. Photography of GDS Resonant Column Apparatus with tested sample.

based on the GDS Resonant Column Apparatus (RCA). An experimental study was performed, using a modern laboratory device, in order to investigate the small- to medium-strain soil behaviour. In this article, the test equipment and the research programme, as well as the results obtained, are presented and discussed next.

2. Experimental setup

The GDS Resonant Column Apparatus is used in this study (Fig. 1) to excite one end of a isotopically confined solid cylindrical soil specimen. This apparatus is an example of fixed–free resonant column (Sas and Gabryś [15]). In this system, an upright cylindrical specimen of soil, with an aspect ratio of 2:1 (length: diameter), is employed (Kalinski and Thummaluru [11]). The ratio of the length over the diameter amounts typically to: 100×50 mm or 140×70 mm. The soil specimen is usually fixed at the base (*passive end*), but is free at the top (*active end*) to oscillate in torsion or in flexure (a precise description of torsional and flexural test can be found in e.g. Cascante and Santamarina [16]). The instrumentation, placed on the top of the sample, includes a loading cap, an electromagnetic drive system incorporating precision wound coils and a permanent magnet, a counter-balance and an accelerometer. Energisation mode of coils is switchable by software in order to provide the torsional and bending tests (longitudinal).

The GDS Resonant Column Apparatus includes a very strong connection between coils and the support plate. Each pair of coils are encased in a Perspex jacket, which is rigidly connected to the support plate. A magnetically neutral, circular plate is connected to the top of each Perspex block to fit all the coils together. Additionally, the support cylinder is designed in a manner, which ensures a maximum rigidity. The GDS Apparatus also minimizes the damping effect of the equipment. The software can switch the hardware to provide an ‘open circuit’ during free vibration decay, which prevents from a back electromotive force generation (Cascante et al. [17]).

The GDS device is equipped with a standard cell, capable of achieving 1 MPa gaseous cell pressure. Back pressure is applied by the GDS Standard pressure/volume controller. The specimen is placed in a latex membrane and it is tested in a pressurized cell. To reinforce the membrane sealing, the system is equipped with an inner cell for silicon oil (Cascante et al. [17]). The axial deformations of the sample are measured with an internal LVDT, which is mounted inside the confining chamber (Khan et al. [18]).

The resonant column test is an effective method of determining G_O, ξ_O, and G, ξ as a function of γ, where G is the dynamic shear modulus, ξ is the damping ratio and γ is the shear strain. There are some general rules in determining above-cited parameters. The column specimen is prepared and then consolidated. The frequency of the electromagnetic drive system is slowly increased, until the first mode resonant condition is encountered. The value of the resonant frequency is known, which allows the back-calculation of the wave propagation velocity (V_s –S-wave velocity) and thereby establishing G_O (taking into account the sample geometry and the conditions of end restraint). After measuring the resonant conditions, the electromagnetic drive system is cut off and the column specimen is brought to a state of free vibration. ξ_O is calculated by observing the decay pattern (Cascante et al. [17]).

3. Tested soils

For their laboratory tests, the authors chose samples in the vast majority with medium fines content, 10% < FC < 20%. The selected moraine clayey soils are commonly found in Poland, also in a large part of the Warsaw area, where, nowadays, more and more engineering challenges emerge, such as: underground constructions or development of new railways and roads. Therefore, using the European classification [19], the laboratory experiments were conducted on clayey sands (clSa), silty clays (siCl), sandy clays (saCl) and sandy silty clays (sasiCl). The range of the index properties of the investigated soils is presented in Table 1. Their specific gravity was equal to 2.71g/cm^3.

The position of the soils in the plasticity chart is shown in Fig. 2. According to the plasticity chart, all samples were identified as average cohesive and cohesive soils (CL). The authors in their research were tested semi-solid, LI < 0, and hard-plastic soils, 0 < LI < 0.25, with a various level of plasticity, from slightly plastic, 3% < PI < 15%, to medium plastic soils, 15% < PI < 30%.

The first test site was located on one section of the expressway No. S2, between its two nodes: “Konotopa” and “Airport”, in the area of the road embankment No. WD-18 (Fig. 3). The road embankment No. WD-18 is one of the twenty embankments on the Southern Warsaw Bypass S2, along its nodes: “Konotopa”-“Airport” (PIG [20]). The soil in this area was investigated to a depth of 25.0 m and there can be found the complex of cohesive soils - plastic and stiff clays with interbeds of sand.

The second test site was situated in the region of Pełczyńskiego Street, in Bemowo, one of the western districts of Warsaw (Fig. 3). In this area, under the surface of turf and uncontrolled embankments, a layer of dammed lake materials was located, e.g. cohesion-less (fine sands, silty and loamy sands) and below them existed cohesive dammed soils (clays, compacted clays and silts, with distinct bands of fine and silty sands). Dammed materials were found mostly up to the depth of about 4.0–5.0 m. Then, a layer of moraine soils (sandy clays and clayey sands) was located, until the maximum depth of about 10.0–13.0 m. Next, grey river sands were found, reaching the depth of 15.0 m.

A standard routine sampling procedure was employed in order to guarantee the consistency of the samples. One of the sampling methods, for the most samples, was a collection of the samples in block forms. Thereby, the sampling process was very cautious, so as not to affect the structure of the soil. The second way of sampling was by collecting the drilled material in the Shelby type, cylindrical probes, but only for test site No. 2. The samples for laboratory tests were collected right below at the ground surface (at the depth around 0.5 m) and next, from shallow depths of approx. 2.0 and 2.5 m. The block samples, for example, were carefully trimmed at the depth of 2.0 m from an excavated pit. All collected samples were sealed and stored in a humidity room until needed.

The material represented one geological layer for each test site. In