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LABORATORY MEASUREMENT OF SHEAR STIFFNESS IN RESONANT COLUMN APPARATUS

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Abstract. This paper concerns evaluation of initial stiffness in natural cohesive soils. Initial stiffness is here represented by the small strain shear modulus (G_0), which was measured for the variety of the confining pressures and the mean effective stresses. The researches were conducted in laboratory, using the resonant column (RC) technique. The soil was isotropically consolidated and subsequently stiffness parameter was determined for each effective stress level. Different values of G_0 were evaluated, depending on the test conditions, then summarized on the general graphs. This study demonstrates as well conclusively high non-linear stress – strain behaviour of an examined material. The principal motivation of the article was improvement of our understanding of the stiffness property of natural soils at small strains.

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

INTRODUCTION

In the last several decades, it has been worldwide recognized that the stress-strain response of almost all kind of soils and soft rocks is highly non-linear. This fact has led to the special design methods which take stiffness non-linearity into account. Nowadays, the described phenomenon is routinely incorporated into many standard computer codes. Together with these great achievements in situ and laboratory testing techniques have been developed, which allow the stress-strain response details to be examined, even in the range of low strains (ex. 10^{-6}) [Gomes Correia et al. 2004, Viana da Fonseca et al. 2009].

Due to this non-linear behaviour of soil in nature, the shear modulus depends on the shear stain amplitude. However, the reaction of soils at strain levels below 10^{-3}% can be considered practically elastic and, hence, the resultant shear modulus is treated as G_0 – the small strain shear modulus or G_{max} – the maximum shear modulus. The knowledge about

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the small strain shear modulus is important particularly in two areas: earthquake ground response analysis as well as soil liquefaction evaluation [Andrus and Stokoe 2000, Yang and Yan 2009]. A key role of this parameter is also observed in excavations and foundations field [Atkinson 2000].

Direct calculation of seismic wave velocities in laboratory conditions has increasingly become a common practice globally. It gives a powerful potential in the determination of the stiffness at small strains, recognized lately as a reference characteristic in soils. Among various methods for laboratory measurement of shear stiffness, bender elements and resonant column tests are accepted to be most reliable. Bender elements, originally developed for soft soils, enable transmitting and receiving shear and/or compression waves and can be installed virtually in any conventional soil testing device. These transducers are most usual for oedometer or triaxial, although may be found as well in more complex systems, like: calibration chambers, centrifuges, even cubical true triaxial apparatuses [Dyvik and Madshus 1985]. More information about this technique is presented in the article Ferreira et al. [2011], whereas details of resonant column procedure are described in the further part of this paper. Both methods have different limitations and advantages. For instance, the interpretation of RC experiments has been well established, while the reading of BE signals is somehow difficult and involves uncertainty [Joviciv et al. 1996, Lee and Santamarina 2005].

In this study, a series of resonant column tests have been performed on natural cohesive soils from Warsaw area investigations site. A set of researches have been conducted at various confining pressures and various mean effective stresses, then shown on the figures included. Moreover, non-linearity as well as dependence on stress level have been introduced here. The major objective of this article has become, however, improvement of our understanding of the stiffness property of natural soils at small strains.

TEST EQUIPMENT

The resonant column device is a laboratory apparatus specifically designed to measure dynamic characteristics of soils for shear strains between 10^{-6} and 10^{-2}. The resonant test is essentially non-destructive, therefore the dynamic properties can be evaluated at different confining pressures for each soils specimen. The small shear strain produced with the resonant column equipment is in the same order of magnitude as that of geophysical in situ tests [Cascante et al. 1998].

The resonant column device successfully used in this work were manufactured by British company GDS Instruments Ltd. The apparatus is schematically shown in Figure 1. It is a Stokoe fixed-free type of resonant column. The sample is fixed to the pedestal at the bottom end, to the drive plate through the top cap at the other end. The applied testing system is composed of: testing unit (testing chamber), control computer, back pressure system, cell pressure controller, resonant column controller and data acquisition box. The appliance of the GDS equipment is to excite one end of a confined soils or hollow cylindrical soil specimen. The sample is aroused in torsion or flexure (bending) with the help of electromagnetic drive system. Once the fundamental resonant frequency is recognized from measuring the motion of the free end, the velocity of the propagating wave as well

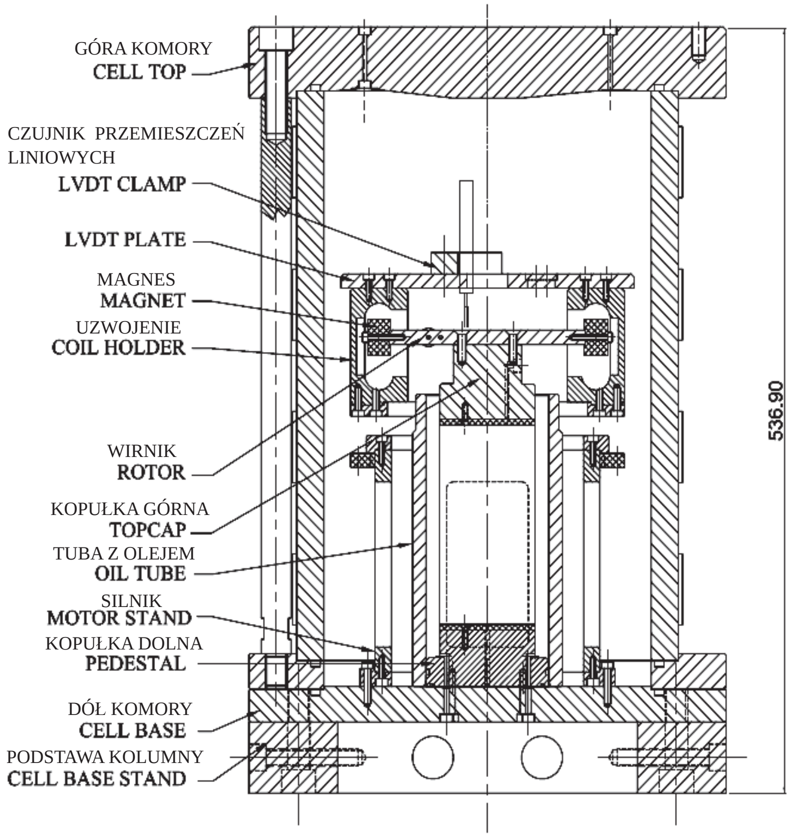

Fig. 1. Schematic illustration of the apparatus used
Rys. 1. Schemat wykorzystanego w badaniach własnych urządzenia

as the degree of material damping can be received. The shear modulus (torsion test) or Young's modulus (flexure test) are, at that time, obtained from the calculated velocity and the density of the specimen [GDS Instrument 2009].

The GDS RCA system has a lot of advantages. Among others, it includes a very robust connection between the coils and the support plate. This involves encasing each pair of coils in a Perspex jacket, which is rigidly combined to the support plate. Additionally, a magnetically neutral, circular plate is connected to the top of every Perspex block to tie all the coils together. The special design of the support cylinder gives this part maximum rigidity itself. The equipment was projected as well to minimise the damping effect. During free vibration decay (after the power is shut off normally at resonance), usually the back EFM is generated in the coils by the movement of the magnets. This situation causes large equipment damping errors. In the GDS RCA the software can switch the hardware to provide an "open circuit" while free vibration decay, which prevents the back EFM production [GDS Resonant Column 2010].

TEST MATERIAL AND PROCEDURES

The soil in these researches, referred to clayey sand, was collected from the Warsaw area, taken from the test side located near the planned express route (S2), between its two nodes "Puławska-Airport". The testing material was selected carefully considering the uniformity of the soils structure, its physical properties and its double-phase. It is composed mainly of sand (61%), the fines content (particle size < 63 μm) of the soil is 39%. Figure 2 brings the grain size distribution curve of the examined soil. The principal properties are: specific gravity G_S = 2.68 g·cm^{-3}; D_{10} = 0,001 mm, D_{30} = 0.023 mm, D_{50} = 0.092 mm, D_{60} = 0.145 mm, coefficient of uniformity C_u = 145, coefficient of curvature C_c = 3.65.

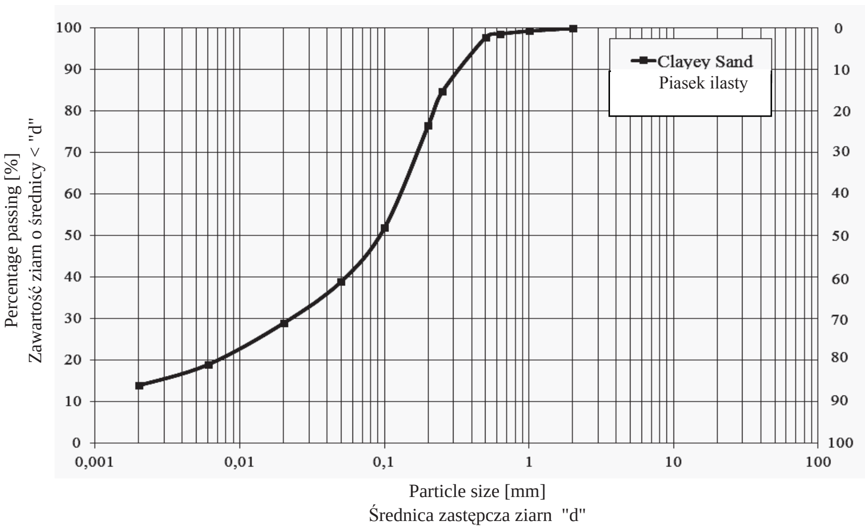

Fig 2. Particle size distribution curve of the studied material
Rys. 2. Krzywa uziarnienia badanego materiału

The testing procedures can be found in another article of the authors [Sas et al. 2012], which relates to the same topic. Nevertheless, some important phases of the experiments must be outlined here as well. Before the proper dynamic measurements were performed, the soil required correct preparation. The initial stages of the study, consisting in modelling of the natural conditions of the samples in field, included: flushing of the equipment, saturation, control of Skempton's B parameter and consolidation. Undisturbed material was set up in the cell, then saturated by back pressure methods, which was increased accordingly to ensure the saturation of the sample until the Skemption's B value was higher than 0.90. When full saturation was achieved, consolidation process started. The soil was consolidated to predetermined isotropic stress. In every test, an isotropic effective confining pressure was applied in steps, namely 45, 90, 135, 180, 225, 270 and 315 kPa. The experiments were stopped with the mean effective stress equal to 315 kPa, due to the equipment's limitations. During the consolidation phase, the volume change and the axial deformation of the specimen were measured. Moreover, the void ratio of the sample was updated during consolidation at each loading stage. In order to excite the electromagnetic field and induce a wave propagating through the examined material, the corresponding coil voltage values were placed, starting with 0.1 V till 1.0 V, with a change in the value of 0,1V. Then finally, RC tests were performed to calculate G_0 for the each specified stress state.

RESULTS AND DISSCUSION

The methods of shear stiffness determination are covered by Drnevich et al. [1978] and the details of the apparatus calibration procedure are given in the resonant column operating manual [ASTM Standard 2003]. Knowing the resonant frequency of the analysed sample, its length and its mass moment of inertia, the shear wave velocity can be calculated from the frequency equation (1):

$$\frac{I}{I_0} = \left(\frac{\omega l}{V_S}\right) \tan\left(\frac{\omega l}{V_S}\right) \tag{1}$$

where I_0 represents the mass moment of inertia of the top cap and drive plate, I is the mass moment of inertia of the assembled soil column, and ω is the undamped natural frequency. A system calibration formula gives the value of I_0.

The small strain shear modulus (G_0) can be obtained from the shear wave velocity (V_S) since they are related through the theory of elasticity as follows:

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

where ρ is the soil density. The shear modulus estimated from the resonant column test is the secant modulus because only the points of peak response are measured [Zavoral 1990].

The stiffness of the natural cohesive soils is affected by many various factors, among which are important: strain amplitude, density, void ratio or water content (when saturated with water), effective stress, overconsolidation, time of consolidation and prestraining (previous cyclic loading). Three first examples have greater implication than others, but in this study only two of them were examined, as mentioned in the introduction.

The effect of confining pressure (σ_0) on the small strain shear modulus of examined material is presented in Figure 3. The initial void ratio for the soil was 0.2388. The measurements show that G_0 values increase with confining pressure at a polynomial function. The coefficient of determination gives the quality of the function's matching to the data at 95%. With the confining pressure at the level of 180 kPa, no significant changes in the value of G_0 are observed. The same trend of variations applies to the relation between G_0 and mean effective stress (p') (Fig. 4) with the coefficient of determination of the polynomial function in the range of 95%. The smallest value of G_0, around 47 MPa was noted for p' equal to 45 kPa and σ_0 = 430 kPa, the biggest one G_0 = 237 MPa for p' = 315 kPa and σ_0 = 700 kPa. It can be therefore concluded that an increase of both confining pressure and mean effective stress causes an increase in the soil stiffness.

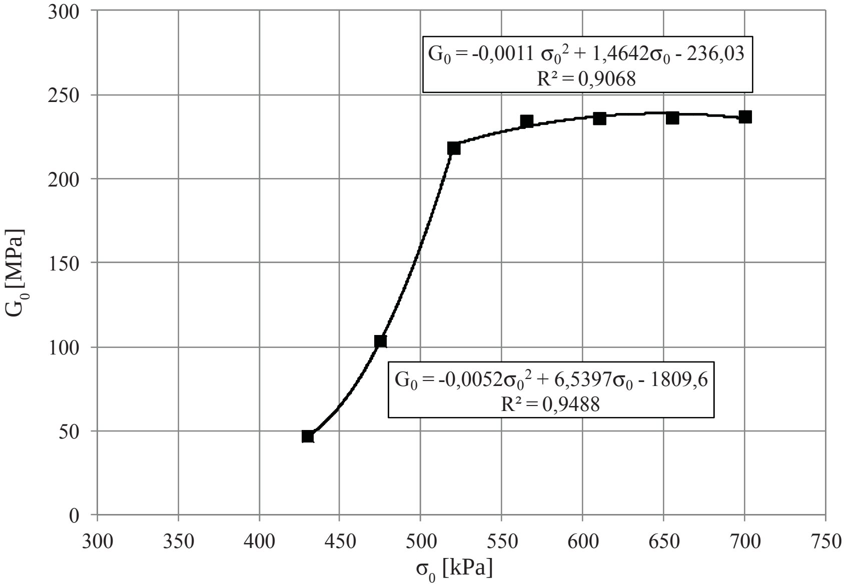

Fig. 3. Small strain shear modulus from RC tests as a function of confining pressure

Rys. 3. Moduł odkształcenia postaciowego z badań w kolumnie rezonansowej w funkcji naprężenia otaczającego

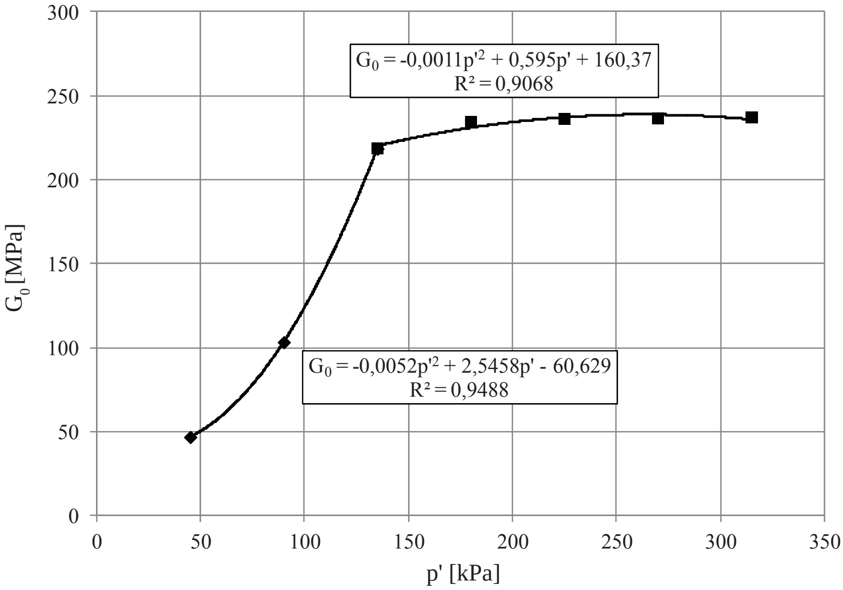

Fig. 4. Small strain shear modulus from RC tests as a function of mean effective stress

Rys. 4. Moduł odkształcenia postaciowego z badań w kolumnie rezonansowej w funkcji średniego naprężenia efektywnego

Figure 5 illustrates the small strain modulus as a function of the normalized pressure (p'/pa), where pa is a reference stress of 98 kPa. The characteristic of this graph is similar to the above two.

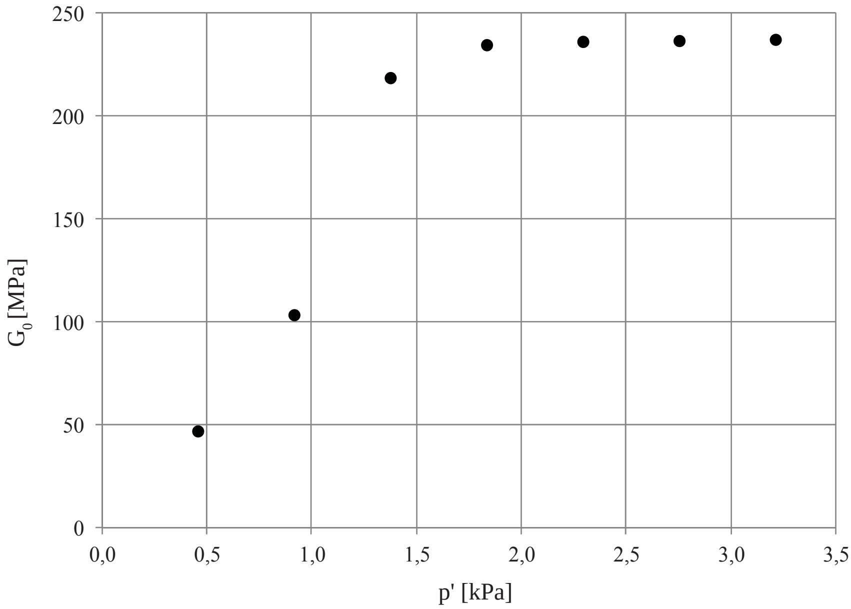

Fig. 5. Small strain shear modulus from RC tests as a function of normalized pressure
Rys. 5. Moduł odkształcenia postaciowego z badań w kolumnie rezonansowej w funkcji znormalizowanego średniego naprężenia efektywnego

The impact of strain amplitude on the soil stiffness is shown in Figure 6. Strong nonlinearity and dependence on stress level is evidence. At small strain ($< 10^{-5}$), a stress-strain loop is reduced to a nearly straight line: and elastic behaviour. The secant modulus of G decreases as the strain amplitude increases. The degradation of G oscillates between the values 230 MPa and even 30 MPa, depending on the test conditions, namely on the mean effective stress (p'). Shear strain (γ) varies from the value around 5E-04% till 9E-02%, as well according to p'. The first measurement of resonant frequency and thus the small strain shear modulus was made immediately after saturation and before consolidation phase of the soil; is called here simply "saturation". The results got from this stage of the studies are the smallest, then gradually increase with the raise of the mean effective stress, up to the largest values for p' = 315 kPa.

The effect of strain is indicated as well by shear modulus ratio (G/G_0) presented in Figure 7. This graph indicates the following:

1. G/G_0 decreases as the strain amplitude increases.
2. The reduction of G/G_0 is less significant when the effective stress is higher.

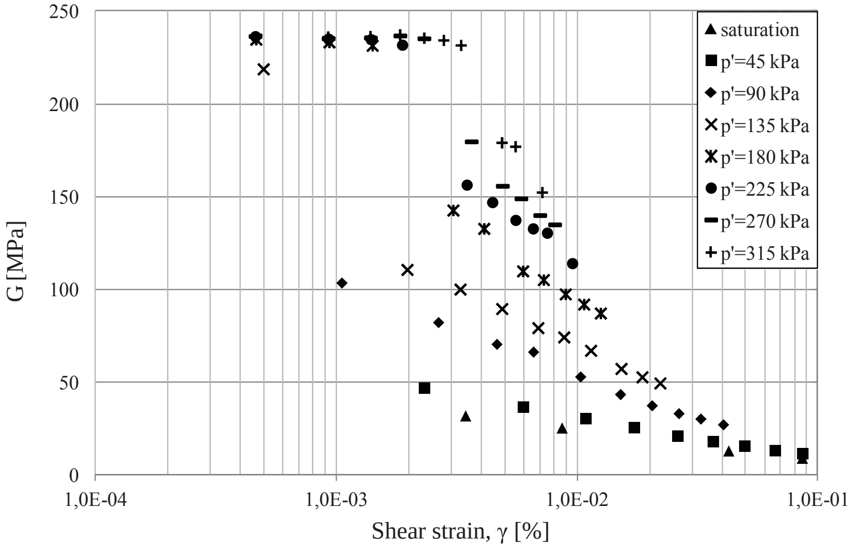

Fig. 6. Variation of shear modulus with strain
Rys. 6. Zmiana modułu ścinania w zależności od odkształcenia postaciowego

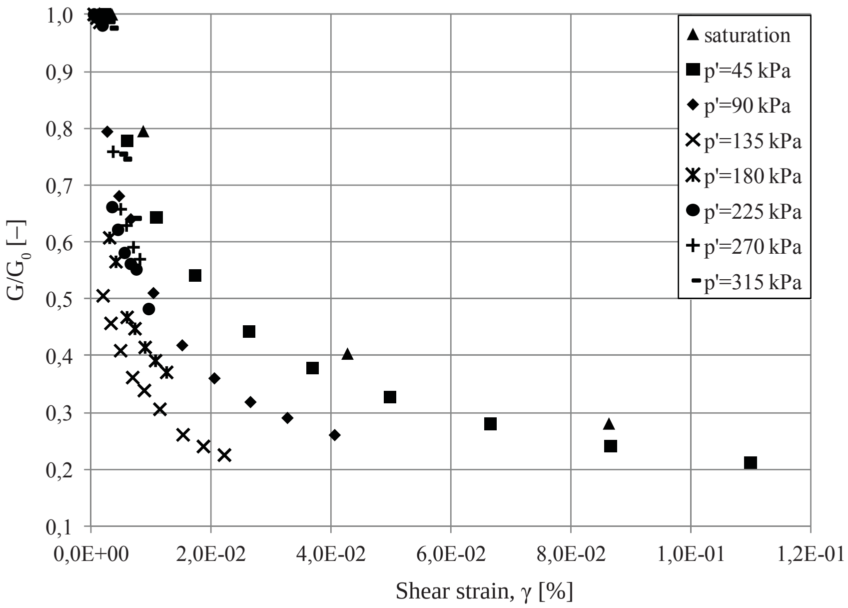

Fig. 7. Variation of shear modulus ratio with strain
Rys. 7. Zmiana wskaźnika modułu ścinania w zależności od odkształcenia postaciowego

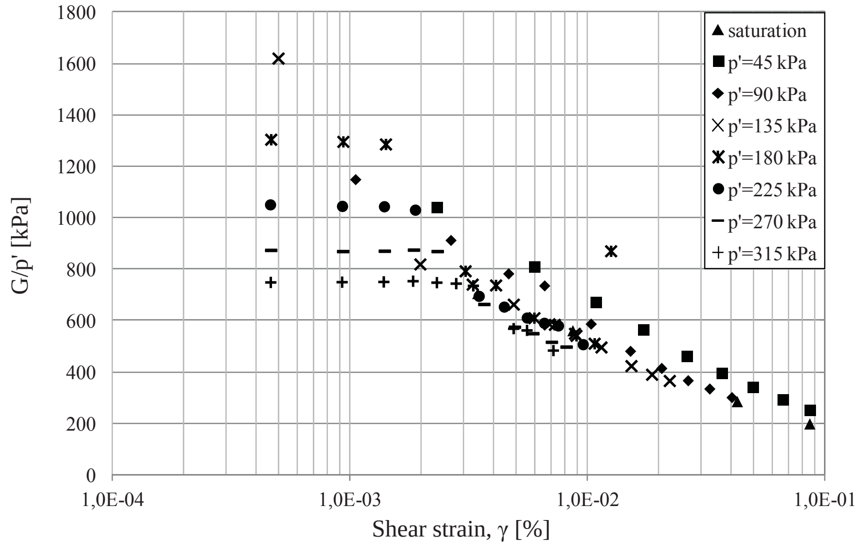

Fig. 8. Variation of normalised shear modulus with strain
Rys. 8. Zmiana znormalizowanego modułu ścinania w zależności od odkształcenia postaciowego

In Figure 8 stiffness has been normalised with respect to effective stress. The normalised stiffness varies between 200 kPa and even 1600 kPa for the stress range 45–315 kPa. The bigger value of G/p' corresponds to $p' = 135–180$ kPa, which suggests that p' can be successfully used as normalising parameter.

SUMMARY AND CONCLUSIONS

The present study has provided some insight into the stress-strain behaviour of natural cohesive soils from Warsaw area test site. Stiffness characteristics is the key parameter for, exemplary, seismic design and performance evaluation of dams. In order to define the stiffness of examined soil small strain measurements have been performed. Laboratory experiments have been conducted by means of resonant column, developed by a British company GDS Instruments Ltd. The apparatus applied by the authors of this paper is an example of Hardin-Drnevich device, projected in configuration “fixed-free”. The results from the researches are summarized on the graphs. The conclusions can be as follows:

1. The effect of confining pressure (σ_0) as well as mean effective stress (p') on the small strain shear modulus (G_0) can be observed.
2. G_0 values increases with σ_0 and p'.
3. Stiffness non-linearity is evidenced. Moreover, its depends also on the stress level.
4. Degradation in value of the small strain shear modulus and shear modulus ratio corresponds to the raise in the strain amplitude. The impact of strain amplitude on G and G/G_0 is significant.

5. Variation of shear modulus is closely related to the test conditions, that is to the mean effective stress. The more important effect of *p*' occurs in G_0 at small strain amplitude. At higher amplitudes, the differences in the values of G are not so important.

6. The mean effective stress can be employed as a normalising parameter.

To sum up, wide range of research on the effect of different other factors on stiffness is required to better understand the dynamic behaviour of soil.

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LABORATORYJNE POMIARY SZTYWNOŚCI GRUNTU W KOLUMNIE REZONANSOWEJ

Streszczenie. Praca dotyczy oceny początkowej sztywności naturalnych gruntów spoistych. Sztywność początkową reprezentuje tutaj moduł odkształcenia postaciowego w zakresie małych odkształceń (G_0), którego pomiarów dokonano przy różnych wartościach ciśnienia otaczającego, jak również zmiennych wartościach średniego naprężenia efektywnego. Badania zostały przeprowadzone w laboratorium przy użyciu kolumny rezonansowej. Materiał badawczy poddawano najpierw izotropowej konsolidacji, by następnie przejść do wyznaczenia sztywności gruntu dla zadanych wartości naprężeń efektywnych. W zależności od przyjętych warunków badania otrzymano różne wartości G_0, a ostateczne wyniki zilustrowano na wspólnych wykresach. Ponadto podjęto próbę ukazania silnej nieliniowości charakterystyki naprężenie – odkształcenie dla analizowanych gruntów. Główną motywacją do przeprowadzenia opisanych w pracy eksperymentów stała się potrzeba zrozumienia właściwości sztywności gruntów naturalnych w zakresie małych odkształceń.

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

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