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Soil testing in the RC/TS apparatus. Part 1.

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Dynamic tests of material characteristics such as stress-strain has long been a very important part of many aspects of maritime, seismic engineering and placement of foundations of machines or structures subjected to different dynamic interactions. In the past two decades, tremendous progress is noticeable in the development of laboratory and field methods of dynamic tests that become routine research and analytical techniques of practicing engineers. This makes it possible to solve complex problems of the dynamic nature in the matters regarding cooperation of structure with subsoil. This progress, however, is not sufficiently used by engineers dealing with problems of statics. One reason for the existence of a gap between the soil dynamics and traditional geotechnical engineering was, and in many cases still is, the belief that the dynamic properties of the soil cannot be used in analyzes of static geotechnical problems. It turns out that for very small deformations, soil parameters demonstrating its stiffness are comparable in dynamic and static issues [19].

The correct description of the soil behavior within the range of small deformations is an extremely important element in the prediction of the movement of structures cooperating with subsoil, and thus has a great impact on the quality of the actual mapping of the internal forces in the structural system of the whole building, including the foundation. Stiffness modules for very small deformations are now recognized as the fundamental properties of the soil. For this reason, in geotechnical engineering we commonly use information obtained from laboratory and field dynamic and seismic tests to solve conventional problems of interaction between the building and the substrate. This group of studies primarily covers geophysical techniques, based on the theory of propagation of elastic waves. In most cases, the purpose of this study is to determine the speed of propagation of transverse (shear) wave and/or longitudinal (compression) wave between two points of the substrate geotechnical profile. The stiffness of the soil layer is estimated based on the amorphous elastic modulus G and the longitudinal elastic modulus E calculated according to the following equation:

$$G = \rho \cdot V_S^2 \quad (1)$$

$$E = \rho \cdot V_L^2 \quad (2)$$

where: ρ - soil volume density; V_S – transverse wave velocity; V_L – longitudinal wave velocity.

The movement of particles consequent to the propagation of elastic waves is a non-destructive. The resulting number of modules corresponds to very small deformations, therefore the modules are often called primary modules (G_0, E_0 or G_{max}, E_{max}). Under field conditions most commonly are used methods allowing for measurement of the propagation speed of transverse wave (CHT - crosshole test DHT - downhole test, suspension logging, seismic reflection, seismic refraction and SASW - Spectral analysis of surface waves). In addition, receivers of seismic waves are installed in the classical probes, such as static (SCPTU) and dilatometric (SDMT). While comparing the results of the seismic field studies and classical soundings correlations are created that allow for determination of the initial modulus based on knowledge of the parameter derived from the sounding (see [20]).

In order to confirm the results obtained in the field, direct laboratory measurements of the above parameters are necessary. The results of tests carried out in the laboratory are often regarded as reference values for the geotechnical properties determined in the field. Comparison of the results of field studies with conventional laboratory tests is performed in order to improve the reliability of the results of the in-situ tests. In the laboratory, one can change the stress state of soil samples according to the assumed path of stress. In the laboratory dynamic tests one can also analyze the impact of parameters such as frequency of interaction, the number of cycles, pore fraction or OCR ratio, on the nature of the soil response in selected conditions. In addition, for certain sensitive soils, the correlations are of little use and require immediate testing in laboratory conditions [23].

Nowadays (and in the last 20 years) to determine the velocity of wave propagation in soil under laboratory conditions, piezoelectric elements "bender" are usually used [9]. Some may, however, raise questions of interpretation methods for the results of measurements that lead to the designation of the shear wave velocity. This issue has been presented in [24]. Usage of 'bender' spread in the 90-ies of XX century, when the need to take into account the non-linear behavior of soil characteristics in the engineering analysis became more and more popular [3]. Since the output parameter characterizing the soil stiffness is G_{max}, increased focus is now on developing techniques for determining its value. The most authoritative study allowing for estimation of the initial modulus is generally considered to be the the resonant column (RC) test.

The resonant column test in is a well-known technique for determining the dynamic shear modulus, dynamic modulus of elasticity and the damping coefficient of soils and rocks. The main objective of this research technique is to analyze the properties of materials subjected to harmonic vibrations representing seismic interaction. The sample is placed in a triaxial stress chamber, and its ends are loaded with torque or axial force. Measurement of the resonant frequency of the sample material using the compounds of elastic wave propagation theory, allows for estimation of the speed of wave propagation in the sample.

The method of resonant column testing technique has been known in geotechnical engineering from the 30's of the twentieth century. The first studies showing the method were published by Japanese engineers Ishimoto and Iida [13, 14]. One of the earlier constructions of the resonant column apparatus was built in the USA, and was used to determine the velocity of transverse waves during torsional shear of rock samples [5]. In the 60's of the last century, the resonant column was already widely used in studying the dynamic behavior of the soil. Many contemporary researchers, as Hardin and Richart [10], or Drnevich [8], promoted the technique among a wide range of geotechnicians. Subsequent successes took into account the anisotropic strain application [11] and the apparatus modifications allowing for the use of hollow samples [8], which minimized shear amplitude variation along the radius of the sample with torsional excitation. The apparatus is also modified to allow testing at high strains [2] and at high pressures in the chamber [12]. Further construction work on the apparatus helped to further expand its capabilities, giving rise to its TS (torsional shear) version, i.e. cyclic torsional shear [18]. Modern designs of the apparatus allow for application of amplitudes of large deformations in combination cyclic torsional shear, and resonant column. The device developed by a team of professor Stokoe at the

University of Texas, Austin is widely known as the RC/TS (resonant column/torsional shear) apparatus. Currently, the RC/TS method is considered one of the most reliable, effective and pragmatic laboratory methods for the determination of the shear modulus and damping ratio of soil and other materials [30]. The remainder of this article will present the subject of research in the resonant column that could work as torsional shear (RC/TS) apparatus.

BASIC PRINCIPLES

The idea of resonant column tests is based on theoretical solutions related to the links between the dynamic deformation modulus G and the resonant frequency of the soil material sample. Developments in the sample subjected to harmonic torsional may be described by the different physical models, such as the torsion pendulum or twisted rod with one degree of freedom (Kelvin-Voigt SDOF), including in the analysis the mathematical description of the effects of external loads and harmonic suppression, additionally taking into account the equations of propagation generated in the material of elastic deformation waves. In order to clarify the nature of the main formulas used in the analysis of the results of the RC/TS apparatus tests, also the derivation of the main theses of theoretical model describing the phenomena that occur during the test were presented.

If from the uniform rod of length L and circular cross-section of radius R, mounted at one end and subjected to twisting moment T on the other, free end, a fragment of length dx is mentally separated, it can be assumed that the values of torsional moments at the ends can vary by some amount dT (Fig. 1):

$$dT = \frac{\partial T}{\partial x} dx , \tag{3}$$

where $\partial T/\partial x$ is the intensity of torque changes. The value of external load T corresponds to the interior elastic force generated according to the equation

$$T = GJ \frac{\Theta}{L} , \tag{4}$$

where G is the shear modulus, J – moment of inertia of the circular cross-section $\pi R^4/2$, and Θ – the angle of cross-section torsion (Fig.1). In the case of homogenous rod we may write it down as follows:

$$\frac{\Theta}{L} = \frac{\partial \Theta}{\partial x} \rightarrow T = GJ \frac{\partial \Theta}{\partial x} \rightarrow \frac{\partial T}{\partial x} = GJ \frac{\partial^2 \Theta}{\partial x^2} . \tag{5}$$

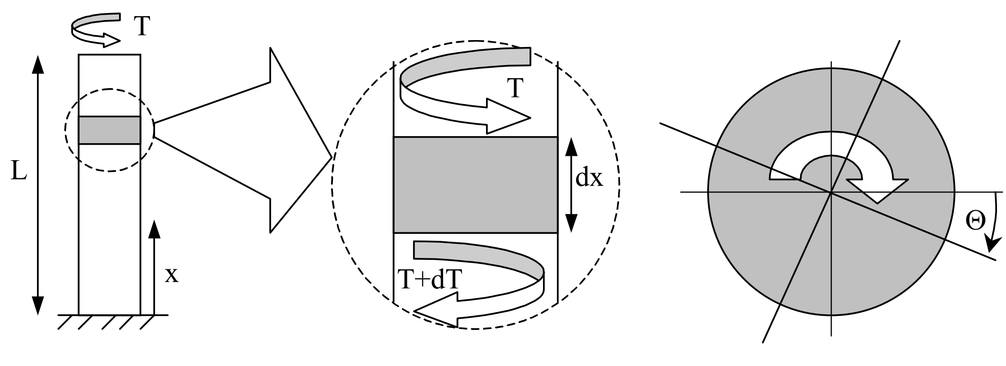

Fig.1. Scheme of twisted rod

After substitution of (5) to (3) the result is:

$$dT = GJ\frac{\partial^2\Theta}{\partial x^2}dx \,. \tag{6}$$

If we assume that the moment T is applied quickly, which means that the appearance of the target value of angle Θ requires overcoming the inertia of the material, the equilibrium equation can be written:

$$dT = I\alpha = I\frac{\partial^2\Theta}{\partial t^2} \rightarrow I\frac{\partial^2\Theta}{\partial t^2} = GJ\frac{\partial^2\Theta}{\partial x^2}dx \,, \tag{7}$$

where α is the angle acceleration, and I – moment of inertia of the mass M of the analyzed segment of the rod:

$$I = \frac{MR^2}{2} = \frac{\rho A dx R^2}{2} = \frac{\rho\pi R^4 dx}{2} = \rho J dx \,, \tag{8}$$

where A – segment cross-section area, and ρ – material density. After substitution of (8) to (7) the result is:

$$\rho J\frac{\partial^2\Theta}{\partial t^2}dx = GJ\frac{\partial^2\Theta}{\partial x^2}dx \rightarrow \rho\frac{\partial^2\Theta}{\partial t^2} = G\frac{\partial^2\Theta}{\partial x^2} \rightarrow \frac{\partial^2\Theta}{\partial t^2} = \frac{G}{\rho}\frac{\partial^2\Theta}{\partial x^2} \,, \tag{9}$$

and taking into account the formula for the velocity of the transverse wave generated by cross-section torsion (see e.g. [6, 27]):

$$V_S = \sqrt{\frac{G}{\rho}} \tag{10}$$

basic differential equation is obtained (see [7]):

$$\frac{\partial^2\Theta}{\partial t^2} = V_S^2\frac{\partial^2\Theta}{\partial x^2} \,, \tag{11}$$

simplification of the solution of which may be in the form [6, 7]:

$$\Theta(x,t) = U(x)V(t), \tag{12a}$$

$$\begin{cases} U(x) = C_1\cos\left(\dfrac{\omega x}{V_S}\right) + C_2\sin\left(\dfrac{\omega x}{V_S}\right) \\ V(t) = C_3\cos(\omega t) + C_4\sin(\omega t) \end{cases} \tag{12b}$$

where ω is the angle frequency, and $C_i$are are constants dependent on the boundary conditions.

Including in the solution (12) of enhancement at the end of the rod: x=0 → Θ=0 leads to:

$$\Theta(x=0,t) = [C_1\cos(0) + C_2\sin(0)][C_3\cos(\omega t) + C_4\sin(\omega t)] = 0 \,, \tag{13}$$

and in consequence to condition C_1=0, which additionally simplifies the final form of the solution:

$$\Theta(x,t) = C_2\sin\left(\frac{\omega x}{V_S}\right)[C_3\cos(\omega t) + C_4\sin(\omega t)]. \tag{14}$$

In the RC/TS apparatus drive system inducing torque has a certain mass, which is usually quite significant (Fig. 2). Thus, it can be assumed that the load torque T is generated by accelerated weight of the drive system of inertia I_0 according to the formula:

$$T = I_0\frac{\partial^2\Theta}{\partial t^2} \,. \tag{15}$$

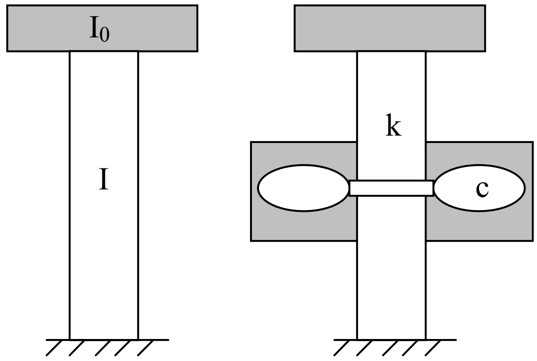

Fig. 2. Sample models in RC/TS apparatus. a) rod with mass, b) Kelvin-Voigt model

The test sample corresponds to the external force by reaction according to formulas (4) and (5), which can be written as follows:

$$I_0 \frac{\partial^2 \Theta}{\partial t^2} = -GJ \frac{\partial \Theta}{\partial x}, \tag{16}$$

and taking into account transformed relation (8) and the corresponding derivative solution (14):

$$\frac{\partial \Theta}{\partial x} = C_2 \frac{\omega}{V_S} \cos\left(\frac{\omega x}{V_S}\right)\left[C_3 \cos(\omega t) + C_4 \sin(\omega t)\right]. \tag{17}$$

$$\frac{\partial^2 \Theta}{\partial t^2} = -C_2 \omega^2 \sin\left(\frac{\omega x}{V_S}\right)\left[C_3 \cos(\omega t) + C_4 \sin(\omega t)\right]. \tag{18}$$

the following relationship is obtained for the free rod end (x=L):

$$-I_0 C_2 \omega^2 \sin\left(\frac{\omega L}{V_S}\right)\left[C_3 \cos(\omega t) + C_4 \sin(\omega t)\right] = -G \frac{I}{\rho L} C_2 \frac{\omega}{V_S} \cos\left(\frac{\omega L}{V_S}\right)\left[C_3 \cos(\omega t) + C_4 \sin(\omega t)\right]. \tag{19}$$

After simplifying and taking into account the mutual dependence (10), formula (19) takes the form:

$$I_0 \frac{\omega L}{V_S} \sin\left(\frac{\omega L}{V_S}\right) = I \cos\left(\frac{\omega L}{V_S}\right), \tag{20}$$

or form well known by the researchers dealing with this subject [6, 22, 15]:

$$\frac{I}{I_0} = \frac{\omega L}{V_S} \tan\left(\frac{\omega L}{V_S}\right) \text{ albo } \frac{I}{I_0} = \beta \tan(\beta). \tag{21}$$

From equation (21) the searched velocity V_S is determined, burdening the sample torque acting harmonically of the resonant frequency $\omega = \omega_r$.

The above derivation does not include the effect of absorption of energy by the vibrating material. This effect, in the form of damping, can be included in a simple manner by using SDOF model with the assumptions of Kelvin-Voigt - Figure 2. [6]. Torque T affecting the system produces not only the elastic response of the sample material (see (4)), but also the reaction associated with the viscosity of the material, which is proportional to the velocity of rotation of the sample cross-section:

$$T = GJ \frac{\Theta}{L} + \frac{\mu_c J}{L} \frac{\partial \Theta}{\partial t} = K\Theta + C \frac{\partial \Theta}{\partial t}, \tag{22}$$

where μ_c is the constant material viscosity, K – constant torque elasticity, and C – constant damping. If one adds up the inertia forces originating from the accelerated mass of the propulsion system (see formula (15)), then:

$$T = K\Theta + C\frac{\partial\Theta}{\partial t} + I_0\frac{\partial^2\Theta}{\partial t^2}. \tag{23}$$

In SDOF model, the harmonic load is sinusoidal and it is described by the following equation:

$$T = T_0 \sin(\omega t), \tag{24}$$

where T_0 is the maximum amplitude of moment T. Comparing formulas (23) and (24), a basic relationship between external and internal influences in the RC system is obtained:

$$T_0 \sin(\omega t) = K\Theta + C\frac{\partial\Theta}{\partial t} + I_0\frac{\partial^2\Theta}{\partial t^2}. \tag{25}$$

The solution to the equation, assuming that the damping will not exceed the critical value [26, 6]:

$$C_{cr} = \sqrt{4KI_0}, \tag{26}$$

is the open formula for the value of angle Θ:

$$\Theta = \Theta_0 \sin(\omega t + \pi + \varphi), \tag{27}$$

where

$$\Theta_0 = \frac{T_0}{\sqrt{\left(K - I_0\omega^2\right)^2 + C^2\omega^2}}, \tag{28}$$

is the maximum amplitude of Θ, and φ – the phase shift angle, which can be determined from the relation:

$$\varphi = \arccos\left(\frac{-K + I_0\omega^2}{\sqrt{\left(K - I_0\omega^2\right)^2 + C^2\omega^2}}\right). \tag{29}$$

Accelerometer installed on the selected item of drive weight records the acceleration, which can be described analytically by differentiating the solution twice (27):

$$\frac{\partial^2\Theta}{\partial t^2} = -\Theta_0\omega^2 \sin(\omega t + \pi + \varphi). \tag{30}$$

If the system oscillates at the resonant frequency, in the case of small damping values this frequency is very close to the natural frequency ω_n, and then if $K - I_0\omega^2 = 0$, the phase angle is 90^o and the following relationship is true:

$$\omega = \sqrt{\frac{K}{I_0}} = \omega_n. \tag{31}$$

From the solution (26) directly results the definition of the damping coefficient D, which after taking into account (28) takes the form [6]:

$$D = \frac{C}{C_{cr}} = \frac{C}{\sqrt{4KI_0}} = \frac{C}{2I_0\omega} = \frac{\mu_c J}{2I_0\omega L}. \tag{32}$$

In determinations of the D-value the technique of registration of the nature of the oscillations amplitude fading after their instantaneous forcing, is often used. If the damping is less than the critical value, the equation describing the fading oscillations samples is [6, 21]:

$$z(t) = Ae^{-\delta\frac{t\omega_d}{2\pi}}\sin(\omega_d t + \varphi_d), \tag{33}$$

where A is a constant, δ – logarithmic damping factor, and ω_d and φ_d are the angular frequency and phase angle of damped oscillations. There is a relation among the C and δ values [26]:

$$C = \frac{I_0\omega_d}{\pi}\delta, \tag{34}$$

therefore, the damping factor may be re-defined in the following way:

$$D = \frac{C}{2I_0\omega} = \frac{\delta\omega_d}{2\pi\omega} = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \tag{35}$$

and

$$\frac{\omega_d}{\omega} = \sqrt{1 - D^2}. \tag{36}$$

Analyzing the obtained results one can also conclude that with the increase in the damping value the resonant frequency becomes larger, and deviates from the frequency of the system's own oscillation [6].

A slightly different technique of interpretation of the test results in the RC apparatus is the use of retrospective analysis, based on an iterative matching of special analytic or semi-analytic solutions to the measurement results. If the mathematical description of the changes in the angle of torsion Θ in time t and at the length of the sample x will re-use the viscoelastic Kelvin-Voigt model, the differential equation may take the following form [15]:

$$\frac{\partial^2\Theta}{\partial t^2} = \frac{G}{\rho}\frac{\partial^2\Theta}{\partial x^2} + \frac{c}{\rho}\frac{\partial^3\Theta}{\partial x^2\partial t}. \tag{37}$$

Considering the boundary conditions, one of the dedicated solutions (37) involves the following relation [15]:

$$\frac{T_0(\omega)}{\Theta_0(\omega)} = \frac{I\omega^2}{\beta\tan(\beta)} - I_0\omega^2. \tag{38}$$

Applying the approach presented in publications [15, 16], after substitution of (38) to the shear module G in a combined form (in the formula β, see (21)):

$$G^* = G_R + iG_I, \tag{39}$$

and taking into account the phase shift φ between applied torque and forced angle of twist of the sample cross-section, presented in the form of the imaginary part of torque T, the following form of the modified relation (38) is obtained:

$$\frac{T_0(\omega)e^{-i\varphi(\omega)}}{\Theta_0(\omega)} = \frac{I\omega}{H\sqrt{\frac{\rho}{G^*}}\tan\left(\omega H\sqrt{\frac{\rho}{G^*}}\right)} - I_0\omega^2. \tag{40}$$

This relation takes the form of so-called transfer function, which describes the relationship between the transmitted signal (harmonic load), and received signal (harmonic shift). With the measurement results in the form of T/Θ in the entire analyzed frequency range ω, using the technique of iterative selection of stiffness modulus values, one can approximate the analytical solution form (40) to the measured values, thus estimating the value of the searched G. In interpretation practice, the following form of transfer function is more frequently used [15, 16, 21]:

$$TF(\omega)=\frac{T_0(\omega)e^{-i\varphi(\omega)}}{\Theta_0(\omega)}=\left(I_0+\frac{I}{3}\right)\omega_r^2\left(1-\left(\frac{\omega}{\omega_r}\right)^2+i2D\left(\frac{\omega}{\omega_r}\right)\right). \tag{41}$$

A more detailed function that takes into account the specific characteristics of the propulsion system geometry can be found in [17]

$$TF(\omega)=\frac{-\left(\frac{\omega}{\omega_r}\right)^2\left(\frac{Br_m r_a}{I_t}\right)}{1-\left(\frac{\omega}{\omega_r}\right)^2+\left(c_E r_m^2+c_S\right)\frac{i\left(\frac{\omega}{\omega_r}\right)}{I_t\omega_r}}, \tag{42}$$

where: B is a dimensionless magnetic efficiency factor of coils and magnets of the drive system, r_m - the distance of magnets from the axis of sample, r_a - the distance of acceleration sensor from the axis of sample, c_E - damping coefficient associated with energy losses in the coils of the drive system, c_S - damping coefficient associated with energy losses in the sample, and I_t - the total moment of inertia of the sample mass and the propulsion system.

Presented in this article the theoretical basis for modeling the phenomena occurring during the tests in the RC apparatus represent only a small part of the results of the work that is carried out in laboratories around the world.,The example of an extensive mathematical model is the Electromechanical Model presented in work [28], and for the interpretation of only the tests results it is the Complex Exponential Method, which is described in detail in publication [25]. Also indirect methods, such as neuro-fuzzy networks (ANFIS, see [1]), are used in elaboration of test results.

DESCRIPTION OF THE DEVICE. TESTING METHODS.

The described apparatus (31-WF 8500) is the latest product of Wykeham Farrance, purchased by the Department of Geotechnical Engineering and Road Construction, University of Warmia and Mazury in Olsztyn in 2011. It is a dual-function device acting as a resonant column (RC) or the cyclic torsional shear apparatus (TS). It was designed to test the mechanical properties that describe the static and dynamic deformation characteristics of soil samples or weak rocks in the small and medium-sized amorphous deformation (up 0.1%). Depending on the nature of the load, the apparatus is designed for dynamic or static tests of the soil in the form of cylindrical samples with a diameter of 50 mm or 70 mm.

Tested test sample is placed in a sealed chamber of triaxial pressure, based on the basis equipped with two drain valves with sensors. One of the valves is used for measuring the pressure in the soil pores, the second - to control the pressure surge. The sample in a sealed rubber membrane is placed on a pedestal fitted with a porous stone. Changes in volume of the samples are measured using volumeter. With the compressor and the pressure application one may carry out, in a controlled manner, the isotropic consolidation process until the desired level of average effective stress. In addition, samples may be impregnated into the state of partial or complete saturation by applying compensating pressure, controlling the value of the parameter B [29] on ongoing basis.

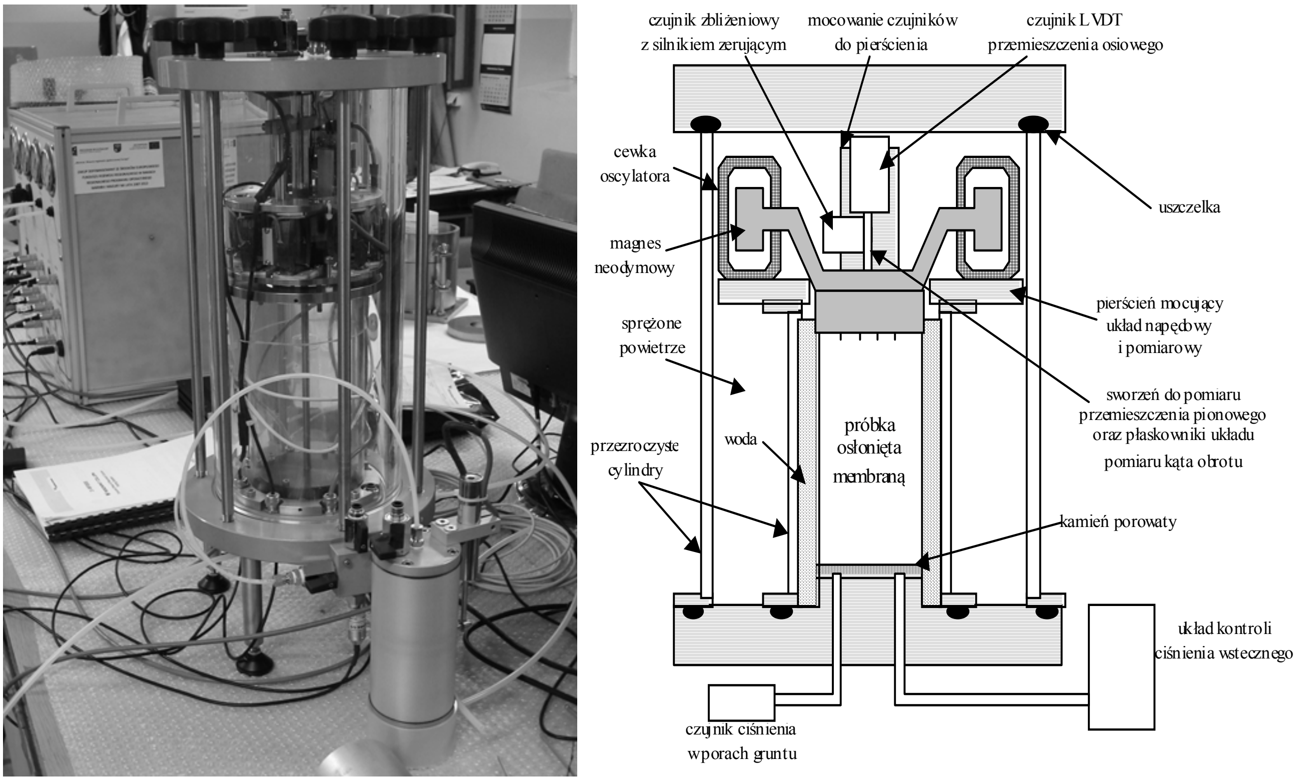

Fig. 3. Picture and scheme of RC/TS apparatus

The basic component of the apparatus is an electromagnetic drive system (Figure 4), whose task is to load the upper free end of the sample. The drive system includes four permanent neodymium magnets that are on the four arms of the cross. Cross with the magnets is attached with screws to the metal head based on the upper surface of the sample. Magnets are placed between the pairs of driving coils fixed to flat aluminum ring (Figure 4) forming a platform connecting the stator of the propulsion system with the cylinder housing. Transparent, polycarbonate supporting cylinder is also the chamber for the liquid surrounding the sample. This system allows the charging of the top free sample by the torque of given force characteristics.

Fig. 4. A view of the drive system used in the apparatus WF8500

The WF8500 apparatus measuring system enables control of applied load and tracking of the response of soil sample using direct measurements of the following parameters: the pressure in the chamber, the water pressure in the soil pores, compensating pressure, the axial displacement of the upper surface of the sample, sample volume change, rotation and acceleration of the sample head.

The measuring system of angular movement is composed of the accelerometer mounted on the drive system rotor and proximity sensors mounted on the stator. The accelerometer generates signal that has an amplitude proportional to the measured acceleration. After amplification this signal is forwarded to the resonant column controller and the computer. The value of the torque is proportional to the current flowing in the coils, which is controlled directly from a computer through an electronic system used for control and data acquisition.

Test in the resonant column

After the preparation and consolidation of soil samples, the sample is subjected to the torque of constant amplitude and variable frequency in the range, which includes the induced resonant frequency of the entire system (see ASTM D4015-92). This RC apparatus allows for testing at frequencies from 10 Hz to 300 Hz.

The frequency of the load is gradually or continuously increased from a preset minimum value until the reaction of the system (the amplitude of the oscillations or acceleration) is locally the greatest and the phase shift between the transmitted signal and the measured acceleration is equal to π. The lowest frequency with the local maximum response function of the sample is marked as the fundamental frequency of the sample oscillations with the rotor. This frequency is a function of the soil stiffness, sample geometry and characteristics of the apparatus. The result of the study is the resonant frequency f_r, from which one can determine G_{max} (see formulas (10) and (21)) and the frequency f_1 and f_2, which allow for specification of the value of the damping coefficient using the "half-power bandwidth method".

Torsional shear (TS) testing

In this test the sample is subjected to torque of sinusoidal changing values and low frequencies (typically below 2 Hz). The amplitude and number of load cycles are additional parameters of the test. Torque is applied in the same manner as in the RC test. Its value is calculated based on calibration coefficients and the value of the current flowing in the stator coils. In accordance with ASTM-D4015-92 (2000) [30] the average value of the tangential component of the stress is determined as $0.8\tau_{max}$, where:

$$\tau_{\mathbf{max}} = \frac{T \cdot R}{J} \tag{43}$$

where R is the sample radius.

Amorphous deformation is calculated using the following formula:

$$\gamma = \frac{r \cdot \Theta}{H} \tag{44}$$

where Θ – twist angle; H – sample height; r – distance between the analyzed sample point and the sample axis.

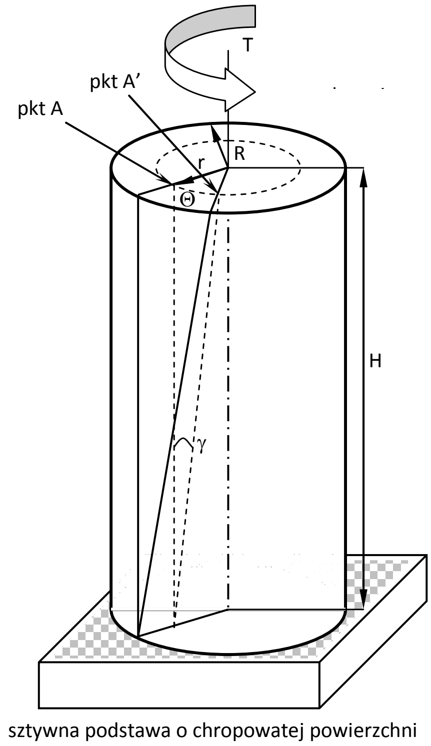

Fig. 5. Computational scheme for interpreting the results of torsional shear

Torsion angle Θ of cross-section is measured using a proximity sensor or accelerometer. In accordance with the standard ASTM-D4015-92 (2000) [30] it is assumed that the average amorphous deflection of the cylindrical sample constitutes a deformation at the point lying within 0.8 of the radius R from the axis of the sample.

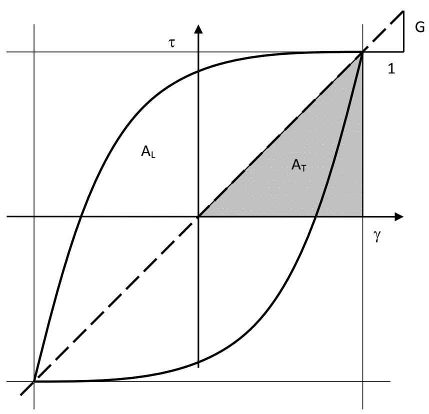

Fig. 6. Computational scheme for interpreting the results of torsional shear test

The idea of determining the value of the shear modulus and damping factor of the sample soil material is based on the stress – strain relation, designated in the form of hysteresis loop generated by the torque and shift measured by proximity sensor at the free end of the sample. For each cycle, the measurement of secant module of shear is taken, according to the scheme shown in Figure 6 The damping factor of the sample material is calculated on the basis of the hysteresis loop area (A_L) and the surface of the triangle (A_T) representing the potential energy stored by the sample material, Figure 6 [4]. Damping factor is calculated from the formula:

$$D = \frac{A_L}{4 \cdot \pi \cdot A_T} = \frac{A_T}{2 \cdot \pi \cdot G \cdot \gamma^2}\,. \qquad (45)$$

SUMMING UP

Properly designed structure must meet the established utility functions without excessive deformation. Designing buildings for the normal operation conditions requires new, more comprehensive analytical methods and more sophisticated substrate models. In such analysis one must take into account the variability of soil stiffness (deformation module) in a wide range of deformation. The main difficulty in using multiple computational methods is the right choice of realistic values of the parameters describing the deformability of the soil. The test in apparatus RC/TS allows for determination of reliable values of the modules in the field of small and medium-sized elastic deformations and damping properties of the soil. Relevant research programming of tests in the RC/TS apparatus can also determine the nature of the variability of elastic modules in strain function, which is particularly important in times of commonly used computer applications using Finite Element Method.

The theoretical basis and description of the equipment and research methodology, presented in this paper, constitute the first part of the publication devoted to research in the RC/TS apparatus. The second part will provide detailed procedures for equipment calibration and sample test results of sample soils.

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SUMMARY

Dyka I., Srokosz P.: **Soil testing in the RC/TS apparatus. Part 1.**

The study presents the characteristics of soil tests performed in resonant column (RC) and torsional shear apparatus (TS). The focus was placed on theoretical analysis of the phenomena occurring during the tests. The aspects of the mathematical solutions were presented, the results of which are used in the calibration procedure and in the interpretation of recorded measurements. Research methodology and the description of the device which is located in the Chair of Geotechnics and Road Engineering at University of Warmia and Mazury in Olsztyn were also presented.