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The use of resistivity and seismic cone penetration tests for site characterization

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Abstract: *The use of resistivity and seismic cone penetration tests for site characterization.* Recent application of cone penetration tests to geotechnical and environmental site characterization has generated a wide collection of new sensors. This paper presents methods of interpreting geotechnical in situ investigations carried out by electrical resistivity (RCPT) and seismic (SCPT) cones. It contains some fundamental equations and the description of in situ electrical resistivity and shear wave velocity measurements and presents the results of SCPT and RCPT investigations at the experimental Stegny site in Warsaw. The aim of the paper is to present the approach to determination of shear wave velocity and porosity of clayey soils. According to the test results obtained, it can be concluded that both applied techniques are very useful to estimate the distribution of clay deposits and some of their geotechnical parameters.

Key words: RCPT, SCPT, electrical resistivity, shear wave velocity, porosity.

INTRODUCTION

A great demand for in situ tests to assess geotechnical and environmental parameters caused evolution of CPTU measuring sensors. Modern CPTU cones (e.g. Envirocone, Chemoprobe, Visioncone, RCPT, SCPT, LIF) include sensors for determination of soil moisture content, temperature, pH, dielectric constant, electrical resistivity and seismic wave velocities (Campanella et al. 1986, Olie et al. 1992, Pluimgraaff et al. 1995, Hryciw and Raschke 1997, Lunne et al. 1997). Mentioned devices can be very useful in urban areas, waste disposal and contaminated sites for proper design of engineering structures and contamination transport modelling.

This paper presents the results of electrical resistivity (RCPT) and seismic (SCPT) tests carried out at the site in Warsaw. Geophysical methods have been applied to soil sciences for a considerable period and the addition of seismic and resistivity measurements during standard CPTU gives information about soil parameters in details (Campanella and Weemees 1990, Robertson 2001, Mayne and Campanella 2005). The use of resistivity module in RCPT test permits to evaluate groundwater quality (contamination), soil porosity and saturation. The seismic measurements added to SCPT cone allow to measure compression and shear wave velocities.

TEST PROCEDURES AND EQUIPMENT

There are several kinds of geophysical tests that can be used for geological, geotechnical and environmental applications including surface analysis of seismic waves (SASW), electrical resistivity and electromagnetic methods. Recently, the most developing techniques which are represented by combination of standard geotechnical tests with geophysical module have been used in the field. The combination of standard penetration tests and seismic measurements and electrical resistivity module has made a significant improvement to the CPTU test. The measurement of shear wave velocity using SCPT seismic cone (Fig. 1a) enables to obtain the initial shear modulus of soil at very small strain level, less than 0.0001%. The knowledge about it is important in practical geotechnical solutions especially in earthquake engineering and in prediction of soil structure interaction (LoPresti et al. 1999, Bajda 2002, Stokoe et al. 2005, Markowska-Lech 2006). Elastic wave theory relates the small strain shear modulus (G_0) using:

$$G_0 = \rho \cdot V_s^2 \tag{1}$$

where:
G_0 – initial shear modulus [MPa],
ρ – soil mass density [Mg/m^3],
V_s – shear wave velocity [m/s].

During standard cone penetration test the following parameters are usually measured: cone resistance q_c, sleeve friction resistance f_s and pore pressure u. The SCPT cone is additionally equipped with two geophones located in the distance of 1 m which permit to measure shear wave velocity in one-meter layer. During each SCPT test the cone penetration is stopped every 1m and from the ground surface shear wave is generated. When the impulse arrives to the upper geophone, the oscilloscope starts and the impulse which is running to the lower geophone is being recorded (Fig. 1b). The travel time obtaining from the oscilloscope readings and the distance between geophones allow to estimate the shear wave velocity from:

$$V_s = \frac{h}{t} \tag{2}$$

where:
V_s – shear wale velocity [m/s],
h – distance between geophones [m] (in case of SCPT cone h = 1.0 m),
t – travel time from 1st (upper) to the 2nd (lower) geophone [s].

The electrical resistivity of soils is a function of a number of soil properties, including mineralogy, particle size distribution, porosity (intergranular and fracture), water content, degree of saturation, salt concentration of the pore fluid and temperature. These parameters affect the electrical resistivity, but in different ways and to different extents (Keller and Frischknecht 1966, Abu-Hassanein et al. 1996, Lech, 2006). Soils, unconsolidated sediments and rocks are principally composed of silicate minerals, which are electrical insulators and they carry no current. The air medium is an insulator too and the current is mainly carried by ions in pore solutions. In most porous materials there is an empirical relationship established by Archie (1942), between the ratio of the bulk and pore fluid resistivity (called the formation factor) and the porosity. The relationship, called Archie's law is:

$$F = \frac{\rho_{bSAT}}{\rho_f} = a \cdot n^{-m} \tag{3}$$

where:
F – formation factor [–],

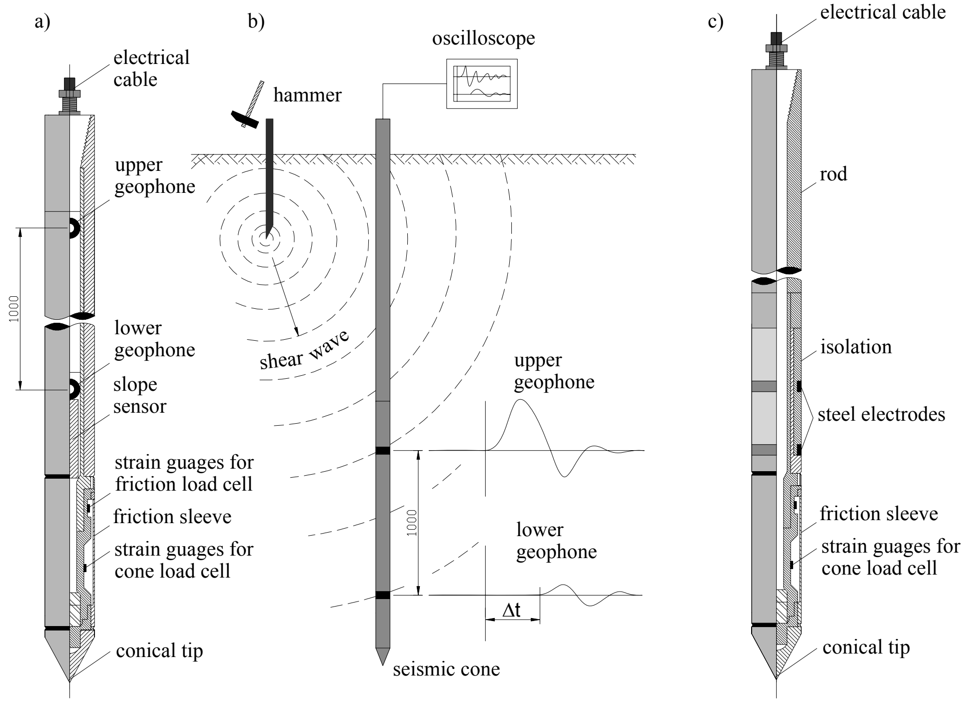

FIGURE 1. The SCPT seismic cone (a) with schematic diagram of shear wave measurements (b) and RCPT resistivity cone (c)

ρ_{bSAT} – electrical resistivity of soil in fully saturated conditions [Ω·m],
ρ_f – electrical resistivity of fluid in pore spaces [Ω·m],
n – porosity [–],
a, m – empirical constants ("a" in most cases is equal to 1; "m" varies between 1.4 for quartz sand and 3.0 for sodium montmoryllonite (Atkins and Smith 1961, Jackson et al. 1975)).

The RCPT resistivity cone (Fig. 1c) is equipped with a module made from two electrodes separated by insulators. The measuring system of the penetrometer enables registration of electrical conductivity (δ [S] = 1/R [Ω]) within the range from 0 to 400 mS. The measurement is carried out with AC current at the frequency level of 2000 Hz. To determine soil electrical resistivity (in Ω·m) the calibration tests was carried out in a chamber using different concentrations of potassium chloride solutions. The RCPT test results were recorded by *TouchScreen* data acquisition system.

IN SITU INVESTIGATIONS

The in situ tests were carried out at the experimental site located in the southern district of Warsaw in the Vistula river valley. The stratigraphy consists of Quaternary deposits developed as fine and medium dense sand layers of thicknesses not exceeding 7 m, underlain by overconsolidated Pliocene clays. The free groundwater table is at a depth of

3.2 m (Fig. 2). The index properties of clays at the Stegny site are listed in Table 1. Cone penetration tests (SCPT and RCPT) were carried out using 200 kN hydraulic equipment in 10 profiles to the depth of about 15 m.

TEST RESULTS AND DISCUSSION

In this paper selected results from in situ investigations are presented. Figure 3 presents the example of RCPT and SCPT test results in the form of continuous soil profiles of cone resistance q_c, friction

TABLE 1. Index properties of cohesive soils at the Stegny site

Parameter	Unit	Clay	Silty clay	Clay
depth	[m]	4.3–7.7	7.7–8.9	8.9–12
fines content	[%]	68–80	30–34	32–46
w_n	[%]	26–34	19–25	19–27
LL	[%]	77–98	56–76	86–110
PI	[%]	52.6–76.4	39.3–55.6	61.9–84.0
ρ	[t/m^3]	2.0–2.1	2.0–2.4	2.0–2.1

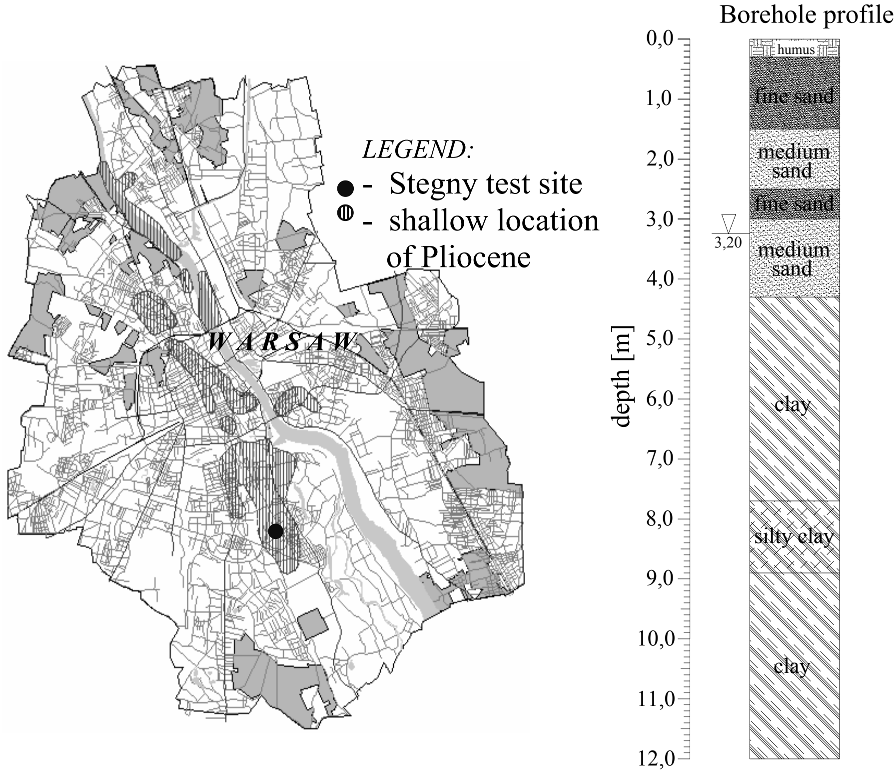

FIGURE 2. The location of the Stegny test site in Warsaw and borehole profile

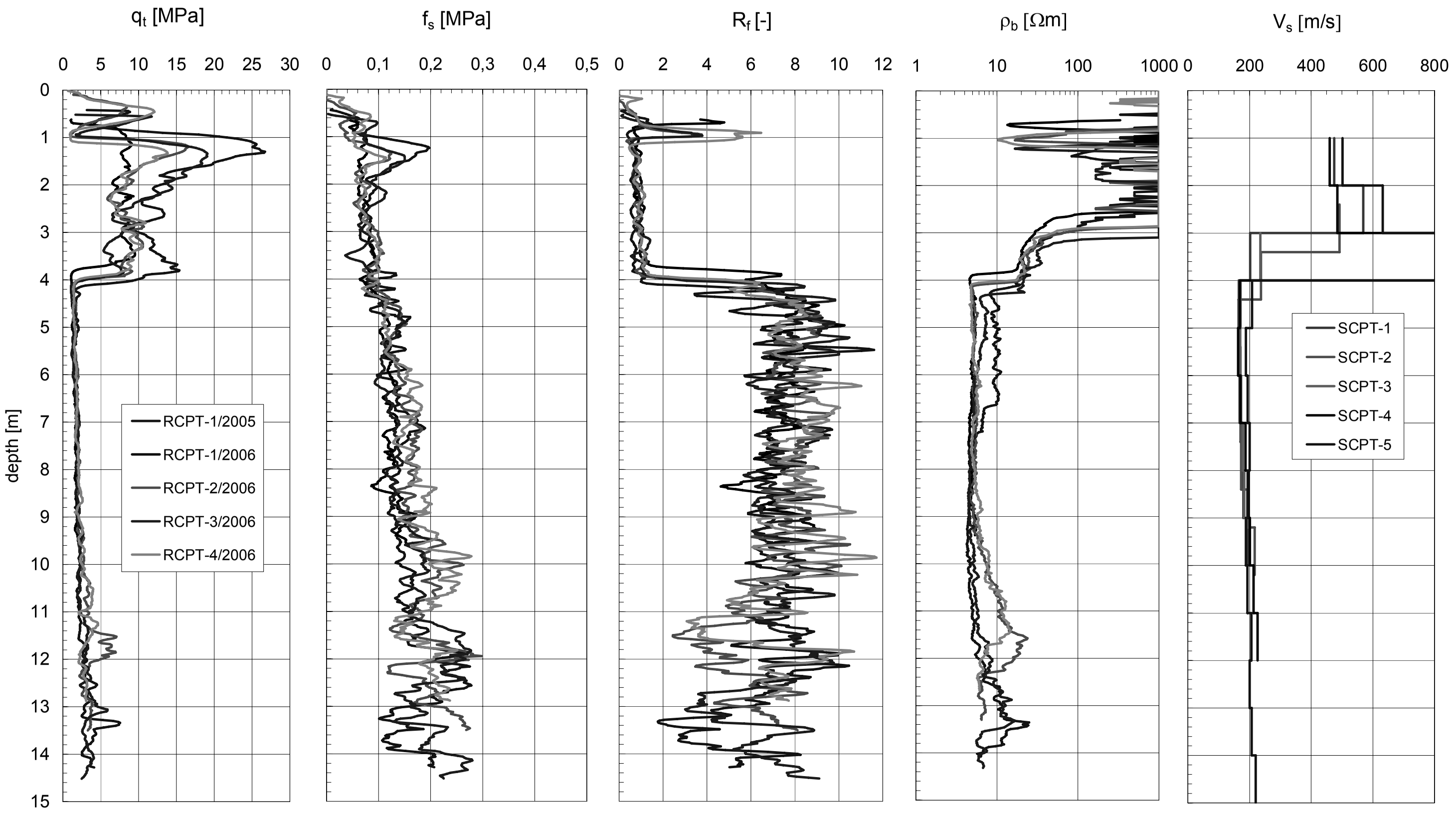

FIGURE 3. Cone penetration test results with electrical resistivity and shear waves velocity measurements at the Stegny site in Warsaw

ratio R_f, sleeve friction resistance f_s, electrical resistivity ρ_b and shear wave velocity V_s. There is a visible difference among sand and clay on these graphs. Values of cone resistance for sand vary from about 8 MPa to 25 MPa while for clays from 2 MPa to 5 MPa. The type of soil can be classified using friction ratio R_f. It sharply increases from 1 to 8 at the depth of about 4.2 m and it separates sands and clays.

Similarly as cone resistance and friction ratio results, the resistivity and shear wave velocity plots show differences between soil layers. In Figure 3 sands showed relatively higher resistivity values than clays. The presence of fine particles in clays, decrease the resistivity due to the presence of conducting clay minerals and the increase of specific surface area (in clayey soils electrical conduction takes place in the surfaces of electrically charged clayey minerals and it is known as a surface conduction). Values of electrical resistivity for sands are in range of about 100 and 1000 Ω·m while in clays does not exceed 10 Ω·m. Electrical resistivity in sands at the depth between 3 and 4.2 m is decreasing from the value from 100 to 20 Ω·m due to the influence of ground water table at the depth of 3.2 m.

Observing Figure 3 there is a significant difference between values of shear wave velocity at the depth of about 4 m due to effect of soil type changes and influence of ground water table. Values of shear wave velocity in sands exceed 500 m/s while in cohesive soils vary from 150 to 200 m/s (Bajda 2002, Markowska-Lech et al. 2007). It was also noticed that resistivity plot correlates with shear wave velocity, cone resistance and friction ratio plots.

On the basis of field investigations simple and multiple regression analyses were performed with V_s and n as the dependent parameters and independent parameters including q_c, f_s, σ'_{v0} LI and ρ_b. The purpose of this analyses is to develop a correlation to estimate porosity (Fig. 4) and shear wave velocity (Fig. 5) in clays at Stegny site. Taking into account that clayey soils are fully

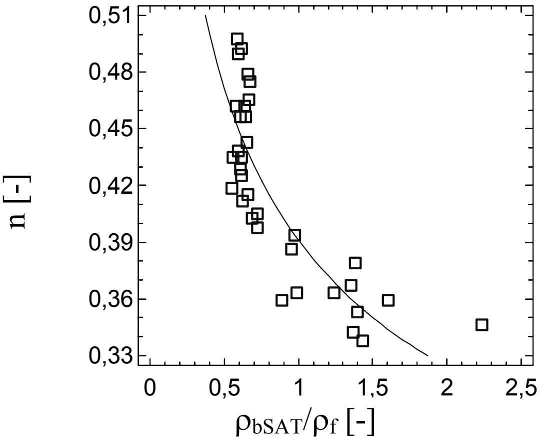

FIGURE 4. Relationship between porosity n and formation factor F (ρ_{bSAT}/ρ_f)

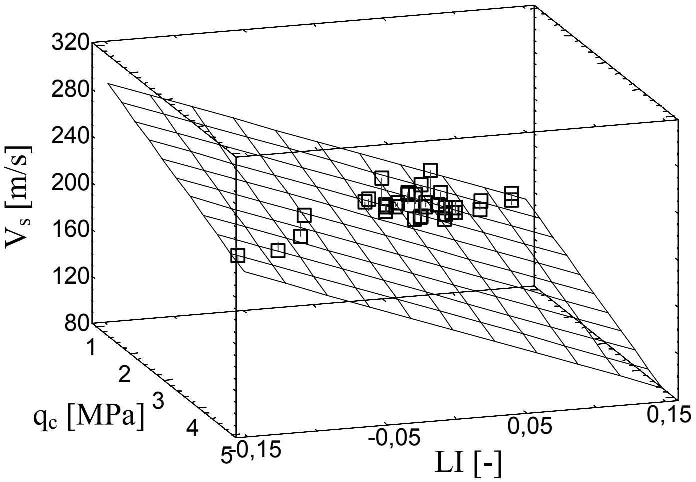

FIGURE 5. Relationship between shear vawe velocity V_S and cone resistance q_c and liquidity limit LI

saturated material and using Archie's formula we can write that porosity of clays at Stegny site is:

$$n = 0.39 \cdot \left(\frac{\rho_{bSAT}}{\rho_f} \right)^{-0.27} \qquad (R^2 = 69.9\%) \qquad (4)$$

where:
n – porosity [–],
ρ_{bSAT} – electrical resistivity of soil in fully saturated conditions [Ω·m],
ρ_f – electrical resistivity of pore fluid measured by conductivity meter in laboratory [Ω·m] (ρ_f was found to be 8.3 Ω·m),

The second purpose is to give the estimation of V_s in clays directly from standard cone penetration test. The shear wave velocity may be calculated according to the following equation:

$$V_s = -17.15 \cdot q_c - 429.26 \cdot \text{LI} + 239.36 \quad (R^2 = 65.6\%) \qquad (5)$$

where:
q_c – cone resistance [MPa],
LI – liquidity index [–].

This relationship may have practical meaning due to the possibility to determine initial shear modulus (G_0) using standard cone penetration tests without geophones.

In order to verify proposed relationships, both porosity calculated according to proposed formula and obtained in laboratory tests (Baranski et al. 2004) were ploted in Figure 6. According to equation (4) and laboratory tests porosity in tested clays vary between 0.30 and 0.50.

Figure 6 shows also changes of shear wave velocity based on SCPT tests and predicted from proposed relationship (5). The shear wave velocity both measured and predicted vary between 160 and 220 m/s. Comparing values from SCPT and predicted on the basis of cone resistance and liquidity index it can be noticed that they are similar and the velocity is growing with the depth. Moreover, observing Figure 6 it can be noticed that for the maximum value of porosity we have the minimum value of shear wave velocity.

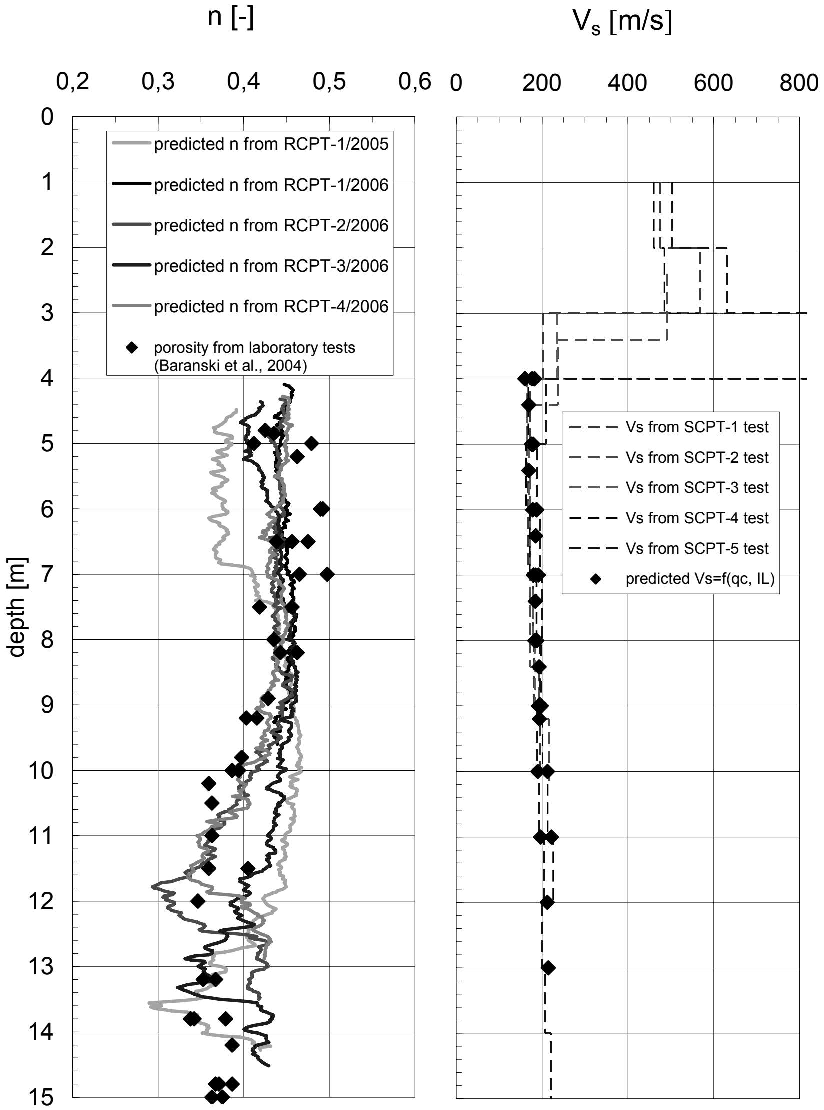

FIGURE 6. Measured and predicted values of porosity and shear wave velocity for clays at Stegny site

CONCLUSIONS

The RCPTU and SCPTU cones are a combination of standard geotechnical devices with geophysical modules. These tools provide a simple in situ testing methodology and give more reliable site characterization. In conclusion it can be drawn that the trend for measured porosity and shear wave velocity is similar to that proposed in this study. The most reliable method to obtain the shear wave velocity is the direct in situ measurements. The predicted porosity values using electrical resistivity method compared well with those measured in laboratory. Hence it can be concluded that the electrical measurements could predict porosity in clays. Proposed equations are still preliminary and needs more verification by being applied at different clay sites.

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LIST OF SYMBOLS

f_s	sleeve friction resistance
F	formation factor
G_0	initial shear modulus
h	distance between geophones
LI	liquidity index
LL	liquidity limit
n	porosity
PI	plsticity index
q_c	cone resistance
R_f	friction ratio
t	time
V_s	shear wave velocity
w_n	natural water content
ρ	soil mass density
ρ_b	electrical resistivity
ρ_{bSAT}	electrical resistivity in fully saturated conditions
ρ_f	electrical resistivity of fluid
δ	electrical conductivity
σ'_{v0}	horizontal stress in effective conditions

Streszczenie: Obecnie obserwuje się dynamiczny rozwój zastosowań badań geotechnicznych, w tym zwłaszcza sondowań, do oceny stanu środowiska. W związku z tym można zaobserwować zapotrzebowanie na specjalistyczne badania podłoża gruntowego, mogące pomóc w określeniu różnych parametrów stosowanych w geotechnice środowiskowej, takich jak np. temperatura gruntu, oporność elektryczna, odczyn pH gruntu, potencjał redoks i innych. W niniejszym artykule przestawione zostały wyniki sondowań geotechnicznych stożkiem wyposażonym w moduł do pomiaru oporności elektrycznej gruntu (RCPT) oraz stożkiem sejsmicznym (SCPT). W artykule przedstawiono podstawowe informacje na temat techniki badań, opis stosowanych urządzeń oraz wyniki badań na terenie poligonu badawczego na Stegnach w Warszawie. Celem pracy było określenie zależności empirycznych pomiędzy parametrami uzyskanymi z badań sondami RCPT oraz SCPT a porowatością i prędkością fali poprzecznej badanych gruntów spoistych. Na podstawie przeprowadzonych badań można wnioskować, że zastosowane urządzenia pozwalające na pomiar oporności elektrycznej i prędkości rozchodzenia się fali poprzecznej w gruncie mogą być z powodzeniem wykorzystane do rozpoznania budowy geologicznej podłoża i określania pewnych parametrów gruntu.

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