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## Estimation of geotechnical properties of municipal solid waste by field method

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### ABSTRACT

As biodegradation proceeds, municipal solid wastes (MSW) acquire pronounced soil-like properties and upon completion of the process can be used as the foundation. The solid waste massif is an inhomogeneous soil-like mass which requires non-destructive and minimally invasive methods of research. The cone penetration testing of MSW by piezocone (CPTU) in combination with the multichannel analysis of surface waves (MASW) provide extensive data about physico-mechanical properties of wastes, which are usually unavailable in traditional approaches and which can be directly used in geotechnical stability calculations of the waste massif.

**Keywords:** CPTU of MSW, specific gravity profile

### 1 INTRODUCTION

The biological decomposition of municipal solid waste is associated with the decomposition of the organic component and is accompanied by the reduction of the particle size of the remaining material. As biological degradation proceeds, the MSW becomes more like soil by its characteristics and features of the stress-strain state development with the application of load. The term "landfill soil" is proposed for the decomposed waste at the age of more than 25 years. It is necessary to apply specific field and laboratory test procedures for such soil-like materials, taking into account their particular properties as well as sanitary and epidemiological restrictions. One of the minimally invasive methods of field evaluation of solid waste is the method of cone penetration testing by cones (CPT) and piezocones (CPTU).

### 2 PURPOSE OF THE STUDY

The main goal of the research was to obtain and evaluate by modern non-destructive and minimally invasive field methods the MSW physico-mechanical characteristics which are necessary for subsequent geotechnical calculations of the solid waste massif as a structure foundation.

### 3 METHODOLOGY OF WASTE FIELD TESTING BY CPT(U)

Modern recording equipment, devices and techniques of CPT (U)-soundings allow obtaining a wide variety of data on the characteristics of the investigated material. At the same time, the personnel contact with the MSW material is minimized and consists in handling equipment units immersed in the garbage array (tips, sounding rods, and connecting cables).

The most versatile data can be obtained by examining the waste array by electrical piezocones. This type of test is indicated by the abbreviation CPTU. In this case, 5 parameters are registered (cone resistance  $q_c$ , sleeve friction  $f_s$ , inclination from the vertical in 2 axes, and pore pressure  $u_2$ ). All information is transmitted through the data collection system to the control computer in real time.

Immediately before CPTU sounding, a saturated and deaerated filter must be installed in the piezocone.

The combination of static sounding by CPTU and field survey by the method of multichannel analysis of surface waves (MASW survey) (Ofrikhter and Ofrikhter, 2013) provides data on the speed of waves in the waste array, which can later be used for an extended interpretation of sounding results. For this purpose, the CPTU studies reported in this paper were conducted in the area of MASW survey recording points (Fig. 1) (Ofrikhter and Ofrikhter, 2013).

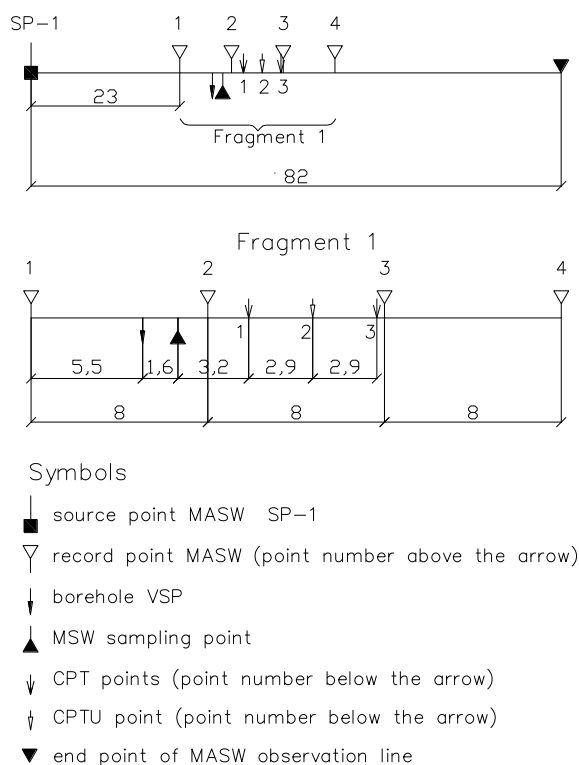


Fig. 1. Connection of the boreholes and penetration points to the MASW observation line. Length of MASW observation line is 82 m. All dimensions are in m.

#### 4 CPTU SOUNDING OF MSW MASSIF

During the CPTU process, five parameters are registered: tip resistance  $q_c$ , sleeve friction  $f_s$ , inclination from the vertical in two axes, and pore pressure  $u_2$ , and during the CPT process - 4 parameters, with the exception of the pore pressure. The parameters were recorded every centimeter in depth during the sounding. Based on the 5 measured parameters and considering the waste as a soil-like material, it is possible to obtain a number of evaluation characteristics.

A total of 3 tests were performed, including 2 CPT tests and one CPTU test. The connection of the sounding points to the MASW survey line is shown in Fig. 1. The position of survey line on topographic plan of the area is shown in Fig. 2.

#### 5 RESULTS OF CPTU TESTING

The results of CPT tests allow us to identify MSW as a soil-like material and to obtain information on the structure of waste pile and underlying soil, the type of soil behavior and the mechanical characteristics of the waste. Solid inclusions appear as local peaks on the sounding charts, which quickly disappear as the cone tip passes through the inclusions (Fig. 3).

Based on the results of the sounding, it is possible to distinguish two characteristic layers - the cover soil and solid waste. The transition from the cover layer of soil,

consisting of loam, to the layer of solid waste is clearly recorded on the sounding charts at all three points at a depth of 2-2.5 m. Submergence of the probe below the groundwater level led to an increase in pore pressure during the CPTU test at point 2 (Fig. 3)

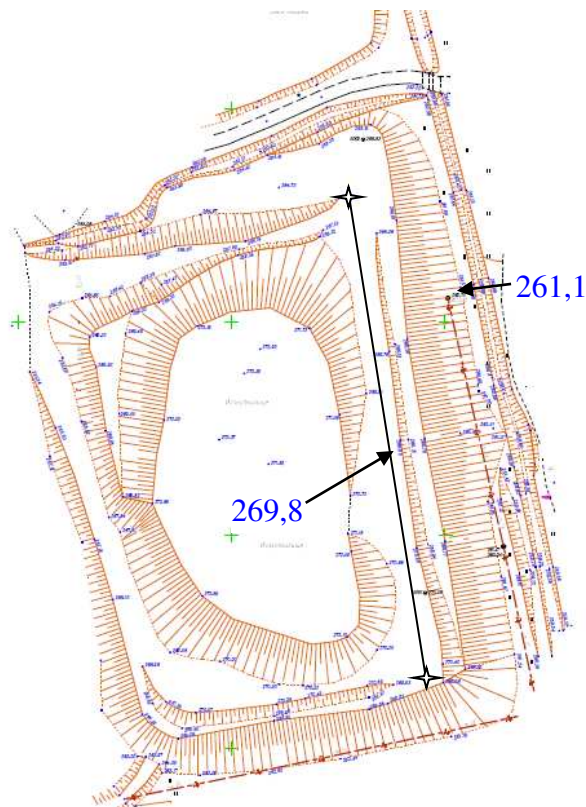


Fig. 2. Topographic plan of the area with the contour of shooting configuration (scale adjusted, length of shooting line between two four-pointed stars is 115m)

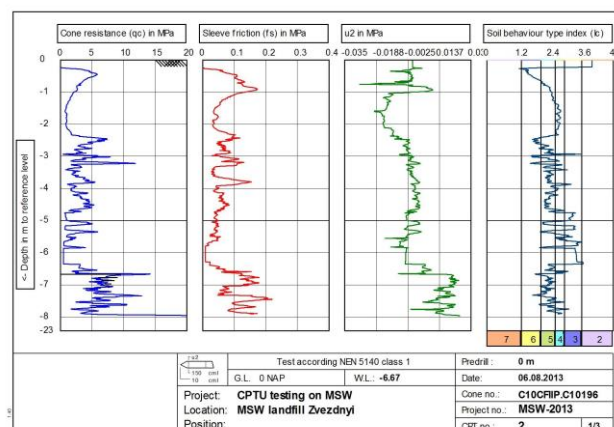


Fig. 3. CPTU raw results at point 2. Results in columns from left to right: 1 – cone resistance ( $q_c$ ), MPa; 2 – sleeve friction ( $f_s$ ), MPa; 3 – pore pressure ( $u_2$ ); 4 – soil behavior type index according to Robertson classification ( $I_c$ ). Types of soil behavior  $I_c$ : 2 – organic soils, 3 – clay, 4 – silt mixture, 5 – sand mixture, 6 – sand clean to silty, 7 – gravelly sand. Vertical scale – penetration depth in m.

## 6 DISCUSSION OF THE CPT(U) TESTING RESULTS

Due to the fact that the results of the CPT tests of MSW are characterized by a large variation of the readings, they were filtered by the mean geometric method (Eslami and Fellenius, 1997), and then graphically represented by geometric mean values at every meter in depth.

Deviation in the arithmetic mean, as opposed to the geometric mean, is the result of the influence of the absolute value instead of the deviation ratio (Kennedy and Neville, 1986). The geometric mean is closer to the dominant value compared to the arithmetic mean. Taking the geometric mean of tip resistance, we obtain a filtered characteristic value which is not affected by deviations.

The "filtered" average values of test results are shown in Fig. 4.

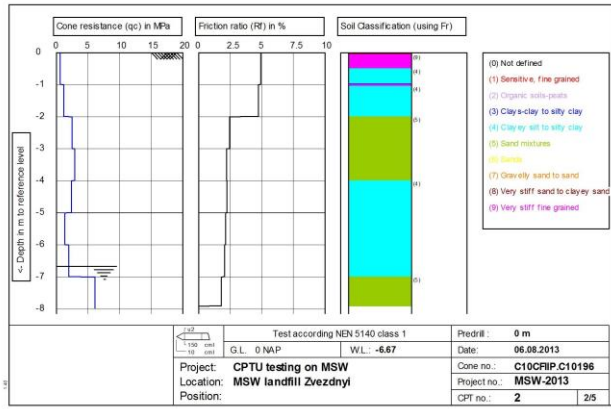


Fig. 4. «Filtered» mean results of CPTU testing at point 2. CPTU results in columns from left to right: cone resistance ( $q_c$ ), friction ratio ( $R_f$ ), soil type according to Robertson classification ( $I_c$ ). Vertical scale – penetration depth in m

The results of CPT tests at the landfill site correspond to typical values for clays, clayey mixtures and sand mixtures (see Fig. 4). Based on the CPTU results (test point 2), instead of the tip resistance  $q_c$ , the corrected tip resistance  $q_t$  is used, taking into account

$$I_c = \sqrt{(a - \log q_{norm})^2 + (\log f_{norm} + b)^2} \quad (3)$$

$$a \approx 3.47; \quad b \approx 1.22$$

Later (Robertson, 2010), a method was proposed for determining the type of soil behavior from a non-normalized ISBT, calculated from the measured resistance parameters for the cone tip and friction sleeve (4)

$$I_{SBT} = \sqrt{(a - \log(q_c / p_a))^2 + (\log R_f + b)^2} \quad (4)$$

$$a \approx 3.47; \quad b \approx 1.22$$

the effect of the pore pressure and the cone unit features.

The corrected tip resistance is determined from Eq. (1) (Robertson and Cabal, 2015).

$$q_t = q_c + (1 - a_s) \times u_2 \quad (1)$$

where  $a_s = A_n / A_c$  and  $a_s \approx 0.81$

$A_n$  is the cross-sectional area of the inside of the probe connected with the cone, on which the cone sensors are fixed.

### 6.1 Evaluation of undrained shear strength and internal friction angle

As a result of the measured parameters processing, it is possible to preliminary estimate the values of the undrained shear strength. The undrained shear strength can be estimated by the method of (Houlsby and Teh, 1988) by the Eq. (2)

$$S_u = (q_t - \sigma_{vz}) / N_k \quad (2)$$

where  $q_t$  is the corrected cone resistance

$\sigma_{vz}$  is in-situ vertical stress

$N_k$  is cone factor varying from 12 to 20. For conservative reasons the factor value is 20.

$$\sigma_{v0} = \gamma_{MSW} \times z = 8.87 \times 4.8 = 42.6 \text{ kN/m}^3$$

$$S_u = (q_t - \sigma_{vz}) / N_k = (0.71 - 0.0426) / 20 = 0.0334 \text{ mPa} = 33.4 \text{ kPa}$$

By the "filtered" CPTU results, the angle of internal friction of MSW is estimated in the the range from  $33^\circ$  to  $37^\circ$  (Ofrikhter et al., 2018).

### 6.2 Assessment of the type of soil behavior

Based on the results of sounding, it is possible to identify the type of soil behavior according to the soil behavior index (ISBT)  $I_c$  (Robertson, 1990). To calculate the index (3), the normalized resistance parameters for the cone tip and friction sleeve are used.

where  $q_c$  is cone resistance or corrected cone resistance  $q_t$ ;

$p_a$  is atmospheric pressure;

$R_f = (f_s / q_c) 100\%$  is friction ratio; and  $f_s$  is sleeve friction.

The non-normalized soil behavior index  $I_{SBT}$  is essentially the same as the normalized one  $I_c$ , only for its calculation the initial measured values of cone resistance and friction sleeve are used. In general, a normalized index provides a more reliable identification of the type of soil behavior than a non-

normalized one, but according to (Robertson, 2010), when the vertical effective stresses are in the range of 50 to 150 KPa, the difference between the normalized and the non-normalized types of soil behavior is small.

According to the index of soil behavior  $I_c$ , established by CPTU results, the MSW correspond to typical values for clays, silt mixtures and sand mixtures (see Fig. 4).

The cone resistance  $q_c$  and friction ratio  $R_f$  make it possible to identify the type of MSW soil behavior in accordance with the Robertson classification chart (Robertson, 1990). Characteristics of solid waste are typical for cohesive soils from clays to sandy loams. The structure of solid waste with a large number of inclusions leads to the frequent occurrence of local peaks and the scatter of readings on the sounding plot, primarily for the tip resistance. Based on the results of sounding, according to the soil behavior index the waste is identified as belonging to the type of cohesive soils.

The soil types from the piezocone sounding data filtered by the geometric average method are shown in Fig. 4. According to the Robertson classification chart (Robertson, 1990), wastes in the upper part of the test site at a depth of 2 ÷ 4 m are identified as belonging to the type of sand mixtures from silty sands to sandy loams, and lower - to the type from clayey silts to silty clays and loams. Presumably, such a change in the type of soil behavior can be explained by an increase in humidity and an increase in the degree of biological decomposition in the lower part of the waste massif. Indirectly, in favor of this assumption is a slight increase in pore pressure from the depth of 4 m (see Fig. 3).

### 6.3 Estimation of initial void ratio

The results of CPTU testing can be used to estimate the initial shear modulus at a known initial void ratio of the testing material (5). The evaluation technique is proposed in (Mayne and Rix, 1993).

$$G_0 = 99,5 (p_a)^{0.305} (q_t)^{0.695} / (e_0)^{1.13} \quad (5)$$

where  $G_0$  is the initial shear modulus;

$p_a$  is atmospheric pressure in the same units as  $G_0$ ;

$q_t$  is the corrected cone resistance;

$e_0$  is the initial void ratio for the soil.

On the basis of the described method, within the framework of the present paper, we propose a solution of the inverse problem - to estimate the value of the initial void ratio from the known piezocone test parameters and the initial shear modulus.

The initial shear modulus can be determined from the results of the solid massif surveying by the

multichannel analysis of surface waves. According to the results of MASW survey (Ofrikhter and Ofrikhter, 2013), the initial shear modulus was 10.7 MPa with an average velocity of shear waves in the MSW layer 110 m / s. Atmospheric pressure on the day of sounding was 745 mm Hg or 0.0993 MPa. The average value of the corrected cone resistance on the cone at elev. -4.0 from the surface is equal to 1.75 MPa. As a result of the calculation, the initial porosity coefficient of MSW is estimated at 5.4. The porosity of the solid waste massif was 0.84.

$$10.7 = 99.5 (0.0993)^{0.305} (1.75)^{0.695} / (e_0)^{1.13} \\ \Rightarrow e_0 \approx 5.4; \quad n \approx 0.84$$

### 6.4 Estimation of the specific gravity based on CPTU results

A technique for estimating the specific gravity from the CPTU results is presented in (Robertson and Cabal, 2010). The specific gravity can be estimated from Eq. (6)

$$\gamma / \gamma_w = [0.27 \log R_f + 0.36 \log (q_t / p_a)] + 1.236 \quad (6)$$

where  $R_f$  is friction ratio  $(f_s / q_t) \cdot 100\%$ ;

$\gamma$  is unit weight of the soil (kN/m<sup>3</sup>);

$\gamma_w$  is unit weight of the water in the same units as  $\gamma$ ;

$p_a$  is atmospheric pressure in the same units as  $q_t$ .

The average specific gravity of solid particles for most soils is in the range of 2.6-2.7. For other specific gravity values of solid particles, expression (6) should be corrected by the ratio of this specific gravity to the mean value of 2.65. If soil samples of the disturbed structure are available, on which the specific gravity of the solid particles can be determined, the expression for the specific gravity of the soil from the CPTU test results has the form (7)

$$\gamma / \gamma_w = \{ [0.27 \log R_f + 0.36 \log (q_t / p_a)] + 1.236 \} G_s / 2.65 \quad (7)$$

where  $G_s$  is specific gravity of the solids.

The paper (Yesiller et al., 2014) publishes the results of determining the specific gravity of solid particles of MSW. The specific gravity of the old waste is  $G_s = 2.201$ . Waste is covered with a layer of soil 2 m thick, so on the first two meters the specific gravity was estimated by formula (6), and then by formula (7).

The profile of the estimated values of the MSW specific gravity according to the results of CPTU testing by the method of (Robertson and Cabal, 2010) is shown in Fig. 5.



## 7 CONCLUSIONS

As a result of field testing of the solid waste massif it was established that

1. According to the soil behavior type index, obtained by the results of CPT testing, the MSW correspond to typical values for clays, clayey mixtures and sand mixtures. The index of soil behavior type varies in the range from 2.0 to 3.6.

2. The cone resistance and friction ratio make it possible to identify the type of soil in accordance with the classification (Robertson, 1990). Characteristics of solid waste are typical for cohesive soils from clays to sandy loams. Based on the results of sounding, the waste is identified by the nature of soil behavior as related to the type of cohesive soils. The MSW friction ratio varies from 1.0% to 4.2%.

3. After the sounding results filtration by the geometric mean method, the waste in the upper part of the landfill at a depth of 2 ÷ 4 m is identified as belonging to the type of sand mixtures from silty sands to sandy loams, and lower - to the type from clayey silts to silty clays and loams.

4. The angle of internal friction of solid waste is estimated in the range from 33 ° to 37 °. The initial void ratio of solid waste is estimated at 5.4. The porosity of the solid waste massif was 0.84. The undrained shear strength of MSW is estimated at 33 kPa.

5. The average specific gravity is estimated by the CPTU results at the value of 15.2 kN / m<sup>3</sup> (1.52). According to the sounding results, profile of the specific gravity along the depth of the solid waste massif has been plotted (see Fig. 5).

8. The paper suggests an assessment of the characteristics of solid waste as a soil-like material based on combination of the results of CPTU and MASW testing, using the relations obtained by different authors for the soils.

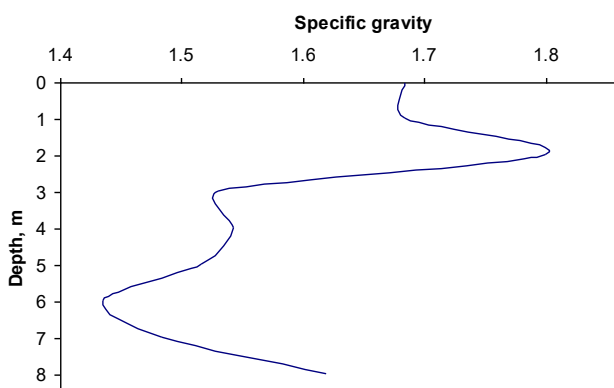


Fig. 5. MSW specific gravity profile based on CPTU results.

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