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Development of nondestructive techniques for preliminary soil foundations geotechnical assessment

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ABSTRACT

Modern nondestructive techniques of wave analysis can be applied for the express preliminary geotechnical soil assessment. One of them is Multichannel Analysis of Surface Waves (MASW) which allows obtaining velocities profile of shear waves and the initial shear modulus for the upper section promptly and at minimal labor costs. But for soil deformation properties assessment the deformation modulus obtained by the direct technique of plate load test (PLT) is required. The purpose of the performed study is an assessment of the correlation between the PLT deformation modulus and the initial shear modulus obtained via MASW.

Keywords: PLTMASW, deformation modulus, initial shear modulus.

1 INTRODUCTION

Modern nondestructive techniques of wave analysis can be applied for the express preliminary geotechnical soil assessment. One of these techniques is Multichannel Analysis of Surface Waves (MASW) which allows obtaining velocities profile of shear waves and the initial shear modulus for upper section in a short time and at minimal labor costs. But for soil deformation properties assessment a deformation modulus obtained by direct technique of plate load test (PLT) is required. The purpose of the performed study is assessment of the correlation between the PLT deformation modulus and the initial shear modulus obtained via MASW.

PLT were carried out for various plates and moduli of deformation were calculated. Deformation modulus adjustment factors were applied to bring values of different size plates to the 5000 cm² plate one in order to perform a comparative analysis. Wave analysis was carried out by the active method of MASW.

During the comparative analysis a correlation coefficient was evaluated for the deformation modulus determined strictly according to GOST 20276-2012. In this case “correlation coefficient - unit weight” indicative dependence was observed. The regression equation was presented.

Correlation between the two types of tests was established by the results of in-situ tests. The proposed empirical regression equation allows us to obtain the value of the deformation modulus on the basis of

MASW data and to perform an express soil foundation geotechnical assessment for the future construction.

2 PURPOSE OF THE STUDY

Preliminary assessment of the geotechnical situation of the site enables making a technical and economic analysis of the object of a reconstruction or a new construction. Preliminary geotechnical evaluation includes: determination of the geotechnical category of the object of construction or reconstruction, analysis of nearby structures, assignment of the scope of survey works, determination of arrangement options for the underground part of the object of construction or reconstruction and their economic comparison. To correctly choose the variants of constructive solution of the underground part of the future construction it is necessary to know the existing layering of soils on the construction site, their physical and mechanical characteristics and the presence of anomalous inclusions (mines, pipeline cavity, other underground structures, etc.) that will allow performing the feasibility study as correctly as possible. Modern non-destructive research methods enable rapid and cost-effective construction of ground layer sections and estimation of physical and mechanical characteristics of soils. One of such methods is MASW.

The MASW technique was first introduced in (Park et al., 1999) and continues to develop and improve up to now (Park and Carnevale, 2010; Park, 2011). It was described and used by such scientists as Park, Xia, Miller, Foti, Louie, Ryden, Suto, etc. (Louie, 2001;

Foti, 2000; Foti et al., 2015; Suto, 2007). The results of modern research on the application of wave analysis methods for geotechnical evaluation of ground layers are presented in (McGrath et al., 2016; Pegah and Lui, 2016; Madun et al., 2016; Schofield and Burke, 2016, Lu and Wilson, 2017). Practical application of various modern modifications of the wave analysis is described in publications (Mi et al., 2017; Li et al, 2018; Taipodia and Dey, 2018). The authors of this study also conducted a number of natural and numerical experiments to determine the possibility of using wave analysis for geotechnical calculations (Ofrikhter and Ofrikhter, 2015; Antipov and Ofrikhter, 2016; Antipov et al., 2016; Shutova et al., 2017; Antipov et al., 2017). The MASW technique is used to measure the surface wave velocities in layered soil thicknesses. From the received velocities it is possible to pass to the initial shear modulus at small deformations by the known dependence (Foti et al., 2015). For practical purposes, it is very useful to establish the relationship between the surface wave velocity, the initial shear modulus, and the soil deformation modulus from the plate tests. The purpose of the researches is to establish the correlation between the initial shear modulus determined by MASW results and the soil deformation modulus determined by the results of PLT.

3 EXPERIMENTAL DESIGN MATERIALS AND METHODS (Antipov and Ofrikhter, 2019)

3.1 Description of the sites

PLT and MASW surveys were performed at five sites with different soil conditions:

1. Site No. 1. Soil under the foundation slab:
 - a. Sand fill of fine homogeneous dense low moisture sand;
2. Site No. 2. Highway. Site beside a pillar of bridge crossing:
 - b. Medium strength loose fractured saturated argillite-like clay with pockets of low and medium strength sand rock;
 - c. Fine-grained loose fractured saturated sand rock of low and medium strength;
3. Site No. 3. Site of the former factory that is free of constructions:
 - d. Tough and medium-hard clay;
4. Site No. 4. Base of the foundation plate for a residential building:
 - e. Gray-brown arenaceous fluid clayey sand with veins and pockets of 3–5 cm fine gray saturated sand and very soft brown clayey sand;
 - f. Dark-grey heavy silty very soft sandy clay with up to 15% inclusions of well-decomposed black organic matter;
5. Site No. 5. A test site of the Department of Construction Operations and Geotechnics of PNRPU that is free of constructions:
 - g. Brown fine-grained sand.

Physical properties of the soils determined in the laboratory are presented in Table 1.

Table 1. Physical properties of the soils at testing sites.

Site No.	Soil type	w	w_L	w_P	γ , kN/m ³	γ_s , kN/m ³
1	a	0.068	–	–	17.84	25.68
2	b	0.170	0.34	0.14	19.99	25.68
	c	0.170	–	–	20.09	26.07
3	d	0.129	0.33	0.07	20.78	26.46
4	e	0.296	0.24	0.18	19.80	26.46
	f	0.299	0.35	0.19	18.42	25.87
5	g	0.099	–	–	15.97	24.60

w is water content; w_L is liquid limit; w_P is plastic limit; γ is unit weight of soil; γ_s is unit weight of soil particles

3.2 PLT

PLT were performed in accordance with the standard procedure set out in the Russian State Standard (GOST 20276-2012). The true value of the deformation modulus is assumed as the modulus E_{5000} obtained for a plate of 5 000 cm² (Kashirsky, 2014; Kalugina et al., 2017). Deformation modulus determined for the 600 cm² plate was transformed to the modulus E_{5000} using the formula (1) (Lushnikov, 2014):

$$E_{5000} = E_{600} \cdot m \quad (1)$$

where E_{600} is deformation modulus for the 600 cm² plate; m is conversion factor depending on the void ratio e according to Table 3 of (Lushnikov, 2014).

According to (Lushnikov, 2014), for the plates of other areas the coefficient m in equation (1) can be calculated by the expression (D.3) from Annex D of (SP 23.13330.2018):

$$m = (A_{5000} / A_i)^{n/2} \quad (2)$$

where A_{5000} is the 5 000 cm² plate; A_i is the i cm² plate area; n is reduction argument according to Annex D of (SP 23.13330.2018), for silt-loam soil $n = 0.15$ – 0.3 , for sandy soil $n = 0.25$ – 0.5 , minimum or maximum value from the conditions $\sigma_{z,p} = 0,5\sigma_{z,g}$ or $\sigma_{z,p} = 0,2\sigma_{z,g}$ respectively (p. 11.6.2 of SP 23.13330.2018).

3.3 MASW

MASW is an express non-expensive non-invasive in-situ technique of wave analysis of the low velocity zone in the upper part of soil profile. The procedure of in-situ survey and further data processing used by the authors is described in detail in (Park et al., 1999; Suto, 2007). A telemetric 24-channel seismic exploration system TELSS-3 was used for carrying out MASW technique. The system consists of: seismic wire interface for communication with a laptop; vibration seismic receivers – 24 vertical 10 Hz geophones; 7 seismic streamers for 4 geophones; telemetric modules for signal transmission from receivers to the interface; a

4.5 kg (10 lbs) sledgehammer with a metal base plate used as a wave source. The trigger was carried out by closing the sledgehammer and the plate. The signal from the trigger at the beginning of the recording was transmitted to the interface via a connecting cable. A streamer test and a full seismic station test were performed on each shot before recording.

MASW tests were performed using active flank observation system ZZ with an offset of 10 m. Two layouts of the surveillance system were used: a 46 m receiving line with a 2 m receiver spacing; a 11.5 m receiving line with a 0.5 m receiver spacing. As an example, Fig. 1 shows the scheme of second layout type on the site no. 4 at the location of the soil type e. Fig. 2 illustrates the actual in-situ testing. The length of the receiving line corresponds to the maximum measured wavelength, the step of the receivers corresponds to the minimum wavelength. The centers of the receiving lines were located as close as possible to the points of the PLT tests.

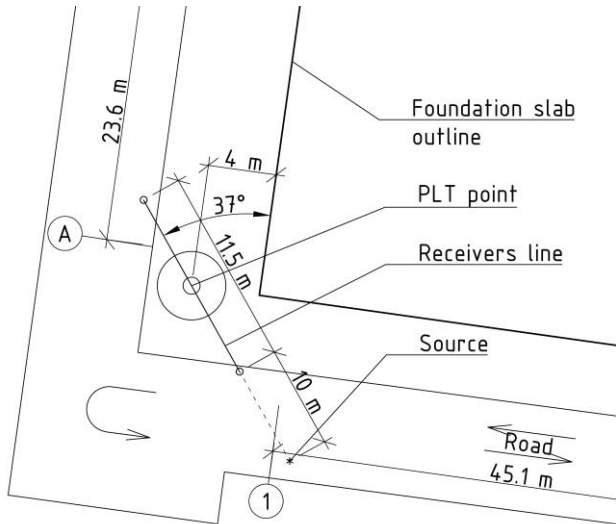


Fig. 1. Scheme of surveying system on the site no. 4 at the location of soil type e.



Fig. 2. Surveying system during in-situ testing on the site no. 4 at the location of the soil type e.

Optimum parameters were taken according to (Park and Carnevale, 2010; Antipov et al., 2016; Ofrikhter and Ofrikhter, 2015; Ofrikhter et al., 2018). The number of repeats at each point was 3 (two main and one reconnaissance). Noise interference and distortions were eliminated by repeating the record in each measurement at each point 5–8 times. The accepted MASW parameters are shown in Table 2.

Table 2. MASW testing parameters.

Site No.	Soil type	D , m	X , m	dx , m	dt , ms	m	N
1	a	11,5	2,5	0,5	0,5	2048	5–8
2	b	46,0	10,0	2,0	0,5	2048	5–8
	c	46,0	10,0	2,0	0,5	2048	5–8
3	d	46,0	10,0	2,0	0,5	2048	5–8
4	e	11,5	2,5	0,5	0,5	2048	5–8
	f	11,5	2,5	0,5	0,5	2048	5–8
5	g	11,5	2,5	0,5	0,5	2048	5–8

D is receivers line; X is source offset; dx is receiver spacing; dt is sampling interval; m is amount of samples, i.e. total recording time; N is number of sticking data

Experimental data processing was carried out using “RadexPro 2014 Starter” software package in a semi-automatic mode. The obtained average values of the S-wave velocities in the tested soil layers were used to calculate initial shear moduli from the expression (Mayne, 2001):

$$G_0 = \rho \cdot V_s^2 \quad (3)$$

where ρ is soil density determined in laboratory tests, kg/m^3 ; V_s is soil layer shear wave velocity, m/s .

It is worth noting that expression (4) proposed in (Mayne, 2001) allows calculation of the soil unit weight with values of S-wave velocities and depth:

$$\gamma = 8.32 \cdot \lg(V_s) - 1.61 \cdot \lg(z) \quad (4)$$

where γ is unit weight of the soil layer, kN/m^3 ; z is layer base depth, m .

4 EXPERIMENTAL DATA (Antipov and Ofrikhter, 2019)

As an example, the MASW result for site no. 4 at the location of the soil type e is given in Fig. 3. Fig. 4 shows PLT result for the same soil type e.

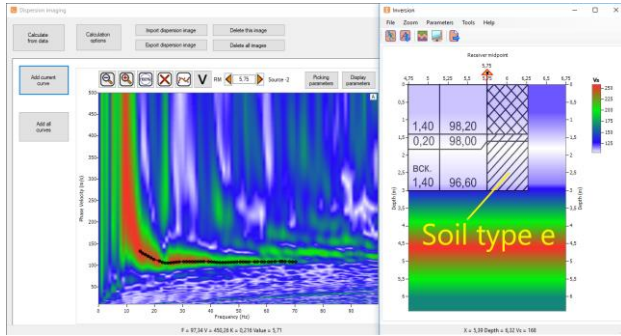


Fig. 3. MASW result for the site no. 4 at the location of the soil type e.

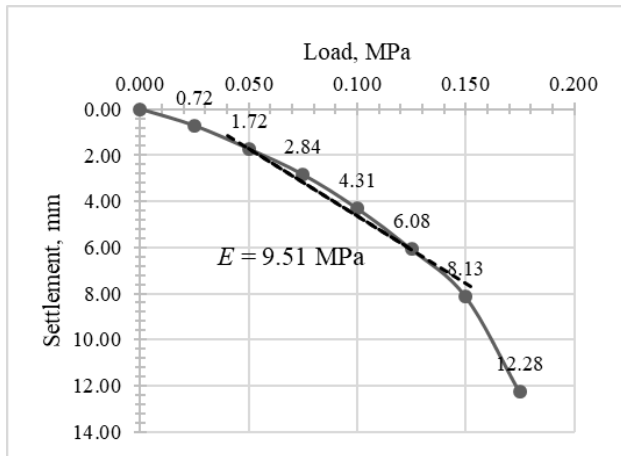


Fig. 4. PLT result for the soil type e.

The summarized MASW results are presented in the Table 3 together with the soil unit weight calculations. Unit weights determined in the laboratory are presented for comparison. Calculated deformation moduli and initial shear moduli according to PLT and wave analysis are given in Table 4. Deformation modulus E was calculated according to the standard procedure recommended by Russian State Standard (GOST 20276-2012) using well-known Schleicher's equation for the first four points of the load-settlement curve counting from initial pressure under plate.

Fig. 5 and Table 5 present correlation coefficients between the deformation modulus and the initial shear modulus. The correlation coefficient was calculated by the formula: $k = E_{5000} / G_0$; and next the dependency was obtained:

$$k = -0.003321\gamma^3 + 0.206374\gamma^2 - 4.281230\gamma + 29.789383 \quad (5)$$

where γ is soil unit weight, kN/m^3 ; k is the correlation coefficient between the MASW initial shear modulus and the soil deformation modulus determined by the formula (6):

$$E = k \cdot G_0 \quad (6)$$

Table 3. Summary table of the MASW results and data of unit weight calculation.

Site No.	Soil type	V_s , m/s	G_0 , MPa	z , m	$\gamma_{\text{calc}} (4)$, kN/m^3	γ_{lab} , kN/m^3
1	a	245	109.25	1.5	19.59	17.84
2	b	332	224.86	11.5	19.27	19.99
	c	417	356.47	12.6	20.03	20.09
3	d	151	48.34	0.5	18.61	20.78
4	e	172	59.76	3.0	17.83	19.80
	f	118	26.18	3.1	16.45	18.42
5	g	142	32.87	1.0	17.91	15.97

Table 4. Evaluation of deformation modulus by (GOST 20276-2012).

Site No.	Soil type (plate area)	h_{pl} , m	P_n , MPa (S_n , cm)	P_0 , MPa (S_0 , cm)	E , MPa	n	m	E_{5000} , MPa
1	a (2 500)	0.00	0.250 (0.390)	0.100 (0.139)	24.24	0.25	1.09	26.43
2	b (600)	9.19	0.800 (0.350)	0.200 (0.053)	40.14	0.15	1.17	47.06
	c (600)	11.70	0.800 (0.255)	0.200 (0.044)	53.12	0.15	1.17	62.28
3	d (600)	0.10	0.200 (0.560)	0.050 (0.035)	5.24	0.15	1.17	6.14
4	e (5 000)	1.60	0.125 (0.608)	0.050 (0.172)	9.51	0.15	1.00	9.51
	f (5 000)	2.40	0.125 (1.326)	0.050 (0.506)	4.84	0.15	1.00	4.84
5	g (600)	0.10	0.200 (0.251)	0.050 (0.026)	13.25	0.25	1.30	17.27

h_{pl} is the plate level from the surface; P_n is plate pressure corresponding to the fourth point of the linear part of the load-settlement curve; P_0 is initial pressure corresponding to vertical intergranular stress from soil self-weight at the test level; G_0 is initial shear modulus of small strains; E is PLT deformation modulus; n is reduction argument according to Annex D of (SP 23.13330.2018), accepted minimum recommended values for the condition $\sigma_{z,p} = 0,5\sigma_{z,g}$; m is deformation modulus conversion factor; E_{5000} is calculated deformation modulus of 5 000 cm^2

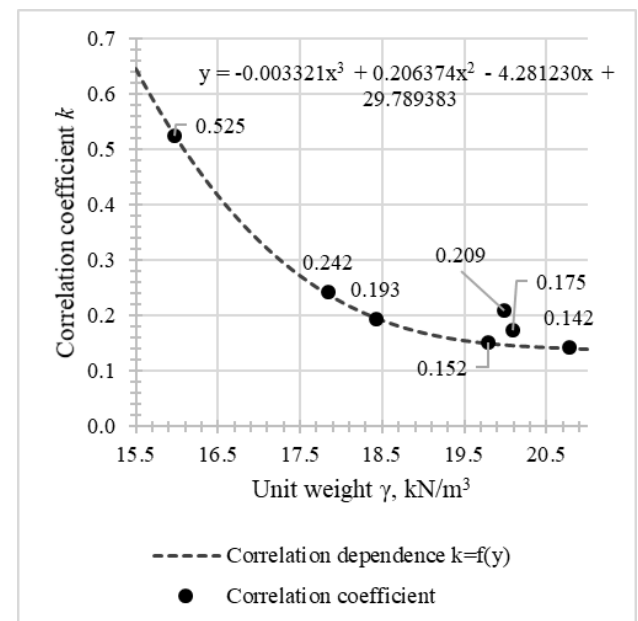


Fig. 5. Unit weight – correlation coefficient.

Table 5. Unit weight – correlation coefficient data.

No.	Soil type	G_0 , MPa	E_{5000} , MPa	γ_{lab} , kN/m ³	$k = E_{5000}/G_0$
1	a	109.25	26.43	17.84	0.242
2	b	224.86	47.06	19.99	0.209
3	c	356.47	62.28	20.09	0.175
4	d	48.34	6.14	20.78	0.142
5	e	59.76	9.51	19.80	0.152
6	f	26.18	4.84	18.42	0.193
7	g	32.87	17.27	15.97	0.525

5 DISCUSSION OF THE RESULTS

In the course of the experiments, a simple mathematical dependence (6) was obtained between the deformation modulus comparable with the results of the plate test and the initial shear modulus. The transition coefficient k in the formula depends only on the specific gravity of the soil. Taking into account that the magnitude of the initial shear modulus depends only on the speed of surface waves and the soil specific gravity, and that the specific gravity is directly related to the speed of surface waves in accordance with formula (6), the obtained dependences make it possible to estimate the soil deformation modulus in the shortest time both by the velocity of surface waves and by soil unit weight. The soil unit weight can be determined by the results of standard engineering and geological surveys or can be calculated using formula (4) in case of a site without geological surveys data. The proposed approach seems to be very convenient for the specialists in assessing the geotechnical situation at the site.

6 CONCLUSION

The article presents the results of plate load testing of the soils and wave analysis by the MASW method at the sites of Perm and Perm Region, Russian Federation, for different soils and their comparative analysis. Based on the results of field researches, regularity was established and the relationship between the initial shear modulus G_0 according to the results of wave surveys and the soil deformation modulus E according to the results of standard plate load tests was determined. The correlation coefficient k between the deformation modulus E of the soils and the initial shear modulus G_0 varies within 0.142–0.525 according to the explicit regularity presented in Fig. 1, and it decreases as the soil unit weight increases. The simple empirical formula (6) is proposed, which allows one to perform express an evaluation of the soil deformation modulus by the results of wave survey with MASW and make a preliminary geotechnical assessment of the proposed construction site of the future facility.

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