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Express assessment of deformation modulus of dispersive soils by multichannel analysis of surface waves

Evaluation par express du module de déformation des terrains dispersifs basée sur les résultats de l'analyse multicanale des ondes superficielles

Vadim V. Antipov & Vadim G. Ofrikhter
Perm National Research Polytechnic Universit, Perm, Perm Krai, Russia

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. However, the soil deformation properties assessment requires the deformation modulus that is obtained by the direct technique of plate load test (PLT). The purpose of the study is to assess the correlation between the PLT deformation modulus and the initial shear modulus determined with MASW.

RÉSUMÉ: Les méthodes actuelles non-destructives de l'analyse des ondes peuvent être appliquées pour effectuer l'évaluation géotechnique des terrains par express. Une des méthodes est présentée par l'analyse multicanale des ondes superficielles permettant de recevoir le profil des vitesses des ondes transversales ainsi que le module initial de déplacement pour la partie supérieure de la section le plus vite poissible et aux dépenses minimales de travail. Mais pour évaluer les propriétés déformées du terrain il est nécessaire de déterminer le module de déformation par la méthode directe des essais des étampes. L'objectif de la recherche donnée est l'évaluation de la corrélation entre le module de déformation par étampes et le module initial de déplacement, reçu par l'analyse multicanale des ondes superficielles.

KEYWORDS: PLT, MASW, 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 the upper section in a short time and at minimal labor costs. However, the soil deformation properties assessment requires the deformation modulus that is obtained by the direct technique of plate load test (PLT).The purpose of the performed study is to assess the correlation between the PLT deformation modulus and the initial shear modulus determined with MASW.

PLTs 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 5,000 cm^2 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 the Russian State Standard (GOST 20276-2012). In this case "correlation coefficient - unit weight" indicative dependence was observed. The regression equation is presented.

Correlation between the two types of tests was established by in-situ tests. The proposed empirical regression equation allows us to obtain the deformation modulus on the basis of MASW data and to perform an express soil foundation geotechnical assessment for the future construction.

Preliminary assessment of the geotechnical situation on the site enables carrying out a technical and economic analysis of the object of reconstruction or 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 survey work scope, determination of arrangement options for the underground part of the object and their economic comparison. To correctly choose the variants of constructive solution of the future construction underground part, 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 & 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 & Lui 2016; Madun et al. 2016; Schofield & Burke 2016; Lu & 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 & 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 & Ofrikhter 2015; Antipov & Ofrikhter 2016; Antipov et al. 2016; Shutova et al. 2017; Antipov et al. 2017). The MASW technique is applied 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 with MASW and the soil deformation modulus determined with PLTs.

2 MATERIALS AND METHOD (ANTIPOV & OFRIKHTER 2019)

2.1 *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 from construction:
d. Tough and medium-hard clay;
4. Site No. 4. Base of the foundation plate for a residential building:
e. Gray-brown areneceous 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 from construction:
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

2.2 *PLTs*

PLTs 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 cm^2 (Kashirsky 2014; Kalugina et al. 2017). Deformation modulus determined for the 600 cm^2 plate was transformed to the modulus E_{5000} using formula (1) (Lushnikov 2014):

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

where E_{600} is the deformation modulus for the 600 cm^2 plate; m is the 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):

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

where A_{5000} is the 5,000 cm^2 plate; A_i is the i cm^2 plate area; n is the 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).

2.3 *MASW*

MASW is an express inexpensive non-invasive in-situ technique of wave analysis of the low velocity zone in the upper part of the soil profile. The procedure of the 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 applied for carrying out the 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 implemented by closing the sledgehammer and the plate. The signal from the trigger at the beginning of recording was transmitted to the interface via a connecting cable. A streamer test and a full seismic station test were made at each shot before recording.

MASW tests were performed with an 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, and a 11.5 m receiving line with a 0.5 m receiver spacing. As an example, Fig. 1 shows the scheme of the second layout type on the site No. 4 at the location of the e soil type. Fig. 2 illustrates the actual in-situ testing. The receiving line length corresponds to the maximum measured wavelength, and the receiver step corresponds to the minimum wavelength. The centers of the receiving lines were located as close to the points of the PLT tests as possible.

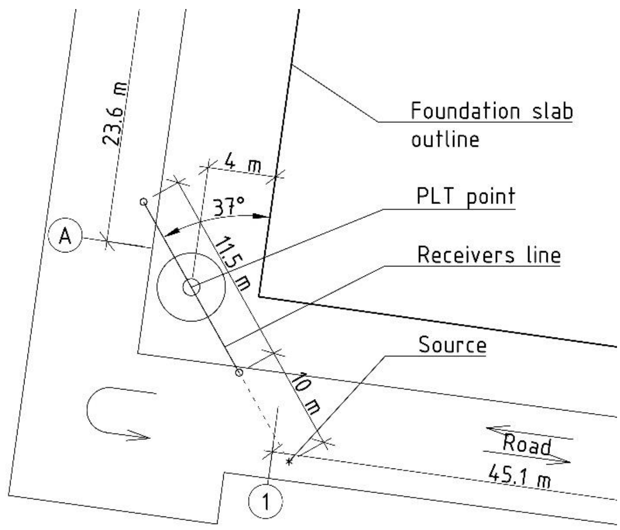

Figure 1. Surveying system on the site No. 4 at the location of the e soil type.

Figure 2. Surveying system at in-situ testing on the site No. 4 at the location of the e soil type.

Optimum parameters were taken according to (Park & Carnevale 2010; Antipov et al. 2016; Ofrikhter & 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 5–8 times in each measurement at each point. 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	*tn*	*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 the receivers line; *X* is source offset; *dx* is receiver spacing; *dt* is the sampling interval; *tn* is the number of samples, i.e. the total recording time; N is the number of stucking data

Experimental data were processed with 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):

$$G_0 = \rho \cdot V_s^2 \tag{3}$$

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:

$$\gamma = 8.32 \cdot \log V_s - 1.61 \cdot \log z \tag{4}$$

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

3 EXPERIMENTAL DATA (ANTIPOV & OFRIKHTER 2019)

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

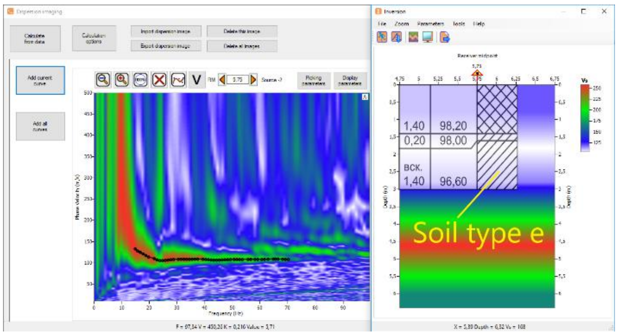

Figure 3. MASW for the No. 4 site at the location of the e soil type.

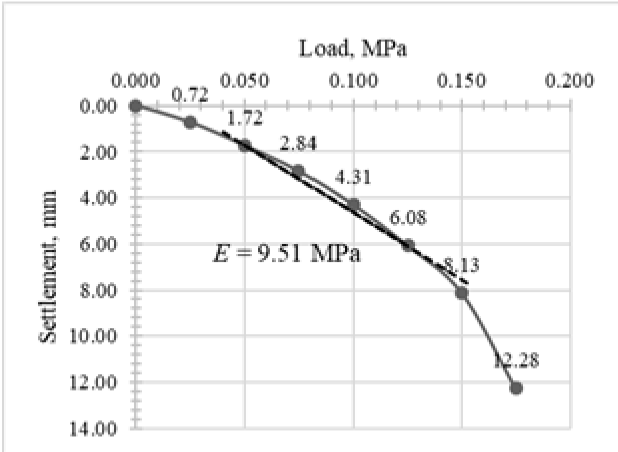

Figure 4. PLT result for the e soil type.

The summarized MASW results are presented in Table 3 together with the soil unit weight calculations. Unit weights determined in the laboratory are provided 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 the Russian State Standard (GOST 20276-2012) using the well-known Schleicher's equation for the first four points of the load-settlement curve counting from the 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:

$$k = -0.003321\gamma^3 + 0.206374\gamma^2 - 4.281230\gamma + {}+29.789383 \tag{5}$$

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

$$E = k \cdot G_0 \tag{6}$$

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	γ_{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 the plate pressure corresponding to the fourth point of the linear part of the load-settlement curve; P_0 is the initial pressure corresponding to the vertical intergranular stress from the soil self-weight at the test level; G_0 is the initial shear modulus of small strains; E is the PLT deformation modulus; n is the reduction argument according to Annex D of (SP 23.13330.2018) accepted as the minimum recommended value for the condition $\sigma_{z,p} = 0.5\sigma_{z,g}$; m is the deformation modulus conversion factor; E_{5000} is the calculated deformation modulus of a 5,000 cm^2 plate.

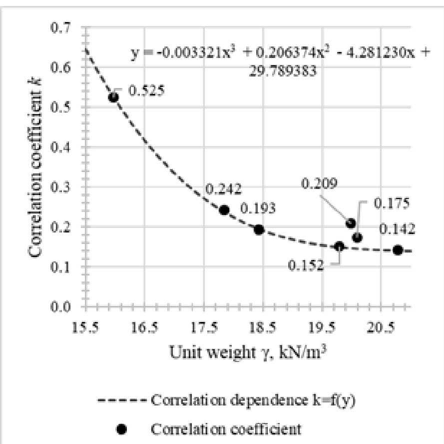

Figure 5. Unit weight – correlation coefficient.

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

4 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 the soil unit weight. The soil unit weight can be determined by the standard engineering and geological surveys or can be calculated using formula (4) in case of a site without geological survey data. The proposed approach seems to be very convenient for the specialists in assessing the geotechnical situation at the site.

5 CONCLUSION

The article presents the results of soil plate load testing 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 field researches, regularity was established and the relationship between the initial shear modulus G_0 according to wave surveys and the soil deformation modulus E according to standard plate load tests was determined. The correlation coefficient k between the soil deformation modulus E and the initial shear modulus G_0 varies within 0.142–0.525 according to the explicit regularity presented in Fig. 5, and it decreases as the soil unit weight increases. A simple empirical formula (6) is proposed, which allows one to perform express evaluation of the soil deformation modulus by MASW and make a preliminary geotechnical assessment of the proposed construction site of the future facility.

6 ACKNOWLEDGEMENTS

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