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Determining G-γ Degradation Curve in Cohesive Soils by Dilatometer and in situ Seismic Tests

Ivandic Kreso, Spiranec Miljenko, Kavur Boris, Strelec Stjepan

***Abstract*—**This article discusses the possibility of using dilatometer tests (DMT) together with in situ seismic tests (MASW) in order to get the shape of G-γ degradation curve in cohesive soils (clay, silty clay, silt, clayey silt and sandy silt). MASW test provides the small soil stiffness (G_o from v_s) at very small strains and DMT provides the stiffness of the soil at 'work strains' (M_{DMT}). At different test locations, dilatometer shear stiffness of the soil has been determined by the theory of elasticity. Dilatometer shear stiffness has been compared with the theoretical G-γ degradation curve in order to determine the typical range of shear deformation for different types of cohesive soil. The analysis also includes factors that influence the shape of the degradation curve (G-γ) and dilatometer modulus (M_{DMT}), such as the overconsolidation ratio (OCR), plasticity index (IP) and the vertical effective stress in the soil (σ_{vo}'). Parametric study in this article defines the range of shear strain γ_{DMT} and G_{DMT}/G_o relation depending on the classification of a cohesive soil (clay, silty clay, clayey silt, silt and sandy silt), function of density (loose, medium dense and dense) and the stiffness of the soil (soft, medium hard and hard). The article illustrates the potential of using MASW and DMT to obtain G-γ degradation curve in cohesive soils.

***Keywords*—**Dilatometer testing, MASW testing, shear wave, soil stiffness, stiffness reduction, shear strain.

I. Introduction

NON-LINEAR behaviour of the soil can be determined by in-situ and lab tests. Degradation *G-γ* curve describes the behaviour of the soil from very small to very high strains. In order to get its shape, it is necessary to use more than one in-situ and lab test methods.

For determining the shear stiffness of the soil (G_o) at very small strains, more methods should be used – Down- and Cross-Hole seismic method, seismic dilatometer (SDMT), seismic CTP device (SCPT), Spectral analysis of surface waves (SASW) and Multichannel analysis of surface waves (MASW). Shear stiffness of the soil at medium and high strains can be determined with in-situ tests by using a dilatometer and Presiometer and Plate load tests (IPLT). By using the lab tests, we can also determine maximum shear stiffness of the soil (G_o) and the degradation *G-γ* curve. The downside is that these tests require expensive and sophisticated equipment and furthermore, the results depend on the quality of undisturbed samples [7].

This article discusses the possibility of using the DMT with MASW when determining the degradation G-γ curve. There are three ways to do that. The first one is based on shear stiffness of the soil (G_o) at very small strains, when the degradation curve is determined out of shear wave velocity (v_s) by the MASW method. The shear stiffness of the soil (G_{DMT}) was determined from dilatometer modulus (M_{DMT}) at medium and high strains. The third and the last way is based on calibration of shear stiffness (G_o i G_{DMT}). When using this way of determining the *G-γ* curve, one should look up in the literature the theoretical degradation curve because it takes into consideration parameters which influence its shape, such as over-consolidation ratio (*OCR*), I_P and effective vertical stress (σ_{vo}').

Kreso Ivandic,Stjepan Strelec and Boris Kavur are with the Geotechnical Faculty, Hallerova aleja 7, 42000 Varaždin, Croatia (e-mail: geokod.eu@gmail.com, stjepan.strelec@gmail.com, boris.kavur@gmail.com).
Miljenko Špiranec is with the SPP d.o.o., Trstenjakova 3, 42 000 Varaždin, Croatia (e-mail: spiranec@spp.hr).

II. Degradation G-γ Curve in the Coherent Soil

A. Determining the Stiffness of the Soil at Very Small Strains (G_o) by MASW

For determining the stiffness of the soil at small strains a lot of different lab and in-situ tests are being used. Lab tests (e.g., bender elements, resonant column) represent one of the main ways to determine the shear stiffness of the soil at small strains, but as such, they also have some negative sides like disturbance of samples, quality of sample preparation and sophisticated equipment [8].

In-situ tests (e.g., Down-Hole test, Cross-Hole test, SDMT, SCPT, SASW and MASW) are being used in practice for determining the soil stiffness at small strains.

In this article, an active MASW method has been used and it is based on dispersion property of surface waves. This property is used for determining shear wave velocity of the soil (v_s) in 1D or 2D form. It records frequencies in the range from 3 to 50 Hz by using a multichannel system (24 or more channels) where seismic profile is distributed in the length from several to a couple of hundreds of meters. An active MASW method creates surface waves with the help of a hammer and a passive MASW method uses surface waves created by traffic noise or other tremors. Depth of the interpretation by the active method varies in the range from 10 to 30 meters. The whole process is based on three steps:

1) multichannel recording of in-situ seismic note
2) determining the dispersion curve for every recording
3) analysis of the dispersion curve in order to get shear wave velocity (v_s) in 1D or 2D profile

Shear Modulus of the soil at small strains (G_o) is based on:

$$G_o = \rho \cdot v_s^2 \tag{1}$$

where ρ - total soil mass density, v_s – shear wave velocity.

B. G-γ Degradation Curve

Concept of the threshold shear strain was introduced in 1991 by Presti [1] and in 1994 it was worked out by Vucetic [2]. Threshold shear strain represents border strains in the soil between very small to medium and high shear strains. The soil behaves linear-elastic beneath the linear boundary of the shear strains. In the area between the linear and volume shear strains, the soil behaves non-linearly, but most of it stays in the area of elastic strains.

By doing various lab tests on clayey soils, Vucetic [2] recommended a model where volume shear strain increases together with the I_P. This means that normalized degradation curve (G/G_o-γ) has a tendency to move up and right together with the I_P. On the normalized degradation curve, the volume shear strain moves in the range from *0.65* to *0.7 G/G_o*.

Reference shear strain ($\gamma_{0.7}$) is accepted as one of the parameters in the process of defining the degradation curve. The first method for determining the reference shear strain was suggested by Vucetic and Dobry [3]. Vucetic [2] presumed that the reference shear strain is in the linear correlation with the I_P, according to the equation:

$$\gamma_{0.7} = 0.0021 \cdot I_p - 0.0055 \quad (2)$$

In this article a more complex method, defined by Ishibashi and Zhang [4] was used. It takes into consideration the influence of the I_P and mean effective stress (σ'_{mo}). The shape of the degradation curve is defined by a mathematical equation:

$$\frac{G}{G_o} = K(\gamma, I_P) \cdot \sigma'^{\,m(\gamma, I_p)}_{mo} \quad (3)$$

$$K(\gamma, I_p) = 0.5 \cdot \left[1 + tanh\left\{ln\left(\frac{0.000102+n(I_p)}{\gamma}\right)^{0.492}\right\}\right] \quad (4)$$

$$n(I_P) = \begin{Bmatrix} 0 \quad za \quad I_P = 0 \ (\,sandy\ soil) \\ 3.37 \cdot 10^{-6} \cdot I_P{}^{1.404} \ \ za \quad 0 < I_P \leq 15\ (low\ plastic\ soils\,) \\ 7.0 \cdot 10^{-7} \cdot I_P{}^{1.976} \quad za \quad 15 < I_P \leq 70 (medium\ plastic\ soils) \\ 2.7 \cdot 10^{-5} \cdot I_P{}^{1.115} \quad za \quad I_P > 70\ (high\ plastic\ soils) \end{Bmatrix} \quad (5)$$

$$m(\gamma, I_p) = 0.272 \cdot \left[1 - tanh\left\{ln\left(\frac{0.000556}{\gamma}\right)^{0.4}\right\}\right] \cdot e^{-0.0145 \cdot I_P^{1.3}} \quad (6)$$

In-situ mean effective stress (σ'_{mo}) is defined by:

$$\sigma'_{mo} = \left(\frac{1+2 \cdot K_o}{3}\right) \cdot \sigma'_{vo} \quad (7)$$

where σ'_{vo} is vertical effective stress in the soil and K_o coefficient of lateral earth pressure at rest.

Reference strain ($\gamma_{0.7}$) has a tendency to rise together with the mean effective stress (σ'_{mo}) for soft clays [5]. For I_P higher than 100, the influence of the mean effective stress can be neglected.

C. Shear Stiffness of the Soil GDMT („Modulus at a Work strain") Is Given on the Basis of the DMT

Shear modulus G_{DMT} at the „work strain" can be determined on the basis of oedometer modulus M_{DMT} which is given by dilatometer test [6] using linear-elastic correlation defined by the relation given by [7] and [8]:

$$G_{DMT} = \frac{M_{DMT}}{2 \cdot (1-\vartheta)/(1-2\vartheta)} \quad (8)$$

where ν - Poisson coefficient (at the cohesive soils, $\nu = 0.25$ was taken).

The assumption that oedometer modulus M_{DMT} can provide a reasonable stiffness of the soil at the work strain (modulus which is used for settlement calculation by a linear-elastic method for work surchage on a foundation) is supported by well documented case histories [9], [10].

For determining the degradation curve it is necessary to know the shear strain γ_{DMT} at the shear stress G_{DMT}. Various authors recommend various range of the shear deformation γ_{DMT}. Mayne [11] gives the range of γ_{DMT} from 0.05 to 0.1%, Ishihara [12] gives considerably bigger range from 0.01% to 1% and Marchetti [10] gives the range of the shear strain based on the type of the soil. Therefore, for the sand the range goes from 0.01 to 0.1% and for silts from 0.1 to 1%. Recently Amoroso et al. [7] and Amoroso & Monaco [8] have given the range of shear strain γ_{DMT} for different types of the soil: sand 0.01-0.45%, silt and clay 0.1-1.9% and soft clay >2%.

Currently in the literature are available different ranges of the shear deformation γ_{DMT} and they are quite wide for some types of the soil. Because of the non-linear shape of the G-γ curve, shear stiffness of the soil (G_{DMT}) can significantly vary inside of a given range of the shear strain. For that reason, there is a need to define the range of shear strain γ_{DMT} in a considerably narrowed range; depending on the classification of the cohesive soil (clay, silty clay, clayey silt, silt and sandy silt), considering the function of compaction (loose, medium dense and dense) and considering the strength of the soil (soft, medium hard and hard).

III. In-Situ Test Sites

The tests have been done at four locations in the north-west and one location in the south Croatia. Test locations are Turčin (near Varaždin), Soblinec (near Zagreb), Kalinovec (near Đurđevac), Samarica (near Bjelovar) and Ploče.

On the test locations MASW tests and dilatometer probing of the ground (DMT) have been made. The soil is classified based on dilatometer material index, I_D. Material index (I_D) is connected with the classification of the soil:

$$I_D = \frac{p_1 - p_o}{p_o - u_o} \quad (9)$$

where p_o – contact pressure, p_1 – expansion pressure (we get it by a dilatometer measuring) and u_0 – pore pressure in the soil.

Fig. 1 Locations of the in-situ tests

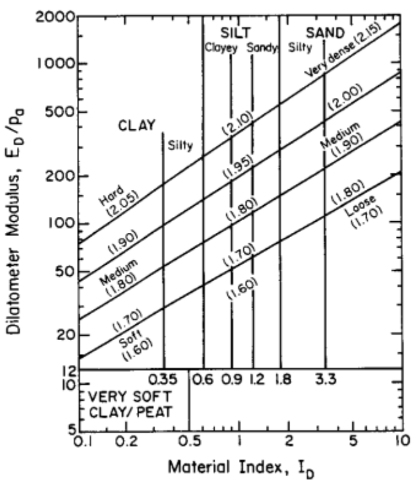

Fig. 2 Classification of the soil based on the DMT

The soil is classified in the following classes:

- clayey material: $I_D<0.6$
- silty material: $0.6<I_D<1.8$
- sandy material: $I_D>1.8$

Index of the horizontal stress (K_D) is connected with in-situ horizontal stress state. K_D index is always higher than K_o due to deformations in the soil which happen during the injection of the probe:

$$K_D = \frac{p_o - u_o}{\sigma'_{vo}} \tag{10}$$

At rest, lateral earth pressure coefficient (K_o) is given out of the equation:

$$K_0 = \left(\frac{K_D}{1.5}\right)^{0.47} - 0.6 \tag{11}$$

Dilatometer modulus (E_D) is connected with the stiffness of the soil:

$$E_D = 34.7 \cdot (p_1 - p_o) \tag{12}$$

Degree of the overconsolidation, OCR:

$$OCR = 0.5 \cdot (K_D)^{1.56} \tag{13}$$

Oedometer modulus of compressibility is based on dilatometer measuring (M_{DMT}):

$$M_{DMT} = R_m \cdot E_D \tag{14}$$

$$\begin{aligned} R_m &= 0.14 + 2.36 \cdot \log K_D \quad \leftarrow \text{if } I_D < 0.6 \\ R_m &= R_{M,o} + (2.5 - R_{M,o}) \cdot \log K_D \quad \leftarrow \text{if } 0.6 < I_D < 3.0 \\ R_{M,o} &= 0.14 + 0.15 \cdot (I_D - 0.6) \\ R_m &= 0.50 + 2.00 \cdot \log K_D \quad \leftarrow \text{if } I_D \geq 3.0 \\ R_m &= 0.32 + 2.18 \cdot \log K_D \quad \leftarrow \text{if } K_D > 10 \end{aligned}$$

Unit weight of the soil, γ:

$$\gamma = 1.12 \cdot \gamma_w \cdot \left(\frac{E_D}{p_a}\right)^{0.1} \cdot I_D^{-0.05} \tag{15}$$

where γ_w – unit weight of the water and p_a – atmospheric pressure.

A. Results of the In-Situ Tests

Shear stiffness of the soil at very small strains on the in-situ test locations was determined on the basis of the MASW method by measuring the shear wave velocity (v_s) and using (1). Results we got by measuring the shear wave velocity (v_s) for five locations are shown on Fig. 3 and the depth of the seismic profiles goes up to 13 meters. Values of the shear stiffness of the soil (G_o) at small strains for all five locations are shown in Table I. Also, exploration boreholes have been made at the locations where we have done our research. Lab tests have been done to get the I_P. Results of the I_P are shown for each depth on Fig. 4 and values of the I_P that we used for analysing the data are given in Table I.

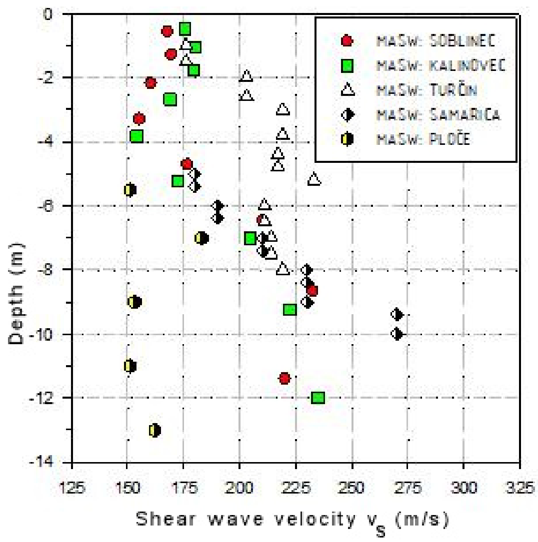

Fig. 3 1D profile of shear wave velocity for all five locations

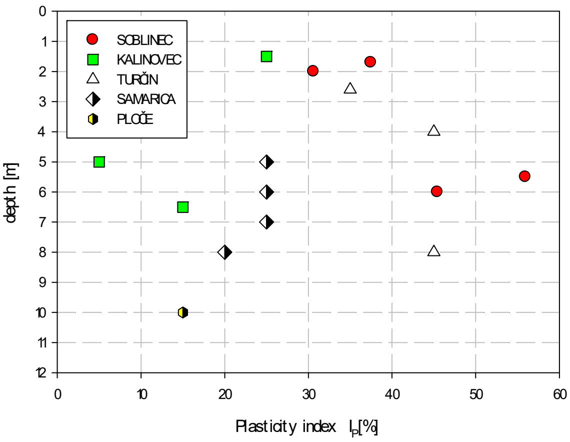

Fig. 4 Profile of the plasticity index for all five locations

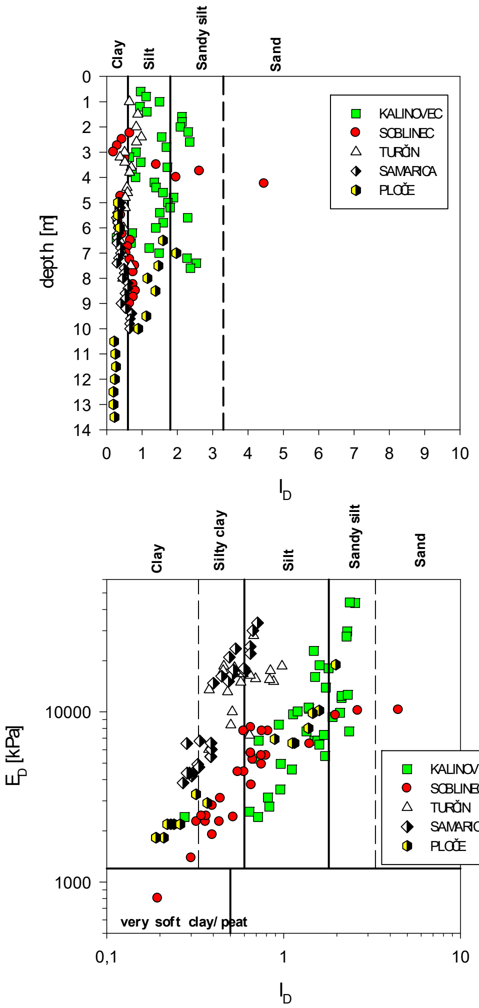

Fig. 5 DMT - material index I_d and the classification of the soil

DMT have been done on all locations up to the maximum depth of 13 meters. Classification of the soil was done on the basis of the material index I_D and dilatometer modulus E_D (Fig. 5). The investigation sites are predominantly clayey and silty deposits (Fig. 5). On the basis of the dilatometer modulus E_D (Figs. 2 and 5), additional classification of the soil was made depending on the compaction of the soil (loose, medium dense, dense) and the strength of the soil (soft, medium hard, hard). Detailed results are shown in Table I.

The most of the soil deposits are normally or lightly overconsolidated (Fig. 6) and the some soil deposits are overconsolidated which can be seen in a higher value of the at rest lateral earth pressure coefficient (K_o) which moves in the range from 2.0 to 2.8 (Fig. 6). Detailed display of the at rest latral earth pressure coefficient (K_o) and the *OCR* is given in Table I.

Oedometer modulus of compressibility (M_{DMT}) we got by the DMT is given from (14) and the results for our test locations are shown on Fig. 6 and explained in detail in Table ı where it can be seen that M_{DMT} is greatly influenced by the type of the soil and the *OCR*.

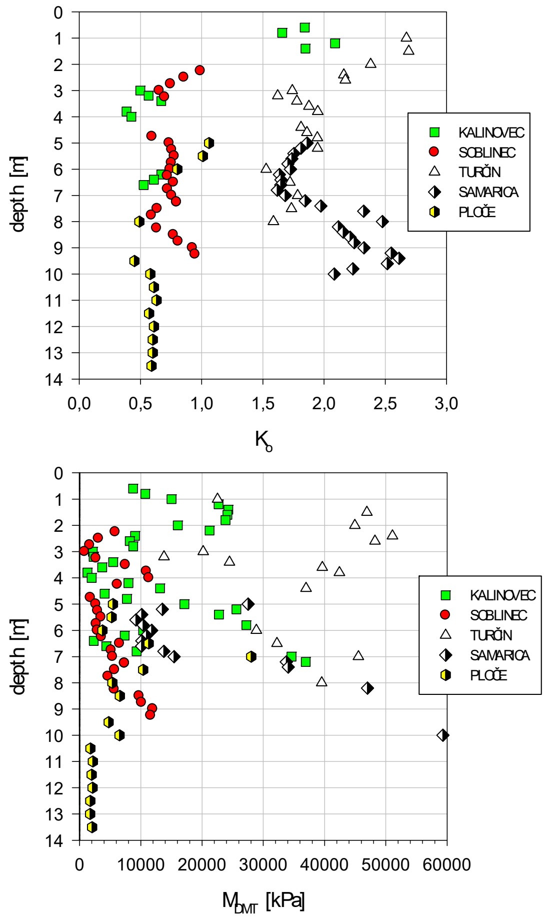

Fig. 6 DMT for the horizontal stress index (K_o) and the oedometer modulus (M_{DMT})

TABLE I
DATA ABOUT THE CLASSIFICATION OF THE SOIL, STIFFNESS OF THE SOIL AT SMALL STRAINS (G_o), EDOMETER MODULUS M_{DMT}, WORK SHEAR STIFFNESS OF THE SOIL G_{DMT} AND WORK SHEAR STRAIN γ_{DMT} FOR ALL FIVE TEST LOCATIONS DETERMINED ON THE BASIS OF A SECTION WITH G/G_o-γ REFERENCE DEGRADATION CURVE

Location	Depth	Classification	K_o	OCR	I_P	M_{DMT}	γ	G_o	G_{DMT}	G_{DMT}/G_o	γ_{DMT}
	[m]		[-]	[-]	[%]	[kPa]	[kN/m^3]	[kPa]	[kPa]	[-]	[%]
Soblinec	2.5	Silty clay,soft	0.85	2.2	35	3100	15.9	40700	1036	0.025	5.8
Soblinec	3.0	Clay,very soft	0.65	1.4	35	840	15.0	33800	280	0.0083	16.3
Soblinec	5.0	Clay, soft	0.73	1.7	50	2673	16.1	49300	890	0.018	12.5
Soblinec	5.5	Silty clay,soft	0.78	1.8	50	3511	16.4	53100	1169	0.022	10.0
Soblinec	6.0	Clay, soft	0.74	1.7	50	2920	16.3	65200	972	0.015	15.0
Ploče	6.0	Silty clay,soft	0.80	1.9	15	3742	16.5	37600	1246	0.033	2.5
Ploče	10.5	Clay, soft	0.61	1.2	15	1775	16.2	37000	591	0.016	6.8
Ploče	11.0	Clay, soft	0.63	1.3	15	2183	16.4	37400	727	0.019	5.8
Ploče	11.5	Clay, soft	0.57	1.1	15	1976	16.3	37100	658	0.018	6.2
Ploče	12.0	Clay, soft	0.61	1.2	15	2123	16.4	37400	707	0.019	5.8
Ploče	12.5	Clay, soft	0.60	1.2	15	1749	16.3	37100	582	0.016	6.8
Ploče	13.0	Clay, soft	0.60	1.2	15	1727	16.3	42300	575	0.014	8.2
Ploče	13.5	Clay, soft	0.59	1.1	15	2043	16.4	42500	680	0.016	6.8
Ploče	5.0	Clay, medium	1.06	3.4	15	5455	16.8	38300	1816	0.047	1.9
Samarica	5.4	Clay, medium	1.75	10.9	25	10147	17.3	56000	3379	0.06	2.0
Ploče	5.5	Clay, medium	1.01	3.1	15	5217	16.8	38300	1737	0.045	2.0
Samarica	6.0	Clay, medium	1.72	10.5	25	11780	17.5	63000	3922	0.06	2.0
Samarica	6.4	Clay, medium	1.65	9.4	25	10148	17.4	62700	3379	0.054	2.35
Samarica	7.4	Clay, hard	1.68	14.7	25	34066	18.6	82000	11343	0.138	0.82
Samarica	5.0	Silty clay, medium	1.86	12.6	25	27526	17.5	56800	9166	0.161	0.68
Samarica	7.0	Silty clay, medium	1.68	9.9	25	15443	17.8	78600	5143	0.065	1.90
Turčin	3.0	Silty clay, medium	1.74	10.7	40	20189	18.0	86300	6723	0.078	2.2
Turčin	3.2	Silty clay, medium	1.62	9.0	40	13800	17.7	84900	4600	0.054	3.3
Turčin	3.4	Silty clay, medium	1.78	11.3	40	24485	18.4	88200	8153	0.092	1.86
Turčin	4.4	Silty clay, medium	1.81	12.9	40	36973	18.9	89000	12312	0.138	1.2
Turčin	6.0	Silty clay, medium	1.53	7.8	40	28864	18.9	84100	9612	0.114	1.45
Turčin	6.5	Silty clay, medium	1.72	10.4	40	32243	19.2	85500	10737	0.126	1.3
Turčin	7.0	Silty clay, medium	1.78	11.4	40	45522	19.6	89800	15159	0.169	0.93
Turčin	8.0	Silty clay, medium	1.59	8.5	40	39529	19.5	93500	13163	0.141	1.1
Turčin	4.6	Silty clay, hard	1.86	12.7	40	84370	19.0	89400	28095	0.314	0.42
Turčin	4.8	Silty clay, hard	1.94	14.2	40	86770	19.3	90880	28894	0.318	0.41
Turčin	5.2	Silty clay, hard	1.94	14.2	40	94367	19.5	105800	31424	0.297	0.46
Samarica	8.0	Silty clay, hard	2.47	26.6	20	96826	19.4	102500	32243	0.315	0.32
Samarica	8.4	Silty clay, hard	2.15	18.5	20	99410	19.3	102300	33103	0.324	0.31
Samarica	9.0	Silty clay, hard	2.32	22.5	20	85027	19.3	102300	28314	0.277	0.39
Soblinec	6.5	Clayey Silt, loose	0.77	1.7		6549	17.0	75000	2181	0.029	4.0
Soblinec	7.5	Clayey Silt, loose	0.64	1.3		5746	16.9	81800	1913	0.023	5.1
Soblinec	8.5	Clayey Silt, loose	0.77	1.8		9723	17.5	92500	3238	0.035	3.2
Ploče	10.0	Clayey Silt, loose	0.58	1.1	10	6533	17.2	39200	2175	0.055	1.9
Turčin	1.0	Clayey Silt, medium	2.67	32.6		22530	17.6	54500	7502	0.138	1.14
Turčin	3.6	Clayey Silt, medium	1.87	12.9	40	39642	18.9	90600	13200	0.146	1.1
Turčin	3.8	Clayey Silt, medium	1.95	14.2	40	42426	19.0	91100	14127	0.155	1.03
Kalinovec	3.6	Clayey Silt, medium	1.40	6.4		13960	17.1	38500	4649	0.121	0.68
Kalinovec	4.4	Clayey Silt, medium	1.40	6.8		19254	17.9	54800	6411	0.117	0.71
Samarica	10.0	Clayey Silt, medium	2.08	30.6	20	59337	19.6	143000	19760	0.138	0.92
Turčin	2.0	Clayey Silt, dense	2.38	23.9		44953	18.6	76600	14970	0.195	0.76
Turčin	2.6	Clayey Silt, dense	2.17	18.9	40	48247	18.9	77900	16066	0.206	0.73
Turčin	7.5	Clayey Silt, dense	1.73	10.6	40	67417	20.0	91600	22450	0.245	0.59
Kalinovec	5.4	Clayey Silt, dense	2.20	18.5		47044	19.2	69300	15665	0.226	0.29
Samarica	9.4	Clayey Silt, dense	2.60	16.9	20	89966	20.4	148500	30000	0.202	0.58
Ploče	8.0	Silt, loose	0.49	0.9	5	5353	16.9	56600	1782	0.031	3.5
Ploče	9.5	Silt, loose	0.45	0.8	5	4758	16.9	39600	1584	0.040	2.6
Turčin	1.5	Silt, dense	2.69	33.2		46917	18.6	57600	15623	0.271	0.5
Turčin	2.2	Silt, dense	2.28	21.3		52617	18.9	77900	17521	0.225	0.63
Kalinovec	5.0	Silt, dense	1.74	10.8		51902	19.2	58800	17283	0.294	0.168
Soblinec	3.5	Sandy silt, loose	0.70	1.3		7498	16.7	42700	2496	0.058	1.05
Kalinovec	2.0	Sandy silt, loose				8996	16.6	50800	2995	0.059	1.52
Kalinovec	2.4	Sandy silt, loose				5748	16.3	50000	1914	0.038	2.50
Ploče	6.5	Sandy silt, loose		1.2		11266	17.4	58300	3751	0.064	1.04
Ploče	7.5	Sandy silt, loose				10394	17.4	58300	3461	0.060	1.08
Ploče	8.5	Sandy silt, loose				6571	17.1	58300	2188	0.038	1.9
Kalinovec	1.0	Sandy silt, medium				21284	17.2	52600	7087	0.135	0.36
Kalinovec	1.4	Sandy silt, medium				24934	17.5	53600	8303	0.155	0.296
Kalinovec	1.8	Sandy silt, medium				18032	17.3	52900	6005	0.114	0.45
Kalinovec	3.0	Sandy silt, medium				22272	17.7	54200	7416	0.137	0.54

Shear modulus G_{DMT} at the „work strain“ is determined on the basis of the oedometer modulus M_{DMT} by using the linear-elastic correlation defined under (8) and with an assumption of the constant Poisson's coefficient ($\nu=0.25$). Detailed data about the shear modulus G_{DMT} for all test locations ARE shown in Table I.

In order to determine the degradation curve it is necessary to know the value of shear deformation γ_{DMT} at the shear stress G_{DMT} (shear stress can be determined with the help of a normalized degradation curve G/G_o-γ. In this article constitution equation (3) according to [4] was used. It takes into consideration the influence of I_P and mean effective stress (σ'_{mo}) which depends on the vertical effective stress (σ_{vo}') and the at rest lateral earth pressure coefficient (K_o). Normalized degradation curve has been chosen since it takes into consideration the type of material and actual state of the strain in the soil.

On the location Ploče, settlement of the embankment was measured by a vertical deformeter which is taken as a preload in order to speed up the consolidation of the subsoil. Settlements were measured in time intervals. The degradation curve G/G_o was determined based on the data of measured settlements on two depths (8.0 m (layer of silt) and 12.0 m (layer of clay)). It can be seen that the degradation curve given on the location of Ploče by using the in-situ tests, falls in the range which is defined by a constitutional equation (3) although it is not complete.

Two groups of material have been analysed: clayey soil (clay, silty clay) and silty soil (clayey silt, silt, sandy silt).

For the clayey soil the range of normalized degradation curve G/G_o-γ has been defined based on the value of the effective vertical stress (σ_{vo}') in the range from 50 to 100 kPa, I_P in the range from 25% do 50% and at rest lateral earth pressure coefficient (K_o) in the range from 0.7 to 2.4 (it is shown by the hatched area on Fig. 7).

For the sandy soil, the range of normalized degradation curve G/G_o-γ has been defined based on the value of effective vertical stress (σ_{vo}') in the range from 25 to 100 kPa, I_P in the range from 0% to 40% and at rest latral earth pressure coefficient (K_o) in the range from 0.7 to 2.4 (it is shown by the hatched area on Fig. 8).

The values of the shear deformation γ_{DMT} at the shear stress G_{DMT} resulting from the intersection of the G_{DMT}/G_o data points with the degradation curve G/G_o defined with (3). Value of effective vertical stress, I_P, and at rest lateral earth pressure coefficient were taken into consideration. This way of determining the shear strain was presented and used by [8]. These values of G_{DMT}/G_o and γ_{DMT} are shown in detail in Table I and graphically on Figs. 7 and 8.

IV. Analysis of the Test Results

Figs. 7 and 8 graphically show results from all test locations. The results for clayey and silty materials are separated due to different shape of a normalized degradation curve G/G_o-γ.

For determining the shear strain γ_{DMT} at the value of shear soil stiffness G_{DMT}/G_o which is given by the DMT, we used constitutional equation (3) according to [4] to define the normalized degradation curve. The reason we used this equation is because it takes into consideration the type of material and the actual state of the stress in the soil through the I_P and mean effective stress (σ'_{mo}).

It is problematic to determine the shear deformation γ_{DMT}, at least approximately because it gives us another number necessary to form the degradation curve. Based on the available information typical range of shear strain associated to the working strain shear moduli G_{DMT} can be approximately assumed as: 0.1 to 1.9% in silt and clay and >2% for soft clay [7], [8], [10]-[12].

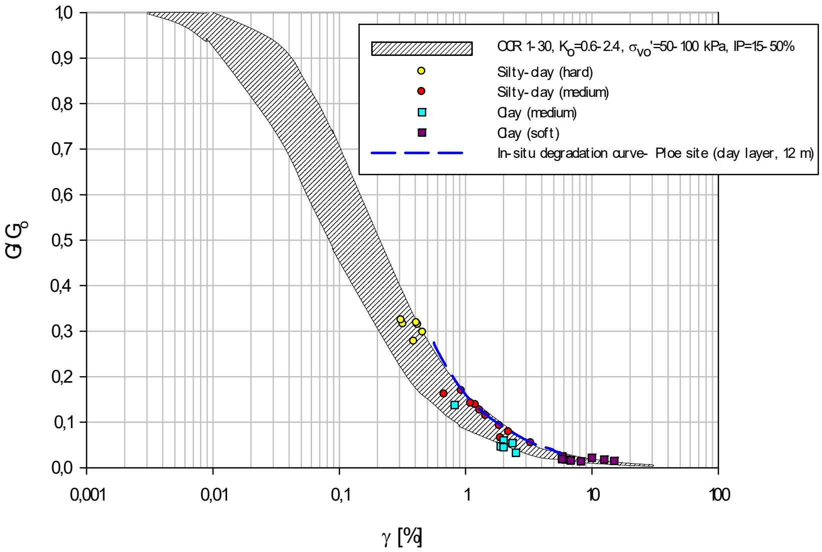

Fig. 7 Shape of the normalized G/G_o-γ degradation curve's range and values of G_{DMT}/G_o-γ_{DMT} based on the DMT for clayey materials (clay, clayey silt)

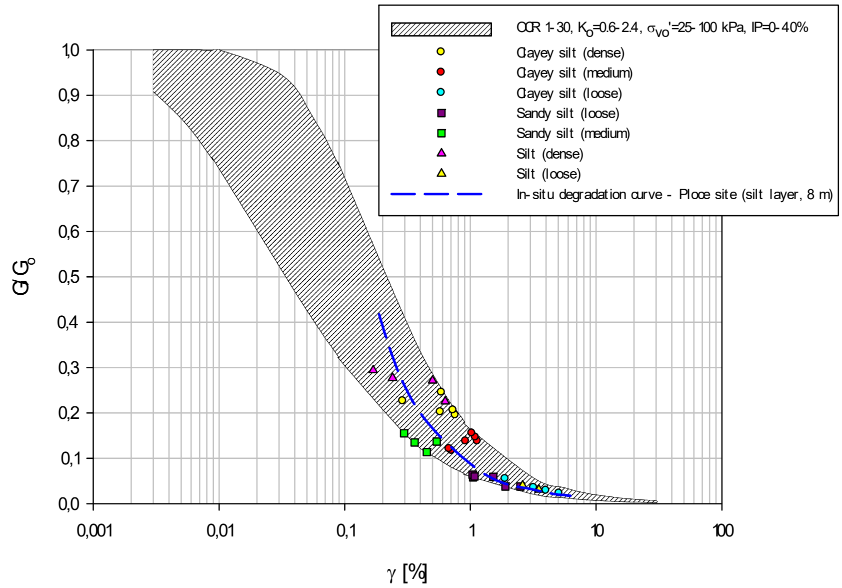

Fig. 8 Shape of the normalized G/G_o-γ degradation curve's range and values of G_{DMT}/G_o-γ_{DMT} based on the DMT for silty materials (clayey silt, silt, sandy silt)

In this article, another classification inside of some soil groups was made with and intention of a higher precision in the process when determining the shear strain γ_{DMT} and a G_{DMT}/G_o relation based on the DMT. Studied groups of the soil (clayey and silty materials) have been additionally classified considering the value of the dilatometer modulus (E_D) because it defines the classification inside a separate soil group in the function of compaction (loose, medium dense and dense) or strength (soft, medium hard and hard).

Stiffness at small strains (G_o) is determined by MASW tests by which we measured shear wave velocity (v_s) using (1). Also, stiffness at small strains could be determined by other methods as it was mentioned in Section II *A*.

By analysing the given results of the DMT, we got the values of the shear strains γ_{DMT} and G_{DMT}/G_o relation. Synthesis of the results is shown in Table II.

Based on the data in Table II and shear modulus at small strains (G_o) if we know the stiffness and type of the soil (from laboratory or some in situ tests), we can approximately determine the working strain shear modulus G_{DMT}. Led by this statement, Young modulus of the soil elasticity (E_{DMT}) can be approximately determined using:

$$E_{DMT} \approx G_{DMT} \cdot 2 \cdot (1 + \vartheta) \quad (16)$$

V. Conclusion

Results presented in this article confirm the possibility of using DMT and MASW tests when determining in-situ normalized degradation curve G/G_o-γ at the state of strain in the soil for cohesive soils. MASW test provides the small soil stiffness (G_o from v_s) at very small strains.

Shear modulus G_{DMT} at a „work strain" can be determined on the basis of oedometer modulus M_{DMT} with an assumption of their linear-elastic relation.

Information about the stiffness at small strains (G_o) and the value of shear modulus at shear strain gives us two points through which we can make interpolation of the data from the lab in order to get the complete in-situ degradation curve G-γ.

Typical range of the shear strain γ_{DMT} available in the literature are relatively wide, so we had determined a much smaller range of shear strain γ_{DMT} depending on the classification of a cohesive soil (clay, silty clay, clayey silt, silt and sandy silt), function of density (loose, medium dense and dense) and the stiffness of the soil (soft, medium hard and hard). Results are given in Table II.

TABLE II
Range of the Value of Shear Strains γ_{DMT} and G_{DMT}/G_o Relation for Cohesive Soils

Soil group	Classification of the Soil (DMT)	γ_{DMT} [%]	G_{DMT}/G_o
Silty soil	Clayey silt - dense	0.30 - 0.80	0.20-0.25
	Clayey silt - medium	0.70 - 1.1	0.12-0.15
	Clayey silt - loose	3.0 - 5.0	0.02-0.03
	Silt - dense	0.20 - 0.60	0.23-0.30
	Sandy silt - medium	0.30 - 0.60	0.12-0.15
	Sandy silt - loose	1.0 - 2.5	0.05
Clayey soil	Silty clay - hard	0.30 - 0.50	0.28-0.32
	Silty clay - medium	0.70 - 2.0	0.08-0.17
	Clay - hard	0.8	0.14
	Clay - medium	2.0 - 2.5	0.05-0.06
	Clay - soft	5.0 - 15.0	0.018-0.025

Based on the data of G_{DMT}/G_o, shear modulus G_{DMT} can be approximately determined just on the basis of shear modulus at small strains (G_o). This also enables us to approximately determine the Young modulus of elasticity of the soil (E_{DMT}).

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