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Determining G-γ decay curve in overconsolidated clays from Seismic Dilatometer Test

Déterminer les courbes de décomposition G-γ dans les argiles surconsolidés d'essai sismique de dilatomèt

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ABSTRACT: Analysis of soil-structure interaction demands properly determined parameters for a particular calculation method. It means that moduli should correspond to stress-strain range of a particular construction. Degradation of G-γ curve describes the behavior of the soil from very small to very large strains. In order to get its shape, it can be determined using a variety of laboratory testing procedures. However such tests are sophisticated and expensive, and also rely on the retrieval of good quality samples. Another option it may be use of a database, as a complementary source of information. In this case in-situ tests can be used to measure G-γ curves complementary with reference G-γ degradation curves from laboratory tests. The article presents the methods of stiffness parameters determination and possibility of using seismic dilatometer tests to get the shape of G-γ degradation curve for stiff overconsolidated clays characterization. The article presents results for Neogene clays of Poznań formation and Quaternary glacial clays (tills), a subsoil for many structures (deep excavation) in almost 75% area of Poland. Results taking from chosen test sites, from Seismic Dilatometer (shear stiffness and constrained modulus), has been compared with the theoretical G-γ degradation curve (reference typical shape) from laboratory tests in order to determine the shear deformation for overconsolidated soils.

RÉSUMÉ: Analyse des demandes d'interaction sol-structure correctement détermine les paramètres pour une méthode de calcul particulière. Cela signifie que les modules doivent correspondre à la gamme de contrainte-déformation d'une construction particulière. Dégradation de la courbe G-γ décrit le comportement du sol de très petites aux souches très élevés. Afin d'obtenir sa forme, il peut être déterminé en utilisant une variété de procédures d'essais en laboratoire. Cependant, ces tests sont sophistiqués et chers et s'appuient également sur la récupération des échantillons de bonne qualité. Une autre option, on peut utiliser une base de données, comme une source d'information complémentaire. Dans ce cas, essais in-situ peuvent servir à mesurer les courbes de G-γ complémentaires avec les courbes de dégradation de référence G-γ des essais de laboratoire. L'article présente les méthodes de détermination des paramètres raideur et possibilité d'utiliser des tests sismiques dilatomètre pour obtenir la forme de G-γ dégradation courbe pour la caractérisation des argiles surconsolidé raide. L'article présente les résultats pour les argiles Néogène de formation de Poznań et argiles quadruple glaciaires (till), un sous-sol de nombreuses structures (excavation profonde) dans presque 75 % région de Pologne. Résultats prise de choisis test sites, dilatomètre sismique (rigidité en cisaillement et module confiné), a été comparée à la courbe théorique de dégradation des G-γ (forme typique de référence) des essais de laboratoire afin de déterminer la déformation de cisaillement pour les sols surconsolidés.

Keywords: soil stiffness; seismic dilatometer; reference degradation curve; overconsolidated clays.

1 INTRODUCTION

The actual soil behavior depends on geological processes related to the original sedimentation and other post genetic processes, as well as stress history, physical and chemical processes (e.g. age and cementation). The deformation parameters estimation for natural normally consolidated (NC) soil are describe very well in many extensive publications attempting to address this issue (e.g. Atkinson 2000, Mayne 2001, Massarsch 2004, Vardanega and Bolton 2010, Clayton 2011), and to give some proposals for interpretation (e.g. Annexes to Eurocode 7 Part 2). In the case of overconsolidated cohesive soils, a number of studies have been conducted to characterize various aspects of their behavior and variability; for example focused on overconsolidated soil or directly on stiff clays (e.g. Gasparre et. al. 2007, Simpson 2010). But these correlations between sounding results and geotechnical parameters require regional determination or adaptation for local conditions to accurately estimate soils parameters.

In Poland, Pliocene clays (very similar with London clays) and glacial tills have been investigated from many years, but using an advance methods (using seismic instrumentation) to some extent, mostly based on a limited number of laboratory tests and recently on various in situ tests: (Lipiński and Tymiński 2011, Godlewski and Szczepański 2015, Godlewski and Wszędyrówny 2016, Młynarek et al. 2017, Lechowicz and Rabarijoely 2017). Majority of these studies including laboratory and in situ tests, aimed to establish some new correlations or validated existing which maybe use in practice for parameter estimation. Additional difficulties refer to many other factors that have an influence on the soil properties. One of them is the problem of estimating correctly deformation characteristic for overcosolidated (OC) soils.

Determination of soil-structure interaction demands that properly determined parameters should be used with a particular design method. In the case of deformation modulus determination, it is essential to take into consideration the moduli at corresponding stress-strain range of the particular construction, together with possible dynamic loads (Młynarek et al. 2017, Mitew-Czajewska 2018). It means that these moduli should correspond to the so-called small strain, semi-elastic range of deformations. Realization of non-linearity of stress-strain relationship has led to the need of measuring soil stiffness over a range of small strain ($10^{-6}\div10^{-3}$) and utilization of many methods for this purpose (Atkinson 2000). As described by (e.g. Mayne 2001, Massarsch 2004, Clayton 2011), several in-situ and laboratory test methods are employed to determine the maximum shear modulus G_0 (from the shear wave velocity, V_s): Down-Hole (DH) and Cross-Hole (CH) seismic methods, Seismic Dilatometer Test (SDMT) and Seismic Cone Penetration Tests (SCPT), Spectral Analysis of Surface Waves (SASW), Bender Elements Test (BET), Resonance Column (RC). The Dilatometer test (DMT), Pressuremeter Test (PMT), Triaxial Test (TRX), Oedometer test (OET) are also performed to allow assessment of the stiffness of soils at moderate to large strains. It's mean that non-linear behavior of the soil can be determined by many in-situ and lab tests, but to get shape of this curve its necessary to make complex research (in situ and laboratory tests). However such tests are sophisticated and expensive (due to the cost of taking the good quality samples, and cost of necessary good quality equipment). It is therefore of interest to investigate if in-situ tests can be used to measure G-γ curves. This paper considers the seismic dilatometer test (SDMT) as a possibility where the G-γ curve is derived from the "initial elastic modulus" G_0 from the shear wave velocity V_S, a "working strain modulus" (G_{DMT}) corresponding to the Marchetti (1980) constrained modulus M_{DMT}. The present paper aims to provide some recommendations for the interpretation of the results from in situ tests used in Polish practice

(SDMT) for estimating the G-γ degradation curves for overconsolidated soils.

2 METODOLOGY

The seismic dilatometer (SDMT) is the combination of the mechanical flat dilatometer (DMT), introduced by Marchetti (1980), with a seismic module for measuring the shear wave velocity V_S. From V_S the small strain shear modulus G_0 may be determined using the theory of elasticity. Marchetti et al. (2008) first proposed the possible use of the SDMT for deriving in situ elemental soil stiffness variations with strain level (G-curves or similar). Now is known in literature as tentative method for deriving in situ G-γ decay curves from SDMT. A challenging issue, which the scientific community has focused in the last decade (e.g. Marchetti et al., 2008, 2009; Amoroso et al., 2014, Ivandic et al. 2018), concerns the possibility of assessing the in situ decay curves of soil stiffness with shear strain (G-γ curves), based essentially on the G_0 and G_{DMT} experimental data. This approach has proven applicable to different soil types, as shown by (Amoroso et al. 2014). However, limited data are available as to ascertain the reliability of this procedure for soft materials, especially for organic soils.

In short, this procedure allows that some curves could be tentatively constructed by fitting “reference typical-shape” laboratory G- curves through two points, both obtained by SDMT: (1) the initial small strain modulus G_0, and (2) a working strain modulus G_{DMT}. To locate the second point on the G-curve it is necessary to know, at least approximately, the elemental shear strain corresponding to G_{DMT}. Researches classified the DMT within the group of methods of measurement of soil deformation characteristics involving an intermediate level of strain (0.01-1%).

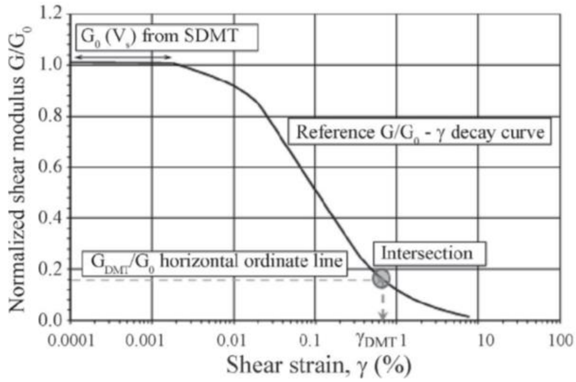

Figure 1. Scheme of procedure to derive in situ G-γ decay curves from SDMT (Amoroso et al. 2014)

As suggested by Marchetti et al. (2008, 2009), a *working strain shear modulus* G_{DMT} can be derived from the constrained modulus M_{DMT} provided by the usual DMT interpretation (Marchetti 1980). As a first approximation, by referring to linear elasticity:

$$G_{DMT} = \frac{1-2\nu}{2(1-\nu)} M_{DMT} \qquad (1)$$

Where ν (-) is a Poisson's ratio.

The above tentative method is heavily founded on the assumption that M_{DMT} is a reasonable estimate of the "operative" or *working strain* modulus (Marchetti et al. 2009, Amoroso et al. 2014).

The procedure describe in Figure 1 was adopted in presented results. This paper illustrates the use of the SDMT to assess the in situ decay of stiffness at various test sites, where (OC) clays were found, where both SDMT data and "reference" stiffness decay curves from laboratory tests were available. In this case a advance triaxial apparatus with bender elements and local (on sample) displacements transducers were used as one of the preferred laboratory methods for obtaining soil strength and stiffness parameters of the soil. More details about this equipment and technical information is described in (Bogusz, Witowski 2018).

3 INVESTIGATION METHODS

The ample set of information collected and the experience gained within the framework of research and development activities at the Building Research Institute concern data of significance for actual applications, such as identifying correlation relationships at test sites, or results from observation of various structures' behavior (settlements), especially, concerning overconsolidated soils. This allowed to conduct research in the field of determination of regional relationships between in situ methods (Godlewski, Wszędyrówny-Nast 2016), including the presentation of practical applications of results obtained with the dilatometer (DMT/SDMT).

The paper focuses on the presentation of the overview of the database of triaxial test results conducted for soil samples taken in various regions of Poland. This results were used as a background for estimated decay curve which were validated by SDMT results. Due to limitations of the paper, the presentation and the analysis of the results contained in the database has been limited mainly to two soil type were investigated, namely: “Pliocene” clays and glacial tills. The thickness of the ice overburden after two main glaciation period is estimated max. to 1 km (Kaczyński 2003). This process make some overconsolidation loading over this soils, observed now in OCR ratio from typical value 8-12 up to 50 (for Warsaw clays).

<u>*DMT results*</u>

Building Research Institute has got extensive experience concerning in situ soil investigations by means of cone penetration test and dilatometer test. The huge number of data points including different types of soils for different types of construction has been collected. This described correlations are based on the results from more than 30 test sites on different types of soils in Poland. Each test site was considered as a node, consisting of CPTU profile, DMT profile, geological profile and settlement data. After extreme values elimination, the data was divided into litho-genetic groups from all test sites. The results for analysed soil types were plotted on existing DMT material index nomogram (Figure 2).

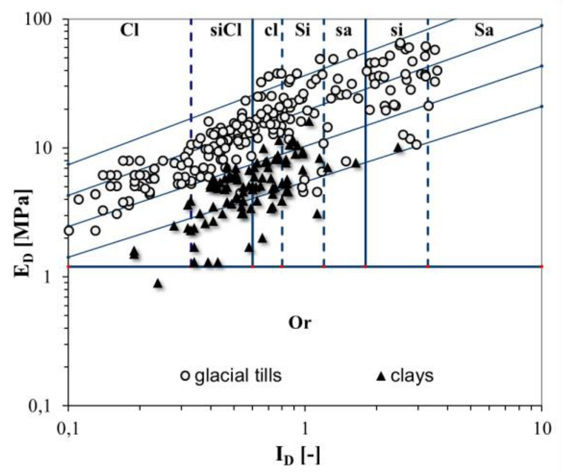

Figure 2. All results for different test sites for two types of soils plotted on Marchetii's nomogram (Marchetii 2008)

The Marchetti flat dilatometer is a device dedicated to determine the deformation parameters of soils. This is supported by the specificity of measurement itself (Marchetti 1980). Worldwide experience (Monaco et. al. 2006) indicates that DMT is highly useful in determination of soil deformation modulus.

This method is reliable, provided that it is calibrated and validated (by other methods). In this case, the best method is to compare the settlement values measured at given structures or performance of test loads against the settlement values obtained from DMT. Comparison of settlement values measured at the structures with respect to those obtained by dilatometer and literature data (Monaco et. al. 2006) and own observations (Godlewski 2015). The results of this papers show that the dilatometer is a well-calibrated device for typical structures founded on tested ground condition (soil type). This results give a good recomedation for using M_{DMT} (as the "operative" or *working strain* modulus) for shear stiffness estimation.

<u>*SDMT results*</u>

Currently, apart from the standard DMT test, the tests involving geophysical measurements with a dilatometer with a seismic sensor (SDMT) have been performed increasingly often. These tests allow to determine the soil stiffness profile as a function of shear modulus (G_0) by measuring the propagation of velocity of a transverse wave (Vs). The SDMT method is validated by surface geophysical methods (CSWS and SASW). More information on the obtained results of seismic measurements and observations related to the impact of testing methodology in polish ground condition is available in previous papers (Godlewski & Szczepański 2015). To the estimation of decay in situ curves the both results (from DMT and SDMT) were use. The small strain shear modulus G_0 is determined by the theory of elasticity by the well-known relationships:

$$G_0 = \rho V_s^2 \qquad (2)$$

Where ρ (Mg/m^3) is soil unit density and V_s (m/s) is shear wave velocity.

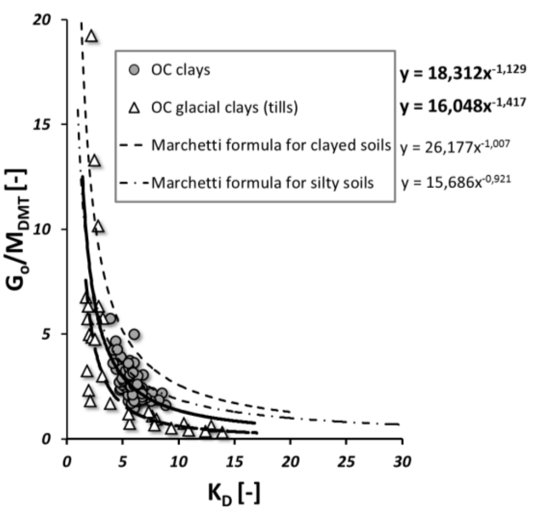

Figure 3. Graph of the G_{DMT}/G_0 indicator vs K_D for chosen types of OC soils from Poland

Based on this results the next step it was create correlations of G_{DMT}/G_0 as a function of K_D. Such relationship was presented originally by Monaco et. al. (2009), and theoretically, it allows for assessment of G_0 having only G_{DMT} (calculated from dilatometer modulus M_{DMT}) and K_D from standard DMT. This relationships have been examined for typical OC soils present in Poland, for which the possibility of estimation of modulus of shear stiffness G_0 is sought on the basis of the standard results from DMT tests (Figure 3). Points on the graph affect average values for a chosen layer on the test sites (28 data points for glacial tills and more than 100 data point for clays).

<u>*Results from Laboratory*</u>

A total of more than 100 samples were taken from the investigation site for laboratory tests. The tests were carried out using triaxial testing devices. The tests were conducted on undisturbed soil samples, either 70 mm in diameter and the height of 140 mm, or the diameter of 38 mm and the height of 75 mm. The samples were saturated with an automatic pressure control algorithm, until B coefficient reached a value greater than 0.95. After the saturation phase, the isotropic consolidation stage was carried out, followed by the S-wave transition measurements with bender element tests (BET) together with the use of local displacement transducers. In the case of 38 mm diameter samples, both the shear wave and the compressional wave (P-wave) velocities were measured. More details about using procedure and some aspects about measurement (also with new developed in-house instrumentation is available in paper (Witowski 2018). The statistical primary information concerning selected parameters contained in the database is shown in Table 1. More characteristic and statistical distributions for analyzed soils in (Bogusz Witowski 2018). The tests were conducted at the confining pressures between 15 kPa to 2000 kPa, but more data is from 100 up to 500 kPa.

Table 1. Summary of basic properties for analyzed soils a) clays; b) glacial tills.(Bogusz, Witowski 2018)

Statistical parameters	Moisture content w_c [%]		Initial void ratio e_0 [-]		Plasticity index I_P [%]		Liquidity index I_L [%]		Unit density ρ [Mg/m^3]		Initial shear modulus G_0 [MPa]	
	a)	b)	a)	b)	a)	b)	a)	b)	a)	b)	a)	b)
Min	16,80	8,57	0,44	0,23	34,76	10,22	-0,12	-0,07	1,93	2,01	44,54	45,90
Max	30,82	20,08	0,82	0,54	140,4	25,69	-0,01	0,41	2,15	2,38	217,7	592,5
Arithmetic average	20,71	13,21	0,57	0,37	55,39	15,08	-0,06	0,19	2,06	2,20	119,1	185,1
Standard deviation	4,37	2,69	0,10	0,06	30,74	3,69	0,04	0,12	0,06	0,07	47,62	114,9
CoV [%]	21,1	20,4	17,9	16,2	55,5	24,5	-58,7	63,2	3,08	3,18	40,0	62,1

4 SUMMARY OF THE RESULTS

The obtained results from all tests (laboratory and in situ) were summarized in graphs (Fig. 4a and b).

a)

b)

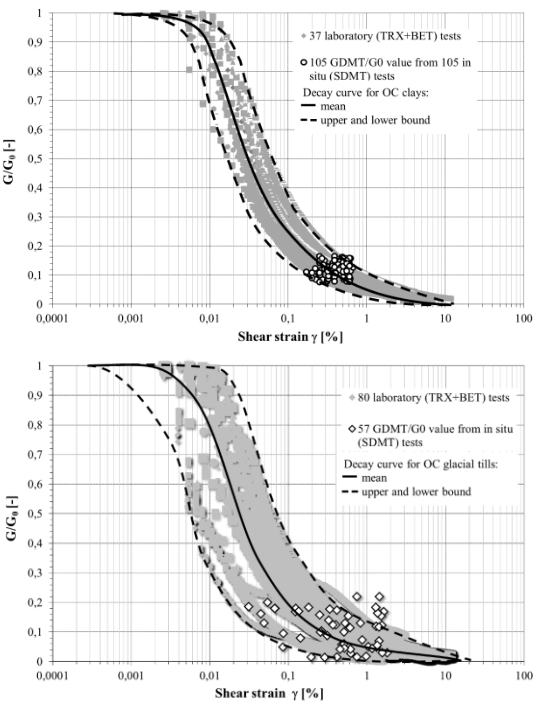

Figure 4. Shape of the normalized G/G_0-γ degradation curve's range and values of G_{DMT}/G_0-γ_{DMT} based on the SDMT for a) OC clays, b) OC glacial tills.

They show that results from laboratory tests for OC clays and glacial tills are separated due to different shape of a normalized degradation curve (in function G/G_0-γ). Results obtained for glacial tills exhibit larger scatter of decay range than in the case of clays. This situation is typical for this type of soil because of his natural variability of soils generally classified as glacial tills. Next for estimating the shear strain the SDMT data obtained at the same depth were use. Base on M_{DMT} and using constitutional equation (2) a working strain modulus G_{DMT} was derived. For both types of soils, the estimated values of Poisson's coefficient from laboratory, for calculation an average value were chosen (0,3). Also for getting a normalized value a small strain value G_0 was derived from Vs. After that the horizontal ordinate line was superimposed to the same depth on proposed reference stiffness decay curve. The intersection of the G_{DMT}/G_0 value provides a shear strain value referred as γ_{DMT}. Information about the stiffness at small strains (G_0) and the value of shear modulus at shear strain gives us two points through which we can make interpolation of the data from the laboratory in order to get the complete in-situ degradation curve G-γ.

Finally, Figure 5 presents the obtaining relationship for OC soils versus original relationship (as a background) from literature (Marchetti et al. 2008, 2009, Amoroso et al. 2014).

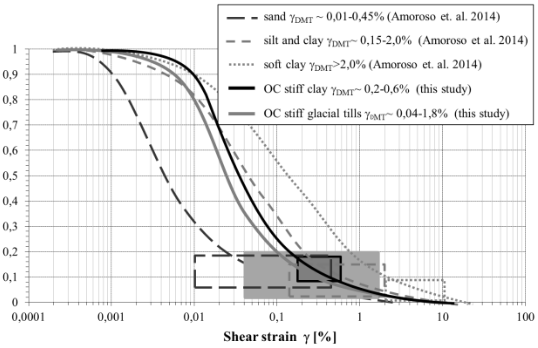

Figure 5. Reference decay curve for OC soils and range of in situ results from SDMT (after Amoroso et. al. 2014).

The values of the normalized working strain shear modulus G_{DMT}/G_0 range from 0.08 to 0.16 in clays and 0.01 to 0,2 in glacial tills, while the range of values of the shear strain γ_{DMT} are 0.2% to 0.6% in clays, 0.04% to 1.8% in silty, sandy stiff clays (tills).

This results show that in OC soils is visible effects of the fastest increase in stiffness with stress level and the fastest reduction in stiffness with strain level than typical NC, soft soils. These observations are in agreement with preliminary literature indications (Massarsch 2004, Marchetti 2009, Ivandic 2018).

5 CONCLUSIONS

The paper presented the results support the possible use of the SDMT as a well-calibrated method to determining the degradation G-γ curve G-γ for OC clays and glacial tills. The proposed hyperbolic relationship, together with an estimate of γ_{DMT}, can provide a useful first order estimate of a soil's G-γ degradation curve.

Observed higher variability in range of shape of shear stiffness for glacial tills (than in the case of clays) is cause by their natural genesis, could be précised and correct in future research using more sophisticate classification.

Depending on the engineering application and the site data available, engineers can make predictions of clay and tills stiffness degradation with confidence in the reference shape stress-strain curve from laboratory database.

Presented results have good statistical value because more than 100 decay curve from laboratory tests were used for the analysis and more than 160 results from in situ (SDMT). Of course, the author realized that given values require consideration of additional factors affecting poor correlation parameters (especially in the case of glacial tills). However, the shape for each soils type are very well characterized in relation to specificities of Polish ground conditions. The results presented in the article are the examples which may be used in the Polish practice and from the scientific point of view, the obtained value (reference decay curve and DMT shear strain range) may be compared to the data from literature as a background. The main goal of these analyses was get a relationship between laboratory and in situ (SDMT) method using for estimating a soil shear stiffness non-linear behavior tests for typical (in Polish condition) OC soils .

Because of the article size limit, not all issues have been presented. The author gave only the information about the problem which needs further investigations. The article show that these methods are very useful for tentative determination of stiffness parameters for practical geotechnical design.

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