Practical Use of the Dilatometer Tests - some Case Studies from Poland

Tomasz Godlewski
Building Research Institute, Department of Geotechnics and Foundation, Warsaw, Poland. E-mail: t.godlewski@itb.pl

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ABSTRACT: The article presents the issues concerning the forecasts and evaluation of settlement based on field tests. The example of the DMT application for settlements for the schoolhouse, residential building and chosen sewage treatment plant object in which excessive displacement of the construction appear, and other collected examples confirm gauging the used method. An extrapolation of long-term observation is confirm the forecast in similar conditions. As another example for DMT application refers to dynamic soil improvement method. About the DMT effectiveness a fact of the development of this method also provides stiffness's of ground towards the evaluation (module Go), through measurements with the seismic application.

1 INTRODUCTION

This article presents the issues concerning the practical application of field test results obtained mainly by flat dilatometer (Marchetti dilatometer). The ample set of data collected and experience gained within the framework of research and development activities at the Building Research Institute concern data of significance for actual application, such as looking for correlation relationships in research at test sites or results of observation of various structures (settlements). This, among others, allowed to develop a research and development project (No 4 T07E 047 30) in the field of determination of regional relationships in *in situ* methods (Wysokiński et. al. 2009, Godlewski 2011a) including the presentation of practical applications of results obtained with the dilatometer.

The referenced in these article examples of various practical applications of DMT test results confirm the effectiveness of this method in the evaluation of soil substrate and settlement estimations.

2 PREFACE

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 2001). Expanding a steel membrane in the soil is a controlled displacement test, i.e. measurement of pressure at desired displacement. This allows estimating the deformation modulus directly in the soil (*in situ*) which is the basis for determination of displacements of the designed structure.

Determining the magnitude of settlement and foreseeing such settlement is, for any structure designed especially in difficult geotechnical conditions, an element which is crucial to determination of foundation method. Depending on the type and importance of the structure, the difference between shallow founding with the necessity to execute soil improvement or "avoidance" of the problem by deep foundations is small. For typical buildings (up to 11 storeys) the value of permissible settlement is 5cm (as per National Annex to Eurocode 7), Polish Standard (PN-81/B-03020 1981) allowed for 7cm. Direct evaluation of parameters (including moduli) of soil is possible only on the basis of test loads and by *in situ* methods. The requirements of new European standards EN-1997-1 and -2 result in the necessity to carry out quantitative tests (mainly probing) when preparing the soil documentation. The correlations applied in practice between probing results and information on soil conditions of a founded structure require regional adjustments or adaptation to local conditions. However, the practical application of theoretical solutions is still subject to difficulties since both the results of probing and behavior of soil underlying a structure are affected by a number of different factors, the measurement of which is still impossible or not sufficiently reliable (Wysokiński et. al. 2009). For the new types of static penetration probes (such as: CPTU with a piezocone or dilatometer) sufficiently good (regional) Polish correlations for interpretation of results have not been issued yet or they are not sufficiently verified. The literature data (including that specified in the annexes to Eurocode 7) obtained abroad in other soils are often unsatisfactory under Polish conditions and sometimes lead to incorrect conclusions – see example 4.

3 RESEARCH RESULTS

Worldwide experience (Marchetti et. al. 2001), (Monaco et. al. 2006) indicates that DMT is highly useful in determination of soil deformation moduli. 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 against the settlement values obtained from DMT or performance of test loads. Comparison of settlement values measured at the structures with respect to those obtained by dilatometer and literature data (26 structures) (Monaco et. al. 2006) and own observations (23 structures) (Godlewski 2011b) is presented in Fig.1. For a total of almost 50 structures, the type of foundation (pad, strip or slab foundation) and soils at the foundation level were indicated (sandy soil: Sa, cohesive: saSi, sasiCl, Cl and organic: Or). These are mainly typical residential and industrial buildings not exceeding 11 storeys with the exception of 2 road structures (abutment and embankment). Additionally a set of measurements for improved soil was added, wherein the dilatometer was used to determine the deformation modulus of the "composite" – soil and soil improvement elements (Dynamic Replace / sand and gravel / Controlled Modulus Columns / concrete columns) – see examples 2 and 3. The described set of buildings shows extremely high correlation (R^2 = 0.92). It should be added that the given set of buildings was limited to structures with shallow foundation (including those on improved soil). For the purpose of evaluation and forecasting settlement, the dilatometer is a well-calibrated device for typical structures. In the cases of founding on plastic and organic soils in which the quality of drilling and collected samples is insufficient, only *in situ* probing allows for obtaining reliable parameters for design calculations. In the further part of the article, several examples of applications and possibilities for use of the dilatometer tests in practice are presented.

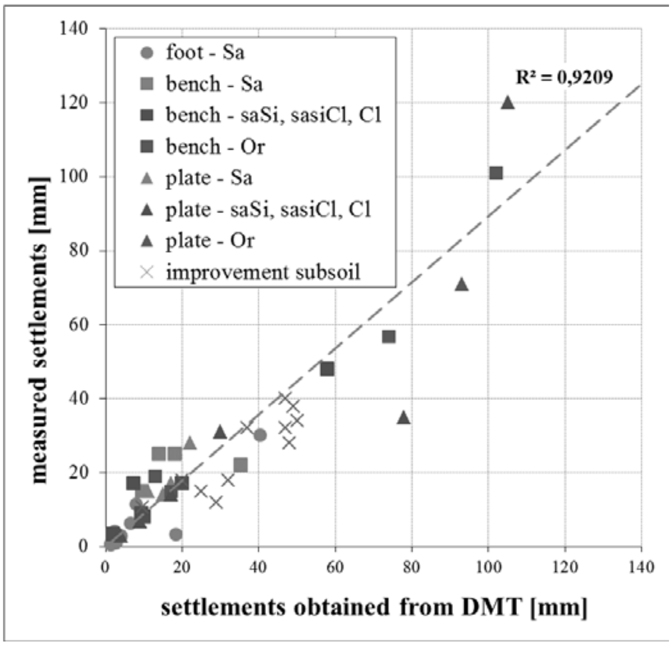

Fig. 1. Calibration curve get for Polish conditions Godlewski 2011) relating to measurements from literature (Monaco et. al. 2006).

4 CASE STUDIES

4.1 *Example 1 - Evaluation and forecasting of settlement*

The example refers to execution of a school building in which incorrect soil evaluation led to erroneous decisions related to founding as a result of which, excessive settlement is observed presently. Difficult soils in the sub-base of the analyzed structure is a layer of settled deposits (alluvial soils and aggradate mud) in the form of silty clays, silts of differentiated condition: in the upper layer it was found to be plastic (layer IIa), in the bottom layer, it was defined as soft soil (layer IIb). The total thickness of layer is 2÷3 m. At the stage of basic (documentation 1) identification, the evaluation of condition of fine soils, and subsequently, the remaining parameters were determined on the basis of macroscopic analysis and a probe providing a qualitative analysis.

Table 1. Compile of ground parameters according to archival documentation and own tests (Godlewski 2011b).

Layer number	Soil type	density index I_D [-]		liquidity index I_L [-]		oedometer modulus E_{oed} [MPa]		dilatometer modulus M_{DMT} [MPa]
As per documentation		1	2	1	2	1	2	own in situ tests
0	Fill	-	-	-	-	-	-	80
I	FSa, MSa	0.40	0.40			50	45	40
IIa	clSi, Si			0.45	0.20	**17**	**28**	**9.5**
IIb	Si / clSi			0.75	0.30	**9**	**25**	**2.8**
III	MSa/ FSa	0.45	0.45			80	80	60

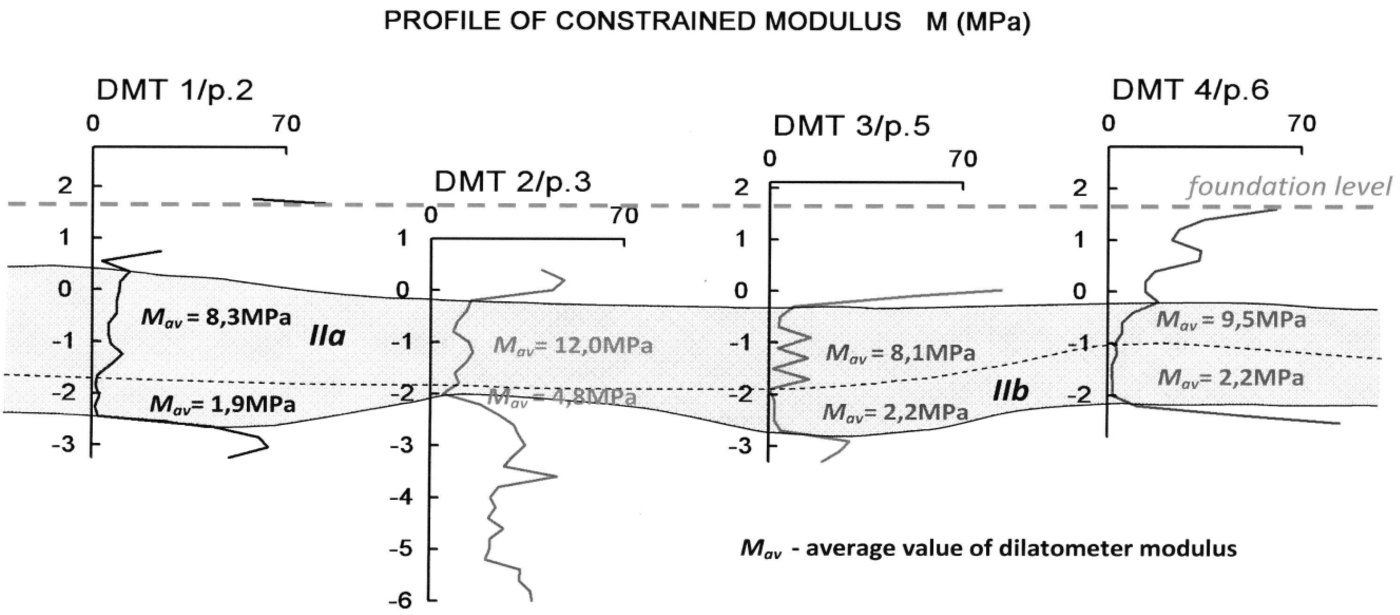

Fig. 2. Geotechnical cross-section through the subsoil of the schoolhouse, a level of bedding and a course of aggradate mud were indicated (Godlewski 2011b).

Additional identification of soil conditions was performed in subsequent documentation (2) and concerned mainly the properties of alluvial soils presented in the ground. As can be seen from Table 1, in the evaluation of properties of alluvial soils, both documentations differed considerably. As a consequence, the soil strength and deformation parameters determined on this basis are generally different. For the needs of further analyses, dilatometer examinations were carried out and the results (modulus values) determined on their basis are shown in Table 1 and in the layout of of soil layers on a cross-section - Fig. 2.

The values obtained from the dilatometer are 2÷3 times lower than those specified in documentation 1 and 3÷9 times lower than those specified in documentation 2.

The design stipulated the construction of a building with two storey's and with the basic load-carrying structure of the building comprising reinforced concrete ceilings, columns and walls. The initial concept for building founding stipulated execution of a construction embankment of the height of 2m (pressure under the foundations established at the level of ca. 200kPa). The concept adopted finally for execution was based on the design which assumed that the soil would be improved with DSM /Deep Soil Mixing/ columns only for foundations resting on the original soil (in the part with basement). Improving the soil only under remaining foundations was considered unnecessary because the solutions in the improvement design were based on documentation 2, in which the soil conditions of the settled deposits was found to be much more advantageous than in documentation 1, and on the observation of 3÷4-storey buildings founded directly on soils of such type (alluvial soils), which did not suffer significant settlement. In accordance with design recommendations, settlement measurements were carried out during the construction and use of the school building. The analysis of overall settlement indicates that settlements of a fragment of the structure with underlying DSM columns (eastern wall, staircase) are small (2÷4mm), which suggests high effectiveness of the performed soil improvement. Settlement values for the remaining structure fragments founded on "unimproved" soil are much higher. In the remaining part of the structure, the settlement values are currently within the range 40÷100mm.

The results of measured settlement indicate that the causes of significant settlement should primarily be sought in the deformability of settled deposits present in the soil. This notion is supported by long time of settlement stabilization and considerable settlement increase that occurred after the construction. To support this conclusion, soil settlement calculations were carried out with the use of deformation moduli for settled deposits resulting from dilatometer tests.

Table 2. Geotechnical characteristic parameters.

Location	*settlements [mm]*			
	initial		final	acoding to DMT
	s_p	Δs	s_c	
Gym	-76.5	-32.5	***-109***	**-102**
Auditorium	-61.7	-23.2	***-84.9***	**-78.9**
Classroom part	-47.7	-12.3	***-60.0***	**-73.7**

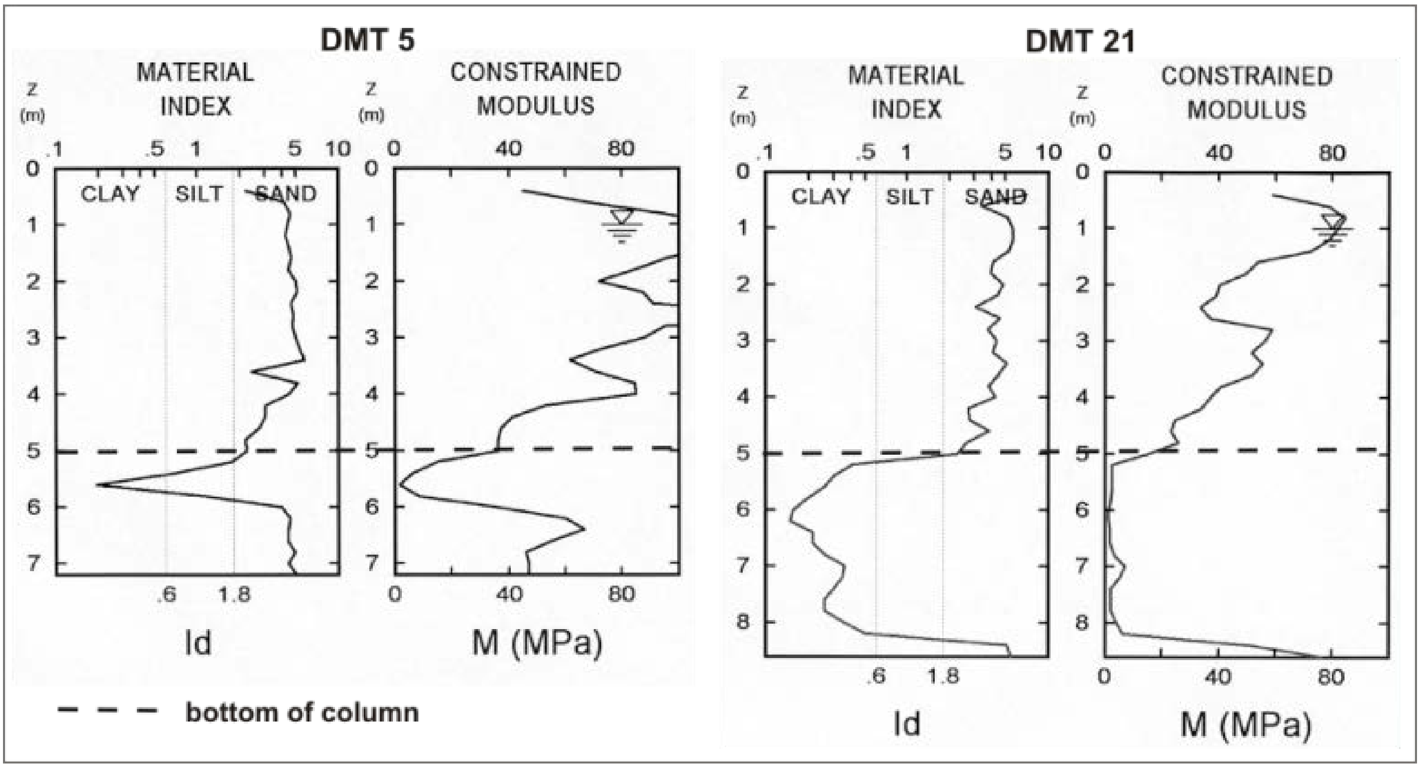

Fig. 3. Result of DMT tests executed in colums, from left column on carrying basis based, from right hanging column (Godlewski 2007).

The settlement values were determined as the sum of settlement caused by construction of the embankment and loading of the soil with the structure. The calculations were carried out for a 2.5 x 2.5m pad foundation and pressure on soil of 200kPa. Table 2 shows the calculation results. The calculation results were compared to the forecast determined on the basis of measured settlement approximation. The values of final settlement based on moduli measured by DMT are in line with the results obtained on the basis of the expected structure settlement expressed in the form of a function diagram (with assumed settlement stabilization time of ca. 10÷15 years).

4.2 *Example 2 - Evaluation of effectiveness of soil improvement by dynamic compaction method*

The problem of performance of acceptance tests of soils improved by dynamic soil replacement method is discussed in detail in papers (Godlewski 2007, Wysokiński et. al. 2007). The main problem is the evaluation of quality performed soil improvement in the context of design criteria, during its execution. Most often, the tests include quality tests, i.e. drilling and uncovering to determine the geometric characteristics of columns, dynamic probing, which is helpful in determining the scope of replacement, whereas due to the character of used material (sand and gravel mix), the obtained compaction assessment (I_D) is often of qualitative character. A reliable quality assessment is obtained by test loads and settlement measurement. These tests, however, are performed rarely and in a limited scope due to time and cost factors. The dilatometer allows direct obtaining of the values of deformation moduli. It is an excellent method allowing for precise determination of column reach and for continuous quantitative information on column quality - expressed in deformation moduli (Fig. 3) which, based on design criteria, is one of the main acceptance criteria. The procedure for performance of measurement and resistance of the blade to damages allows applying this method even in columns including large quantity of aggregate.

4.3 *Example 3 - Designing foundations on improved soil*

An example for application of DMT tests in designing foundations on improved soil is a residential building located within the area of the so-called "Żoliborz channel" filled with lacustrine deposits (aggradate mud and gyttja). The thickness of aggradate mud and gyttja (layer III_1) under the structure is ca. 8÷10m (Fig. 4). Below this weak layer, the layer of good bearing capacity was found (glacial clays - layer IV).

The planned structure is a compound of multistorey (6÷12 storeys with 2 garage levels)

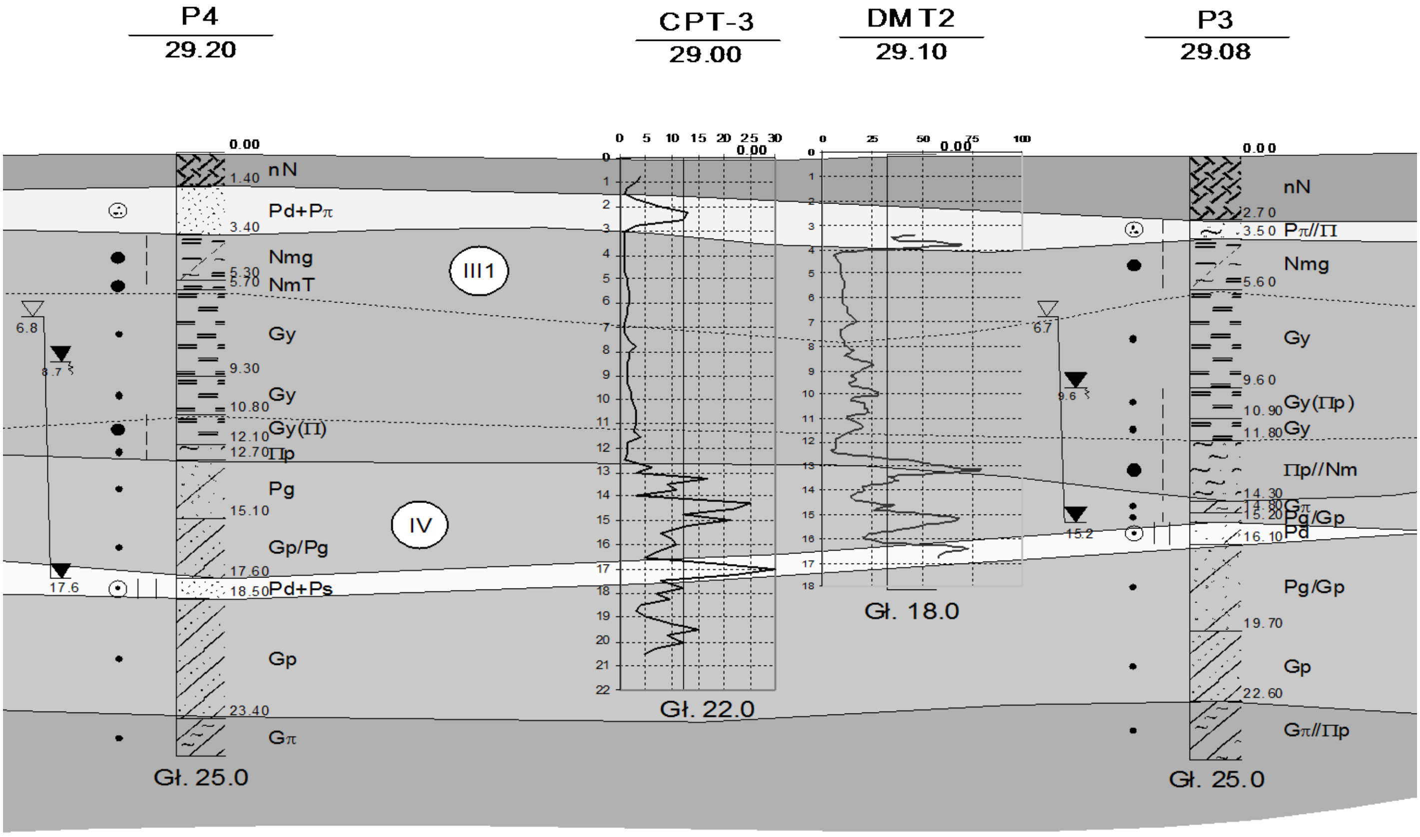

Fig. 4. Geotechnical cross-section below the designed building – soil description in text (Godlewski et. al. 2007).

buildings (A and B), which exerts actual replacement pressure under the soil of up to 220kPa and up to 400kPa locally under the staircases.

In order to replace deep foundations with a cheaper foundation on improved soil, a program of geotechnical tests and test loads was presented to determine the values of settlement of unimproved and improved soil. These tests were intended to prove the suitability of the CMC /Controlled Modulus Columns/ method to execute the foundations of the designed building. On the construction site, test loads on unimproved soil and on soil after improvements were carried out for a group of CMC columns. The tests for improved soil included loading and removal of loads for 9 columns in a 2 x 2m arrangement and for a 5 x 5m slab (Fig. 5). The observations were carried out for a period of ca. 1 - 1.5 month. The ballast was placed in stages with measurements carried out in a continuous manner; the maximum ballast weight was 300T with soil stress of ca. 120 - 150kPa.

The value of settlement of a slab resting on columns with respect to a slab founded directly on ground was more than 5 times smaller. Settlement of a slab resting on columns was ca. 4mm (3÷6.2mm).

The calculations performed on this basis showed that the adopted value of deformation modulus obtained from the DMT tests for aggradate mud and gyttja at the level of 15MPa correctly reflects deformability of the analyzed soil.

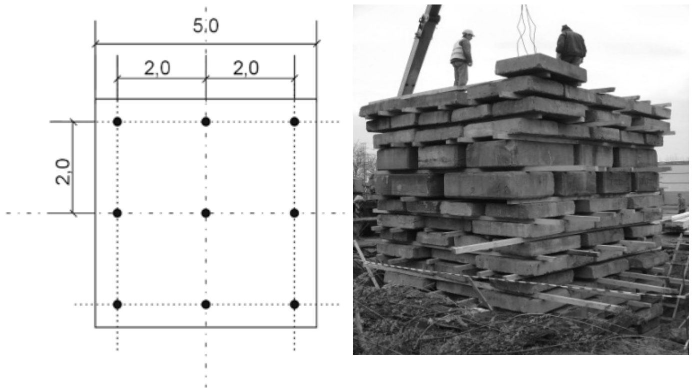

Fig. 5. Set out of columns and sizes and the view (from right) positions to load tests (Godlewski et. al. 2007).

On this basis, and after carrying out additional test loads of individual columns, FEM calculations were carried out to recreate the behavior of the soil-column "composite". Subsequently, the soil reinforced was carried out. The design assumed founding of the building on the reinforced concrete slab in separated soil settlement zones. The division into soil settlement zones was determined on the basis of differences in building height with the column span adjusted to the value of stress. The analysis of actual settlement values of building executed in such manner showed high compliance between the adopted assumptions (moduli from DMT for numerical calculations) and effectiveness of applied soil improvement method (CMC columns). The highest average settlement values were recorded for zone A2-20mm, while the lowest were those recorded for zone B3-6mm. At the same time, clear stabilization of settlement measured for zones A and B was discovered. This proves that the consolidation process related to the construction phase has ended.

4.4 *Example 4 - Verification of soil conditions*

This example refers to deformability of soils present in the ground under wastewater treatment plant facilities (bioreactors and sedimentation ponds) and determination of settlement values for their structures founded on alluvial soils (fluvial sands). It was important to determine settlement values for ponds during leak test and during operation to determine on that basis whether the adopted foundation method will require the soil to be improved. Performance of additional DMT tests and test loads was found to be purposeful due to disparities determined at the stage of documenting soil conditions (Fig. 6).

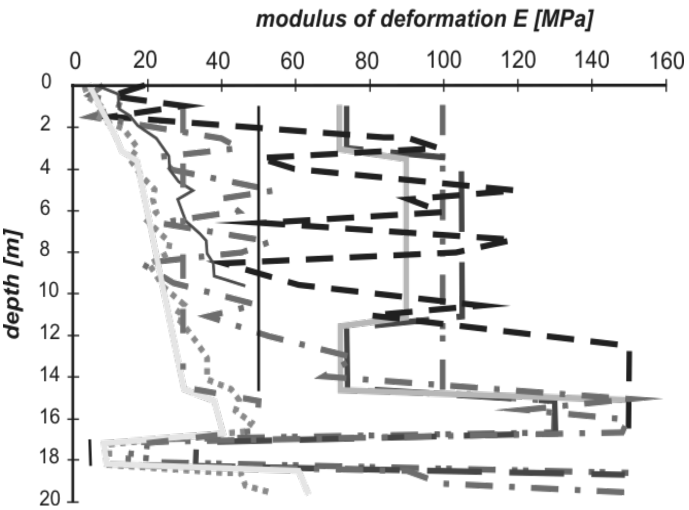

Fig. 6. Demonstrative picture depicting the scale of the dispersion of the value of the module of the deformation interpreted according to different available methods for one research point (Godlewski 2011).

Fig. 7. View of the load structure after laying on the plate (10x10m), height of the ca 6 m.

The diagram concerns the deformation modulus value (E) derived from various methods (DP and CPT) and correlations (DIN, EC7, Polish Standard, own) for the same results obtained from a single testing point located in alluvial material of fluvial origin. The range of settlement values determined on the basis of derived moduli values for the designed structure was between 4 and 11cm!

To verify the actual conditions in soil, a test load was carried out (Fig. 7) and the obtained settlement values were used to calculate the settlement of the designed structure.

Settlement of the structure loading the soil was calculated in accordance with the recommendations of standard PN-81/B-03020 (1981). It has been adopted in the calculations that: excavation depth under the loading structure is 1.0m; the maximum pressure on soil is 130kPa; the loading structure constitutes an elastic foundation. The soil deformation moduli were determined on the basis of results of dilatometer test performed near the loading structure. The average value of dilatometer modulus of ca. 45MPa was obtained.

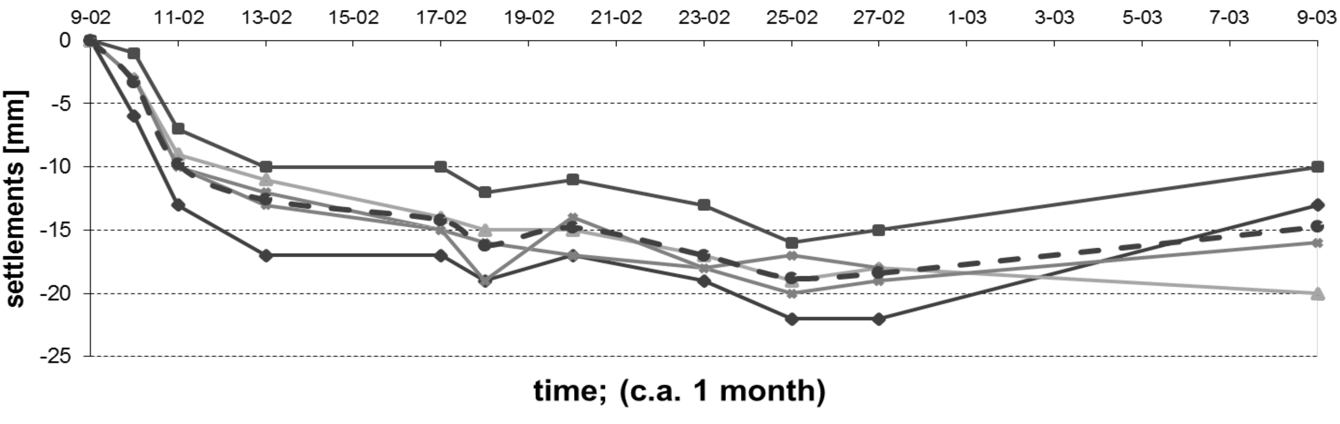

Fig. 8. Graph of settlements of the load structure – benchmarks (solid lines) and averages settlements (dashed line) (Godlewski 2007).

The total structure settlement value determined on the basis of calculations is ~17mm. The obtained results were referred to actual settlement results of the loading structure (Fig. 8).

On the basis of the diagram (Fig. 8), the settlement values considered final and suitable for further analyses were as follows: 17mm – maximum value of average structure settlement and 13mm – permanent settlement value. Comparison of calculated values against measured values shows that the soil deformation moduli determined with the dilatometer can be considered reliable for forecasting settlement values. The obtained full conformity between calculated settlements and measurement settlements is obviously accidental.

5 EXTENSION OF THE DMT METHOD

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 determining the soil rigidity profile as a function of shear modulus (G_0) by measuring the propagation velocity of a transverse wave (V_s). The pioneering works in this scope are being performed in cooperation with the Institute of Hydrogeology and Engineering Geology of the Faculty of Geology of the University of Warsaw. The SDMT method is validated by surface geophysical methods (CSWS and SASW). New correlation relationships have been examined for typical soils present in Poland, for which the possibility of estimation of modulus of rigidity G_0 are sought on the basis of the standard results from DMT tests. The author of this paper was inspired by very interesting results obtained for various soils presented in the works of Marchetti (2009). Similarly, the results from SDMT were used to obtain correlation relationships for the tested soils - Fig. 9. More information on the obtained results of seismic measurements and observations related to the impact of testing methodology is available in papers (Godlewski & Szczepański 2012 and 2015). The data presented there is the first correlation of this type for soil in Poland. The amount of data is already statistically significant in some cases (e.g. sands); however, the coherence of the results is still below the level for the relation to be meaningful. The observed scatter undoubtedly originates from the variability and diversity of the studied material. Nevertheless, it should be checked how the results can be influenced by factors associated with methodology. In the case of seismic methods, consideration should be given to the type of sources used for producing waves and the selection of the frequency. In the authors' view, methodological aspects may be factors in variation which are just as important as properties of the subsoil itself (porosity, state of stress, and the like). The described problems require further tests and gathering of larger data set. In Poland the problem of determining the shear modulus in field tests (including SDMT) and searching for local correlation (for e.g. DMT/CPT) deals with several research centers (Młynarek et. al. 2012, Rabarijoely & Garbulewski 2013).

The necessity to determine reliable values of G_0 modulus used in numerical calculations (FEM) to correctly describe the interaction between the structure and the soil indicates the direction of further studies.

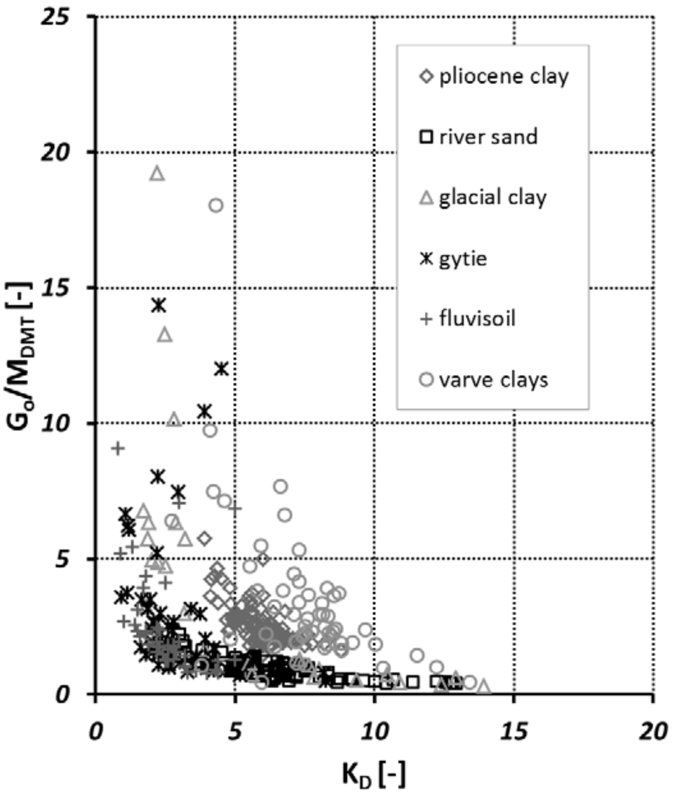

Fig. 9. Graph of the Go/M_{DMT} indicator vs K_D for chosen types of soils (Godlewski & Szczepański 2012 with modification from Godlewski & Szczepański 2015).

6 CONCLUSION

The actual application of dilatometer tests confirms the suitability of this method in determining the extent and forecasting settlement. The obtained values of dilatometer moduli in typical cases of direct founding correspond to the modulus values obtained by "back analysis" method – as the compression moduli obtained in standard PN-81/B-03020 (1981). The settlement values obtained on this basis are similar to the actual displacements recorded at structures, which is of particular importance for soils with high deformability parameters, in which due to the difficulty in obtaining high quality samples, the values of moduli obtained in laboratory testing are often underestimated.

Correct application of the method and new correlations requires verification and validation by other methods or requires reference to actual measurements prior to implementation into Polish conditions.

The analyzed examples indicated that the use of DMT test results allows for correct verification of soil conditions, selection of an effective method for soil improvement, evaluation whether it was performed effectively or enables direct founding of structures in complex soil conditions.

The starting point for the design analysis in each mentioned case should be determination of requirements for structure settlement, supported by diligent soil identification, primarily basing on *in situ* tests. By performing DMT tests supported by adequate approach of Designers and Client, considerable reduction in founding costs can be achieved. For this purpose it is necessary to spread this method and its application scope and to expand the data base, including that for the tests with seismic sensor (SDMT).

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