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Determination of Soil Stiffness Parameters for Clays as a Construction Subsoil for Warsaw Underground

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Abstract. Analysis of soil-structure interaction demands properly determined parameters for a particular calculation method. In the case of deformation modulus determination, it is essential to take actual construction activities into consideration. It means that these moduli should correspond to stress-strain range of a particular construction. The use of numerical methods, allowing for more realistic soil-structure interaction, compatibility of displacements, as well as to account for the stiffness of the structure and the soil, may provide more realistic prediction of displacements. The article presents the methods of stiffness parameters determination including all factors that should be taken into consideration in geotechnical design. The article characterizes clays of Poznań formation, a subsoil for many structures in almost 75% area of Poland. Investigations conducted for clays in Warsaw were used as a background with the focus on an underground Metro station. Direct measurements of the unloading of the bottom of the excavation in clays were used for validation. Finite Element Method (FEM) was used to verify stiffness parameters and their determination methods. The correctness of obtained results was verified by comparison with deformation measurements of station construction and displacement measurements in the adjacent area. As a conclusion, the article shows that the type of a construction and its character should be taken into consideration in geotechnical parameter determination. The analysis with stiffness parameters determined in the small-strain range of deformations allows to obtain displacement values approximate to real ones. In the case of an underground station, large area of soil interacts with a structure, and in this case, the deformations are small, which should be taken into account in a design analysis.

1. Introduction

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 [1], [2]. 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 deformations (10^{-6} – 10^{-3}) and utilization of many methods for this purpose. Non-linear behaviour of the soil can be determined by in-situ and lab tests. Degradation of G - γ curve describes the behaviour of the soil from very small to very high strains. In order to get its shape, it can be estimated from in-situ and laboratory tests. As described by [3], [4], 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 (TXT), Oedometer test (OET) are also performed to allow assessment of the stiffness of soils at moderate to large strains. The maximum shear modulus G_0 and the shear stiffness-shear strain ($G-\gamma$) degradation curve can be determined using a variety of laboratory testing procedures. This article shows the fact that these methods of stiffness parameter determination provide useful results as is confirmed by back-analysis calculations based on the data from monitoring of existing structures.

2. Case study

2.1. Site location and geological structure

The underground station under consideration is located in Warsaw (Poland). The station is an underground object except from exit zones. The station is 21 m wide and 156 m long. It was constructed in an open excavation in retaining wall casing with the use of top & down method. In its central part, steel struts were installed in two levels during construction. The height of the station is about 15.5 m from the bottom of foundation slab up to the top. The depth of retaining walls embedment was about 22-25 m below the surface – figure 1. The geological profile contains: man-made soil (NN), tills (Qg3) and fluvioglacial sands (Qf3) of Warta glacial period, stiff tills (Qg2) of Odra glacial period and limnic deposits (stiff clays, silty clays, and silts – Q12). Mio-Pliocene formation of Poznań clays is represented mainly by stiff clays, silty clays, silty loams (PI II). The roof of Tertiary clays of Pliocene age is characterized by strong glaciotectionic deformations.

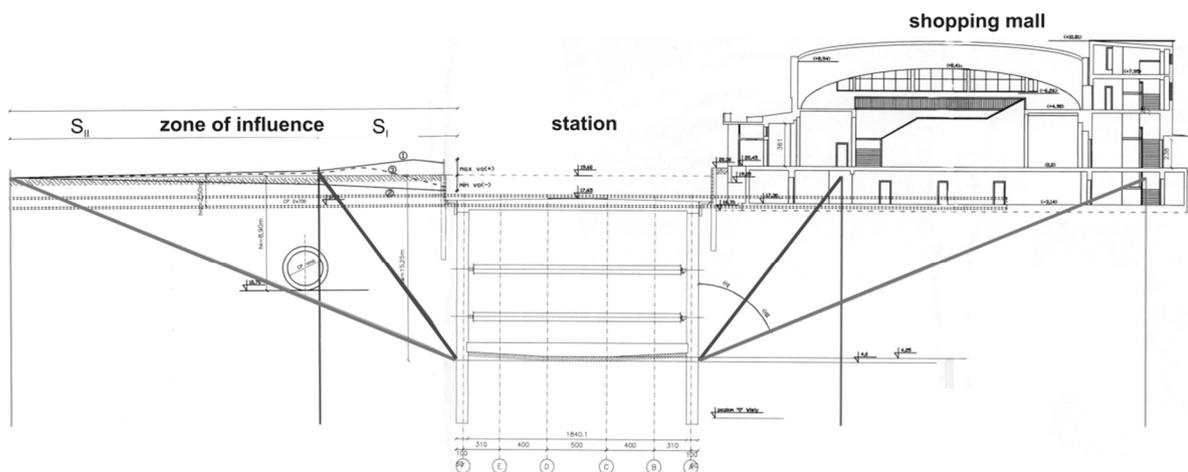


Figure 1. Cross section of station with the zones of possible influence on adjacent objects.

2.2. Monitoring data

The construction of the station in a deep excavation required continuous monitoring. The observations included: settlement measurements of the station and adjacent objects (vertical displacements measurements) and measurements of bending of retaining walls during each phase of construction (horizontal displacement measurements). The measurements of horizontal displacements of retaining walls in characteristic sections (chosen for numerical analysis) are presented in figure 2. The highest values of horizontal displacements of retaining walls (of about 10 mm) were recorded at central part, while at the head of the station, the values ranged from 4 to 6 mm.

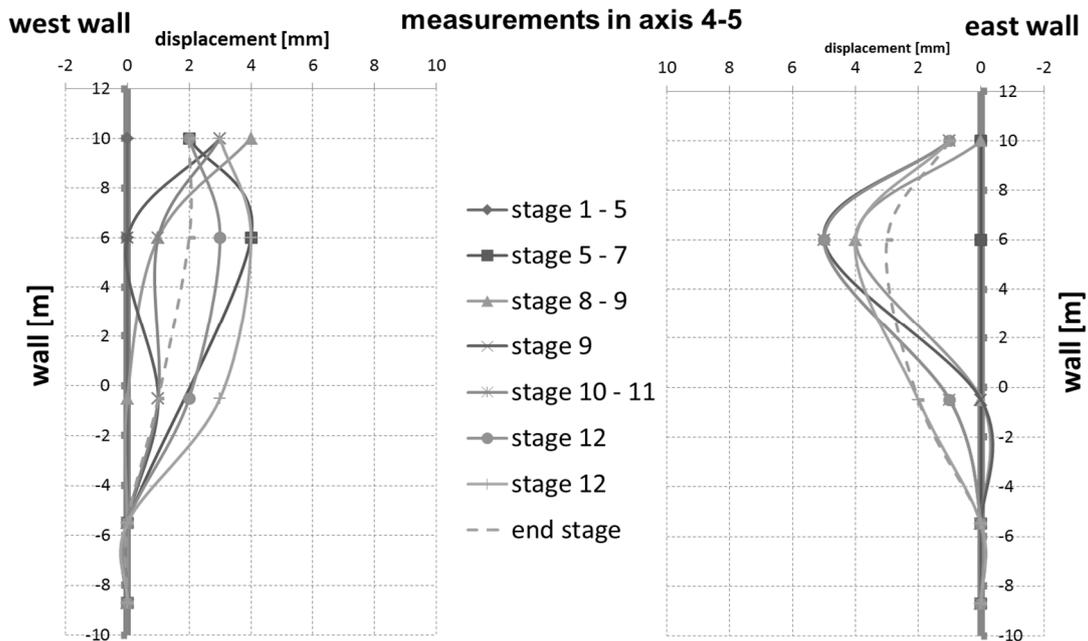


Figure 2. Horizontal displacements of retaining walls for head part of station in axis 4-5.

At the station, direct measurements of the uplift of the bottom of the excavation (not the bottom slab) were obtained. Warsaw deep excavations very often reach the Mio-Pliocene clays of Poznan Formation. Those clays swell and unload easily in favorable conditions. In these soils, the uplift of the bottom of excavation and the entire structure is observed. Before the construction works started, two deep-seated measurement points had been installed at depths approximate to final excavation level. After excavation, their levels were measured again. The graph (figure 3) indicates that the uplift of retaining walls is noticeable up to the end of earthworks.

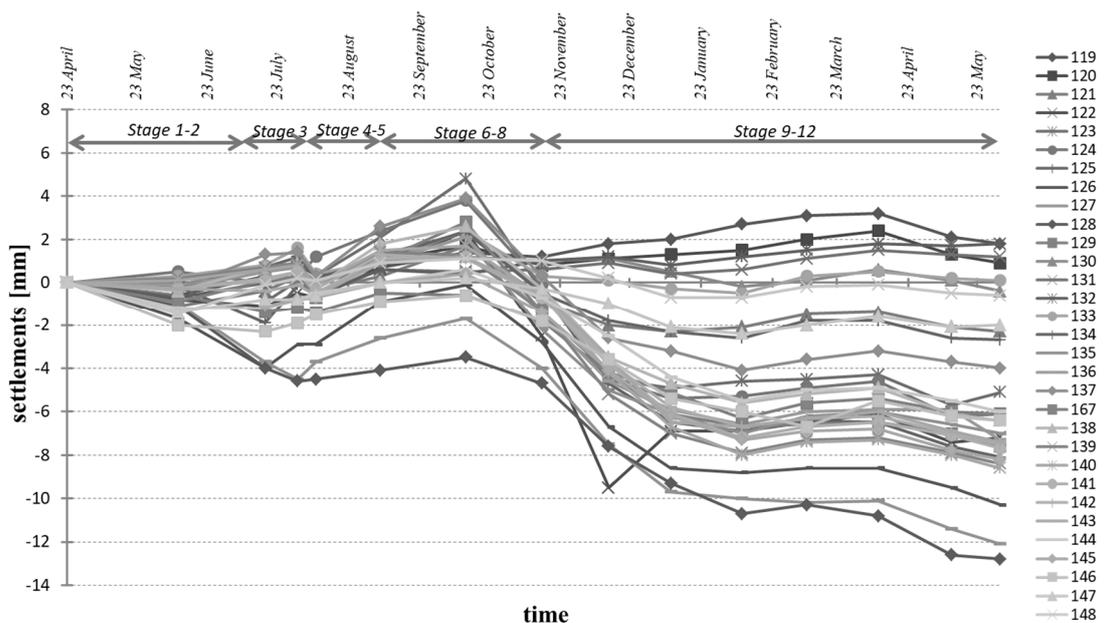


Figure 3. Results from measurement points at the neighboring shopping mall during each stage of station construction.

Successive works (bottom slab, platform and internal walls execution) caused noticeable settlement of a structure due to continuous loading by these new elements. For comparison, the previous results for another station (A14) in similar soil condition (Pliocene clays) were also presented in the table 1. The values of uplift displacements are approximate. This confirms the occurrence of unloading in clays and indicates that this phenomenon may have a significant impact. Measured and calculated values of vertical displacements of the bottom (Stage 6-8) were set together in table 1. The last column shows calculated values of vertical displacement of the bottom from numerical modelling. As expected, the maximum values were observed in the middle part of the excavation – 71.5 mm.

Table 1. The results of the excavation bottom displacements

measuring points	distance from the wall	actual values of vertical displacement of the bottom [mm]			calculated values of vertical displacements of the bottom [mm]
		initial measurement after final excavation	measurement after 6 days	measurement after 14 days	for 8th stage (final excavation without bottom slab)
R1 A-19 Station	6.0 m	57.0	62.0	63.0	65.0
R2 A-19 Station	0.8 m	8.00	-	-	22.0
R1 A-14 Station	7.5 m	64.0	-	-	-
R2 A-14 Station	2.3 m	31.0	-	-	-
R3 A-14 Station	7.3 m	68.4	-	-	-
R4 A-14 Station	2.0 m	26.4	-	-	-

The values of displacements increase at stages 6-8, what was connected with unloading due to excavation and horizontal displacement of excavation walls induced by soil pressure. The maximum values of settlements, measured at points that were installed at the market hall's wall, exceeded 12 mm (at two measurement points at the station side).

2.1. Investigations from different excavation levels

During each stage of construction as well as before it, a total of almost 100 samples (also undisturbed) were taken from the investigation site for laboratory tests. The influence of cracks in clays on mechanical features was tested. The Shelby Samplers were used or block samples were taken for laboratory tests. The evaluation of variability of particular soil parameters is very important in estimation of parameters for design. During investigations the „breccia” structure of Poznań Formation clays was observed – figure 4. Next to the laboratory tests, a lot of in situ tests were conducted (borehole, CPTU, SDMT, SAWS). This research noted a large variability and heterogeneity of the tested material. Also, the effects of subsoil unloading were observed in the CPTU soundings (figure 4), which were performed from successive levels of the excavation and showed decreasing values of resistance. In their geological history, those clays were loaded and unloaded many times due to glaciations. Therefore, “breccia” structure cracks and mirror structures may be often observed. These features increase the internal friction angle value and decrease cohesion by about 50%. The influence of cracks on clay's parameters depends on spatial orientation of weak surfaces towards the stress direction. This occurs only when the surfaces correspond with theoretical stress direction. The more weak surfaces correspond with shear direction, the lower the parameters. While knowing the range of deformation of a structure, the appropriate value of deformation modulus can be estimated. The obtained results of the tests were summarized in table 2. The relationships of shear modulus (G_0) in clays taken from laboratory (BET) tests (figure 5a) and in situ tests (SDMT) are presented, to show the range and the variability of these results.

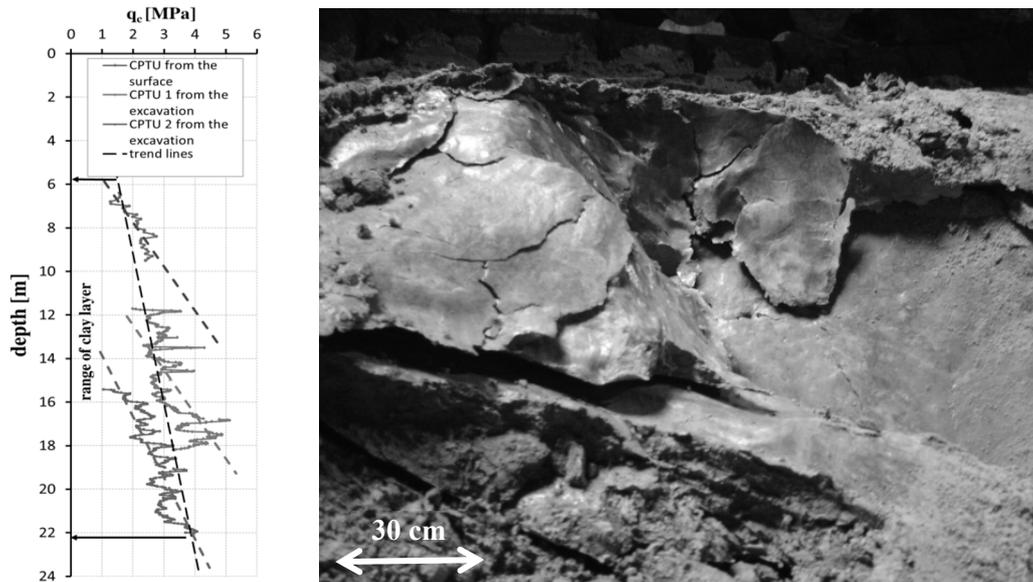


Figure 4. Effect of unloading in clays shown in CPTU results (left), and mirror structures and cracks observed in station excavation (right)

Table 2. Summary of basic properties for clays – generally from different locations in Warsaw [5]

Statistical parameters	Moisture content	Initial void ratio	Plasticity index	Liquidity index	Volume density	Initial shear modulus
	w_c	e_0	I_p	I_L	ρ	G_0
	[%]	[-]	[%]	[%]	[Mg/m ³]	[MPa]
Min	16.80	0.44	34.76	-0.12	1.93	44.54
Max	30.82	0.82	140.40	-0.01	2.15	217.7
Arithmetic average	20.71	0.57	55.39	-0.06	2.06	119.1
Standard deviation	4.37	0.10	30.74	0.04	0.06	47.62
CoV [%]	21.1	17.9	55.5	-58.7	3.08	40.0

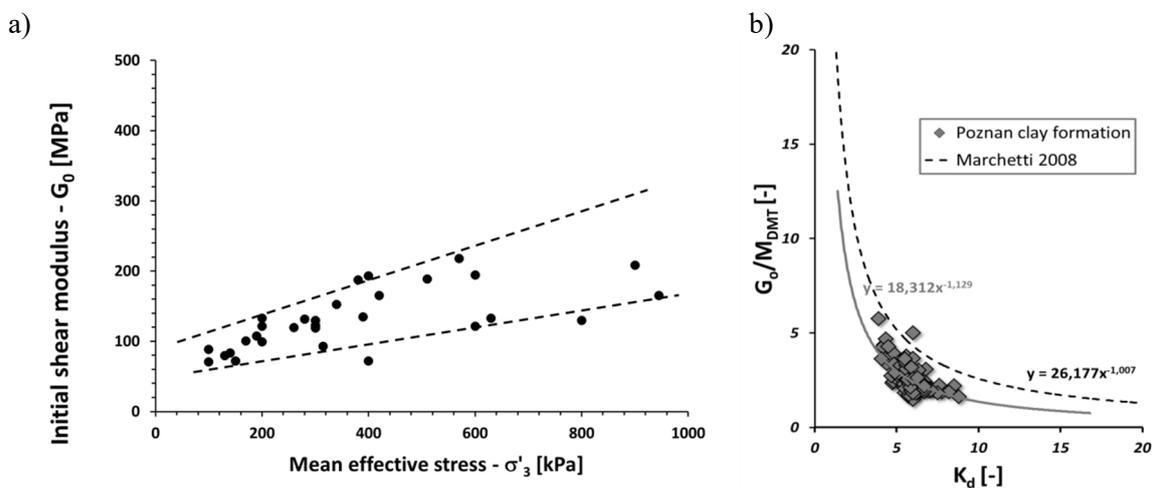


Figure 5. Relation between: a) shear modulus (G_0) vs mean effective stress σ'_3 – from BET [5], b) the G_{DMT}/G_0 indicator vs K_d – from SDMT [4], [7]

3. Results and discussions

The station deformation values during construction were measured. Thanks to „backward analysis” the information about parameter values that should be taken to calculate the deformation values observed at the station were obtained. Investigations made by the author on deformation parameters determination by various methods for Poznań formation clays at station are summarized in figure 6. The curve confirms the fact (known from literature) that the deformation moduli are non-linear in small deformation ranges. FEM method (in Plaxis software) was used for calculations in order to compare deformation values measured during station construction with those obtained with different values of moduli of deformation. The example of these calculation results is presented in table 3.

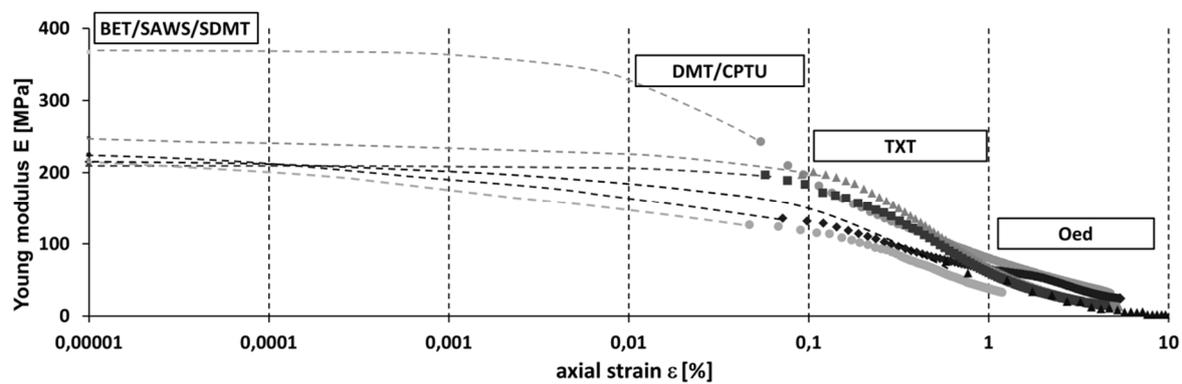


Figure 6. Non-linearity of the deformation module for Poznań formation clays with range of the applicability of the methods for estimation of soil stiffness parameters.

Table 3. The results of retaining walls bending in 4-5 section: measured and calculated

point/ location	Calculations				measurement (section 4-5) E wall	measurement (section 4-5) W wall
	oedometer	TXT	BET	SDMT/SAWS		
A /3.0 m	-8.5 mm	-11.0 mm	3.0 mm	3.3 mm	1 mm	2 mm
B /7.0 m	8.3 mm	6.0 mm	2.2 mm	2.8 mm	3 mm	2 mm
C /12.0 m	47.0 mm	41.0 mm	1.3 mm	1.7 mm	2 mm	1 mm

The results were compared with real measurements obtained from monitoring. The values of E parameter obtained from BET and SDMT/SAWS indicated better correspondence with real measurements. The results from oedometer tests and triaxial test do not correspond so well and give 4 times higher values of deformations than the real ones from the station.

The back-analysis for deformation parameter $E=200$ MPa and strength parameters (taken for design) $\phi'=12,5^\circ$ and $c'=21$ kPa corresponded well with those from direct measurements at the station. These results were calculated only in Coulomb-Mohr model (calculated in Plaxis Software). From practical point of view, the Mohr-Coulomb model can be used only when the expected strain-range is known and the provided parameters are of good quality [7], [8]. When various strain ranges can be expected or they are not knowing at the beginning of calculations, application of more advanced constitutive models is justified. It has to be recognized that there is no one truly universal model that can be used and its choice is dictated by the problem under consideration. There is no point in applying very advanced methods and models for simple geotechnical problems.

4. Conclusions

The investigations, observations and measurements of underground station led to some important conclusions:

- Estimation of soil parameters is a difficult task due to the complexity of the material type, especially considering its variability. During determination of parameters of Poznań Formation Clays, random variability should be taken into consideration. The larger the area is; the higher random variability may occur. A possible weakening of clays due to some cracks occurrence should also be taken into account, especially for a construction with small area (e.g. anchors). According to PN-EN 1997-1:2005 parameters should be carefully estimated.
- The type of a construction and its character should be taken into consideration in geotechnical parameter determination. The investigation method and the environment of a test as well as interpretation of results should be appropriate for particular construction deformation. The analysis with parameters determined in a small range of deformations allows to obtain values approximate to real ones. In case of underground station, large areas of soil cooperate with a construction and in this case the deformations are small. It seems that the values of modulus used in computer programs should account for small deformations when underground structures are considered.
- Finite element method offers a very accurate calculations of displacements, especially near the excavation. Furthermore, it is one of a few methods allowing for estimation of uplift of a bottom of an excavation due to its unloading [7], [8], [9]. However, as all methods, it requires verification of obtained results by direct measurements during construction, especially for calibration purposes.

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