10.2478/v10060-008-0097-z

Annals of Warsaw University of Life Sciences – SGGW
Land Reclamation No 43 (2), 2011: 113–120
(Ann. Warsaw Univ. of Life Sci. – SGGW, Land Reclam. 43 (2), 2011)

Settlement evaluation of spread foundations on heavily preconsolidated cohesive soils

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Abstract: *Settlement evaluation of spread foundations on heavily preconsolidated cohesive soils*. The paper presents the results of field and laboratory tests performed on the heavily preconsolidated boulder clays which prevail on the campus of the Warsaw University of Life Sciences – SGGW as foundation layers. Based on the results of field and laboratory tests a problem of spatial variability assessment of the thickness of foundation layers and the soil parameters is discussed. Special attention is drawn to the selection of the design values of oedometer moduli and the suitability of calculation methods for settlement evaluation. Calculated settlements were approved by the field measurements performed during building construction.

Key words: spread foundations, Eurocode 7, Serviceability Limit States, cohesive soils.

INTRODUCTION

In Eurocode 7 a distinction is made between ultimate limit states and serviceability limit states (EN 1997-1 Eurocode 7 Part 1). Generally, limit state design codes devote more attention to ultimate limit states (ULSs) than to serviceability limit states (SLSs) (Orr and Farrell 1999; 2001; Orr 2005; Bond and Harris 2008). In case of serviceability limit states the estimation of settlements and differential settlements is a fundamental aspect of the design of shallow foundations (Poulos et al. 2001; Frank et al. 2004; Simpson et al. 2009). In many geotechnical designs, the size of pad or strip footings is determined by SLS rather than by ULS requirements particularly when building with basement is founded on preconsolidated clays.

The paper presents the results of field and laboratory tests performed on the heavily preconsolidated boulder clays which prevail on the campus of the Warsaw University of Life Sciences – SGGW as foundation layers. Based on the results of field and laboratory tests a problem of spatial variability assessment of the thickness of foundation layers and the soil parameters is discussed. Special attention is drawn to the selection of the design values of oedometer moduli and the suitability of calculation methods for settlement evaluation. In order to evaluate differential settlements the numerical calculations were performed using the finite element program Sage-Crisp based on the Modified Cam-Clay model. Calculated settlements were approved by the field measurements performed during building construction.

DESCRIPTION OF THE TEST SITE

The test site is located at the campus of the Warsaw University of Life Sciences where in last ten years several new buildings were

FIGURE 1. View of the building No 37 at the campus of the Warsaw University of Life Sciences – SGGW

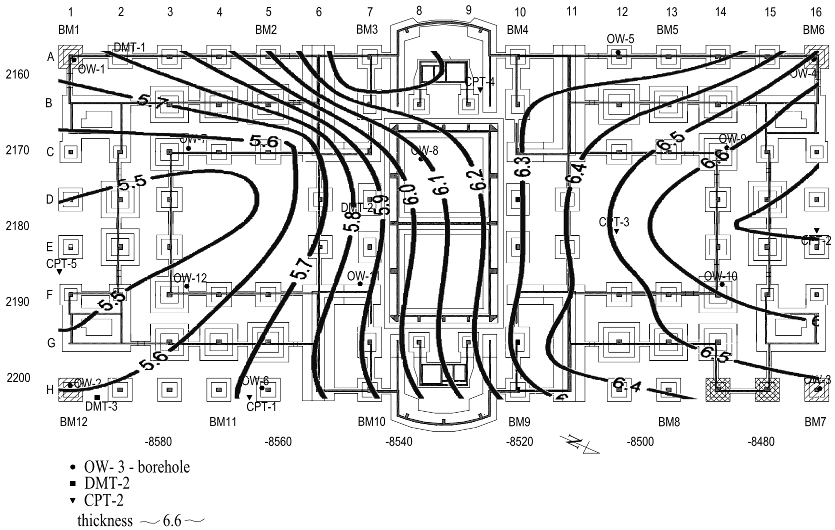

FIGURE 2. Thickness of moraine deposits of Warta and Odra Glaciations below foundation level

constructed. An example is building No 37 in plan 120 m × 57 m with the basement (B) and five-floors (5F) (Fig. 1). Due to expected differential settlements building was constructed as three dilated parts (Fig. 2).

In each side part two halls with two floors height were located. In the rest of the building the structural loads varying between 5–12 MN were transmitted by the columns with 7.8 m spacing to the ground by pad footings. Rectangular pad footings were designed with size from 3.4 m × 3.4 m up to 6.5 m × 6.5 m. Pad footings with size 3.4 m × 3.4 m which cause unit loads about 633 kPa taking in account eccentric loading on footing are considered in this paper.

FIELD AND LABORATORY TESTS

In general the tested subsoil with the exception of 2–3 m of surface layers consists of moraine deposits underlain by fine sand layer. Moraine Quaternary deposits consist of two layers – brown boulder clay of Warta Glaciation and grey boulder clay of Odra Glaciation. Index properties of boulder clays are presented in the Table 1. Tested soils can be classified as preconsolidated low plasticity sandy lean clays CL according to ASTM D.2487 and saCL or sasiCL (ISO 14688–2).

Building was founded below the surface of brown boulder clay. Figure 2 shows the thickness of moraine deposits of Warta Glaciation (brown boulder clay) and Odra Glaciation (grey boulder clay) below foundation level. Because of the difference in thickness of boulder clays below foundation level (Fig. 2 and Fig. 3) and in properties of grey boulder clay the differential settlements were expected.

Compression curves obtained from IL oedometer tests conducted up to 30 MPa indicate that preconsolidation stress σ'_p is much higher than the effective stresses induced by loading. The profiles of index

TABLE 1. Index properties of boulder clays

Properties	Boulder clay (brown)	Boulder clay (grey)
Water content w_n (%)	10.0–11.5	10.5–12.0
Unit density ρ (t· m^{-3})	2.1–2.2	2.1–2.2
Liquid limit w_L (%)	21–22	22–23
Plasticity index I_P (%)	11.0–13.0	12.0–15.0
Liquidity index I_L (%)	0.0–0.10	0.05–0.15
Content of fraction (%) sand (0.063–2 mm) Sa silt (0.002–0.063 mm) Si clay (≤ 0.002 mm) CL fines (≤ 0.063 mm) fines (≤ 0.074 mm)	 58–60 27–29 12–13 40–42 43–46	 55–58 27–30 13–15 42–45 46–50

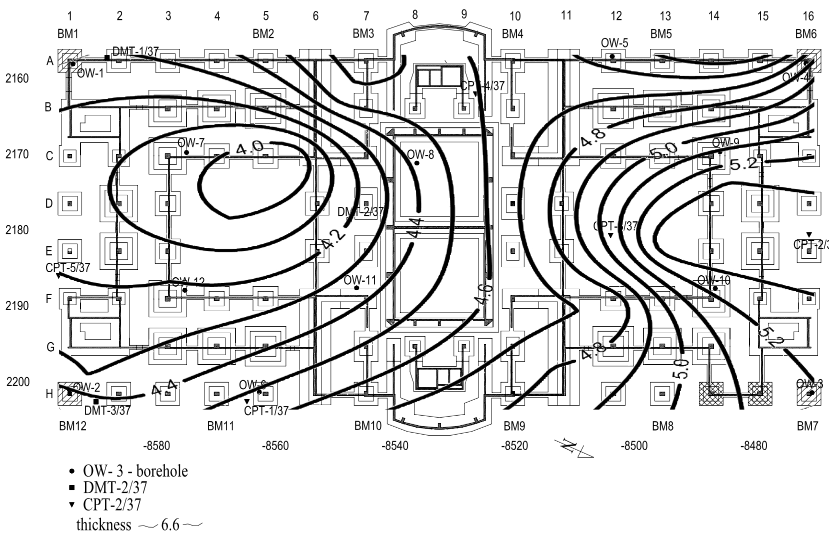

FIGURE 3. Thickness of moraine deposit of Odra Glaciation (grey boulder clay) below foundation level

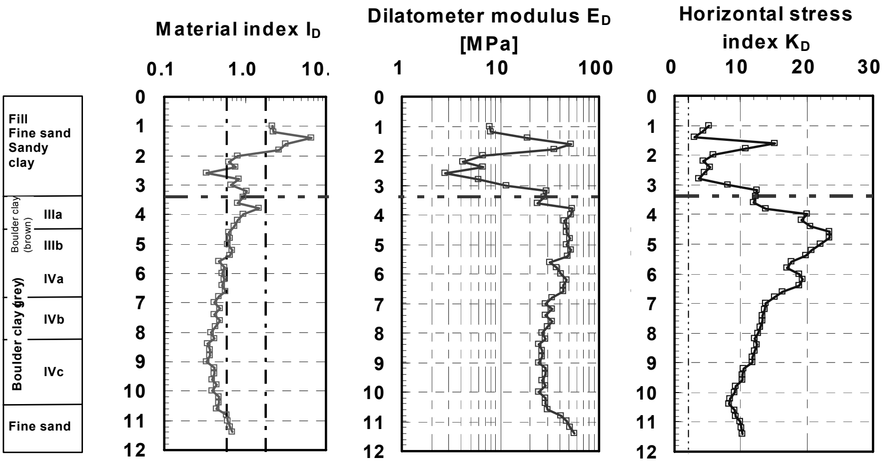

FIGURE 4. Profiles of I_D, K_D and E_D from dilatometer test under the building No 37

parameters I_D, K_D and E_D from dilatometer test are shown in Figure 4. DMT test results indicate that grey boulder clay is softer than brown boulder clay.

In order to evaluate constrained modulus M from dilatometer test the empirical correlations proposed by Marchetti (1980) for $0.6 < I_D < 3.0$ were used as follows:

$$M = R_M \cdot E_D \tag{1}$$

$$R_M = 0.14 + 0.15 \cdot (I_D - 0.6) + \left[2.5 - 0.14 + 0.15 \cdot (I_D - 0.6)\right] \cdot \log(K_D) \tag{2}$$

where:

E_D – dilatometer modulus (MPa),

R_M – factor related to horizontal stress index K_D (–)

I_D – material index (–).

A comparison of constrained modulus obtained from oedometer test during

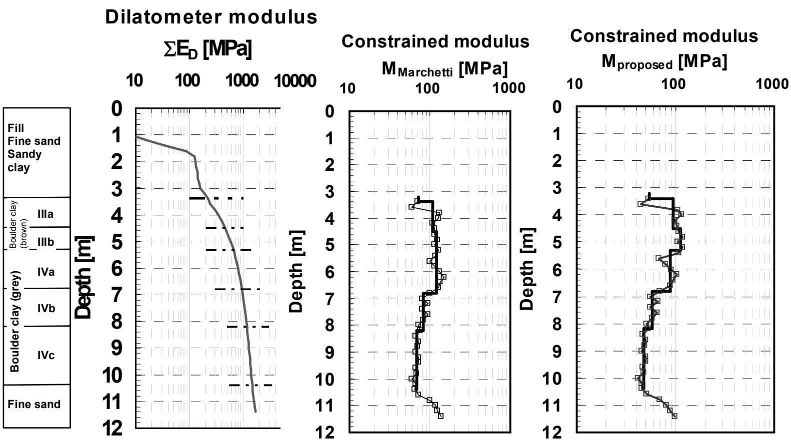

FIGURE 5. Cumulative profile of E_D and the change of mean values of constrained modulus M_{DMT} with depth

reloading indicates that for interpretation of dilatometer tests in boulder clays the following relation can be used:

$$R_M = 0.14 + 1.6 \cdot \log K_D \qquad (3)$$

In Figure 5, the profiles of cumulative values of dilatometer modulus E_D as well as constrained modulus M obtained from Marchetti formulae and from proposed formula are shown with mean values of constrained modulus calculated for sublayers separated based on cumulative curve of E_D.

SETTLEMENT ANALYSIS

During the building construction the settlement gauges (BM 1–BM 12) were installed on the selected columns of three dilated parts of the building No 37 (Fig. 2). The measurements of settlements were started after the completion of second floor (2F). The settlement measurements proved that the displacements of three dilated parts were different. The settlement gauges installed in the middle part and left part under loading caused by the second stage of building construction (3F–5F) were 3–6 mm but in the right part 8–10 mm. In the paper the results of settlement calculation for selected footings in the right part are presented.

Calculation of settlements were carried out based on the constrained modulus evaluated from DMT tests and numerical analysis using finite element program Sage-Crisp based on the modified Cam-Clay model. In order to compare calculated settlements with field measurements the calculations were carried out for two stages of building construction: first stage (B–2F) and second stage (3F–5F). Calculation of settlements based on DMT tests were performed using the values of constrained modulus evaluated using Marchetti formulae and proposed formula for boulder clays. In case of the numerical analysis the calculations were carried out for single footing and multi footing cases. Isolines of vertical displacements of three footings H-14, H-15 and H-16 are shown in Figure 6.

A comparison of calculated and measured settlements of selected footings A-16 and H-16 are shown in Table 2. In Table 2 the values of constrained modulus as well as compression index λ and recompression index κ used in calculations are presented. From comparison of the settlements calculated based on the

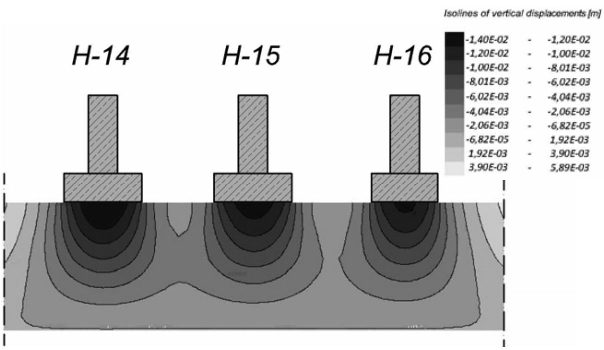

FIGURE 6. Contours of vertical displacements of H-14, H-15 and H-16 footings below the building No 37

TABLE 2. Comparison between measured and predicted settlements

Building stage	Footing	Settlement [mm]				
		Predicted				Measured
		Constrained modulus from DMT		From FEM Modified Cam-Clay Model single footing	From FEM Modified Cam-Clay Model multi footings	
		Marchetti	Modified			
		(1)	(2)	(3)	(4)	(5)
B÷2F	A-16	11.36	14.31	8.74	7.84	8.0
3F÷5F		6.67	8.41	8.14	7.01	
B÷5F		18.03	22.72	16.88	14.85	
B÷2F	H-16	11.17	14.40	9.07	8.05	10.0
3F÷5F		7.45	9.60	8.57	7.37	
B÷5F		18.62	24.00	17.64	15.46	
(1)	$M_{DMT(IIIa)}$ = 108MPa, $M_{DMT(IIIb)}$ = 119MPa, $M_{DMT(IVa)}$ = 122MPa, $M_{DMT(IVb)}$ = 83MPa, $M_{DMT(IVc)}$ = 69MPa					
(2)	$M_{DMT(IIIa)}$ = 94MPa, $M_{DMT(IIIb)}$ = 112MPa, $M_{DMT(IVa)}$ = 90MPa, $M_{DMT(IVb)}$ = 58MPa, $M_{DMT(IVc)}$ = 49MPa					
(3), (4)	$\lambda_{III} = 0.0026$, $\kappa_{III} = 0.00086$, $\lambda_{IVa} = 0.0027$, $\kappa_{IVa} = 0.0020$, $\lambda_{IVb\text{-}c} = 0.0050$, $\kappa_{IVb\text{-}c} = 0.0039$					

TABLE 3. Comparison of ULS calculation results of H-16 footing

	Drained conditions			Undrained conditions		
	$\frac{R_d}{V_d}$[−]	$V_d \leq R_d$ [MN]	$\Lambda = \frac{V_d}{R_d}$[−]	$\frac{R_d}{V_d}$[−]	$V_d \leq R_d$ [MN]	$\Lambda = \frac{V_d}{R_d}$[−]
DA1(1)	2.05	6.89≤ 14.12	0.49	1.41	6.89 ≤ 9.72	0.71
DA1(2)	1.48	5.10≤ 7.60	0.67	1.38	5.10≤ 7.10	0.72
DA2	1.46	6.89≤ 10.10	0.68	1.01	6.89 ≤ 6.95	0.99
DA3	1.10	6.89 ≤ 7.60	0.91	1.03	6.89 ≤ 7.10	0.98
DA_k	2.77 (OFS)	5.10 ≤ 14.12	0.36	1.90(OFS)	5.10 ≤ 9.72	0.52

where:
DA_k – calculations with use of characteristic values of actions, material parameters and resistance,
OFS – overal factor of safety.

constrained moduli determined using Marchetti formulae and measured values for second stage of building construction indicates that the calculated values are smaller than measured values. The settlements calculated based on DMT tests using constrained moduli obtained from proposed formula are closer to measured values. Numerical analysis indicates that the calculated values of vertical displacements were smaller than the measured values. Moreover, smaller values of vertical displacements were obtained in case of multi footings.

In Table 3 as an example a comparison of the calculation results of ultimate limit states for selected footing (H-16) is presented. The results of calculations indicate that overal factor of safety (OFS) in case of undrained conditions is 1.90 but in drained conditions is 2.77. The highest value of the utilization factor

Λ in case of undrained conditions was obtained from DA2 and DA3 and in case of drained conditions the highest value of Λ was from DA3.

CONCLUSIONS

The results of field and laboratory investigations indicate that differential settlements of the building founded on the heavily preconsolidated clays was mainly caused by the spatial variability of the thickness and the difference in compressibility of brown and grey boulder clays below foundation level. A comparison of calculated and measured settlements shows that the settlement calculated based on constrained moduli determined using Marchetti formulae are smaller than measured values. A better agreement between calculated and measured settlements was obtained in case of settlements calculated based on constrained moduli obtained from proposed formula.

Acknowledgments

This research was supported by two Grants No N N506 395135 and No N N506 432436 from the Ministry of Science and Higher Education, Warsaw, Poland.

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Streszczenie: *Ocena osiadań fundamentów bezpośrednich posadowionych na prekonsolidowanych gruntach spoistych.* Projektowanie budynków z użytkową częścią podziemną stwarza często warunki bezpośredniego posadowienia fundamentów na występujących w podłożu silnie prekonsolidowanych gruntach spoistych. Duże wartości parametrów wytrzymałościowych prekonsolidowanych gruntów spoistych powodują, że decydujące znaczenie ma zapewnienie nieprzekroczenia stanu granicznego użytkowalności. Zróżnicowanie obciążenia przy zmiennej miąższości występujących warstw, charakteryzujących się najczęściej różną ściśliwością, wymaga od projektanta bardziej precyzyjnej prognozy osiadań. Poprawna prognoza osiadań, oprócz oceny obciążeń i dobrego rozpoznania warunków geotechnicznych posadowienia, wymaga właściwego doboru parametrów geotechnicznych do obliczeń. W artykule przeprowadzono ocenę przemieszczeń pionowych fundamentów bezpośrednich posadowionych na silnie prekonsolidowanych glinach zwałowych. Moduły ściśliwości wyznaczono na podstawie badań dylatometrycznych wykorzystując w interpretacji zależność podaną przez Marchettiego oraz zależność opracowaną dla gruntów spoistych z rejonu Warszawy. Obliczenia przemieszczeń pionowych pozwoliły na ocenę doboru modułów ściśliwości z badań dylatometrycznych oraz porównanie obliczonych przemieszczeń pionowych na podstawie wyznaczonych modułów oraz analizy numerycznej z wartościami pomierzonymi.

Słowa kluczowe: fundament bezpośredni, Eurokod 7, stany graniczne użytkowalności, grunty spoiste.

MS. received 30 November 2011

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