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Suction - swelling relations for Warsaw clays

Le relation gonflement-succion pour l'argile de Varsovie

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ABSTRACT
The paper presents recent experimental testing of expansive clays distinguished in foundations of the Warsaw subway, a high-rise hotel building and the water intake at the Stegny test site. Swelling parameters of clays were assessed by classification methods and direct laboratory measurements (standard consolidometer), in which soil volume and stress changes were measured during specimen saturation with water. Moreover, the swelling potential of Warsaw clays was determined by soil suction measurement. The tests were carried out using suction controlled UPC consolidometer, in which the "axis – translation" technique was applied. The results of tests were interpreted within the context of a constitutive model for expansive, partially saturated soils. After analysis of test results, the relationship between soil suction and swelling potential for Warsaw clays is discussed. The soil suction concept provides more reliable estimation of the clay volume change (swelling) than other methods used in the geotechnical engineering practice.

RÉSUMÉ
L'article présente les résultats d'essais faits dernièrement pour l'argile de Varsovie provenentes: de fondation du métro, d'un haut bâtiment hotelière et d'un captâge d'eau du terrain experimental de Stegny. Les paramètres de gonflement d'argile ont été detérminés avec utilisation des mèthodes de classification et des essais directs eu laboratoire (essais standard de consolidation), pendant lesquels ont a mesurés les changements de volume d'échantillon de sol et les contraintes durant d'une saturation. En plus, le potentiel de gonflement d'argile de Varsovie a été déterminé sur la base de mesures de succion de sol. Pendant les essais on a utilisé le consolidomètre UPC avec d'une technique «translation – axe». L'interprétation des résultats d'essais est basée sur le modèle constitutif de sols expansifs qui sont partiellement saturés. On été constaté que la conception d'utilisation de succion présente une possibilité plus reélle de détermination des changéments de volume de sol (gonflement) que les autres mèthodes appliqueés dans la pratique géotechnique.

1 INTRODUCTION

The project of the Warsaw City development involves the construction of many high-rise structures, pavement roads and extension of subway lines. Much of the land available for planned residential or commercial development in the metropolitan area is underlain by high plasticity clays (Fig. 1). The Warsaw area is located within the tectonic unit known as the Mazovian Basin, a vast depression developed during the Tertiary. The Tertiary strata comprise Pliocene deposits represented by clays, slimes and locally sands, generally referred to as motley clays. Pliocene clay behavior constitutes a significant threat to foundation systems and underground structures. The main engineering problem, which has been identified in the case of deep excavation pits, is the potential of Warsaw clays to swelling. Damage to houses and other light structures constructed in areas underlain by expansive soils is a problem that occurs in many areas of Poland. It is commonly known that swelling, accompanied by increasing soil water content is a result of stress relief, particularly when high horizontal stresses are involved, which induces negative pressure, or suction pressure $u_s = u_a - u_w$ in the pore water. It has been observed, also during excavation of massive trenches in the Warsaw area, that the negative pore pressures do not remain constant with time, but the pore pressure changes with time to a new equilibrium groundwater flow regime (Walker and Mohen, 1987; Taylor and Cripps, 1987; Garbulewski and Żakowicz, 1995).

The paper includes description of recent experimental testing of the characteristics of Warsaw clays recognized in foundations of three projects: the Warsaw subway, a high-rise hotel building and the water intake at the Stegny experimental site (Fig. 1).

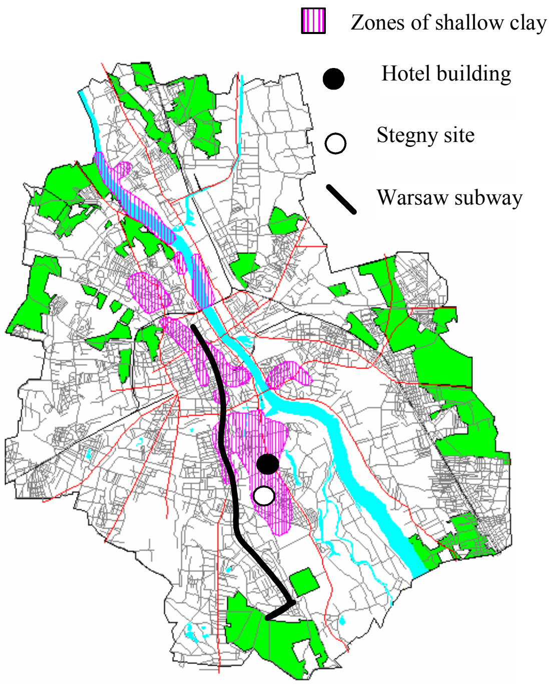

Figure 1. Distribution of Warsaw clays and location of sites tested

2 CHARACTERISTICS OF SITES TESTED

Warsaw subway. Stations of the first subway route were built using the cut-and-cover method. The average trench width during station construction was 23.5 - 24.5m, and the average depth - about 12m.The type of temporary trench boarding applied was the so-called "Berliner wall" consisting of vertical piles made of I-bars, spaced every 1.8-2.0m. Capping beams were used to spread the wall with steel pipe struts on several levels.

The studied area is located within the Warsaw Basin, composed of Upper Cretaceous deposits, developed as marls and marly high plasticity clays, the top of which lies at approximately 250 below ground level. Pliocene deposits are represented by clays as well as slimes interbedded with fine and silty sands. The thickness of Pliocene deposits is variable and depends on the intensity of glaciotectonical processes. The swelling pressure of clays was considered in designing the reinforced concrete walls of the stations.

Hotel building. The hotel building, including five storeys below ground level and eight over-ground storeys has been constructed by the "top-down" method. The underground part of the building has been performed in diaphragm walls, in order to ensure the stability of the excavation both during the construction and permanently after completion of the works. The building structure is based on steel columns-piles foundation system, 38m of total depth.

The upper part of the subsoil consists of anthropogenic fill containing mineral soil of different grain-size distribution. Below, fluvial deposits (from sand to gravel) were distinguished and Pliocene clays have been encountered below the depth of 6 to 9 m. Thickness of Pliocene clays reaches approximately 100 m (Fig. 2). In order to prevent the bottom slab damage, the compensation layer made of stirofoam was applied.

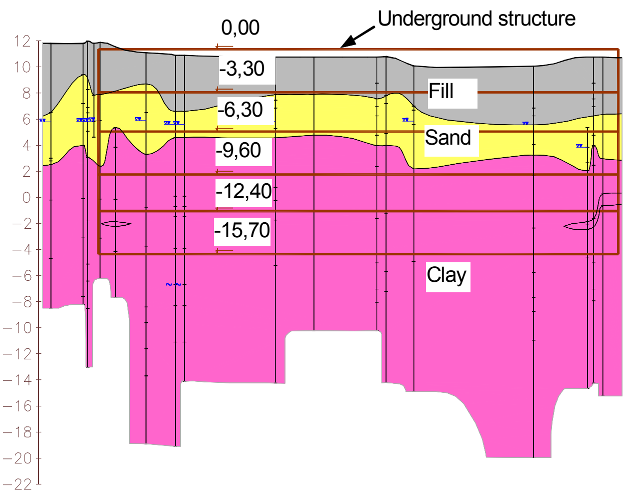

Figure 2. Geological cross-section of the Hotel building subsoil

Stegny site. The experimental plot in Stegny (district of Warsaw) is located on a Quaternary overflood terrace of Vistula River. From the surface down to 4.3 m deep, occur dark-yellow homogeneous medium and fine sands that exhibit alternate deposition in the vertical direction. Within these sands, the groundwater level is at a depth of 3.2 m. Beneath the sands, a complex of Tertiary clay has been found, which is treated as a geological barrier protecting water intake

The index properties of Warsaw clays distinguished in all above test sites are listed in Table 1. It should be noticed that clays encountered in the foundations of all projects are of the same origin (Pliocene age). Clays from the test sites are denoted by numbers 1, 2, 3a and 3b, respectively.

Table 1: Characteristics of tested Warsaw clays

Soil property	Units	Warsaw Subway[1] (1)	Hotel building[2] (2)	Stegny Site[3] Upper (3a)	Stegny Site[3] Lower (3b)
Grain sizes:	%				
Sand		4 - 14	0 – 1	3 -10	4 – 16
Silt		17 - 50	81 - 38	12 – 27	46 – 64
Clay (< 2 μm)		46 - 73	55 - 61	68 – 80	32 – 46
ρ_s	g/cm^3	2.68	2.67	2.68	2.69
w_P	%	29.2	28.0 – 39.8	17.8 – 23.0	24.5 – 25.6
w_L	%	72.9	63.1 – 118.4	75.6 – 98.0	86.4 – 109.6
I_P	%	43.7	35.1 – 77.0	52.6 – 76.4	61.9 – 84.0
Activity	-	0.59	0.81 – 2.11	0.87	1.87
COLE	%	7.5 – 12.3	9.1 – 10.1	11.4 – 13.5	5.0 – 7.5

[1] Garbulewski & Żakowicz (1995); [2] Skutnik et al. (2001); [3] Lech & Bajda (2002)

3 SWELLING AND SUCTION TESTS

For determination of compression and swelling properties of clay from the hotel building foundation, a standard oedometer device has been used. The tests were carried out according to the procedure proposed by Wittke (2000), modified by the authors. For the swelling pressure determination, the volume change of sample due to swelling has been constrained by increase of vertical stress. Once the swelling pressure had been attained, the sample has been unloaded in steps. This test procedure leads to a curve (Fig. 3) from which the swelling strain may be determined.

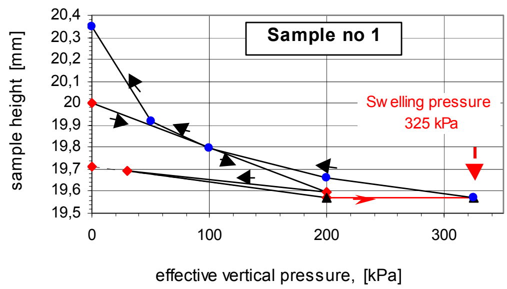

Figure 3. Result of swelling tests for clay from the hotel building foundation

Deformation under suction controlled conditions was investigated by means of a UPC consolidometer (Fig. 4). The apparatus allows performing swelling/consolidation tests on unsaturated soil samples controlling suction through the application of the axis translation technique. Three samples collected from the Stegny site were tested with application of different soil suction values (u_s= 50, 200 and 400 kPa), and variable vertical net stresses ($\sigma_v - u_a$). It has been noticed that due to the imposed suction value and vertical net stress, the samples have swollen or settled. For example, at suction of 400 kPa (Fig. 5), a clay sample has swelled until vertical net stress of app. 220 kPa has been applied.

Figure 4. View of the UPC consolidometer

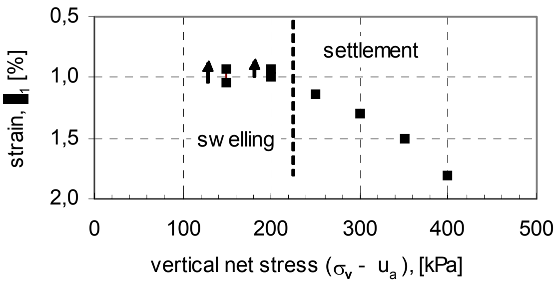

Figure 5. Results of the swelling test at suction 400 kPa for clay from Stegny site

4 PREDICTION OF SOIL SWELLING

In engineering practice, for identifying expansive soils and predicting their swelling potential, soil index properties, such as clay fraction (less than 2μm) content and Atterberg limits are the most widely used. The swell potential has been related by Skempton (1953) to activity, defined as ratio of the plasticity index to the percentage of clay size finer than 2 μm. The activity of various types of clay minerals as a function of the plasticity index and the clay fraction has been presented by van der Merwe (1975) and Williams and Donaldson (1980). Seed et al. (1962) have developed a chart based on the activity and percent clay sizes. According to this chart (Fig. 6), the Warsaw clays can be classified to a medium, high and very high expansion potential.

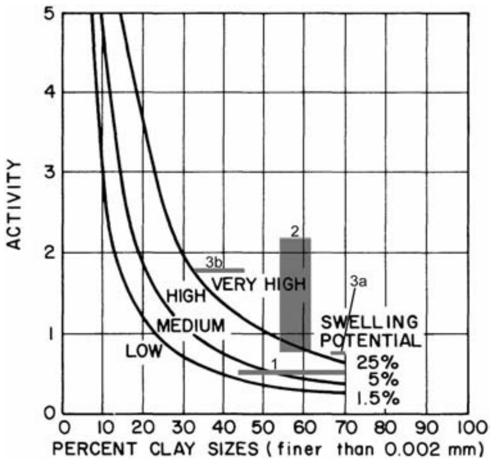

Figure 6. Identification of the expansion potential of tested soils acc. to the chart of Seed et al. (1962) (1, 2, 3a and 3b – clay tested, see Table1)

Magnitudes of the swelling potential may be estimated from tests performed in consolidometers on representative, undisturbed samples.

In recent years, the soil suction approach has been introduced to predict the soil swelling potential (Snethen 1980, Acar and Nyeretse 1992, Al-Soudi and Jabbar 1990, Al-Hello 1993). Techniques for measuring soil suction are now well documented and described (e.g. Ridley & Wray 1995). McKeen & Hamberg (1981) have suggested the use of the relationship between COLE (Coefficient of Linear Extensibility) and clay content. A new chart with five mineralogically regions was developed (Fig. 7).

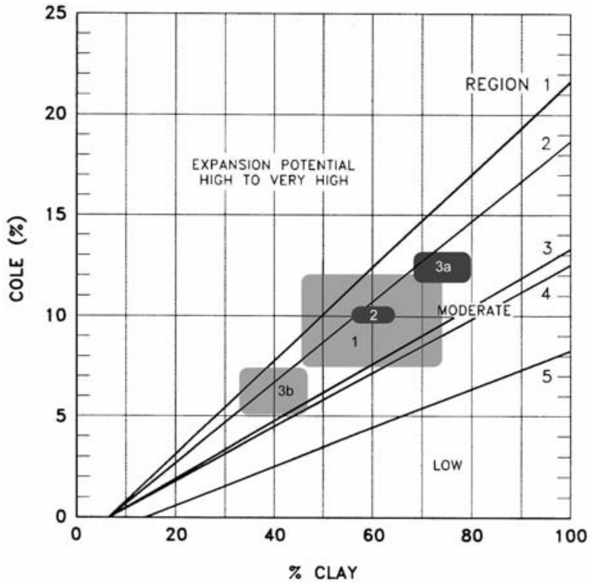

Figure 7. Identification of the expansion potential for the tested soils acc. to the COLE value classification chart

The COLE value can be measured in the laboratory or estimated from the corresponding relationships (Nelson & Miller 1992). The COLE test determines the linear strain of an undisturbed, unconfined, sample coated with flexible plastic resin draying from 33 kPa suction to oven dry suction (1000 MPa). The COLE has been related to swell-shrinkage potential as follows (Parker et al. 1977): COLE < 0.03 – low potential, from 0.03 to 0.06 – medium, from 0.06 to 0.09 – high, COLE > 0.09 – extremely high. Based on data obtained for 250 soil samples in Poland, Szatyłowicz (1998) proposed the following relationship (1) between the COLE value and clay content (TC):

$$COLE = -63.28 \cdot 10^{-4} + 17.71 \cdot 10^{-4} \cdot TC \qquad (1)$$

The COLE values for Warsaw clays are given in Table 1. In calculations average values of the clay content were assumed for each site.

The CLOD test is a modification of the COLE procedure. The basic difference between the methods is that in the CLOD method, the changes in soil volume are measured for gradually changing moisture content values. The CLOD method allows receiving a smooth shrinkage or swelling line for each soil sample. The slope of the curve in Figure 8 is designated as the CLOD index; C_w can be used for determining the soil heave Δz_i:

$$\Delta z_i = \frac{\Delta e}{1+e_0} z_i = \frac{C_w \Delta w}{1+e_0} z_i \qquad (2)$$

where: z_i – initial thickness of uniform soil layer i, Δe – change in void ratio of layer i, e_0 – initial void ratio, Δw – change in moisture content.

The CLOD test has been applied for determining shrinkage characteristics of the Warsaw clay (Fig. 8). The tests were performed using the procedure developed by Miller in the Colorado State University (Nelson & Miller 1992). Test results allow to determine the CLOD index value at C_w = 0.020. The COLE for Warsaw clay equalled to 0.108.

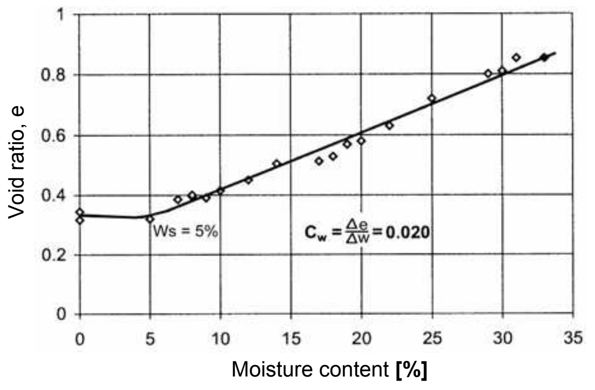

Figure 8. Results of CLOD tests for Warsaw subway clay

For Pliocene clays investigated here, the suction tests were made in a modified oedometer, called "sucoedometer" (Garbulewski & Żakowicz 1995), where a microporous tensiometric ceramics element (air entry at 140-160 kPa) connected by a rigid conduit to a pressure gauge was assembled into the oedometer ring. Determinations of swelling force and suction pressure for the same clay sample were used to establish a direct dependence between these parameters (Fig. 9). Results show that the dependence between suction pressure (h) and swelling pressure (p) is exponential and may be expressed by the following equation:

$$p = a(h)^n \tag{3}$$

where a and n determined using the last squares method are: a = $9.4 \cdot 10^{-4}$ and n = 2.90.

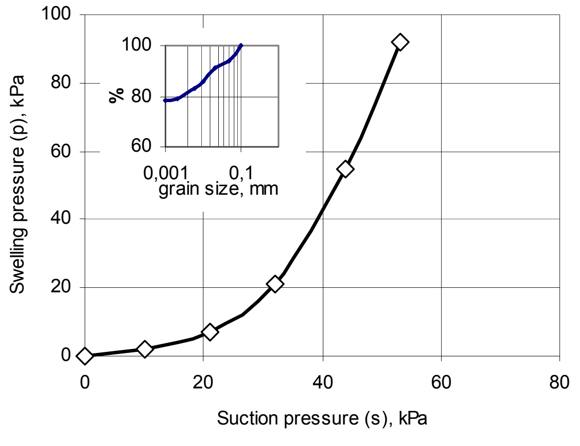

Figure 9. Relationship between swelling and suction pressures for the Warsaw clay

5 SUMMARY AND CONCLUSIONS

Warsaw Pliocene clay behavior constitutes a significant threat to foundation systems and underground structures (e.g. Warsaw subway, high-rise buildings). The main engineering problem, which has been identified in case of required massive trenches (deep excavations), is their potential to swelling.

The data described above shows that numerical methods have been proposed for qualitative evaluation of the expansion potential. Despite the fact that the Warsaw clays investigated here are of the same origin, the classification methods indicated a wide range of swelling potential from low to very high. Therefore, they should be used only as guidelines.

The swelling potential of clays, which is required in design calculations, should be determined using direct measurements. Based on standard swelling tests, the Warsaw clay can be classified to the very high potential group with swelling pressure values from 200 kPa to 500 kPa and swell index values higher than 7 %.

It can be concluded after the analysis of test results that the soil suction concept provides a more reliable estimation of the clay volume change (swelling) than other methods used in geotechnical engineering practice.

The suction measurements showed that the swelling potential of the soil can be determined very fast; the time to attain the maximum level of soil swelling was less than 48 hours.

The CLOD test is a simple and informative test for soil volume change estimation. For Warsaw clays, the CLOD index value was C_w = 0.020 and the COLE value = 0.108.

Investigations of clay samples from the Warsaw subway showed that suction potential permits assessing the capability of clay soils into swelling groups. The exponent value (n) may be used as a criterion for soil classification into high swelling (n > 1) or low swelling (n < 1).

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