A R C H I T E C T U R E C I V I L E N G I N E E R I N G E N V I R O N M E N T
The Silesian University of Technology No. 4/2008

SELECTED GEOTECHNICAL PROBLEMS OF EXPANSIVE CLAYS IN THE AREA OF POLAND

Maciej Kordian KUMOR*

* Faculty of Civil and Environmental Engineering, University of Technology and Life Sciences in Bydgoszcz, S. Kaliskiego 7, 85-791 Bydgoszcz, Poland
E-mail address: *mkkumor@utp.edu.pl*

Received: 18.06.2008; Revised: 28.07.2008; Accepted: 29.10.2008

Abstract

In Central European conditions, each building stratum in its surface zone is exposed to the impact of numerous diverse anthropogenic and natural factors. Expansive clays are soils that are very special as regards the impact of external factors. From an engineering point of view, the occurrence of the substratum shrinkage phase after the swelling phase is the most dangerous for constructions. Expansive clays are typical for nearly half of Poland area. These are tertiary mio-Pliocene clays of the Poznań series. Characteristic symptoms of buildings damage due to the base expansiveness include: expanding cracks of bearing walls from the foundation upwards, cracked lintels, distorted windows, etc. The Poznań series clays are characterised by expansive properties that are high cohesiveness (strength) and a low compressibility is a feature of an expansive substratum in a natural condition. The leading idea of the paper is to present to practitioners some selected results of the studies on the nature of these soils, generally considered to be good from a civil engineering point of view but, at the same time, dangerous for those who ignore their genetically shaped geotechnical properties.

Streszczenie

W warunkach środkowo europejskich każde podłoże budowlane w strefie przypowierzchniowej jest narażone na działanie wielu różnorodnych czynników antropogenicznych i przyrodniczych. Do szczególnych gruntów pod względem wpływu czynników zewnętrznych należą iły ekspansywne, które pod względem geotechnicznym wyróżnia specyficzna reakcja na działanie wody i przesuszanie oraz wrażliwość na działanie temperatur. Iły ekspansywne są typowe dla blisko połowy powierzchni Polski. Są to trzeciorzędowe mio-plioceńskie iły serii poznańskiej. Charakterystyczne symptomy uszkodzeń budynków z przyczyn ekspansywności podłoża to: rozszerzające się pęknięcia ścian nośnych od fundamentu w górę, pęknięte nadproża, itp. Cechą podłoża ekspansywnego w stanie naturalnym, jest duża spójność (wytrzymałość) i mała ściśliwość. Myślą przewodnią niniejszego artykułu jest zbliżenie ku praktyce budowlanej wybranych wyników badań o naturze tych gruntów, powszechnie uznawanych za dobre pod względem budowlanym a jednocześnie niebezpiecznych dla ignorujących ich genetycznie ukształtowane właściwości geotechniczne.

Keywords: **Geotechnics of expansive clays; Tertiary mio-Pliocene clays posnanian series; Symptoms of building damage; Expansive properties the clays of North Poland.**

1. INTRODUCTION

The most important factor in actual cases of founding buildings is the type of soil and its sensitivity to humidity changes. In Central European conditions, each building stratum in its surface zone is exposed to the impact of numerous diverse anthropogenic and natural factors, e.g., pollution, the activity of frost and precipitation.

Expansive clays are soils that are very particular as regards the impact of external factors. In geotechnical terms, these very cohesive soils distinguish themselves with a specific reaction to the water impact and drying as well as their sensitiveness to temperatures. From a practical point of view, expansive soils show an increase in the initial volume when in contact with water and, therefore, shrink as a result of drying. A characteristic feature is the occurrence of differentiated phases of shrinkage and swelling at every change in humidity.

The notion of soil expansiveness in geotechnics is most frequently related to the definition of swelling, Chen [2]. As it is well known, the soil expansiveness encompasses more general phenomena of swelling and shrinkage, Przystański [33, 34].

***Shrinkage** – is the process of reducing soil volume as a consequence of a pore water loss; it is a characteristic property of cohesive soils with significant contents of the clay-like fraction.*

*The **swelling** of cohesive soils is the process opposite to shrinkage, which generates, apart from an increase in volume, significant swelling pressure values.*

In the literature related to classification of expansive soils, e.g., Chen [2], Seed et al. (1962), Sorochan [37], van der Merwe [42] and others, attention is chiefly paid to the swelling process. In the classifications, the following indicative features are used in the first place: liquid limit – w_L, contractility limit – w_s, plasticity index – $I_p = w_L - w_p$, soil humidity index – w_o, specific surface – S.

In practice, there are few clay expansiveness classifications that introduce shrinkage parameters as classification criteria, e.g., Holtz (1959), Rangantham and Satanarayana (1965), Niedzielski [32].

From an engineering point of view, the occurrence of the substratum shrinkage phase after the swelling phase is the most dangerous for constructions. Shrinkage brings about a post-consolidation settlement of expansive clays which is the principal cause of nearly all construction failures in Poland's geotechnical conditions.

1.1. The range and conditions of occurrence

Expansive clays, as typical for nearly half of our country's area (Fig. 1), commonly occur in the centre of Poland, in the regions of Poznań, Wronki, Bydgoszcz, Warsaw, Zielona Góra and other large conurbations. These are tertiary mio-Pliocene clays of the Poznań series [3, 5, 6, 7].

The expansive properties of these soils are the cause of numerous failures in building constructions and their behaviour is determined mainly by a significant lithological and mineralogical variability and sensitivity to the water environment action.

The high variability of numerical values of geotechnical parameters depends in the first place on the genesis and mineralogical composition and hydrogeological conditions, as well as on the anthropopressure impact, including the engineering activity of man.

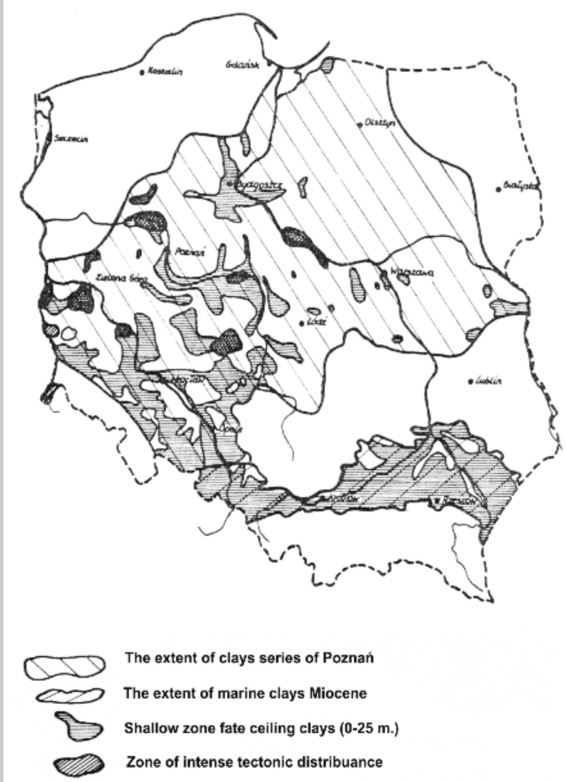

Figure 1.
Occurrence of expansive soils in Poland

Clays are characterised by a high variability in graining and mineralogical composition. A mineral with strong expansive properties, i.e., *beidelite*, *montmorillonite*, prevails in the mineralogical composition. The contents of clayey minerals are as follows:

- smectite: 11 % to 23 %, with the exchangeable ion Ca^{++}, Na^{+},
- illite: 5 % to 9 %,
- kaolinite: 6% to 11 %,
- other minerals, chlorite, silica.

The thickness of the Poznań series usually does not exceed 20 m in Poland.

1.2. Factors activating expansive clay features

It follows from the geotechnical studies conducted that the course and scope of changes in the clay humidity in the substratum depends on numerous varied factors. The factors can be divided into two basic groups: the group of genetic and geologic factors characterising material properties of the clay and the group of environmental factors determining the environmental impact on the soil base condition (Table 1).

Table 1.
Factors determining humidity changes in the expansive stratum

Genetic & geologic	Environmental factors	Other factors
• specific surface (S), • soil graining (f_p, f_π, f_i), • mineralogical composition (M), • exchanging cation type (ν), • soil structure (ST), • plasticity index (Ip).	• climatic factors (K), • vegetation (R), • external soil loading (σ_d), • water table position (h_w), • anthropogenic factors (L), • massif humidity distribution (w).	• depth (h), • time (t).

The studies of clays from Bydgoszcz [4, 25, 30, 39, 45], coming from various depths and representing different sedimentation phases, indicate a relatively homogenous mineralogical composition. A quantitative predominance of minerals of the smectite group, mainly beidelite, was found. The shares of other clayey minerals, i.e., kaolinite and illite, are smaller and their mutual proportions are variable. In beidelite interpackage spaces, mainly bivalent exchangeable cations (Mg^{2+}, Ca^{2+}) were observed. The differences observed in the mineralogical composition are noticeable since samples with a similar grain composition had different values in the liquid limit and plastic limit [12, 15].

Significant genetic and geologic features of clay include the plasticity index (I_P) and the structure. The plasticity index is treated as an independent variable; it is a *material constant of the cohesive soil*. It defines the expansiveness degree [7, 8]; it also shows a very strong relation to the clay fraction contents and reflects the variability of its mineralogical composition. Clays in Bydgoszcz are characterised by a breccia macrostructure which divides the massif into polyhedral, irregular lumps [13, 18]. Cracks occur along natural surface discontinuities. The aggregate disintegration grows as a result of the cyclical shrinkage brought about by seasonal drying and humidifying clay. The generated fissures facilitate water penetration deep into the substratum.

This affects the dynamics, scope and nature of interrelations between the substratum humidity and the height (h), Fig. 2.

As a result of intensive town development in urban areas, the first water table permanently decreases. In Bydgoszcz, it is currently assessed at 3-5 meters [28, 29, 31].

The general function of humidity changes in the expansive base can be written down as the following formula:

$$\Delta w_n = f\,(I_P, K, R, L, h, t) \tag{1}$$

The knowledge of the function of the volume of expansive clay changes in shrinkage and swelling phases has an important practical aspect, i.e., the need to determine the scope and dislocations of the contact zone between the foundation and the expansive substratum at free swelling or shrinkage.

The results make it possible to practically forecast important behaviours of the building in relation to natural fluctuations found in the expansive base

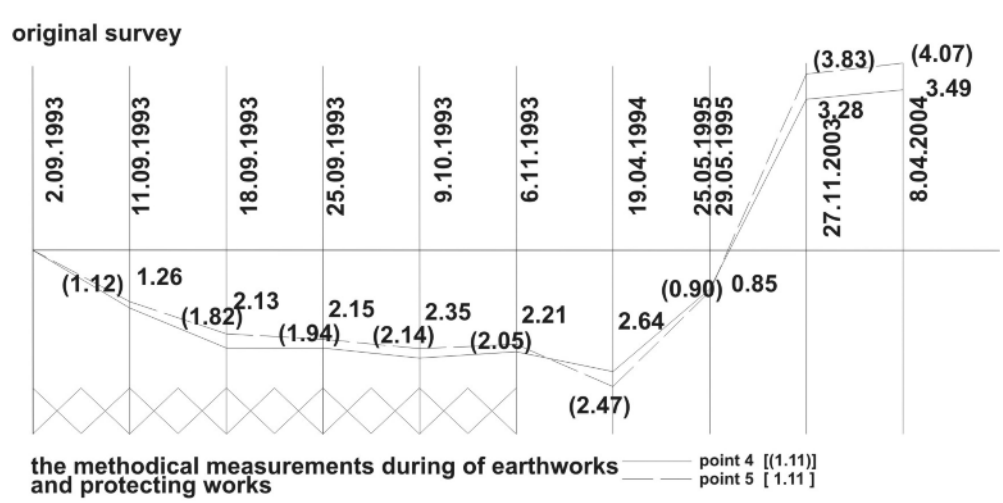

Figure 2.
Vertical alternate dislocations (shrinkage-swelling phase) of building points [23, 24]

humidity. They can also be useful for proper interpretation of failures, for geotechnical reasons, of buildings founded on expansive clays and for the choice of the reinforcement method. In spite of the progress in engineering knowledge, numerous failures of buildings caused by an expansive base are still being recorded.

1.3. Examples of building failures caused by the shrinkage and swelling of clays

The expansive base, and in particular tertiary clays of the Poznań series, has been causing serious problems in exploitation of buildings and structures for over a hundred years, Jentsh (1902), [10, 11, 43, 44]. Below are examples of geotechnical failures of buildings caused by shrinkages and swellings of expansive clays. Building failures are usually recorded in a greater number in autumn, after a dry summer, or spring, after winter thaw. The examples of building failures listed below were recorded after the dry summer of 2006.

Figure 3.
An example of a building failure as a result of cyclical swelling-shrinkage. Maximum lowering of the foundation wall (Δs=10 cm)

Figure 4.
2 cm cracks in a foundation wall as a result of a shrinkage (Δs=5 cm) of the expansive clay, settlement of a concrete band (Δs=10 cm)

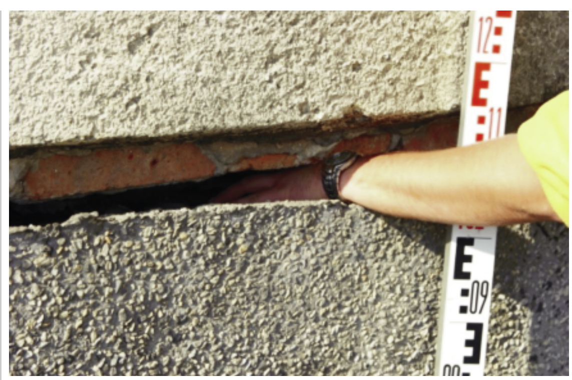

Figure 5.
An example of damage to a foundation wall, an outer view

Figure 6.
An example of wall damage, an outer view

Table 2.
Stratigraphy of expansive formations as typical for a building base

Stratigraphy	***Lithologic & genetic description***		
Quaternary-Q	***Holocene Qh***	Anthropogenic	Humus soils (H) Uncontrolled embankments (nN) Building embankments (NB)
		Fluvial *(f)*	Sands (**P_d, P_s, P_π**)
		Fluvial-marginal lake *(f-li)*	Warps (**Nmp, Nmg**) Peats (**T**), gythias (**Gy**)
	Pleistocene Qp – Fluvial-glacial *(f-g)*		Sands and gravels (**P_r, P_s, P_d, P_π, Ż, P_o**) Clays (**G_p, P_g, G_π, G_{pz}**, Π)
Tertiary-Tr	***Pliocene (Tr pl)*** - deposits of the epic continental reservoir *(li-m)*		Clays, loams (**I_p, I, I_π, G_p, G_{pz}, G_z, $G_{\pi z}$, Π, P_d**)
	Miocene (Tr M) – deposits of closed freshwater reservoirs *(li)*		Sands (**P_s, P_r, P_d**), lignite (**WB**)

Figure 7.
Raising of a manhole as a result of expansive base swelling (Δs=22 cm)

Characteristic symptoms of building damage due to the base expansiveness: expanding cracks of bearing walls from the foundation upwards (Fig. 3, 4, 5, 6), cracked lintels (Fig. 6), distorted windows, impossibility to close doors and windows, an out-of-plumb deviation of walls, ceiling cracks (Fig. 3), ground deformations around a building (Fig. 7), etc. The analysis of a number of building failures indicates that the primary source of structure deformations is the cyclic change in humidity of expansive clays which generates dislocations in the massif in the alternate swelling and shrinkage process. The clay shrinkage occurs seasonally, usually in summer and in autumn, in the period of tree vegetation or after a large-scale area drainage, e.g., when a new drainage system has been laid. Swelling dominates with different intensity in autumn and in spring, after winter thaw [14, 19, 26].

2. GEOTECHNICAL CHARACTERISTICS OF THE EXPANSIVE BASE

2.1. Stratigraphy and geology of the Poznań series

Areas of shallow occurrence of tertiary clays of the Poznań series are characterised by a slight overlay of tertiary clays of the Poznań series, i.e., the Miocene and Pliocene [5, 9, 16]. From the above, most frequently a thin layer of young quaternary deposits occurs – Q, that covers the basic complex of tertiary formations – Tr, see: Fig. 1, Table 1, 2:

– **the Holocene** (Qh) is represented by a layer of humus, non-cohesive, organic and embankment soils. The thickness of organic soils is variable and amounts to 0.3-1.4 m, and in case of the sandy-gravel series up to 1.4 m, and slightly more in places,

– **the Pleistocene** (Qp) covers continuous mantle tertiary deposits and, locally, also Mesozoic ones. These are glacial, aqueous-glacial, fluvial and lacustrine deposits. Regional eolian sands occur on Pleistocene formations. The thickness in erosion valleys reaches several meters,

– **the Tertiary** (Tr) has been exposed mainly along river valleys of the Vistula, the Odra, the Brda, the Drwęca and the Warta. It is developed in the form of mio-Pliocene ($Tr_{\text{mio-pl}}$, Poznań series clays) mottled clay, locally washed away and broken. The Miocene is mainly sandy deposits interbedded with lignite and insertions of weakly bonded sandstone.

Miocene fine sands and silty sands with lignite silt and lignite occur underneath the Pliocene clays.

Clays are characterised with a significant variability of graining and colours.

The thickness of the Poznań series in Poland usually does exceed 20 m.

Table 3.
Strata of Poznań complex clays as exemplified by the outcrop in Fordon and identified on the basis of lithological features

Stratum number, designation	Roof depth [m.p.p.t.]	Soil symbol as per PN-88/B-02480	Dominating colours	Lithostratigraphy	
0	0.0	***Pd, Ps, Pr***	*yellow, yellow-brown*	quaternary –Q	fluvial-fluvial-glacial
1	1.1-1.3	***Iπ***	*grey*	tertiary Miocene -Pliocene - Tr	flaming clays level
2	1.4-1.6	***I//G***	*grey-red-cherry-red*		
3	2.7-3.0	***Gpz//Gπ//Pd***	*grey*		
4	3.4-4.0	***I+G, Gpz, Iπ***	*grey-red, grey-brown-red*		
5	4.2-4.6	***Iπ//G//Pπ***	*grey-violet-cherry-red, grey-brown, grey*		
6	6.0-6.2	***Iπ***	*grey-brown*		
7	5.4-5.2	***Iπ***	*yellow-cherry-red-grey*		
8	6.3-6.4	***Iπ***	*black*		green clays level (?)
9	7.0-7.4	***Gpz//Gπz//Pπ, Pd***	*grey, yellow-grey, green-grey*		
10	7.9-8.0	***Iπ***	*grey-brown*		
11	8.3-8.7	***Iπ***	*dark-grey*		
12	9,0-9.5	***Iπ//WB***	*black*		
13	10.4-10.9	***Iπ***	*steel-grey*		

2.2. Lithologic differentiation of the Poznań series

The characteristic lithologic composition of formations in the region of Poland is presented in Table 1. Cohesive and very cohesive soils are represented by clays, silty argils, clays with loam admixture, firm sandy clays and loams (Table 3). They form strata with a thickness ranging from 0.4 to 1.6 m, limits between different strata of cohesive soils are sharp, Fig. 8.

Expansive tertiary clays of the Poznań series in the whole sedimentation basin in the area of Poland are characterised by a high variability of physical properties and in particular the grain composition. The grain composition is a derivative of the contents of minerals of the smectite group (sodium and calcium montmorillonite) and determines the values of geotechnical parameters and provides them with specific expansive properties.

Figure 8.
Vertical differentation of clays, general view

In the expansive clays massif, diversified, macroscopically legible anisotropy surfaces were distinguished [18, 22].

- Horizontal structures in conformity with the stratification. They are formed mainly on the border of two different soils. They do not seem to reconstruct the soil structure in their vicinity. In all likelihood, they have originated as a result of sedimentation processes, e.g., strata borders (Fig. 8).
- Horizontal and slightly slanting (<10°) zones characterised by a distinct jointing, probably of the diagenetic origin (compaction?).
- Slanting zones showing traces of mirrorings on jointing surfaces, however, without a legible displacement. A structure reconstruction is legible at a distance of ca. 1mm from the mirroring surface. The so-defined mirroring surfaces are conformable with two directions, nearly perpendicular to each other. The angle between these directions and the vertical direction is ca. 45°. The high frequency of occurrence of these zones, their regularity and orientation suggest that they have originated under the influence of the triaxial changes in stresses (Fig. 9).
- Slanting zones at a scale of several meters, traversing strata, frequently with a displacement along the zone of the order of several to several tens of cen-

timetres. The clay structure reconstruction in that zone is related to the occurrence of a large number of quasi-parallel oriented mirrorings (every ca. 0.5-2 cm) which divide the soil into sigmoid clasts with a structure similar to a non-deformed clay massif. They are probably slight glacial tectonic faults and overfolds (Fig. 9, 10).

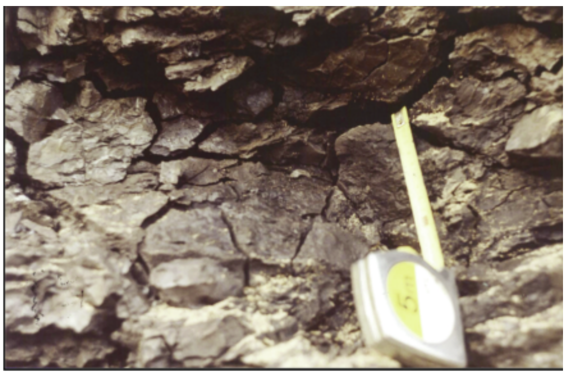

Figure 9.
Exemplary mirroring surface and shrinkage cracks (breccia macrostructure)

Figure 10.
A glacial tevtonic fault in a clay massif

The results of resistance tests conducted so far on soils with natural impairment surfaces show a significant decrease in shear strength as dependent on normal stresses and soil humidification. The character of clay natural impairment surfaces (genesis, spatial distribution, mineral composition, etc.) significantly influences resistance characteristics of the whole soil massif as a building case.

2.3. Hydrogeological conditions

The hydrogeological conditions are of great significance not only for determining changes in the clay expansiveness but, in many cases, they render it difficult or even impossible to perform earthwork safely [15]. Under-groundwaters within the Poznań series usually occur at **three** main **levels** and have an essential impact on geotechnical conditions of the tertiary substratum.

1st level of quaternary waters. The first level includes free groundwaters occurring periodically in overlaying sandy formations in which the impermeable or slightly permeable base is made of tertiary clays. The level is supplied directly with precipitation water. There is a noticeable dependence on the water table upon precipitation, the type of vegetable and temperature as well as the distance from local watercourses.

2nd level of subartesian waters. The second level of groundwater is maintained in sand lenses occurring within Mio-Pliocene clays. Waters belonging to that level are under pressure and they are of the subartesian type.

3rd level artesian waters. The third level of groundwaters is formed by artesian and Miocene waters. The water-bearing stratum is made of Miocene sands occurring under Pliocene sands.

To generalize, it should be noted that tertiary clays at the building base occur in an adverse and difficult hydrogeological system which is characterised by:

- three different levels of under-groundwaters of a pressured, subartesian and free nature,
- the existence of a hydraulic interrelation between these three levels,
- the occurrence of water-saturated dusty and sandy interbeddings and sand lenses in the tertiary massif,
- the existence of glacial tectonic cracks that exclude the possibility of treating the massif as a completely impermeable, hermetic layer.

2.4. Geological/dynamic processes

Geological/dynamic processes within the Poznań series are generated mainly by changes in clays humidity as a result of groundwater fluctuations. The hydrated expansive clays swell and thereby change their condition and strength. When drying, they shrink intensively in volume and in the massif, a spatial system of cracks is generated; the cracks are easily penetrated by precipitation water. Cracks resulting from drying and frost penetration have been observed in nature to a depth of more than 2 m from the clay floor [20, 27]. They make potential surfaces of impairment along which landslide processes are initiated.

In actual geological conditions, there are always differentiated, genetic zones of water saturated or dried soils. These problems obviously hinder the execution of foundation works in a uniform manner. The photograph presents a large-space open excavation where locally dried clays were found which were, at the same time, sodden in other zones (Fig. 11).

Figure 11.
A view of a typical system of clays in the gout of a large building excavation with extremely diverse proprieties, simultaneous drying – the nearer zone and irrigation – the background

As an example of destruction of expansive clay in an excavation bottom under the influence of natural drying, a macro-disintegration of the clay massif is initially noticed, then a volumetric shrinkage and a further granular disintegration of the massif which leads to breccia occurrence (Fig. 9, 12, 13).

It results from the photographs presented that the clay drying (shrinkage) process is characterised by a volumetric shrinkage and an occurrence of a breccia structure with numerous separated grains and deep shrinkage fissures [13, 27, 37]. An undesirable geotechnical effect is a locally different stiffness and deformability of such a base. When monitoring a foundation settlement (upon a uniform loading), differences in the settlement were found from Δs = 0.0 mm (a dry zone) to Δs = 30.0 mm in humidified clay zones (Fig. 11).

The width of opening of large fissures reached 5 cm. Due to the above reasons, the Poznań clays reveal tendencies to generate landslides even at a slight slope (4° to 7°). The slide usually develops along the border of frost penetration or glacial tectonic mirroring.

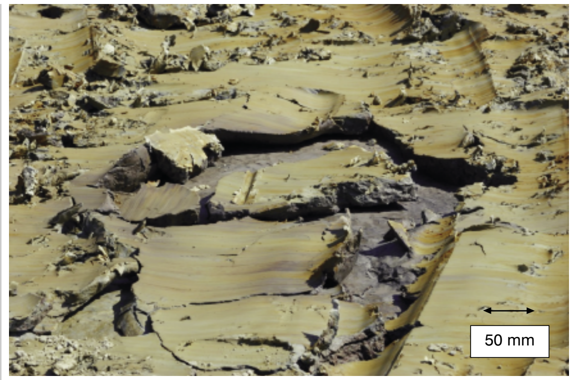

Figure 12.
The natural process of the clay drying after the exposure of the excavation bottom, (after 2 hours) the superficial macro-disintegration is fully developed

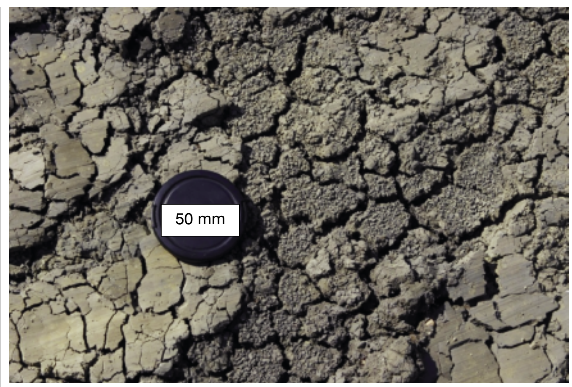

Figure 13.
The granular disintegration of the dry clay in natural conditions, after 24 hours

2.5. Geotechnical properties

2.5.1. Physical properties

From a geotechnical point of view, the Poznań series is primarily formed by clays and less frequently by silty clays and firm clays, Table 4.

Table 4.
Physical properties of Poznań clays

Soil specific gravity		Natural humidity	Grain size content [%]			Consistency limits [%]			Plasticity Index	Liquidity Index
	ρ Mg/m³	w_n [%]	2.0-0.05	0.05-0.002	<0.002 [mm]	w_S	w_P	w_L	Ip [%]	I_L/1/
Medium	**1.92**	**26.51**	**4.8**	**40.2**	**45.0**	**13.70**	**27.20**	**82.1**	**56.3**	**0.03**
Max.	2.21	46.80	17	49	84	18.53	50.50	148.5	99.0	0.19
Min.	1.63	11.80	0	26	30	12.81	11.90	45.6	30.0	-0.10
N (number)	1726	1727	821	921	921	58	1693	1693	1693	1693

A significant variability of the natural humidity (range R=35%, variation coefficient v = 66.7%) is noticeable. The variability reflects the genesis and, in particular, post-syngenetic glacial tectonic disorders and the glacier impact, i.e., cyclic frost penetration and defrosting, [15, 16], as well as periodical drying and humidification.

The Poznań series clays are characterised by expansive properties high cohesiveness (strength) and a low compressibility is a feature of an expansive substratum in a natural condition. In general, these are soils with favourable geotechnical properties, basically half-cohesive or rigid-flexible at the outmost (Table 4).

2.5.2. Expansive properties

The clays of the Poznań series are characterised by expansive properties that are atypical in comparison with other genetic clays in Poland [3, 6, 30]. Below, expansive indices values as typical for the Poznań series in Poland are presented (Table 4). Taking into consideration the different intensity of the factors that activate the expansiveness, including the natural ones, e.g., climate, these factors can generate wide-ranged changes in humidity and thereby disturb the existing thermal and humidity equilibrium of the base. Practically, in each case of even a slight change in humidity, volumetric deformations of the clays and the construction occur.

Table 5.
Expansive clays indices values

Parameter	Max.	Medium	Min.
Swelling time t_p *(h)*	>340	24 - 36	6 - 8
Swelling pressure p_c *(kPa)*	1200*	200-400	~12
Shrinkage v_o *[%]*	44.1	32-34	~5
Swelling humidity w_c *[%]*	137.0	80-99	38.2
Shrinkage limit w_s *[%]*	18.5	13.7	12.8
Liquid limit w_L *[%]*	148.5	82.1	45.6
Swelling index v_p *[%]*	62.0	21.7	5.6

*) values determined with the GEONOR apparatus for powdered samples in an air-dry condition

The expansive indices of Mio-Pliocene clays also depend on the temperature as they grow along with the temperature growth. For example, a ca. 18% higher selling index was obtained at a temperature growth from +20°C to +55°C, [20, 21].

In the event of a geotechnical evaluation of expansive clays characteristics, it is necessary to consider the complete process of expansiveness that includes both swelling and shrinkage. The shrinkage of clays occurs seasonally, usually in summer and in autumn, during tree vegetation or after large-scale area drainage, e.g., when a new drainage system has been laid.

2.5.2.1. Clay drying – shrinkage

The soil contractibility examination is a determination infrequently performed for practical purposes. The volumetric shrinkage (V_s) of expansive clay was examined according to the following rule [21, 27]:

$$V_s = (V' - V'') / V' \quad (\%) \qquad (2)$$

where:

V' – soil sample initial volume [cm^3],

V'' – final volume of the sample after drying [cm^3].

Typical results of the shrinkage progress are presented in Fig. 14 and in Table 6.

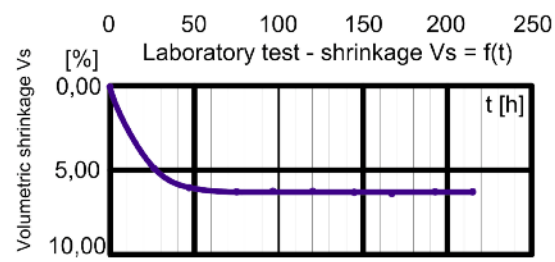

Figure 14.
A typical progress of expansive clay shrinkage over time

Table 6.
Shrinkage parameters of the expansive clays

Shrinkage parameter	Max.
Shrinkage time t_s *(h)*	50 -96
Volumetric shrinkage V_s *[%]*	23-24
Shrinkage limit w_s *[%]*	18.2-18.9

The shrinkage examination results reveal losses in the massif volume and a high sensitivity of expansive clays to changes in humidity in a short time after the commencement of drying, see: Fig. 11, 12, 13.

The volume loss ΔV_s, for the shrinkage phase of the expansive clay in Poland's region can be determined by means of formula 3:

$$\Delta V_s = 0.783 * (w_o - w_k) \quad at \quad w_k > w_s \qquad (3)$$

where:

w_o – initial humidity, *[%]*

w_k – final humidity *[%]*.

From a practical point of view, it is important to learn the volumetric shrinkage values. The graph of the function between relative volumetric shrinkage (V_s) and humidity is linear for expansive clay, with the statistical significance $R^2 = 0.9545$:

$$V_s = -3.5731 + 0.783 * w \qquad (4)$$

where:

V_s – relative volumetric shrinkage [%],

w – humidity, > w_s [%].

In the process of drying and with humidity lowered by the value of $-\Delta w = (w_o - w_k)$, the volume of the relative volumetric shrinkage is important for prognosticating after-consolidation settlements of newly erected buildings, as well as for prevention of failures of buildings used for many years. It results from observations made by Gorączko, Kumor [8, 20, 24] that differences in actual shrinkage settlements under a damaged building amount to tens of millimetres (Fig. 2).

The parameters describing the shrinkage process, as well as the swelling one, are individual *material features* of each expansive soil.

2.5.2.2. Humidity increase – the swelling phase

The swelling parameters of expansive clays were examined by means of methods applied in soil mechanics laboratories [21]. The following values were measured: swelling humidity – w_c, swelling index – V_p, according to Vasiliev method, swelling pressure – p_c, in a consolidometer, swelling time – t_p. Exemplary testing results are presented in Table 7, and in Figs. 15 and 16.

Table 7.
Swelling parameters of the expansive clays

Swelling parameters	Value
Swelling time t_p *(h)*	>340
Swelling pressure p_c *(kPa)*	1200
Swelling index V_p *[%]*	44.1
Swelling humidity w_c *[%]*	137.0
Shrinkage limit w_s *[%]*	18.5

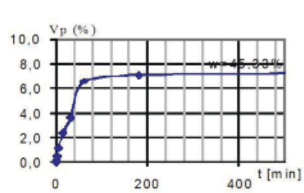

Figure 15.
Dependence of the swelling index on the expansive clay swelling time

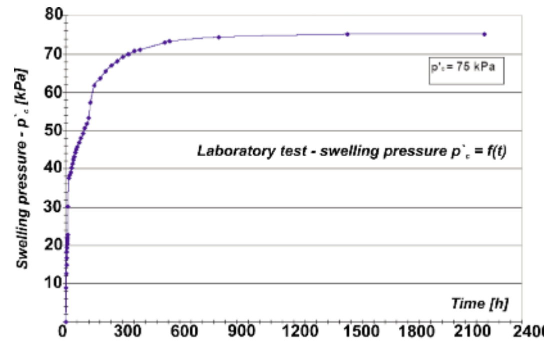

Figure 16.
Dependence of the swelling pressure on the expansive clay swelling time

Characteristics obtained in the progress of potential volumetric change in the examined clays, in relation to the humidity condition, are presented above (Fig. 15). The dependence between the swelling index and humidity can be written down in a general formula:

$$V_p = f(w) \qquad (5)$$

where: V_p – swelling index,

$$V_p = (h_k - h_o) : h_o \qquad (6)$$

w – humidity.

The function formula of the potential expansiveness change characteristics for the examined clay with statistical significance $Rxy = 0.912$ is as follows:

$$V_p = 3E\text{-}05w^3 + 0.011w^2 + 0.102w - 5{,}867 \qquad (7)$$

The characteristics of dependence on the swelling index in relation to humidity, as presented in Fig. 17, allows determining the progress and expansiveness phase characteristics as well as changes in clays deformation values during swelling.

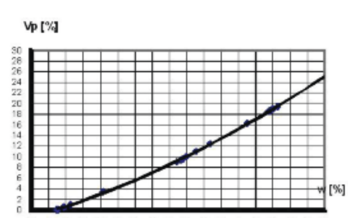

Figure 17.
Dependence of the swelling index – Vp on the swelling expansive clay's humidity – w

Knowing the final swelling humidity of a particular clay w_k, and anticipating the direction of the humidity change on the base of initial humidity w_o, we know that one expansiveness phase will occur, i.e., $(+\Delta w)$ –

humidity increase – swelling phase, when (-Δw) - drying – shrinkage phase.

Having the characteristics of potential volumetric changes in relation to humidity as determined experimentally for a particular type of clay, one can relatively easily make a prognosis of the scope of substratum displacements in practice.

A potential increase in the swelling clay volume can be calculated from the received relationship (8) in the following formula:

$$\Delta V_p = V_p (w_o) - V_p (w_k). \quad (8)$$

In case of a humidity increase by value $\Delta w = (w_o - w_k)$, we will determine a positive swelling index – ($+\Delta V_p$) in relation to the initial condition.

In the clay shrinkage phase, during the swelled massif drying, we receive from the characteristics and calculations made according to formula (8), a negative value (-ΔV_p) – shrinkage, in relation to the initial state after the completed swelling, with humidity w_o.

2.5.3. Mechanical parameters

Below (Table 8), selected values of mechanical characteristics are presented, i.e.: *cohesion – c*, *internal friction angle - ϕ*, *edometric compression modulus - M_o*.

The test results compiled in Table 8, indicate that mechanical parameter values for the Poznań clays occurring in the building base are very differentiated in respect to geotechnics and usually achieve lower numeric values than the ones recommended by Polish standards.

2.5.4. Variability of physical and mechanical properties

The variability of physical properties for expansive clays is significant from the point of view of the classification and solving practical problems. It has been found that the differences in physical and mechanical properties concern clays with a similar or close grain composition and plasticity index [15, 22].

An important result of the analyses is obtaining very low correlation coefficients (practically, a lack of correlation) between the *plasticity index – I_L and strength parameters*, which are treated as a leading geotechnical parameter in Polish standards. They indicate that in case of Poznań clays, the correlation dependences as recommended in the standard must be treated carefully by engineers.

Differentiated numerical values of physical and mechanical parameters of the Poznań series clays, as resulting from the analysis of the results contained in Table 8, may be related to the breccia structure of those formations and to a high variability of the sedimentation material. The variability of geotechnical indices of Pliocene clays was pointed to by W. Fortunat [6]. The conclusions allowed determining the thickness of so called "active zone" through an "in situ" experiment, eg. Gorączko, [18, 28].

Vertical variability – *active zone*. The depth of occurrence in the floor of so-called "active zone" as determined experimentally amounts to ca. 3.2 m to 4.5 m below the ground level in most of Poland's area, Fig. 18.

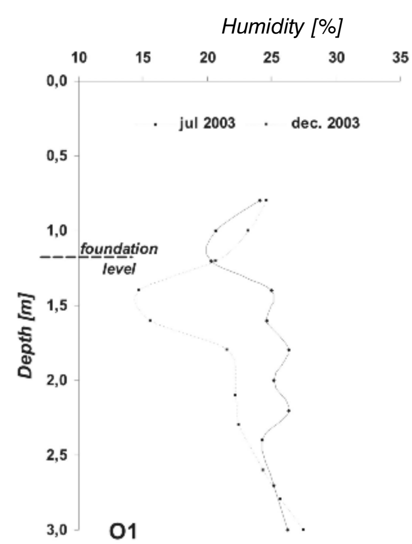

Figure 18.
An exemplary distribution of humidity changes in the clayey base, in half a year, borehole O1, [8]

Table 8.
Mechanical parameters of expansive clays [18]

	Cohesion c [kPa]	Internal friction angle - Φ [°]	Edometric compression modulus – M_O [MPa]	
			Δσ = 0-100 kPa	Δσ = 100-200 kPa
Medium	**57**	**6.5**	**4.0-8.0**	**5.5**
Max.	180	25.0	15.0	6.3
Min.	15	0.0	2.8	4.5
N-number	1047	1047	40	40

On the basis of many-sided analyses conducted with the use of the method of successive approximations, three zones were justifiably separated in the substratum with differentiated values of characteristic leading parameters.

The following zones were [15]:

- next-to-surface zone - I - from 0.0 m to 3.50 m below the ground level,
- transitional zone - II - from 3.51 m to 6.0 m below the ground level,
- deep zone - III - from 6.01 m to 12.0 m below the ground level and deeper.

Zone I – the next-to-surface one, corresponds to the rhizosphere determining the range of the root lump of plants and trees [1, 10, 11, 33, 34].

The variability of physical and mechanical properties of the Poznań series clays as occurring in the building base was expressed in mathematical terms through analysing individual statistical values. The statistical values of the geotechnical characteristics and parameters analysed for the Bydgoszcz region are presented in Table 9.

The average values of geotechnical parameters and characteristics analysed in Table 9 justify the observations below concerning the Poznań clays:

- natural humidity decreases as the depth of individual zones grows; however, the differences between the mean values are insignificant w = 30.31 % in zone I - next-to-surface, and w = 27.96 % in zone III,
- cohesiveness, the mean value grows as the depth of occurrence in individual zones grows, from value c = 48.0 kPa in zone I to 56.9 kPa in zone II and 64.8 kPa in the zone below 6.0 m below the ground level,
- internal friction angle, average values grow as the depth in individual zones grows, from ϕ = 6.5° in the next-to-surface zone to 8.7° in zone III,
- the strength parameter values as determined for the Poznań clays in direct surveys distinctly deviate from the relationships specified in the Polish standard.

2.5.5. Distributions of geotechnical characteristics and parameters

When determining expansive properties, it is not always possible to determine the reliability of the relationships between expansive soils parameters, e.g., plasticity index (I_p), liquid limit (w_L) and swelling index (Vp). The swelling index values (Vp) for two macroscopically identical layers were received that significantly deviate from each other. The layers were characterised by high and comparable values of consistency limits, which may suggest that in spite of similar mineralogical and graining compositions, the swelling process is additionally affected by other factors, e.g., microstructure and contents of organic parts.

It has been repeatedly emphasized in the literature, e.g., [Grabowska-Olszewska 1998], as being related to the impact of structure and microstructure to the rate of migration of water deep down into the soil, the structure and microstructure attraction pressure and the stability of bonding by clayey minerals. The spatially variable distribution of humidity, graining composition, mineralogical composition and microstructure has a decisive impact on shaping numerical values of parameters of the Poznań expansive clays.

In order to become more familiar with the variability

Table 9.
Statistical values for selected parameters and geotechnical characteristics of the Poznań clays as exemplified by Bydgoszcz region [16]

Parameters	Zone number	x	x_{min}	x_{max}	σ_x	v_x [%]
Liquidity Index – I_L [1]	I	0.03	-0.19	0.19	0.08	280.8
	II	0.02	-0.18	0.16	0.07	414.5
	III	-0.005	-0.18	0.19	0.08	-1727.7
Natural humidity – w_n [%]	I	30.31	15.20	46.00	6.2	20.7
	II	29.62	16.40	48.80	5.9	19.9
	III	29.96	15.50	43.90	6.3	22.6
Cohesion – c [kPa]	I	48.0	20.0	136.0	19.9	41.4
	II	56.9	22.0	160.0	21.7	38.2
	III	64.8	30.0	150.0	23.2	35.9
Internal friction angle – Φ [°]	I	6.5	0.0	25.0	3.4	52.5
	II	7.2	1.0	24.5	3.0	41.9
	III	8.7	2.5	25.0	3.9	44.4

I zone N= 549; II zone N = 463; III zone N = 247 of the individual features of clays, an attempt was made to describe the statistical distributions for these features. Only some geotechnical parameters were taken into consideration, as marked with the "A" method, such as:

- z – sample collection depth [m b.g.l.],
- f_i – clayey fraction content [%],
- w_n – natural humidity [%],
- σ_d – soil specific gravity [Mg/m^3] - (marked as "gest" on the diagrams),
- w_L – liquid limit [%],
- w_p – plasticity limit [%],
- I_p – plasticity index [%],
- I_L – liquidity index [1],
- c – soil cohesiveness (as examined in the three axis apparatus) [kPa],
- ϕ – internal friction angle (as examined in the three axis apparatus) [o] – (marked as "kat" on the diagrams).

Selected variability distributions for the parameters examined are presented in Figs. 19 and 20, in the form of histograms with curves describing the theoretical distributions assigned to them. In case of most numeric values of the clay geotechnical parameters (natural humidity, liquid and plasticity limits, volumetric density), the distributions are close to normal, whereas for strength parameters (cohesion, natural friction angle), distributions close to the logarithmic/normal are characteristic.

It results from the parametric significance tests conducted for medium values (on the assumption that the distributions are normal) between the regions that the differences between the mean values are insignificant at a significance level as low as α=0.05.

The statistical analysis of numeric values of geotechnical parameters was based on primary indices: mean value – x, standard deviation – σ_x, extreme values – x_{max}, x_{min}, variability index – $v_x = \sigma_x/x$, range – $r = x_{max} - x_{min}$ as well as ancillary values of variance, skewness and kurtosis. The characteristic values determined for the geotechnical parameters as well as their statistics are collected in Table 10.

The Poznań series clays are characterised by a high differentiation in numeric values of the analysed geotechnical parameters. The extreme values of all parameters do not comply with the three sigma rule ($3\sigma_x$) which states that the values from outside the range ($x-3*\sigma_x$, $x+3*\sigma_x$) are hardly probable. Most frequently, right-sided crossings of the range occur. As a measure of dispersion, a variability measure v_x was assumed which amounts to ca. v_x =20% for most of the parameters analysed.

Histograms that cannot be approximated with any of the basic theoretical distributions occur in case of two features: the clayey fraction content and the plasticity degree.

The plasticity degree has one narrow peak with a sharp outline on the left side in the range I_L from 0.01 to 0.07.

Correlation relationships were established for the analysed samples of tertiary clays upon preparing statistics of individual parameters. Correlation coefficients for the characteristics analysed are collected in Table 11.

When analysing individual correlations, one can notice the existence of statistical relationships between the parameters that are considered to be so-called *cohesive soils condition constants*, (plasticity limits, liquid limits, plasticity indices, clayey fraction content, volumetric density). The correlations are

Table 10.
Statistical values for geotechnical parameters of the expansive building base in Bydgoszcz [16, 22]

Parameters	f_i [%]	w_n [%]	ρ_d [Mg/m^3]	w_p [%]	w_L [%]	I_p [%]	I_L [1]	c [kPa]	ϕ [1^o]
x	48.6	28.8	1.93	28.0	86.0	58.0	0.01	56.9	7.9
σ_x	10.3	6.1	0.09	5.8	16.0	12.6	0.08	24.1	4.0
x_{max}	84.0	48.1	2.21	50.,5	148	99.0	0.28	164.0	28.0
x_{min}	30.0	11.8	1.61	12.4	45.6	30.0	-0.24	19	1.0
R	54.0	36.3	0.6	38.1	102.4	69.0	0.52	145	27.0
v_x	20.6	21.2	0.05	20.7	18.6	21.7	800	42.3	50.1
skewness	0.42	0.20	0.023	0.42	0.12	0.13	-0.42	1.40	1.35
kurtosis	-0.13	-0.31	-0.072	0.10	-0.32	-0.12	0.48	2.37	2.61
variance	105.7	37.9	0.009	34.2	256.8	161.1	0.006	587.7	15.8
N – number of samples	**888**	**1619**	**1619**	**1582**	**1579**	**1577**	**1576**	**966**	**996**

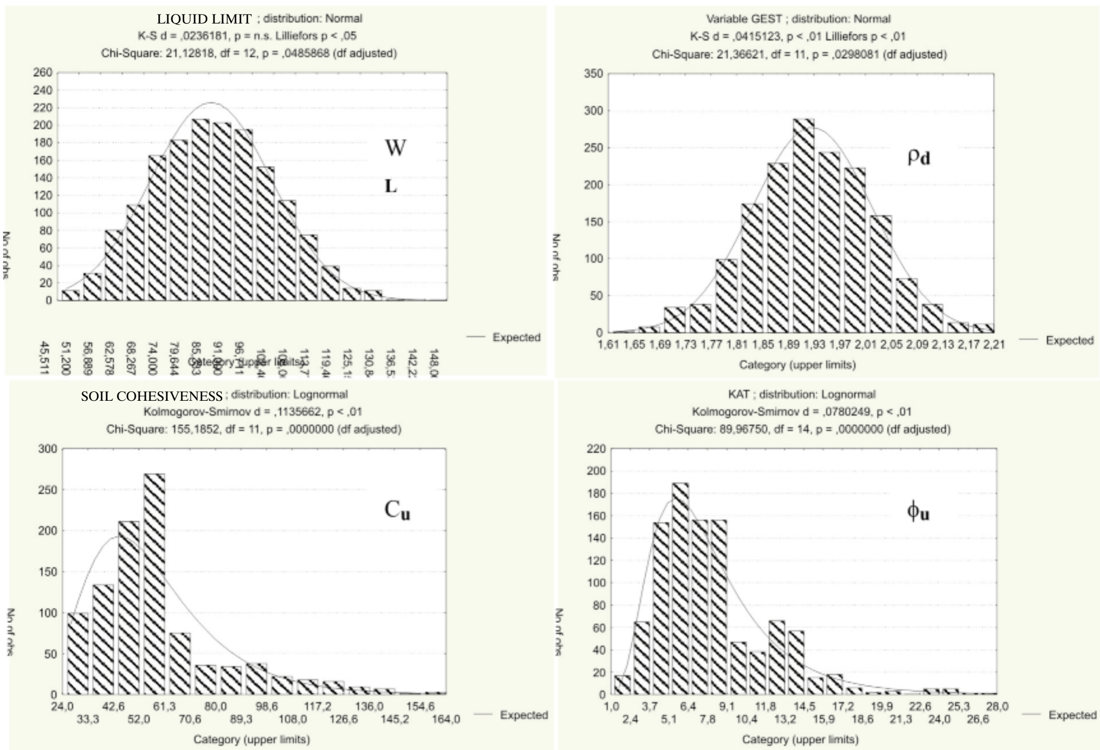

Figure 19.
Distributions of numerical values of some selected geotechnical parameters of clays with theoretical distribution curves attributed to them

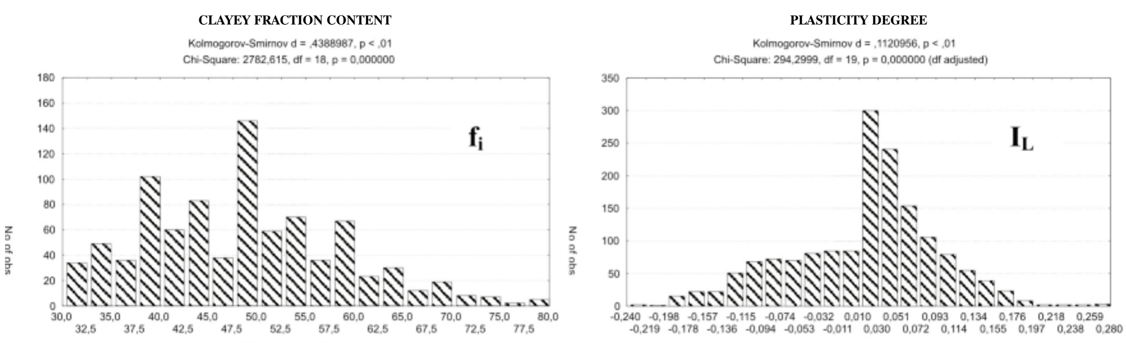

Figure 20.
Distributions of numerous values of a clayey fraction content f_i and plasticity degree I_L

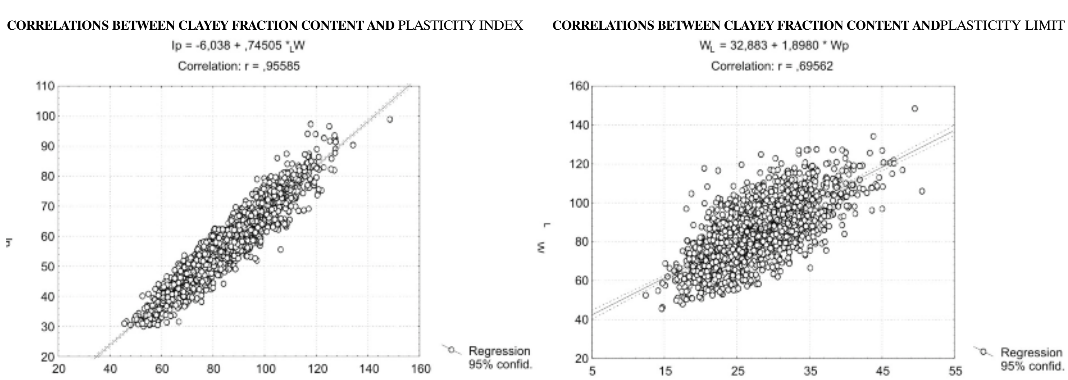

Figure 21.
Correlations between some "material" parameters.
On the left side – correlation between w_L and I_P, on the right – correlation between w_L and w_p

Table 11.
Correlation matrix for the examined geotechnical parameters

	z	**f_i**	**w_n**	**ρ_d**	**w_L**	**w_p**	**I_p**	**I_L**	**c**	**ϕ**
z	1.00	0.01	-0.15	0.16	0.00	0.01	-0.00	-0.23	0.27	0.16
f_i	0.01	1.00	0.47	-0.41	**0.64***	0.43	**0.61**	0.08	-0.12	-0.08
w_n	-0.15	0.47	1.00	**-0.75**	**0.67**	**0.68**	0.56	0.55	-0.23	-0.27
ρ_d	0.16	-0.41	**-0.75**	1.00	-0.55	-0.49	-0.48	-0.42	0.26	0.29
w_L	0.00	**0.64**	**0.67**	-0.55	1.00	**0.70**	**0.96**	0.06	-0.17	-0.20
w_p	0.01	0.43	**0.68**	-0.49	**0.70**	1.00	0.45	-0.22	-0.13	-0.08
I_p	-0.00	**0.61**	0.56	-0.48	**0.96**	0.45	1.00	0.16	-0.16	-0.21
I_L	-0.23	0.08	0.55	-0.42	0.06	-0.22	0.16	1.00	-0.18	-0.27
c_u	0.27	-0.12	-0.23	0.26	-0.17	-0.13	-0.16	-0.18	1.00	0.35
ϕ_u	0.16	-0.08	-0.27	0.29	-0.20	-0.08	-0.21	-0.27	0.35	1.00

usually of a linear nature (Fig. 21).

A significant result in the analysed case is **very low correlation coefficients between the plasticity degree – I_L and strength parameters** that are treated in Polish standards as the leading geotechnical parameter. **The analysis results show that in case of the Poznań clays, the correlations recommended by the standard must be treated very carefully.**

To summarise, in case of expansive clays, one can hardly talk about any certain and reliable geotechnical relationship that is safe in the respect of foundation design.

The presented results of the variability survey of the Poznań series clays allow formulation of the following general conclusions:

- Mio-Pliocene clays are characterised by a local variability of physical and mechanical properties as depending on the region and site of the sample collection and the collection depth as well as the high value of expansive indices; this is a phenomenon that is typical for genetically similar clays in the region of Poland,
- the high variability and differentiation of strength parameters (c and ϕ) as well as of the natural humidity and volumetric density suggest a significant relationship with its geological history, whereas in the next-to-surface zone, i.e., up to 3.5 m below the ground level, an impact of post-syngenetic factors (e.g., freezing, weathering, trees) is noticeable,
- the least favourable physical and mechanical properties characterise zone I, next-to-surface zone of the Poznań series that occurs from 0.0 to 3.50 m below the ground level, where a decrease in average cohesiveness and inner friction angle values were found as well as a high variability of natural humidity in relation to the zones situated underneath. This is reflected in numerous cases of building failures recorded [8, 14, 43],
- the consistency of the clay occurring in the deposit, usually being half-cohesive or, at the outmost, a rigid-flexible condition, $I_{Lmax} \leq 0,19$, reveals the highest variability and should not be acknowledged as a leading geotechnical parameter for determining other parameters from correlation dependencies since the variation coefficient amounts from $v_{IL} = 280\%$ to over 1,700%, and it does not show any statistically significant correlations with other clay parameters,
- relative dispersions of strength parameters are at a level of $v_x = 40\text{-}56\%$ and do not reveal any significant correlations with other geotechnical parameters,
- the very low value of correlation coefficients between the plasticity degree - I_L, treated in the design practice as a leading geotechnical parameter, and the strength parameters suggest that as regards the Poznań clays, the known correlation relationships must be treated very carefully.

Therefore, it should be assumed now that in case of a base formed of the Poznań clays, one can hardly talk about any certain and reliable geotechnical relationship that is essential in that respect for a safe foundation design.

2.5.6. The strength of clays with natural impairment surfaces

As a result of a detailed analysis of the impairment surfaces' impact, strength parameters were determined for the silty clay originating from stratum no. 11, see: Table 2 – homogenous, not revealing macroscopically any visible impairment zones. Clay samples were sheared in the three-axial compression appara-

Table 12.
Strength testing results for exemplary expansive clay

Shear strength testing method	ϕ [°]	c [kPa]
Triaxial compression test – AT, method CU effective stress – post glacial genetic impairment surface	8.08	23.7
Triaxial compression test – AT, method CD, effective stress	12.1	30.0
Triaxial compression test – AT, method CU	5.4±2.7	60.3±10.9
Shear strength (box) – AB	12.1±3.5	37.4±6.5

tus and in the AB direct shearing apparatus. The results are presented in Table 12.

In reality, natural samples of clay without genetic impairment surfaces are rare. In the clay massif, numerous spatial zones of natural impairment occur.

They cause, among other things, the breaking up of NNS samples into pieces prepared for testing. Impairment surfaces in dried clays with very high expansive parameters are the easiest to read. During the soil drying, there occurs the phenomenon of a very distinct shrinkage and a related volume decrease Δv_{max} = 33%. In the course of the process, normal stresses occur in the soil in relation to the existing, inner anisotropy series. They result in shrinkage cracks along the zones of the weakest contacts, first coagulation and then phasic ones, between clay particles in the existing natural impairment surface.

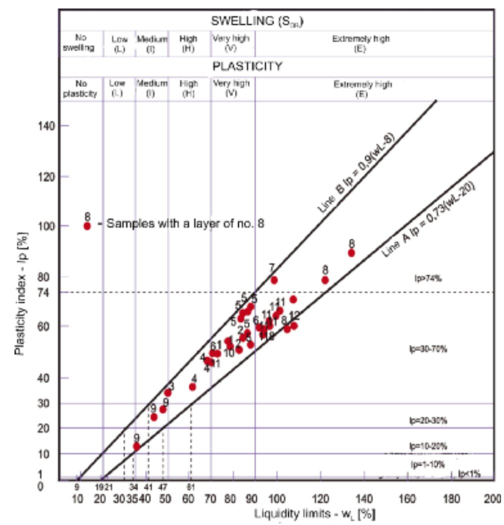

Figure 22.
Expansive clays of the Poznań series on the Casagrande's classification diagram as modified by Grabowska-Olszewska [9]

2.5.7. Classification of expansive clays

In the Polish soils expansiveness classification worked out by Niedzielski [32], a so-called contractibility range ($w_L - w_s$) (%) was introduced to characterise the shrinkage. Four expansiveness stages were separated on the basis of the range:

- very high ($w_L - w_s$) > 50 %,
- high 35 < ($w_L - w_s$) < 50,
- medium 20 < ($w_L - w_s$) < 35,
- low ($w_L - w_s$) < 20.

Expansive clays in Northern Poland can be classified as highly expansive due to the contractibility range ($w_L - w_s$) = 82,1% > 50%.

Relatively high values of liquid and plasticity limits are usually typical for the Poznań series. On the basis of a nomogram of the cohesive soils classification, Grabowska-Olszewska [9], most of the Poznań series clays should be classified as **very cohesive soils with a very high plasticity and a very high and extremely high swelling** (Fig. 22).

When analyzing numerical values of expansive parameters of the Poznań series tertiary clays, one should describe them as **very cohesive soils with very high and extremely high plasticity and a very high and extremely high swelling as well as a very high expansiveness degree, Niedzielski** [32].

The very high expansiveness degree suggests the necessity of a careful prognostication of dislocations in case of buildings founded on the Poznań series clays, [4, 36, 37].

3. CONCLUSION

Problems related to the studying, evaluation and practical aspects of expansive clays are very extensive and complicated and detailed geotechnical issues are considered in both world and Polish literature.

By necessity, in the paper presented, only selected geotechnical problems from the area of Poland have been discussed as they differ from those in hot or monsoonal climate countries.

The above presented material, concerning selected properties of expansive clays from the western basin region of the Poznań series, has been addressed in particular to design engineers.

The leading purpose of the paper is to present to practitioners some selected results of the studies on the nature of these soils, generally considered to be good from a civil engineering point of view but, at the same time, dangerous for those who ignore their genetically shaped geotechnical properties.

This paper has been prepared on the basis of varied publications and archive materials from the Poznań and Warsaw centres as well as own research conducted by the Department of Geotechnics of the Faculty of Civil and Environmental Engineering of the University of Technology and Life Sciences in Bydgoszcz.

Selected basic literature items the paper has been based on are presented below. Further details and more expanded contents will be presented in the author's monograph to be published in the end of 2008.

REFERENCES

[1] *Biddle G.*; Tree root damage to buildings. Proc. of Conf.: Expansive Clay Soils and Vegetative Influence on Shallow Foundations, Houston, United States, 2001, pp. 24-43.

[2] *Chen F.H.*; Foundations on Expansive Soils. Dev. In Geot. Eng. Elsevier, Amsterdam, 1988.

[3] *Choma-Moryl K.*; Badania wybranych gruntów spoistych z terenu Dolnego Śląska jako uszczelnień składowisk odpadów komunalnych (Evaluation of chosen cohesive clays from Lower Silesia as mineral lines for municipal landfills), Acta Universitatis Wratislaviensis, 2004, Wyd. Uniwersytetu Wrocławskiego, Hydrogeologia. (In Polish)

[4] *Danilov A.A.*; Grafik dla rozdelenia gruntov na obuhnye, prosadochnye i nabukhajushhie. Osn. Fund. i Mekh. Gruntov, 5, 1964, pp. 26-26.

[5] *Dyjor S.*; Rozwój sedymentacji i przebieg przeobrażeń osadów w basenie serii poznańskiej w Polsce (Evolution of sedimentation, and process of alternations of sediments in the Poznań suite In Poland). Acta Universitatls Wratislaviensis, 1992, Prace Geologiczno-Mineralogiczne XXVI, s. 3-18. (In Polish)

[6] *Fortunat W.*; Charakterystyczne cechy trzeciorzędowych iłów Warszawy, Bydgoszczy i Tarnobrzega. Biul. IG., 163, 1960, Warszawa. (In Polish)

[7] *Fortunat W.*; Właściwości fizyczne i zagadnienia klasyfikacji iłów, Biul. Inst. Geologicznego 163, 1960 s. 81-119. (In Polish).

[8] *Gorączko A., Kumor Ł.A.*; Damage diagnosis of buildings founded on expansive soils. Geotechnics Conference of Young Sciences, Budapest 2004.

[9] *Grabowska-Olszewska B.* (red).; Geologia stosowana – właściwości gruntów nienasyconych, Wyd. Naukowe PWN Warszawa 1998, s. 113-150. (In Polish)

[10] *Jeż J.*; Przyrodnicze aspekty bezpiecznego budownictwa, Wydawnictwo Politechniki Poznańskiej nr 1818, 1998. (In Polish)

[11] *Jeż J.*; Ocena właściwości geotechnicznych podłoża gruntowego na podstawie szaty roślinnej, Roczniki Politechniki Poznańskiej, Rozprawy nr 218, 1989. (In Polish)

[12] *Kumor M.K.*; Wytrzymałość na ścinanie cyklicznie zamrażanych i odmrażanych iłów (Zeszyty Naukowe ATR nr 164 – Budownictwo (26, 1988). s. 33-64. (In Polish)

[13] *Kumor M.K.*; Zmiana mikrostruktury iłów monomineralnych i iłu plioceńskiego pod wpływem cyklicznego przemrażania i odmrażania (The change of microstructure monomineral clays and pliocene clay due to freezing and thawing processes). Rozprawy nr 34, 1989, ATR Bydgoszcz s. 139. (In Polish)

[14] *Kumor M.K.*; Ocena stanu awarii budynków posadowionych w iłach plioceńskich na terenie Bielaw w Bydgoszczy. Przegląd Budowlany 11, 1989. (In Polish)

[15] *Kumor M.K.*; Typical geotechnical parameters of the Poznań suite of the Bydgoszcz area) [in:] Geologiczno-inżynierskie problemy serii poznańskiej, Acta Universitatis Wratislaviensis, No 1354, Prace Geologiczno-Mineralogiczne XXVI Wrocław, 1992, pp. 67-90. (In Polish).

[16] *Kumor M.K.*; Geotechniczna charakterystyka iłów trzeciorzędowych serii poznańskiej podłoża budowlanego Bydgoszczy. Materiały seminarium pt. „Iły poznańskie – praktyczne aspekty budownictwa na gruntach ekspansywnych". Bydgoszcz, 1994, s. 1-18. (In Polish)

[17] *Kumor M.K.*; Geotechniczna ocena posadowienia na palach podpór mostu przez Wartę w Poznaniu w iłach ekspansywnych, materiały niepublikowane Katedra Geotechniki, Bydgoszcz – Politechnika Poznań, 2001. s. 54. (In Polish)

[18] *Kumor M.K.*; Reperowe właściwości geotechniczne iłów ekspansywnych z podłoża budowlanego Bydgoszczy, XI Krajowa Konferencja Mechaniki Gruntów i Fundamentowania, Szczyrk-Gliwice 2003. (In Polish)

[19] *Kumor M.K.*; Wybrane problemy geotechniczne gruntów ekspansywnych (Some geotechnical problems of expansive clays), XX Ogólnopolska Konferencja Warsztat Pracy Projektanta Konstrukcji, Wisła-Ustroń 1-4 marca 2005. (In Polish)

[20] *Kumor M.K.*; Investigation of shrinkage-swelling of clays as the potential tool to predict deformation of expansive subsoil. XIV Krajowa Konferencja Mechaniki Gruntów i Inżynierii Geotechnicznej, (in Polish) Białystok, 2006, Vol. 1, pp. 234-242

[21] *Kumor M.K.*; The shrinkage and swelling of Northern Poland's expansive clays. I Kongres Geologiczny, Kraków 26-29.06. 2008. (in Polish)

[22] *Kumor M.K.*, Andrzejewski W.; Geologiczno-inżynierska charakterystyka iłów serii poznańskiej z Bydgoszczy na przykładzie reperowej odkrywki w Fordonie. Mat. Konf.: Aktualne Problemy Geologiczno-Inżynierskich Badań Podłoża Budowlanego i Zagospodarowania Przestrzennego Terenu, Warszawa, 1999, s. 83-93. (in Polish)

[23] *Kumor M.K., Gadomski J.*; Wybrane problemy identyfikacji przemieszczeń fundamentów na podłożu ekspansywnym, VII Konferencja Rzeczoznawstwa Budowlanego ITB, Cedzyna k. Kielc 2004. (In Polish)

[24] *Kumor M.K., Gadomska M., Gadomski J.*; The monitoring of the structure vertical displacement founded on expansive ground, Technical Sciencec, supplement 2, UWM Olsztyn, 2005, pp. 77-86.

[25] *Kumor M.K., Gorączko A.*; Zmiany wilgotności naturalnej iłów ekspansywnych po usunięciu grupy drzew na podstawie obserwacji poligonowych. Zeszyty Naukowe ATR nr 239, 2001, Budownictwo i Inżynieria Środowiska (33). (In Polish)

[26] *Kumor M.K., Kumor Ł.A.*; Opinia geotechniczna o przyczynach awarii budynku szpitala uniwersyteckiego w Bydgoszczy. Technical Report, UTP Bydgoszcz, 2003, s. 47. (In Polish)

[27] *Kumor M.K., Kumor Ł.A.*; The shrinkage and swelling of Northern Poland's expansive clays. International Geotechnical Conference "Development of Urban Areas and Geotechnical Engineering" Saint Petersburg, 16-19 June 2008.

[28] *Kumor M. K., Wojciechowski E.*; Właściwości geotechniczne strefy przypowierzchniowej iłów plioceńskich w Bydgoszczy. Wyd. Uczelniane ATR w Bydgoszczy, Budownictwo 21, 1986, s. 59-65. (In Polish)

[29] *Madej J., Najder J., Werno M.*; Awarie budynków mieszkalnych w dzielnicy Bielawki w Bydgoszczy. Inżynieria i Budownictwo nr 6/1966. Warszawa. (In Polish)

[30] *Meissner K.*; Własności inżyniersko-geologiczne iłów poznańskich rejonu Konina (The geological-engineering properties of Posnanian clays of Konin area), Biuletyn Inst. Geologicznego 231, 1970, s. 114-187. (In Polish)

[31] *Najder J., Werno W.*; The effect of climatic fluctuations on displacement of buildings founded on pliocen clays. Stavebnicky Casopis. 1968, No. 2, s. 83-94

[32] *Niedzielski A.*; Factors Determinig swelling Pressure and Free Swelling of Posnanian and Varved Clays. Rozprawy Akademia Rolnicza zeszyt nr 238, 1993, Poznań.

[33] *Przystański J.*, and all.; Foundation on Expansive Soils, (In Polish) Zeszyt Politechniki Poznańskiej Rozprawy 224, Poznań 1991.

[34] *Przystański J. i zespół*; Wytyczne posadowienia obiektów na gruntach ekspansywnych (Foundation on Expansive Soils), temat nr 16,5/86 w ramach CPB-R nr 6.4 s. 120 + załączniki, 1989. (In Polish)

[35] *Przystański J., Borowczak P., Jeż J., Młynarek Z., Kumor M.K., Niedzielski A., Wojnicki Z., Wojtasik A., Zawalski A.*; Foundation on Expansive Soils, (In Polish) Zeszyt Politechniki Poznańskiej Rozprawy 224, Poznań 1991.

[36] *Roguski W., Kasperska W., Łabędzki L.*; Warunki termiczne i opadowe w Bydgoszczy w latach 1945-1994 na tle lat 1848-1930. (Meteo Report of Bydgoszcz) Wiadomości Instytutu Melioracji i Użytków Zielonych. 1996, Wyd. IMUZ, Falenty, s. 7-20. (In Polish)

[37] *Sorochan E.A.*; Stroitelstvo Sooruzenijj na Nabukhajushhikh Gruntach. Stroizdat, Moskva, 1974.

[38] *Stępkowska E.T.*; Model fizyczny układu woda-ił (The phisical model of water-clay system), VII Krajowa konferencja Mechaniki Gruntów i Fundamentowania, Poznań, 1984, s. 367-373. (In Polish)

[39] *Szyszło D.*; Właściwości fizyczne i mechaniczne frakcji ilastej iłów poznańskich na tle ich litologii. Biuletyn Geologiczny. 1967, t. 9, s. 51-120. (In Polish)

[40] *Thomas H.R., Rees S.W.*; Seasonal ground movement in unsaturated clay: an examination of field behaviour. Geotechnique. 1994. Vol. 44, No. 2, p. 353-358.

[41] *Totoyev Y.Z, Kleeman P.W.*; An infiltration model to predict suction changes in the soil profile. Water Resources Research. 1998, Vol. 34, No. 7, p. 1617-1622.

[42] *Van der Merwe D.H*; The prediction of heave from the plasticity index and percentage clay fraction of soils. Trans. South Africa Inst. Civ. Engrs. 1964, No. 6, p. 103-107.

[43] *Zawalski A, Woziwodzki Z.*; Dyskusja oceny zagrożenia przez drzewostan budynków posadowionych na podłożu ekspansywnym na przykładzie awarii szkół. Zesz. Nauk. Politechniki Poznańskiej, Budownictwo Lądowe, nr 40. Poznań, 1995, s. 353-371. (In Polish)

[44] *Zawalski A., Woziwodzki Z.*; Wpływ drzew na budynki posadowione na gruntach ekspansywnych. [w:] Ekologia a Budownictwo – X Ogólnopolska Interdyscyplinarna Konferencja Naukowo-Techniczna. Bielsko-Biała, 1998, s. 283-292. (In Polish)

[45] *Wiewióra A., Wyrwicki R.*; Minerały ilaste poziomu iłów płomienistych serii poznańskiej (Clay minerals of poznanian tertiary clays) KWART. GEOL. t. 18, nr 3, 1974, s. 615-625. (In Polish)