Original Research

Prediction of Heave from the CLOD Index for Natural and Contaminated Clay Soils from the Mazovia Area

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Abstract

This paper deals with the prediction of free heave in expansive soils from central Poland. Thirty-nine soil samples differing in plasticity were selected for a comparative analysis. The soil types examined – Neogene clays, alluvial soils, and glacial tills – differ in CLOD index (C_w) values, which range from 0.027 to 0.019, with values for undisturbed samples being higher than those for the remoulded ones. The variability of the C_w index correlates best with the sand-to-clay ratio. Studies of soils contaminated with diesel oil (ON) have revealed that the C_w index decreases with growing ON content. Calculations of the potential heave, assuming a 1% moisture change for a 1 m thick soil layer, show the heave to be 18 to 12 mm and 15 to 11 mm for Neogene clays and glacial tills, respectively, depending on the *in situ* void ratio. Petroleum contamination significantly reduces the potential heave of the soil. The present analysis clearly suggests that glacial tills are more susceptible to oil-derived contamination than Neogene clays.

Keywords: soil contamination, cohesive soils, soil shrinkage, heave

Introduction

Evaluating volume changes in expansive soils is a crucial engineering problem. Soil expansiveness is controlled chiefly by regional geological background and post-genetic transformations due to natural factors and human impact. The swelling of highly plastic clays has resulted in severe damage to such lightly loaded structures as houses, warehouses, small industrial buildings, and pavement in several areas of the world [1-3]. Therefore, a proper evaluation of expansivity and determination of potential heave is of key significance in geotechnical design.

Heave prediction can be conducted in ways to imply various degrees of accuracy. Earlier methods predicted heave in terms of very high, high, medium, and low, and they were based on index soil parameters. Some of the most recognized empirical relationships for predicting heave came from liquid limit, plasticity index, clay content, initial water content, and dry density, along with depth of expansive layer and overburden load as summarized by [4-5]. A different approach to estimate heave values are analytical methods that use laboratory-measured specified parameters. They could be classified into two groups: methods based on oedometer tests and methods based on soil suction tests [6].

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Table 1. Basic properties of the studied soils.

Soil no	Soil type	Specific density ρ_s (Mg/m³)	Sand content Sa (%)	Silt content Si (%)	Clay content Cl (%)	Shrinkage limit SL (%)	Plastic limit PL (%)	Liquid limit LL (%)
C1	Neogene clays	2.72	2	18	80	13.5	41.0	96.0
C2		2.69	8	20	72	13.8	35.0	83.0
C3		2.71	0	37	63	12.3	22.5	69.5
C4		2.70	13	57	30	13.8	39.3	69.9
C5		2.70	1	29	70	14.2	31.3	70.1
C6		2.72	0	20	80	16.0	30.3	83.0
C7		2.71	4	31	65	14.0	32.3	99.0
C8		2.71	0	10	90	19.0	43.6	91.7
C9		2.68	4	34	62	12.0	27.6	68.2
C10		2.69	3	36	61	13.0	25.4	64.4
C11		2.72	2	18	80	13.5	41.0	96.0
C12		2.69	8	20	72	13.8	35.0	83.0
C13		2.71	0	37	63	12.3	22.5	69.5
C14		2.72	4	28	68	14.7	41.1	81.0
C15		2.73	5	32	63	12.2	36.9	77.2
C16		2.69	18	51	31	13.9	24.6	48.0
C17		2.67	10	57	33	14.6	24.1	45.2
C18		2.66	2	18	80	11.1	38.3	104.1
C19		2.68	6	31	63	11.6	27.0	76.9
C20		2.66	9	31	60	11.4	26.1	68.0
C21		2.81	1	11	88	9.1	28.6	78.9
C22		2.79	0	17	83	11.3	30.5	69.6
C23		2.80	0	27	73	10.4	29.3	68.1
C24		2.77	3	27	70	5.1	19.6	54.4
C25		2.78	4	29	67	7.2	18.9	52.8
C26		2.66	1	14	85	16.5	33.8	87.0
G1	Glacial tills	2.70	42	37	21	5.8	12.0	20.6
G2		2.69	61	21	18	9.6	13.7	19.3
G3		2.68	60	16	24	7.0	14.3	25.8
G4		2.70	56	17	27	9.3	12.4	23.6
G5		2.70	52	23	25	9.7	12.8	24.0
G6		2.71	59	17	24	7.8	13.0	23.3
G7		2.69	61	13	24	8.1	13.5	23.5
G8		2.66	47	23	29	7.5	14.1	36.6
G9		2.66	47	23	29	8.2	14.1	36.6
A1	Alluvial soils	2.68	23	62	15	13.6	23.4	48.0
A2		2.69	18	55	27	13.0	19.0	38.2
A3		2.66	45	46	9	10.0	17.9	26.0
A4		2.68	9	78	13	12.8	18.9	38.8

Considering the significance of soil expansiveness for safe and effective soil management for engineering purposes, the main objective of this study is to predict the heave of natural and contaminated cohesive soils commonly occurring in the Mazovia region from shrinkage tests, according to the method proposed by Miller et al. [7]. Shrinkage limit and the CLOD index (C_w) were determined for Neogene clays, glacial tills, and alluvial soils. The C_w index variability was explored with respect to the selected index parameters of the soils as well as the soil structure (disturbed/undisturbed) and microstructure. Last but not least, the C_w index and potential heave were determined for Neogene clays and glacial tills contaminated with diesel oil. The need to investigate contaminated soils results from the sustainable development of economic-industrial infrastructure and the growing use of liquid fuels, mainly oil-derived, which add to the progressing contamination and even degradation of the subsoil (e.g. [8-13]). A high percentage of the identified petroleum-contaminated sites has been localized around busy transport routes, which can be classified as lightly loaded structures.

This paper is a continuation of a previous study by the present authors [14] focused on prediction of heave based on suction measurements, and contributes to the examinations of contaminated soil properties and estimating expansive soil behaviour for typical clay soils widely occurring in Poland [15-21].

Materials and Methods

Expansive soils, widespread in Poland, are a common building foundation. Samples of natural soils, differing in genesis and lithology and representing a wide range of plasticity, have been selected for the present study: Neogene clays (Mio-Pliocene, samples C1-26), glacial tills (samples G1-9), and alluvial soils (samples A1-4). A total of 39 samples from various parts of the Mazovia area (Warsaw, Mszczonów, and Dobre) were examined. For all samples, the following basic parameters have been determined: grain size distribution, plastic limit, liquid limit (BS1377: Part 2: 1990 [22]), shrinkage limit (according to BS1377: Part 2: 1990 [22] and the CLOD test method), and specific density (a gas pycnometer method, AccuPyc 1330, Micromeritics, USA). The qualitative analysis of soil microstructure was performed using a Scanning Electron Microscope (JSM 6380 LA, Jeol, Japan).The basic soil parameters are summarized in Table 1. According to Casagrande nomogram, tills and alluvial soils have low to medium plasticity. Neogene clays can be classified into soils of medium to extremely high plasticity, thus occurring in the active zone and subjected to changing environmental conditions, they will exhibit volume deformations.

Laboratory tests for determining soil shrinkage have been completed in accordance with BS1377: Part 2: 1990 [22], as well as using the CLOD test method developed by [23]. Both methods are analogous and refer directly to the definition of the shrinkage limit after Casagrande. The difference between them lies only in the way volume is measured.

Volume measurements of soil samples conducted according to BS1377: Part 2: 1990 [22] requirements were made using a mercury apparatus (Wykeham Farrance WF 2/756, UK). However, due to high toxicity of mercury and restrictive laboratory safety rules, some of the tests were carried out using a GeoPyc 1360 pycnometer (Micrometrics, USA). In this apparatus a soil sample is analysed in a DryFlo® quasi-fluid displacement medium composed of microspheres with a high degree of flowability that do not wet the sample or fill its pores. This non-destructive test permits accurate repetitive measurements of the sample during the drying process. [24] proposed a similar method – the bead replacement method based on the use of spherical beads of an inert material of a uniform grain size. The results obtained were in good agreement with those from the conventional mercury displacement method.

The CLOD method is suitable for testing hard fractured soils or irregularly shaped specimens that can be easily obtained from the broken pieces. It consists in covering the sample with liquid resin (DOW Saran F310 resin diluted in methyl ethyl ketone at a powder:solvent ratio of 1:7), which acts like a delicate membrane adjusting to the shape of the sample. The resin protects the natural soil structure and allows volume measurements during slow air-drying. It permits a gradual release of vapour from soil, while in short contact with water it becomes impermeable. Volume is determined by weighing samples in distilled water following Archimedes Law.

The final outcome of the shrinkage measurement is the shrinkage curve, which serves to determine such parameters as shrinkage limit w_s and CLOD index C_w (Fig. 1). The CLOD index, characteristic of each type of soil, is defined by the slope of the void ratio–water content relationship that corresponds to the proportional shrinkage phase.
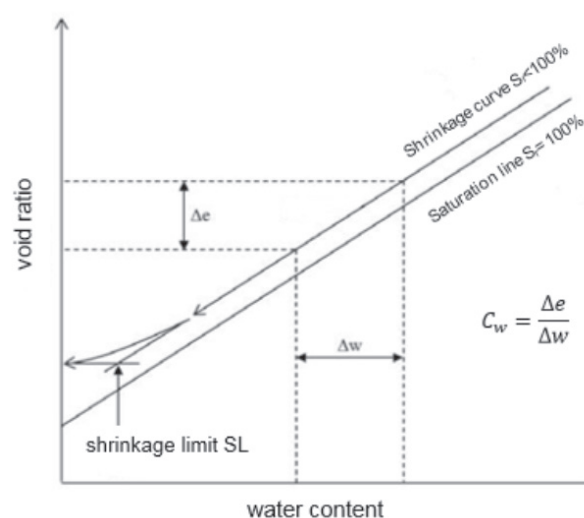

Fig. 1. CLOD test shrinkage curve.

Miller et al. [7] proposed a method for predicting total heave based on CLOD index values. Total heave is the sum of heaves calculated for individual layers according to the equation:

$$\rho = \sum_{i=1}^{n} \frac{(C_w \Delta w)_i}{(1+e_0)_i} z_i$$

where:

ρ is total heave [mm]

C_w is CLOD index [-]

Δw is change of moisture content in the soil layer [%]

z_i is thickness of the soil layer [mm]

e_0 is void ratio [-]

This method, however, does not consider net normal stress. Therefore, it is applicable only for determining free field heave or heave under very light loads such as pavements or floating floor slabs.

In the present study, this method was used to characterize the potential heave of Neogene clays and glacial tills from Poland with respect to the measured shrinkage characteristics of the considered soils. The heave was computed for a 1 m thick soil layer assuming a 1% change of moisture content. The following assumptions were made:

1. C_w – average values were assumed from the measurements of the tested soil samples (see Fig. 4 and Table 2)

2. e_0 – several values of void ratio were assumed to reflect various conditions in the ground, for Neogene clays: $e_0 = 0.50$; 0.75; 1.00; 1.25 and 0.67 which is the measured average *in situ* void ratio; for glacial tills: $e_0 = 0.25$; 0.50; 0.75 and 0.40 – the measured average *in situ* void ratio.

The influence of petroleum contamination on soil shrinkage was analyzed for Neogene clays and glacial tills. The soil samples passing through a 10-mesh sieve were oven-dried at 105°C and mixed with diesel oil (ON) in the amount of 0%, 4%, 8%, 12%, and 16% by dry weight of the soil. They were kept in closed containers for three months to allow ageing and possible reactions between the pollutant and the soil. Then the equilibrated samples were mixed with distilled water in the amount corresponding to the plastic limit of the soil. The cylindrical specimens were prepared and the shrinkage tested according to BS1377: Part 2: 1990 procedure [22]. The void ratio was calculated with respect to the specific density of the contaminated soils. In the case of glacial tills, it was impossible to complete the measurements for samples containing 12% and 16% of diesel oil. Due to reduction of cohesiveness, the samples behaved like non-cohesive fine grained soils and disintegrated in the course of taking measurements.

Results and Discussion

A summary statistics of the CLOD index (C_w) results for the remoulded soil samples are presented in Table 2.

The study showed that C_w for Neogene clays is within a narrow range of values $C_w = 0.024 - 0.029$ (mean 0.027). These results are in agreement with [20], who reported that the average CLOD index for Neogene clays from the Bydgoszcz area is 0.027. Glacial tills exhibited a wider C_w variation ($C_w = 0.012 - 0.022$), the mean being 0.019. Alluvial soils, regardless of the compositional diversity within the tested sample set (see Table 1), showed a narrow range of C_w values ($C_w = 0.023 - 0.025$; mean 0.024) similar to Neogene clays.

As is clear from previous studies, the soil shrinkage characteristics are controlled by soil plasticity and fabric (e.g. [18, 25-27]). In this study, the relationship between CLOD index and plasticity index, clay content, and the sand-to-clay ratio was analyzed. For selected soil samples, soil shrinkage values of undisturbed and remoulded soils were compared and discussed with respect to the soil microstructure.

Analysis of the data given in Figs. 2a-c indicates a strong and very strong correlation between C_w and the considered index parameters. In all cases, the polynomial function best fits the given set of data. Higher values of correlation coefficients were obtained for undisturbed samples than for the remoulded ones. The sand-to-clay ratio best explains the C_w variation (70% and 80% for the remoulded and undisturbed samples, respectively). It is noteworthy that on each plot the best fit line for undisturbed samples is below that for the remoulded soils, which simply points to the lower values of C_w noted in undisturbed soils. A deeper insight into this effect is given in Fig. 3. Double analysis of soil shrinkage for disturbed and undisturbed soil samples was carried out for five samples of Neogene clays (C1 to C5), two samples of glacial tills (T1, T2), and four samples of alluvial soil (A1 to A4). It has been found that for all soil types, C_w achieves higher values for remoulded samples than for the undisturbed ones. In the case of Neogene clays the average difference is of 12%, while for alluvial soils it ranges from 33% (A1) to 76% (A3) (mean 53%). The possible reason of such discrepancies between the behaviour of Neogene clays and alluvial soils might be accounted for by the natural soil microstructure. The scanning electron microscope (SEM) analysis of the tested Neogene clays showed that they have a matrix-turbulent microstructure

Table 2. Summary statistics of CLOD index for the remoulded samples of the tested soils.

	Neogene clays	Glacial tills	Alluvial soils
Number of samples	26	9	4
Mean	0.027	0.019	0.024
Min	0.024	0.012	0.023
Max	0.029	0.022	0.025
Median	0.027	0.020	0.024
Standard deviation	0.00164	0.0029	-

a)

$y = -1E-06x^2 + 0,0002x + 0,0174$
$R^2 = 0,3972$

$y = -4E-06x^2 + 0,0006x + 0,0027$
$R^2 = 0,8292$

■ undisturbed ● remoulded

CLOD index C_w [-]

Clay content [%]

b)

$y = 0,0011x^2 - 0,0061x + 0,0275$
$R^2 = 0,7006$

■ undisturbed ● remoulded

$y = 0,0012x^2 - 0,009x + 0,0232$
$R^2 = 0,7989$

CLOD index C_w [-]

Sand to clay ratio

c)

$y = -3E-06x^2 + 0,0004x + 0,0163$
$R^2 = 0,6121$

$y = -9E-06x^2 + 0,0009x + 0,0013$
$R^2 = 0,821$

■ undisturbed ● remoulded

CLOD index C_w [-]

Plasticity index PI [-]

Fig. 2. Variation of CLOD index C_w with: a) clay content, b) sand to clay ratio, and c) plasticity index PI.

that is characteristic of this soil type [28], while the alluvial soils showed a matrix-skeletal microstructure. The micrographs of the undisturbed samples of the Neogene clays and alluvial solids are presented in Figs. 4a-b. The transformation of natural microstructure of alluvial soils in remoulded samples and the disintegration of natural bonds between the structural elements promotes different patterns of solids arrangement in the process of shrinkage. A disturbed fabric with a high content of silt

and sand (skeletal microstructure) strongly promotes denser packing of solids, which in turn leads to a steeper shrinkage curve and higher CLOD index values. These findings must be considered preliminary due to the small number of samples, and require further investigation.

The results of shrinkage examinations of soils contaminated with diesel oil (ON) are presented in Fig. 5. Although they generally show a reduction of CLOD index values with the increasing ON content, for Neogene clay the tendency is non-uniform (C_w = 0.028; 0.024; 0.026 for 0, 8, and 16% ON, respectively). This reduction is faster for glacial till (C_w = 0.021; 0.012 for 0 and 8% ON, respectively), which, in addition to the loss of cohesion in more contaminated samples, proves a higher susceptibility of glacial tills to petroleum contamination.

The free field heave values were calculated for Neogene clays and glacial tills for both uncontaminated (Fig. 6) and contaminated soils (Fig. 7). Considering the assumptions made, it was found that the heave of Neogene clay is about 18 mm to 12 mm, depending on the initial void ratio (e = 0.5 to 1.25, respectively). For glacial tills the predicted heave ranges from about 15 mm to 11 mm (e = 0.25 to 0.75, respectively). For a given soil, the increase of void ratio corresponds to increasing moisture content, which in turn results in a decrease of potential heave of the soil. It was also found that petroleum contamination significantly
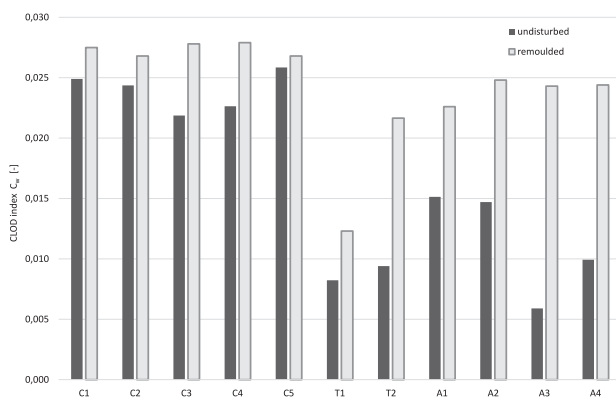
CLOD index C_w [-]

■ undisturbed
□ remoulded

C1 C2 C3 C4 C5 T1 T2 A1 A2 A3 A4

Fig. 3. Comparison of CLOD index C_w for undisturbed and remoulded specimens.
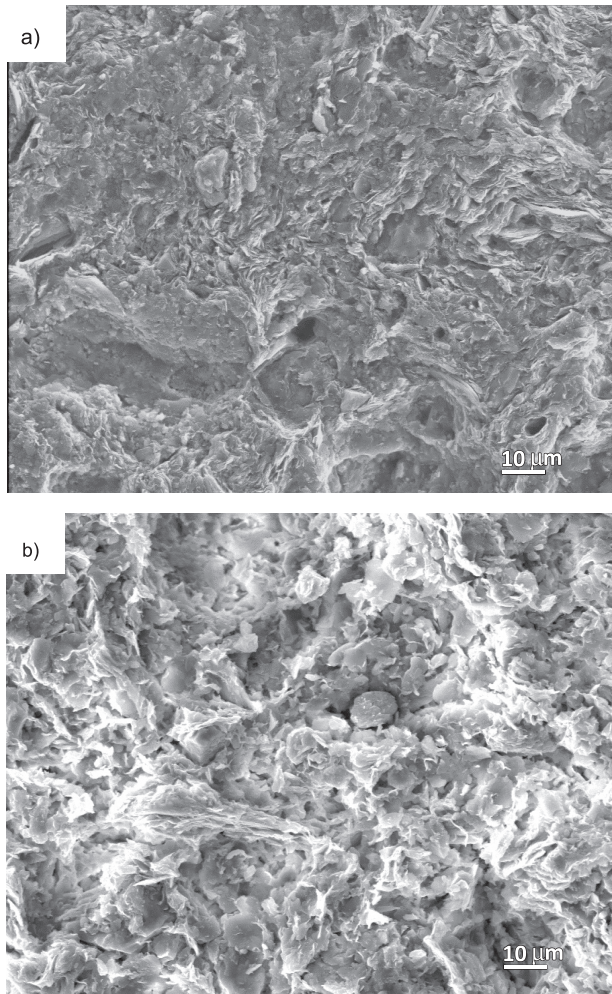
a)

b)

Fig. 4. SEM micrographs of: a) Neogene clays and b) alluvial soils (magnification 800x).

reduces the potential heave of the soil (Figs. 7a-b). The variability of results is parallel to the C_w changes. For both Neogene clays and glacial tills, the lowest values of heave were obtained for 8% ON samples (ρ = 16-11 mm and ρ = 11-7 mm, respectively). Preparation of test samples
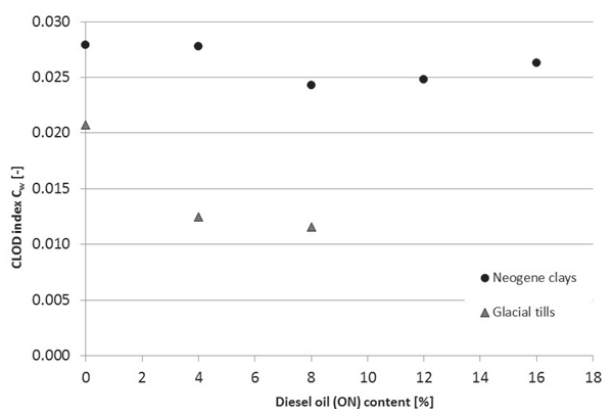

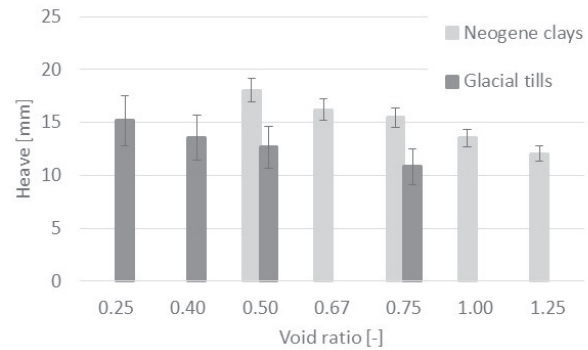Fig. 5. Influence of diesel oil (ON) on CLOD index C_w of Neogene clays and glacial tills.

Fig. 6. Prediction of potential heave of Neogene clays and glacial tills.

by mixing diesel oil with dry soils allows the results to simulate the effect of long-term contamination, where the pollutant gets into immediate contact with the soil particles. The assembled data provide a basis for heave prediction for any assumed change of soil moisture content and thickness of the soil layer by simple multiplying the values presented herein according to the equation given in [7]. Due to a high homogeneity of the CLOD index of Neogene clays, the outcome of this study seems especially valuable for predicting heave for this type of soil. The method here described is another approach (compare [14]) to estimating expansive soil behaviour of typical clay soils widely occurring in Poland, differing in genesis and compositional characteristic. According to some
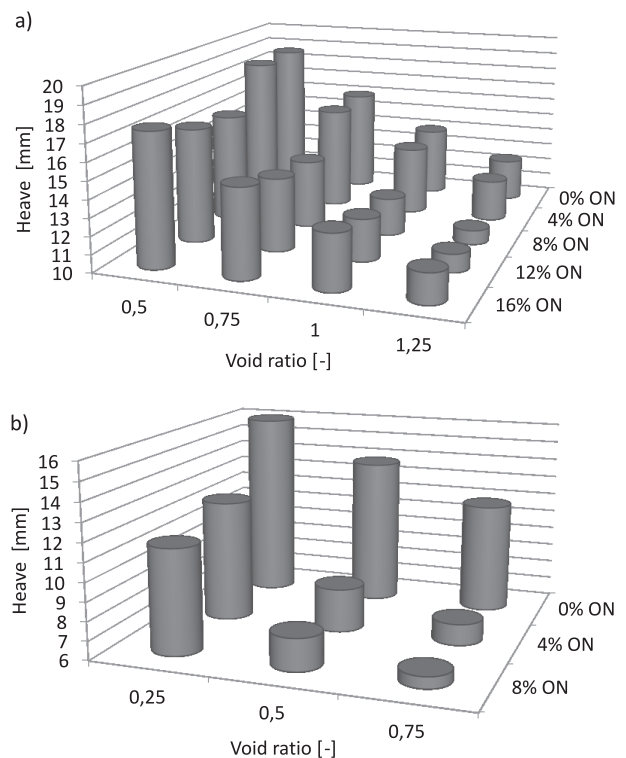

a)

b)

Fig. 7. Prediction of potential heave of soils contaminated with diesel oil (ON): a) Neogene clays and b) glacial tills.

authors, soil shrinkage characteristics are not suitable for predicting soil behaviour related to swelling. [25] showed that shrinkage is a function of grain size distribution and fabric, irrespective of the plasticity of the soil. Based on field and laboratory investigations of Neogene clays from the Bydgoszcz area, [20] reported that C_w depends on the range of changes in the soil moisture content, thus it cannot be used to estimate soil heave.

Conclusions

An experimental study was carried out to determine the shrinkage characteristics and the potential heave of natural and diesel oil-contaminated cohesive soils commonly occurring in the Mazovia region. The results showed that the average values of the CLOD index C_w for Neogene clays, glacial tills, and alluvial soils are: 0.027 ± 0.0016, 0.019 ± 0.0029, and 0.024, respectively. The correlation of C_w and selected index parameters showed that the sand-to-clay ratio best explains C_w variability.

It was also revealed that C_w achieves higher values for remoulded samples than for the undisturbed ones. The lowest difference has been found for Neogene clays and the highest for alluvial soils, which could be attributed to the difference in the natural microstructure between the considered soil types. The free field heave has been calculated according to the method given in [7], assuming 1 m thick soil layer and 1% change of soil moisture content, which provides a basis for heave prediction for any assumed change of environmental variables. It has been predicted that the heave of Neogene clay is about 18-12 mm and for $e_0 = 0.5$-1.25, whereas for glacial tills it is 15-11 mm for $e_0 = 0.25$ to 0.75.

The examinations of diesel oil-contaminated Neogene clays and glacial tills have revealed the reduction of C_w and the potential heave due to contamination. The lowest values have been noted for 8% ON samples, for which the heave ranges 16-11 mm for clays and 11-7 mm for tills, depending on the initial void ratio. The higher rate of changes in C_w and heave values in function of soil contamination was obtained for glacial tills than Neogene clays, which suggests higher susceptibility of glacial tills to petroleum contamination.

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