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Technical Note

Compressibility of Organic Soils Polluted with Diesel Oil

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Abstract

The paper presents results of experimental study on the compressibility of soils contaminated by diesel oil from Żuławy region. The investigation results show that compressibility of the soils increases with increasing diesel oil content. A significant increasing in compression was found when diesel oil content in soil exceeded 3%. The compression index C_c changes inversely to changes in the dielectrical constant of a porous medium. The index C_c for contaminated organic soil can be estimated from the established compression index of "clean" soil and dielectric constant of the porous medium of polluted soil.

Key words: organic soils, diesel oil, compression index, dielectric constant

1. Introduction

Young Holocene organic formations in a form of strongly transformed loamy alluvia usually form the substratum in estuaries of Poland's main rivers. In many cases these agricultural deltaic areas hosted machinery repair workshops and fuel bases. Local anthropogenic changes in the soil-water environment are the remainders of these activities. They include dangerous soil pollution caused chiefly by uncontrolled leakage of fuels and petroleum products, mainly of diesel oil. For many reasons these areas are now attractive for investors and will undergo intensive transformation due to planned building and engineering constructions.

As known, the presence of petroleum products in any dispersed medium, particularly in unconsolidated young organic soils, causes extensive changes in geotechnical deformation characteristics including those which determine settlement of substratum and deformation of the soil-construction system (Izdebska-Mucha 2005, Zadroga, Olańczuk-Neyman 2001).

Knowledge of numerical parameters of substratum compressibility, and the range of their changes and deformation characteristics, are especially important when designing and in safety assessment of exploitation in anthropogenically altered geotechnical conditions.

This paper presents results of empirical studies on selected parameters of compressibility in typical young, organic, cohesive soils from the delta of Vistula Żuławy, variously polluted with diesel oil.

2. Study Material and Analyses of Compressibility

Organic soils from Elbląg Żuławy, varying in organic matter content were taken for analyses of compressibility parameters. Samples of natural soils were collected from grounds in Markusy, Raczki Elbląskie and Dłużyna, i.e. in those areas which are most affected by negative human impact.

Compressibility was studied in soil samples appropriately prepared for analysis. Samples were collected with a special cylindrical sampler from the whole profile of an average thickness of 2.0 m, i.e. from the possible pollution zone (Polish Standard PN/B-04452 2002). The top of the layer was 0.5 m beneath ground level, directly under humus. Soil samples were homogenised, thoroughly mixed, and closed in tight polyethylene bags to secure even moisture. Samples prepared in this way were treated with diesel oil (ON). The properties of the applied oil were typical of fuel for diesel engines:

- density, $\rho = 0.83$ Mg·m^{-3},
- kinematic viscosity, $\mu = 1.4 - 4.7$ mm^2·s^{-1},
- solubility in water, $w_s = 3$ mg·dm^{-3},
- dielectric constant, $\varepsilon = 2.1$.

Soils for analysis were saturated with oil in various proportions. Oil volume per unit soil mass was ON/G = 0.00, 0.03, 0.06 and 0.12. Prepared samples were placed in tight vessels and kept for at least a week at a temperature of 20°C to obtain highly homogenous study material of even distribution and saturation of soil pores with oil. State parameters, i.e. liquid limit of natural soils and those polluted with diesel oil, were determined before analysing compressibility. Liquid limit was determined with the cone method according to PN-88/B-04481. Organic matter content was determined with the thermo-gravimetric method based on relative loss of soil mass in the range of temperatures between 105° and 440°C according to the British standard BS 1377; Part 3; 1990; p. 4.

Basic physical parameters of analysed soils and the content of organic matter are given in Table 1. According to the division of Polish organic soils recommended in standards (PN-B-02481 1998, PN-86/B-02480 1986), the studied organic soils are classified as loamy alluvia, Nmg (or according to (PN-EN ISO 14688-1 2006, PN-EN ISO 14688-2 2006)). Alluvia differ mainly in plasticity index and in the content of sandy and clay fraction. They are typical organic soils of Elbląg Żuławy (Olchawa 2003).

Compressibility was analysed in laboratory oedometers of EL-1 type in natural “clean” samples and in soils polluted with diesel oil. Initial moisture of samples

Table 1. Basic physical parameters of the studied organic soils

Sampling site	Particle density, ρ_s	Liquid limits, w_L	Plastic index, I_P	Content of fraction:			Organic matter content, I_{om}	Soil type according to PN-86/B-02480
				2–0.05	0.05–0.002	< 0.0002		
	$Mg \cdot m^{-3}$	%		mm			%	–
Markusy (M)	2.52	79.7	39.2	50.0	41.9	8.1	4.9	Nmg
Dłużyna (D)	2.50	114.0	74.1	37.8	51.1	11.1	6.4	Nmg
Raczki (R)	2.52	89.4	44.4	33.7	57.1	9.2	5.6	Nmg

was equal to the liquid limit $w_o = w_L$. The degree of saturation ranged from S_r = 0.988 to 1.00. The consolidation pressure ranged from 12.5 to 200 kPa. A load increment ratio of 1.0 was adopted. The ring was smeared with silicone grease to minimise side-friction between the specimen and the ring. Special precautions were taken to minimise evaporation of pore mixture from the top of the cell.

Loading time in every applied pressure was 24 h. The compression index C_c was adopted as a compressibility parameter. Compression index is defined as:

$$C_c = \frac{(e_i - e_{(i+1)})}{\left(\log \sigma'_{c(i+1)} - \log \sigma'_{ci}\right)}, \tag{1}$$

where:
e_i – void ratio at the end of primary consolidation at a given consolidation stress $\sigma_{ci.}$

The duration of the primary consolidation stage t_p was estimated by a logarithm of time fitting method (Whitlow 1990). The longest applied consolidation pressure time did not exceed t_p = 8 h at the stress of σ_n = 200 kPa.

The values of compression index C_c were determined by approximating the line described by the equation $e = -C_c \log \sigma'_c + A$. Coefficients C_c and A were determined by the least squares method (Draper, Smith 1973) based on experimentally obtained pairs: equation $e_p(\sigma_{ci})$ and $\log \sigma_{ci}$. The number of pairs of independent and dependent data varied from 10 to 15 (depending on the number of replications $N_{\min}$ = 3 to 5).

Multiple determination coefficients R^2 of estimated functions ranged from 0.974 to 0.998 (Draper, Smith 1973).

3. Results and Discussion

Liquid limits w_L of analysed loamy alluvia polluted by diesel oil are shown in Fig. 1.

As seen from the analysis of polluted organic soils, the liquid limit values w_L increased with increasing content of diesel oil (Fig. 1). A similar relationship was found in mineral soils by Zadroga and Olańczuk-Neyman (2001). In view

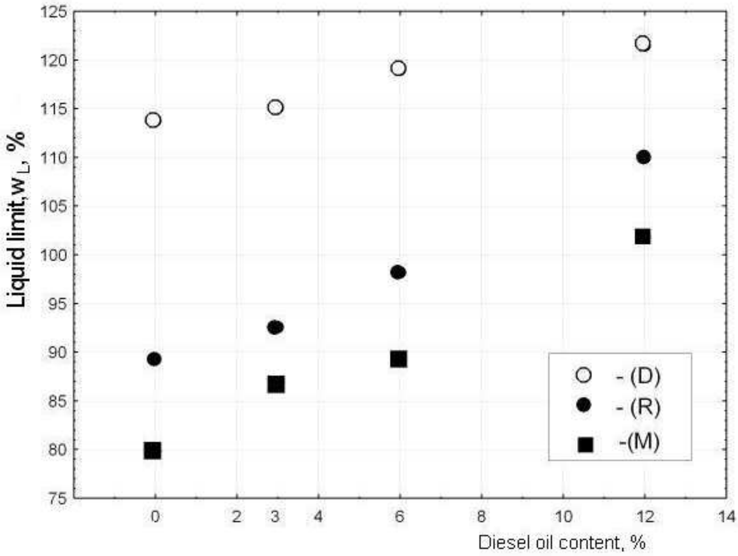

Fig. 1. Liquid limit w_L in relation to the content of diesel oil

of the complex microstructure of very plastic organic soils, these results might seem surprising since the liquid limit of two-phase system soil-diesel oil is always significantly lower than that for a clean soil-water system (Izdebska-Mucha 2005). Increasing w_l value with the increase of the diesel oil content could be associated with the formation of emulsion, interaction between a new porous medium (change of dielectric constant) and mineral skeleton, an increasing effect of smearing the cone's surface or with the content of humic acids.

Compression index, measured in this study, increased with increasing content of diesel oil (Table 2) in every examined soil. Significant increase of C_c was found when ON content in organic soil exceeded 3%. For the content of diesel oil between 6% and 12%, the C_c index in loamy alluvium from Dłużyna increased from 6% to 34% respectively, and for soils from Raczki and Markusy the compression index increased from 2% to 30% and from 3% to 24% respectively.

As seen from experimental data, the increase of diesel oil content, especially above 3%, resulted in a distinct increase in compressibility.

Table 2. The compression indices, C_c, range of applied stress $\Delta\sigma$ (12.5–200 kPa)

Sampling site	Diesel oil content – (%)			
	0	3	6	12
Dłużyna (D)	0.530	0.532	0.562	0.687
Raczki (R)	0.453	0.455	0.462	0.578
Markusy (M)	0.412	0.414	0.425	0.512

Increasing C_c values were probably associated with a decrease in the dielectric constant of a mixture of new dielectrics-water and diesel oil (new porous medium). Fig. 2 presents the relationship between the compression indices and the values of dielectric constants of porous medium present in pores of consolidated soils.

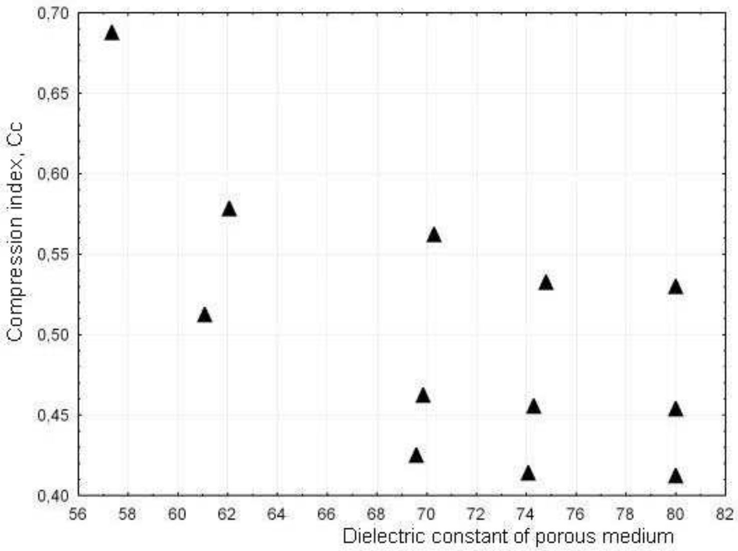

Fig. 2. Compression indices in relation to dielectric constants of the porous medium

In the model two-phase systems pore solution-clay, for the same external load, a half of the distance between particles of clay minerals, d depends on the dielectric constant of the porous medium, ε (Sridharan, Jayadeva 1982). This relationship is expressed as:

$$\frac{d_1}{\sqrt{\varepsilon_1}} = \frac{d_2}{\sqrt{\varepsilon_2}}. \tag{2}$$

It appears from Eq. (2) that decreasing the dielectric constant of the porous medium will reduce the thickness of the diffusion layer and thus decrease the porosity of soil-water system.

Assuming the applicability of Eq. (2) to the analysed example, one may assume that the relationship between the compression index of "clean" soil, C_c, and that of the same soil polluted with diesel oil, $C_{c(ON)}$, can be expressed as:

$$C_{c(ON)} = \frac{C_c \cdot \sqrt{\varepsilon_w}}{\sqrt{\varepsilon_{(ON)}}}, \tag{3}$$

where:

ε_w – dielectric constant of water = 80,

$\varepsilon_{(ON)}$ – dielectric constant of a water/diesel oil mixture.

Together with increasing content of diesel oil in pore solution, the dielectric constant of a new medium will decrease. Its value can be calculated from the equation given by Ansoult et al (1985):

$$\sqrt{\varepsilon} = \sqrt{\varepsilon_1} \cdot V_1 + \sqrt{\varepsilon_2} \cdot V_2 + \ldots \sqrt{\varepsilon_i} \cdot V_i, \tag{4}$$

where:

ε – dielectric constant of a mixture,
ε_i – dielectric constant of the i-th component,
V_i – volume of the i-th component in unit volume of a mixture.

Calculated values of the dielectric constant of the porous medium in the studied soil samples in relation to the content of diesel oil are shown in Table 3.

Table 3. Values of the dielectric constant of porous medium calculated from Eq. (4)

Soil samples	Content of diesel oil ON/G		
	0.03	0.06	0.12
Dłużyna (D)	74.8	70.32	57.4
Raczki (R)	74.3	69.90	62.1
Markusy (M)	74.1	69.60	61.1

Figure 3 presents the relationship between compression indices calculated from Eq. 2 and those obtained in the experiment.

Correlation between the compression indices obtained by different methods is expressed by a linear function of the form: $C_{c(ON)E} = A \cdot C_{c(ON)(cal)} + B$. Parameters A and B estimated by the least squares method (Draper, Smith 1973) are: $A = 1.19$ and $B = -0.08$ at multiple determination coefficient $R^2 = 0.858$, and Fischer-Snedecor's coefficient $F = 60.49 > F_{cr} = 19.4$ (Nowak 2002).

Based on the statistically established relationship $C_{c(ON)E} = 1.19C_{c(ON)(cal)} - 0.08$, it is possible, in practice, to estimate the compressibility coefficient of loamy alluvium polluted with diesel oil using the equation (5):

$$C_{c(ON)} = 1.19 \cdot C_c \cdot \sqrt{\frac{80}{\varepsilon_{(ON)}}} - 0.08. \tag{5}$$

It was assumed in calculations that the oil to water volumetric ratio is constant, i.e. that during the dissipation of mixture pore pressure, the volumetric ratio of both liquids in the displaced mixture is the same as in the soil shortly before the analyses of compressibility. Having in mind different physical properties and different wetting of mineral surfaces by both liquids (Izdebska-Mucha 2005), one

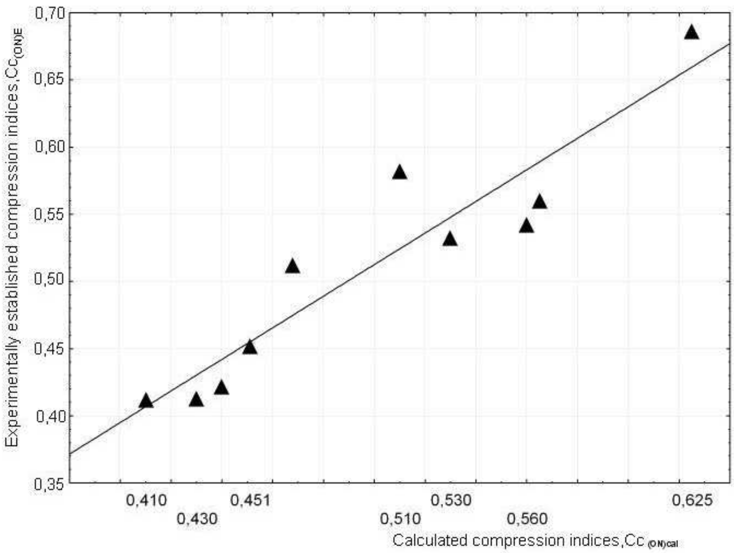

Fig. 3. Experimentally established and calculated according to Eq. (2) compression indices for organic soils polluted with diesel oil

may assume that the volumetric water to oil ratio in displaced pore liquid will increase with increasing consolidation pressure. This means that the result value of dielectric constant of porous medium will be lower than that given in Table 3, and calculated values of the compression indices would be higher than those calculated at the assumption of constant ratio of both liquids.

To fulfil the empirical equation $C_{c(ON)E} = C_{c(ON)cal}$ ($A = 1$; $B = 0$) for soil samples with ON/G = 12%, dielectric constants should be lower than calculated and should equal: (D) $\varepsilon = 47.6$, (R) $\varepsilon = 49$ and (M) $\varepsilon = 51.9$. For such values of $\varepsilon_{(ON)}$ the mean volumetric ratio of oil to water is (D) ON/W = 0.375, (R) ON/W = 0.349, (M) ON/W = 0.302, while before the experiment, the respective ratios were ON/W = 0.158, 0.164 and 0.166.

Estimating statistical correlations between the compression index of organic soils polluted with diesel oil, the compression index of the soil, and the dielectric constant of the porous medium, i.e. $C_{c(ON)} = C_{c(ON)}$ (C_c; $\varepsilon_{(ON)}$) seems promising and certainly needs to be studied further. If confirmed, such relationships would enable estimation of the compressibility of soils polluted by diesel oil or by other petroleum products. Knowledge of the C_c index of "clean" soil and dielectric constant of porous medium $\varepsilon_{(ON)}$ would be sufficient to calculate the compression index $C_{c(ON)}$ of polluted soil.

The dielectric constant of porous media may be calculated from results of laboratory studies on the soil content of petroleum products and moisture. Another way of calculating dielectric constant consists in direct measurement of dielectric constant in a soil/porous medium system (Malicki 1999, Mojid, Cho 2004, Saatretenko 1998) and basic soil parameters (moisture and bulk density) may be easily determined in any soil mechanics laboratory.

4. Conclusions

Obtained results allow for formulating the following conclusions:

1. Compressibility of loamy alluvia increases with increasing content of diesel oil – or other petroleum products (increased compression index).
2. The compression index of organic soils changes inversely to the changes of dielectric constant of a new porous medium i.e. the former increases when the latter decreases.
3. The compression index for soils polluted with diesel oil can be estimated from the established compression index of clean soil and dielectric constant of polluted porous medium calculated with the use of the correlation described by Eq. (5).
4. Further studies on compressibility of organic soils and on pollution with petroleum products in relation to dielectric properties of porous medium should establish close statistical relationships between strain parameters and medium parameters.

References

Ansoult M., De Backer L. W., Declerq M. (1985) Statistical relationship between apparent dielectric constant and water content in porous media, *Soil Science Society of American Journal*, **49**, 47–50.

Draper N. R., Smith H. (1973) *Applied Regression Analysis*, PWN, Warsaw (in Polish).

Izdebska-Mucha D. (2005) Influence of oil pollution on delescted geological-engineering properties of clay soils, *Przegląd Geologiczny*, **53** (9), 766–769 (in Polish).

Malicki A. M. (1999) Methodical Questions of Monitoring of Water Status in Selected Biological Materials, *Acta Agrophysica*, Lublin.

Mojid M. A., Cho H. (2004) Evaluation of the time-domain reflectometry (TDR) – measured composite dielectric constant of root – mixed soils for estimating soil water content and root density, *Journal of Hydrology*, **295**, 263–275.

Nowak R. (2002) *Statistics for Physicist*, Wyd. Naukowe PWN, Warsaw (in Polish).

Olchawa A. (2003) *The Properties of Soils Composites as a Material for Constructing Flood Embankments*, Water-Environmental-Rural Area. Treatises and Monographs, Edition of IMUZ Falenty.

PN-B-02481 (1998) *Geotechnics – Basic terms, symbols and units.*

PN-88/B-04481 (1988) *Building soils. Laboratory tests.*

PN/B-04452 (2002) *Geotechnics – field tests.*

PN-86/B-02480 (1986) *Building soils, Nomenclature, symbols, classification and description of soils.*

PN-EN ISO 14688-1 (2006) *Geotechnical investigation. Testing, identification and classification. Part 1: Identification and description.*

PN-EN ISO 14688-2 (2006) *Geotechnical investigation. Testing, identification and classification. Part 2: Principles for classification.*

Saatretenko T. (1998) Electrical properties of water in clay and silty soils, *Journal of Applied Geophysics*, **40**, 73–88.

Sridharan A., Jayadeva M. S. (1982) Double layer theory and compressibility of clays, *Geotechnique*, **32** (2), 133–144.

Whitlow B. (1990) *Basic Soil Mechanics*, Longman Scientific and Technical, New York.

Zadroga B., Olańczuk-Neyman K. (2001) *Protection and Remedia of a Subsoil*, Publishing House of Gdańsk University of Technology.