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Factors affecting the oedometric modulus of till soil

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Abstract. Soil deformation moduli are affected by a number of factors including the intensity of applied load in drained or undrained conditions, stress-strain characteristics, confining pressure, stress history, and soil type. Determination of the deformation properties of glacial soils requires long-term research. As evidenced by a review of previous studies, Lithuanian glacial soils are still insufficiently explored. Our study focuses on the deformation properties of till soil, specifically, on the properties that have a significant impact on soil settlement or compressibility, and its calculations. The current study presents the oedometer deformation modulus determined and predicted under stress at 0.2 and 0.4 MPa levels, which are most often used in geotechnical design. These index values allowed identifying the major factors responsible for the variation in deformation behaviour of different groups of till soils. The most significant finding of this study was the absence of a direct correlation between the oedometer modulus (E_{oed}) and cone resistance (q_c). Instead, based on the content of natural soil water (w), proportion of fine fraction (clay), and cone resistance (q_c), we found that the most reliable correlation exists between the determined (E_{Doed}) and estimated (E_{Eoed}) oedometer moduli.
It is important to note that regression models are applicable and reliable only within specific ranges of these factors. The valid limits for these models are: water content in the range of 7.7%–15.4%, clay fraction in the range of 4.0%–20.0%, and cone resistance in the range of 1 MPa–5 MPa.

Keywords: *Soil compressibility; Robertson soil behaviour index (SBT)* I_c; *Sand-clay mixture; cone resistance (qc)*

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INTRODUCTION

Estimation of the soil deformation modulus is not an easy task because it is affected by a number of various factors such as soil type, soil properties, various conditions, natural stress and strain, or stress history. Moreover, to determine soil deformation properties, it is crucially important to take into consideration soil composition. Another difficulty in estimating the deformation modulus lies in the fact that there are different types of deformation, and, hence, different types of deformation moduli. The type of soil deformation modulus to be estimated depends on a number of factors including design objectives, foundation types, etc. (Gaur, Sahay 2017; Huang *et al.* 2018; Samorodov *et al.* 2019; Panulinova, Harabinova 2020; Tamošiūnas *et al.* 2020; Saleh *et al.* 2021; Bian *et al.* 2021). Designers and researchers select an appropriate deformation modulus depending on specific conditions, challenges, and ultimate aims of a particular project. In order to understand the value of the deformation modulus, one has to have a comprehensive understanding of the interplay between soil properties and external factors.

The modulus of deformation generally describes soil compressibility, which ensures that buildings and structures are durable, efficient, and safe during their construction and exploitation. From the perspective of engineering geology and geotechnical engineering, deformation is the basic property to be taken into consideration when estimating the subsidence of the foundations designed. The estimated deformation modulus highlights differences in characteristics of different types of soil (Podolka *et al.* 2016; Utenov *et al.* 2019).

Factors such as the geological age and type of soil play a significant role in determining the composition of soil. Geological conditions in Lithuania mainly depend on properties of the Pleistocene sediments, which most often consist of glacial soils (Guobytė *et al.* 2001; Putys *et al.* 2010). Till soils, which are derived from glacial deposits, are predominant. They are classified as cohesive soils and are often called fine soils. In their natural state, these soils have a complex microstructural composition. They are a blend of gravel, sand, silt, and clay mixtures. These soils possess physical and mechanical characteristics that are greatly influenced by their internal properties, particularly by their heterogeneity, anisotropy, and the geological age during which they were formed (Clarke 2018; Chen *et al.* 2019; Yin *et al.* 2021; Hailemariam, Wuttke 2021). Consequently, it is essential to carefully consider the proportions of clay, silt, and sand in the soil, since these elements determine the properties and behaviour of soils under various loading conditions or any other influences.

Pleistocene glacial soils cover a significant area of Lithuania (Guobytė *et al.* 2001; Putys *et al.* 2010) and, as a medium, are often used for various purposes, e.g., for infrastructure, buildings, and structural components. Extensive studies available on the deformation characteristics of Lithuania's glacial till soils are still insufficient.

The primary focus of this study was on the deformation properties of Pleistocene glaciation till soil with special emphasis on the properties that predetermine soil settlement or compressibility, which is estimated using multinomial logistic regression models. According to the soil behaviour type index (I_C), the studied till soils were divided into three types – silty sand to sandy silt (sand mixture), clayey silt to silty clay (silt mixture), and clay to silty clay (clay mixture). The determined (E_{Doed} – directly from the laboratory oedometer test) and the estimated (E_{Eoed} – using a multinomial logistic regression model) oedometer deformation moduli presented in this paper were determined at 0.2 and 0.4 MPa stress levels. The main objective of this study was to identify the factors responsible for differences in deformation moduli of different till soil behaviour groups.

KEY CONCEPT OF DEFORMATION MODULUS

Soil mechanical behaviour and its characteristics are nonlinear, anisotropic, and elastoplastic, and they mainly depend on soil structure and stress under different loading/unloading conditions (Huang *et al.* 2018; Li *et al.* 2022).

Stress change is considered to be one of the most important factors affecting soil deformation properties, which are closely related to its structure (Li *et al.* 2022). Soil settlement or compressibility under self-weight or under applied foundation loading shows that stress path and consolidation pressure critically affect the volume strain (Wei *et al.* 2023). Soil compressibility occurs due to the rearrangement of soil grains and depends on the strength of particle bonds, skeletal strength, and stability. The rearrangement of soil grains causes soil particles to wreck, roll, and slide, and water to be extracted or compressed from voids. Consequently, it is essential to predict the behaviour of time-dependent soil compressibility and the main factors behind it (Adeyer 2015; Adeyeri 2018; Jayalekshmi, Elamathi 2020).

One of the consolidation characteristics of soil is its compressibility, mainly described by the deformation modulus of elasticity *(E)*, defining the elastic region of soil (Figs 1, 2) (Sharma *et al.* 2017; Meyer, Olszewska 2021). One of the elastic moduli, –

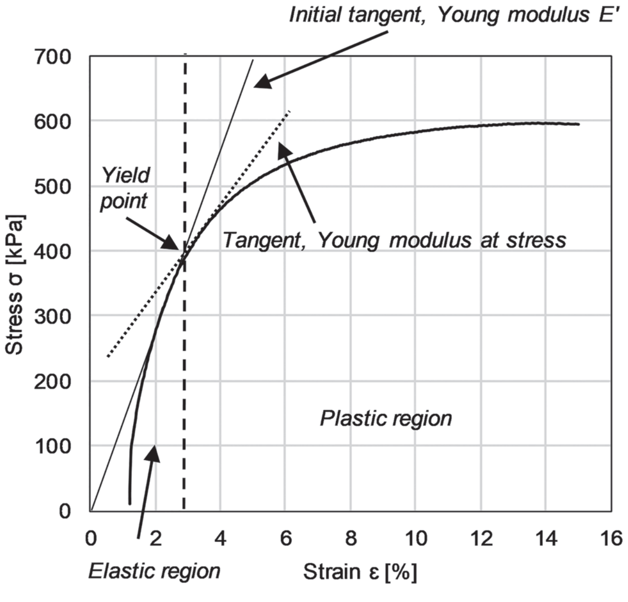

Fig. 1 Example of the triaxial shear test results with the identified elastic and plastic zones and the tangent (Young's) modulus

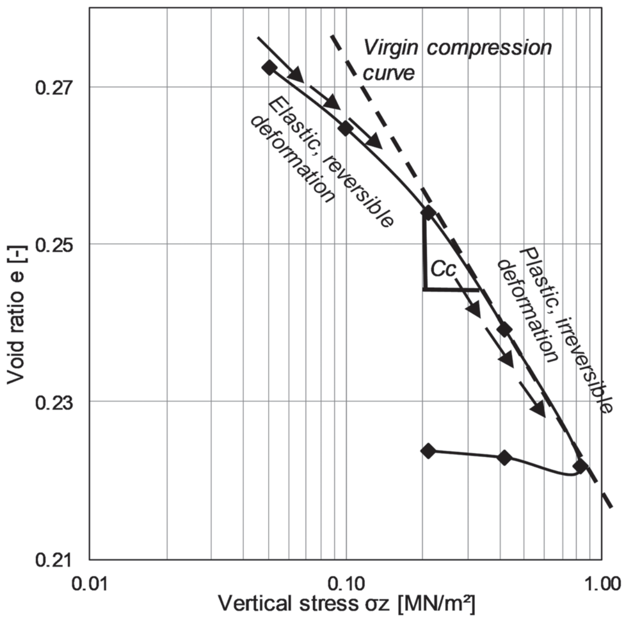

Fig. 2 Example of the oedometer compression test results with the identified elastic and plastic zones in the soil consolidation graph

Young's (E') modulus, (Podolka *et al.* 2016; Jones, Ashby 2019) (Fig. 1) is used in the numerical Mohr-Coulomb (MC) foundation design model.

In Hardening Soil (HS) model, the oedometer modulus (E_{oed}) is used (Gaur, Sahay 2017; Saleh *et al.* 2021). Young's (E') and constrained oedometer deformation (E_{oed}) moduli are related by Poisson's ratio (Sivakugan *et al.* 2015). The oedometric deformation represents the constrained elastic modulus determined from the oedometer compression test results (Fig. 2) (Laloui, Rotta Loria 2020; Meyer, Olszewska 2021).

As Lithuanian researchers, engineering geologists, and geotechnicians understand the deformation modulus differently, it is either described by Young's modulus (Fig. 1), constrained oedometer deformation modulus (Fig. 2), or the general deformation (E_0) modulus.

The general deformation modulus can be calculated from the cone penetration test results based on the correlation coefficient α (Brilingas 1988). This modulus is still in use with some changes in the correlation coefficient α (EN 1997-2:2007; TAR, 2015-11-16, Nr. 18162).

The EN 1997-2:2007 standard is an important document specifying formulas and methodology for calculating E' and E_{oed} deformation moduli from cone resistance. However, it should be noted that these formulas are applicable only to spread foundations and only in drained conditions, and the results obtained are only theoretical.

In the laboratory, Young's and oedometer deformation moduli can be determined by conducting an oedometer test (EN ISO 17892-5:2017) or a triaxial test (EN ISO 17892-9:2018), which allow considering all conditions and impacts on the actual soil deformation values.

IMPACT OF SOIL COMPOSITION ON ITS DEFORMATION

Soil composition and correct determination of soil deformation moduli impact the general understanding of soil deformability or stability. Among the main factors determining soil deformation is the particle size and the amount of fine fraction in soil, which are responsible for soil's mechanical properties and stability. Eventually, all cracks, layers, and large pores directly impact soil deformation and its mechanical properties under load (Wang *et al.* 2021).

Soil is less deformable when it contains less fine fraction (Habtemariam *et al.* 2022). Grain size and its distribution in soil are the determining factors of sandy soils' deformation. Deformation modulus increases with fraction coarsening (Sabarishri *et al.* 2017).

In fine fraction soils, the deformation modulus decreases with the increase of clay content. In such cases, soil compressibility and the compression index (C_c) increase (Fig. 2), while permeability decreases (Akayuli *et al.* 2013; Reece 2021). Under applied load, the mechanism of soil failure changes from the splitting one to the shear one with the increasing soil particle size (Wang *et al.* 2021). Generally, the content of grain size in soil is crucial for determining soil's stress-strain and strength characteristics.

As mentioned above, the most common soil in Lithuania is glacial till, which consists of gravel, sand, silt, and clay. It is a mixture of all fractions, so it is essential to emphasize the impact of the number of particle-size fractions in soil on its deformation and strength properties.

The interaction between coarser and finer grains affects soil stress and strain. As reported in some studies, oedometer tests conducted on clay-sand mixtures have revealed that the percentage of fine particles and stress conditions play a crucial role in soil compaction (Murat, Ozden 2007). Research findings indicate that up to a certain point the content of fine particles (this part is called transitional fine particles (*FCt*)) ranges from 19% to 34% and has a dominant impact on the compressive behaviour of soil mixtures. However, once the concentration of fine particles exceeds *FCt*, soil compaction is affected by clay fraction (Murat, Ozden 2007).

The percentage of fine particles in soil mixtures significantly affects their strength. The compressive strength of sand–clay mixture was observed to increase with the increasing content of fine particles up to < 55% slowly, faster when the concentration of fines was in the range of 55%–75%, and slowly again when the concentration of fines was > 75% by weight (Jiang *et al.* 2015). It was observed that the presence of fine particles had a more significant effect on the strength of mixtures than on their deformation behaviour. The ratio of compressive strength also varied depending on the concentration of fine particles (Jiang *et al*. 2015).

The amount and density of natural water content also significantly affect the deformation behaviour and strength of soil. The understanding of the existing correlation between these soil properties is essential for working out practical application solutions. As highlighted by numerous researchers, an increase in water content leads to a decrease in soil strength, deformation modulus value, coefficient of consolidation (C_v), and the angle of internal friction (φ) (Malizia, Shakoor 2018; Habtemariam *et al.* 2022; Hov, Gaharia 2023). Some research indicates that compressive strength of soil increases with clay plasticity (Malizia, Shakoor 2018). On the other hand, the impacts of medium and high plasticity clays on compressive strength do not differ significantly (Malizia, Shakoor 2018). These findings emphasize the importance of natural water content in soil, its density and their combined effects on soil deformation behaviour, strength, and stability for practical soil applications.

METHODOLOGY

This study examined and summarized the databases of more than 150 samples of Middle Pleistocene glacial till soil, which were collected by the authors, focusing on their physical and mechanical properties, from southeastern Lithuania. (Fig. 3). According to the soil classification system (EN ISO 14688-2:2018), the aanalysed till soil samples represent sandy low plasticity clay (saClL), sandy low plasticity clay–silt (saClL–SiL), and clayey sand (clSa). It is the geotechnical properties of these glacial till soil types of different genesis that are taken into consideration when designing foundations for the majority of complex buildings in Lithuania.

This study analysed the databases of physical and mechanical soil properties focusing on the following specific physical and mechanical soil properties: grain size distribution (EN ISO 17892-4:2016), Atterberg limits (EN ISO 17892-12:2018), natural water content (EN ISO 17892-1:2015), density (EN ISO 17892-2:2015) and oedometer modulus (EN ISO 17892-5:2017).

For further analysis, the Robertson soil behaviour

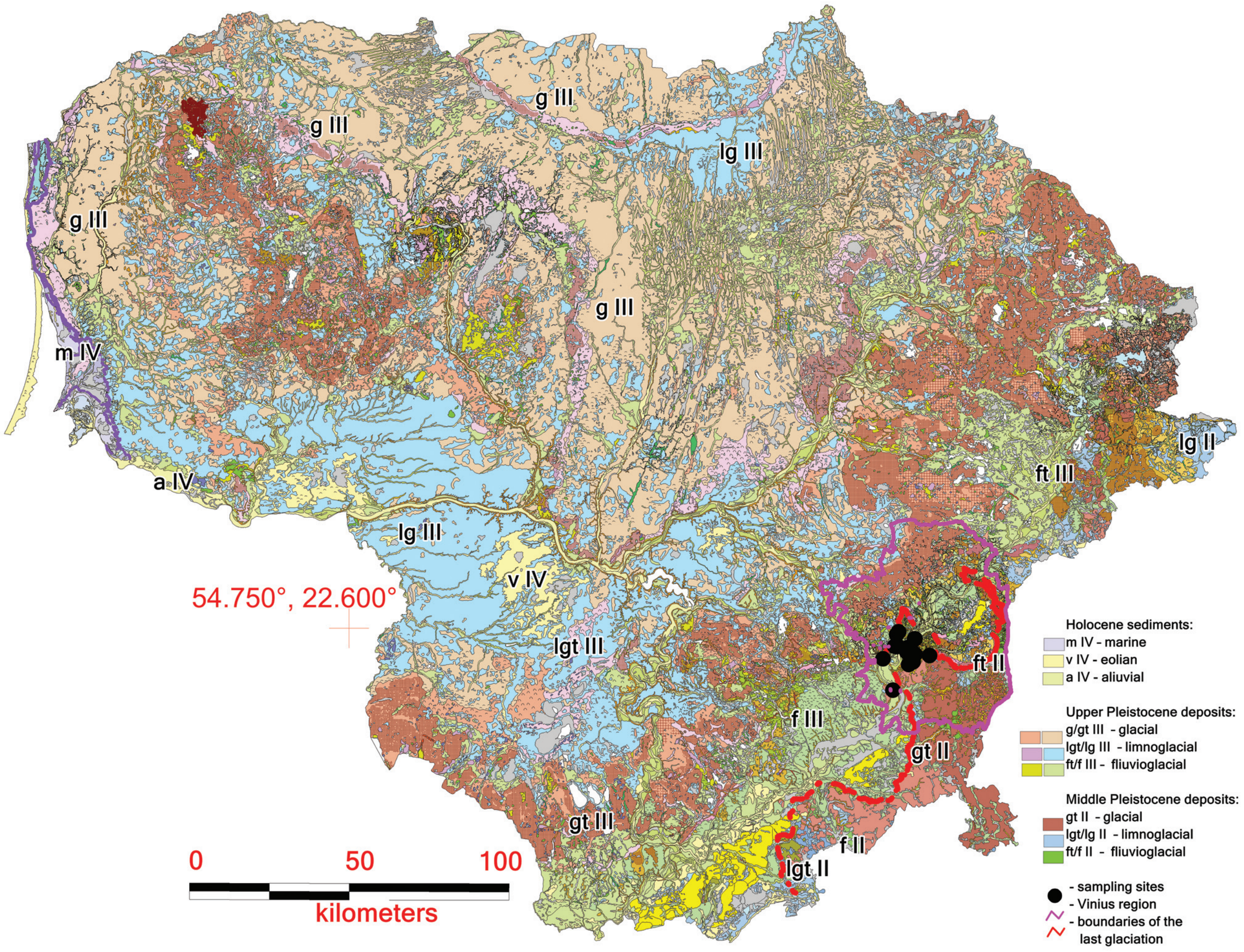

Fig. 3 Locations of the analysed Pleistocene glacial till soils on the Lithuanian Quaternary geological map M 1:200 000 (after Guobytė 1999; State geological information system GEOLIS, www.lgt.lt)

index (SBT) was calculated (Robertson 2016). Based on the I_C indicator, the investigated soil samples were divided into three groups representing soil behaviour types:

- silty sand to sandy silt (I_C = 2.05–2.60) – sand mixture
- clayey silt to silty clay (I_C = 2.6–2.95) – silt mixture
- clay to silty clay (I_C = 2.95–3.60) – clay mixture

Subsequently, following P.K. Robertson soil classification system (Robertson 2009), each I_C group was divided into subgroups based on the 1–5 MPa cone resistance (q_c). A multinomial logistic regression model was chosen to analyse the E_{Eoed}. The properties of soil were analysed and interpreted to discover their correlation with E_{Doed}, which was determined during the oedometer laboratory test.

For estimation of E_{Eoed} values, values of the cone penetration resistance were measured. These q_c values were filtered, and the values characteristic of each soil depth interval were estimated (Bond, Harris 2006) based on which the oedometer modulus was determined (EN ISO 17892-5:2017). Regression equations for defining the best relationship between the E_{Doed} and the E_{Eoed} based on soil properties were created during the analysis.

The current study presents the oedometer deformation modulus at 0.2 and 0.4 MPa stress levels. These stress magnitudes are widely used in geotechnical design practices. Both stress levels allow properly assessing both the mechanical behaviour and deformation characteristics of soils. The choice of this specific stress levels is in line with the one applied in foundation design practices in Lithuania.

RESULTS AND DISCUSSION

Investigated till soil variation in soil behaviour type zones

The analysed glacial till soil is characterized by varied strength (according to (q_c) and friction (f_s)), grain size distribution, and physical properties, all of which indicate its complex structure, and, consequently, account for the complexity of its database.

The soil under analysis was divided into subgroups and analysed to reveal correlations between physical and mechanical soil properties and to improve the accuracy of study results. Robertson's (Robertson 2016) soil behaviour type (SBT), specifying the boundaries between zones of distinct soil behaviour types under stress and load, was chosen for soil grouping (Fig. 4). This criterion is one of the most appropriate and effective in assessing mechanical properties of soils since it not only describes, but also helps to determine the boundary between non-cohesive (sandy) and cohesive (clayey) soils. It can also be used to describe the soil type independently of the knowledge (or without it) of the exact soil grain size distribution or plasticity (Ku *et al.* 2010). The reliability of this measure has been demonstrated in the case study of liquefaction susceptibility (Ku *et al.* 2010; Green, Ziotopoulou 2015).

According to the soil behaviour index I_C, the studied till soil was divided into three main groups of soil behaviour types (Figs 3, 4). Group 5 comprising silty sand to sandy silt (I_C = 2.05–2.60) was the largest. It was followed by group 4 consisting of clayey silt to silty clay (I_C = 2.60–2.95) and group 3 including clay to silty clay

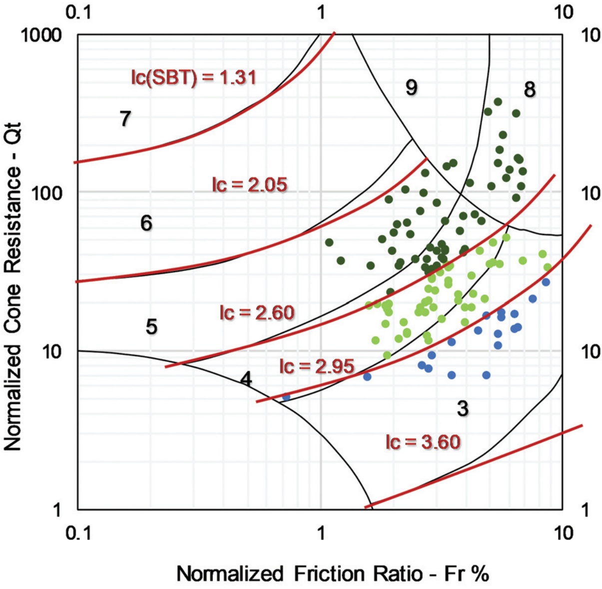

Fig. 4 Distribution of the investigated Pleistocene glacial till soils in P.K. Robertson's (2016) soil behaviour type graph with the indicated I_C soil behaviour type boundaries: 3 – clays, 4 – silt mixture, 5 – sand mixture, 6 – sands, 7 – gravelly sand, 8 – very stiff sand to clayey sand, 9 – very stiff fine-grained sand

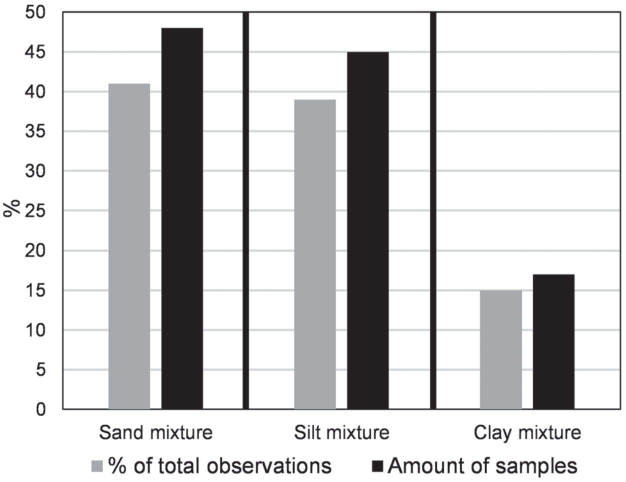

Fig. 5 The amount and percentage of the investigated Pleistocene glacial moraine soils in the main groups of soil behaviour types: sand mixture I_C = 2.05–2.60, silt mixture I_C = 2.60–2.95, and clay mixture I_C = 2.95–3.60

(I_C = 2.95–3.60) and clay mixture. Each group comprised a different amount (%) of soil samples (Fig. 5).

Silty sand to sandy silt (sand mixture), clayey silt to silty clay (silt mixture), and clay to silty clay (clay mixture) soil behaviour types are composed of the varying amounts of the following soil types: low plasticity clay (saClL), clayey sand (clSa), sandy low plasticity clay–silt (saClL–SiL), and sandy low plasticity silt (saSiL) (Fig. 6).

Soil behaviour analysis showed that grain size distribution plays no role in distinguishing soil behaviour types by I_C if clay amount in soil does not exceed 10–15%. However, the I_C index is more impacted by plasticity properties of the soil, which is a mixture of clay, silt, sand, and gravel. In this group, the average amount of fine (clay) fraction exceeds 9%.

The soil behaviour types distinguished by I_C (Figs 5, 6) show that the Middle Pleistocene till soil names, used in EN ISO 14688-2:2018, do not reflect the actual behaviour of soil accurately enough (Thusyanthan 2012; Yuliet *et al.* 2021). To provide a more accurate understanding of soil behaviour, it is necessary to evaluate soil properties and characteristics more comprehensively.

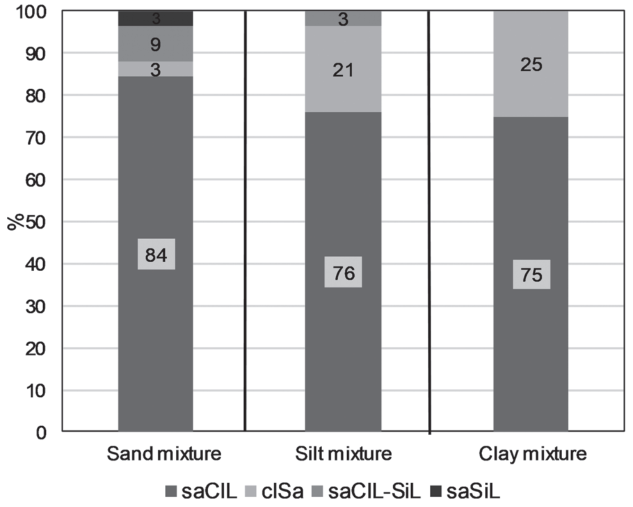

Fig. 6 Amount of the investigated soil types (saClL, clSa, saClL–SiL and saSiL) in the main three soil behaviour groups in percentage terms: sand mixture I_C = 2.05–2.60, silt mixture I_C = 2.60–2.95, and clay mixture I_C = 2.95–3.60

This paper focuses on the analysis of the correlations existing between the above-mentioned main soil groups 3, 4, 5 (Figs 3, 4) representing different soil behaviour types. In this study, the obtained results and the established correlations apply to the soil, whose cone resistance (q_c) is in the range of 1.0–5.0 MPa, and which is subjected to stress levels of 0.2 and 0.4 MPa. These stress levels were chosen as the most suitable for the validation of this model. The specific stress levels of 0.2 and 0.4 MPa are in line with those applied in foundation design practices in Lithuania.

Dependence of oedometer deformation modulus on cone penetration resistance

A regression analysis was conducted to assess the relationship between the cone resistance (q_c), which is in the range of 1–5 MPa, and the deformation moduli, determined at stress levels of 0.2 and 0.4 Mpa, regardless of the soil type and its behaviour (Fig. 7a, b).

The obtained correlation shows no direct relationship between the E_{oed} and q_c. These two soil indicators are not directly dependent on each other (Fig. 7). It is difficult to compare the oedometer consolidation test values with those obtained under in-situ conditions. Generally, the soil deformation results obtained from laboratory tests differ from those obtained in field conditions, which is due to the existence of various interlayers, inclusions, lenses, and mainly due to the complexity of till soil composition. All the above-

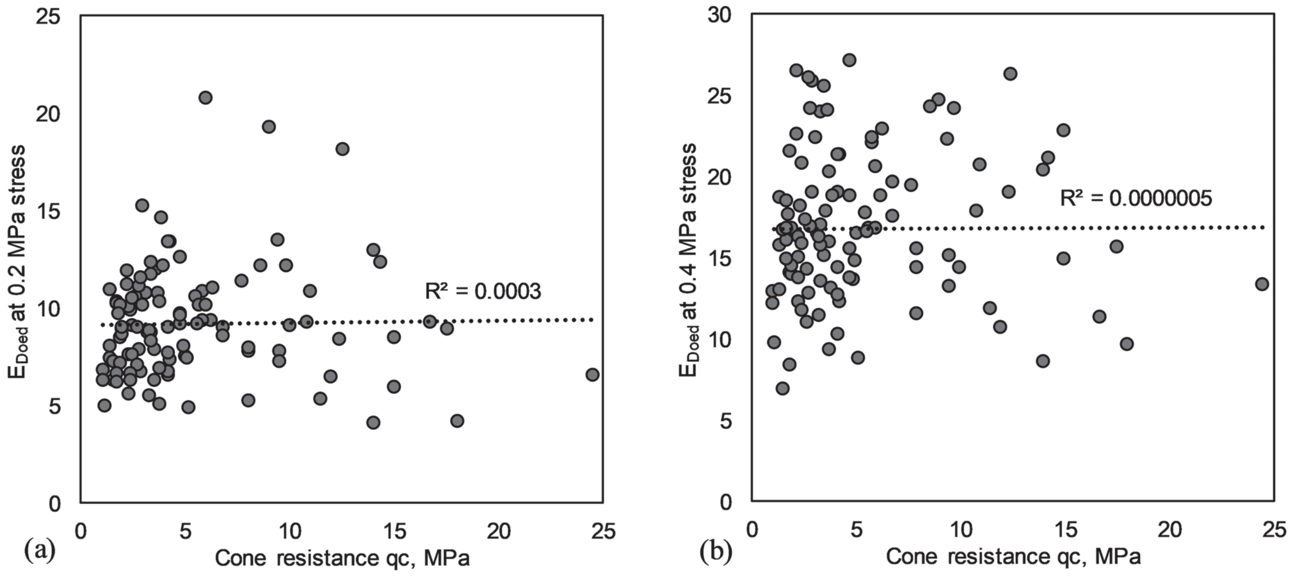

Fig. 7 Regression model analysis of the correlation between the 1–5 MPa cone resistance (q_c) of the investigated till soils, and the determined oedometric modulus (E_{Doed}): (a) at stress level of 0.2; (b) at stress level of 0.4 MPa

mentioned indicators affect soil deformability on a much larger scale than in cases of small sample examination in laboratory conditions. Field and laboratory research methods simulate soil loading under natural conditions. The oedometer test results represent the deformation of the specimen in the vertical direction, which allows determining its relative deformations while the constant vertical stress is being applied. The comparison of the constrained modulus values determined in laboratory conditions with those obtained under in-situ conditions revealed that laboratory values are about 3–5 times lower than the in-situ ones (Creer *et al.* 2011; Wang *et al.* 2015). When comparing the oedometer moduli values obtained in the laboratory with those obtained in field conditions, it should be kept in mind that the soil is evaluated under different stress conditions. During the laboratory test, the soil is subjected only to vertical stress, and only its vertical deformation is obtained. Meanwhile, when testing the soil in field conditions, it is subjected not only to vertical but also to horizontal stresses, and the total deformation is obtained. Therefore, the results obtained in the laboratory cannot be compared with those obtained in field conditions, because different deformation modules are obtained, which define different deformability of the soil. Various correlation coefficients are used for calculating the deformation moduli based on cone resistance. Therefore, it may be necessary to reconsider whether the result obtained corresponds to the actual modulus value.

Multinomial logistic regression model analyses of all the distinguished soil behaviour types under 0.2 MPa stress

The performed analysis of the derived model's reliability (Table 1) shows that the content of natural water and that of fine fraction (clay) as well as soil cone resistance are the most reliable indicators for the correlation existing between the determined and the estimated oedometer deformation moduli. According to numerous researchers, the content of natural water content and that of fine fraction (clay) in soil are the main factors determining its deformation properties (Wang *et al.* 2021; Hov, Gaharia 2023).

The performed analysis of the model equation for silty sand to sandy silt under 0.2 MPa stress (Fig. 8a; Table 1) revealed that the main factor determining

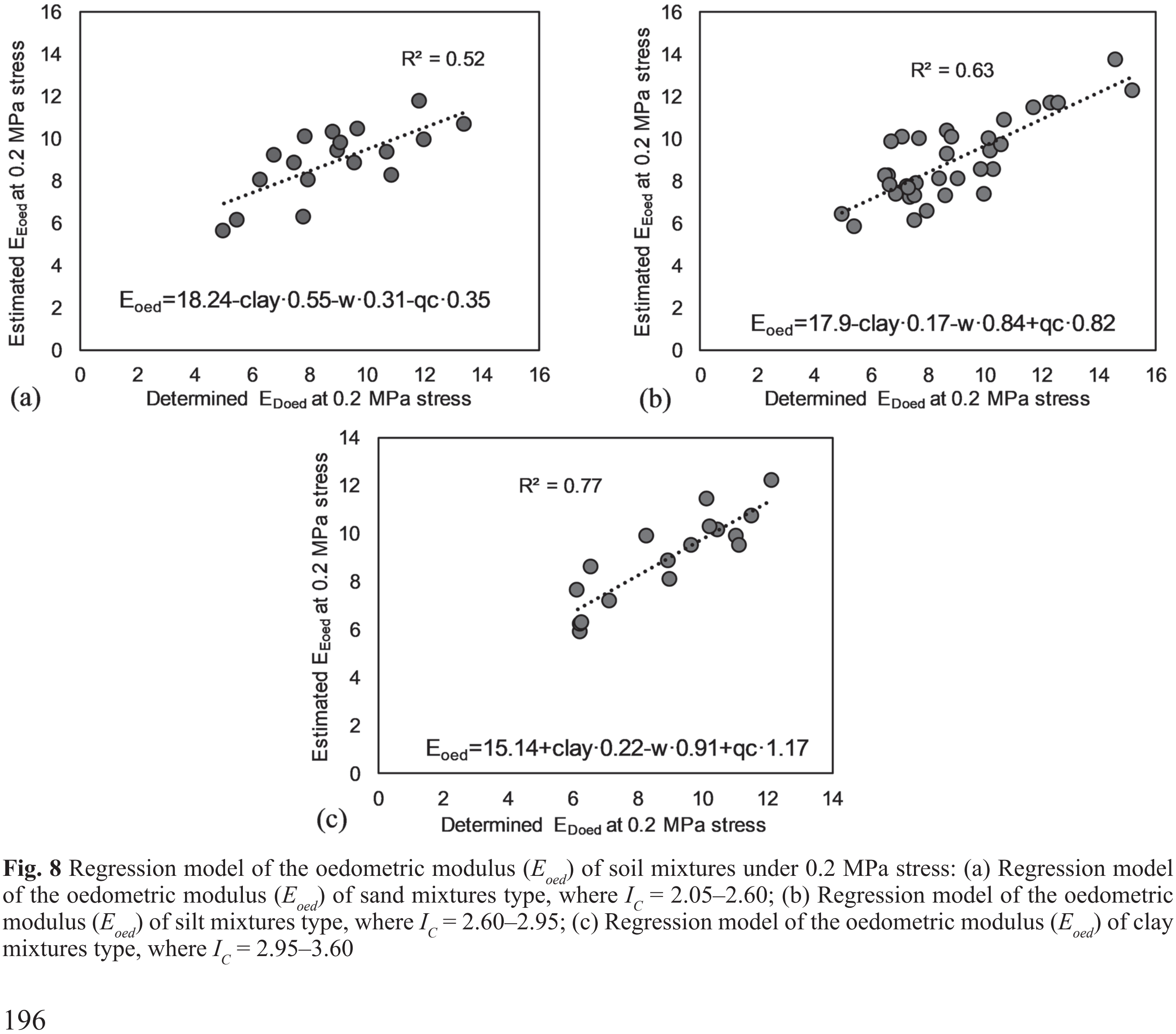

Fig. 8 Regression model of the oedometric modulus (E_{oed}) of soil mixtures under 0.2 MPa stress: (a) Regression model of the oedometric modulus (E_{oed}) of sand mixtures type, where I_C = 2.05–2.60; (b) Regression model of the oedometric modulus (E_{oed}) of silt mixtures type, where I_C = 2.60–2.95; (c) Regression model of the oedometric modulus (E_{oed}) of clay mixtures type, where I_C = 2.95–3.60

soil deformation is the clay fraction content (clay). Due to its extreme receptivity to water, as well as high compressibility, high volumetric changes, high plasticity, permeability, bearing capacity, and settlement characteristics, clay content in soil is one of the significant characteristics allowing understanding soil compressibility under load (Malizia, Shakoor 2018).

The analysed soil behaviour types, i.e., clayey silt to silty clay (Fig. 8b) and clay to silty clay (Fig. 8c), show that natural water content has a major influence on both the above-mentioned soil behaviour types under stress of 0.2 MPa. Findings of other studies into clay behaviour show that water content in soil is responsible for changes in soil mechanical properties (Wei *et al*. 2022).

The summarized study findings confirm that the interaction between the finest fraction (clay) content and the amount of water exerts the greatest control over the engineering behaviour of till soils (Ural 2018; Wang *et al*. 2021; Hov, Gaharia 2023; Shaochun *et al.* 2023).

Each regressor relating to soil characteristics contributes to the accurate prediction of the deformation modulus (Fig. 9).

As is evident from the silty sand to sandy silt (sand mixtures) sample examination (Fig. 9a), the removal of the clay fraction's influence causes the model's reliability to decrease to 0.34.

The clay fraction index exerts the most significant impact on sand mixtures (Akayuli *et al.* 2013).

Removal of the impact of natural water content from the analysis of silt (Fig. 9b) and clay (Fig. 9c)) samples

Table 1 Statistics of the multinomial logistic regression model of the estimated E_{Eoed} and determined E_{Doed} under 0.2 MPa stress

		Standard Error	*p*-value
Regression statistics*		1.524	
Equation input statistics	Intercept	2.69	$2.17 \cdot 10^{-7}$
	Clay	0.094	0.076
	w, %	0.187	$9.27 \cdot 10^{-5}$
	q_c, MPa	0.299	0.01

*Multiple R = 0.795; *R^2 = 0.632.

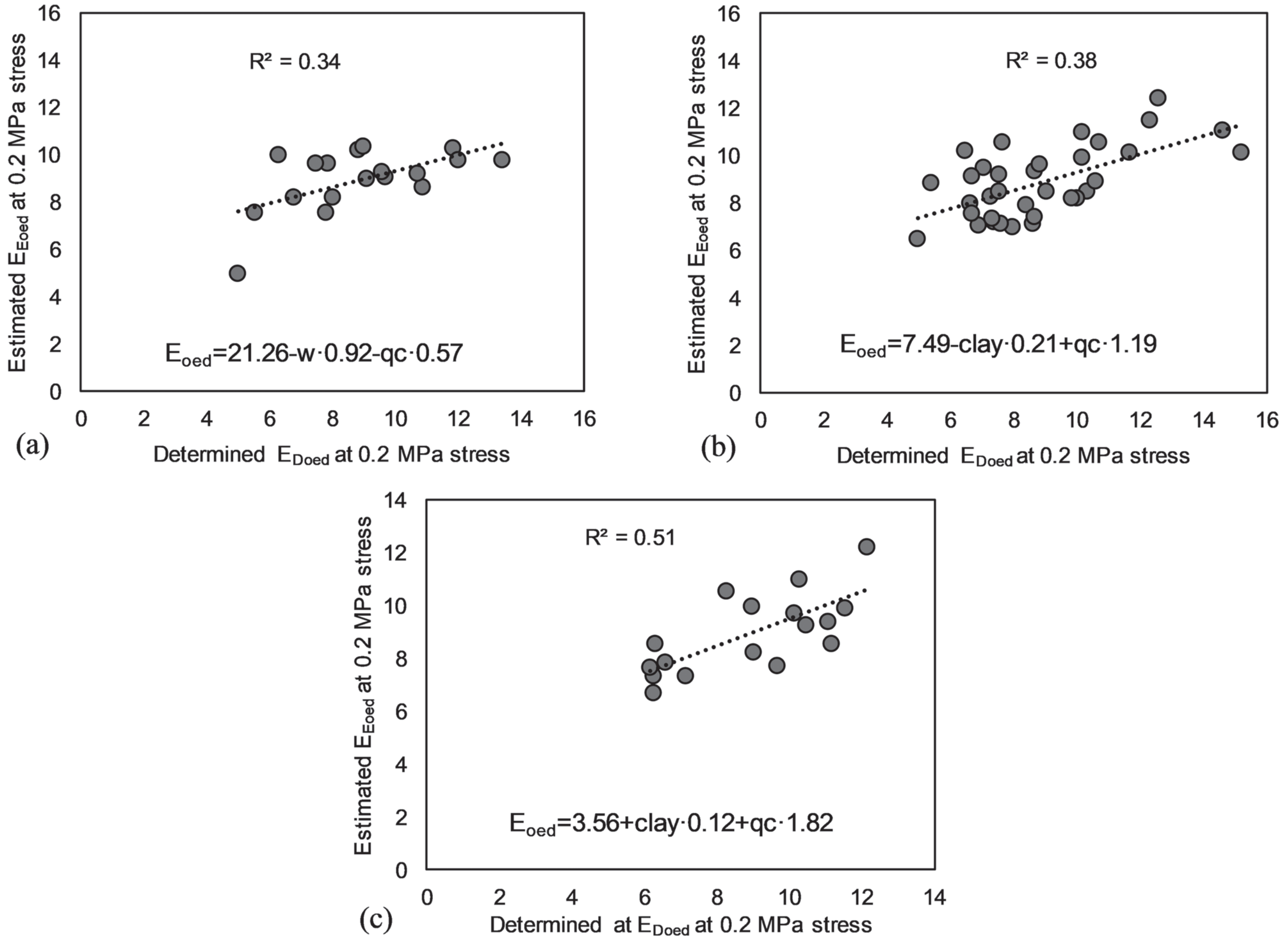

Fig. 9 Regression model of the oedometric modulus (E_{oed}) of soil mixtures without regressors of fine fraction (clay) and natural water content (*w*) under 0.2 MPa stress: (a) Regression model of the oedometric modulus (E_{oed}) of sand mixtures without a regressor of fine fraction (clay), where I_C = 2.05–2.60; (b) Regression model of the oedometric modulus (E_{oed}) of silt mixtures without a regressor of fine fraction (clay), where I_C = 2.60–2.95; (c) Regression model of the oedometric modulus (E_{oed}) of clay mixtures without a regressor of natural water content (*w*), where *Ic* = 2.95–3.60

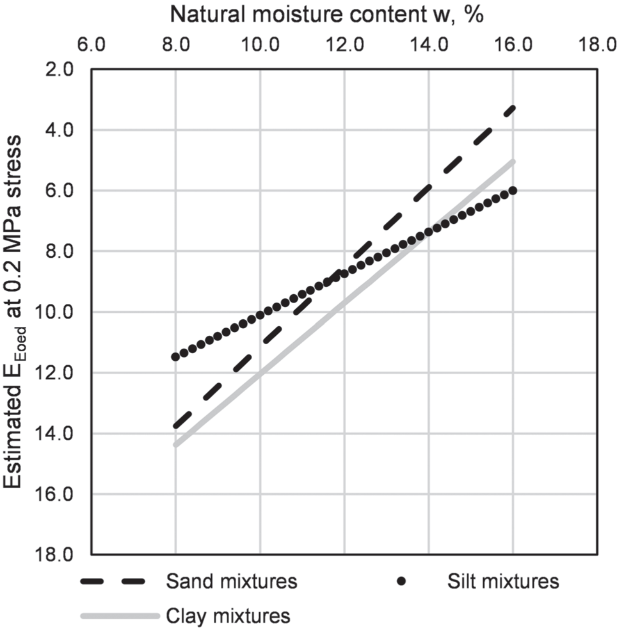

Fig. 10 Correlation of the estimated oedometric modulus (E_{oed}) of the investigated till soils under stress of 0.2 MPa with natural water content in soil (w)

caused the model's reliability to decrease to the values of 0.38 and 0.51, respectively. Natural water content significantly affects values of the oedometer deformation modulus of the examined till soil mixtures.

Results of the performed analysis show that increasing content of natural water causes a linear decrease in the oedometer deformation modulus (Fig. 10), i.e., soil compressibility increases, and settlement of the soil layer due to applied stress increases (Ural 2018).

Also, these regression models are proved reliable only for the regression limitation intervals. Water content is a valid limit for the models and must be within the range of 7.7–15.4%, clay fraction within the range of 4.0–20.0%, and cone resistance must be within the range of 1–5 MPa, respectively.

Multinomial logistic regression model analyses of all the distinguished soil behaviour types under 0.4 MPa stress

Results of the performed analysis of the created model's reliability under stress loads of 0.4 MPa, pre-

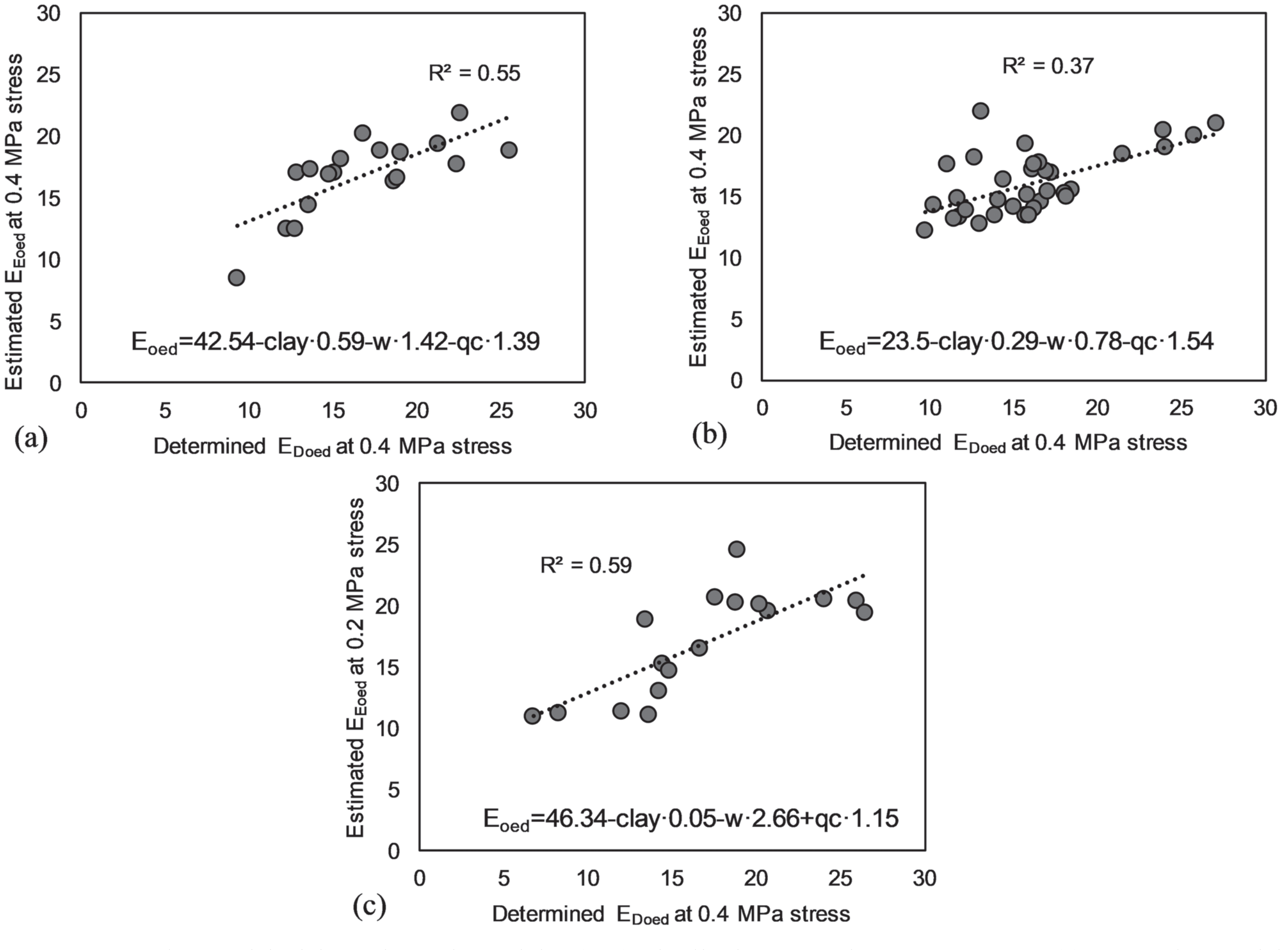

Fig. 11 Regression model of the oedometric modulus (E_{oed}) of soil mixtures under 0.4 MPa stress: (a) Regression model of the oedometric modulus (E_{oed}) of sand mixtures, where Ic = 2.05–2.60; (b) Regression model of the oedometric modulus (E_{oed}) of silt mixtures, where I_C = 2.60–2.95; (c) Regression model of the oedometric modulus (E_{oed}) of clay mixtures, where I_C = 2.95–3.60

sented in Table 2, show that the content of natural water and that of fine fraction (clay) as well as soil cone resistance are the key parameters revealing the strongest correlation between the determined oedometer deformation and the estimated deformation moduli (Fig. 11).

The comprehensive study of all mixture behaviour types (Fig. 11a, b, c) shows that water content is the determining factor in soil deformation under the stress of 0.4 MPa. It is worth emphasizing that numerical values of q_c are higher than those of natural water content. However, it is necessary to evaluate numerical values of q_c and of water content. The variation range of natural water content values (8.0–22.0%) is broader than that of the cone strength values, which in the soil under investigation was 1–5 MPa.

The input p-values in models are not always suitable for all regressors (when $p < 0.05$) (Table 1, row 5). In some cases, the input p-value exceeds the specified value. However, the removal of unsuitable regressors reduces the determination index R^2, which means that the inputs cannot be removed because the model becomes unsuitable.

It is also important to make it plain in this section that each regressor relating to soil characteristics has a certain impact on the accurate prediction of the deformation modulus.

It can be affirmed that in all cases when the influence of natural water content in soil mixtures was eliminated (Fig. 12a, b, c), the reliability of the model decreased to the range of 0.42–0.27. This drop confirms that under the stress of 0.4 MPa, the regressor of water content has the strongest effect on all mixtures.

Table 2 Statistics of the multinomial logistic regression model of the estimated E_{Eoed} and determined E_{Doed} under 0.4 MPa stress

		Standard Error	*p*-value
Regression statistics*		3.970	
Equation input Statistics	Intercept	3.335	0.001
	clay	0.119	0.086
	w, %	0.237	0.002
	q_c, MPa	0.381	0.009

*Multiple R = 0.770; *R^2 = 0.594.

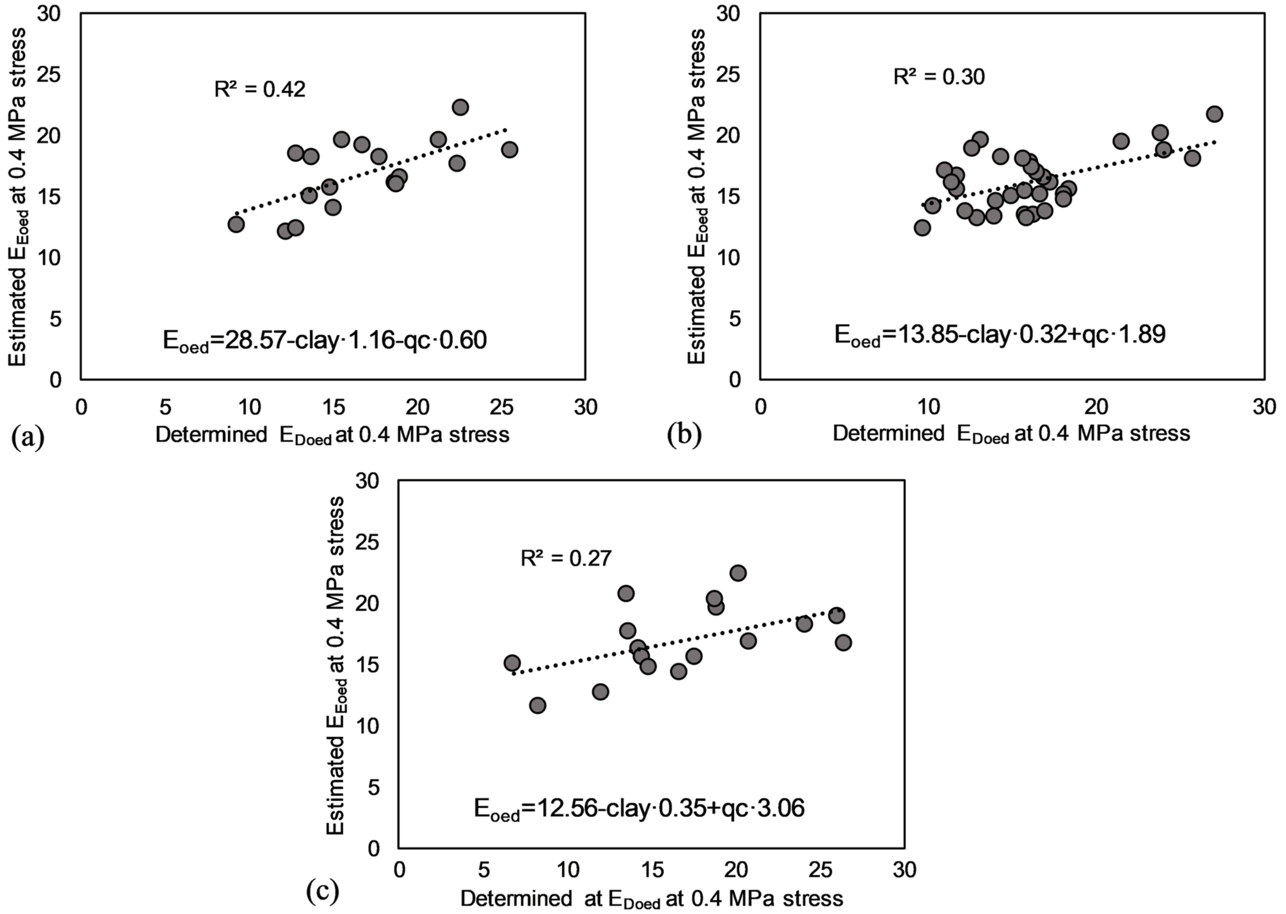

Fig. 12 Regression model of the oedometric modulus (E_{oed}) of soil mixtures under 0.4 MPa stress without a regressor of natural water content (w): (a) Regression model of the oedometric modulus (E_{oed}) of sand mixtures, where I_C = 2.05–2.60; (b) Regression model of the oedometric modulus (E_{oed}) of silt mixtures, where I_C = 2.60–2.95; c) Regression model of the oedometric modulus (E_{oed}) of clay mixtures, where I_C = 2.95–3.60

This study shows that an increase in values of natural water content in soil causes a linear decrease in values of the estimated oedometer deformation modulus (Fig. 12), implying that soil compressibility increases, and so does the settlement of the soil layer due to applied stress (Adeyer 2015).

Based on the data obtained, we can draw the logical conclusion that there is a linear decrease in the calculated values of E_{Eoed} with an increase in natural water content in soils both under 0.2 MPa (Fig. 10) and 0.4 MPa stress (Fig. 13).

As mentioned in the previous section, these regression models are proved and reliable only for the regressor limitation intervals. Generally, when comparing model equations for the stress levels at 0.2 and at 0.4 MPa, a similar determination index is observed only for sand mixtures. This similarity indicates that the suitability of the model remains consistent regardless of the applied stress magnitude. However, notable variations in the determination index are observed for silt and clay mixtures under different stress levels. The determination index decreases from 0.77 in silt mixtures to 0.63 in clay mixtures under 0.2 MPa stress and increases from 0.37 in silt mixtures to 0.59 in clay mixtures under the stress of 0.4 MPa. Therefore, the suitability of the model decreases as the stress levels increases.

Data distribution

In this study, regression analysis was followed by the statistical validation of each modulus data distribution, which is shown in the figures provided. In Fig. 14a and 14c, the box plot visualizes the determined E_{Doed} modulus. In Fig. 14b, d, values of the estimated E_{Eoed} modulus are presented. In this study, the data were grouped by I_C as follows: silty sand to sandy silt (I_C = 2.05–2.60), clayey silt to silty clay (I_C = 2.60–2.95), and clay to silty clay (I_C = 2.95–3.60), with the latter referred to as the clay mixture. The above-mentioned figures provide a visual representation of how the deformation modulus varies within and across these types of soil behaviour, which aids in interpreting and analysing the distribution and characteristics of the data sets.

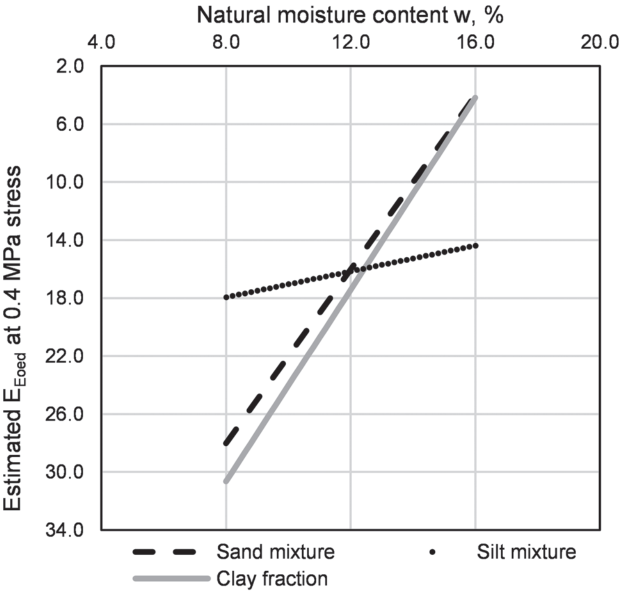

Fig. 13 The correlation of the estimated oedometric modulus (E_{Eoed}) of the investigated till soils under 0.4 MPa stress with natural water content in soil (*w*)

The comparison of the corresponding medians of each soil mixture under stress in the level at 0.2 and at 0.4 MPa presented in the box plots (Fig. 14a, b, c) shows that the median lines sit inside the boxes of the comparative box plot, implying that values of the determined E_{Doed} modulus show no significant differences among the distinguished groups of soil mixtures. In Fig. 14d, the median line of the estimated E_{Eoed} values for the clay mixture under the stress of 0.4 MPa sits outside the box of the comparative box plot, visualizing the difference between E_{oed} values of the clay mixture and those of sand and silt mixtures.

The analysis of interquartile ranges was followed by the examination of the data dispersion for each mixture, which revealed that values of the estimated E_{Eoed} in soil mixtures are less dispersed than those of the determined E_{Doed}. However, values of the estimated E_{Eoed} modulus of the clay mixture under 0.4 MPa stress (Fig. 14d) were found to be more dispersed than the respective values of silt and sand mixtures, and then those of the determined E_{Doed} under 0.4 MPa stress. Meanwhile, values of the determined E_{Doed} modulus show almost the same dispersion in all groups of soil mixtures. However, the overall spread (extreme values at the end of two whiskers) of the determined E_{Doed} modulus values indicates their wider scattering, proving their wider distribution.

Careful inspection of the interquartile range (IQR) (Fig. 14a, c) in boxes of soil mixtures showed that values of the determined E_{Doed} modulus are more symmetric than those of the estimated E_{Eoed} modulus where values are left- (positive) or right- (negative) skewed.

The comparison of the determined and estimated values of the oedometer modulus under 0.2 MPa stress (Fig. 14a, b) with the corresponding values under 0.4 MPa stress (Fig. 14c, d), revealed that at higher stress values (0.4 MPa) the interquartile range is more compacted than at the lower ones (0.2 MPa). This tendency can be explained by the start of soil consolidation, and decreased dispersion of the determined and predicted values in response to load increase.

In general, the probability Q–Q plots for predicted and determined values of the oedometer modulus of all groups of soil mixtures under the stress of 0.2 MPa show a normal distribution of values (Fig. 15). However, when examined separately, discrepancies in the data for sand, silt, and clay mixtures become apparent.

The distribution of the data for silt and clay mixtures is slightly skewed (Fig. 15). The distribution of the data for silt mixtures is noticeably (positively) right-skewed and that of the clay mixture data is (negatively) left-skewed. The box plot (Fig. 14a, b) discussed in the previous section confirms this tendency. However, skewness is rare and extensive.

The Q–Q plots for the oedometer deformation values of all types of soils under the stress of 0.4 MPa show a normal distribution of values (Fig. 16). However, when the data for sand, silt, and clay mixtures under the stress of 0.2 MP are examined separately, discrepancies become apparent.

The distribution of data for sand, silt, and clay mixtures shows a noticeable skewness (Fig. 16). Slight right (positive) or left (negative) skewness can be detected in the distribution of the determined and estimated E_{Eoed} values of sand, silt, and clay mixtures. The predicted oedometer modulus values are more skewed, and this tendency can be confirmed by the box plot median lines (Fig. 14c, d) discussed in the previous section. As is evident from the plot, at the stress level of 0.4 MPa, the clay data show disper-

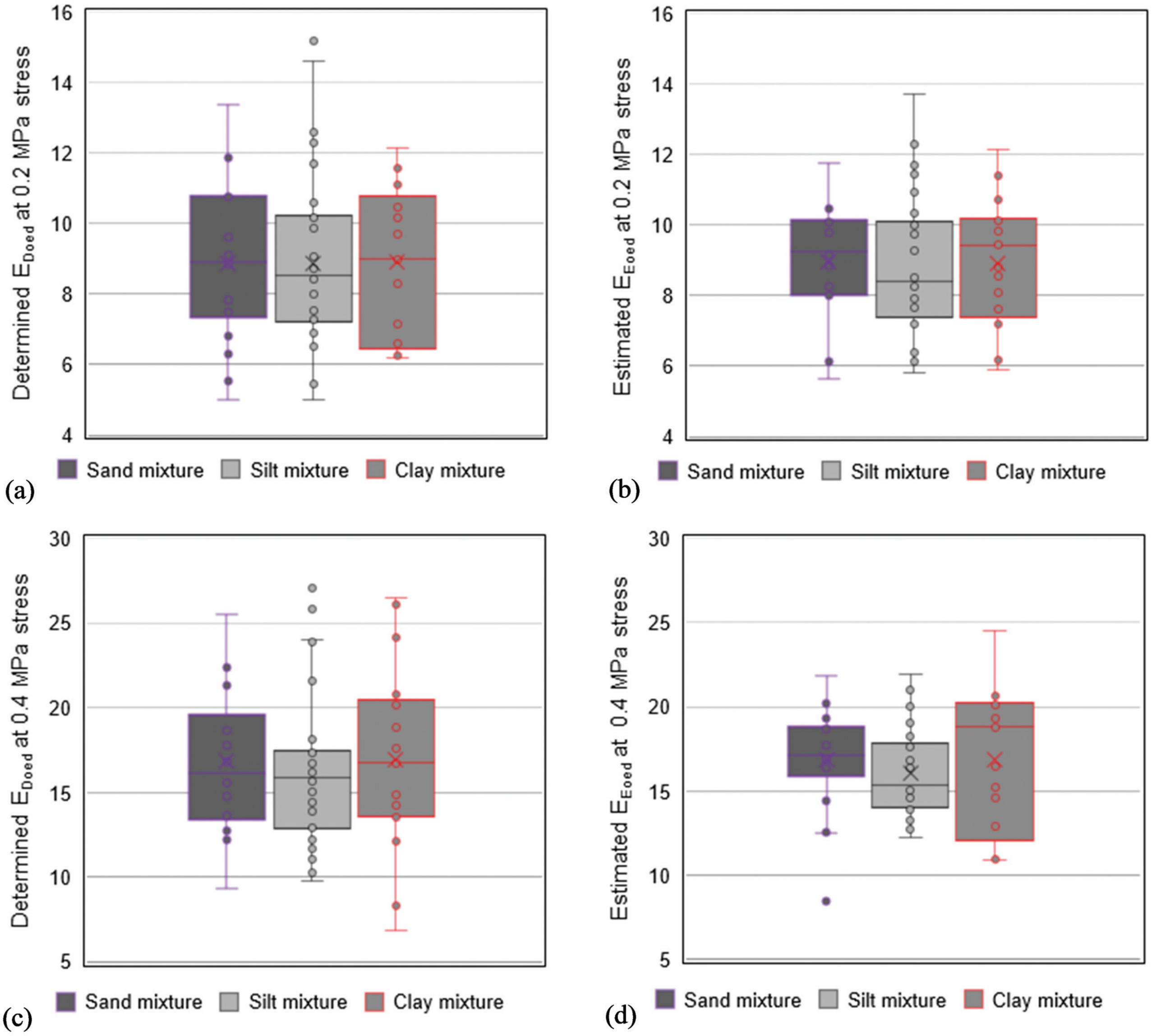

Fig. 14 The variation and distribution of the oedometric deformation modulus E_{oed} (determined E_{Doed} and estimated E_{Eoed}) among three main soil behaviour types (sand mixture, silt mixture and clay mixture): (a) Variation of the regression model of the determined oedometric modulus (E_{Doed}) across the investigated till soil mixtures under 0.2 MPa stress; (b) Variation of the regression model of the estimated oedometric modulus (E_{Eoed}) across the investigated till soil mixtures under 0.2 MPa stress; (c) Variation of the regression model of the determined oedometric modulus (E_{Doed}) across the investigated till soil mixtures under 0.4 MPa stress; (d) Variation of the regression model of the estimated oedometric modulus (E_{Eoed}) across the investigated till soil mixtures under 0.4 MPa stress

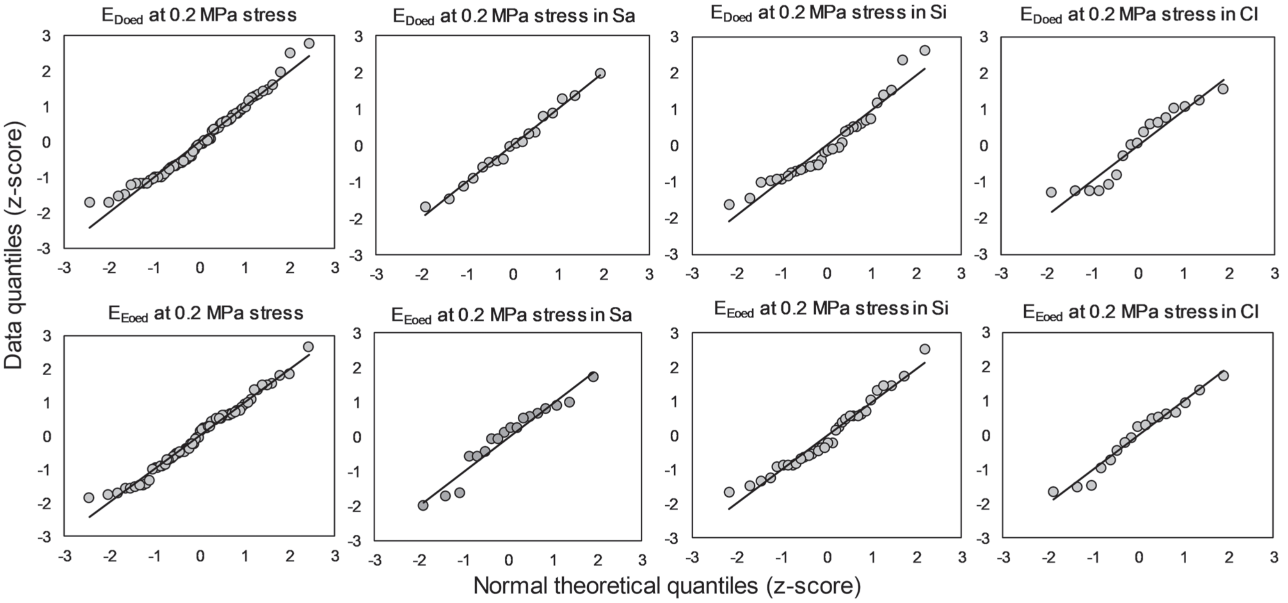

Fig. 15 Probability (Q–Q) plots for the determined E_{Doed} (above) and estimated E_{Eoed} (below) oedometric deformation moduli across the investigated till soil mixtures under 0.2 MPa stress: Sa – sand mixture; Si – silt mixture; Cl – clay mixture

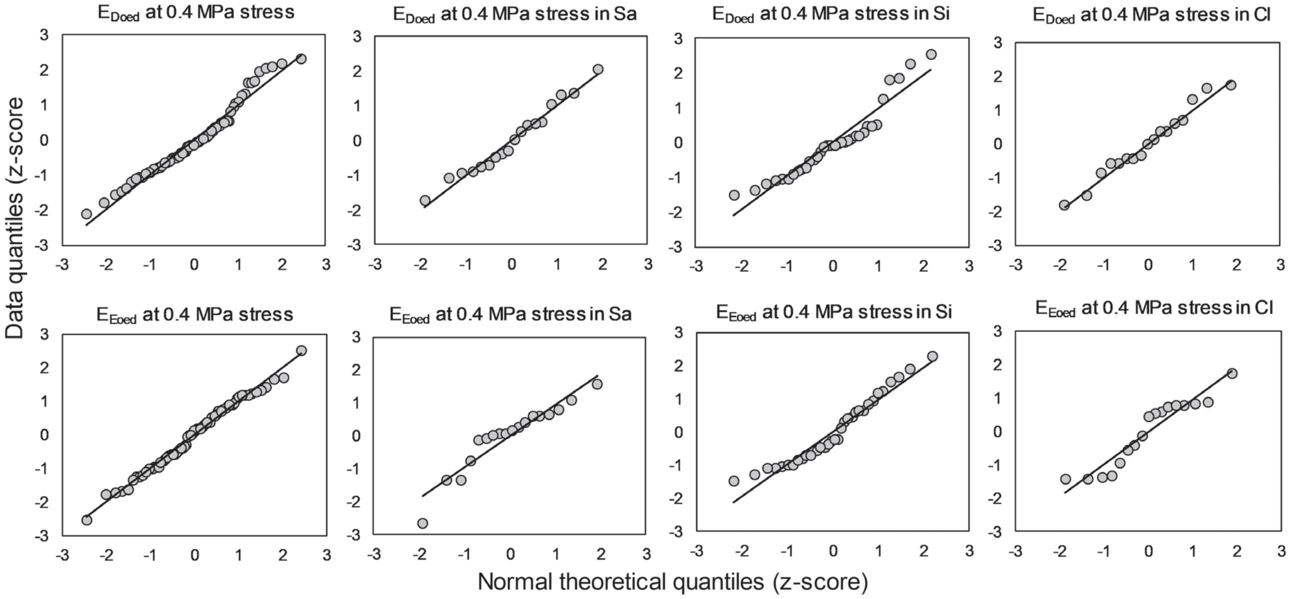

Fig. 16 Probability (Q–Q) plots for the determined E_{Doed} (above) and estimated E_{Eoed} (below) oedometric deformation moduli across the investigated till soil mixtures under 0.2 MPa stress: Sa – sand mixture; Si – silt mixture; Cl – clay mixture

sion, which means that more data are located at the extremes of the distribution and fewer data in the distribution centre. The distribution of values for clay mixtures is visualized in the box plot (14 d), showing a wider IQR.

CONCLUSIONS

1. Soil grain size distribution plays no role in distinguishing soil types according to I_C where clay amount in soil does not exceed 10–15%. However, the I_C index is more affected by plasticity properties of the soil, which is a mixture of clay, silt, sand and gravel, where the average amount of fine (clay) fraction exceeds 9%.

2. There was no direct relationship found between the oedometer modulus and the cone resistance of the analysed soil mixtures under the stress of the investigated levels.

3. The strongest correlation was found to exist between the determined E_{Doed} and the estimated E_{Eoed} by analysing the relationship among content of natural

soil water, the amount of fine fraction (clay), and the cone strength resistance of the soils under study.

4. Regression models are proved and are reliable only for the regressor limitation intervals. The acceptable limit for the models is water content within the range of 7.7–15.4%, silt fraction within the range of 4.0–20.0%, and cone resistance within the range of 1–5 MPa.

5. A similar determination index is observed only for sand mixtures when comparing the model equations for the stress levels of 0.2 and 0.4 MPa. Notable variations in the determination index are observed for silt and clay mixtures subjected to different stress levels. The suitability of the model decreases with the stress level increase from 0.2 to 0.4 MPa, in the case of which the determination index decreases from 41 to 23%.

6. The interquartile range for the determined and estimated values of the deformation modulus at 0.4 MPa stress level is more compacted than that for the respective deformation modulus values at 0.2 MPa stress level, which can be explained by the start of soil consolidation, and, therefore, a lower dispersion of the determined and estimated deformation modulus values.

7. The performed statistical analysis revealed that values of the estimated E_{Eoed} are less dispersed than those of the determined E_{Doed}. Values of the estimated E_{Eoed} modulus of clay mixture under 0.4 MPa stress are more dispersed than the respective values of silt and sand mixtures. The estimated E_{Eoed} modulus values of clay mixtures are more scattered than the determined E_{Doed} values of clay mixtures subjected to 0.4 MPa stress.

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