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Overview of the Quaternary sediments deformation modulus dependence on testing methodology

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Abstract. The surface of earth on the territory of Lithuania is covered by sediments of the Quaternary system, which are the object of human economic activities. Reliable assessment of sediment deformations is an important task of modern engineering geology and geotechnical engineering. The deformation of sediments is most often described using the modulus of deformation. The current article overviews different methods employed in deformation moduli determination and their application possibilities. The deformation moduli, which are used in various calculations, are usually calculated using correlation formulas and empirical coefficients. Thus, the obtained results may be inaccurate or completely unsuitable for further interpretation of the numerical situation. This article presents recommendations with regard to the use of various calculated deformation moduli in interpreting Lithuanian Quaternary system sediments.

Keywords**:** *secant modulus of deformation; residual modulus of deformation; dynamic modulus of deformation; oedometer; triaxial compression test apparatus; CPT*

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INTRODUCTION

Human economic activities undertaken on the territory of Lithuania most often encompass only the strata of quaternary sediments up to a depth of 20–30 m, in rare cases deeper. Quaternary continental sediments are formed by glaciers and glacial meltwaters. The thickness of these sediments is different. Depending on the surface of pre-quaternary rocks, the thickness of quaternary coating may vary from several meters to 200–300 m. In North Lithuania, the Quaternary cover is the thinnest due to the prevailing glacial erosion. In territories of highlands and in buried valleys, the Quaternary cover is the thickest (Šliaupa 2004; Guobytė, Satkūnas 2011). Quaternary sediments are used directly as a foundation and as a medium for engineering structures. From the engineering-geological point of view, Quaternary sediments are classified as soils because they are loose or poorly cemented natural mineral materials. The most common and important from the engineering point of view are glacial (moraine), glaciolacustrine and glaciofluvial soils. The assessment of deformations of these soils is one of the most important tasks in geotechnical calculations, which are one of the main parts in engineering calculations of structure (Urbanavičienė, Skuodis 2019). The bearing capacity and deformations of the existing or designed foundations, retaining walls, soil embankments, ground anchors, underground passages or car traffic tunnels, and slopes are checked by means of geotechnical calculations (Medzvieckas, Gadeikis 2002; Gabrielaitis *et al.* 2013; Medzvieckas, Sližytė 2012), which are performed using physical and mechanical parameters of soil. When assessing soil deformations, it is very important to know the intensity of future loads and the type of the foundations structure. The knowledge of these data allows making the right choice as to which type of soil and what magnitude and intensity of loads should be investigated. As engineering geological and geotechnical investigations often precede design work, the intensity of loads on foundations and the type of structure are still not known. Researchers decide for themselves which type of tests should be performed and what intensity of loads should be used. This is best illustrated by the oedometric deformation modulus test when the intensity of loads on foundations is not known and the most often vertical stress varies from 100 kPa to 500 kPa. The modulus of deformation estimated for such a range of stresses may prove to be several times higher or lower than the one required in reality (Lekstutytė *et al.* 2019).

One of the main indicators describing soil deformations is the deformation modulus E. This indicator may be estimated directly or based on correlation dependencies: oedometer test, cone penetration test (CPT), triaxial compression test, etc. (Skuodis *et al.* 2017; Žaržojus, Kelevišius 2016; Dirgėlienė 2013; Robertson, Cabal 2015). However, values of the deformation modulus calculated applying different methods and different loads differ, in some of the calculated situations being correct, but incorrect in others, the obtained final result being misleading.

The purpose of this article is to provide an overview of the different test methods used for estimating the deformation modulus and to explain the use and applicability of differently estimated soil deformation moduli for solving various geological, engineering geological and geotechnical tasks.

METHODS FOR ESTIMATING MODULUS OF DEFORMATION

All the test methods listed in this section must be performed in accordance with the corresponding standards. It should be borne in the mind of engineers and/or investigators that the methods used in investigating different soil types (cohesive, non-cohesive) differ substantially. The loads to test and the methods to employ must be chosen with respect to the existing construction or the one that is under design. Tests should be carried out on maximum, minimum and on intermediate loads. The number of loading tests to be performed should be not less than the one specified in the relevant standard.

Dynamic modulus of deformation E_{vd}

The dynamic devices that are most often used for checking the quality of loose soil compaction were invented in the late 1970-ies (Tompai 2008). The thickness of the tested soil layer depends on the diameter of the plate of the device, i.e. the bigger the diameter, the thicker the tested layer is (Tirado *et al.* 2015; Koukoulidou *et al.* 2017). The thickness of the tested layer, as indicated in relevant literature, is approximately 30–50 cm (Kamal *et al.* 2018; ZTVE–StB 09:2009). The tests performed using a lightweight dynamic device are standardized in the USA and Germany, ASTM 2583 and TP BF-StB Part B 8.3 respectively, however in Lithuanian standards (STR 1.04.02:2011; STR 2.05.21:2016), recommendations (R IGGT 15:2015) and structure rules (ST 188710638.06:2004), these tests are merely mentioned, and there is no valid standard according to which these tests should be performed.

The dynamic modulus of deformation E_{vd} is estimated in tests using dynamic devices. The two most often used types of devices are a dynamic plate and a falling weight deflectometer (Fig. 1). When measurements are made using dynamic devices, the load is produced by the impact of a falling cylinder on a

Fig. 1 On the left side – dynamic plate, on the right – a falling weight deflectometer (https://www.dynatest.com/)

certain area over a very short time period (Bertulienė 2011). The deflection of a foundation caused by the cylinder impact is used to calculate the dynamic modulus of deformation. Based on the elasticity theory (Mikolainis *et al.* 2016), the general formula for the dynamic modulus of deformation may be as follows:

$$E_{vd} = \frac{1-v^2}{2} \cdot \frac{P}{r \cdot s}. \quad (1)$$

E_{vd} – dynamic modulus of deformation, MPa, v – Poisson's ratio, r – plate diameter, m, P – force into plate, MN.

Static modulus of deformation E_v

The static modulus of deformation E_v, which is used in assessing road foundations, is estimated in a test using a static plate (Fig. 2). During the test, a certain area of the foundation structure (plate) is gradually loaded and unloaded (White, Vennapusa 2017; Bertulienė 2011). The modulus of deformation is calculated by the following equation:

$$E_V = 1{,}5 \cdot r \cdot \frac{1}{\alpha_1 + \alpha_2 \cdot \sigma_{0max}} \quad (2)$$

E_v – static modulus of deformation, MPa, r – plate radius, m, σ_{0max} – the highest average normal tension in the first loading cycle, MN/m^2, α_1 – 2nd degree polynomial constants, mm/(MN^2/m^2), α_2 – 2nd degree polynomial constants, mm/(MN^2/m^4).

The polynomial constants are calculated from the values measured in the first and second load cycles as follows:

$$\alpha_0 \cdot n + a_1 \sum_{i=1}^{n} \sigma_{0i} + a_2 \sum_{i=1}^{n} \sigma_{0i}^2 = \sum_{i=1}^{n} s_i \quad (3)$$

$$a_0 \sum_{i=1}^{n} \sigma_{0i} + a_1 \sum_{i=1}^{n} \sigma_{0i}^2 + + a_2 \sum_{i=1}^{n} \sigma_{0i}^3 = \sum_{i=1}^{n} s_i \cdot \sigma_{0i} \quad (4)$$

$$a_0 \sum_{i=1}^{n} \sigma_{0i}^2 + a_1 \sum_{i=1}^{n} \sigma_{0i}^3 + + a_2 \sum_{i=1}^{n} \sigma_{0i}^4 = \sum_{i=1}^{n} s_i \cdot \sigma_{0i}^2 \quad (5)$$

α_0 – 2nd degree polynomial constants, mm, σ_{0i} – average normal tension below loading on the plate, MN/m^2, s_i – static plate sediment, mm.

Fig. 2 Static plate load test (https://www.hmp-online.com)

The index that is assigned to the modulus of deformation E_v depends on the loading cycle, e.g. E_{v1} – modulus of deformation after the first loading cycle, E_{v2} – after the second one. The thickness of the tested soil layer depends on the plate diameter just like in the tests performed using dynamic devices. When a foundation is affected by a static load, stress spreads vertically to a distance, which is 1.5–2 times bigger than the diameter of the plate (Tang *et al.* 2017; Smith 2014). In Lithuania, this test is regulated by the standard LST 1360-5:2019, which specifies three different plate diameters: 300 mm, 600 mm and 762 mm. In this case, static load stresses may spread within a range of 60–152 cm. As the use of plates with a smaller diameter results in a bigger subsidence, the use of small diameter plates for testing sands and fine soils is not allowed (clays, silt and their mixes).

Oedometric modulus of deformation E_{oed}

One of the laboratory test methods that is most widely used to determine the modulus of deformation is the oedometer test. This test is performed with an oedometer apparatus (Fig. 3). A sample is placed into a steel cylinder, with porous stones placed at the top and at the bottom of the sample. The load transmitted through the porous stones causes deformations in the sample, which are then measured (Maleksaeedi 2018; Smith 2014). The oedometric modulus of deformation is estimated (LST EN ISO 17892-5:2017; Prušinskienė 2012) as follows:

$$E_{oed} = \frac{\delta \sigma'_V}{\delta \varepsilon'_V} \quad (6)$$

$\delta\sigma_v$' – change in stresses between the last loading stage and the tested loading stage, $\delta\varepsilon_v$' – change in relative deformations during the loading stage, regarding the height of the sample at the start of loading.

In Lithuania, this test is regulated by the standard LST EN ISO 17892-5:2017 „Geotechnical investigations and testing. Part 5. Incremental loading oedometer test".

Secant modulus of deformation E_{50}

Improvement in the numerical modelling of soil behaviour allows using various parameters, which help define soil mass behaviour in detail. Most soils have been noticed to exhibit nonlinear behaviour (Dolarevic, Ibrahimbegovic 2009; PLAXIS 2019), which can be described using the secant modulus of deformation (Choobbasti, Kutanaei 2017; CEN ISO/TS 17892-9:2004) as follows:

$$E_{50} = \frac{(\sigma_1)_{50} - \sigma_{1c}}{(\varepsilon_1)_{50}} \quad (7)$$

$(\sigma_1)_{50}$ – the ratio between the maximum total stress at the time of failure of the sample and the maximum

Fig. 3 Oedometer device

Fig. 4 Triaxial test apparatus

total stress at the end of consolidation in the sample, MPa, σ_{1c} – the maximum total stress at the end of consolidation in the sample, MPa, $(\varepsilon_1)_{50}$ – corrected (due to possible erroneous displacements) vertical shortening at $(\sigma_1)_{50}$, MPa.

The secant modulus of deformation E_{50} is estimated using a triaxial compression test apparatus (Bogusz, Witowski 2019) (Fig. 4). Typically, this apparatus consists of a compression generating system, a compressor, a triaxial compression apparatus chamber, a constant speed transmission device, and an automatic data reading and transmission system (Dirgėlienė 2007). As the name of the apparatus implies, in this test, a sample of soil is affected by three normal stresses, and failure of the sample is achieved by increasing one of these stresses (Smith 2014; Ranjan, Rao 2000; Hatanaka *et al.* 2003).

In Lithuania, this test is regulated by standards LST EN ISO 17892-8:2018 "Geotechnical investigation and testing. Laboratory testing of soil. Part 8: Unconsolidated undrained triaxial test" and LST EN ISO 17892-9:2018 "Geotechnical investigation and testing. Laboratory testing of soil. Part 9: Consolidated triaxial compression tests on water saturated soils". Formula (7) is presented in the older edition of LST EN ISO 17892-9:2018 – CEN ISO/TS 17892-2:2004. The secant modulus of deformation E_{50} may be also estimated based on the results of pile foundations test with a static load or according to the correlation dependencies based on the acquired experience (Do, Pham 2018; Briaud 2001).

Residual modulus of deformation E_r

The residual modulus of deformation is one of the main parameters used in assessing and designing road foundations. It can be also used to ascertain the response of road foundation to traffic loads (Buchanan 2007). This indicator is determined using a triaxial compression test apparatus, which allows cyclic loading of soil samples (Fig. 4). To stabilize relative deformations of the sample, during the test, cyclic stabilization of material is performed by applying cyclic loading to the sample (Fedrigo *et al.* 2018; LST EN 13286-7:2004). The residual modulus of deformation is determined as follows:

$$E_r = \frac{{\sigma_1^r}^2 - \sigma_1^r \sigma_3^r - 2{\sigma_3^r}^2}{\sigma_1^r \varepsilon_1^r + \sigma_3^r \varepsilon_1^r - 2\sigma_3^r \varepsilon_3^r} \tag{8}$$

σ_1^r – residual axial stress, kPa, σ_3^r – residual radial stress, kPa, ε_1^r – residual or restored axial relative deformation, ε_3^r – residual or restored radial relative deformation.

Based on the test results, deformation modulus values as well as parameters for analytical and numerical nonlinear foundation modelling may be determined at various stresses, (LST EN 13286-7:2004; Skuodis *et al.* 2018). In Lithuania, this test is regulated by the standard LST EN 13286-7:2004 "Unbound and hydraulically bound mixtures. Part 7: Cyclic load triaxial test for unbound mixtures“.

Modulus of deformation E_{CPT} according to data of CPT tests

One of the most common soil engineering research methods in Lithuania is the cone penetrometer test (Fig. 5). This test involves pressing a cone penetrometer into the investigated soil so as to determine the resistance of the soil to the cone (q_c) penetration as well as soil friction with the friction joint (f_s) (Robertson 2016; LST EN 1997-2:2009). This article reviews only the current normative documents, which describe dependencies between q_c and E_{CPT}. In accordance with the standard valid in Lithuania LST EN 1997-2:2009 “Eurocode 7. Geotechnical design. Part 2: Ground investigation and testing“ and the “Recommendations for design engineering geological and geotechnical investigations” (Projektinių…2015) published by the Lithuanian Geological Survey (LGT), the modulus of deformation may be calculated according to the following correlational dependencies:

$$E_{oed} = \alpha \cdot q_c \text{ (LST EN 1997-2:2009)} \quad (9)$$

$$E_{CPT} = 3 \cdot q_c \text{ (LGT recommendations (Projektinių… 2015) for sand and gravel)} \quad (10)$$

E_{oed} – oedometric modulus of deformation, MPa, E_{CPT} – modulus of deformation, MPa, q_c – resistance to cone penetration, MPa.

Using this method, it is not difficult to determine the deformation modulus of all soil layers investigated with a penetrometer. Performance of this test is regulated by LST EN ISO 22476-1:2012 “Geotechnical investigation and testing. Field testing. Part 1: Electrical cone and piezocone penetration test“.

STUDY RESULTS SUMMARY

The deformation modulus of intact structure soil samples of various genesis, which were collected from various localities of Lithuania, was investigated. The data reported by Martinkus (2016) and Lekstutytė *et al.* (2019) were also included into the analysis and the interpretation of the results obtained. The results of the investigation are presented in Table 1. Most of the data were obtained from the calculations of CPT data and from the oedometric test. As can be seen from the data presented, E_{CPT} correlates with E_{oed} only for the modulus of deformation, which was estimated at the vertical stress (σ_v) of 750–790 kPa (Fig. 6). Correlation coefficient R = 0.85, determination – R^2 = 0.73. This fact indicates that it is necessary to know load intensities and the limits of their variation when assessing or calculating values of the deformation modulus, as randomly selected values may be erroneous.

The value reported by Lekstutytė *et al.* (2019) and presented in Table 1 (the last value in Table 1) refers to a different glaciation, i.e. all the values refer to the upper Pleistocene, Nemunas glaciation, Baltija (IIIbl) and Grūda (IIIgr) stages, whereas the last one to the Medininkai glaciation (IImd), the middle Pleistocene. As gIImd values significantly differ from all the others, additional investigations should be carried out and the glaciation age needs to be included into analysis to check values. That is why the last results from Table 1 were not included into Figure 6.

EVALUATION OF TEST RESULTS AND RECOMMENDATIONS

Not all the deformation moduli that are determined using various methods are suitable for evaluating typical engineering geological and geotechnical situations. Field and laboratory testing methods most often imitate soil loading in natural conditions *in-situ*. From this, preliminary conclusions can be drawn about the suitability of the test results for the task at hand.

The dynamic modulus of deformation E_{vd} estimated using dynamic devices is rarely applied in typical engineering geological and geotechnical calculations,

Fig. 5 Cone penetration test

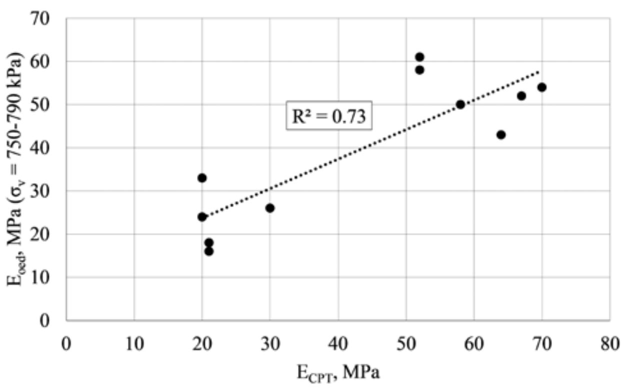

Fig. 6 Correlation of deformation moduli E_{CPT} and E_{oed} when σ_v ranges from 750 kPa to 790 kPa

Table 1 Investigation results

Soil type	Geological index	q_c, MPa	E_{CPT}, MPa	E_{oed}, MPa						E_{vd}, MPa	$E_{50,}$ MPa
				Vertical stress, σ_v, kPa							
				25	50–75	150–175	350–370	750–790	1550		
Fine sand	fIIIgr	14	52		5	15	31	58			
Fine sand	fIIIgr	18	64		7	14	30	43			
Fine sand	fIIIgr	16	58		5	13	29	50			
Fine sand	fIIIgr	20	70		10	20	35	54			
Medium coarse sand	fIIIgr	14	52		7	13	33	61			
Fine sand	fIIIgr	19	67		6	14	33	52			
Medium coarse sand *	tIV	5	25							23	
Sandy dusty clay	gtIIIbl	3	30	3	4	7	13	26			
Clay of average plasticity	lgIIIbl	3	21		2	5	9	16			
Clay of average plasticity	lgIIIbl	3	21		1	6	10	18			
Clay of low plasticity	gtIIIbl	2	20		3	6	13	24	43		
Clay of low plasticity	gtIIIbl	2	20		1	7	15	33	55		
Clay of low plasticity **	gIImd	7	70			7	12	23			14

Soil genesis: g – glacial (moraine), gt – glacial marginal (end-moraine), f – glaciofluvial, lg – glaciolacustrine, tIV – technogenic (Holocene age).
* Data taken from the article by Martinkus (2016); ** Data taken from the article by Lekstutytė *et al.* (2019), but not included into Fig. 6, because they refer to a different soil age.

whereas the falling cylinder imitates only a one-time ultra-short loading situation. The dynamic modulus of deformation is applied to checking the quality of soil compaction (Jitareekul 2017; Sližytė *et al.* 2012). It is advisable not to rely on results of this test completely, but rather to examine the recommendations on the use of the test device and the normative documents applicable for such tests in detail. Also, it should be borne in mind that in this test, the short-time stress in soil must not exceed approximately 280 kPa (Fig. 7).

The application of the static modulus of deformation E_{v2} as estimated by a static plate is much wider than that of the dynamic modulus E_{vd}. As can be seen from the static plate test examples presented in LST 1360-5:2019, the load transmitted by a static plate to ground may reach 500 kPa (Fig. 7). Therefore, the obtained results can be used for evaluating the bearing capacity of the structures that are similar to a shallow foundation. It is important to remember that the distribution of stresses in a foundation depends on its dimensions. Therefore, in order to use the static modulus of deformation, obtained in a static plate test, it is necessary to make sure that the shallow foundation under design or the tested one has a contact surface area similar to that of a static plate.

The deformation modulus estimated using an oedometer may be applied in calculations of various structures: embankments, shallow foundations, retaining walls. The modulus of deformation is most often estimated using this apparatus when vertical stress value does not exceed 1000 kPa, although some apparatuses can generate vertical stress up to 4000 kPa (Wille 2010). Oedometer test results are exact, because the deformation of a sample in a vertical direction makes it easier to determine relative deformations, to ensure constant vertical stress.

When the structure is sensitive and soil behavior is non-linear, e. g. underground passages or car traffic tunnels constructed from thin corrugated steel sheets (Fig. 8), the ability of soil to deform is interpreted based on the secant modulus of deformation E_{50}. It is very important to know the future vertical stress ranges in the investigated foundation. Typically, vertical stress in soil above corrugated culverts or tunnels varies from 100 to 1000 kPa. Most often, the secant modulus of deformation for soils can be estimated using a triaxial compression test apparatus up to the vertical stress value of 2000 kPa (Fig. 7).

When the ground is affected by cyclic loading, e. g. roads, to calculate settlement, the residual modulus of deformation E_r is applied. Detailed calculations of concentrated loads of cars, trucks, aircrafts or special transport have shown that vertical stresses in foundations may reach 1500 kPa. Therefore, as it was mentioned above, it is important that intervals of design loads should be evaluated prior to tests with a triaxial compression test apparatus (Fig. 4).

The modulus of deformation $E_{CPT,}$ which is estimated in the cone penetration test, is suitable for calculating deformations of pile foundations base: during the test, stress at the cone surface may reach 50 MPa, stress under the pile bottom, according to LST EN 1997-2:2007, is limited to 15 MPa, therefore, if stress under the pile bottom is 2–15 MPa (Fig. 7), it is appropriate to use the modulus of deformation E_{CPT}, estimated in the cone penetration test.

The stress limits investigated using the above listed different methods for determining deformation moduliare presented in Fig. 7. For engineering aplication exemplary construction scheme of Skuodis

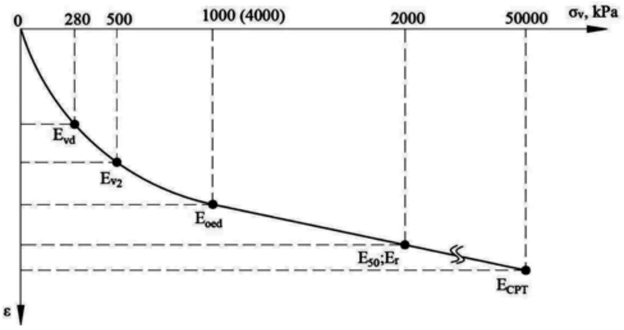

Fig. 7 Stress limits for the deformation moduli derived from different tests

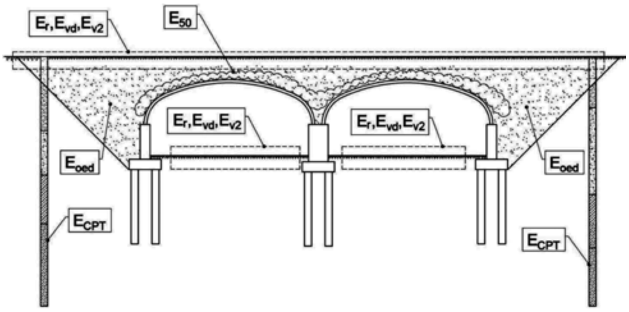

Fig. 8 Deformation moduli for calculations of typical geotechnical situations (underground passages or car traffic tunnels covered with compacted natural soil made of thin sheets of corrugated steel)

and Tamošiūnas (2019) was improved, in which the places are marked to calculations of typical geotechnical situations with required methods of determination of deformation moduli (Fig. 8).

The exemplary construction scheme devised and improved for engineering application by Skuodis and Tamošiūnas (2019) indicates the sites that warrant calculations of typical geotechnical situations by relevant methods for deformation moduli determination.

These recommendations are valid only for natural undisturbed soil types including the technogenic soil (tIV) given in Table 1. For other remoulded soil types, separate assessments should be carried out.

CONCLUSIONS

The analysis of the data showed that the value of the deformation modulus depends not only on the chosen test load, but also on the test methodology. The current study revealed that the modulus of deformation determined employing different methods shows different values in the same soils.

The dynamic modulus of deformation (E_{vd}), the static modulus of deformation (E_{v2}) and the residual modulus of deformation (E_r) should be used in designing foundations and checking the quality of soil compaction.

The modulus of deformation (E_{oed}), which is estimated using an oedometer, can be applied to calculations of various structures: embankments, shallow foundations, retaining walls.

When soil behaviour is non-linear, e. g. underground passages or car traffic tunnels are constructed from thin corrugated steel sheets, the secant modulus of deformation E_{50} should be used.

The modulus of deformation E_{CPT}, which is estimated by conducting the cone penetration test, is suitable for calculating deformations of the pile foundation base if stress under the pile bottom is within the range of 2–15 MPa.

As for further investigations, it is recommended to include more test data in the correlation study.

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