



Neringa DIRGĖLIENĖ

**RESEARCH OF SOIL SHEAR STRENGTH
IN TRIAXIAL TESTS AND PROBABILISTIC
ASSESSMENT OF RESULTS**

**Summary of Doctoral Dissertation
Technological Sciences, Civil Engineering (02T)**

1433

Vilnius  **2007**

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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The summary of the doctoral dissertation was distributed on 20 November 2007.

A copy of the doctoral dissertation is available for review at the Library of Vilnius Gediminas Technical University (Saulėtekio al. 14, LT-10223, Vilnius, Lithuania).

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VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

Neringa DIRGĖLIENĖ

**GRUNTO STIPRUMINIŲ IR DEFORMACINIŲ
SAVYBIŲ TYRIMAS TRIAŠIO SLĖGIO
APARATE BEI JŲ TIKIMYBINIS VERTINIMAS**

Daktaro disertacijos santrauka
Technologijos mokslai, statybos inžinerija (02T)

Vilnius  2007

Disertacija rengta 2002–2007 metais Vilniaus Gedimino technikos universitete.

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Disertacija bus ginama viešame Statybos inžinerijos mokslo krypties tarybos posėdyje 2007 m. gruodžio 20 d. 14 val. Vilniaus Gedimino technikos universiteto senato posėdžių salėje.

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Disertacijos santrauka išsiuntinėta 2007 m. lapkričio 20 d.

Disertaciją galima peržiūrėti Vilniaus Gedimino technikos universiteto bibliotekoje (Saulėtekio al. 14, LT-10223 Vilnius, Lietuva).

VGTU leidykla „Technika“ 1433 mokslo literatūros knyga.

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General characteristic of the dissertation

Topicality of the problem. Necessary information about soil properties, which is needed for designers and constructors, is obtained in each construction site while examining physical and mechanical properties of soils. Soil strength parameters and using them determined soil bearing resistance usually are defined with some errors. If we know the reasons of errors, disadvantages of testing equipment could be eliminated, methodology of data evaluation could be developed, soil parameters could be determined more precisely and foundation designed more economically.

At present triaxial and direct shear tests are the most common tests for determination of soil shear strength parameters in laboratories. Different values of soil shear strength parameters are determined using laboratory equipment of various types. Triaxial test is the most widely used method for determination of soil shear strength parameters. This is one of the most reliable methods to model stress-strain state of ground. It is assumed that soil sample deforms uniformly during the triaxial test. But it is not often the case that a sample in triaxial apparatus deforms uniformly. Questions arise, what is stress-strain distribution in soil sample, when a load is transmitted in a prescribed way? What influence does a non-uniformity have on the soil strength parameters and on foundation size calculated using determined soil strength parameters? Why sandy soil strength parameters obtained from triaxial test are bigger than the one's, obtained from the direct shear test?

According to currently valid geotechnical design standards soil bearing resistance can be calculated applying partial factors method, or partial factors method in addition doing the tests, or applying direct informational-statistic method. Partial factors method doesn't assure an equal ground failure probability. Applying statistic-probabilistic methods, it is possible to design foundations of a chosen reliability. Lithuania's design regulations recommended SECANT method allows to calculate design condition arguments which makes the highest influence on the uncertainty of margin of soil bearing resistance. According to this trying to reduce the uncertainties, it is possible to foresee the directions of further investigations. The investigations carried out show that the highest influence on the uncertainty of margin of soil bearing resistance is made by the of angle of internal friction and cohesion. Therefore, it is essential that these strength parameters should be determined as precisely as possible. This would enable to achieve the economy of materials and labour expenditures for the construction of foundations without decreasing reliability of soil bearing resistance.

Aim of the work – to improve the triaxial compression test of soil for determination soil strength parameters as precisely as possible and using them to forecast the soil bearing resistance more reliable.

Tasks of the work. In order to achieve the aim of the work, these tasks were formulated:

1. To analyse stress distribution in the soil sample during triaxial test and influence of sample boundary conditions on the soil strength parameters.
2. To prove in experimental way that the horizontal component of stress in horizontal cross-section in the case of soil axisymmetric test is distributed non-uniformly.
3. To analyse theoretically sandy soil sample height/diameter ratio influence on the soil shear strength in triaxial test.
4. To investigate experimentally the influences of sample height/diameter ratio and free horizontal movement of sample base on the soil shear strength.
5. To determine the influence of free horizontal movement of sample base by the numerical modeling method on soil stress-strain distribution in the sample.
6. To prove determination of design values of soil strength parameters applying the probabilistic-statistic method and using them to evaluate soil strength reliability.

Scientific novelty. Novelty of the work is showed by:

1. Review of literature suggests that in order to get a more uniform stress-strain distribution in soil sample during triaxial test, it is necessary to reduce the sample height/diameter H/D ratio from 2 to 1 and to eliminate friction between the sample ends and the plates. The results obtained show that the values of the angle of internal friction φ and cohesion c of samples with $\varphi \neq 0$ are increased. For determination of soil shear strength parameters the decrease of sample H/D ratio till 1 is recommended only for soils with $\varphi = 0$.
2. It is experimentally proved that the horizontal component of stress in case of axisymmetric circular test in the middle of the sample cross-section is smaller than at the ends of the sample cross-section.
3. The theoretical analysis has shown that soil shear strength depends on the height/diameter ratio of the soil sample.

4. Comparison of test results obtained in triaxial apparatus for dense sand sample with free horizontal movement of base and for sample with regular ends shows that shape of graphs $\varepsilon_1 = f(\sigma_1 - \sigma_3)$ are different.
5. The residual soil shear strength parameters are different for soil sample with free horizontal movement of sample base and for sample with regular ends. Mean values of the tangent of angle of internal friction obtained from values of vertical component of stress, when axial relative deformation ε_1 is equal to 15 % for sample with free horizontal movement of base are up to 15 % smaller than for sample with regular ends. Mean values of cohesion are smaller in 42 %.
6. Foundation width calculated using results of usual triaxial test according to the residual shear strength parameters are 23 % smaller than values calculated using results of improved apparatus.

Methodology of research

1. The literature analysis of stress state in soil sample during the triaxial compression test and analysis of influence of sample boundary conditions on soil shear strength parameters.
2. The experimental research of stress distribution in soil sample during triaxial test and sample boundaries conditions influence on soil strength parameters.
3. A numerical modeling by COSMOS/M programme of influence of free horizontal movement of sample base on stress-strain distribution in soil sample during triaxial test.
4. Determination of the design values of soil shear strength parameters applying the probabilistic-statistic method and assessment of soil bearing resistance reliability by solving optimization problem.

Practical value

1. It was proposed method for reducing restraint effects of sample ends on soil shear strength testing by improved triaxial apparatus with free horizontal movement of sample base. It enables to determine soil shear strength parameters more accurately.
2. It was proposed method for calculation of argument design values of soil bearing resistance design condition which would satisfy the design conditions itself and the probability function of these values would be at maximum.
3. It was proposed method for calculation of soil bearing resistance applying probabilistic-statistic methods without using partials factors.

Defended propositions

1. It was proposed method to sustain experimentally that the horizontal component of stress in the sample cross-section distribute non-uniformly in the case of axisymmetric circular test.
2. By using numerical modeling there has been shown that the vertical component of stress in soil sample with free horizontal movement of base is different in comparison with the vertical component of stress for sample with regular ends when the same vertical displacement acts on top surface of samples.
3. Increased values of soil shear strength parameters are determined by standard triaxial test. Design values of the tangent of angle of internal friction obtained from values of vertical component of stress, when relative axial deformation is equal to 15 % for sample with free horizontal movement of base are up to 10,8 % smaller than for sample with regular ends. Design values of cohesion are smaller in 43 %.
4. Reliability of soil bearing resistance is different designing according to partial factors method because of determined partial factors are used. Arguments design values of the ultimate limit state of soil bearing resistance depend on the derivatives of resistance margin according to each argument and standard deviations of arguments.
5. It is advisable to design ground using probabilistic-statistic methods without applying partial factors method.

The scope of the scientific work. The scientific work consists of the general characteristic of the dissertation, 5 chapters including general conclusions and proposal, list of literature, list of author's publications and addenda. The scope of the dissertation – 92 pages without addenda, 66 pictures, 14 tables and 2 addenda.

1. Review of methods for determination of soil shear strength parameters

Literature analysis of experiments and numerical modeling shows that stress-strain distribution in soil sample is not uniform during triaxial test. The main reasons mentioned in the literature are: not only normal stress on soil sample surface acts, as usual is assumed, also tangential stress acts; influence of sample height/diameter ratio; insufficient drainage; membrane effects, etc. Maybe these reasons decide that values of sandy soil strength parameters, obtained from triaxial test are higher than the one's, obtained from the direct shear test.

Limit states method in the normative documents СНиП and EN 1997 is used for the calculation of foundations. It does not design rational foundations using partial factors. Normative documents do not present common calculation method of partial factors. Eurocodes and Lithuania's design regulations provide information regarding structure resistance reliability evaluation methods without use of partial factors. These methods are most generally used for partial factors calibration or the purposes of comparing construction reliability, these methods are applied indirectly. According to the currently valid standards soil bearing resistance can be calculated applying direct informational-statistical (DIS) method. DIS designing may be carried out using SECANT method – secant second moments method. This method is applied to design future members, for assessment of existing members of construction works and standard calibration. While applying theoretical model of this method, the uncertainties of all the arguments $X_1, X_2, \dots, X_n$ that influence uncertainty of margin of resistance Z are taken into account. In addition, errors of models – $\Delta R, \Delta Z$ for calculation of resistance R and effect of actions E may also be evaluated. Margin of resistance is expressed as follows:

$$Z = R - E + \Delta R + \Delta Z = z(X_1, X_2, \dots, X_n). \quad (1)$$

DIS method is based on random values functions Z according (1) to the mean μ_Z probabilistic assessment problem. Limit states probabilistic calculation is made by solving the following equation system:

$$\begin{aligned} z(\mu_{X1}, \mu_{X2}, \dots, \mu_{Xn} | A) - \beta \sigma_z &= 0, \\ \frac{\Delta z(A)}{\Delta X_i} &= \left[z(\mu_{X1}, \mu_{X2}, \dots, \mu_{Xn} | A) - z(\mu_{X1}, \dots, \mu_{Xi} + \right. \\ &\quad \left. \beta \frac{\Delta z(A)}{\Delta X_i} \frac{\sigma_{Xi}^2}{\sigma_z}, \dots, \mu_{Xn} | A) \right] \cdot \beta \frac{\Delta z(A)}{\Delta X_i} \frac{\sigma_{Xi}^2}{\sigma_z}, \end{aligned} \quad (2)$$

$$i = 1, 2, \dots, n,$$

where

$$\sigma_z = \left[\sum_{i=1}^n \left(\frac{\Delta z(A)}{\Delta X_i} \sigma_{Xi} \right)^2 \right]^{0,5}, \quad (3)$$

where μ_{X_i} ir σ_{X_i} – the means and the standard deviations of normally distributed non-correlated random values $X_i, i = 1, 2, \dots, n$; if random values X_i are distributed not according to the normal law, then they are appropriately normalized; β – reliability index, i.e. parameter of the Laplacian-Gaussian function $\Phi(\beta)$; A – parameter of equation (1), e.g. cross-section of structure element, foundation area, etc, are calculated in the course of designing.

In order to determine which design condition argument makes the highest influence on the uncertainty of margin of resistance, the importance factor of argument should be calculated:

$$\alpha_{X_i}^2 = \left[\frac{\Delta z(A)}{\Delta X_i} \cdot \sigma_{X_i} \right]^2 / \sigma_z^2, \quad i = 1, 2, \dots, n. \quad (4)$$

2. Experimental analysis of soil shear strength parameters in triaxial test

For experimental approval that soil sample deforms non-uniformly during the triaxial test, in geotechnical laboratory a device was designed to analyse the distribution of horizontal component of stress in soil sample. Experimental findings of dense sand show that horizontal component of stress inside soil sample is distributed non-uniformly. 55–61 % higher horizontal component of stress was found in the sides of soil specimen cross-section and smaller was found in the centre of soil specimen.

Theoretical analysis of influence of sample H/D ratio on soil strength parameters has been carried out. The results obtained for sandy and clayey soils when sample height $H \geq D \cdot \tan(45^\circ + \varphi/2)$ show no influence of the sample H/D ratio on soil strength parameters. For determination of soil shear strength parameters the decrease of sample H/D ratio till 1, as recommended in literature, is recommended only for soils with $\varphi = 0$. This decrease does not have influence on clayey soil shear strength parameters.

Investigating dense sands during standard triaxial compression testing, failure plane forms up and separate parts of sample situated on the opposite sides of the plane are moving not only in vertical, but also in horizontal directions. Friction between the ends of sample and plates is resisting to horizontal displacements. Not only normal but also tangential stress on the ends of sample will act. Therefore, for calculation of shear strength design parameters it should be evaluated. If horizontal displacement of sample ends is

restricted higher values of vertical stress will be required to move soil sample parts respectively each other in comparison with non restricted displacements of ends.

In order to determine experimentally what influence of sample ends restraint makes on soil shear strength parameters, triaxial test apparatus has been improved (Fig 1), experiments have been carried out and influence of obtained results on soil bearing resistance have been evaluated. The friction between the sample ends and the plates was eliminated by allowing the sample base to move freely in the horizontal direction.

In the geotechnical laboratory, consolidated-drained triaxial tests on poorly-graded sand with fine (SP-SM) have been carried out. Samples with ratio $H/D = 2$ and $H/D = 1$ were used for experiments. Samples of 6 % water content have been prepared by compacting. Dense and loose samples properties were: density $\rho = 1,871 \text{ gr/cm}^3$, void ratio of $e = 0,51$ and $\rho = 1,610 \text{ gr/cm}^3$, $e = 0,74$. The samples of the same density under the same cell pressure have been sheared at least three times. Conditions of sample boundaries: in the first case, when the sample top cap can rotate, and the friction between the sample ends and the plates is not eliminated (regular ends) (Fig 1a); in the second case, when the sample top cap can rotate, and the friction between the sample base and plate is eliminated (free horizontal movement of sample base) (Figs 1b, 2, 3).

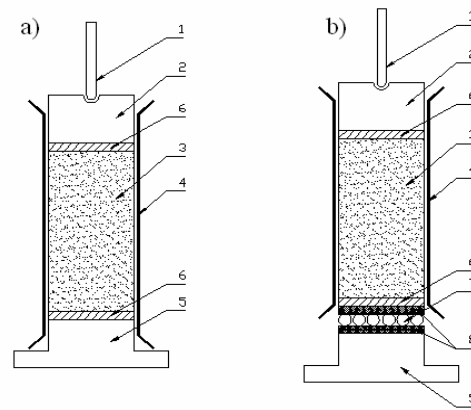


Fig 1. Triaxial samples: a) with regular ends (standard apparatus); b) with free horizontal movement of sample base (improved apparatus): 1 – rod; 2 – cap; 3 – soil sample; 4 – latex membrane; 5 – pedestal; 6 – porous stone; 7 – thrust bearing; 8 – stainless steel plates

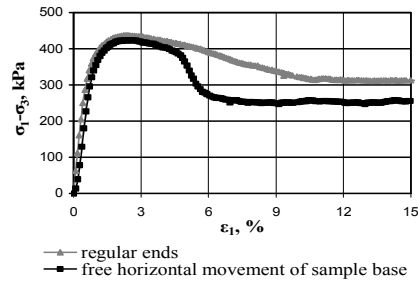


Fig 2. Stress-strain obtained in triaxial compression test on sand sample, which ratio $H/D = 2$



Fig 3. Triaxial test sample with free horizontal movement of sample base

Comparison of test results obtained in triaxial apparatus for dense sand sample with free horizontal movement of base and for sample with regular ends shows that shape of graphs $\varepsilon_1 = f(\sigma_1 - \sigma_3)$ are different (Fig 2). Values of vertical component of stress vary evenly till it research relative axial strain $\varepsilon_1 = 3\%$. In the first case of sample with regular ends, when the failure plane begins develop, vertical component of stress decreases evenly as the axial strain increases. In the second case of free horizontal movement of sample base, when the axial strain of 4–5 % is achieved, a significant vertical component of stress decrease is observed, then the curve declines very insignificantly, it remains stable. In this case vertical component of stress in the bottom of sample is up to 10 % smaller in comparison with vertical stress for sample with regular ends when relative axial deformation ε_1 is equal to 15 %.

Mean values of soil shear strength parameters (Table 1) were calculated by means of methods provided in design regulations. Mean values of the tangent of angle of internal friction obtained from maximum values of vertical stress σ_1 (peak angle of internal friction) in both cases differs insignificantly. Difference is no higher than 5 %. Mean values of the tangent of angle of internal friction obtained from values of vertical component of stress, when ε_1 is equal to 15 % (residual angle of internal friction) for sample with free horizontal movement of base are up to 15 % smaller than for sample with regular ends. Mean values of cohesion obtained from maximum values of vertical stress σ_1 (peak cohesion) are smaller in 31 %, when ε_1 is equal to 15 % (residual cohesion) are smaller in 42 %.

Table 1. Mean values of soil shear strength parameters

Porosity e and H/D ratio	Soil shear strength parameters		Standart apparatus	Improved apparatus
$e = 0,51$ $H/D = 2$	Peak	$\varphi, ^\circ$	36,6	38,0
		c, kPa	30,9	21,4
	Residual	$\varphi, ^\circ$	33,6	31,0
		c, kPa	17,8	10,3
$e = 0,51$ $H/D = 1$	Peak	$\varphi, ^\circ$	42,7	43,4
		c, kPa	27,2	23,9
	Residual	$\varphi, ^\circ$	38,5	39,3
		c, kPa	17,6	11,4
$e = 0,74$ $H/D = 2$	Residual	$\varphi, ^\circ$	26,8	28,3
		c, kPa	17,7	11,4
$e = 0,74$ $H/D = 1$	Residual	$\varphi, ^\circ$	31,7	32,03
		c, kPa	17,0	15,6

Free horizontal movement of soil sample base does not have influence on dense sand samples, which $H/D = 1$, and loose sand samples, which $H/D = 2$ and $H/D = 1$, strength parameters. H/D ratio of sample has influence on dense and loose sand strength parameters. The sandy soil potential failure plane is $45^\circ + \varphi/2$. If the sample H/D ratio equal to 1, soil sample is sheared at other angle, thus obtained values of σ_1 , φ , c are increased.

3. Numerical modeling of stress-strain distribution in soil sample during triaxial test

A numerical modelling was carried out by COSMOS/M programme which analyses stress-strain distribution in soil sample during triaxial test. Drucker-Prager model was used to simulate the behaviour of sand performing nonlinear analysis. Different parameters of soil were used for the sand specimen and for the failure plane. The parameters for the specimen: elasticity modulus – 50 MPa, mass density – $1,80 \text{ Mg/m}^3$, Poisson's ratio – 0,3, the cohesion – 25,97 kPa, the angle of internal friction – $37,9^\circ$; the parameters for the failure plane: elasticity modulus – 30 MPa, mass density – $1,67 \text{ Mg/m}^3$, Poisson's ratio – 0,45, the cohesion – 17,04 kPa, the angle of internal friction – $30,0^\circ$. The triaxial sample, 0,05 m in diameter and 0,10 m in height, was discretised into 4-node tetrahedral solid elements. Only three translational degrees of freedom are considered per node. Two principal diagrams were

designed: a) in the first case when the sample top cap can rotate, and the friction between the sample ends and the plates is not eliminated (regular ends). Displacement $u_y = \text{const}$ uniformly vertically acts on the top surface of the model and pressure $p = \text{const}$ acts on all surface of the model; b) in the second case when the sample top cap can rotate, and the friction between the sample ends and plates is eliminated. The friction is eliminated by allowing the sample base to move in the horizontal direction. Displacement $u_y = \text{const}$ uniformly vertically acts on the top surface of the model and pressure $p = \text{const}$ acts on all surface of the model.

As a result of analysis it was determined that, taking into account changed soil properties in the failure plane (area) and restriction of a sample ends horizontal movement, tangential stress in the sample-plate plane develops. Such tangential stress does not allow horizontal movement of sample ends. Modeling stress-strain distribution in sample with free horizontal movement of base, horizontal displacement of sample base was received. In this case vertical component of stress in the bottom of sample is up to 10 % smaller in comparison with vertical component of stress for sample with regular ends. Similar results have been obtained from experimentally tests in triaxial compression apparatus.

4. Assessment of reliability of soil strength parameters and soil bearing resistance

Design values of dense sand, which ratio $H/D = 2$, shear strength parameters were calculated by means of methods provided in Eurocode. Design values of the residual angle of internal friction obtained for sample with free horizontal movement of base are up to 10,8 % smaller than for sample with regular ends. Design values of the residual cohesion are lower in 43 %.

Design values determined using EN 1997 are not the most probable. Method was proposed to calculate arguments design values of the design condition which would satisfy the design condition $z_d = 0$ itself and the probability function of these values would be at maximum. Optimization problem according to the first order reliability method (FORM) is expressed as follows:

$$\begin{aligned} f(x_1, x_2, \dots, x_n) &\rightarrow \max \\ z_d = g_i(x_{1d}, x_{2d}, \dots, x_{nd}) &= 0, \end{aligned} \quad (5)$$

where $f(x_1, x_2, \dots, x_n)$ – the probability density function of limit state arguments;
 $g_i(x_{1d}, x_{2d}, \dots, x_{nd})$ – design condition.

Foundation width B has been calculated by recommendations of Eurocode according to the results of standard triaxial apparatus using the peak values and residual values of shear strength parameters. Values of B are respectively 4 % and 23 % smaller than B values calculated using the results of improved triaxial apparatus (Fig 4).

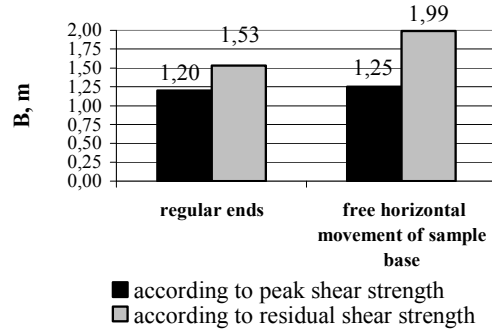


Fig 4. Values of foundation width B

Reliability index of soil bearing resistance designed according to EN 1997 and arguments values G_{d*} , Q_{d*} , $\tan\phi_{d*}$, c_{d*} , B_{d*} at design point have been calculated using the FORM method. It is accepted that permanent action G , variable action Q , soil strength parameters $\tan\phi$, c and foundation width B are random values whereas other arguments are known without deviations. Standard deviations are established according to the published findings.

It was determined that values of arguments G_{d*} , Q_{d*} , $\tan\phi_{d*}$, c_{d*} , B_{d*} at design point are different from design values G_d , Q_d , $\tan\phi_d$, c_d , B_d determined according to Eurocode. G_{d*} , Q_{d*} , c_{d*} values are smaller, while $\tan\phi_{d*}$, B_{d*} values are obtained higher than the design ones determined according to the design regulations. Values G_{d*} , Q_{d*} , $\tan\phi_{d*}$, c_{d*} , B_{d*} at design point satisfy the design condition, their probability density function at this point has the highest value, while the value of reliability index obtained is the smallest.

Calculations demonstrate that reliability index β for soil sample with free horizontal movement of sample base is higher than that of sample with regular ends. $\tan\phi$ of the latter samples is higher, thus the obtained foundation width B and reliability index β are smaller. In samples with free horizontal movement

of base, $\tan\phi$ decreases because friction between sample base and plates is eliminated, but B increases. Hence, foundation width calculated according to the results of standard triaxial tests is smaller than calculated according to soil strength parameters determined in the improved triaxial test apparatus.

Importance factors of argument G , Q , $\tan\phi$, c , B have been calculated according to formula (4). These importance factors demonstrate influence of soil bearing resistance design condition arguments on the uncertainty of margin of soil bearing resistance. Uncertainty of margin of bearing resistance is the most significantly influenced by the angle of internal friction and cohesion (Fig 5), therefore, it is essential that these shear strength

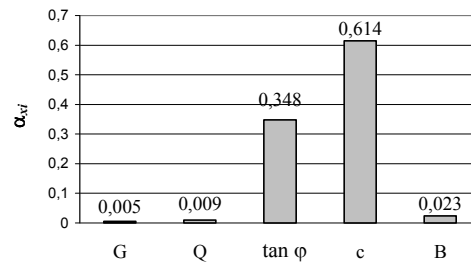


Fig 5. Influence of design condition arguments on the uncertainty of the margin of soil bearing resistance

parameters should be determined more precisely. This would enable to achieve the economy of materials and labour expenditures for the construction of foundations, without decreasing reliability of foundations.

5. General conclusions and proposal

1. Axisymmetric circular tests findings of dense sand show that horizontal component of stress inside soil sample is distributed non-uniformly. 55–61 % higher horizontal component of stress was found in the sides of soil specimen cross-section and smaller was found in the centre of soil specimen.
2. It was suggested method for reducing restraint effects of sample ends on soil shear strength testing by improving triaxial test apparatus with free horizontal movement of sample base.
3. Comparison of test results obtained in triaxial apparatus for dense sand sample with free horizontal movement of base and for sample with regular

ends (standard triaxial compression testing) shows that shape of graphs $\varepsilon_1 = f(\sigma_1 - \sigma_3)$ are different.

4. Design values of the residual angle of internal friction obtained for sample with free horizontal movement of base are up to 10,8 % smaller than values for sample with regular ends. Design values of the residual cohesion are smaller in 43 %. It explains proposition given in literature that sandy soil strength parameters obtained from triaxial test are higher than parameters, obtained from the direct shear test.
5. Foundation width was calculated using results obtained from standard triaxial test according the residual values of soil shear strength parameters are 23 % smaller than foundation width calculated using improved apparatus results.
6. Applying statistic-probabilistic methods it was determined that uncertainty of ground ultimate limit state design condition is the most significantly influenced by the angle of internal friction and cohesion. Therefore, soil strength parameters determination methods should be improved intending to correct soil ground calculation methods.

**List of published works on the topic of the dissertation
In the reviewed scientific periodical publications**

1. AMŠIEJUS, J.; DIRGĖLIENĖ, N. Probabilistic assessment of soil shear strength parameters using triaxial test results. *The Baltic Journal of Road and Bridge Engineering*, 2007, Vol 2, No 3, p. 125–131. ISSN 1822-427X (ISI Web of Science).
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GRUNTO STIPRUMINIŲ IR DEFORMACINIŲ SAVYBIŲ TYRIMAS TRIAŠIO SLĖGIO APARATE BEI JŲ TIKIMYBINIS VERTINIMAS

Mokslo problemos aktualumas. Projektuojant ir statant įvairius pramoninius ir civilinius pastatus, visada reikalingi duomenys, kurie apibūdintų gruntų, sudarančių pastatų pagrindus, fizines ir mechanines savybes. Tokia projektuotojams ir statybos specialistams būtina informacija gaunama tiriant gruntų fizines, mechanines savybes kiekvienoje statybų aikštelėje. Šių savybių rodikliai ir pagal juos apskaičiuotas pagrindo stiprumas nustatomi su tam tikromis paklaidomis. Atskleidus tų paklaidų priežastis, šalinami tyrimo prietaisų trūkumai, tobulinami tyrimo duomenų apdorojimo metodai, tiksliau nustatomi grunto stiprumo rodikliai, ekonomiškiau projektuojami pamatai.

Šiuo metu grunto kerpamojo stiprumo rodikliai dažniausiai nustatomi laboratorijose triašio slėgio ir tiesioginio kirpimo aparatais. Šių savybių rodikliai nustatyti įvairių konstrukcijų prietaisais gaunami skirtingi. Grunto įtempimų ir deformacijų būvis grunto pagrinde geriau modeliuojamas triašio slėgio aparatu nei tiesioginio kirpimo aparatu, todėl triašio slėgio aparatas šiuo

metu yra plačiai naudojamas pasaulyje nustatant grunto kerpamojo stiprumo savybių rodiklius. Daroma prielaida, kad bandinys triašio bandymo metu deformuojasi vienodai. Šis teiginys yra pagrindinė triašio bandymo idėja. Tačiau dažniausiai bandinys deformuojasi nevienodai dėl grunto bandinio galų suvaržymo, bandinio aukščio, nepakankamo drenavimo, guminės membranos poveikio, jo savojo svorio ir kt. Apžvelgtoje literatūroje pažymima, kad smėlinio grunto stiprumo rodiklių reikšmės nustatytos triašio slėgio aparatu gaunamos didesnės, nei nustatytos tiesioginio kirpimo aparatu. Kyla klausimas, dėl kokių priežasčių grunto kerpamojo stiprumo rodikliai nustatyti triašio slėgio aparatais yra didesni nei nustatyti tiesioginio kirpimo aparatais. Koks įtempimų ir deformacijų būvis yra grunto bandinyje, kai jam apkrova perduodama triašio slėgio aparate numatytu būdu? Kokią įtaką turi prietaiso konstrukcija grunto stiprumo savybių rodikliams ir pagal šiuos rodiklius apskaičiuotiems pamato matmenims?

Pagal geotechninio projektavimo norminius dokumentus pamato pagrindas gali būti skaičiuojamas taikant arba dalinių koeficientų metodą, arba dalinių koeficientų metodą kartu atliekant bandymus, arba taikant tiesioginį informacinį-statistinį metodą. Dalinių koeficientų metodas neužtikrina vienodos grunto pagrindo suirimo tikimybės. Taikant tikimybinis-statistinius metodus galima projektuoti pasirinkto patikimumo grunto pagrindus ir pamatus. Statybos techniniame reglamente jau pateikiama informacija apie konstrukcijų stiprio patikimumo įvertinimo metodus (EN rekomenduojamas FORM metodas – pirmos eilės patikimumo metodas; STR pateiktas SECANT metodas – kirstinės antrųjų momentų metodas). STR pateiktas metodas leidžia pilniau panaudoti turimą informaciją apie apkrovas ir medžiagas, nustatyti pagrindo stiprumo patikimumo rodiklį ir kurio projektavimo sąlygų argumento įtaka pagrindo stiprumo atsargos neapibrėžtumui yra didžiausia. Pagal tai, siekiant sumažinti neapibrėžtumus, galima numatyti tolesnių tyrimų kryptis. Atlikti tyrimai rodo, kad pagrindo stiprumo atsargos neapibrėžtumui didžiausią įtaką turi vidinės trinties kampas ir sankiba, todėl reikia tiksliau nustatyti šiuos stiprumo rodiklius. Taip būtų galima sumažinti medžiagų ir darbo sąnaudas, reikalingas pastatų pamatų statybai nesumažinus pagrindo stiprumo patikimumo.

Darbo tikslas – tobulinti grunto tyrimą triašio slėgio aparatu, kad būtų galima tiksliau nustatyti grunto savybių rodiklius ir pagal juos patikimiau prognozuoti pagrindo laikymo galią.

Pagrindiniai darbo uždaviniai. Darbo tikslui pasiekti buvo suformuluoti šie uždaviniai:

1. Išanalizuoti triašio slėgio aparato įtempimų būvį grunto bandinyje ir bandinio kraštinių sąlygų įtaką grunto stiprumo rodikliams.
2. Eksperimentiniu būdu patvirtinti arba paneigti, kad įtempimų horizontalioji komponentė horizontaliame pjūvyje ašiai simetrinio bandymo atveju pasiskirsto nevienodai.
3. Teoriškai išanalizuoti triašio slėgio bandinio aukščio ir skersmens santykio įtaką smėlinio grunto kerpamajam stiprumui.
4. Eksperimentiškai ištirti bandinio aukščio ir skersmens santykio bei paslankios atramos įtaką grunto kerpamajam stiprumui.
5. Skaitinio modeliavimo metodu nustatyti paslankios atramos įtaką įtempimų ir deformacijų pasiskirstymui bandinyje.
6. Pagrįsti grunto kerpamojo stiprumo rodiklių skaičiuotinių reikšmių nustatymą tikimybinio-statistiniu metodu ir įvertinti pagrindo, apskaičiuoto naudojant šias reikšmes, stiprumo patikimumą.

Mokslinis naujumas

1. Triašio slėgio aparato bandinyje vienodesniems įtempimams gauti apžvelgtoje literatūroje siūloma naudoti bandinį, kurio aukščio ir skersmens santykis $H/D = 1$, ir eliminuoti bandinio galų ir šampų trintį. Tokiu atveju gruntams, kurių vidinės trinties kampas $\varphi \neq 0$, gaunamos didesnės vidinės trinties kampo φ ir sankibos c reikšmės. Nustatant grunto kerpamojo stiprumo rodiklius, galima tirti bandinius, kurių $H/D = 1$, tik gruntų, kurių $\varphi = 0$.
2. Eksperimentiškai patvirtinta, kad įtempimų horizontalioji komponentė ašiai simetrinio bandymo atveju bandinio skerspjuvio viduryje yra mažesnė nei ties bandinio skerspjuvio kraštais.
3. Teoriškai pagrįsta triašio slėgio bandinio aukščio ir skersmens santykio įtaka grunto kerpamajam stiprumui.
4. Tiriant tankius smėlius standartiniame triašio slėgio aparate ir modernizuotame aparate, kuriame yra nevaržomi bandinio apačios horizontalieji poslinkiai, deformacijų priklausomybė nuo įtempimų $\epsilon_1 = f(\sigma_1 - \sigma_3)$ kreivės pobūdis gaunamas skirtingas.
5. Nustatyta, kad bandiniams, su paslankia ir nepaslankia atramomis grunto liekamosios kerpamojo stiprio reikšmės yra skirtingos. Pagal liekamąjį kerpamąjį stiprį apskaičiuotos vidinės trinties kampo tangento vidutinės reikšmės bandiniams, su nepaslankia atrama gautos 15 % didesnės negu nustatytos bandiniams, su paslankia atrama, o sankibos reikšmės atitinkamai didesnės 42 %.

6. Pagal grunto liekamojo kerpamojo stiprio rodiklius, nustatytus standartiniu triašio slėgio aparatu, apskaičiuotas pamato plotis B gautas 23 % mažesnis negu apskaičiuotas pagal grunto tyrimo modernizuotu triašio slėgio aparatu duomenis.

Tyrimų metodika

1. Įtempimų būvio triašio slėgio aparato grunto bandinyje, bandinio kraštinių sąlygų įtakos grunto stiprio rodikliams literatūros analizė.
2. Įtempimų pasiskirstymo triašio slėgio aparato grunto bandinyje ir kraštinių sąlygų įtakos grunto savybių rodikliams eksperimentinis tyrimas.
3. Paslankios atramos įtakos įtempimų ir deformacijų būvio triašio slėgio aparato bandinyje skaitinis modeliavimas baigtinių elementų programiniu paketu COSMOS/M.
4. Grunto kerpamojo stiprio rodiklių skaičiuotinių reikšmių nustatymas tikimybinio-statistiniu metodu ir pagrindo stiprio patikimumo įvertinimas taikant optimizacijos metodus.

Praktinė vertė

1. Pasiūlyta įrengti paslankią atramą triašio slėgio aparate, siekiant sumažinti bandinio galų horizontalių poslinkių suvaržymo įtaką grunto kerpamajam stiprumui ir tokiu būdu tiksliau nustatyti kerpamojo stiprumo rodiklius.
2. Pasiūlytas metodas pagrindo stiprio projektavimo sąlygos argumentų skaičiuotines reikšmes nustatyti taip, kad jos tenkintų projektavimo sąlygą, o šios sąlygos argumentų tikimybės tankio funkcija turėtų didžiausią reikšmę.
3. Pasiūlyta pagrindo skaičiavimui naudoti tikimybinį-statistinį metodą netaikant dalinių koeficientų.

Ginamieji teiginiai

1. Pasiūlytas metodas, kuris leidžia eksperimentiniu būdu patvirtinti hipotezę, kad įtempių horizontalioji komponentė horizontaliame pjūvyje ašiai simetrinio bandymo atveju pasiskirsto nevienodai.
2. Skaitinio modeliavimo duomenys rodo, kad esant vienodam bandinio viršaus vertikaliam poslinkiui, vertikalioji įtempių komponentė yra skirtinga tiriant bandinius su paslankia ir nepaslankia atramomis triašio slėgio aparate.
3. Įprastos konstrukcijos triašio slėgio aparatu gaunamos padidintos grunto kerpamojo stiprio rodiklių reikšmės. Liekamosios vidinės trinties kampo tangento skaičiuotinės reikšmės gautos 10,8 %

didesnės, negu nustatytos pagal tyrimo modernizuotu aparatu duomenis. Liekamosios sankibos skaičiuotinės reikšmės atitinkamai didesnės 43 %.

4. Pagrindo, suprojektuoto naudojant dalinių koeficientų metodą, stiprumo patikimumai yra nevienodi, kadangi grunto rodiklių skaičiuotinių reikšmių nustatymui naudojami determinuoti daliniai koeficientai γ_M . Pagrindo saugos ribinio būvio sąlygos argumentų skaičiuotinės reikšmės priklauso nuo stiprumo atsargos dalinių išvestinių pagal kiekvieną argumentą ir to argumento vidutinio kvadratinio nuokrypio.
5. Pamato pagrindui projektuoti tikslinga naudoti tikimybinis-statistinius metodus netaikant dalinių koeficientų.

Darbo apimtis. Disertaciją sudaro įvadas, 5 pagrindiniai skyriai, paskutinysis skyrius – darbo rezultatų apibendrinimas ir siūlymas, literatūros sąrašas, publikacijų sąrašas ir priedai. Disertacijos apimtis – 92 puslapiai, be priedų, 66 paveikslai, 14 lentelių ir 2 priedai.

Pirmajame skyriuje analizuota užsienio mokslininkų patirtis nagrinėjant svarbiausius veiksnius, darančius įtaką tiesioginio kirpimo ir triašio slėgio aparatų bandinių įtempimų būviui.

Antrajame skyriuje pateiktas būdas įrodyti, kad įtempių horizontaliosios komponentės horizontaliame pjūvyje ašiai simetrinio bandymo atveju pasiskirstymas nevienodas. Šis teiginys patvirtintas eksperimentiškai.

Atlikta teorinė analizė ir eksperimentiniai tyrimai, kad būtų galima įvertinti triašio slėgio smėlinio grunto bandinio aukščio ir skersmens santykio įtaką grunto kerpamajam stiprumui.

Atlikti triašio slėgio bandinio atramų horizontalių poslinkių suvaržymo įtakos grunto kerpamajam stiprumui tyrimai.

Trečiajame skyriuje skaitinio modeliavimo metodu naudojant baigtinių elementų programinį paketą COSMOS/M, ištirta paslankios atramos įtaka įtempimų ir deformacijų pasiskirstymui grunto bandinyje.

Ketvirtajame skyriuje nustatytos labiausiai tikėtinos skaičiuotinės reikšmės tenkinančios pagrindo saugos ribinio būvio projektavimo sąlygą $z_d = 0$. Jos nustatytos sprendžiant optimizacijos uždavinį: apskaičiuoti pagrindo saugos ribinio būvio projektavimo sąlygos argumentų tikimybės tankio funkcijos maksimumą, kartu tenkinant pagrindo projektavimo saugos ribinio būvio sąlygą.

Penktajame disertacijos skyriuje pateikta darbo rezultatų apibendrinimas ir siūlymai.

Darbo rezultatų apibendrinimas ir siūlymas

1. Atlikus ašiai simetrinio bandymo tyrimus nustatyta, kad tankių smėlių įtempių horizontalioji komponentė horizontaliame bandinio skerspjuvyje pasiskirsto nevienodai. 55–61 % didesnės šių įtempių reikšmės gaunamos ties grunto bandinio skerspjuvio kraštais nei bandinio viduryje.
2. Triašio slėgio aparate pasiūlyta įrengti paslankią atramą tarp grunto bandinio apačios ir štampo, kuri sumažina bandinio ir štampo trinties įtaką grunto kerpamajam stiprumui.
3. Tiriant tankius smėlinius gruntu, kurių bandinio aukščio ir skersmens santykis $H/D = 2$, standartiniu ir modernizuotu triašio slėgio aparatais, deformacijų priklausomybės nuo įtempimų $\varepsilon_1 = f(\sigma_1 - \sigma_3)$ kreivės pobūdis yra skirtingas.
4. Tankių smėlių, kurių $H/D = 2$, liekamosios vidinės trinties kampo tangento skaičiuotinės reikšmės, apskaičiuotos pagal Eurokodą 7 tiriant standartiniu aparatu, gautos 10,8 % didesnės negu nustatytos pagal tyrimo modernizuotu aparatu duomenis, o liekamosios sankibos skaičiuotinės reikšmės atitinkamai didesnės 43 %. Tai paaiškina apžvelgtoje literatūroje pateiktą teiginį, kad grunto kerpamojo stiprio rodiklių reikšmės, nustatytos triašio slėgio aparatu, gaunamos didesnės, nei nustatytos tiesioginio kirpimo aparatu.
5. Pagal grunto liekamojo kerpamojo stiprio rodiklius, nustatytus standartiniu triašio slėgio aparatu, apskaičiuotas pamato plotis gautas 23 % mažesnis negu apskaičiuotas pagal grunto tyrimo modernizuotu triašio slėgio aparatu duomenis.
6. Taikant tikimybinis-statistinius metodus nustatyta, kad pagrindo saugos ribinio būvio sąlygos neapibrėžtumui didžiausią įtaką turi vidinės trinties kampo tangentas ir sankiba. Todėl tobulinant pagrindo skaičiavimo metodus, pirmiausia reikia tikslinti šių rodiklių nustatymo būdus.

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**RESEARCH OF SOIL SHEAR STRENGTH IN TRIAXIAL TESTS AND
PROBABILISTIC ASSESSMENT OF RESULTS**

**Summary of Doctoral Dissertation
Technological Sciences, Civil Engineering (02T)**

Neringa Dirgėlienė

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TRIAŠIO SLĖGIO APARATE BEI JŲ TIKIMYBINIS VERTINIMAS**

**Daktaro disertacijos santrauka
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2007 11 20. 1,5 sp. l. Tiražas 100 egz.
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