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

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University of Pisa, April 2008

- **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.**

1. LITERATURE ANALYSIS

- Literature analysis of experiments and numerical modeling shows that:
  - ✓ triaxial test is the most reliable method to model stress-strain state of ground than direct shear test;
  - ✓ stress-strain distribution are not uniform in both triaxial and direct shear tests specimens;
  - ✓ sandy soil strength parameters obtained from triaxial test are bigger than the ones's obtained from the direct shear test.
- The main reasons of non-uniform stress distribution 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.

Tasks of the work is to analyse what influence does a non-uniformity have on the soil strength parameters and find ways to reduce or evualate it.

- **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.**
- **In the normative documents there is no common calculation method for characteristic, design values of soil shear strength parameters.**
- **Partial factors method, where design values are used, doesn‘t assure an equal reliability of foundations.**
- **Soil shear strength parameters determined experimentally are random values therefore its need to evaluate probabilistically.**
- **Not long ago Lithuania started to apply Eurocodes. There was possibility to use probabilistic methods to design construction. These methods should be applied without using partial factors.**

2. EXPERIMENTAL ANALYSIS OF SOIL SHEAR STRENGTH PARAMETERS IN TRIAXIAL TEST

- **Consolidated-drained triaxial tests on poorly-graded sand with fine (SP-SM) have been carried out. Dense and loose samples properties were: density r = 1,871 gr/cm^3, void ratio of *e* = 0,51 and r = 1,610 gr/cm^3, *e* = 0,74.**

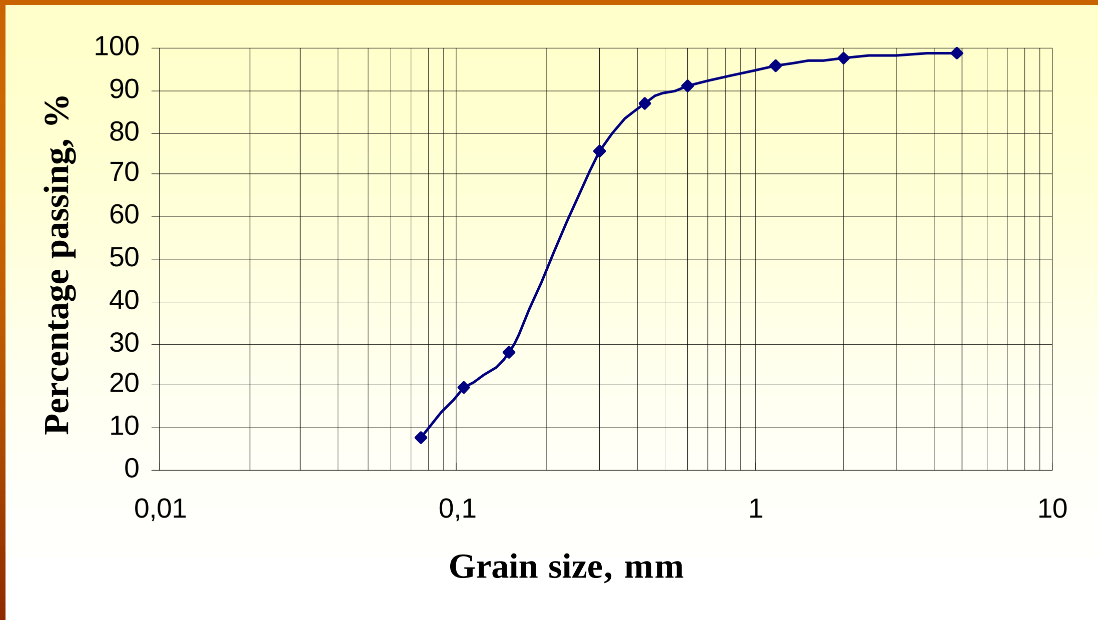


Fig 2. Grading curve of sand

Distribution of the horizontal component of stress in horizontal cross-section in the case of soil axisymmetric test

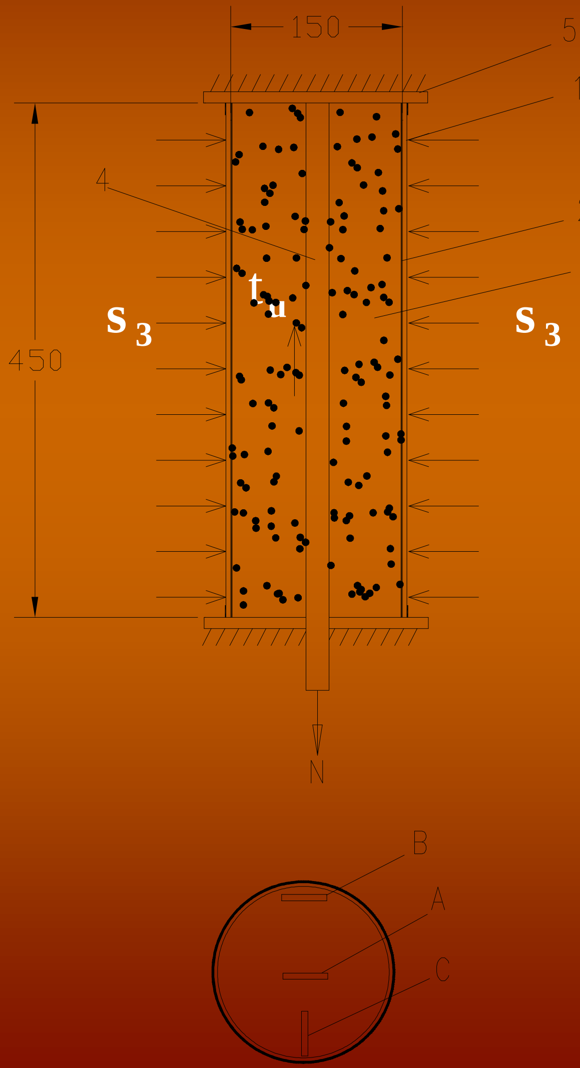


Fig 3. Device to analyse the distribution of horizontal component of stress in soil sample:
1 – metal cylinder; 2 – rubber membrane; 3 – soil sample; 4 – steel strip; 5 – fixed metal plate.

- 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.

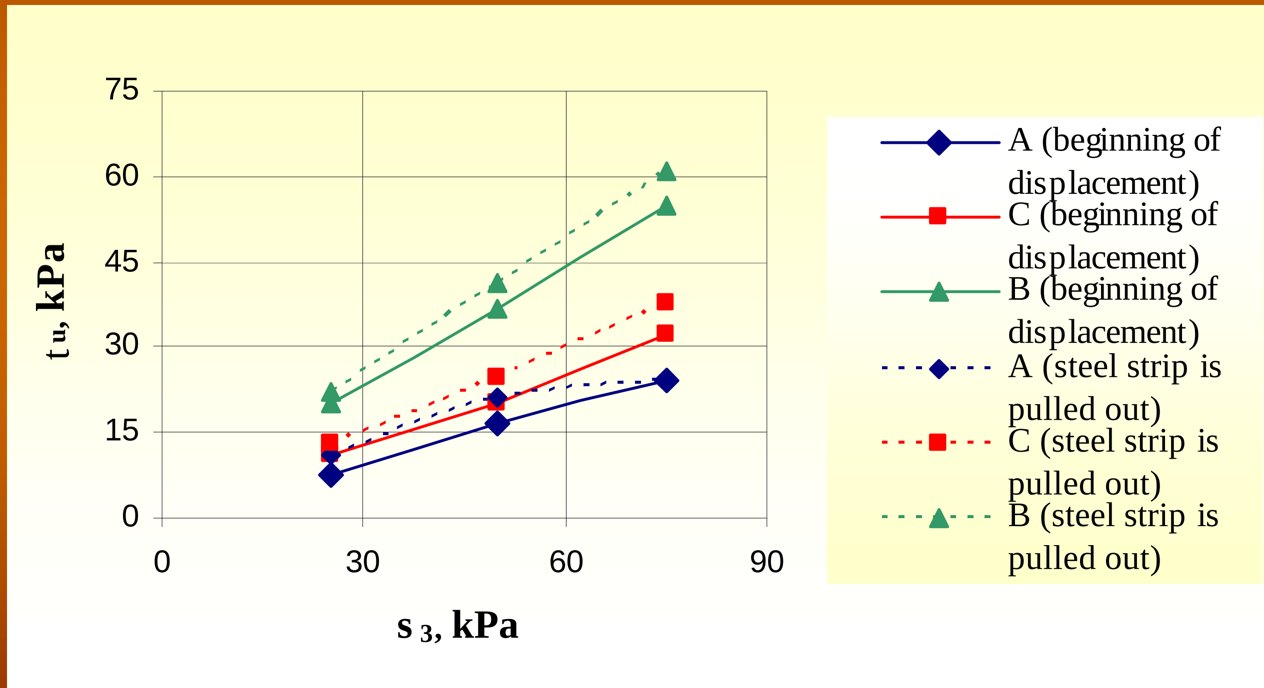


Fig 4. Sand shear strength

Experimental analysis of soil sample heigh/diameter ratio influence on soil shear strength parameters in standard triaxial test

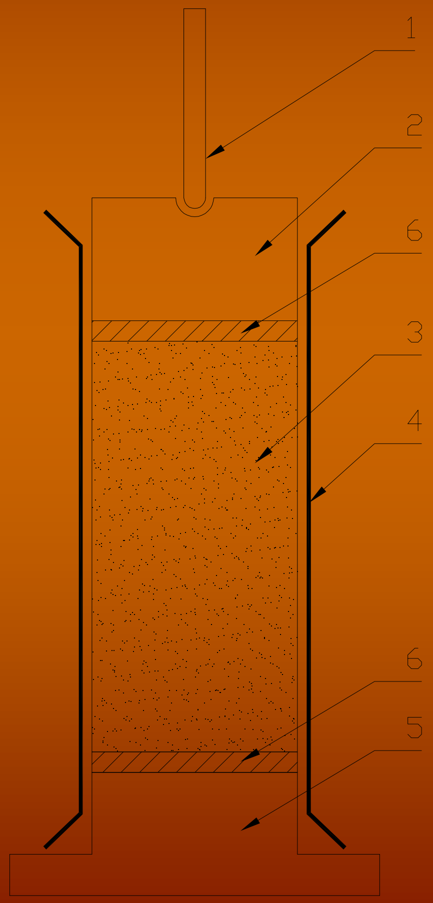
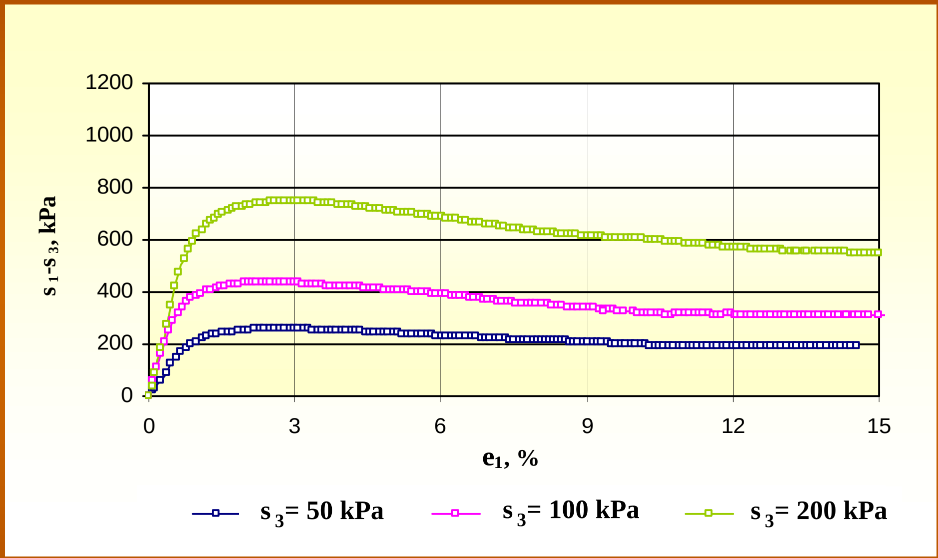


Fig 8. Scheme of standard triaxial test apparatus: 1 – rod; 2 – cap; 3 – soil sample; 4 – latex membrane; 5 – pedestal; 6 – porous stone.

a)



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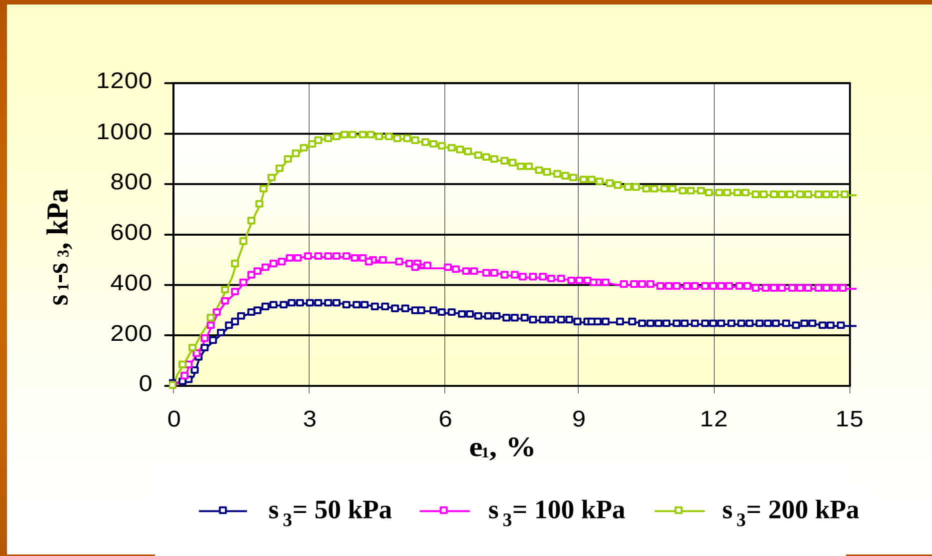


Fig 9. Stress-strain obtained in triaxial compression test on dense sand, when height/diameter ratio: a) *H/D* = 2; b) *H/D* = 1

Experimental analysis of influence of free horizontal movement of sample base on soil shear strength parameters during triaxial testing

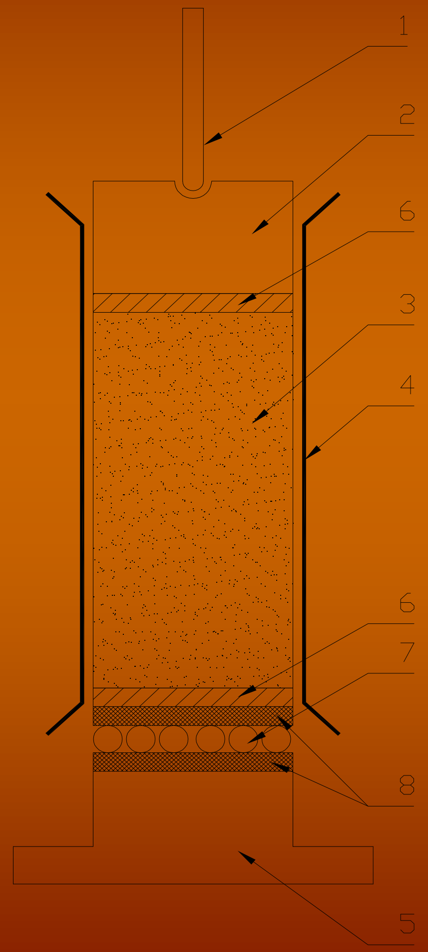
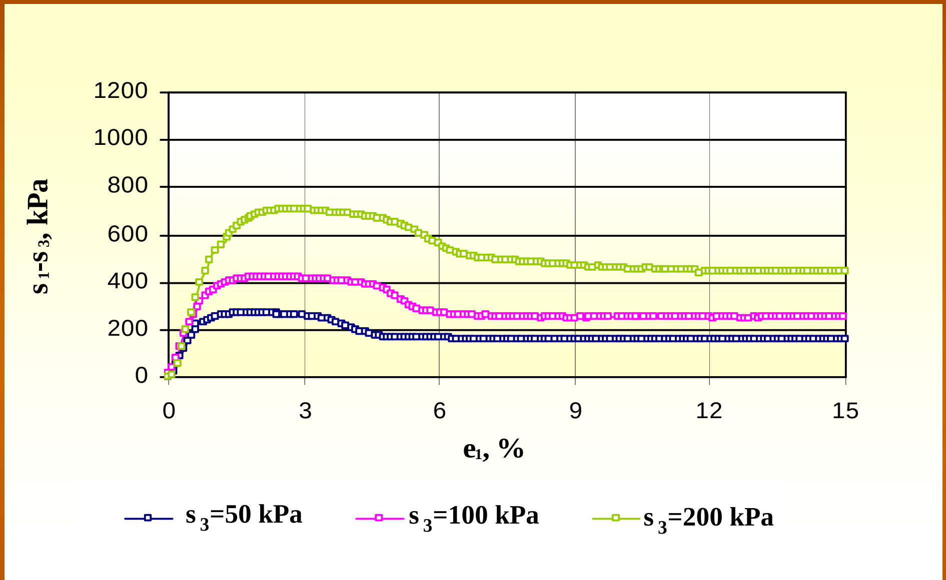


Fig. 10. Scheme of improved triaxial test apparatus: 1 – rod; 2 – cap; 3 – soil sample; 4 – latex membrane; 5 – pedestal; 6 – porous stone; 7 – thrust bearing; 8 – stainless steel plates

a)



b)

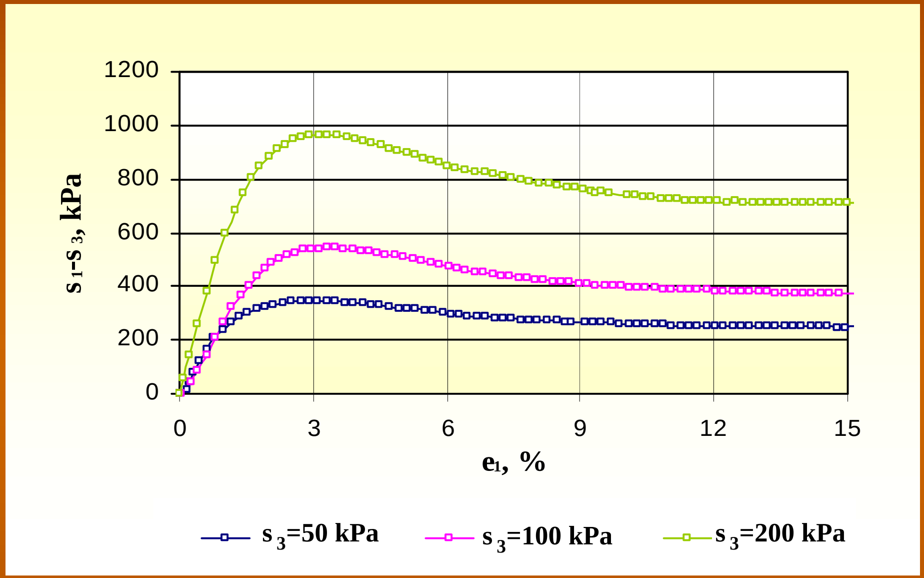


Fig 11. Stress-strain curves obtained in triaxial compression test on dense sand samples when height/diameter ratio: a) *H/D* = 2; b) *H/D* = 1

- **Comparison of test results obtained in triaxial apparatus for dense sand sample, which *H/D* = 2, with free horizontal movement of base and for sample with regular ends (standard triaxial compression testing) shows that shape of graphs $e_1 = f(s_1 - s_3)$ are different.**

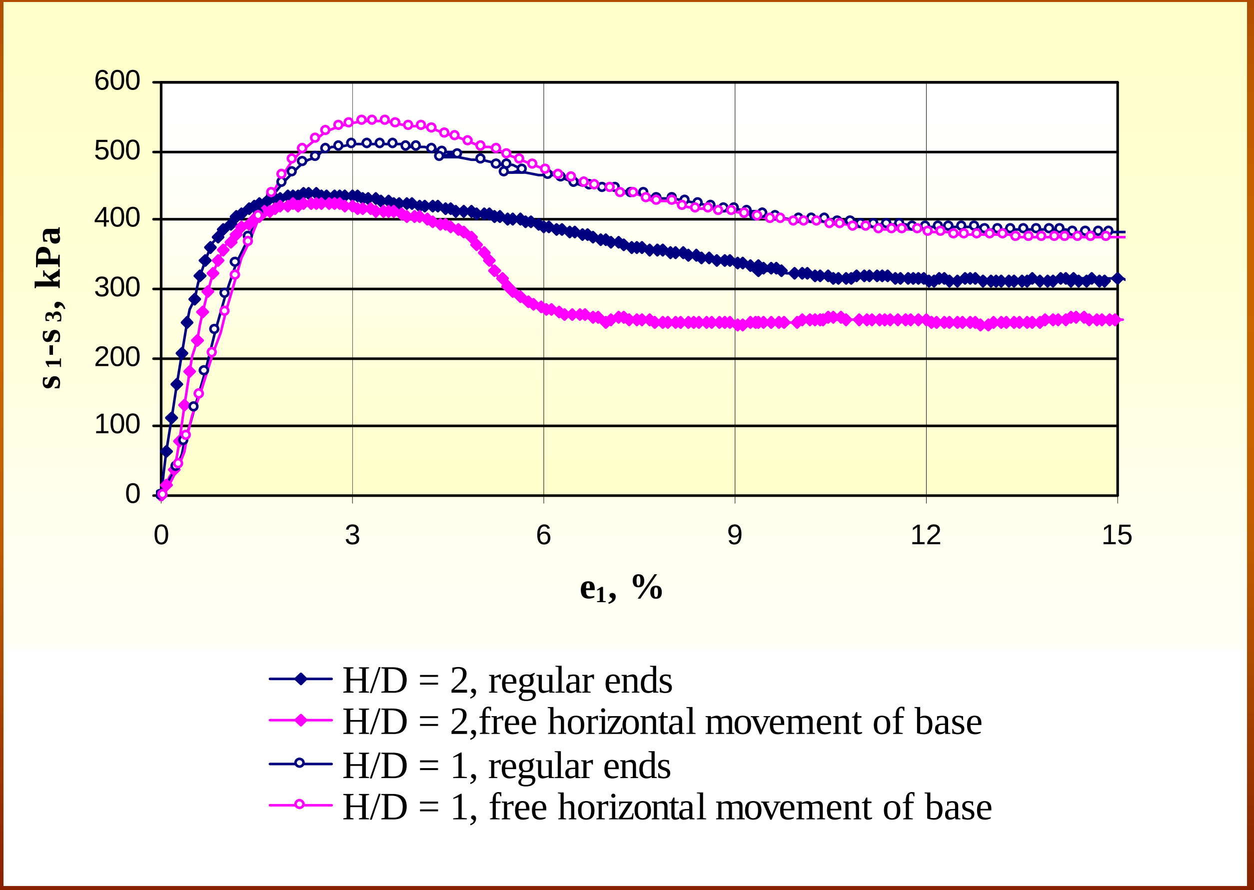


Fig 12. Stress-strain curves obtained in triaxial compression tests on dense sand samples, when s_3 = 100 kPa

Fig 13. Dense sand sample, which *H/D* = 2, in standard triaxial test apparatus

Fig 14. Dense sand sample, which *H/D* = 2, in improved triaxial test apparatus

3. NUMERICAL MODELING OF STRESS-STRAIN DISTRIBUTION IN SOIL SAMPLE DURING TRIAXIAL TEST

- **Drucker-Prager model was used to simulate the behaviour of sand performing nonlinear analysis. The yield criterion can be defined as:**

$$F = 3\alpha\sigma_m + \sigma_f - k = 0,$$

where a and *k* - material constants which are assumed unchanged during the analysis; s_m - the mean stress; s_f - the effective stress; a and *k* are functions of two material parameters and obtained from experiments where f is the angle of internal friction and *c* is the material cohesion strength.

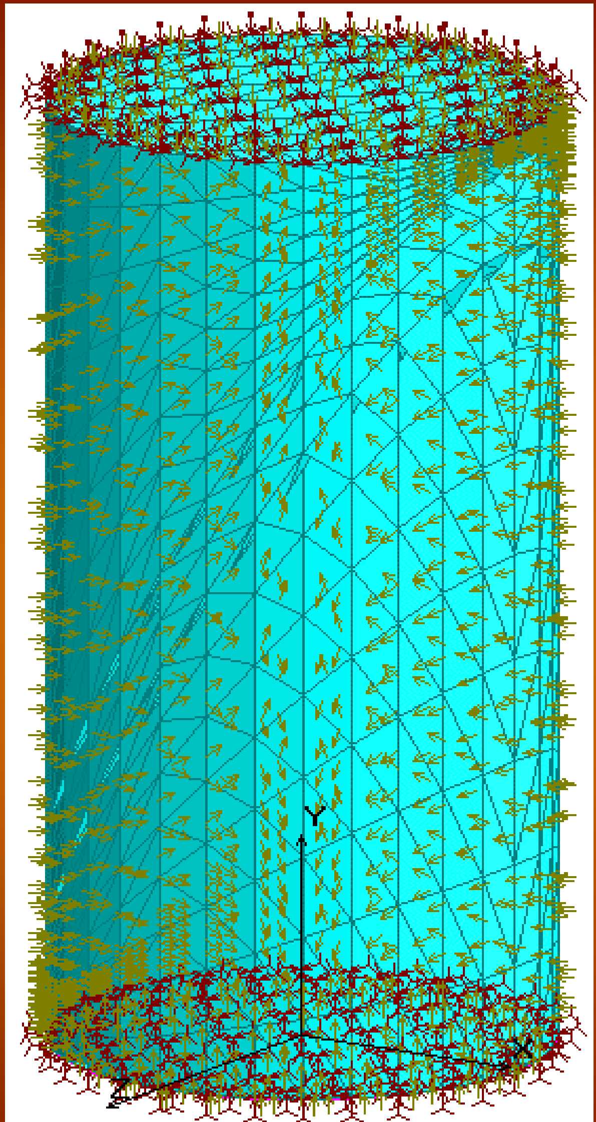
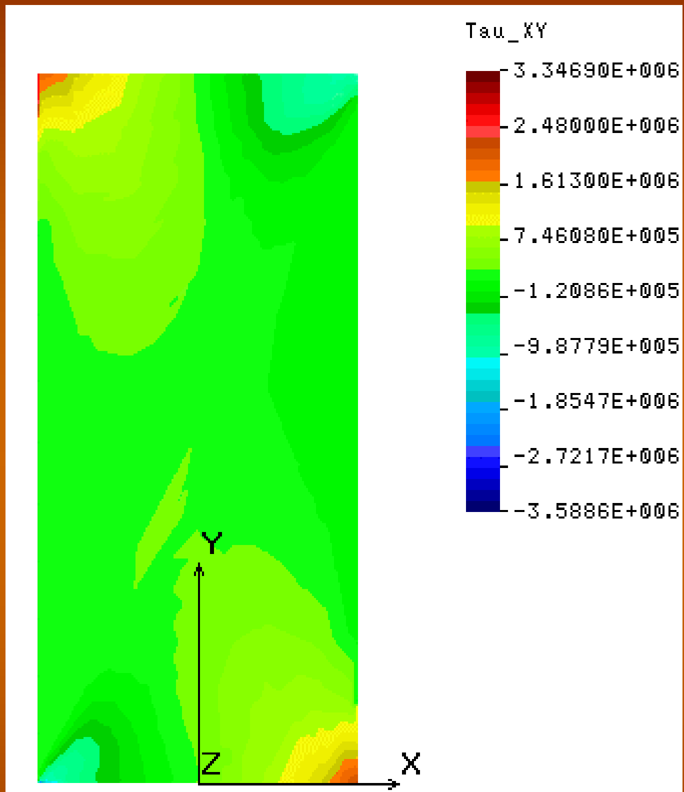


Fig 15. Finite elements of soil sample

Values of soil shear strength parameters

Soil shear strength parameters	Parameters for specimen	Parameters for failure plane
Angle of internal friction j, °	37,9	30,0
Cohesion *c*, kPa	26,0	17,0

a)



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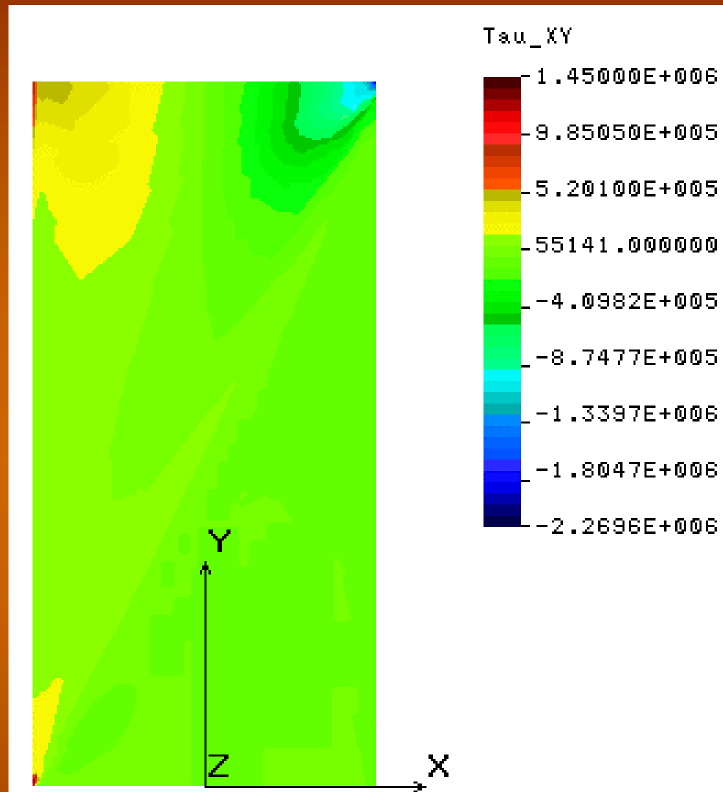
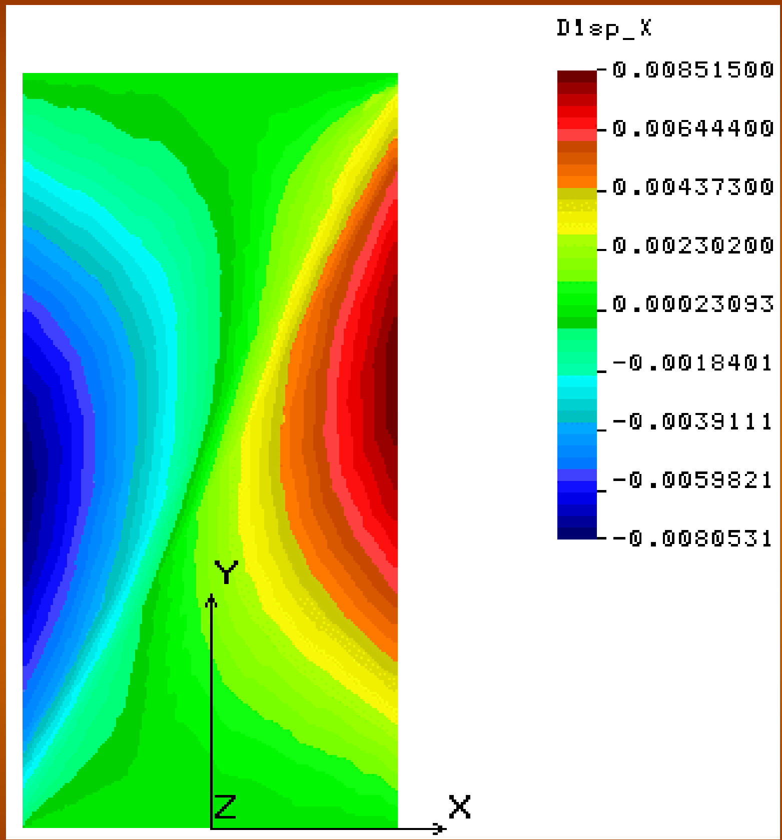


Fig 16. Shear stress t_{xy} distribution in the samples:
a) with regular ends;b) with free horizontal movement of base

a)



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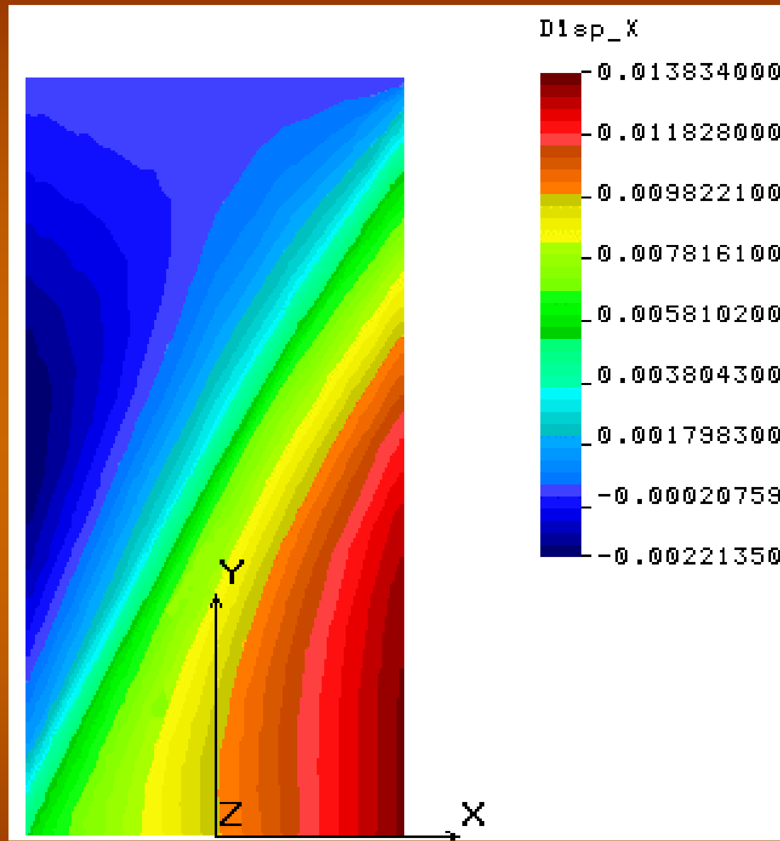


Fig 17. Horizontal soil displacements u_x distribution in the samples: a) with regular ends;b) with free horizontal movement of base

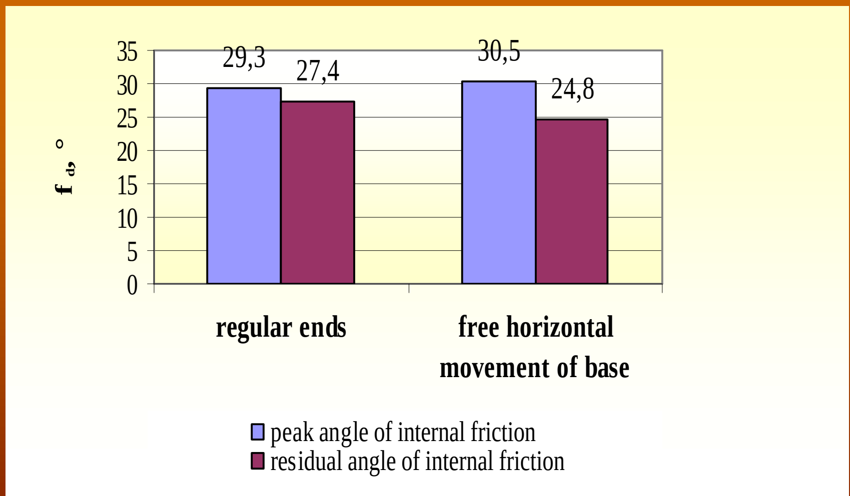
- **Analysis of stress–strain distribution in sample using finite element method shows that for sample with regular ends tangential stress in the contact plane sample-plate builds up. Such stress restricts displacement of sample ends in horizontal direction. In the case of free horizontal movement of sample base horizontal displacement of sample base occurs.**

- **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 restricted ends.**

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 %.**

a)



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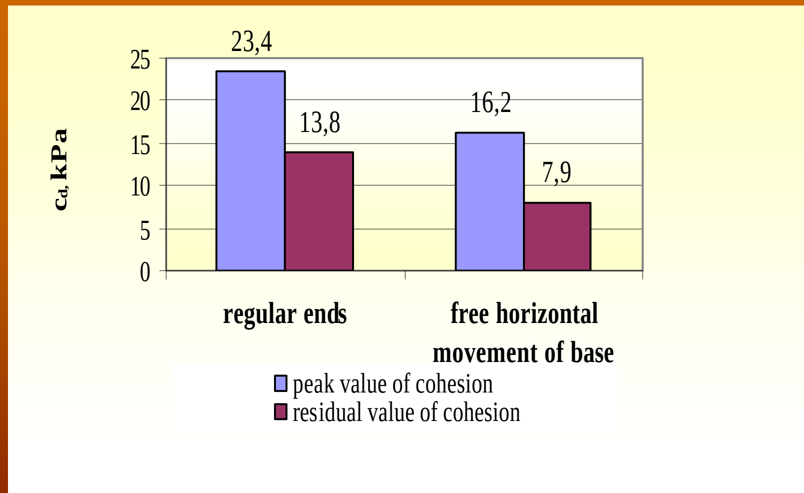

Fig 20. Design values calculated according to Eurocode 7: a) angle of internal friction; b) cohesion

Assessment of soil bearing resistance reliability by solving optimization problem

- **Design values of soil shear strength parameters determined using EN 1997 and SNiP 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:**

$$f(x_1, x_2, \ldots x_n) \rightarrow \max$$

$$z_d = g_i(x_{1d}, x_{2d}, \ldots x_{nd}) = 0,$$

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

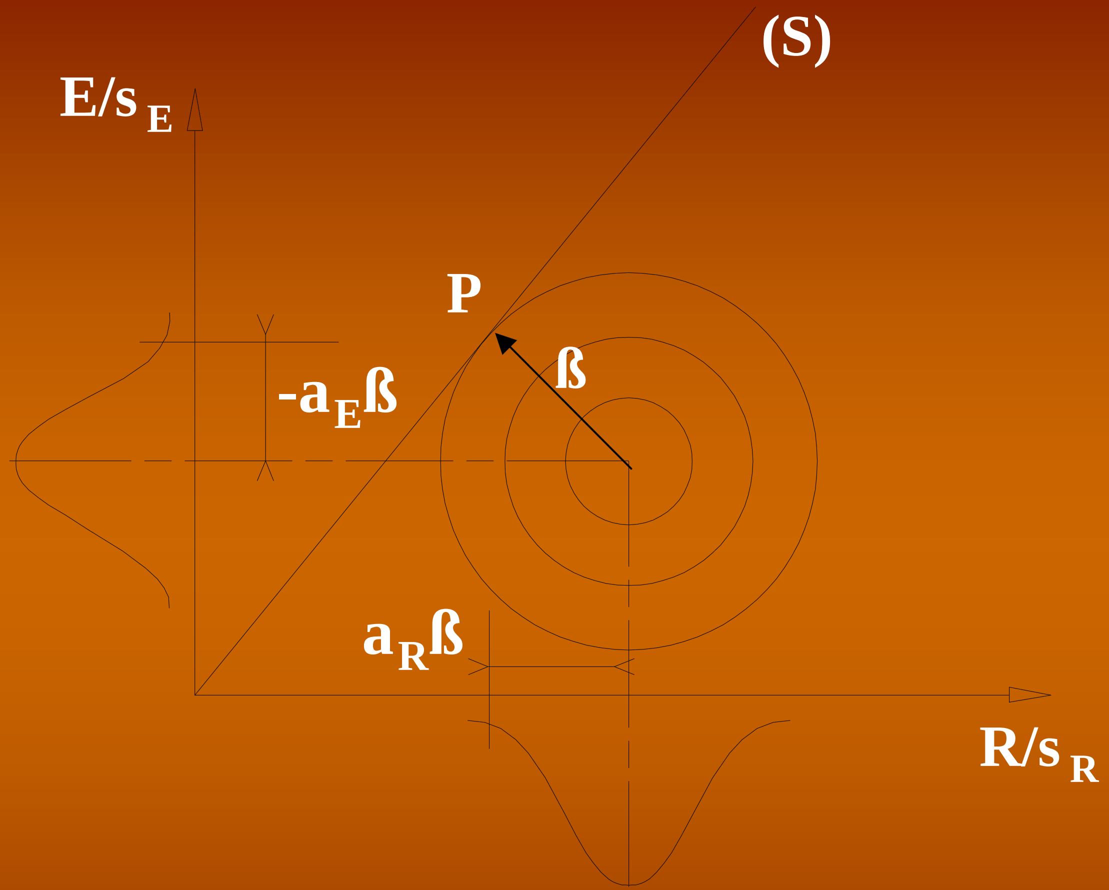

Fig 21. Izolines of the reliability index b**:**
(S) – design condition $g = R_d - E_d = 0$**;**
P **– design point**

Probabilistic assessment of soil bearing resistance calculated according to improved triaxial apparatus results

- **Spread foundation width *B* calculated according to the parameters of residual shearing strength, determined by usual triaxial test apparatus is smaller by 23 % than that calculated according to the data obtained in the improved triaxial test apparatus.**

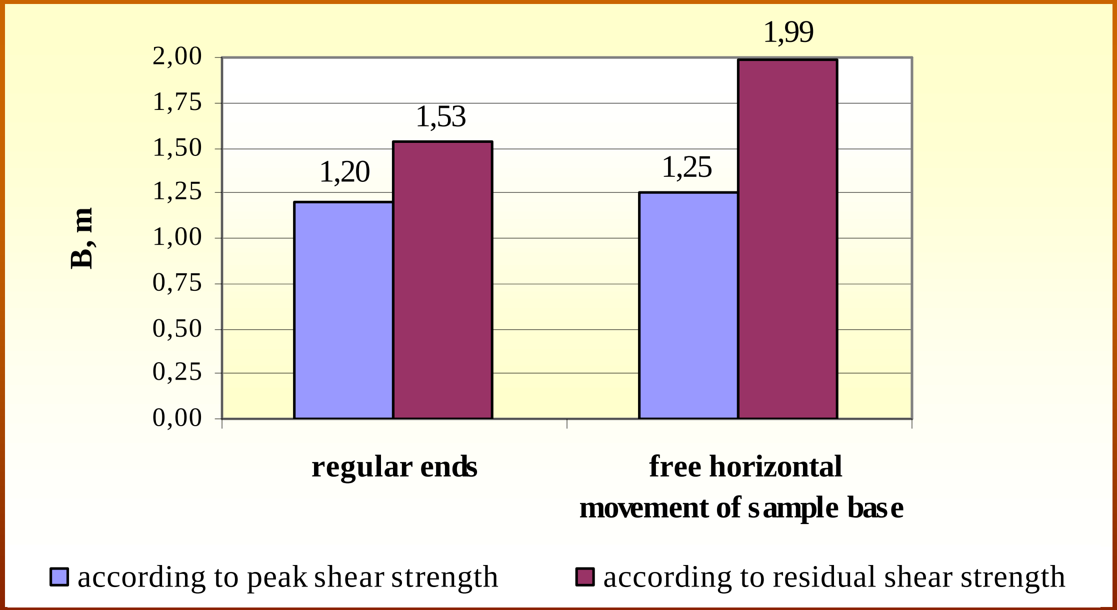

Fig 22. Values of foundation width *B*

- Reliability index of soil bearing resistance designed according to EN 1997 and arguments values G_d*, Q_d*, tan j $_d$*, c_d*, B_d* at design point have been calculated using the FORM method. It was accepted that permanent action *G*, variable action *Q*, soil strength parameters tan j , *c* and foundation width *B* are random values whereas other arguments are known without deviations.

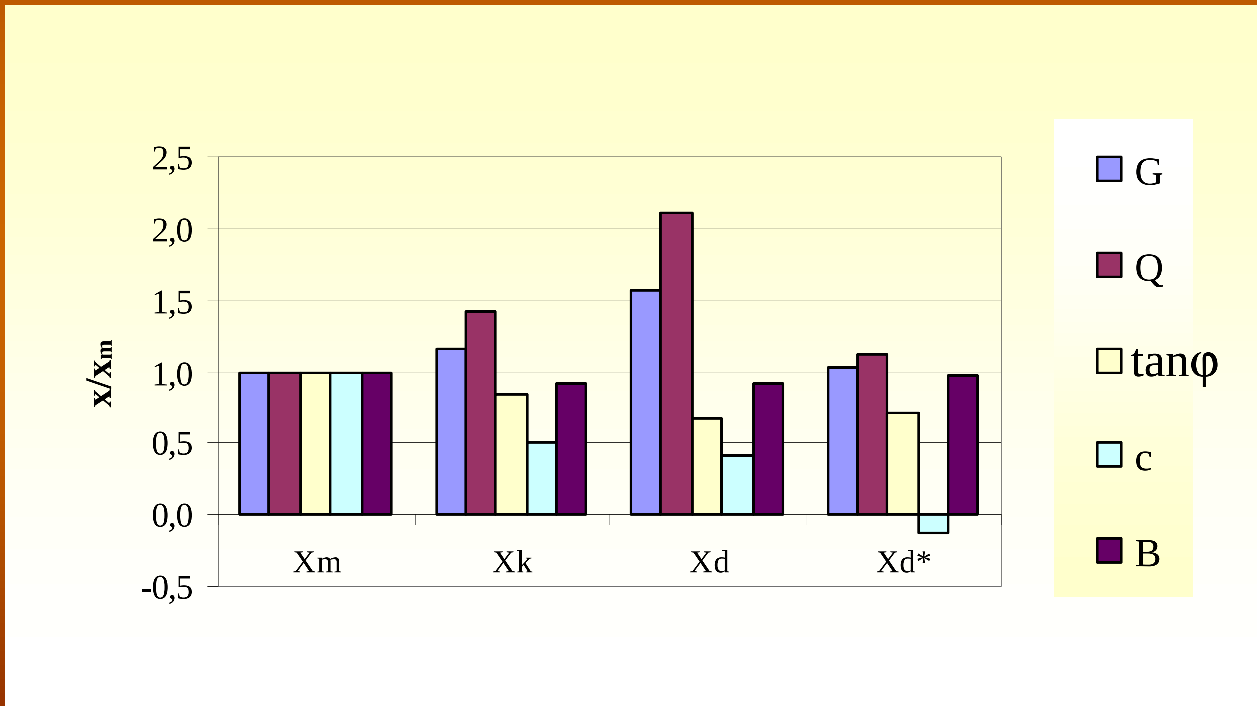

Fig 23. Mean, characteristic, design values of soil bearing design condition arguments obtained for sample with free horizontal movement of sample base using residual shear strength parameters

- **Reliability index of bearing resistance for sample with regular ends calculated by means of first order probabilistic methods for design approach 3 is ß=4,4 using residual soil shear strength parameters. For sample with free horizontal movement – ß = 4,8.**

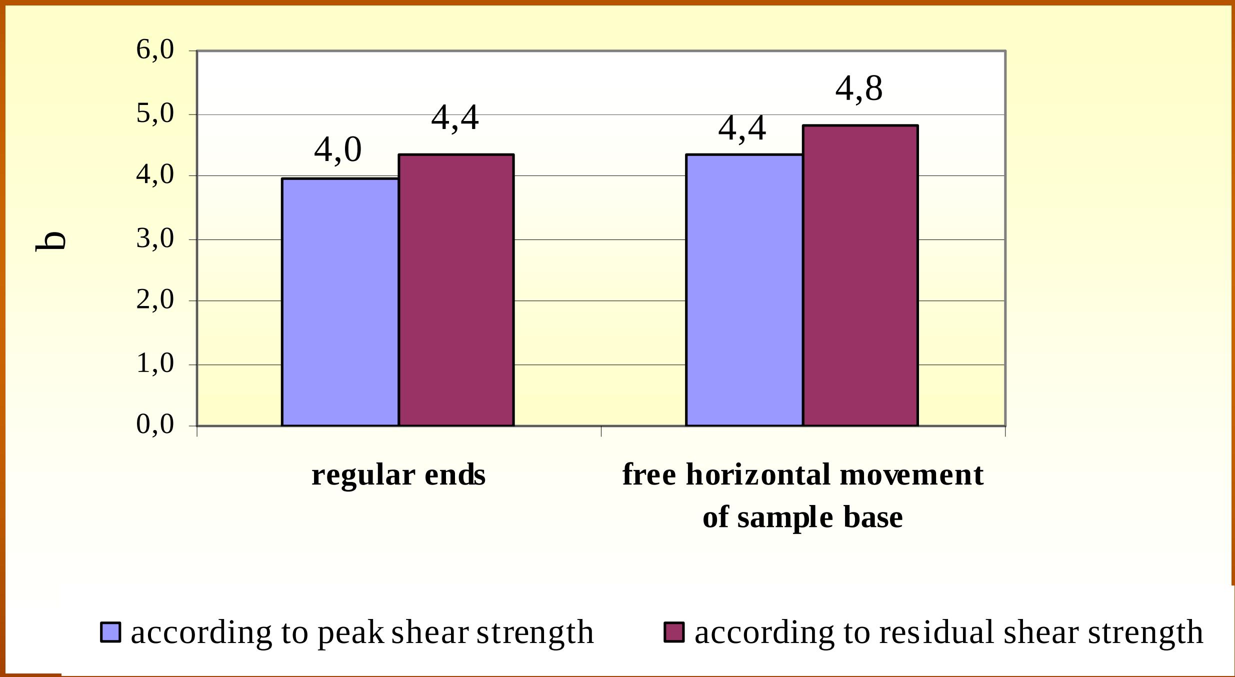

Fig 24. Reliability index b values of soil bearing resistance

- **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:**

$$\alpha^2_{X_i} = [\frac{\Delta z(A)}{\Delta X_i} \cdot \sigma_{X_i}]^2 / \sigma^2_z, \qquad i=1,2,\ldots,n.$$

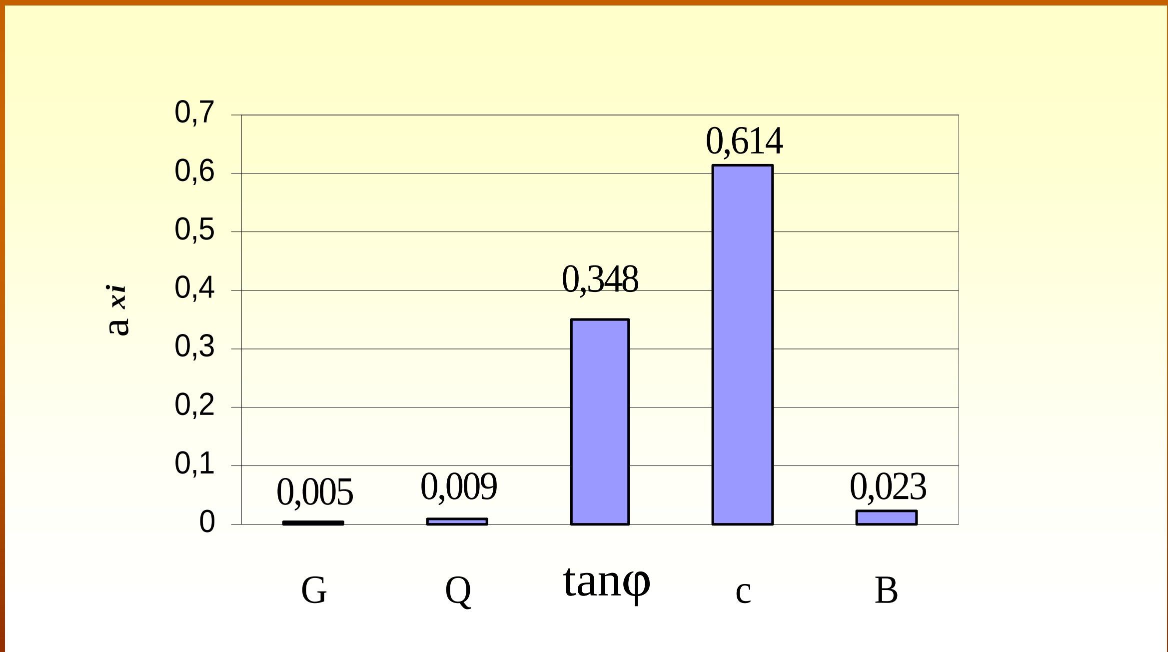

Fig 25. Influence of design condition arguments on the uncertainty of the margin of soil bearing resistance using test results of improved apparatus

- **The calculations made demonstrate that the biggest influence on the uncertainty of margin of bearing resistance is made by the tangent of the angle of internal friction and cohesion.**

5. GENERAL CONCLUSIONS

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. Analysis of stress-strain distribution in sample using finite element method shows that for sample with regular ends tangential stress in the contact plane sample-plate builds up. It are not evualated for calculation of shear strength design parameters.
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 test) shows that shape of graphs are different.

4. **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 %. 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. **Spread 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 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.**

Thanks for your attention!

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