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# Selection of the test method and its influence on the obtained results of soil strength parameters

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**Abstract:** The paper presents issues related to the methodology of measuring soil strength parameters. The laboratory methods for determining the shear strength of soil are described, with particular emphasis on the measurement of soil strength using the direct shear method and the triaxial compression apparatus. An attempt was made to determine the impact of the research methodology on the quality of the obtained strength parameters of the soil.

**Keywords:** shear strength, soils, direct shear apparatus, Krey-Casagrande apparatus, triaxial compression



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## Introduction

In the process of designing geotechnical structures, as well as the foundation of building and engineering structures, an important role is played by the proper determination of the strength parameters that characterize the subsoil.

The mechanical properties of soils depend, among other things, on the state of its compaction, humidity and loading. The presence of water filling the pores in the soil causes us to differentiate between the concept of total stresses and effective stresses transmitted by the soil skeleton. For design calculations, the effective values of strength parameters are most often adopted, because they determine the load-bearing capacity of the soil.

Due to the complex structure of the soil, serious problems arise related to the precise determination of the strength parameters of the soil, which is not a solid medium. This means that the value of the angle of internal friction and cohesion depend on the physical properties of the samples of their genesis and lithology as well as the adoption and application of the methodology for its determination (Zbiciak et al., 2014; Zydroń & Gadowska, 2013). This often leads to a situation where the strength parameters determined according to various standards differ significantly from those obtained as a result of engineering calculations. The article attempts to determine the impact of the methodology of determining the strength parameters on the quality (credibility) of the obtained results.

## 1. Methodology for determining soil strength parameters

Soil mechanics is still being developed, but the specificity of soil conditions makes it difficult to define unambiguous rules for the selection of methods for testing soil shear strength. By analyzing the literature, various methods can be found to determine the shear strength of the soil (Amsiejus et al., 2014; Bishop et. al., 1971; Gill & Vanden Berg, 1967; Karafiath & Nowatzki, 1987; Ghadir et al., 2021; Guo et al., 2021; Johnson et al., 1987; Stefanow & Dudziński 2021). None of the methods used in the past and nowadays specifies which method is the most appropriate to determine the properties of specific soils.

The possible methods of testing soil shear strength can be divided into two groups. The first are forced methods (direct shear) and methods with a free shear plane (indirect shear). In direct shear methods, devices with linear or rotary shear kinematics are mainly used. Indirect methods are based on soil compression, and then, using penetration tests and empirical relationships, they estimate the shear strength of the soil. The selection of the test method for shear strength of the soil should be made depending on the purposes for which the measurements are performed.

The main test methods defined by the Eurocode 7 standard are two laboratory methods, i.e. the direct shear method in the Krey-Casagrande apparatus and the triaxial compression method at which the shear strength parameters are determined on the basis of Mohr's circles.

### 1.1. Strength test using direct shear method

The simplest device for testing the shear strength of soil is the Krey-Casagrande apparatus called a direct shear or box apparatus. The main part of the device is a two-part box, the upper and lower parts of which can be moved to each other (Fig. 1). In order to prevent the sample from slipping on the contact surfaces and to transfer the shear force, it is provided with stop plates at the bottom and top. The test consists in experimentally determining the force T, with which we try to move the upper part of the box over the lower one. This movement is counteracted by the soil's shear resistance in a forced shear plane. The force T cannot exceed the value of the total shear strength of the tested soil. The maximum force recorded on the dynamometer is the quantity sought.

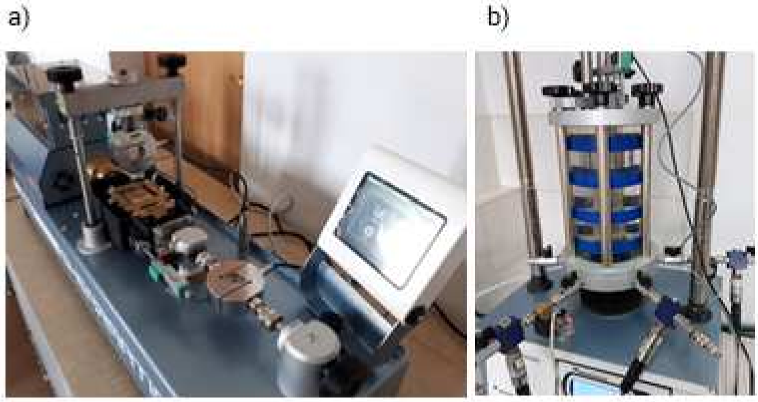


**Fig. 1.** a) Direct shear apparatus Shearmatic, b) Autotriax-2 apparatus for testing triaxial compression (*own photo*)

The value of the force T for a given soil depends on the value of the vertical force P. Searching for the force T at least several times for different values of the force P will determine the Coulomb line, and thus determine the values of the parameters. The force P applied to the specimen through the rigid cover is assumed to be distributed over the specimen surface so evenly that normal stress prevails in the forced shear plane:

$$\sigma = \frac{P}{A} \tag{1}$$

Similarly, we assume that the force T divided by the area of the box A determines the constant value of the shear stress throughout the shear section: $\boldsymbol{\tau} = \boldsymbol{T}/\boldsymbol{A}$. Structurally disturbed samples placed in the apparatus box are examined in the direct shear apparatus. The soil is placed in the box, compacting it with a rammer to a state simulating the natural state until it is full. The box with the sample is placed in the direct shear apparatus.

### 1.2. Shear strength test in a triaxial compression apparatus

Under the conditions of triaxial compression when determining the shear strength (testing parameters c and Φ) the structure of Mohr's circles is used to illustrate the relationships between the stresses occurring during the compression of soil samples. The stresses occurring in this state $\sigma_1$, $\sigma_2$, $\sigma_3$ (where $\sigma_2 = \sigma_3$) we call principal stresses, where $\sigma_1$ means greater, and $\sigma_3$ lesser principal stress. As a result of exceeding the strength on the wall, the soil sample is sheared at the α angle. This occurs where the tangential stress has exceeded the resistance of the frictional force and cohesion.

Relationships between normal and tangential stresses and principal stresses $\sigma_1$ and $\sigma_3$ depict the patterns:

$$\sigma_\alpha = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2}\cos 2\alpha \tag{2}$$

$$\tau_\alpha = \frac{\sigma_1 - \sigma_3}{2}\sin 2\alpha \tag{3}$$

and the basic strength law for soils (Coulomb's law) in the form of principal stresses takes the form:

non-cohesive soils
$$\frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3} = \sin\Phi \tag{4}$$

cohesive soils
$$\frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3 + 2c\,\mathrm{ctg}\,\Phi} = \sin\Phi \tag{5}$$

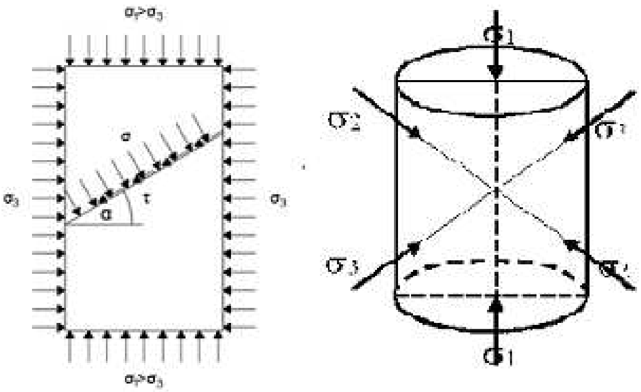


**Fig. 2.** Scheme of ground load in a three-axis compression apparatus (*own study*)

By determining the angle of internal friction and the cohesion with the use of a triaxial apparatus, for different water pressures, pairs of principal stresses are obtained $\sigma_1$ and $\sigma_3$, from vertical and horizontal pressure. The water pressure read on the manometer creates the main stress in the soil sample $\sigma_3$. The greater main stress $\sigma_1$ is the sum of the stresses transferred by the water and the mandrel. To obtain the principal stress pairs in this way $\sigma_1$ and $\sigma_3$ Mohr constructions are made. Tests in a triaxial apparatus are carried out according to one of three methods, differing in loading and sample drainage. Studies without consolidation and drainage (UU). The water content of the sample is kept unchanged throughout the experiment. Studies with consolidation but no drainage (CU). The sample is consolidated for practical purposes, often under isotropic loading $\sigma_3$, but at the time of the load that corresponds to the stress difference $\sigma_1 - \sigma_3$, striving to destroy the sample, drainage of water is prevented. Consolidation and drainage (CD) studies. The sample is consolidated as in the CU tests, but after applying a load corresponding to the stress difference $\sigma_1 - \sigma_3$; water drainage is still allowed; the stress increase should be slow enough so that there is no water pressure in the pores.

## 2. Selection of the methodology for determining the shear strength parameters of soil

Shear in soil is the shift of one part of the soil medium in relation to the rest. The condition for creating a shift along a given surface is that the soil resistance is exceeded by the shear stress. On the other hand, the shear strength of the soil is the resistance related to the boundary surface unit, the resistance described by the shear stress that the soil puts on the shifting forces.

The historical, but still used, formula for determining the result of ground shear is the Coulomb formula from 1773. According to which strength is a function of normal stress ($\sigma_n$), internal friction angle ($\Phi$) and cohesion (c).

Analyzing the work (Lambe & Whitman, 1977; Kaczyński 1984; Wiłun, 1976, 2013), it can be noted that the adopted methodology of sample testing recommends the maximum possible adaptation of the method of loading the model samples so as to reproduce the actual conditions.

The specific engineering task should be taken into account when selecting a test method. It is recommended that the total parameters be adopted for facilities where a rapid increase in ground loads may occur during the construction and operation phase. These are, among others, structures built in less than 3 months and also facilities for which variable loads exceed 50% of the total loads (Pisarczyk 1998, 2014). For other cases, effective parameters should be assumed.

The methodology of soil strength tests based on the indications of the Eurocode 7 (PN-EN 1997-2: 2008) standard assumes that the method of consolidation and loading of samples should be selected so as to obtain effective values of the angle of internal friction and cohesion. According to the standard, tests in a box apparatus or a ring apparatus should be performed with pore water outflow. This is because positive or negative water pressure in the pores that are caused by shear must be avoided. These values cannot be measured and included in the interpretation of the results. The standard states that uniaxial compression tests and triaxial compression tests without initial consolidation and without drainage do not have to show (reflect) the shear strength of the soil in in situ conditions. The use of the direct shear method, in which the slip surface required by the type of the tested sample, does not have to coincide with the weakest surface in a given soil medium. Additionally, due to the lack of pore pressure measurement, it is not possible to determine the effective soil parameters, and additionally, the state of stress and deformation if the sample is non-uniform. The direct shear method is mainly used to quickly estimate soil parameters, but it is a method with many inaccuracies, and the obtained results may be imprecise and do not reflect the actual conditions in the field. Additionally, due to the inability to prevent drainage of the sample, the test is only suitable for the assessment of soil properties under full drainage conditions.

**Table 1.** A short tabular review of the literature on the discussed methods of testing soil strength parameters (*own study*)

| Measurement method of strength parameters | Parameters studied | Type of soil | Bibliography |
|---|---|---|---|
| triaxial compression apparatus, direct shear | strength parameters | kaolinit | Jastrzębska (2012) |
| triaxial compression apparatus | strength parameters, natural humidity, total humidity, degree of humidity, specific gravity of the soil skeleton, soil volumetric weight, porosity index, plasticity index, endometric modulus of elasticity | low-bearing soils – peat | Malinowska & Domanski (2013) |
| triaxial compression apparatus | shear strength, plasticity index | cohesive soils with an intact structure | Tymiński & Kiełczewski (2013) |
| direct shear | strength parameters, degree of plasticity | cohesive soils | Pawlak & Chudy (2013) |
| triaxial compression apparatus, direct shear | granular composition, consistency limit; shear strength, bulk density; natural humidity; skeleton bulk density | gravel-clay formations; sandy and dusty; dusty dusts and shales | Zydroń (2014) |
| direct shear | plasticity rate, cohesion, internal friction angle, bulk density, shear strength | cohesive soils of various cohesiveness | Zydroń et al. (2017) |

Much more accurate and allowing a greater degree to reproduce the prevailing soil and water conditions and the type of load are tests with a triaxial compression apparatus. When testing soil samples in the method of triaxial compression from a specific area, important information should be taken into account, such as the soil and water conditions in the field and the specificity of the building or structure erected there. In addition to this information, it is also important to collect soil samples with a structure that reflects the terrain conditions as much as possible, e.g. using the CPTU probe, which consists of pressing the tip of the cone at a constant speed, which prevents the sample structure from being disturbed. On the basis of the knowledge obtained during the sampling of soil and information about the designed building contained in the construction design, one of the three sample testing options should be selected, i.e. UU, CU or CD. In the case of the UU shear strength test, there is no consolidation and only a very limited outflow of water from the pores. This type of test should be used when in practice the soil is loaded so quickly that its consolidation takes place to a small extent, and additionally, due to the speed of loading and soil and water conditions, water outflow is prevented. The use of the CU test allows for earlier consolidation of the soil, and then during the shear strength test, water drainage is prevented. These test conditions are best reflected in cases where, following the slow erection of the structure, there is a sudden introduction of a high alternating load. The CD test allows the mapping of the conditions of earlier soil consolidation, and allows water to drain during shear, which results in no excess water pressure in the pores. This type of research mainly reflects the service life of the structure without additional loads.

## Conclusions

The paper characterizes the methods of testing soil strength parameters in laboratory conditions, in particular the method of direct shear in the Krey-Casagrande apparatus and the triaxial compression method. The advantages and disadvantages of both methods are presented. Based on the analysis of literature data, it can be concluded that both methods generally give results that are inconsistent with each other. Depending on the method of determining the strength parameters, we can obtain different values of the angle of internal friction and cohesion for the same samples. As a consequence, the results of the stability analyzes may significantly differ from each other. In order to quickly and roughly estimate the soil parameters, the quick method of direct shear can be used, however, for more precise tests allowing for an approximate representation of soil and water conditions and the method of loading a given area, in which the planned investment is in the form of a planned investment, the triaxial compression method is recommended.

Due to the specificity of soil conditions, it is difficult to define unequivocal rules for the selection of the method of soil shear strength testing, however, an appropriate analysis of field conditions and the nature and specificity of a structure may significantly affect the selection of an appropriate test method.

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