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Analysis of residual shear strength parameters of fine-grained sediments from open-pit 'Drmno' using different types of apparatus

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ABSTRACT: One of the prerequisites for the safe exploitation of surface mines is the stability of the final and working slopes of the mine. In order to ensure this, it is necessary to carry out detailed field and laboratory geomechanical tests of the soil and, based on the obtained results, make calculations related to stability analyses. The results obtained in this way are used for the dimensioning of the slope of the exploitation slopes (excavation), i.e. the slopes formed due to the disposal of tailings. Landslides occur when the shear strength limit is reached, and therefore adequate definition of the shear strength parameters is one of the essential prerequisites for successfully solving the stability problem. Through laboratory tests, it is necessary to determine: cohesion - the forces between the contact surfaces of the particles that connect them and the angle of internal friction - occurs between the particles due to their movement, sliding or rolling. Unlike earlier tests, when the residual shear strength parameters were determined based on the usual conventional methods (direct shear apparatus, triaxial apparatus), this time, in addition to the direct shear apparatus, a ring shear apparatus was also selected for testing. The aim of this paper is to determine the difference of the obtained values using these two different devices, as well as the comparison of the obtained values with the world literature.

KEYWORDS: residual strength of sands; ring shear apparatus; direct shear apparatus; slope stability; open pit mines.

1 INTRODUCTION

Residual soil strength is of great importance in slope failure analysis after large shear displacements. It represents the strength attained during significant displacements, which remains stable even after further shearing in the same direction, as it does not decrease but stays constant. Therefore, residual strength does not lead to further reduction in shear strength nor does it cause changes in volume or pore pressures

Laboratory procedures for defining and measuring residual shear strength are carried out using various methods. The oldest and simplest method is the direct shear test, which is conceptually straightforward and has been used in geotechnical investigations for over 200 years. This test was first employed in 1776 by Coulomb, with notable contributions from French engineer Alexandre Collin in 1846. In Great Britain, Bell recorded the first measurements and developed a device for shear strength testing in 1915. The modern shear box was designed by Casagrande in 1932, and devices with a constant deformation rate - based on the principle of "controlled deformation" using a motor with a constant speed - were developed in 1946. Vickers also developed a shear apparatus capable of measuring both drained and undrained samples.

However, ring shear apparatuses, which allow for unlimited shear displacement of the sample and are based on the concepts developed by Hvorslev in 1936 and 1939, have become increasingly popular due to their improved capabilities in both Eastern and Western geotechnical practices. Various models have been developed, such as those by La Gata (1970), Bromhead (1979), and apparatuses by Sassa and colleagues from DPRI starting in 1984, which enable simulation of seismic effects and measurement of pore pressures during undrained tests.

The concept of residual shear strength first appeared in the literature in 1937. This parameter is of great significance in geotechnical engineering because, after large shear displacements, the shear strength remains at the same level and does not decrease, which is crucial for assessing the stability of slopes and landslides. Understanding the sliding mechanism and how residual shear strength is attained is essential for modeling shear failure processes.

Laboratory methods such as direct shear tests typically allow maximum displacements of up to 10 mm for samples measuring 6 x 6 cm. However, such displacements are insufficient for realistic sliding conditions, where displacements can reach several tens of centimeters. Therefore, ring shear tests are recommended, as they permit unlimited shear displacement of the sample and provide more reliable results for determining residual shear strength. These tests are especially important for analyzing shear processes involving large displacements, and their application is explicitly regulated by European standards, such as Eurocode 7: Part 2: 2007.

In practice, both in Serbian and global geotechnical engineering, results from reverse direct shear tests are still most frequently used to assess residual shear strength, although shear box tests are significantly more reliable for simulating real sliding conditions. It is crucial that during the testing process for determining residual shear strength parameters, the shear boxes are kept parallel throughout the shear displacement, which can only be ensured using a ring shear apparatus.

2 THE BROADER GEOLOGICAL STRUCTURE OF OPEN PIT MINE DRMNO

The "Drmno" open – pit mine is located on the right bank of the Danube, approximately 90 km downstream from Belgrade, and encompasses the area east of the Mlava River (Figure 1.). Its boundaries are the Danube River to the north, Boževačka Greda to the east, the Bradarac – Sirovačka Valley line to the south, while the western boundary is the Mlava River.

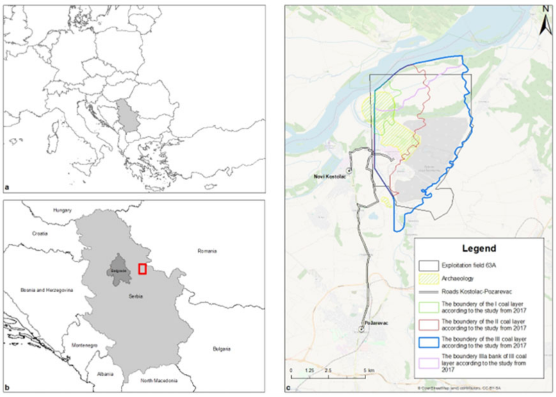

Figure 1. (a). Position of Serbia in relation to Europe. (b). Position of the Kostolac area in relation to Serbia. (c). Position of the Drmno deposit in relation to Kostolac. (Ćorluka, 2024)

The wider geological structure of the Kostolac area consists of Paleozoic, Neogene and Quaternary layers, and PK Drmno itself is built of three layers of coal, marked as III, II and I, arranged from the oldest to the youngest. The deepest and oldest is layer III, which was deposited over the clayey-sandy sediments of the lower Pontus, and its composition includes layers of carbonaceous clay, silt and sand, with local interlayers of coal and siltstone in the lowest parts. Layer II, which extends northwest of the deposit, while the uppermost layer I, which occupies a small part of the western zone, is the youngest and mildest. Overburden deposits are diverse and locally consist of gravel, sand, clay and loess. These deposits can be divided into direct overburden, interlayer overburden and subgrade, where the most overburden occurs in the western parts of the deposit, with sand and clay layers, while coal and siltstone layers occur in the lowest layers. As a whole, sedimentary layers and overburden deposits form a complex deposit structure, the details of which are carefully studied in order to estimate the coal content and designed exploitation works.

For the purposes of this research, laboratory tests of roof sediments were performed on a total of 6 samples, which included: sands - layer no. 4 (3 samples: U-1, U-2, U-3) and sandy silt - layer no. 8 (3 samples: U-10, U-11, U-12) (Figure 2.).

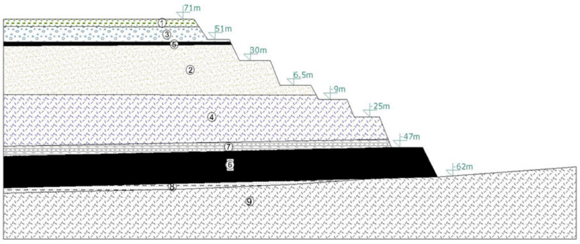

Figure 2. Schematic representation of the final western slope of the open pit mine: 1: humus; 2: sand; 3: gravel; 4: siltstone; 5: second coal layer; 6: third coal layer; 7: gray clay; 8: sandy silt; 9: floor (subsoil).

3 APPARATUS AND TESTING PROCEDURE

3.1 *Apparatus for determining residual strength*

For the purposes of this research, the residual shear strength was tested on isolated soil samples using two apparatuses: a ring shear apparatus (RS) and a direct shear apparatus (DS).

The RS used in the study is based on the original design developed by Bromhead (1979) and manufactured by Wykeham-Farrance Engineering Limited. The sample is in the form of a ring with an inner diameter of 70 mm, an outer diameter of 100 mm and a sample height of 5 mm. Drainage of the sample was facilitated by two bronze porous discs attached to the bottom of the lower section and to the upper section of the shear box.

In the circular shear apparatus, the cross-sectional area of the sample remains constant during the test, so that the shear stresses are induced by the torque.

The fequation for calculating the residual shear strength:

$$\tau_r = \frac{3(F_1+F_2)L}{4\pi(R_2^3-R_1^3)} \qquad (1)$$

where is:

τ_r- residual shear strength, kPa;
F_1, F_2 – the force read at the ends of the torque transmission beam, N;
R_1, R_2 – inner and outer diameter of the sample, mm;
L – beam length for torque, mm.

For determining the residual shear strength parameters through direct shear testing in a box, a apparatus manufactured in Italy by Matest was used. The sample was of square shape, measuring 60 x 60 mm, with an initial height of 21 mm.

The equation for calculating the residual shear strength:

$$\tau_r = \frac{P}{A} \qquad (2)$$

where is:

τ_r - residual shear strength, kPa;
P - horizontal shear force, N;
A - cross-sectional area of the sample, mm.

3.2 *Testing procedure*

For the determination of residual strength with the DS and RS apparatus, processed or reconstructed samples can be used (Skempton 1985). Bishop et al. 1971, point out that the residual shear strength is not affected by the deformation of the samples (previous stress history). Processed samples for testing were prepared first by air drying and then by crushing the soil in an avan. The samples were then sieved through a 2.0 mm sieve, mixed with distilled water to the desired moisture content for compaction, and allowed to hydrate for at least 24 h.

Processed samples for testing were compressed directly into the RS apparatus. In the case of the DS device, the samples were prepared as for the RS device, after which the sample was first pressed into a square mold with dimensions of 6x6 cm and then squeezed out of the mold into a shear box.

In the RS device, samples were directly formed in the form of a ring (Figure 3), while in the DS device, square samples with a disturbed structure were formed (Figure 4).

Figure 3. Appearance of sand samples after testing in a ring shear apparatus

Figure 4. Appearance of sand samples after testing in a direct shear apparatus

The samples were consolidated and sheared at vertical loads of 50, 100, 200 and 400kpa. A constant vertical pressure was maintained during shearing.

When selecting the shear speed, the criterion was set that the speed should be slow enough to eliminate the occurrence of pore overpressure on the fracture plane at the pre-defined fracture criterion. Ramiah et al. (1970) found that the measured residual shear strength was not affected by increasing the feed rate from 0.02 to 60 mm/min. Skempton (1985) concluded that there is less than 5% variation in the value of the angle of internal friction for shear rates ranging from 0.05 to 0.35 mm/min. The Geotechnical Society of Japan (2010) suggests a shear rate of 0.02 mm/min in direct shear machines. In order to reach an acceptable shear rate for the purposes of this research, the processed samples were tested at a shear rate of 0.02 mm/min with both apparatuses.

Ideally, the residual shear strength of a soil can be defined as the shear strength at which the shear stresses and volume of the specimen are constant with further increase in horizontal displacements (strain) (Skempton, 1964). For a ring shear test, Bromhead (1992) concluded that if the shear torque is constant for more than 1 h, then residual shear strength is involved. In this paper, the test specimens in the circular shear apparatus were sheared to a displacement of about 360 mm while in the direct shear apparatus the specimens were sheared until two consecutive cycles with the same values were repeated.

4 RESULTS AND DISCUSSION

The scope of this paper includes an analysis of the results related to the residual shear strength, obtained on sandy silt and sandy samples that are part of the roof of the III coal layer, is presented (Figure 2).

The analysis of the particle size distribution shows that sandy silt consists of 4-8% clay fractions, 72-82% silt fractions and 14-20% sand fractions, and the sand layer consists of 3-5% silt fractions and 0-2% sand fractions. The results of these tests are shown in Figure 5.

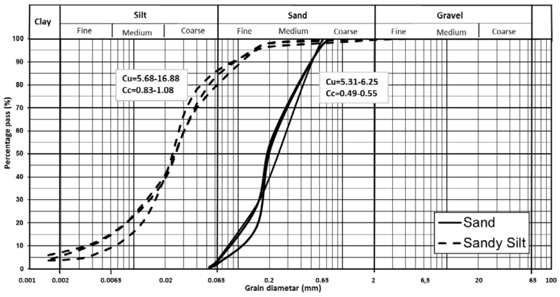

Figure 5. Particle size distribution graph

For sandy silts, the liquid limit is in the range *LL*=46.3-47.5%, while the range of plasticity index values is *Ip*=19.7-21.6%. Sand samples are not plastic.

Shear strength parameters are defined by cohesion and angle of internal friction (Terzaghi, 1951; Stark et al., 2005;). However, the residual angle of internal friction varies depending on the properties of the soil as well as the magnitude of the normal stress, provided that the residual cohesion of the soil is zero (Skempton, 1964; 1985; Kimura et al., 2014), which is adopted in this research.

The residual values of the angle of internal friction obtained in the DS apparatus for sands ranged from $\varphi`_r = 24.8$-25.2°, while the values obtained from the RS apparatus ranged from $\varphi`_r = 25.1$-25.5° (Figure 6)

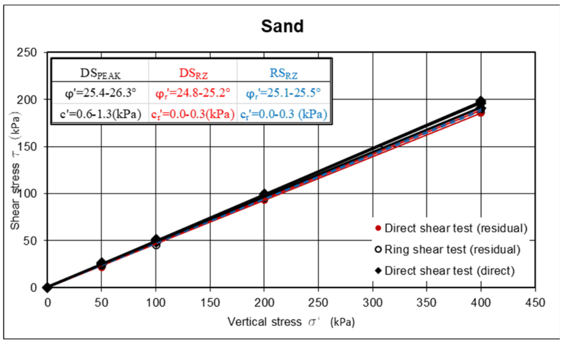

Figure 6. Values of the residual shear strength parameters for sands depending on the testing method

The residual values of the angle of internal friction obtained in the DS apparatus for sandy silts ranged from $\varphi`_r =$ 14.8-15.3°, while the values obtained from the RS apparatus ranged from $\varphi`_r = 12.2$-13.7° (Figure 7).

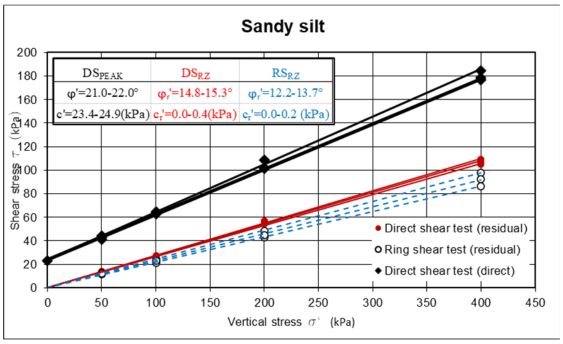

Figure 7. Values of the residual shear strength parameters for sandy silts depending on the testing method

Anaii et al. (1988) found that modified Bromhead ring shear tests yielded lower residual friction angle values than the reverse direct shear test. Heidemann (2020) obtained values of the angle of internal friction in DS of 12.0° on samples of silty soil from a large landslide in Brazil, while in the RS apparatus he obtained a significantly lower value of 7.7°.

For sandy silt samples, the difference in the residual angles of internal friction obtained from DS and RS is more pronounced, with the angle values from DS being 1.6 - 2.6° higher than the values obtained from RS.

The residual strength of sands is not often analyzed in the literature. In his analysis, Lupini (1981) came to the conclusion that the residual angles for sandy soils are usually above 25°, which is in good agreement with the results obtained in this paper.

Yatabe et al. (1996) determined that the residual angle of internal friction (φ'_r) increases significantly when the content of sandy fractions in the soil (*Fs*) exceeds 30%, which was confirmed by the results of this research. (Figure 8). Also, they showed that when *Fs* exceeds 80%, the value of φ'_r becomes approximately equal to that of pure sand (*Fs* = 100%). These results indicate that the presence of sand has a significant effect on the residual strength of the soil, but this effect does not follow a simple linear trend.

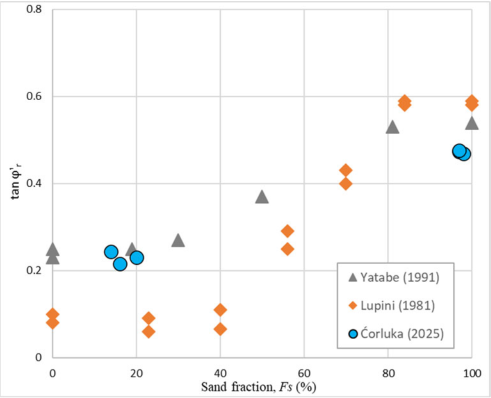

Figure 8. The relationship between tanφ'_r and the percentage of sand fractions (Yatabe, 1996 - modified)

In this study, the obtained results for the relationship between the percentage of sandy fractions (*Fs*) and the tangent of the angle of internal friction ($tan\varphi'_r$) were compared with the results shown in the papers of Yatabe (1991) and Lupini (1981) (Figure 8). The analysis shows good agreement with the results of Yatabe (1991) in situations where the proportion of sandy fractions is less than 30%. However, it is noted that Lupini (1981) tends to show lower values for $tan\varphi'_r$ under similar conditions. For samples with over 80% sand fractions, the $tan\varphi'_r$ values obtained in this study are lower compared to the results of both Yatabe and Lupini. These differences in results are likely due to variations in soil properties and/or test methodology.

5 CONCLUSIONS

In this paper, the residual shear strength of different geological environments at the Drmno open-pit mine was examined. Using the apparatus for direct and circular shear, experimental tests were performed on samples of different types of soil (sand, sandy silt) in order to determine the residual shear strength. A total of 6 samples were tested, and for each sample, tests were performed using four different levels of normal stress (50, 100, 200 and 400 kPa), with a constant shear rate of 0.02 mm/min, in accordance with standard practice.

On the sand samples, the difference was smaller, with a range of $\varphi'_rRS = 25.1°$ to 25.5° (ring shear) and $\varphi'_rDS = 24.8°$ to 25.4° (direct shear).

In the case of sandy silt samples, the difference in the residual angles of internal friction obtained from DS and RS is more pronounced, with the values of the angles from DS being 1.6 - 2.6° higher than the values obtained from RS.

A comparison of the relationship between the percentage of sandy fractions (*Fs*) and the tangent of the angle of internal friction ($tan\varphi'_r$) with the results of the works of Yatabe (1991) and Lupini (1981) showed that the values of $tan\varphi'_r$ in this research for soils with a lower percentage of sand coincide with the values obtained by Yatabe and are higher than those of Lupini, while at higher values of *Fs*, $tan\varphi'_r$ are lower than those of Yatabe and Lupini.

Through the analysis of residual soil strength parameters of non-productive deposits on opet-pit mines, it is possible to significantly contribute to the optimization of the angle of inclination of the working and final slopes of surface mines. By considering the geomechanical characteristics of the sediment, mines can more effectively manage slope stability and reduce the risk of landslides.

6 ACKNOWLEDGEMENTS

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