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Review paper

LABORATORY TESTING OF SHEAR PARAMETERS THROUGH ROCK MASS AND ALONG DISCONTINUITIES – THE KOMARNICA DAM

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Abstract: The paper shows the results of laboratory geo-mechanical tests of shear parameters (c - cohesion and φ - angle of internal friction) established on representative samples isolated at the site of construction of concrete arch dam Komarnica in Montenegro. For the testing of parameters of shear strength through rock mass, representative samples were used isolated from exploration wells. Testing of shear strength along fractures was made on cylindrical samples, which were isolated in exploration galleries. The paper shows test methods, analyses of results and concluding analysis. Tests on fractures were made at the Institute for the Development of Water Resources "Jaroslav Černi" in Belgrade, and tests of shearing through mass at the Faculty of Mining and Geology in Belgrade.

Key words: rock mass, shear, fracture, fault

1. INTRODUCTION

Rock mass failures caused by the load due to the construction or mining works usually occur by exceeding the shearing resistance. Therefore, in the process of researching geo-mechanical properties of working environment, the most important parameters are shear parameters: φ - angle of internal friction and c - cohesion. The angle of internal friction and cohesion are elements of internal resistance of solid, plastic and loose rocks.

Basic methods of determination of shear parameters within solid rock masses are: through solid rock mass or along discontinuities. Tests can be performed in laboratories or "in situ".

The paper shows the results of laboratory geo-mechanical tests of shear strength through mass and along fractures, established on representative samples on the site of construction of concrete arch dam Komarnica in Montenegro.

Canyon of the river Komarnica belongs to the group of magnificent and mainly impassable canyons of river basins of Piva and Tara. It is 4 km long, and its steep banks are at some places, such as Sinjeva kosa, cut up to 600 m depth. Due to its very steep banks, where, at some places, the distance is only 2 to 3 m (Figure 1), Sun beams hardly reach the river, so that this canyon is also called Nevideo (Figure 2).

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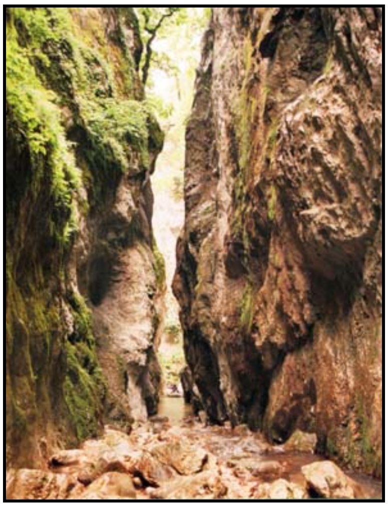

Figure 1 - Nevideo
Canyon of the river Komarnice

Figure 2 - View of the Canyon
at the section of future dam "Komarnica"

The site where the dam is to be constructed is formed by limestone of Lower Cretaceous, with banked to massive texture, with fine-grained structure. There are also subparallel faults, subvertical fractures, stratification fractures (contour lines) and contact between limestone and fault breccia as well (Anđelković et al. 2012).

2. DETERMINATION OF SHEAR STRENGTH THROUGH ROCK MASS

In order to determine parameters of shear strength through rock mass, test pieces of cylindrical or prismatic form are being used in laboratory. Shear is carried out in special molds, which enable shear at the desired angle α (Figure 3). Angles at which shear is to be carried out should be at intervals from 30° to 70°.

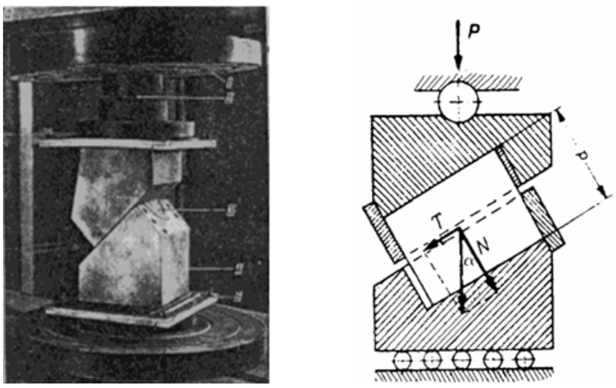

Figure 3 - The look of the mold for angular shear

Tests of shear strength through mass were carried out on 20 samples extracted from exploration wells at the dam site of the Komarnica dam. Samples had diameter of 52.0 mm to 86.0 mm, and h/d ratio h/d ≈ 1.0. Tests were carried out by using a 2000 kN press.

Cohesion *c* and angle of internal friction φ were determined by using method of shearing the sample at the angle $\alpha = 45°$ and $\alpha = 70°$, Figure 3 (Ljubojev and Popović, 2006). For each of the fore mentioned α angles, test was carried out on one test piece each. Values of direct and tangential stress during the shearing process were determined by applying the following expression:

$$\sigma = \frac{P}{A}\left(\cos\alpha - t_{tr} \cdot \sin\alpha\right) \quad (1)$$

$$\tau = \frac{P}{A}\left(\sin\alpha - t_{tr} \cdot \cos\alpha\right) \quad (2)$$

Whereby:
P - failure force,
A - shearing surface,
α - shear angle,
t_{tr} - friction coefficient in case that there are no rolls under the mold ($t_{tr} = 0.15$).

If there are rolls under and above mold, friction coefficient is to be calculated from the relation:

$$t_{tr} = \frac{1}{n \cdot d} \quad (3)$$

Whereby:
n –number of rolls,
d –cross section of rolls.

With values determined for σ and τ, a graph of strength limit state is made, approximated to straight line, whose inclination determines the value of the internal friction angle φ, and the cross section with ordinate defines the value of cohesion *c* Figure 4 (Cvetković et al. 2005).

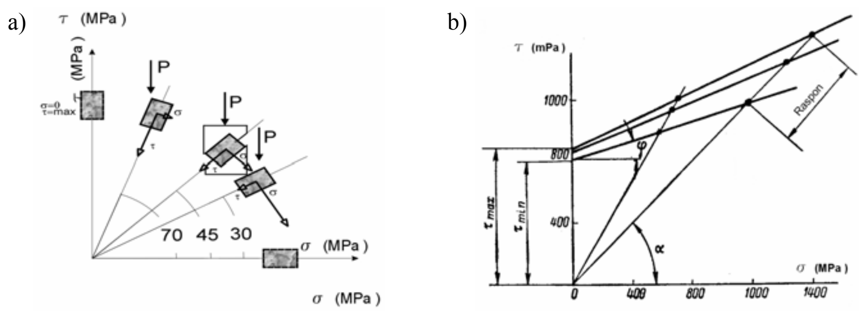

Figure 4 - a) Limiting values of the angle at which angular shear is to be carried out; b) Graph of limit strength state

The results of shear strength testing through mass on representative samples extracted from wells on the right side of canyon are shown in the Table 1 and the results of representative samples extracted from the wells on the left side are shown in Table 2 (Faculty of Mining and Geology, 2011).

Table 1 - Parameters of shear strength (right side of the canyon)

Designation of the well	Depth [m]	Volume weight γ [kN/m^3]	Parameters of shear strength φ [°]	Parameters of shear strength c [MPa]
BD - 1	17.50	26.36	42.5	7.11
	37.50	26.50	41.5	10.75
	70.35	26.23	37.5	9.00
BD - 2	76.60	26.30	38.0	14.50
BD - 3	52.90	26.29	43.0	8.00
BD - 4	26.25	26.29	42.5	9.20
	47.40	26.60	42.0	8.50
	75.00	26.51	43.0	10.00

Table 2 - Parameters of shear strength (left side of the canyon)

Designation of the well	Depth [m]	Volume weight γ [kN/m^3]	Parameters of shear strength φ [°]	Parameters of shear strength c [MPa]
BL - 2	10.00	26.19	39.0	11.00
	40.10	26.20	40.0	13.00
	102.50	26.53	42.5	4.50
BL - 3	29.00	26.52	37.0	6.50
	53.60	26.26	39.0	7.50
BL - 4	30.00	26.39	39.0	5.00
	40.00	26.54	41.5	2.50
	48.30	26.26	40.0	17.00
	82.60	26.48	42.0	12.00
BL - 5	17.20	26.49	41.0	8.00
	19.00	26.50	40.0	10.00
	77.00	26.36	40.0	9.00

3. TESTING OF SHEAR STRENGTH OF THE ROCK MASS ALONG THE DISCONTINUITY

Testing of shear strength along the discontinuity was carried out on the total of 40 samples. Samples to be tested were extracted from all galleries at the dam site by application of the core drilling method along the strike of the representative discontinuities (Figure 5).

The device for testing the shear strength along the fracture is shown in Figure 6. Testing of shear strength along the discontinuity was carried out by experiments of direct shear on cylindrical samples with diameter $\phi = 200 - 300$ mm. Tests were carried out according to dispositive and technical conditions established at the Institute for the Development of Water Resources "Jaroslav Černi", Figure 6 (Majstorović, 2002).

Testing of shear on samples were carried out in three stages:

I stage - stabilization of discontinuity influenced by the nominal stress;
II stage - shear until reaching shear strength and
III stage - friction experiments.

At the first stage, direct stress was applied gradually step by step until reaching nominal value under which the stabilization of fracture infilling was carried out. Nominal values of normal stress, under which shear was carried out, were from $\sigma = 0.1$ MPa to $\sigma = 1.5$ MPa.

Figure 5 - Locations where cylindrical samples of the rock mass along the fracture were taken in order to carry out one series of testing

After that, at the second stage, shearing stress was applied gradually step by step until reaching shear strength along discontinuity. After breakage by shearing, friction experiments were carried out. Those experiments were carried out by applying three direct stresses on each sample, which were selected so that they most optimally cover the range of direct stresses designated for shearing of one series of samples.

The basic feature of those experiments was that the shearing experiments in most cases were carried out on very uneven surfaces of fractres covered with the layer of clay, whose thickness was from severall mm up to several tenths mm, so that in majority of cases this very thickness of clay layer within the infilling was determining features of certain type of discontinuity.

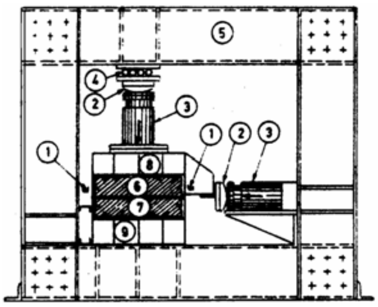

Figure 6 - Device for carrying out shearing along fractures on cylindrical samples: 1 - deflectometer, 2 - joint, 3 - hydraulic press, 4 - rocker bearing, 5 - frame, 6 and 7 - sample

Generally, the results of testing were shown in two ways: as per series of samples extracted from the certain fracture system within the exploration galleries on the left and right bank (8 series of samples) and per main types of discontinuity, regardless the locations of extraction within the exploration galleries (the fault "Med", subvertical fractures, contour lines and contact between limestone and fault breccia). The results of testing are shown in Table 3 (Anđelković et al. 2012).

Figure 7 shows the shearing experiment carried out on one sample, as well as three friction experiments carried out after shearing. The sample bears the designation GL-1/9 (extracted from the gallery GL-1 and it belongs to series GL-1/6-10). As per type of discontinuity it belongs to contour lines, without clay contents within discontinuity.

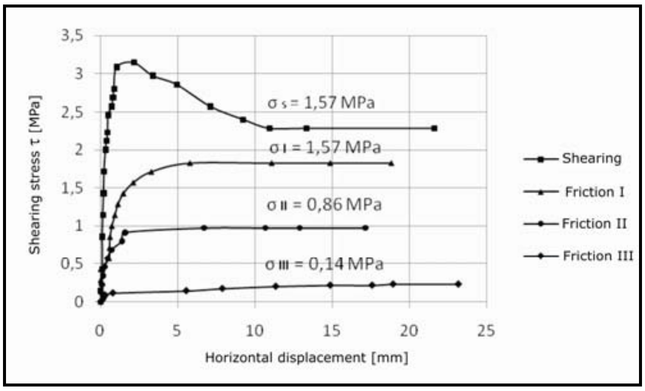

Figure 7 - Results of shearing experiment - charts of shearing and friction

Figure 8 shows charts of shear and friction strength for the type of discontinuity designated as contour lines without clay contents, whose part is the sample GL-1/9, too. For this type of discontinuity, extremely large values of shearing and friction strength were obtained, such as: $\varphi = 45.3°$, angle of shear strength and $c = 0$ MPa, friction: $\varphi = 36.8°$ and $c = 0.025$ MPa.

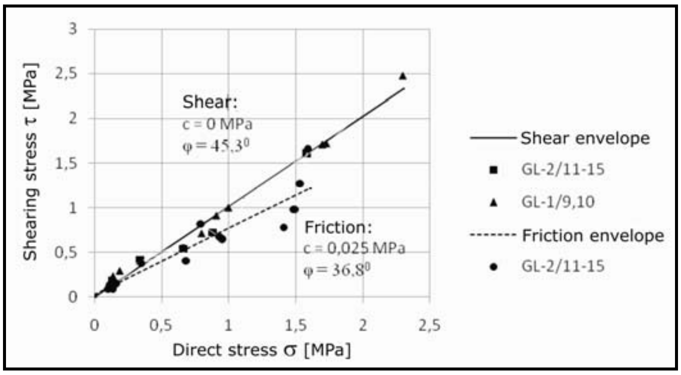

Figure 8 - Charts of shear strength and friction for "contour line" type of discontinuity that do not contain clay in the infilling

Table 3 displays values of shear features for the said discontinuity types, classified as per clay contents where necessary.

Table 3 - Values of shearing features

<table>
<tr><th>Fracture system</th><th>Description of walls and infilling</th><th>Designation of samples</th><th>Shearing</th><th>Friction</th></tr>
<tr><td>Fault "Med"</td><td>Infilling made of clay and a piece of limestone</td><td>GD-1/1-5</td><td>$\varphi = 22.4°$
$c = 0.127$ MPa</td><td>$\varphi = 18.4°$
$c = 0.078$ MPa</td></tr>
<tr><td rowspan="3">Subvertical fractures</td><td>Walls, even, without clay in the infilling</td><td>GD-2/6
GD-2/10</td><td colspan="2">$\varphi = 32.9°$ $c = 0.2471$ MPa</td></tr>
<tr><td>Clay layer, 5 - 20 mm thick in the infilling</td><td>GL-2/1-5
GD-2/7</td><td colspan="2">$\varphi = 31.4°$ $c = 0.037$ MPa</td></tr>
<tr><td>Clay layer thicker than 20 mm</td><td>GL-1/2-5
GD-2/9</td><td colspan="2">$\varphi = 13.9°$ $c = 0.0656$ MPa</td></tr>
<tr><td rowspan="3">Contour lines</td><td>Uneven walls, infilling without clay</td><td>GL-2/11-15
GL-1/9, 10</td><td>$\varphi = 45.3°$
$c = 0$ Mpa</td><td>$\varphi = 36.8°$
$c = 0.025$ MPa</td></tr>
<tr><td>Clay layer up to 10 mm in the infilling</td><td>GL-1/6, 7, 8</td><td colspan="2">$\varphi = 38.4°$ $c = 0.06$ MPa</td></tr>
<tr><td>Clay layer thicker than 10 mm in the infilling</td><td>GD-2/1, 3, 3R, 4, 5</td><td colspan="2">$\varphi = 13.3°$ $c = 0.1431$ MPa</td></tr>
<tr><td rowspan="2">Contact betwee limestone and fault breccia</td><td>Uneven walls of fractures</td><td>GL-2/6, 7, 8, 10</td><td>$\varphi = 29.5°$
$c = 0.055$ Mpa</td><td>$\varphi = 26.6°$
$c = 0.026$ MPa</td></tr>
<tr><td>Even walls with thin clay layer</td><td>GL2/9</td><td colspan="2">$\varphi = 15.2°$ $c = 0.065$ MPa</td></tr>
</table>

4. CONCLUSION

When examining results of shearing throught rock mass at predisposed angles (Tables 1 and 2), it was observed that the range of values of angle of internal friction for twenty representative samples teste was relatively small from $\varphi = 37°$ to $\varphi = 43°$, and that the values for cohesion significantly differ, from $c = 4{,}50$ MPa to $c = 14{,}50$ MPa.

Based on the experiments of shearing along discontinuities performed on cylindrical samples, it was established that there are mainly two influences that the properties of shearing depend on: the influence of unevenness of fracture walls and influence of clay contents within fractures. Both of those influences were observable, so that at shearing along fractures without clay contents, high and very high values of shear strength were obtained, while at the shearing carried out on the clay layer without influence of unevennesses, very low values of strength were obtained. At shearing, carried out partially on unevennesses, and partially on clay, values of shear strength differ quite enough, so that they cannot be analyzed together with those extreme cases. Based on those properties, the results of shearing experiments were analyzed depending on the type of discontinuity established as characteristic in the section of the dam and depending on the influence of clay contents within the infilling.

When analyzing the results obtained, it was concluded that the values of internal friction through solid rock mass are roughly equivalent to the values of the angle of internal friction established for contour lines with uneven walls without clay infilling and for the case that the clay infilling is < 10 mm. In all other cases, the comparison is not possible and each type of discontinuity must be separately examined.

The performed analyses of parameters of shearing through rock mass and along discontinuities, which were classified according to the type of infilling and surface roughness, have produced results that can be used, with a high level of reliability, for a significant structure such as the arch dam.

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