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Pull Experiment to Validate Photogrammetrically Predicted Friction Angle of Rock Discontinuities

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Abstract

The estimation of the mechanical properties of rock joints is crucial in terms of safety when it comes to design of slopes in open pit mines or caverns used for the storage of hazardous materials, for instance – nuclear waste. Photogrammetry provides a simple, objective method for joints roughness assessment, without the need for expensive and time consuming laboratory tests or subjective empirical methods. In this study, a new photogrammetric method was used to estimate the roughness, shear strength and friction angle of a discontinuity of 2 m by 1 m fresh rock joint. The estimation was done by analyzing the profiles of digital models of joint surface. Surface Length and Slope Measurement methods were used to calculate the values of Joint Roughness Coefficient (JRC) of analyzed surfaces. Next, the shear strength and friction angle of the rock discontinuity were obtained experimentally with multistage pull testing. The results obtained with both methods were analyzed and compared. JRC values from photogrammetrically created digital models of the joint surface were overestimated due to the low density of the models, which resulted in high noise to signal ratio. Shear strength obtained with photogrammetrically created models were overestimates in relation to the results of the pull test by approximately 45 %. The errors made during this research are analyzed in the article and recommendations on how to improve reliability of the results are made. Main error in photogrammetric prediction was low density of the point clouds and in laboratory test too low stiffness of the test arrangement. The alternative methodology for photogrammetric studies used in previous stage of the research project was tested during this study and was proven to give significantly higher accuracy of generated digital models. The stiffness of the testing machine and proper positioning of the sample halves on top of each other were identified as the most sensitive aspects of methodology of big scale pull test when it comes to the reliability of results.

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1. Introduction

The determination of shear strength of rock discontinuities is an object of research since the middle of the last century, yet the developed models and failure criterions are based on simplifications which are the topic of ongoing discussion in the field of rock mechanics [1]. The reason for that is the multiplicity and complexity of the parameters affecting the value of the shear strength of a joint. Those parameters include joint surface condition (dry, wet, submerged, weathered, unweathered), roughness of the joint surface, matedness (matching) of the opposites of a joint, compressive strength of a joint, normal load which the joint is subjected to and the mineral composition of the jointed rock, which determines its basic friction angle [2]. The parameter which is the most challenging to quantify is the roughness of a joint surface. That is mainly due to the anisotropic character of natural joints. Directional variation in the joint roughness results in the different shear strength of the same joint depending on the direction of shearing [3]. Therefore, most commonly used method of determining the roughness – Joint Roughness Coefficient (JRC) profiling [4], ISRM suggested method [5] is considered subjective by significant amount of investigators, since it only quantifies the roughness in one direction and involves a human decision on where to measure the shape of the profile, and then to match the obtained profile with a reference [3, 6, 7].

Significant contribution to the improvement of the peak shear strength criteria were made in recent decades, incorporating alternative methods of quantifying the roughness of a rock joint. Fractals are used very frequently as a measure of rock fracture roughness [7-13]. Conventional statistical parameters have been used by some researchers to quantify the joint roughness [6]. Although, those approaches only consider 2D profiles and therefore cannot represent the anisotropy which is present in natural rock joints. The limits of said methods were overcome by taking into account the three-dimensional surface geometry of a joint [3, 14]. The main principle of the criterion proposed by Tatone and Grasselli is to create a high density point cloud model of the joint surface collected by optical instruments – for instance, close range photogrammetry or laser scanning [14, 15]. However, there is a significant economic advantage of photogrammetry in relation to the laser scanning since it can produce good results using off-the-shelf equipment [16]. Photogrammetry has been successfully used for the surface roughness evaluation by many researchers [16-20]. Many publications report that results obtained by photogrammetry are more accurate comparing to other methods such as dial gauges measurement, profilometry or drag measurement system [18]. In practice, the photogrammetry is commonly used to obtain the data for kinematic and numerical analyses in the slope stability assessment [19].

The accurate estimation of the mechanical properties of rock joints is crucial in terms of safety when it comes to design of slopes in open pit mines or caverns used for the storage of hazardous materials e.g. nuclear waste. The goal of presented study was to validate the mechanical properties of a rock joint predicted using photogrammetry procedure described in [21]. The chosen research method is to compare the values of friction angles obtained using pull and tilt tests with results obtained using digital sampling of photogrammetrically created digital surface models. The main objectives of this research can be formulated as steps in the process of validation: first obtain peak friction angle using experiments and photogrammetry, then compare the results and identify any discrepancies, finally propose improvements to the experimental procedure and/or to the photogrammetric approach.

2. Methods

2.1. Sample description

This paper presents the comparative analysis of two methods of obtaining the shear strength of a rock joint: photogrammetric prediction and direct shear testing. The sample used in this study was a block of Grey Kuru granite with artificial tensile fracture. The length of the block was 200 cm, its width 95 cm and the total thickness 26 cm. The mass of the block was approximately 1300 kg and its density about 2630 kg/m³. Uniaxial compressive strength of the material was 218 MPa [22]. Photogrammetric prediction of joints shear strength and friction angle was done by using the methodology presented in [21]. To determine the level of damage done to the sample by shear test, the joint surface was photographed twice, before and after the test. Additionally, the visual damage locations were mapped manually between the intermediate loading stages. Digital and hand measured roughness analysis was conducted at both stages, intact and damaged. Direct shear test was executed by means of a multistage pull test,
2.2. Close range photogrammetry

The camera body Canon 600D and objective Canon EF 35 mm f/2.0 IS USM lens were used. Image acquisition in this study was conducted by following the methodology developed in previous stages of KARMO project [15, 21]. In this methodology, pictures are taken from a set camera position as the sample is revolved 360° (Fig. 1). For that reason sample half was put on a rotational table, and was rotated in intervals of 2°. In between every 2° rotation a picture was taken, which gives 180 pictures per one camera position. Each sample half was photographed from 5 different vertical camera positions. That means, in total about 900 pictures were taken of one joint surface. Main concept of this methodology is that the whole sample is visible and fits in the sharpness area on each picture. The sharpness area is defined by the near and far depth of field (DoF) distance. That value can be controlled by the distance from camera to photographed object and the aperture of the lens. For each camera position, the appropriate distance between camera and object as well as aperture were selected to ensure the sharpness of images.

Acquired images were used to create the digital models of the joint surface. The surface model formation was carried out following the principles of photogrammetric modelling presented in [21]. The RAW images obtained with photography were converted to JPEG file format with Canon Digital Photo Professional software version 3.14.47 to sharpen the images for enhancing data extraction in following modeling steps. A 3D point cloud is constructed with SfM (Structure-From-Motion) routine with VisualSFM 0.5.25 software. The SfM technique identifies local features from the 2D images and constructs a 3D model reconstruction based on the identified features [24]. The images are matched with modified version of SIFT-algorithm [25], known as SiftGPU, which utilizes the GPU for faster calculation speed. The SiftGPU applies the identified DoG (Different of Gaussian) key points as local vectors to match features between different photographs [26].

Fig 1. Work set up for image acquisition.
The matched features are combined into a sparse 3D point cloud by a multicore bundle adjustment routine [27]. The resulting sparse point cloud is expanded to a more detailed reconstruction by applying PMVS/CMVS [28] routine. The CMVS (Clustering View for Multi-view Stereo) arranges the photographs with calculated camera locations, and identified features, to create clusters. The created clusters are combined with PMVS (Patch-based Multi-view Stereo) function. The combined model forms the final dense 3D point cloud reconstruction. The created dense model is saved in PLY (polygon file format) for further handling. The point cloud is cleaned by segmenting redundant parts away from the point cloud. Finally, the point cloud reconstruction is triangulated by applying 2D-Delaunay triangulation [29], applied for the best fit plane of the surface. The triangulated model is saved as STL (Standard Tessellation Language) for roughness assessment.

2.3. The digital roughness assessment

The digital roughness assessment is conducted by following principles presented in [21] and [30]. A relative coordinate system for created surface model is established by applying SVD (Singular Value Decomposition) routine, where the derived orthogonal base vectors are set as the principal axes of the created coordinate system. Defining of a coordinate system is followed by defining of a sectioning plane by taking the dot product of the base vector in shearing direction and the normal vector of the surface plane. The sectioning plane is applied to segment the surface model to extract 2D profiles from the surface model. The roughness profile is extracted from the intersections of the sectioning plane and the surface model triangles, from corresponding line and plane equations.

The roughness assessment is conducted by applying slope length method [31] and surface length method [32], by applying sampling normalization with interval of 0.5 mm. The sampling interval is selected corresponding to the interval applied for originally deriving these functions. The normalization is conducted by taking the mean value for each sampling window, as this sampling method resulted in best match for studies conducted in [15]. The slope length method applies the RMS (root mean square) value from local slopes of the 2D profile between the normalized data points. The RMS to JRC relationship is presented in [31]. The surface length method utilizes the Roughness Coefficient ($R_p$), defined as the ratio of the true profile length to the nominal profile length. The $R_p$ to JRC relationship is presented in [32].

2.4. ASPERT – Aalto Shear Pull Experiment for Rock Tensile Fracture

Pull experiment was selected as the most suitable for the purpose of this study and this sample size. Main principle of the pull test on the rock joint is to apply the pull force at a certain rate on the upper sample half while restraining the movement of the lower sample half. The applied force is increased until the peak shear strength is reached and the shearing is continued until the shear strength reaches its residual level and the required shear displacement is reached.

Aalto Shear Pull Experiment for Rock Tensile fracture (ASPERT) was a multistage test with repositioning of the sample. Experiment process was consist of four stages with different levels of normal load. First undamaged sample was photographed, then first loading with self-weight only (with normal force of 4 kPa), second loading (6.6 kPa), third loading (9.2 kPa), another self-weight only loading (4 kPa) and finally the damaged slab was photographed again. Since there is no suggested method for determining the shear strength using pull test specifically [5, 23] the test procedure was adopted from the ISRM Suggested Method for Laboratory Determination of the Shear Strength of Rock Joints: Revised Version [23].

Pulling force was applied on the upper part of the sample using the hydraulic cylinder. The force was transferred through 2.5 m long chains attached with one end to the head of the cylinder and with two ends to the steel frame installed on the sample. The normal load was applied by putting the additional mass on the top of the sample. Since the equal distribution of the load within the shearing area is necessary, that was the most practical way to apply the load on the sample of significant (1.9 m$^2$) area. Used material was gravel contained in bags. Bags were weighted separately and secured additionally with plastic bags in case of spillage.

Bags were put on the top of the sample in a way that they did not inhibit the motion of the LVDTs. According to [23], the shearing rate during the tests was set to 0.1 mm/min before peak shear strength was reached and 0.5 mm/min after the peak shear strength was reached. Although, those are the rates of the hydraulic cylinder.
movement and not the shear displacement of the sample itself. Due to the ability of the chain to store energy the rate of sample shear displacement was different. Total shear displacement of the sample during all test stages was 5 cm. The sampling frequency used for all the test stages was 10 Hz. The rock dust residue left on the sample surface after the sawing was carefully removed with a soft brush and vacuum cleaner. Sample surface was also cleaned in between the test stages, the debris was collected and the rock dust was removed with a soft brush and vacuum cleaner. A more comprehensive description of this methodology can be found in [33].

3. Results

3.1. Photogrammetric prediction of joint’s roughness and friction angle

To find the roughness of a joint surface without the shear test, the images of the rock sample were processed into the digital models and the further analyzed according to the method described in section 2.2 of this paper. The resulting value was a JRC for each of the analyzed models calculated with surface length and slope measurement methods. The results are compiled in the Table 1.

The JRC values presented in Table 1 were used to calculate the friction angle of a joint with Barton-Bandis criterion. Resulting values of friction angle were higher than 70º, which is outside the limit of applicability of Barton-Bandis criterion [4]. For that reason, linear interpolation was used instead of Barton-Bandis criterion to determine the value of friction angle and the shear resistance of a joint. That means that the linear relation between the shear stress and normal load was assumed [34].

3.2. Aalto Shear Pull Experiment for Rock Tensile fracture

During the ASPERT test, the peak and residual shear strength of the rock joint was measured. The vertical, shear and sideways displacement of the sample was also recorded during the test. Table 2 presents a review of the results from all test stages. The shear displacement at peak shear strength is an average of the readings from two shear displacement sensors. Dilation at the end of the test is as well an average of the readings from four vertical displacement sensors. It should be noted that for third and fourth stage of shearing, the average dilation at the end of the test was still increasing. For both stages the dilation angle at the end of the test was around 2.5º.

Figure 2 compiles the stress strain curves from each of the test stages as well as the relation between normal load and shear strength. The right part of the Figure 2 presents the shear strength of a joint during four stages of the test as a function of shear displacement. The left side of the graph present the peak and residual values of shear strength of a joint as a function of normal load during respective stages of the test. It can be observed that in case of residual shear strength the relation of shear strength and normal load is nearly linear. The red dashed line going through the plot is the linear trend for this data. The inclination of the trend line is equal to 32º, therefore the conclusion can be made that the value of residual friction angle is around 32º. In case of peak shear strength the relation to normal stress is clearly not linear. The inclination of dashed lines connecting the intersection of X and Y axes with the respective points on the function represent the values of peak friction angle at each shearing stage. For the first stage that value was 59º, for the second stage - 66º and for the third 62º.

Table 1. Result of the roughness assessment of photogrammetrically generated models of joint’s surface.

<table>
<thead>
<tr>
<th>Surface models</th>
<th>Top half, before test</th>
<th>Top half, after test</th>
<th>Bottom half, before test</th>
<th>Bottom half, after test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point spacing in non-normalized model [mm]</td>
<td>0.76</td>
<td>0.85</td>
<td>1.07</td>
<td>0.75</td>
</tr>
<tr>
<td>JRC, surface length method</td>
<td>41.6</td>
<td>25.5</td>
<td>33.0</td>
<td>31.2</td>
</tr>
<tr>
<td>JRC, slope measurement method</td>
<td>22.6</td>
<td>18.4</td>
<td>21.1</td>
<td>19.9</td>
</tr>
<tr>
<td>Shearing stage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4th</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal load [kPa]</td>
<td>4</td>
<td>6.6</td>
<td>9.2</td>
<td>4</td>
</tr>
<tr>
<td>Peak shear strength [kPa]</td>
<td>10.9</td>
<td>18.0</td>
<td>25.1</td>
<td>10.9</td>
</tr>
<tr>
<td>Peak friction angle [º]</td>
<td>70</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
</tbody>
</table>
Interesting observation which can be made based on Table 2 and Figure 2 is that both peak and residual shear strength of a joint for fourth shearing stage is lower than the same values for the first shearing stage. Since during the second and third stage of shearing the sample surface was altered, one would expect lower results in the fourth stage. Another observation which can be made from the Figure 2 and Table 2 is that the peak shear strength have occurred for about 1 mm of shear displacement for all shearing stages, except for the first stage. In the first stage of shearing the peak value of the shear strength was recorded at approximately 3 mm of shear displacement. Additionally, from the data presented on Figure 2 it can be clearly seen that the shear movement of the sample during all the test stages was not continuous and smooth. The high elasticity of the test resulted with discontinuous movement of the sample due to the stick-slip phenomenon, which is caused by the changes in the friction force between touching surfaces depending if they stay static or are in motion. Because static friction coefficient is higher than dynamic, the force needed to start the movement of an object is relatively larger than the force needed to maintain the movement of already moving object. Certain elements of the testing arrangement were able to accumulate energy and release it after the level of static friction was reached. That led to situation where sample was moving in steps as the energy was being accumulated and released by the testing system.

4. Discussion

The results of photogrammetric prediction are unsatisfactory due to the low density of produced point clouds. The ISRM standard for shear tests of rock joints [23] suggest that in order to characterize the features of surface roughness precisely enough for the shear damage to be detected the nominal distance between the points in the point cloud should be < 0.5 mm. Perhaps for such sample size different photogrammetry technique should be used, some
which does not require the complete overlapping of pictures but allows to photograph the object in parts. That would allow to reduce the distance from camera to object significantly and therefore improve the resolution of the photographs [35].

The results of experimental studies using the pull test can also arise some questions about the possible mistakes in methodology. Especially questionable here are the results of the first stage shearing and the difference between the results of first and fourth stage of shearing. Unexpectedly, both peak and residual shear strength of the joint were higher in fourth stage of the test comparing to the first. One hypothesis is that the sample surface was contaminated with a residue from the sawing process. Another hypothesis is, that the position of the sample during the first stage shearing was not correct. That means, that the opposite sides of the sample were not aligned correctly and did not overlap each other as they should. This theory is supported by the value of dilation during the first stage of shearing. The dilation continued to be negative for around 1.5 mm of the shear displacement of the sample. In the other stages, the dilation values increased to above zero, before 1 mm of shear displacement was reached. The negative value of dilation is a sign that the joint was matching or finding the correct position. That can result from the poor matedness of a joint as well as from the opposite sides of the sample not being positioned properly at each other. Since in three other stages the dilation increased above zero much earlier it can be concluded that in the first stage incorrect positioning of the sample was the reason for remaining negative dilation values. The suspected surface mismatch problem could have been prevented if the test arrangement included more reliable guiding facilities to position the samples on each other.

Another observed phenomenon was the pronounced amount of stick-slip motion. One hypothesis is that this was due to too high elasticity of the loading arrangement using 2.5 m long steel chains. Sudden jumps in the sample movement during the second and third stage of shearing were observed. The value of shear stress after peak fell below the value of residual shear strength of the sample and the applied shear stress was increased to the level where sample was moving again. The effect of stick-slip phenomenon could have been minimized by increasing the stiffness of the testing arrangement by for example using shorter pulling chains or eliminate usage of chains by choosing push test methodology.

4. Conclusions

Methodology of shear test implemented is appropriate for determining the shear strength of a rock joint. Achieved results are realistic and provide not only the values of peak and residual friction angles but also the shear resistance and dilation of the sample during the test. That additional information, especially the dilation values, enabled to identify some mistakes in methodology. Those mistakes are mainly related to the high elasticity of the loading arrangement and incorrect positioning of the sample halves on top of each other. Methodology of laboratory pull test could be improved by increasing the stiffness of the testing arrangement and applying a more reliable system of positioning the sample halves on top of each other.

In case of the 200 cm x 95 cm sample size used in this study, the methodology of photogrammetric prediction of the surface roughness using a revolving table and fixed camera location developed in KARMO II project seems to produce sparse point clouds for digital roughness measurements. The point spacing varied between 0.75 mm to 1.07 mm. The low density is due to the long distance between the sample and the camera. The suggested method may work better at shorter distances.

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