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DETERMINATION OF JOINT MECHANICAL PARAMETERS FOR STABILITY ANALYSIS IN LOW STRESS OPEN PIT MINES

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ABSTRACT

For low stress mining and civil engineering projects, slope stability is an essential part of safety and financial considerations. While large-scale stability can be modelled using equivalent rock mass properties, at smaller scale the local variations become significant and failure along the fracture planes is possible. The relevant boundary condition for low stress conditions is the Constant Normal Load (CNL), which allows for dilatation to occur. For deep mines the corresponding condition is the Constant Normal Stiffness, which restricts the dilatation. When dilatation is suppressed the normal load is increased. This may lead to shearing of the asperities. If both the vertical and horizontal displacement are recorded during CNL testing, the dilatation may be calculated and numerically removed to provide a CNS estimate. In this paper three rock joint samples from the Siilinjärvi open pit mine were tested in a CNL shear box using displacement resetting at three different low normal loads. Profilometer and photogrammetry were used to measure the roughness of the surfaces. The results show poor match between the expected behaviour and observations. One possible cause is the reduced matedness often associated with natural near-surface rock joints. The potential weaknesses of the method are discussed and future research topics are suggested.

KEYWORDS

Shear strength, constant normal load, constant normal stiffness, joint roughness, photogrammetry

INTRODUCTION

Rock mass discontinuities such as rock joints or fractures control the failure of rock mass. The normal stress acting on the discontinuity strongly influences shear strength. In deep excavations the surrounding rock mass resists displacement and limits the dilatation. In near surface excavations, the normal load is constant and there is no normal stiffness. Typically two boundary conditions are used: either the near-surface Constant Normal Load (CNL) or the deep Constant Normal Stiffness (CNS) (Figure 1). Poturovic (2015) examined this effect in his Master's Thesis and a synopsis of the results was published as a conference paper Poturovic et al. (2015). Poturovic et al. (2015) argue that friction angle and dilatation are key factors in determining the shear strength. At high normal loads of 8 MPa or more the dilatation potential is similar between the methods. The results are consistent with earlier results by Grasselli & Egger 2003, where the dilatation potential was shown to be completely suppressed at normal stress of 20 % of the uniaxial compressive stress. Both methods yield the same results until peak
behaviour, but the CNS procedure requires less samples. The mechanical behaviour differs after the post peak as CNL allows for dilatation and CNS provides an increasing normal stress with the dilatation.

Figure 1. Difference of constant normal load and constant normal stiffness conditions (Poturovic et al. 2015).

For Siilinjärvi open pit mine the CNL condition is more applicable. Low normal pressures from 91 kPa to 577 kPa were used to reflect self-weight of the wedges. The results are converted into higher degrees of confinement to study the effect of increasing in-situ stress. The Siilinjärvi apatite mine is located in Eastern Finland. It has two open pits: Särkijärvi with length 2900 m, width 750 m and depth 250 m and Saarinen with length 350 m and depth 25 m. Extracted phosphate is utilized to produce fertilizers, phosphoric acid and apatite concentrate. Production is carried out by drill and blast stoping. The Särkijärvi pit was opened in 1979, and life of mine plans reach until 2035. In 2013 an estimated total of 27 million tonnes of rock were mined at the site, including 11 million tonnes of ore. The pit presents many rock mechanical challenges, including very weak shear zones, very continuous smooth jointing in diorite and very low-friction heavily undulating joints in the ore.

The research concerning the mechanical properties of rock joints began with a pilot research programme KARMO I in 2014, which demonstrated that rock joint surfaces can be replicated into concrete using photogrammetry (MEE 60/2015). The research continues into KARMO II (2015-2016) where the photogrammetric method was studied more closely in the Bachelor Thesis of Pauliina Kallio (2015) and Master’s Thesis of Joni Sirkiä (2015). In this research, we have applied the photogrammetric method to the results produced during Daniil Iakovlev’s (2015) Master’s Thesis. The paper begins with a description of the laboratory tests and the photogrammetric method used. We present the results from the laboratory tests along with the obtained Mohr-Coulomb and Barton-Bandis parameters. These results are then compared to the digitally obtained estimates. Next the results are converted into equivalent CNS estimates. Finally, we present our discussion and conclusions.

LABORATORY TESTS
Three rock joint samples were tested to define shear behaviour parameters for Mohr-Coulomb and Barton-Bandis models in the rock mechanics laboratory of the Civil and Environmental Engineering Department at Aalto University. The set contained three diorite samples. Five of the samples were gathered by hand from post-blast and post-collapse sites, either by searching for visually undamaged joints in leftover rocks or by carefully removing samples which were loose enough to remove using a hammer.

The following parameters were obtained for use with the Barton-Bandis shear strength model. The uniaxial compressive strength (UCS) of diorite (217 MPa) was determined in previous laboratory tests. Schmidt Hammer tests were used to determine the joint compressive strength (JCS) of each sample, which did not differ significantly from the joint's rock type UCS value. The basic friction angle ($\phi_b$) for each sample was determined using a three-core tilt test, using cores from the same geological horizon as the joint samples. Joint roughness was determined using joint tilt tests, and profilometer determination of joint roughness coefficient (JRC) was carried out for comparison. The prior UCS data is found below, whereas other results are provided in the result and discussion section.

For the Mohr-Coulomb model a total of 9 CNL shear box tests were used. The samples were sawn and casted in concrete to fit in the shear box device with sample dimensions max. 125 mm by 115 mm. Each sample was tested from one to three times at increasing normal stress levels, with displacement resetting. The amount of tests depended on the damage to the sample in each test, e.g. significant asperity shearing was thought to make further tests unreliable. All shear box tests were carried out at a constant shear speed of 0.1 mm/min before peak shear strength and 0.25 mm/min after peak shear strength. While the normal stress was maintained constant, the shear stress and horizontal and vertical displacements were recorded using reading from manual displacement gauges.

**Photogrammetric setup**

The photographing was performed with a Canon EOS 600D DSLR camera and a Canon EF 35mm f/2 IS USM objective. The joint samples were photographed indoors in a constant lighting environment with 4500 lx illuminance at the sample surface. The ISO value was set to 100 to reduce image noise effecting the modelling. The aperture for imaging was set to f/16, to allow shooting to be carried out from close range. Shooting distance of 100 cm was selected according to aperture, to enable the sample surfaces to fit the depth of field (DOF) of the selected imaging configuration. The shooting was conducted in semi-automatic shooting mode, to enable camera automation to adjust the optimal exposure time for each shot.

The imaging was conducted by applying a stable shooting platform for the camera and rotating the joint sample in a rotational platform. Each sample was photographed by 20 degree intervals according to sample rotation, and by taking photographs from three layers, corresponding to 37, 54 and 67 degrees from the horizontal plane defined by the sample surface. The photography results in 54 images from each sample. The imaging configuration is illustrated in Figure 2.

![Figure 2. Illustration of imaging configuration applied in photogrammetric modelling procedure.](image-url)
The photogrammetric modeling follows a modeling procedure presented in Uotinen et al. (2015). A point cloud is created from the photographs using VisualSFM 0.5.25 software. The same points in different pictures are matched, then 3D positions are calculated for the point matches to derive the camera locations in relative coordinate system. This step also constructs a sparse reconstruction point cloud, which is then expanded to a dense reconstruction point cloud by PMVS/CMVS (Furukawa, 2010) procedure. The resulting point cloud is then saved in PLY (polygon file format). After point cloud creation, Cloud Compare 2.6.0 software is used to crop the modelled surface from the reconstructed scene. Finally, the point cloud of the surface is triangulated to a TIN (Triangular Irregular Network) surface by 2D-Delanay triangulation (Delaunay, 1934), applied for the best fit plane of the surface, and saved in STL (Standard Tessellation Language). The final surface models have a point density around 3.6 points per mm².

**Roughness analysis procedure**

Digital surface models were prepared for discontinuity roughness evaluation by defining a reference coordinate system for the TIN surface by fitting a best fit plane for the surface points, and setting orthogonal base vectors as the coordinate system, as illustrated in the Figure 3a. After defining the coordinate system, a sectioning plane is defined by taking a dot product of the base vector in shearing direction and the best fit plane normal, as illustrated in the Figure 3b. Then a search routine is applied to locate the point pairs from the triangulation surface that are divided by the sectioning plane. The sectioning procedure is illustrated in Figure 3. These point pairs define the lines for which line intersections between triangulation lines and sectioning plane are calculated from the corresponding line and plane equations. The resulting intersection points define the 2D roughness profile in the shearing direction.

![Figure 3](image-url) Illustration of sectioning routine for digital roughness characterization: the reference coordinate system definition (a) and the sectioning plane in shearing direction (b).

The roughness characterization is carried out with digital JRC principle by applying slope length method (Tse & Cruden, 1979) for sectioning profile normalization on 0.5 mm sampling interval, the sampling interval was selected according to the sample window used for originally deriving the function. The normalization procedure is conducted with two sampling patterns. First by taking the mean value for height in a sampling interval, as this sampling resulted in the best match for studies conducted in Sirkiä (2015). The second sampling pattern picks the highest value from search window, as this sampling is considered to function in the same way as the traditional profilometry comb.

Slope measurement, proposed by Tse and Cruden (1979), uses the root mean square (RMS) estimate from the local slopes of the profile with intervals between measured data points. The relationship with JRC and RMS presented as,

\[ JRC = 32.2 + 32.47 \log(Z_2), \]  

where \( Z_2 \) represents the RMS.
\[ Z_2 = \sqrt{\frac{\sum_{i=1}^{N-1}(z_i-z_{i+1})^2}{(N-1)ds^2}}, \]  

where \( z \) is the height of the profile above reference line, \( N \) the quantity of measures and \( ds \) the distance between measures.

The digital roughness characterization was performed for measurement lines corresponding to the hand measured profiles originally derived for the samples in Iakovlev (2015). Roughness of samples Diorite-1 and Diorite-2 were modelled with three lines in shearing direction divided evenly on the surface. Roughness of sample Diorite-3 was modelled with two lines in similar manner. Additional roughness characterization measures were conducted for the samples, by measuring post-shear joint roughness profiles for the shear samples.

**RESULTS**

Overviews of the test results for the Mohr-Coulomb and Barton-Bandis models are shown in Table 1 and Table 2, respectively. The parameters are described below.

- \( \sigma_n \) represents the normal stress used in a CNL shear box test
- \( \tau_{\text{peak}} \) represents the peak shear strength of the sample during the CNL test
- \( i_{\text{peak}} \) represents the dilatation angle at \( \tau_{\text{peak}} \). \( i = \tan^{-1}(dv/du) \) (Poturovic et al., 2015), where \( dv \) is vertical displacement and \( du \) is horizontal displacement.
- \( \phi_b \) represents the basic friction angle of a rock, determined using a tilt table test
- \( \phi_r \) represents the residual friction angle of a joint, which is dependent on \( \phi_b \) and the joint’s filling and alterations

**Table 1. Conducted shear box tests and results.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Area (mm²)</th>
<th>Test</th>
<th>( \sigma_n ) (kPa)</th>
<th>( \tau_{\text{peak}} ) (kPa)</th>
<th>( i_{\text{peak}} ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diorite-1</td>
<td>8800</td>
<td>D1A</td>
<td>91</td>
<td>148</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D1B</td>
<td>220</td>
<td>502</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D1C</td>
<td>477</td>
<td>837</td>
<td>50</td>
</tr>
<tr>
<td>Diorite-2</td>
<td>4800</td>
<td>D2A</td>
<td>165</td>
<td>141</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D2B</td>
<td>288</td>
<td>264</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D2C</td>
<td>516</td>
<td>457</td>
<td>28</td>
</tr>
<tr>
<td>Diorite-3</td>
<td>4300</td>
<td>D3A</td>
<td>184</td>
<td>472</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D3B</td>
<td>315</td>
<td>716</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D3C</td>
<td>577</td>
<td>1291</td>
<td>32</td>
</tr>
</tbody>
</table>

* Large asperity at sample front failed during D1B, making D1B & D1C less reliable

**Table 2. Obtained Barton-Bandis parameters.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>( \phi_b ) (°)</th>
<th>( \phi_r ) (°)</th>
<th>JRC (tilt)</th>
<th>JRC (profile)</th>
<th>JMC (tilt/profile)</th>
<th>JCS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diorite-1</td>
<td>31</td>
<td>31</td>
<td>6.0</td>
<td>12</td>
<td>0.50</td>
<td>216</td>
</tr>
<tr>
<td>Diorite-2</td>
<td>29</td>
<td>29</td>
<td>5.3</td>
<td>8</td>
<td>0.66</td>
<td>207</td>
</tr>
<tr>
<td>Diorite-3</td>
<td>31</td>
<td>29</td>
<td>6.1</td>
<td>10.5</td>
<td>0.58</td>
<td>194</td>
</tr>
</tbody>
</table>

**Comparison of profile measured and digital JRC estimates**

The shear samples were inspected post-shearing, and the roughness profiles were defined for reference measure to be used in validation of digital JRC parametrization. The JRC measure for shear samples surface was analyzed with profilometry and compared against the roughness profiles corresponding to JRC values published by Barton
and Choubey (1977). The JRC values were scaled to effective JRC measures by applying scale transformation as proposed by Barton and Bandis (1982),

$$JRC_n = JRC_0 (L_n / L_0)^{-0.02 JRC_0},$$

where $JRC_0$ and $L_0$ refer to 100 mm laboratory scale samples and $JRC_n$ and $L_n$ refer to sample size.

The profile of joint sample Diorite-2 is clearly undulating, while the profile of sample Diorite-3 is clearly stepped and the Diorite-1 sample has a considerable 9 mm asperity step in the corner of the sample. These characteristics are of an extent that is not fully covered by the original roughness profiles, and the profile match characterization would benefit from experience and expertise of the person conducting characterization procedure. The JRC values defined with digital characterization procedure and traditional profiling are presented in the Table 3. The digital characterization results are presented for both applied sampling techniques. The scale corrected roughness values are presented next to the derived parameters. Finally the average and highest values for derived JRC parameters are presented in separate row, for comparison of effective roughness.

The digital roughness parameters derived for sample Diorite-2 are higher that the corresponding hand measured roughness parameters. For sample Diorite-3 on the other hand, the digital roughness parameters are lower than the corresponding hand measured roughness parameters. For sample Diorite-1 the digital parameters are much higher than the profilometric parameters. Additionally, the digital JRC parameters are better in line with JRC values derived with asperity height measures by Iakovlev (2015), where the corresponding average JRC(N) values are, 16.0 for sample Diorite-2, 12.5 for sample Diorite-3 and 18.2 for sample Diorite-1. It should be noted that the asperity height method gives maximum JRC value of 20 for a measurement line in each sample. The variation of roughness parameters derived with different methods is fairly high, but all measures are in line with the inspection of very rough surface.

### Table 3. Roughness parameters for digital roughness using highest, mean, and profilometer values.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Length (mm)</th>
<th>JRC(0)</th>
<th>JRC(N)</th>
<th>JRC(0)</th>
<th>JRC(N)</th>
<th>JRC(0)</th>
<th>JRC(N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Highest</td>
<td>Highest</td>
<td>Mean</td>
<td>Mean</td>
<td>hand</td>
<td>hand</td>
</tr>
<tr>
<td>Diorite-1</td>
<td>113.6</td>
<td>18.0</td>
<td>17.2</td>
<td>17.1</td>
<td>16.4</td>
<td>10-12</td>
<td>9.7-11.6</td>
</tr>
<tr>
<td>Diorite-2</td>
<td>112.4</td>
<td>19.1</td>
<td>18.3</td>
<td>18.5</td>
<td>17.7</td>
<td>14-16</td>
<td>13.5-15.4</td>
</tr>
<tr>
<td>Diorite-3</td>
<td>92.1</td>
<td>15.5</td>
<td>15.9</td>
<td>14.0</td>
<td>14.3</td>
<td>12-14</td>
<td>12.2-14.3</td>
</tr>
</tbody>
</table>

**Comparison of shear strength results and dilation-based estimates**

Shear strength results from the shear box tests are presented in Figures 4-6. Shear strength predictions using Poturovic’s method were calculated for dilation angle values at shear box peak shear strength and the maximum dilation angle values (Figures 7-9). For the diorite samples the dilation angle at peak shear strength and the maximum dilation angle are similar, thus the predictions are also similar. Diorite samples 1 and 2 show typical poorly mated displacement behaviour and do not have a clear shear strength peak (Figures 4 & 5). The predicted basic friction angles are unrealistically low: 11.5° for Diorite-1 and 13.7° for Diorite-2. However Diorite-3 shows a peak during shear testing and the back-calculated friction angle is 34.1° for Diorite-3 (Figure 6). Both Diorite-1 and Diorite-2 show an incline of 11° towards the direction of shearing. If this is taken in account, the friction angle predictions becomes 21.5° for Diorite-1 and 23.7° for Diorite-2. The uncorrected values have been used in the BB predictions shown in Figures 7-9.

**Conversion to equivalent Constant Normal Stiffness results**

The CNL and CNS have a different post-peak behaviour. The post peak behaviour of CNS can be estimated by removing the dilatation from the CNL results. The resulting post-peak strengths are illustrated as horizontal lines in Figures 4-6. The uncorrected values for friction angles were used to make the CNS predictions.
Figure 4. Shear box test results for Diorite-1

Figure 5. Shear box test results for Diorite-2

Figure 6. Shear box test results for Diorite-3
Figure 7. Shear box test results for Diorite-1

Figure 8. Shear box test results for Diorite-2

Figure 9. Shear box test results for Diorite-3
DISCUSSION

Only one vertical measurement device was used in the tilt testing. Any rotating or tilting of the sample during the shearing could not be detected. This may partially explain the large amount of noise seen in the dilatation measurements. This noise was mitigated by using a moving average of five measurements, but it could also be mitigated using more vertical displacement meters or using digital image correlation.

The single surface photogrammetric method cannot account for the imperfect joint matching and it can only replace the manual profilometer measurements to obtain a more objective roughness measurement. The photogrammetric JRC is in theory objective, but it introduces new errors sources such as the implementation of the photogrammetry, post-processing and measurement noise.

Iakovlev (2015) has suggested that the joint matedness coefficient (Zhao 1997a, 1997b) is obtained as a ratio of JRC from the tilt test compared to JRC obtained from profilometry. In this research this approach gave realistic estimates and Iakovlev has also used pressure films in his thesis to obtain a more objective measure. The pressure films may be more realistic approach as they can exhibit increase of the matedness with the increasing normal load. It should be noted that in this research the normal loads were exceptionally low.

CONCLUSIONS

Three diorite rock joints were sampled in constant normal load shear testing using displacement resetting with three low normal stresses. The joint roughness values obtained from the tested samples were compared to roughness values which were obtained using photogrammetry. The shear strength values were compared to values produced using the dilation angle method. In this approach, the measured dilatation is removed to produce an estimate of the residual strength under constant normal stiffness conditions.

For constant normal load shear testing, a manual shear box device was used. Dilation values were recorded using a manual displacement gauge and a five-point moving average was used to calculate the dilation angle. Joint roughness was measured using a profilometer and with tilt table tests. Digital joint roughness was measured using slope length method.

The goal of the research was to compare manually and digitally measured roughness values. The digitally measured roughness is considerably higher (JRC = 16…18) than the hand measured values (JRC = 10…15). The overestimation is larger with smaller values of JRC. The automated JRC measurement removes the subjectivity, but introduces new error sources such as measurement noise.

The Barton-Bandis predictions of the digital JRC showed underestimation for Diorite-1 sample and overestimation for two samples Diorite-2 and Diorite-3. The underestimation could be a result of the 9 mm asperity in the Diorite-1 sample, which is difficult to represent correctly. The overestimation could be a result from the imperfect matedness. Using the ratio of profilometer JRC to tilt table JRC and estimate for the joint matedness can be obtained and it is 50-66 % for the diorite samples. Another explanation may be the large scale undulation with angle of 11°. A test series of replicas with no matedness is suggested.

Dilatation was measured as tangent of vertical and horizontal displacements. Dilatation was numerically removed to produce an estimate of the CNS behaviour. The obtained residual strength estimates are very low. The limited degree of joint matedness may have influenced the results. More tests are needed with higher normal loads to include the cutting of asperities into the prediction.

ACKNOWLEDGEMENTS

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