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Empirical shear strength criteria for filled jointed of metasedimentary sandstone

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Abstract. Rock joint shear failure criteria constitute numerical simulation that significantly governs the calculation for rock mass stability analysis. The presence of joint infilling potentially reduces the estimation accuracy for the deformation of rock joint. This study discovers the role of infilling thickness in governing the empirical calculation of linear Mohr-Coulomb failure criterion and non-linear Barton-Bandis failure criterion. A series of direct shear tests with constant surface roughness and controlled infilling material composition facilitates the joint shear strength with various infilling thicknesses. The results indicate that the joint shear strength decreases primarily with infilling material within the joint aperture. Although all the friction angles are closely similar, different cohesion values show the influence of infilling material thickness on shear strength characteristics. The joint shear strength values indicate significant differences where the filled joint shear strength reduction depends on associated infilling thicknesses and the adopted failure criterion. Multiplication to the Filled Joint Factor (F_{JF}) normalized from the $\tau_{\text{filled joint}}$ / $\tau_{\text{cleaned joint}}$ ratio will precisely evaluate the filled joint shear strength. Hence, the shear strength estimation from Mohr-Coulomb and Barton-Bandis failure criteria to the various thicknesses of joint infilling will provide sufficient filled joint deformability characteristics.

1. Introduction

Empirical estimation of joint shear strength is important to be accessible from the relevant computation of appropriate input parameters, especially for complex joint conditions. The joint shear strength resistance is highly influenced by joint physical characteristics and the degree of weathering exposure. Deformability resistance from the discontinuity in rock mass structure are contributed by and not limited to natural conditions of rock joint such as saturation, surface roughness, aperture, orientation and infilling material. Stresses imposed between the joint surface significantly altered the surface morphology, controlled mechanical properties and shear behavior of joint shear strength as reported by Mohd-Nordin et al. [1].

Meanwhile, Meng et al. [2] described an infilling material as a high deformability and low shear strength medium that significantly produces weaker planes along the rock discontinuity. The presence of infilling joint materials is accelerated by weathering with humid weather in a tropical environment. Infilling rock joint materials, particularly those resulting from in-situ deposition, are among the most critical discontinuities in rock mass structure Amin et al. [3]. As studied by Sinha and Singh [4], it was found that the infilling material thickness condition for the ratio between the infilling thickness and the joint surface roughness amplitude has a significant effect on the joint shear strength. Although the shear strength of an infilled joint is primarily governed by infill thickness, the infill properties such as the degree of saturation and grain-size characteristics, can also influence its strength as reported by Barton [5]. The effects of joint infilling materials on the shear strength of rock joints have been discussed in several studies such explored by Karakus et al. [6], Thirukumaran and Indraratna [7], and Li et al. [8].

Thus, a study on the influence of infilling thickness with respect to established rock joint shear strength criteria models is important as these failure criteria have been employed in the rock mass stability calculation in numerical simulations. According to the conclusion made by Barton [9], the Mohr-Coulomb failure criterion empirically expressed the peak shear strength for the jointed and fractured rock for the shear strength of rock joints. Indeed, strength-displacement modelling for joint surface roughness and joint wall strength was also indicated by another form known as the Barton-Bandis criterion. Hence, the deformation behavior parameters of filled joint metasedimentary sandstone empirically evaluated in this study to assess the sensitivity and consistency of the joint shear strength influenced by the infilling thickness.

2. Meta-Sedimentary Sandstone Joint Conditions

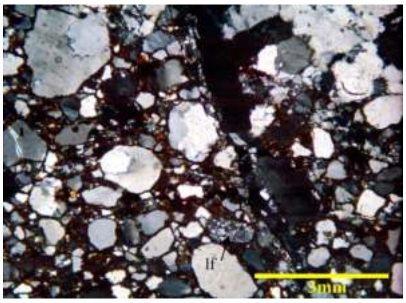
The rock sample was collected from a sedimentary sandstone on a roadside cut slope in area of Puncak Perdana, Selangor, Malaysia (figure 1).

Figure 1. Sampling at study area; location of Puncak Perdana, Selangor State, Malaysia on sedimentary rock formation, [10].

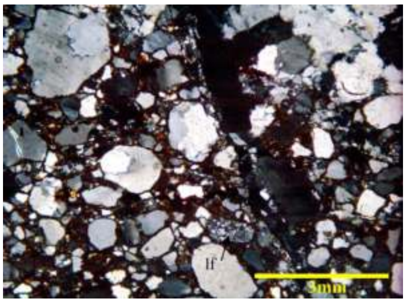
2.1. Rock Material Properties

The basic physical and engineering properties of the host rock sample were determined from an identified rock material. Thin sections were studied using a transmitted light microscope to describe the petrographic images, including grain composition, grain size, roundness, and sorting.

The rock sample was identified as sandstone consisting of fine to medium grain size with mostly quartz (up to 95%) and subordinate rock fragments (up to 10%). According to the QFL classification by Mc Bride [11], the specimen was identified as sub-litharenites, where the detrital grain composition consists of 90% quartz (85% monocrystalline) and 10% lithic fragments. Grain roundness is classified as sub-angular to sub-rounded grain, as presented in figure 2. The grain size is categorized as medium-grained and poorly sorted. There is much evidence of compaction in sandstones in the form of sutured contacts between grains due to pressure solution. Dissolution seams are closely associated with sutured contacts; therefore, the sandstone specimen can be classified as the metasedimentary type.



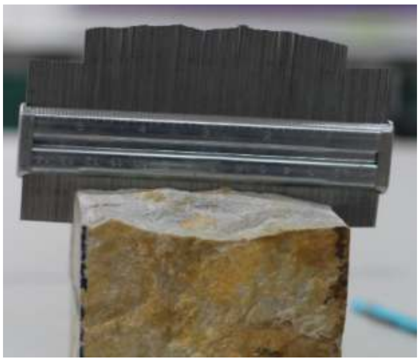
(a)



(b)

Figure 2. Thin section photomicrograph with 5 times magnification showing, (a) lithic fragment (lf) and quartz grain, and (b) size variation of quartz grains that classified as sub-angular to sub-rounded.

Several laboratory testing procedures were conducted to determine the physical and engineering properties of the rock sample. The initial material stiffness, the Schmidt rebound hammer hardness, and ultrasonic pulse velocity were introduced to estimate the grades of weathering and joint compression strength (JCS). The tilt test was conducted to determine the value of basic friction angle, whereas the joint surface profile was determined to categorize profiles according to the investigation by Barton and Choubey [12]. As shown in figure 3, these test procedures were carried out based on study by Hatheway [13] and the results are summarized in table 1.



(a)

(b)

(c)

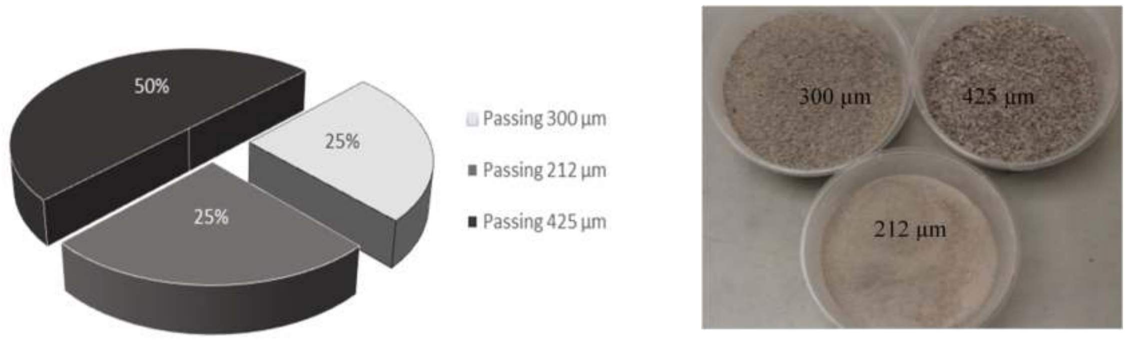
Figure 3. Physical and strength characteristic of jointed rock sample, (a) surface roughness characterization that identified from roughness profile with JRC graphical classification (b) tilt test to determine basic friction angle, and (c) surface hardness determination by using Schmidt rebound hammer.

Table 1. Summarize physical and engineering properties of rock block sample.

Properties	Classification / Characterization
Weathering Grade Classification	Grade I/II
Density, ρ (kg/m^3)	2.829 x 10^{-6}
Average Rebound Hardness Number	46
Joint Roughness Coefficient, JRC	10-12 (Rough & Undulating)
Average P-wave Velocity (ms^{-1})	4030
Basic Friction Angle, ϕ_b	43°
Correlated JCS (MPa)	138

2.2. Joint Infilling Composition

The sand particle composition of the infilling material was identified from the characterization of the sample collected from the residue stain deposited on the exposed joint surface. The sizes were categorized as passing 425 µm, 300 µm, and 212 µm sieves with the composition ratios of 50%, 25%, and 25%, respectively, as shown in figure 4.



(a) (b)

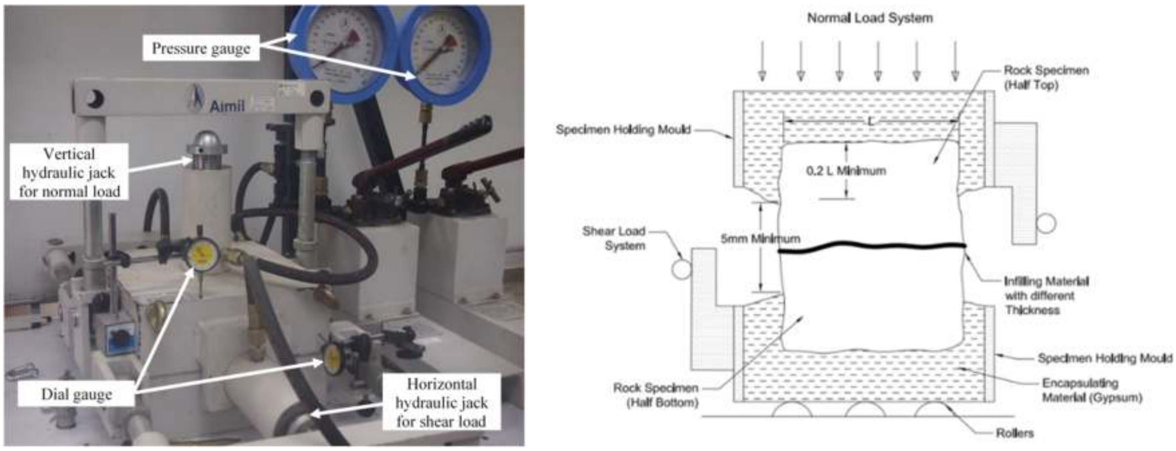
Figure 4. Joint infilling material characterization, (a) particle size distribution of infilling material, and (b) sample of infilling material collected

The ratios in figure 4 were then used to represent the infilling composition modelled during the direct shear test. The remodelling of the infilling material was initiated by producing the sand material from the disintegrated particles of the fragmented sample collected. The fragment rock material was mechanically crushed into smaller and finer grain sizes and then sieved through 425 µm, 300 µm, and 212 µm sieves. This process is assumed to simulate the mechanical process of weathering, which is similarly experienced by the natural residue of the infilling material on joint surfaces. Then, the three categories of sand particle sizes were positioned on the jointed rock surface according to the ratio of 50%, 25%, and 25%, respectively, for each infilling material thickness model.

3. Direct Shear Test for Jointed Metasedimentary Sandstone

The direct shear test procedure is determining the shear strength parameters of jointed rock, i.e., the peak friction angle and cohesion value. The test was carried out in accordance with a guideline in ISRM [14], the suggested method for laboratory determination of direct shear strength.

In this study, the direct shear test was conducted in a stage-testing form, where several different normal loads were applied within a single sample. The magnitude of the normal load was kept constant throughout the whole test. The laboratory setup and schematic diagram for the testing sample with the infilling material as shown in figure 5(a) and figure 5(b), respectively.



(a) (b)

Figure 5. Experimental setup for the direct shear test apparatus for jointed rock of metasedimentary sandstone tested, and (b) Schematic diagram for the arrangement of jointed rock sample and position of infilling material with the direct shear equipment setup as inspired from ISRM [13].

3.1. Test Modelling for Natural Jointed Rock with Infilling Conditions

The solid cube of host rock with the dimensions of 100 mm × 100 mm × 300 mm was splatted along the pre-existing fractured plane to create a jointed rock specimen with natural joint wall surfaces. After trimming the host rock, the jointed rock specimen was then placed into the mold and strongly encapsulated by gypsum. The infilling material was laid onto the surface of the half bottom of the host rock with the average thicknesses of 3 mm, 5 mm, and 10 mm for the first, second, and third variation sets of testing, respectively, before being placed by the half top of the host rock.

The fourth testing variation was carried out without any infilling material for clean joint surface condition. The sequence for the abovementioned jointed host rock with the infilling material setup is illustrated in figure 6.

(a) (b) (c)

Figure 6. Specimen preparation, (a) set of host rock block, (b) infilling material lay on joint surface with identified thickness, and (c) encapsulated jointed rock with infilling at joint interface.

3.2. Shear Strength Parameters of Joint Infilling Condition

The direct shear test conducted empirically characterized the shear stress behavior with respect to the shear displacement along the shear plane. The shear stress versus shear displacement trend for all infilling material thicknesses, and the final test was conducted on a clean joint surface (i.e., without the infilling material). The summary of the results is presented in figure 7. All the friction angles are closely similar. However, different cohesion values indicate the major influence of infilling material thickness on the shear strength characteristic.

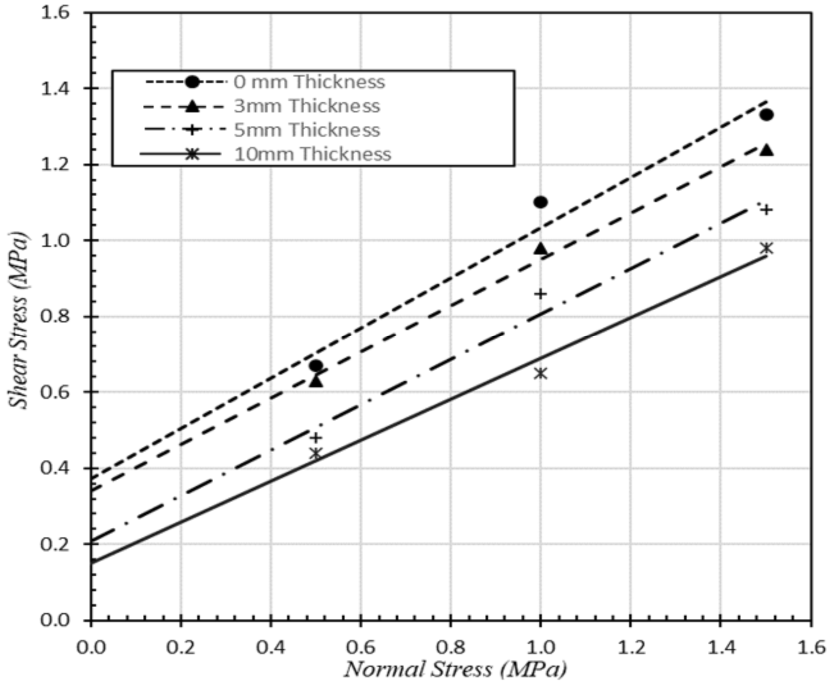


Figure 7. Summarize plots of shear stress over normal stress with different thickness of infilling material at rock joint interface.

4. Shear Strength Failure Criteria

The application of the linear Mohr-Coulomb failure criterion model for joint shear strength is inaccurate because rock joints have cohesive strength that is similarly governed as surface friction and dilatational force resistance, as reported by Barton [9]. However, in the presence of infilling material at the joint interface, the role of joint cohesion may need to be considered. Besides, the Barton-Bandis failure criterion model provides reasonable estimation by considering the joint surface asperity roughness and strength as suggested by Prassetyo et al. [15].

4.1. Mohr-Coulomb Failure Criterion Analysis

The adaptation of the linear shear strength parameter based on the Mohr-Coulomb criterion has a significant contribution to the shear strength for different infilling material thicknesses. Therefore, the measured values of peak friction angle and cohesion are substituted into equation 1.

$$\tau = C + \sigma_n \tan\phi \tag{1}$$

4.2. Barton-Bandis Failure Criterion Analysis

The non-linear failure criterion by Barton-Bandis considers another role of a rock joint that significantly controls the rock joint shear behavior. The estimation of shear strength for this model considers asperity roughness and joint surface strength through the JRC and JCS, as mentioned by Prassetyo et al. [15].

The Barton-Bandis shear failure criterion joint model was described by Barton and Bandis [16] as the following of equation 2:

$$\tau = \sigma_n \tan\left[JRC \log_{10}\left(\frac{JCS}{\sigma_n}\right) + \emptyset_b\right] \tag{2}$$

Where the JRC refers to 20 scales of rock joint roughness asperities estimated using a comb profiler as recommended by Barton and Choubey [12]. Meanwhile, σ_n refers to the normal stress acting on the surface of the rock joint, and the JCS refers to the unconfined compressive strength, which can be estimated from the Schmidt hammer reading correlation as established by Barton [17]. Originally, ϕ_b

that refers to the basic angle of internal friction of the slip surface was altered as the peak friction angle obtained during the filled joint shearing test.

4.3. Comparative Analysis and Interpretation

The empirical estimation of filled joint shear strength commonly applies failure criteria for analysis to minimize the effect of over- or underestimation of joint shear behavior in rock mass during application. The plots of shear strength characteristic with respect to the thickness of joint infilling from the Mohr-Coulomb and Barton-Bandis models are presented in figure 8.

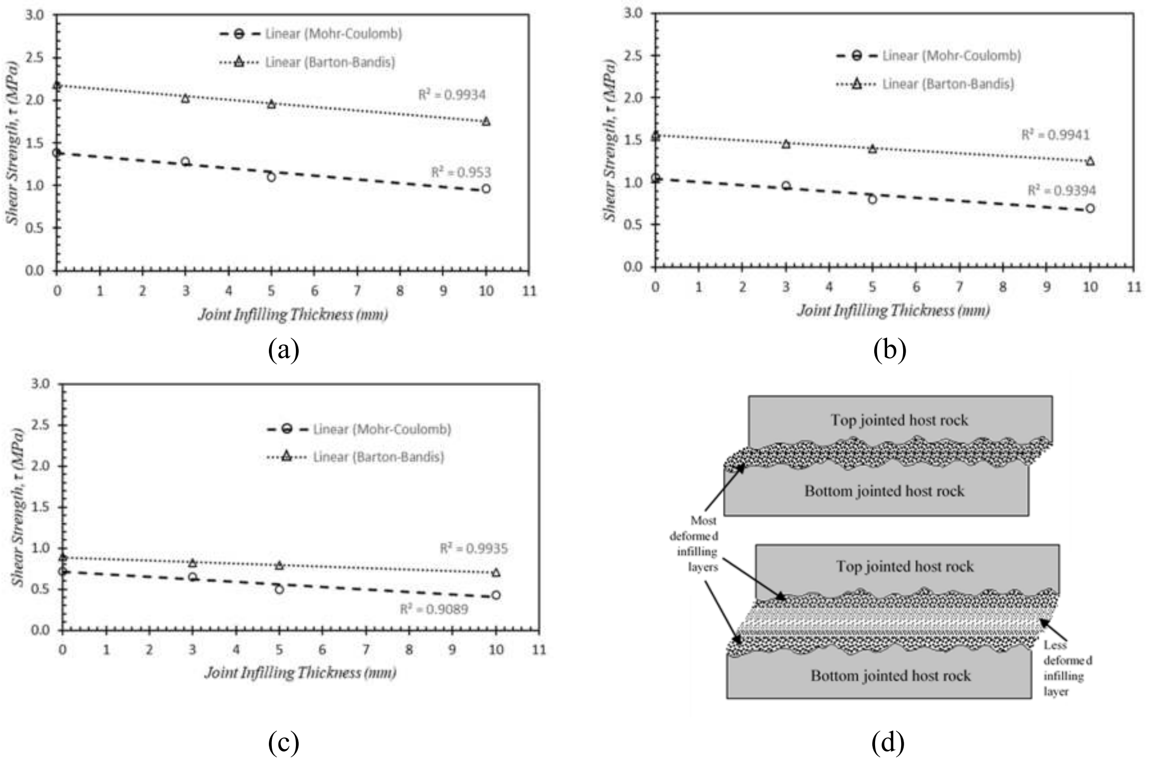


Figure 8. Comparative linear plots between Barton-Bandis and Mohr-Coulomb estimation of filled joint shear strength for variation of infilling thicknesses with respect to applied normal stress, σ_n values; (a) σ_n = 1.5 MPa, (b) σ_n = 1.0 MPa, and (c) σ_n = 0.5 MPa; and (d) pattern illustrated for deformation characteristics between thinner infilling thickness (*top*) and thicker infilling thickness (*bottom*).

As the thickness of infilling material increases, the failure plane is less deformed due to shearing in the infilling medium compared to the layers adjacent to the joint wall surfaces. This observation agreed with a study by Papaliangas et al. [18], when the infilling thickness layer is greater than the mean roughness undulation, the failure planes deformed at both elevation levels along the infilling medium, (i.e., near the joint interfaces and through the infilling). Meanwhile, the thinner infilling material triggered the deformation to all layers along the infilling interface as illustrated in figure 8(d). The clean joint without infilling shows the highest cohesion value due to the contribution of sheared-off crushes' particles from the material with surface irregularities, as stated by Barton [17].

The increasing thickness may reduce the shear strength of the joints of rocks, as indicated by the decrease of both peak friction angles and cohesions. In this condition, the friction resistance from the rock joint surface decreases between each surface of the contact area of rock and produces lower shear strength. The fine sand particles of infilling between the joint surface influences the shear characteristic of cohesion.

4.4. Filled Rock Joint Shear Strength Factor

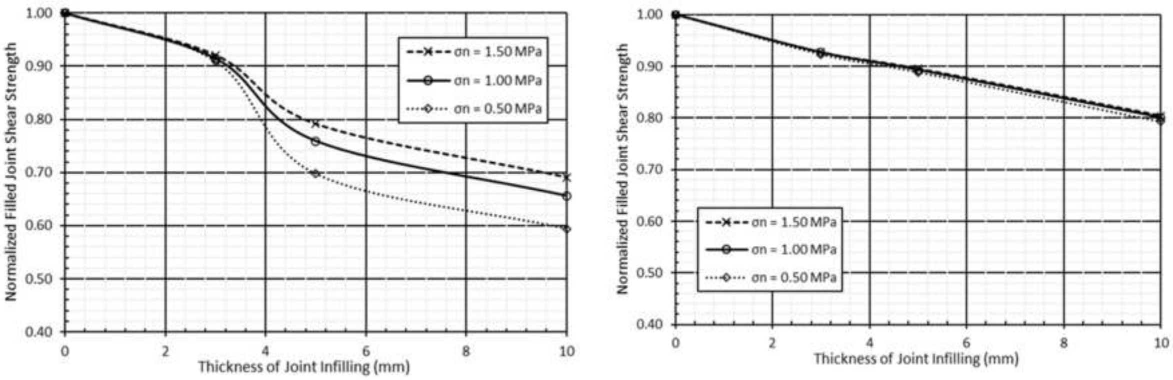
The accuracy of filled joint shear strength estimation can potentially be overestimated by neglecting the infilling material roles to the joint deformation characteristic. Hence, further correlation from the trend relationship between the infilling joint shear strength with clean joint shear strength was established.

The multiplication factor was introduced based on the normalized of joint shear strength known as filled joint factor, F_{FJ} or $\tau_{\text{Filled Joint}} / \tau_{\text{Cleaned Joint}}$ ratio. This rational function as described by the equation 3, and the corrected filled joint shear strength, τ' can be precisely evaluated with multiplication factor of F_{FJ} (equation 4).

$$F_{FJ} = \frac{\tau_{\text{Filled Joint}}}{\tau_{\text{Cleaned Joint}}} \tag{3}$$

$$\tau' = \tau \times F_{FJ} \tag{4}$$

As presented in figure 9, plots for normalized of joint shear strength illustrated the variation thickness of joint infilling to determine respective F_{FJ} value as multiplication factor. The model of normalized joint shear strength as multiplication factor correspond to the states in numerator of infilling joint thickness as variable function and clean joint condition as constant for denominator of the fraction.



(a) (b)

Figure 9. Normalized of joint shear strength fitted with various thickness of joint infilling at 1.50 MPa, 1.0 MPa and 0.5 MPa normal stresses evaluated from; (a) Mohr-Coulomb failure criterion, and (b) Barton-Bandis failure criterion.

5. Conclusion

The average deformation behavior of filled joint under shear and normal loads must be established to understand this issue. This research was conducted to investigate and understand the deformation behavior of filled in jointed metasedimentary sandstone.

The infilling material is graded its size. The residual infilling material is represented by sand as the material disintegrated from the host rock of metasedimentary sandstone. The infilling material influences the rock joint condition and reduces the friction force of the joint and the basic friction angle, thus affecting the shear strength values. With the increasing thickness of the infilling material, the shear strength decreases proportionally. The failure envelope is at a similar inclination angle but differs significantly in the cohesion characteristic.

The empirical estimation of filled joint shear strength from the Mohr-Coulomb and Barton-Bandis failure criteria revealed that the input parameters significantly affect the results, influencing the shear stability analysis of rock mass. The sensitive and consistent of calculated filled joint shear strength from linear Mohr-Coulomb failure criterion and non-linear Barton-Bandis failure criterion significantly improvised with multiplication factor of F_{FJ}. This normalized multiplication factor facilitates from the $\tau_{\text{Filled Joint}} / \tau_{\text{Cleaned Joint}}$ ratio and well verified from the correlation with thickness of joint infilling.

In practice, the filled joint shear strength from the joint model characteristics presented in this study can be incorporated into finite element or discrete element computer programs to estimate the joint shear strength and respective input parameters in the rock mass stability analysis.

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