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Research paper

The Influences of Normal Load Variation in Direct Shear Strength Test Parameters Tuff from Candi Ijo Yogyakarta

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Abstract

This paper presents direct shear strength test results of tuff taken from Candi Ijo of Jogjakarta, Indonesia where the slopes are considered in critical condition and need attention. Serial shear tests were conducted to find the normal loads appropriate for direct shear strength test. The optimum set of normal loads on direct shear strength test for tuff from Candi Ijo were tried by analyzing Mohr & Coulomb criterion against Hoek-Brown criterion. The study shows that excessive normal load may initiate crack caused by a failure on direct shear strength test due to the generated shear stress as well as the normal stress. This can be indicated by the unacceptable high value of cohesion (c) and the low internal friction angle (ϕ). The maximum limit of normal stress (σ_n) on direct shear strength test 12.5% σ_c for Indonesia general area is still applicable for the case of Candi Ijo. This research work recommends applying normal loads for direct shear strength test of tuff are 0.4 kN, 0.6 kN and 0.8 kN. This recommendation was also supported by the analysis using graph suitability of Mohr & Coulomb criterion and Hoek-Brown criterion.

Keywords: *Internal friction angle, Direct shear strength test, Mohr & coulomb criterion, Hoek-Brown criterion*

1. Introduction

In open pit mining design to achieve the best design requires the slope stability data. In the case of Indonesia where the rocks are vary and unstable, the rock condition can be different from one place to another. A thorough study and investigation are therefore required. The current research investigates the case in Candi Ijo region in Jogjakarta, Indonesia (see Figure 1). The spot location is about 18 km eastern of Jogjakarta city at coordinate GPS of 7.775586 S, 110.496991 E, and very close to *Ratu Boko* temple complex.

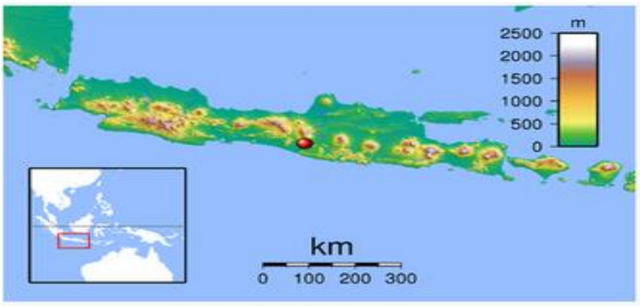

Fig. 1: Location Candi Ijo Region, Jogjakarta

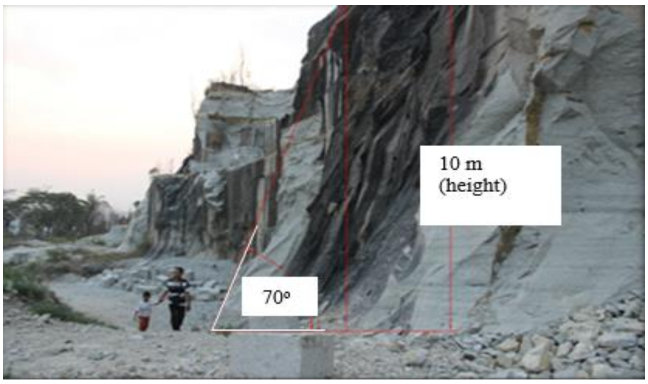

Fig. 2: Slope geometry of tuff at Candi Ijo Region, Jogjakarta

The slope geometry of tuff mining at the location is shown in Figure 2. It has 10 m height with an inclination angle 70^o. In this work, analyzing the slope stability implemented shear strength test of the tuff by using Mohr & Coulomb and Hoek-Brown failure criterion. The test obtained important rock intrinsic parameters such as cohesion (c) and internal friction angle (ϕ) that are critical in slope design. In some cases, the slope design failed because of invalidated value of cohesion (c) and internal friction angle (ϕ). The failure is normally due to inappropriate normal load applied in direct shear strength test.

There are many works reported the maximum limit of normal stress on direct shear strength. The values varies; 15% σ_c [1], 20% σ_c [2], and 12.5% σ_c [3] taken from Coal Bearing strata Warukin, South Kalimantan, Indonesia. The failure on direct shear strength test are influenced by two stresses, i.e. normal stress (σ_n) and shear stress (τ). The direct shear strength test is needed an attention when giving normal load which is lower than rock elastic limit. The rock elastic limit is a limitation where there fracture initiation does not occur during the applied normal load.

Brace, Paulding, and Scholz [4] showed that fracture initiation occured when the normal load reached approximately 30-50% of the uniaxial compressive strength and it is followed by the changed of volumetric strain in uniaxial compressive from linier to non-linier. On residual direct shear strength, the surface roughness occurs because of the fracture of the rock. For the tuff mechanical properties, many researchers have conducted many tests and assessments in different locations, for example in Taiwan [5], Italy [6], Japan [7], Oregon USA [8], Turkey [9] and China [10]. This paper evaluates the effective normal limit applicable to tuff rocks from another location in Candi Ijo, Jogjakarta, Indonesia.

There are many experimental works proposing the approximate maximum normal strength in direct shear strength test peak condition as mentioned previously [1-3] as opposed from the classical theory [11]. The experimental results proposed the range of 12.5% to 20%, while the classical theory showed 30-50%. As an illustration of the calculated normal strength for the uniaxial compressive strength 4379 kPa is shown in Table 1.

Table 1: The Calculation Of Normal Strength Limitation In Tuff Based On Theories

Sources	Uniaxial Compressive Strength (σ_c), kPa	Normal Strength Limit (σ_n), kPa
Brace et al [11] 30-50%	4370	1311-2185
Ladanyi and Archambault [1] 15%		655.5
Graselli [2] 20%		874.5
Saptono [3] 12.5%		546.25

All the experimental reports were conducted in different locations with different rock characteristics. In this current research provides the characteristics of tuff from Candi Ijo region with different weather and rock condition with those presented in Table 1.

2. Methodology

This research is experimental investigation to see the behaviour and characteristics of tuff from a slope in Candi Ijo, Prambanan, Jogjakarta, Indonesia.

Simulation on proprietary software Slide V.7 (Rocscience) was also involved to predict the safety of the slope prior to the calculation on failure criterion. The experimental measurement employed Direct Shear Testing Machine with the maximum capacity of 5 kN. All specimens followed the ISRM-1981 for rock testing materials. The specimens were prepared from the core drilling directly from sample taken the slope. There were three main investigation stages conducted.

The first stage was measuring the displacement and shear stress after applying variation of normal loads until the rock failure. For avaraging purpose, arithmatic average of three measurement (three speciments) in every normal load test. In the second stage, the cohession and internal friction angle were calculated from the normal load vs shear strength. The cohession was obtained from the value of the intersection of the linear Coulomb & Mohr line with the shear strength axis on zero normal stress. The internal angle is the angle of the produced linear line to the shear stress axis. The third stage used safety factor stability based on equlibrium limit. A criterion of safety factor 1.0 is the ideal value. The recommended normal stress was aiming at the ideal criterion. Additional calculated cohession and internal friction of failure criterion was tried after finding the appropriate criterion.

In this research a comparison from the general recommendation proposed in [13] was also assessed.

3. Results and Discussion

3.1. Tuff Shear Strength

Researchers [12, 13] conducted various tests to find the optimum normal loads to obtain the maximum tuff shear strength. The peak of shear strength seen in displacement peak and displacement residual conditions are compiled in Figure 3 and Figure 4. The figures varies the normal loads from 0.2 kN to 1.2 kN.

The results shows that the higher normal produces the higher shear strength to shear the rock as expected. It indicates that the discontinuity of strength plane located in the friction surface requires more strength [12].

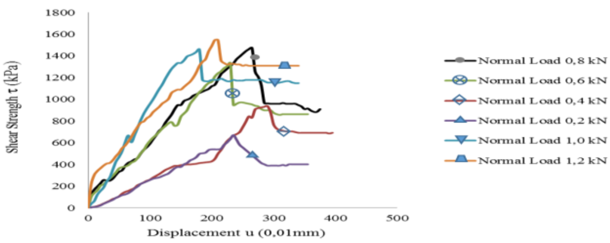

Fig. 3: Shear Strength vs Displacement Peak Condition

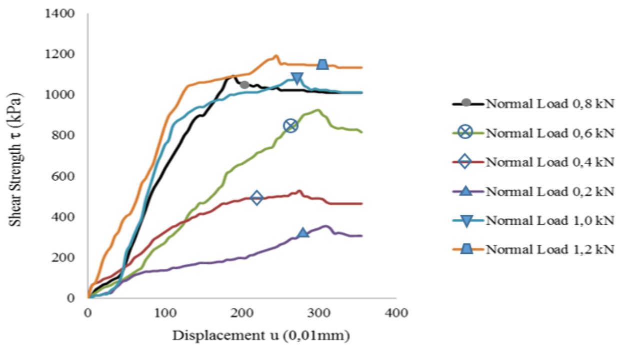

Fig. 4: Shear Strength vs Displacement Residual Condition

Elastic region for each normal load for both peak condition and residual condition shows different characteristics. The higher normal load produces the higher rock elastic condition. This is caused by higher normal load occurring the tuff closing crack. The value of cohesion is therefore showing up because of the similar particle bond having more strength so that tuff more elastic when given a shear strength.

In rock mass there are discontinued plane such as joint, bedding, also fault. Due to the present of rock mass naturally, therefore the residual direct shear strength appears. Figure 4 shows decreasing shear strength in each normal load compared with that shown in peak direct shear strength test condition. It indicates that residual condition is influenced by discontinued plane so the cohesion value becomes smaller. As a result, shear strength needed for shearing the rock is not as big as in peak condition.

The shear strength both peak condition and residual condition was reached the optimum point when normal load was 0.8 kN. There was no significant increasing of shear strength when the normal load higher than 0.8 kN. This optimum result of 0.8 kN is still similar with the previous work [13].

3.2. Direct Shear Strength Test Parameters

The direct shear strength parameters are defined as the cohesion value (c) and the internal friction angle (ϕ). The resuls of the cohesion values for the peak results and the residual results are shown in Table 2 and Table 3. The values were taken from the regression from thre series of normal loads.

Table 2: Cohesion and Internal friction angle on peak results.

Normal Load (σn), kN	Parameter	
	Cohesion (c), kPa	Internal Friction Angle (ϕ), °
0.2; 0.4; 0.6	289.74	68.73
0.4; 0.6; 0.8	364.79	65.85
0.6; 0.8; 1.0	821.45	51.00
0.8; 1.0; 1.2	986.01	43.46
1.0; 1.2; 1.4	1335.50	22.82

Table 3: Cohesion and Internal friction angle on residual results

Normal Load (σ_n), kN	Parameter	
	Cohesion (c), kPa	Internal Friction Angle (ϕ), °
0.2; 0.4; 0.6	35.94	66.19
0.4; 0.6; 0.8	44.56	64.52
0.6; 0.8; 1.0	749.73	27.91
0.8; 1.0; 1.2	843.12	21.82
1.0; 1.2; 1.4	794.93	23.63

The cohesion value is directly proportional to the increasing of normal load. It indicates that the surface friction is getting higher when it receives more compressive strength, causing more similar particle bond with higher strength.The internal friction angle shows the oposite behavior. It inversely proportional to the normal load. The main factor of decreasing internal friction angle is due to rough surface produced by high normal strength. Therefore there is no undulation hold in the flow of shearing process.

In Table 2 and Table 3 show clearly the influence of normal load variation in direct shear strength test in both peak and residual conditions. There was a significant changing value of cohesion and internal friction angle when normal load applied above 0.8 kN.

The significant changing was observed when the direct shear strength test sample deformed not only by shear strength but also normal strength that contributing to failure occurance. According to clasical theory of fracture mechanics of Griffith, fracture initiation in crack boundary limit may cause tensile strength concentration in the tip of a small piece of rock. The stress distribution spreading from outer region showing in both uniaxial and multi-axial cases. In specific limit stress, the tensile strength may reach critical point and it causes crack initiation. The deformation or failure should cause only by shear strength. The normal strength should not be the main factor.

3.3. Safety Factor Using Equilibrium Limit

The safety factors of the slope on various normal load data were obtained by software Slide V.7 implementing equilibrium limit method. The slope geometry at Candi Ijo site has 10 m height with the slope elevation 70° as shown in Figure 2.

The simulation was conducted with the assumption in no weathered condition. Table 4 shows the results of safety factors on various normal loads.

Table 4: Slope safety factor of various normal loads.

Normal Load Variation (kN)	Safety Factor
0.2; 0.4; 0.6	1.54
0.4; 0.6; 0.8	0.87
0.6; 0.8; 1.0	22.95
0.8; 1.0; 1.2	27.61

Results show an increasing safety factor significantly when normal load variation were set higher than 12.5% of uniaxial compressive strength. The direct shear strength by using normal load higher than 12.5% of uniaxial compressive strength produces the direct shear strength value that was not represented in actual condition. High normal load caused normal strength influencing failure process. The cohesion value was therefore higher than that in tuff actual condition.

The safety factor results show that the testing set of 0.4 kN, 0.6 kN and 0.8 kN show the lowest value which is prefereable. Previous research [13] recommended the same values as shown in the current work. This recommendation was supported by using the graph suitability between Mohr & Coulomb envelope and Hoek-Brown envelope used in next section.

3.4. Normal Strength and Shear Strength Relationships

Theoretically the cohesion and internal friction angle could be found by plotting the relation between normal strength and shear strength. In determining the relation between normal strength and shear strength, a linier regression graph (Mohr & Coulomb) and also parabolic graph (Hoek-Brown) can be used.

Figure 5 shows that linear Mohr & Coulomb has the goodness of fit R^2 0.852 while the nonlinear approach Hoek-Brown shows 0.944. Considering the expeermental results, the non-linear graph of Hoek-Brown reprepresents closely the mass characteristics.

The different between Mohr & Coulomb and Hoek-Brown can be devided into 3 regions as shown in Figure 6.

In first region normal load was in the range 0 to 4 kN, the cohesion and shear strength value of Mohr & Coulomb was overestimate than Hoek-Brown, while for the internal friction angle of Mohr & Coulomb was underestimate.

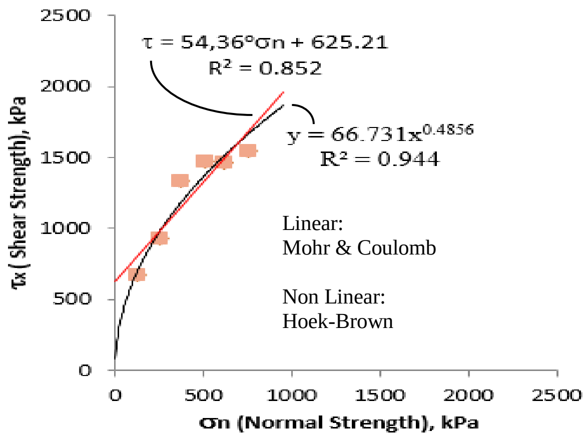

Fig. 5: Comparison of Mohr & Coulomb and Hoek-Brown

The opposite with the first region, the third region was the area when the normal load was more than 1.2 kN. In this region, the cohesion value of Mohr & Coulomb was lower than that shown in Hoek-Brown, while internal friction angle and shear strength of Mohr & Coulomb a bit higher than in Hoek-Brown.

Both Mohr & Coulomb and Hoek-Brown show similar behaviour of cohesion and internal friction angle values in region 2. The applied normal load in this regiona is between 0.4 kN to 1.2 kN. When the applied normal load was 1.0 kN or the normal load was 12.5% of uniaxial compressive strength, a wrecking undulation in friction surface of rock appeared since the value of internal friction angle was considered too small. Considering the characteristics in the three region, it is also recommended to apply normal loads 0.4 kN, 0.6 kN, 0.8 kN.

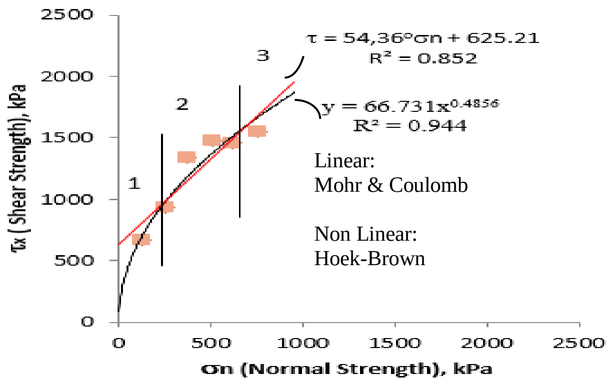

Fig. 6: The Region of Mohr & Coulomb Hoek-Brown results

The applicability of Figure 6 can be seen in Figure 7. Region 1 fits with the characteristics of intact rock following Hoek-Brown pattern. Intact rock is the condition of rock in laboratory testing which is assumed as continual, isotropic, and homogenous. It is high cohesion and shear strength value. In region 3, the rock mass characteristics is discontinued, anisotropic, and heterogeneous.
The discontinued plane contributes to the decreasing of shear strength values. Based on the results shown in figure 5 and figure 6, Hoek-Brown criterion shows lower value of shear strength compared with that in Mohr & Coulomb. This results recommend to calculate the value of cohesion and internal friction angle by using Hoek-Brown Criterion.

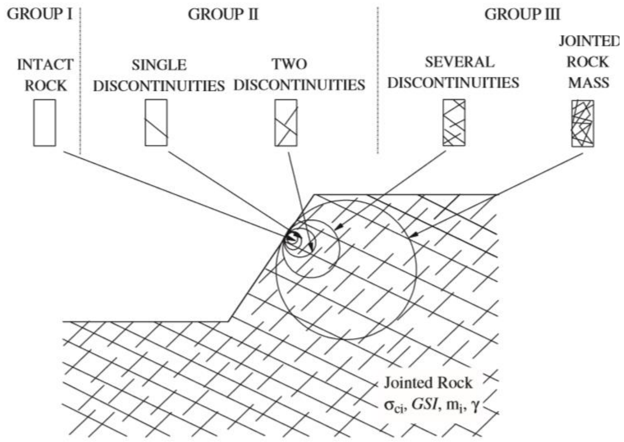

Fig. 7: Applicability of the Hoek–Brown Failure Criterion for Slope Stability

3.5. Rock Mass Value of Tuff for Hoek-Brown Criterion

Hoek-Brown criterion requires the rock constant m_i of tuff. To obtain the rock constant, the major principal stress and minor principal stress in triaxial test are required. In this research, direct shear strength test by varying normal load in range 0.2 kN until 1.2 kN was conducted.
Based on calculation results of experimental values, the rock constant result was 12.38 with the fitness R^2 0.98. By considering the rock constant, the parameters of direct shear strength parameters can be calculated by using Hoek-Brown and Coulomb & Mohr Criterion. The calculated results are shown Table 5.

Table 5: Rock parameters on different failure criterion.

	Parameter	
Criterion	Cohession (c), kPa	Internal Friction angle (ϕ), °
Hoek- Brown	306,70	57,17
Mohr-Coulomb	625,21	54,36

Hoek-Brown Criterion has produced cohesion smaller than Mohr & Coulomb Criterion. Hoek-Brown considers rock mass condition while Mohr & Coulomb uses undisturbed rock condition of intact rock.

4. Conclusion

The current work provides information of rock from Chandi Ijo, Prambanan, Jogjakarta, Indonesia that can be used for stability analysis consideration. Based on the research results, some conclusions can be drawn as follows:
The normal load to obtain direct shear strength follows the recommended value of about 12.5% of uniaxial compressive strength as previous proposed [13]. Although the Candi Ijo area is not a mining region, the characteristics follows the average rock in Indonesia.
The recommendation for optimum normal loads for tuff are 0.4 kN, 0.6 kN and 0,8kN.
The research confirms that implementing higher normal load than 0.8 kN increases direct shear strength caused by the increased cohesion value. It indicates that rougher surface on the crack plane the higher the cohesion value. In this research Hoek-Brown criterion shows a representative rock mass for Candi Ijo tuff.

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