A practical approach to determining the basic friction angle of natural and rough discontinuities in carbonate rock slopes

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ABSTRACT: This study investigates the suitability of an adapted portable shearing box to measure the shear-induced dilation of a discontinuity and how the basic friction angle can be reliably derived from the shear data with dilation. Results show that samples with significant roughness are required. The reliability of the resulting basic friction angle depends on both the magnitude of the applied normal loads and the horizontal base length used to calculate the angle of dilation. We have developed data processing techniques to identify the optimal horizontal base length. The proposed method was successfully applied to estimating the basic friction angle of discontinuities that control the blocks stability in Kaili carbonate slope.

Keywords: Adapted portable shear box, horizontal base length, dilation angle, basic friction angle.

1 INTRODUCTION

When performing stability analysis in blocky rock masses, whether using conventional analysis methods such as kinematic and limit equilibrium techniques or advanced numerical techniques such as distinct-element and discrete-element modelling, the shear strength of discontinuity has always been a key but difficult parameter to determine. Estimates of the shear strength can be obtained directly through shear testing (Muralha et.al. 2014). The main difficulty in using the laboratory test values from finite size specimens is to reliably predict the shear strength for the large in-situ discontinuities due to the rapid change of their roughness in different scales and directions. Under low normal stress conditions, the shear strength of an unfilled and rough discontinuity surface in hard rock can be characterized by two angular components, i.e. the effective roughness angle i due to visible roughness and the basic friction angle ϕ_b of smooth rock surface (Patton 1966 and Barton 1976). This indirect method for estimating discontinuity shear strength has been widely used in engineering practice. In particular, with the recent widespread application of 3D digital surface characterization and processing techniques, practical estimation of discontinuity roughness at different scales has become a reality (e.g. Grasselli et.al. 2002 and Bitenc et.al. 2019). In this paper we use an adapted portable shear box to determine the dilation angle i and show how to derive the basic friction angle ϕ_b from the shear data.

2 EXISTING METHODS FOR MEASURING BASIC FRICTION ANGLE

When determining ϕ_b by tilt test, the smoothness of the specimen should be considered. There is a video on the ISRM webpage (2023) on determining the basic friction angle by tilt test using smooth specimens. This video does not specify the type of saw blade used and the surface smoothness of the sample. Goodman (1976) suggested lapping the sample with #400 grit (roughness ≈ 0.001in) before testing. Alejano et al. (2012) reported that the samples used for tilt testing were sawn directly with a diamond blade. Obviously, for the same rock, the specimens prepared by the above two methods will have different ϕ_b.

Hencher and Richards (2015) proposed a method to derive ϕ_b indirectly by measuring the dilation caused by the surface roughness during the shearing process. The basic steps of the approach include 1) simultaneous acquisition of shear stress (τ), horizontal (h) and vertical (v) displacement using the Golder's shearing instrument that can ensure the normal stress (σ) remains constant during the shearing; 2) calculating dilation angle i by using the vertical (dv) and horizontal (dh) displacements within a certain horizontal base length (HBL), i.e. tan i=dv/dh; 3) converting the shear stress τ and the normal stress σ on the mean shear plane to the shear stress τi and the normal stress σi on the inclined shear plane with the dip of i (Fig. 1). The subscript i means that the effect of dilation component during the shearing has been neutralized, i.e. (τi, σi) stands for the basic friction component without the dilation effect. The relationship between (τ, σ) and (τi, σi) is shown in Fig. 1. Under four normal stress levels, the inclination of the envelope between τi and σi, i.e. the black × marks of the right image of Fig. 1, passing through the zero is the ϕ_b. The maximum shear stress envelope without dilation correction as shown in Fig. 1 is the peak shear strength in the traditional sense. Our evaluation shows that this indirect method for determining ϕ_b has a clear physical concept and the data processing method is simple and easy to implement. However, the Golder's shear instrument is not commercially available. In addition, the question of how to find an optimal HBL for determining i is to be answered.

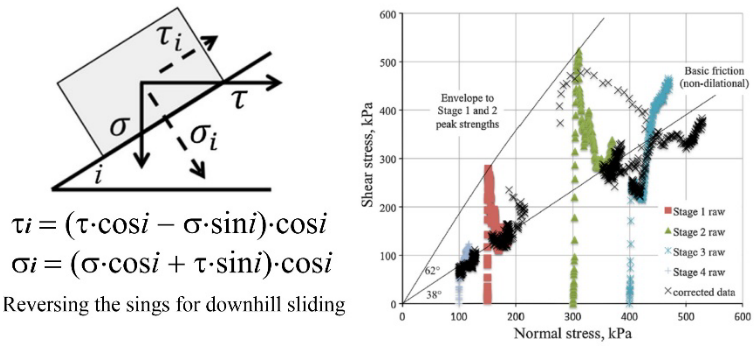

Figure 1. Shear vs. normal stress for both dilation-uncorrected and corrected (Hencher & Richards 2015).

3 BASIC FRICTION ANGLE USING PORTABLE SHEAR BOX

3.1 Adapted shear box and data collection

Fig. 2 shows the photographs of the adapted portable shear box, connected sensors and the data acquisition unit. To reduce the rotation of the upper part of the box during shearing, the wire slings used to transmit the hydraulic pressure of the jacks are replaced by the fixed steel bars. Vertical displacement sensors shown as v1, v2, v3, and v4 are installed on the four corners of the upper box. Two horizontal displacement sensors h1 and h2 are installed horizontally against the shear direction for recording the horizontal displacements. The vertical and horizontal loads and the values of the six displacement sensors are collected synchronously and stored at 0.1 second interval using the data collector YY-8 Data Acquisition Unit for Rock Mechanic Tests.

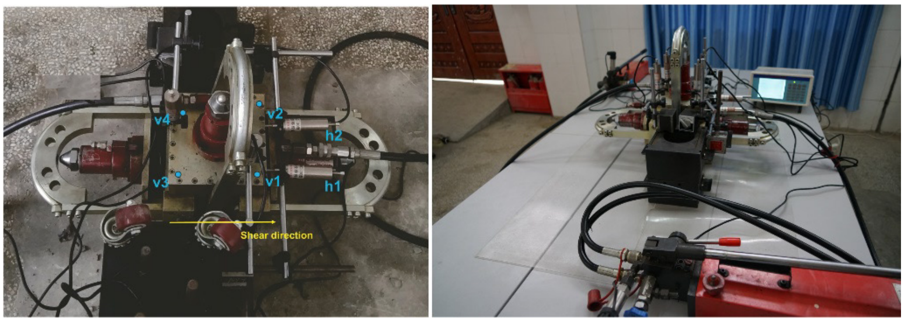

Figure 2. Adapted portable shear box (left) and data acquisition unit (right).

3.2 Sample preparation and testing

Before pouring a specimen, determining if the sample size is suitable for shear box to ensure that the discontinuity is within the shear zone. The poured samples should be dried in the shade for at least one week.

Before the test, weighing the poured upper block of the specimen and using transparent paper to draw the shape of the entire shear plane and estimate its area size. Arranging three lines for roughness measurements along the shear direction and sampling the joint roughness coefficient (JRC) using a profile comb on the three profiles. Shear tests were carried out following the multistage procedure as recommended by Hencher and Richards (2015), i.e. testing the same discontinuity sample at four levels of normal loading. Although the levels of the applied normal load should depend on the specific engineering stress environment, our research shows that too high normal load on the shear box will limit the development of dilation. After each test stage, the upper part of the box was removed, the shear debris was cleaned up, and photographs were taken and three roughness profiles were measured along the shear direction again. In each stage, the normal load was applied to the predetermined level and kept stable, and then the shear force was gradually applied at a shearing rate of about 1 mm per minute. Every time we have a stopwatch next to the jack to make sure the shear loading is complete in about 10 minutes.

3.3 Data processing

At each level of normal load, the total vertical load on the mean shear plane includes the weight of the upper shear box, the weight of the upper poured sample block, and the applied normal pressure. At the beginning of the shearing, since the upper and lower shear boxes are completely overlapping, the total normal load divided by the area of the entire shear plane is the initial normal stress on the mean shear plane. As the horizontal shear displacement increases, although the total normal load remains unchanged, the actual normal stress on the shear plane will increase due to the gradual reduction of the contact area. According Hencher & Richards (2015), this increase in normal stress should be accounted before converting (σ, τ) to (σi, τi) as shown in Fig. 1. In this study, since the specimens we took are roughly rectangular, the actual shear area used for normal stress correction is the initial shear area minus the shear displacement times the mean width of the specimen. Hencher (2023) has posted an Excel file on his webpage. Simply entering the area-corrected normal stress, shear stress, and the corresponding horizontal and vertical displacements into this Excel spreadsheet, a series of (σi, τi) values will be automatically calculated. In this study, we first examined whether the well-established data processing by Hencher & Richards (2015) can be applied to the data collected by the adapted portable shear box. Our evaluations show that if all (σi, τi) pairs, including both dilation and contraction segments of the entire shear course, are used to fit ϕ_b, the (σi, τi) points would be widely scattered, which will be extremely unfavorable for the significance of the fitted ϕ_b. For the shear data recorded by the adapted portable shear box, it is necessary to first select the data segment with continuous dilation, especially the segment near the peak shear stress to get the best estimate of ϕ_b.

In view of the above considerations, the first step in our data processing is to plot the relationship between the horizontal and the vertical displacements, so as to select the data segment with significant dilation for extracting the ϕ_b. The second step is to find an optimal HBL for calculating the representative i. We developed a script under R (2022), which can calculate the characteristic value and dispersion of the i in relation to HBL. In addition, we introduce the coefficient of variation (CV) to measure the quality of an i estimate. CV is defined as the ratio of variance to the mean of a parameter associated with uncertainty and designated as a percentage. According to Harr's statistics (1987) on the CV values of the commonly used design parameters in civil engineering, the dispersion of a parameter whose CV value is less than 40% will not lead to unpredictable uncertainty to the design.

We use an example to elaborate the data processing. Specimen No. 7 is a representative sample of the joint set J21 in a natural slope of the Kaili limestone. Figure 3(left) shows the relations between the horizontal and vertical displacement under an initial normal stress of 96 kPa. Up to the horizontal shear displacement of 4mm, the vertical movement v1 is always in contraction. In the same range, the vertical dilation at v2 also remains at a lower level. On the contrary, at rear end of the shear box, i.e. the position v3 and v4 where the upper and lower shear planes always contact during the shearing, the vertical dilation has always been increasing, which is suitable for calculating the i. Therefore, the mean value of the vertical displacement v3 and v4 is used. Figure 4(left) shows the distribution of the estimated i for the HBL-intervals from 0.1mm to 1.2mm. All the shear data collected over the entire 12mm horizontal shear displacement is used in the calculation. It can be seen that with the increase of HBL, the dispersion of i decreases, but the mean of i under each HBL remains around 15°. The dispersion of i remains stable from HBL=0.7mm. When HBL=0.7mm, the CV of the estimated i is 38.55%, indicating that the quality of the estimated value of i is acceptable. However, if we take a closer look at the role of i on the development of shear stress during the shearing process shown in Fig. 3(right), we can see that the dilation reaches its maximum before peak strength. When the horizontal shear displacement exceeds 4mm, the i oscillates down and up in a range of 5°, and does not provide any significant contribution to the slightly increasing of shear stress. Figure 4(right) is the i distribution got using the shear data just up to the horizontal shear displacement of 4mm. The corresponding statistics are in the last row of Tab.1. It can be seen that the mean of i obtained in this way is 21° for HBL=0.7mm. The corresponding CV is 23.61%, indicating that the quality of this i estimate is far superior to that obtained with all shear data. Figure 5 shows the regression fitting of the peak and basic friction angles of the specimen No. 7, conducted with the shear data of the hor. Disp.≤4mm and HBL=0.7mm. In the left image of Fig. 5, the shear data at four levels (blue, purple, red, green) of normal stress are plotted against area-corrected normal stress. The top 5% of the shear stress data are used to conduct a linear regression analysis for peak friction angle. The fitted peak value is 65° (the left image of Fig. 5), with a highly significant p-value of 3.64×10^{-11}. The basic friction angle is $\phi_b = 44°$ (the right image of Fig. 5), which with a p-value of 2×10^{-16} is also highly significant. If this ϕ_b of 44° is added to the 21° mean of (i) in Table 1, the resulting 65° is identical to the peak friction angle. So far, we have confirmed the feasibility of using the adapted portable shear box to measure the shear-induced dilation and the processing of ϕ_b.

Table 1. Statistics of dilation angle i estimated at HBL=0.7mm.

Data segment	Min. [°]	Median [°]	Mean [°]	Max. [°]	CV [%]
All	7	13	15	27	38.55
Up to 4mm H. Disp.	11	23	21	27	23.61

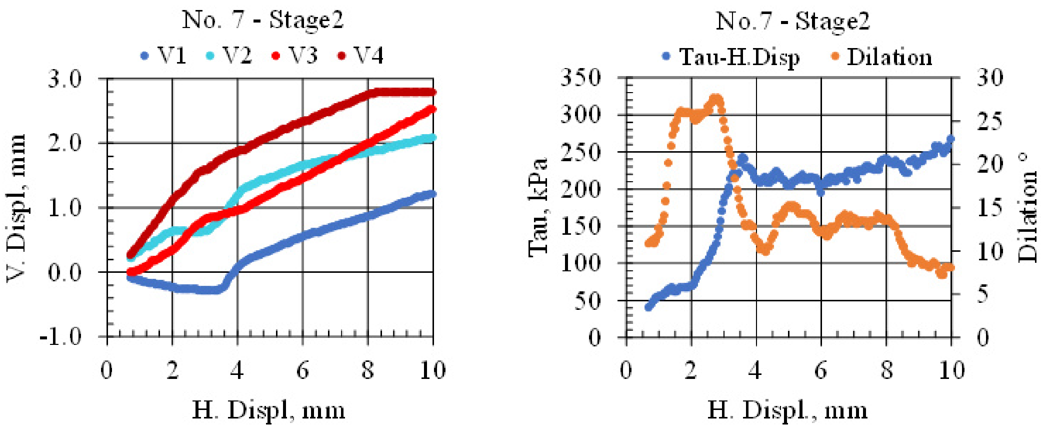

Figure 3. V. displacements (l.), τ & i over HBL 0.7mm (r.) against H. displacement.

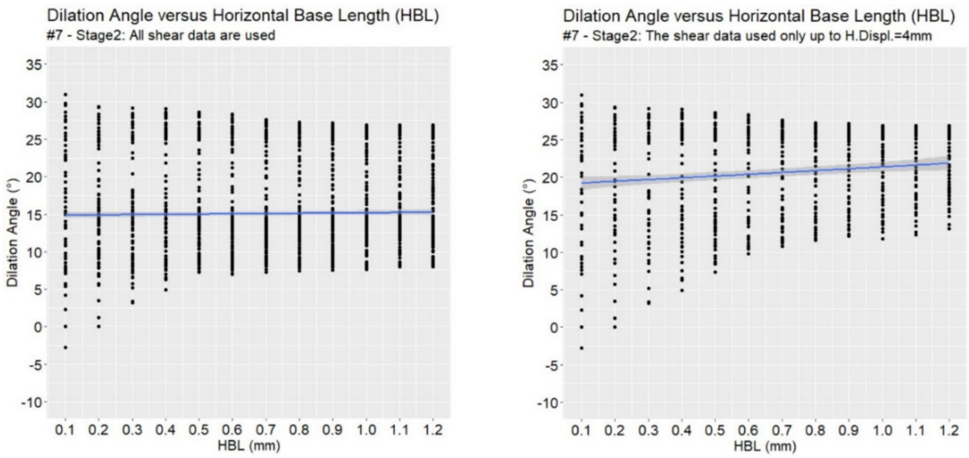

Figure 4. Dilation angle i as a function of HBL.

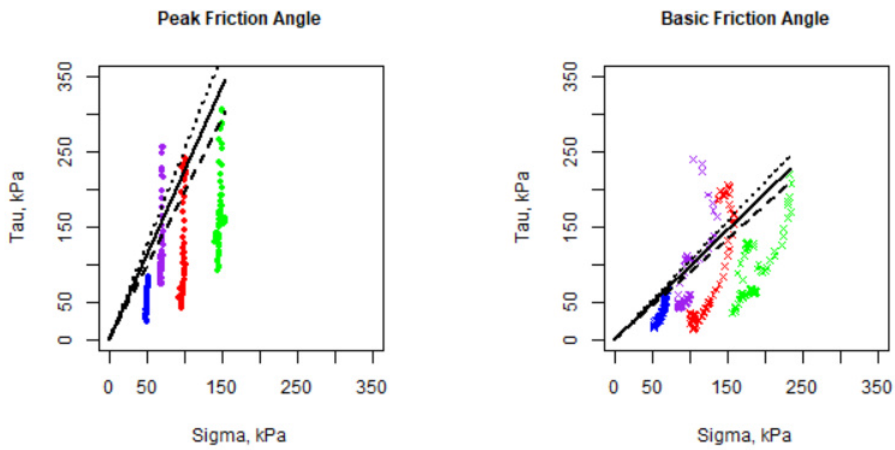

Figure 5. Stress path of multistage direct shear test and fitting for peak (left) and basic friction angel (right) of sample #7. Regressions are solid black line and dashed black lines are 95% confidence interval.

3.4 Application example

The collapse of the blocky rock mass in the steep carbonatite slope in Kaili Area China is one of the common geological hazards of this region. The field investigation identified the controlling effect of rock structure on slope topography (Dong et al. 2019). In a 130 m high and 80 m wide rockfall source area, three orthogonal sets of discontinuities, J11 (joint), J21 (joint) and B (bedding), have broken up the rock mass into an equidimensional block system. The results of the 3D kinematic analysis based on Goodman & Shi (1985) show that the blocks on the slope face are removable and their failure mode is mainly the double-face sliding along J11 and J21. For the stability analysis, the friction angles of J11 and J21 are necessary. The dilation angles of the two sets are 18° (J11) and 20° (J21), determined on the large in-situ discontinuities identified in the point cloud after Dong et al. (2019). To estimate ϕ_b, we sampled nine natural discontinuities, four samples for set J11 and five for J21. The best estimate of ϕ_b for J11 is 39° and for J21 44°. Based on the 3D stability analysis (Shi & Goodman 1989), it is concluded that the blocks are currently stable (using code B20) with a factor of safety (FS) of 3.0 (using code B11).

4 CONCLUSION

If a geotechnical site is difficult to understand empirically, the directly measured parameters can facilitate more reliable designs. This study shows that the adapted portable shear box can be used to determine the basic friction angle of a discontinuity. The advantage of this method is that the equipment is small and simple, and the test can be carried out in the field shed. However, to keep the normal pressure constant during the shearing, the reachable shear displacement is relatively short and only those data segments that have obvious dilatancy around the peak shear stress are suitable for derive the basic friction angle. Additional shear testing and analysis of discontinuities in other rocks using this method can increase our understanding of how the dilation angle varies with the chosen horizontal base length.

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