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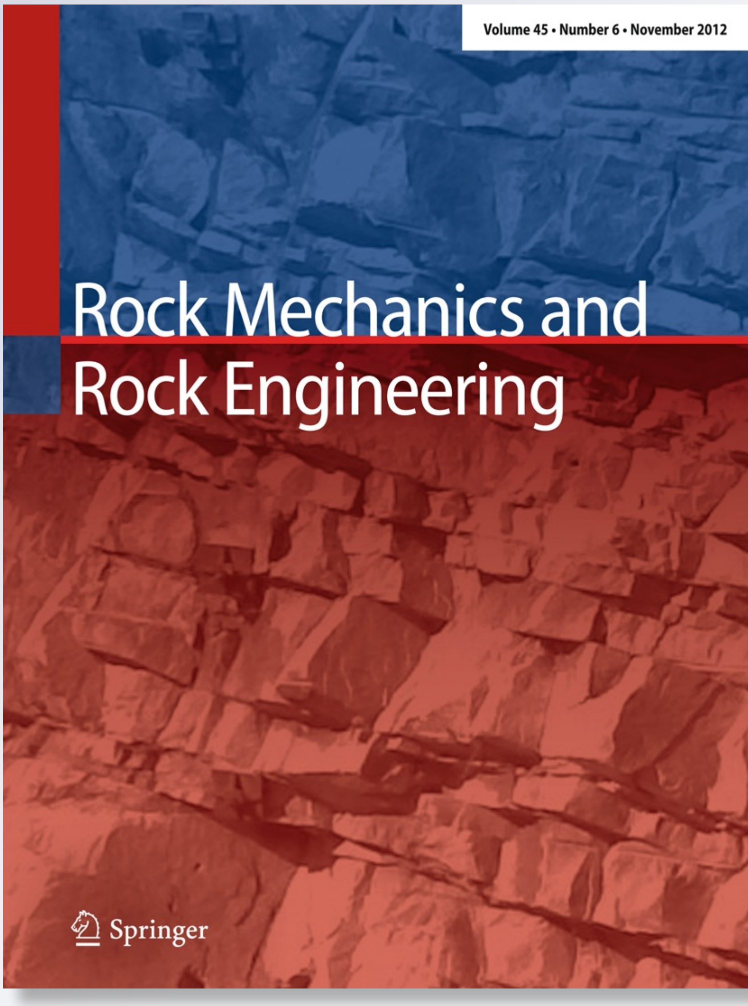

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ORIGINAL PAPER

Comparison of Different Techniques of Tilt Testing and Basic Friction Angle Variability Assessment

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Abstract A relevant parameter for estimating discontinuity shear strength is the basic friction angle, usually derived from different types of tilt tests. However, the tilt tests described in the literature produce varying basic friction angle values. From a large number of different types of tilt tests on different kinds of rocks, it was possible to conclude that the mechanisms of sliding along cylinder generatrixes and planar surfaces are quite different, and that tests based on sliding along generatrixes are not appropriate for determining reliable basic friction angle values for discontinuity planes. Tests on small specimens are also not recommended, for geometry reasons and because ensuring reliable stress conditions is difficult. To quantify the natural variability in tilt testing, large specimens of the same granite were tested. The results revealed coefficients of variation for the basic friction angle in the range of 5–10 %, a variability which is no greater than that found for other rock mechanics parameters. This observation enables to forward some recommendations concerning the appropriate number of tests needed to obtain reliable results.

Keywords Basic friction angle · Tilt testing · Variability assessment · Joint strength

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1 Introduction

Discontinuities usually found in nature are commonly rough and the roughness is typically irregular. In the 70s' and 80s' and based on previous work, Barton and co-workers (Barton and Choubey 1977; Barton and Bandis 1982) analysed in depth the peak strength behaviour of natural unfilled rough joints and proposed an expression to describe this behaviour:

$$\tau = \sigma_n \times \tan\left[\phi_r + \mathrm{JRC} \times \log_{10}\left(\frac{\mathrm{JCS}}{\sigma_n}\right)\right] \quad (1)$$

where τ is the shear strength of the joint, σ_n the normal stress applied to the joint, JRC the joint roughness coefficient, JCS the compressive strength of the joint surface and ϕ_r is the residual friction angle.

The residual friction angle, ϕ_r is estimated according to Barton and Choubey (1977) as follows:

$$\phi_r = (\phi_b - 20^\circ) + 20 \cdot (r/R) \quad (2)$$

where r is the Schmidt hammer rebound number recorded for a weathered and wet discontinuity, such as those normally found in the field, and where R is the Schmidt hammer rebound number recorded for unweathered surfaces of the same rock.

Ever since, the basic friction angle of fresh planar discontinuities has assumed a key role in estimating the shear strength of discontinuities for Rock Engineering projects. The basic friction angle, ϕ_b represents fresh surfaces that are neither weathered nor wet.

The basic friction angle is an essential value in estimating the shear strength of discontinuities in studies of the stability of engineered or natural slopes (Alejano et al. 2010, 2011) and underground excavations (Alejano et al. 2008) against various kinds of failures (planar, wedge or toppling); it is also used to calculate suitable safety factor values for engineering designs.

The value of ϕ_b has been studied for different types of rocks, resulting in typical values of 25°–30° for sedimentary rocks and 30°–35° for igneous and metamorphic rocks. It can be calculated in the laboratory from tilt tests and from direct shear tests on fresh planar surfaces. Some results of tests performed during the 60s and 70s, as compiled by Barton (1973, 1976), are presented in Table 1 with the source references.

To date, there is no ISRM recommended method for reliably estimating the basic friction angle (Ulusay and Hudson 2007), though in Rock Mechanics practice a number of different techniques are used. A method that can sometimes be found in the literature is that proposed by Stimpson (1981), who used rock cores to perform tilt tests with a cylinder-shaped sample placed over other two equal-dimension cylinder-shaped samples. Other proposals exist, but they do not provide full indications for normalizing tilt testing (Horn and Deere 1962; Bruce et al. 1989; Cruden and Hu 1988).

The Stimpson (1981) approach has been used in the past to obtain basic friction angle values for a number of engineering projects. It was observed, however, that the ϕ_b values obtained seemed to be very high (and therefore non-conservative) in comparison with values reported in the literature and presented in Table 1 (Barton 1971; Coulson 1972; Patton 1966; Wallace et al. 1970). Simple tilt tests with available rock samples for Brazilian tests (discs) showed, more often than not, that the values obtained by means of Stimpson's approach were higher than those obtained for planar surfaces.

An experimental study was conducted using various rock lithologies—slate, granite, magnesite and amphibolite—in order to analyse the most suitable methods for

Table 1 Basic friction angle of different rocks, recovered from various literature surfaces

Rock family	Rock type	Wetness	Basic friction angle, ϕ_b (°)	Reference
Sedimentary	Conglomerate	Dry	35	Krsmanović (1967)
	Chalk	Wet	30	Hutchinson (1972)
	Limestone	Dry	31–37	Coulson (1972)
	Limestone	Wet	27–35	Coulson (1972)
	Mudstone	Wet	31	Ripley and Lee (1962)
	Mudstone	Dry	31–33	Coulson (1972)
	Mudstone	Wet	27–31	Coulson (1972)
	Sandstone	Dry	26–35	Patton (1966)
	Sandstone	Wet	25–33	Patton (1966)
	Sandstone	Wet	29	Ripley and Lee (1962)
	Sandstone	Dry	31–33	Krsmanović (1967)
	Sandstone	Dry	32–34	Coulson (1972)
	Sandstone	Wet	31–34	Coulson (1972)
	Sandstone	Wet	33	Richards (1975)
	Slate	Wet	27	Ripley and Lee (1962)
Igneous	Basalt	Dry	35–38	Coulson (1972)
	Basalt	Wet	31–36	Coulson (1972)
	Dolerite	Dry	36	Richards (1975)
	Dolerite	Wet	32	Richards (1975)
	Coarse grain granite	Dry	31–35	Coulson (1972)
	Coarse grain granite	Wet	31–33	Coulson (1972)
	Fine grain granite	Dry	31–35	Coulson (1972)
	Fine grain granite	Wet	29–31	Coulson (1972)
	Porphiry	Dry	31	Barton (1971)
	Porphiry	Wet	31	Barton (1971)
Metamorphic	Amphibolite	Dry	32	Wallace et al. (1970)
	Gneiss	Dry	26–29	Coulson (1972)
	Gneiss	Wet	23–26	Coulson (1972)
	Schist	Dry	25–30	Barton (1971)
	Schist	Dry	30	Richards (1975)
	Schist	Wet	21	Richards (1975)

obtaining a reliable value for the basic friction angle of planar joints. The study was focused so that the results could be applied in combination with Barton's results in order to estimate, to a reasonable degree of accuracy, the shear strength of natural unfilled rough joints for rock engineering project purposes.

2 Preliminary Observations

As already mentioned, preliminary results suggested the possibility that the results of Stimpson's type of tests (sliding along generatrixes) overestimated the basic friction angle values. As part of past engineering studies, two tilt test techniques were used: testing according to the Stimpson approach using cylindrical specimens, with sliding occurring on lines or generatrixes, and testing of disc-shaped rock specimens, with sliding taking place on the planar circular surfaces.

Samples of slate (metamorphic), fresh granite (plutonic) and magnesite (sedimentary) rocks were prepared in the form of fresh clean sawn surfaces obtained using a diamond core bit and saw. The analysed rocks were as follows:

(a) A metamorphic Ordovician slate taken from a deposit quarried for roofing slate, with unconfined compressive strength (UCS) of over 100 MPa, although it is a largely non-isotropic rock due to cleavage.
(b) An intrusive igneous fresh hard granite, with more than 100 MPa of UCS, sampled from an ornamental granite quarry.
(c) A sedimentary magnesite rock (similar to a sparitic limestone), sampled in a research drilling for a cattle feed and fertilizer production plant, with UCS slightly below 100 MPa.

2.1 Test Types

The first test type, following the method described by Stimpson (1981), was based on using three cylindrical samples (as recommended for UCS testing; Ulusay and Hudson 2007), 54 mm in diameter and with a height at least double the diameter. One sample was placed over the other two so that it had one generatrix in contact with each (Fig. 1a, b). Five repetitions of each test were performed along the same sliding lines. For each new test, the locations of the specimens and the sliding generatrixes were changed. Figure 1 depicts the Stimpson and disc tilt tests for slate and for granite, respectively.

With β as the inclination of the set-up at the moment of sliding, as proposed by Stimpson (1981), the basic friction angle was estimated as:

$$\phi_b = \tan^{-1}\left(\frac{2}{\sqrt{3}}\tan\beta\right) \quad (3)$$

The authors think that an erratum could exist in Stimpson's original paper, in such a way that in Eq. (3), $\sqrt{3}/2$ should replace $2/\sqrt{3}$. This would yield more reliable results. However, in this paper we have followed the original reference as presented in Eq. (3).

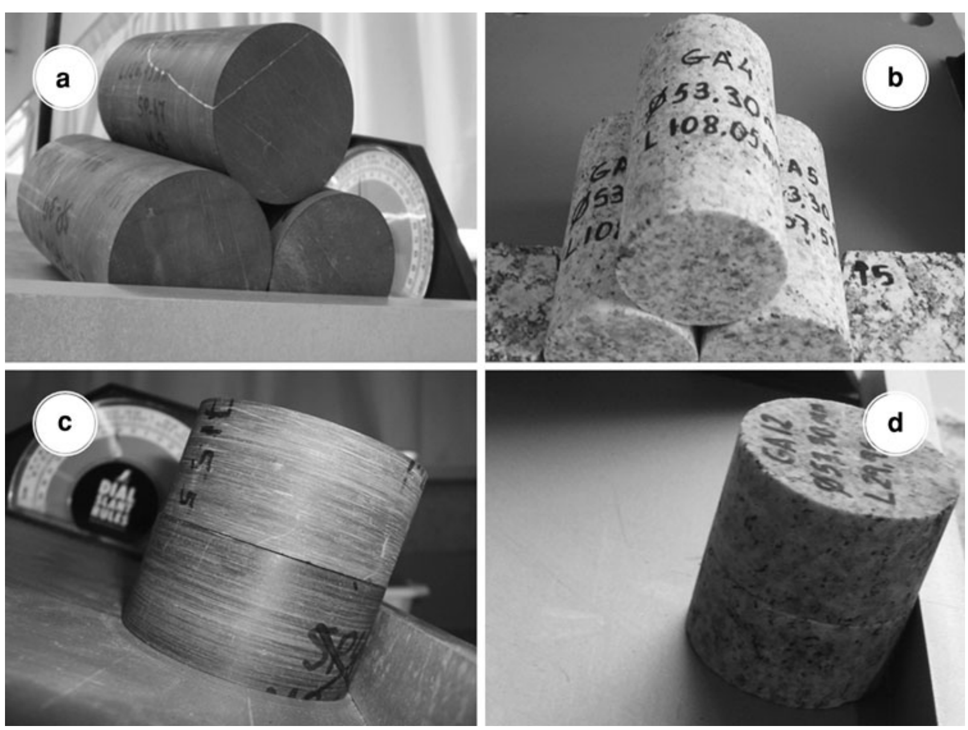

Fig. 1 Tilt tests performed on slate and granite samples

The second type of test uses two disk-like specimens cut with a disk-saw located one over the other with a planar contact (Fig. 1c, d). The utilised samples presented 54 mm diameter and a height roughly equal to half their diameter. The basic friction angle is directly obtained as the angle in which sliding occurs. In this case, more or less ten tests were performed with different samples, with five repetitions each.

Figure 1 shows the execution of Stimpson type and disk tilt tests on slate and granite.

2.2 Results

Very different results were produced by the tests (Table 2). The Stimpson tests yielded average basic friction angle values of around 40° for the three rock types, whereas the tests with sliding on planar failures yielded results in the range 25°–28°. It was concluded that sliding behaviour on generatrixes is different from sliding behaviour on planar surfaces.

Following these results, and in order to further study the differences and develop suitable tests for quantifying the friction angle for planar discontinuities, a laboratory experiment as described in the following section was set up and performed.

3 Methods to Determine the Basic Friction Angle of Discontinuities

3.1 Theoretical Background

Considering a rock block with weight W, length l, width w and height h, resting on a plane plunging β degrees along the direction of the length of the block, and assuming a linear distribution of the stress on the contact surface, the stresses at the top and bottom lower edges of the block are defined (Muralha 1995) as:

$$\begin{aligned} \sigma_{\max} &= \frac{W}{wl}\cos\beta\left(1+\frac{3h}{l}\tan\beta\right) \\ \sigma_{\min} &= \frac{W}{wl}\cos\beta\left(1-\frac{3h}{l}\tan\beta\right) \end{aligned} \tag{4}$$

In order to ensure that these stresses are compressive (positive) on the whole surface, the l/h ratio must be at least three times greater than the tangent of the tilt angle, as otherwise tensile stresses will appear. This relation is easily deduced from Eq. (4) considering that $\sigma_{\min}$ must be larger than 0.

Moreover, in the case of higher tilt angles, since discontinuities cannot tolerate tension, compressive stresses would only act over a smaller surface of length $l' < l$ of the block given by:

$$l' = \frac{3}{2}l\left(1-\frac{h}{l}\tan\beta\right) \tag{5}$$

Still assuming a linear stress distribution on the reduced contact, the maximum stress:

$$\sigma_{\max} = \frac{4W\cos\beta}{3w(l'-h\tan\beta)} \tag{6}$$

would increase rapidly until toppling occurs when the ratio l/h reaches tan β, which is well known from limit equilibrium conditions (Hoek and Bray 1974; Sagaseta 1986).

If the same analysis is performed for a disc-shaped block, with width h and diameter l, the l/h ratio must be at least four times greater than the tangent of the tilt angle to ensure that stresses are positive (compressive).

These simple relations can be plotted as l/h versus tilt angle graphs as presented in Fig. 2. Assuming that tilt test cannot be considered fully reliable whenever tensile stresses occur at the base of the tilted block, results that plot below the $l/h = 3\tan\beta$ line for parallelepiped blocks, or below the $l/h = 4\tan\beta$ line for disc-shaped slabs, should not be used.

These considerations are not so important for saw cut surfaces, but they are particularly relevant for rock joints that due to roughness can easily reach very high tilt angles. This difficulty is well known to practitioners as they preferably use slab-shaped blocks to perform tilt tests.

3.2 Practical Problems

When small surfaces used for the tilt tests are not cut perfectly straight, the contact is less than complete. Occasionally, the contact occurs in a small zone in such a

Table 2 Stimpson and disc tilt test results for roofing slate, fresh granite and magnesite samples

Rock	Test type	Tests (no.)	Repetitions (no.)	Basic friction angle, ϕ_b (°)	
				Mean	Standard deviation
Roofing slate	Stimpson	11	5	40.13	1.19
	Disk-like	9	5	27.09	1.90
Fresh granite	Stimpson	5	5	39.16	1.04
	Disk-like	8	5	25.05	2.74
Magnesite	Stimpson	8	3	40.60	1.18
	Disk-like	10	5	27.10	2.55

way that the upper slab rotates around an axis located in the centre of the reduced contact zone (Fig. 3). This kind of problem can be avoided by carefully preparing and using sufficiently large slabs.

3.3 Experimental Set-Up and Types of Tests Proposed

In order to understand these differences on results, we have planned to perform an experimental study with three types of rocks submitted to different types of inclination tests. In all cases, samples were cut and sawn by different size diamond concretion disk saws and drillers to obtain reasonably plane surfaces.

Four types of inclination tests of different features were devised aiming to understand result differences. In order to perform all these tests in a more rapid and accurate way, a special machine was devised, designed and built for this task. It consisted simply on a plane tilting surface which is softly inclines by means of an electric motor acted by a button. The constructed machine is shown in Fig. 4.

The four proposed tilt tests which are illustrated in Fig. 5 include:

(a) Tests performed on a cylindrical sample longitudinally cut ($d = 54$ mm and $h > 108$ mm) (Fig. 5a),
(b) Test performed on square base slabs (Fig. 5b) with the following dimensions:
   1. Large: 100 mm × 100 mm × 40 mm,
   2. Small: 50 mm × 50 mm × 20 mm,

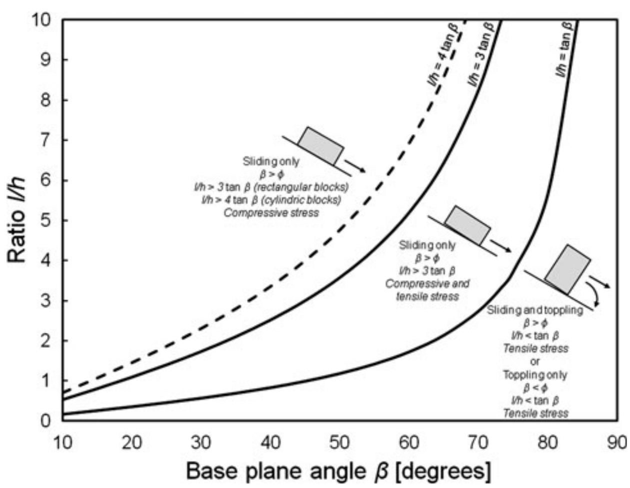

Fig. 2 Theoretical conditions ensuring full stress compressive contact between the sliding plane and the sliding slab. Sliding must occur above the lines $l/h = 3\tan\beta$ and $l/h = 4\tan\beta$ to ensure optimal conditions for parallelepiped and disc-shaped slabs, respectively

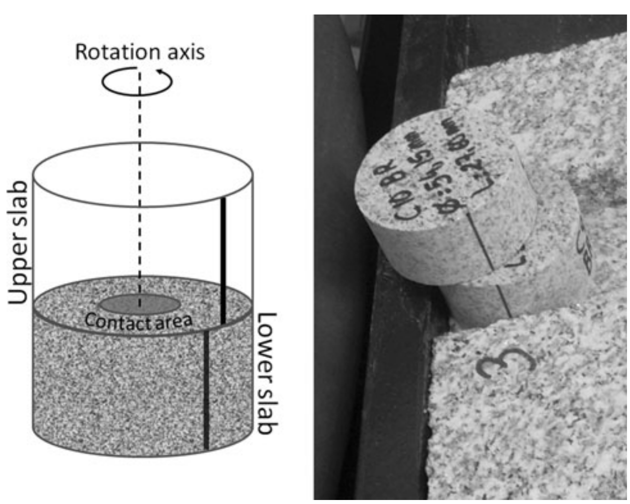

Fig. 3 Rotation during a tilt test with a small surface

Fig. 4 Purpose built tilt testing machine for jointed rock samples, with a motorized platform that tilts at 0.4°/s

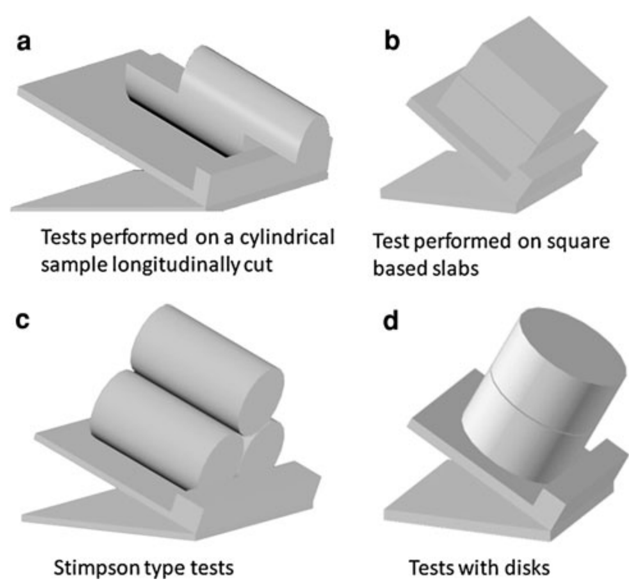

Fig. 5 Different set ups for the tilt tests performed in the experimental study

(c) Stimpson type tests with three cylindrical samples ($d = 54$ mm and $h > 108$ mm), one sliding over the other two with contacts in two generatrixes (Fig. 5c) and
(d) Tests on disk-like samples ($d = 54$ mm and $h = 27$ mm) (Fig. 5d).

A detailed description of the procedures used for performing each of the tests follows.

3.4 Test Conditions

The procedure described below was used for all the tests with the tilting machine. Note that horizontality was confirmed each time using a bubble level (Fig. 6).

1. The specimens were cut according to the indicated dimensions using diamond core drill bits and saws.
2. The lower specimens were placed on the plane-tilting platform in the horizontal position and secured in place (for the Stimpson tests, both lower cylinders were secured).
3. The upper specimens were placed on the fixed specimens in the horizontal position (for the Stimpson tests, the upper cylinder was placed horizontally on the other two specimens and generatrixes were marked for the repetition tests).
4. The platform was progressively tilted at the rate of 0.4°/s until the upper specimens began to slide, and the tilt angle of the platform was recorded. Only tests corresponding to displacements of at least 10 % of the sample length were taken into account.
5. Each test was repeated at least three times. The surface was wiped with a dry cloth between each repetition and specimens were placed in the same initial positions. Tests were performed in both directions for lengthwise-cut specimens.
6. Results were calculated as the mean of the results for all the repetitions of each test.

For the Stimpson tests, three diameters forming 120° were marked on the cylinder bases. The two fixed specimens were placed in such a way that the contact generatrixes with the sliding specimen were the same for each test. The sliding specimen was placed to ensure that two contiguous radii marked the sliding generatrixes for the test, which was repeated five to eight times. The sliding specimen was then rotated and two new contact generatrixes were tested (Fig. 6c).

3.5 Tested Rocks

Four widely available rock types were selected for the experiments (approximate UCS values are provided in brackets):

1. A very hard serpentinized dunite (190 MPa).
2. A slightly weathered coarse grained granite with two micas (76 MPa), locally called Amarelo País.
3. A fresh coarse grained white granite (110 MPa), locally called Blanco Mera.

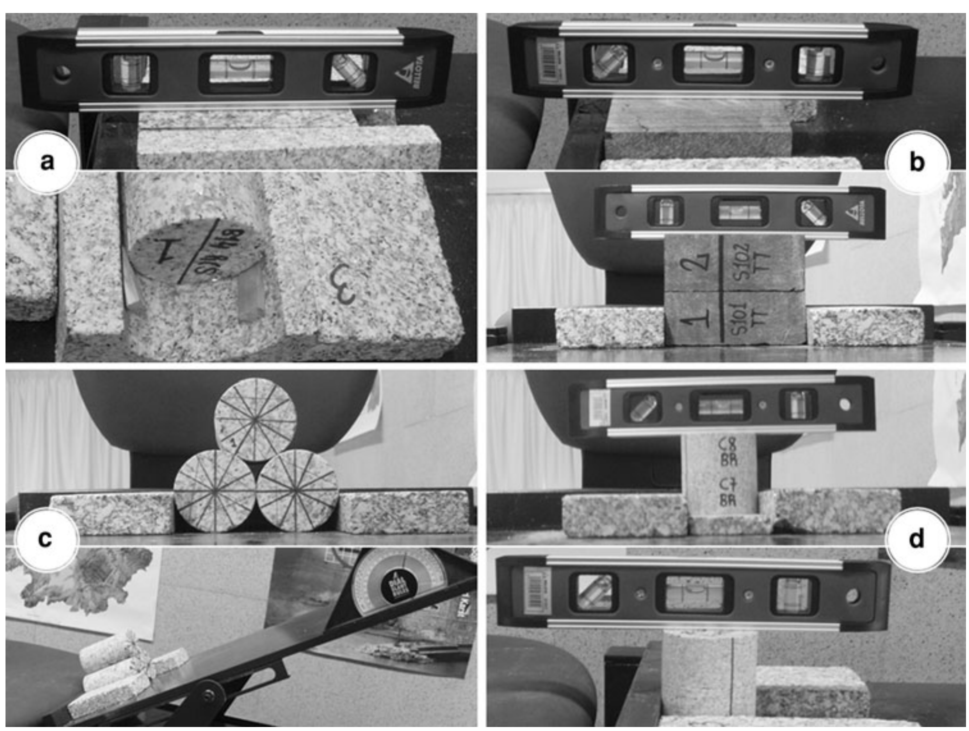

Fig. 6 Preparation of the different tilt tests. **a** Lengthwise-cut cylindrical specimen. **b** Square-based specimens. **c** Three properly oriented cylindrical specimens positioned according to particular generatrixes (Stimpson tilt test). **d** Disc specimens

4. A fresh medium-grained granite (115 MPa), locally called Vilachán.

Table 3 shows the mineralogical composition of these four rocks based on detailed petrographic studies. Figure 7 shows the appearance of these rocks as sawn surfaces and thin plates viewed using crossed nicols.

3.6 Results

The results for more than 500 tests are presented in Table 4. For the three granites, the basic friction angle values obtained in the Stimpson tests (39.5°, 37.3° and 37°, respectively) were much greater than the values obtained in the other tests (around 28° and 29°). Since the mechanisms

Table 3 Mineral composition of the tested rocks

Mineral	Serpentinized dunite	Amarelo País	Blanco Mera	Vilachán
K-Feldspar		25	27	20
Palgioclase		22	35	10
Quartz		26	20	38
Muscovite		18	7	16
Biotite		6	5	4
Chlorite			4	3
Olivine	53			
Serpentine (Antigorite + chrisotile)	37			
Other	10	3	1	2

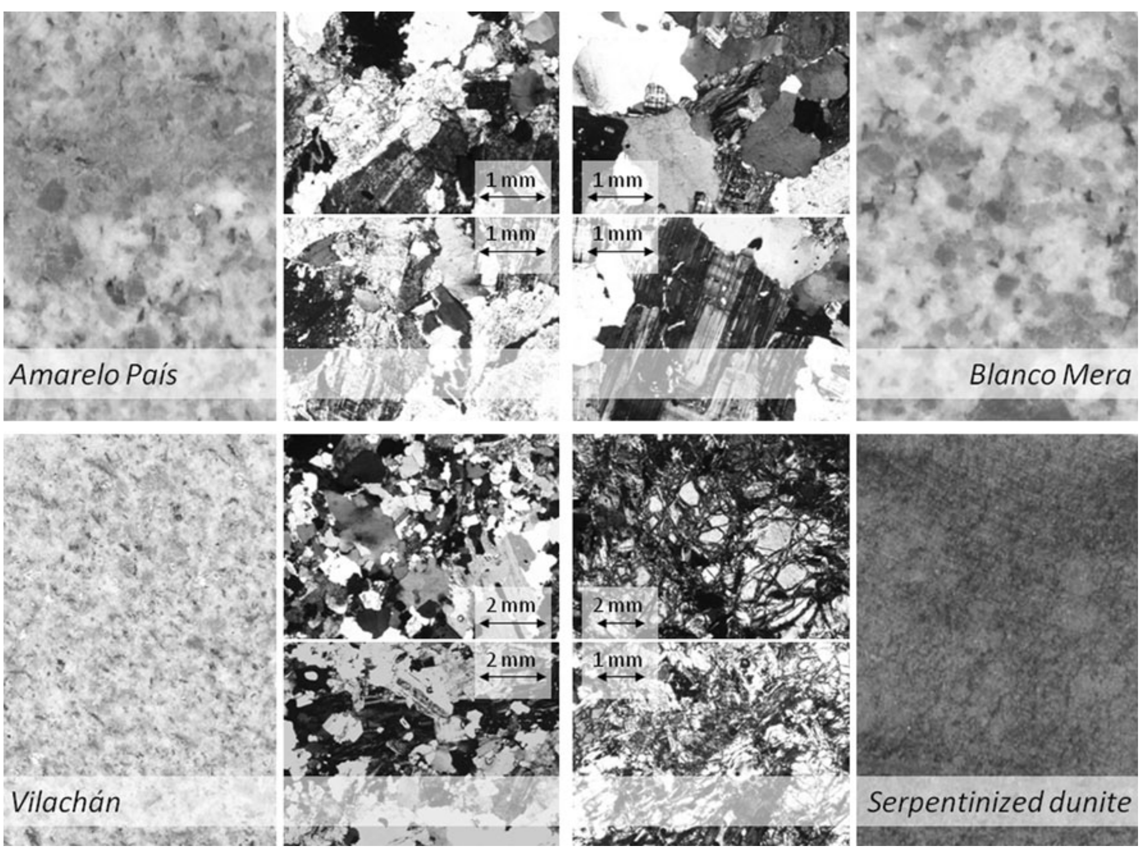

Fig. 7 Images of freshly cut rocks as sawn surfaces and thin plates taken using crossed nicols

Table 4 Main results of the experimental tilt testing program

Rock	Tilt test	Tests (no.)	Repetitions (no.)	Basic friction angle, ϕ_b (°)	
				Mean	Standard deviation
Serpentinized dunite	Stimpson	22	3	29.67	3.42
	Cut cylinder	6	3	26.83	2.01
	Slabs 100 × 100 × 40 mm	5	3	29.53	1.60
	Slabs 50 × 50 × 20 mm	12	3	29.08	1.46
	Disks	12	3	26.83	2.08
Granite (Amarelo País)	Stimpson	4	3	39.56	0.77
	Cut cylinder	4	3	27.75	2.45
	Slabs 100 × 100 × 40 mm	6	3	28.67	1.94
	Slabs 50 × 50 × 20 mm	4	3	28.33	2.15
	Disks	6	3	26.17	3.65
Granite (Blanco Mera)	Stimpson	15	3	37.28	1.08
	Cut cylinder	4	3	27.83	3.69
	Slabs 100 × 100 × 40 mm	6	3	31.50	3.24
	Slabs 50 × 50 × 20 mm	4	3	28.83	3.24
	Disks	3	3	28.78	1.79
Granite (Vilachán)	Stimpson	18	3	37.00	1.31
	Cut cylinder	6	3	27.61	1.94
	Slabs 100 × 100 × 40 mm	4	3	26.33	2.46
	Slabs 50 × 50 × 20 mm	4	3	28.58	2.50
	Disks	13	3	29.77	2.63

of sliding across generatrixes and plane surfaces are different, Stimpson tests cannot be recommended for estimating the basic friction angle of discontinuities in rock.

For dunite, the differences between the Stimpson and other test results were not so marked. This can be attributed to the soft nature of serpentine minerals (like antigorite and chrysotile) and to the fact that, with test repetition, the generatrixes were progressively polished, leading to diminished friction and resulting in smaller average friction angle values. For the Stimpson test, with sliding occurring on the same two generatrixes, initial values tended to be around 30°–35°, but dropped to 10°–15° after 30 repetitions. This effect can be appreciated in Fig. 8.

Figure 9 illustrates, in terms of the l/h ratio and the base plane angle β, the average results for all the tilt tests, consisting of tests (Stimpson's test excluded) for four different rocks. Since Eqs. 4, 5 and 6 are established for slab-shaped blocks with dimensions l, w and h, the lengthwise-cut cylinder and Brazilian disc dimensions were reduced to the equivalent rectangular values. Moreover, regarding the tests of the lengthwise-cut cylinders, the base plane angle considered was the mean of the results obtained when testing the samples in both directions along l.

Figure 9 also shows that, for the lengthwise-cut cylinder, the stress conditions proposed by Muralha (1995) were largely fulfilled. The tests with square-based slabs also fulfilled the stress criteria, although the results were closer to non-reliable conditions. Finally, since the tests on the discs failed to fulfill the criteria (most of the representative points appear under the discontinuous line $l/h = 4 \tan \beta$), these cannot be considered as fully reliable.

In the process of progressively tilting the samples, often the upper specimen moved slightly or rotated around an axis normal to the contact, rendering the tests less reliable,

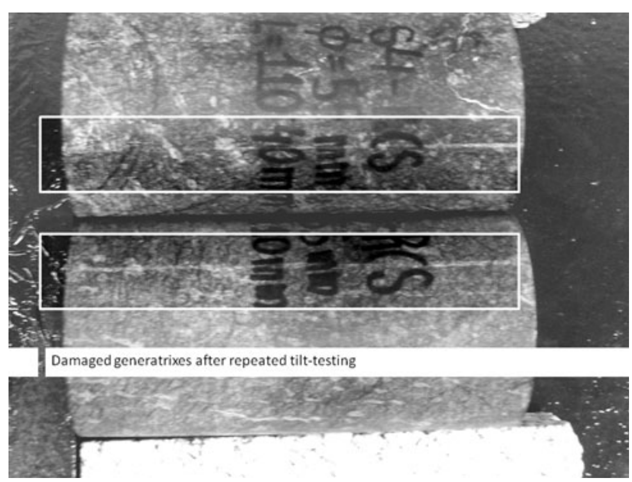

Fig. 8 Damaged generatrixes in peridotite specimens after ten sliding tests. This phenomenon was rarely found on granite samples

if not invalid. This was undoubtedly due to the small curvature of the cut surface. The percentage of tests in which this occurred was recorded and results are summarized in Table 5, revealing that rock type has a bearing on this kind of movement, as it occurred in only 8 % of tests on the Blanco Mera granite, compared with 26 % on the Vilachán granite. This kind of movement was also much more common with smaller samples, Brazilian discs (20 %) and small slabs (15 %) versus cylinder (2 %) and larger slabs (2 %), suggesting the need to use larger specimens for testing.

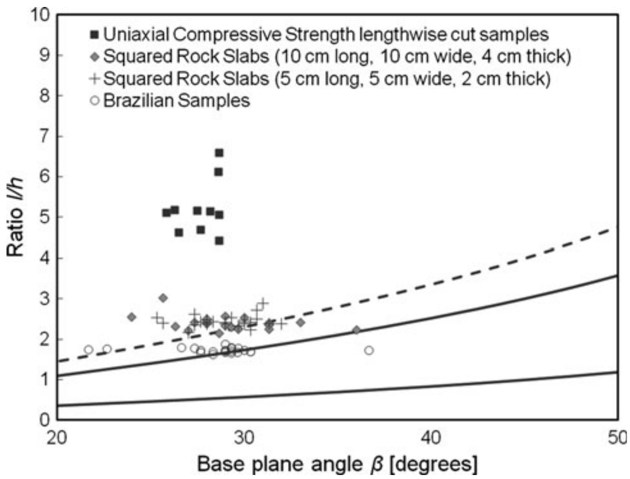

Fig. 9 Representation of the presented results in a graph depicting *l/h* and *β*. The *upper discontinuous line* representing $l/h = 4 \tan \beta$ marks the lower limit for stress reliability in circular samples. Located below it is a *continuous line* representing $l/h = 3 \tan \beta$ marking the lower limit for stress reliability in slab-shaped samples. The *lowest continuous line* represents the toppling threshold

4 Study on Basic Friction Angle Variability

In order to quantify the variability of basic friction angle results, another experiment was set up and performed at the National Civil Engineering Laboratory (LNEC) in Lisbon, Portugal. The tests were performed with prismatic blocks of two different granites cut for uniaxial compressive strength testing of ornamental rock: two grey porphyritic granite blocks (specimens 121 and 122, dimensions 45 mm × 45 mm × 120 mm) and three pinkish-grey porphyritic granite blocks (specimens 316, 317 and 318, dimensions 50 mm × 50 mm × 125 mm). The edges of the prism bases were labelled A–B–C–D and the corresponding opposites as A′–B′–C′–D′. Testing consisted of tilting along the height of all possible combinations of prism faces in both directions for pairs of specimens. Figure 10 illustrates tilt test 317B–316C′.

Table 5 Main results of the tilt-testing experiments

Rock	Test type	Total number of tests	Tests with rotation, sliding or resettlement (%)
Serpentinized dunite	Cut cylinder	18	0
	Slabs 100 × 100 × 40 mm	15	0
	Slabs 50 × 50 × 20 mm	36	25
	Disks	36	0
	Mean		8.6
Granite (Amarelo País)	Cut cylinder	12	8.3
	Slabs 100 × 100 × 40 mm	18	0
	Slabs 50 × 50 × 20 mm	12	16.7
	Disks	18	22.2
	Mean		11.7
Granite (Blanco Mera)	Cut cylinder	12	0
	Slabs 100 × 100 × 40 mm	18	11.1
	Slabs 50 × 50 × 20 mm	12	16.7
	Disks	9	0
	Mean		7.8
Granite (Vilachán)	Cut cylinder	18	0
	Slabs 100 × 100 × 40 mm	12	0
	Slabs 50 × 50 × 20 mm	12	0
	Disks	39	53.9
	Mean		26.0

Fig. 10 Preparation for tilt test 317B–316C′

Accordingly, each set of tests refers to 8 edges × 8 edges × 2 tilt directions, for a total of 128 tilting tests. Each tilt test was repeated three times. The result of each tilt test was the median (intermediate value) of the three repetitions.

The differences between the extreme and the median values were studied in order to assess the variability of the tilt test results. Figure 11 shows the histograms for these differences for the two types of granites. For the grey porphyritic granite (specimens 121 and 122), from a total of 256 values, a mean of 0.20° and a standard deviation of 1.47° were determined. For the pinkish-grey porphyritic granite (specimens 316, 317 and 318), from a total of 768 values, a mean of 0.05° and a standard deviation of 1.81° were found.

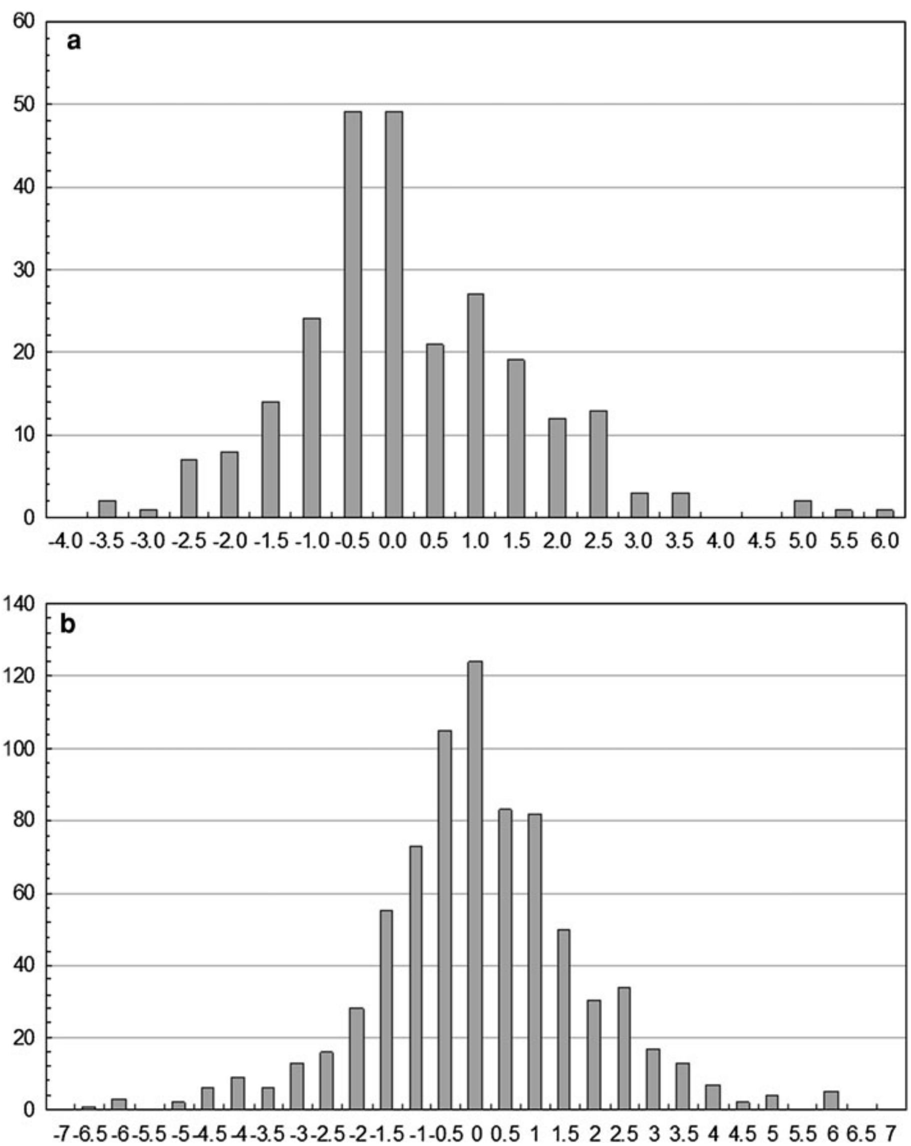

Fig. 11 Histograms representing the differences between extreme values and medians for three repetitions of tilt tests performed on the different sides of granite prismatic blocks. **a** Results for two samples of grey porphyritic granite (specimens 121 and 122). **b** Results for three samples of pinkish-grey porphyritic granite (specimens 316, 317 and 318)

These results indicate that deviations from the median value had approximately null means and standard deviations of around 1.5°–2°. Since around 95 % of the values fell around the median ±3°, it seems convenient to suggest, as a possible recommendation for tilt testing, that a fourth repetition be performed when the deviation between one of the results and the median is larger than 3°.

For the different types of tilt tests on various rocks presented in Sect. 3, this would mean a fourth repetition in 15 tests out of 168, i.e., in roughly 9 % of tests (3.5 % for serpentinized dunite, 15 % for Amarelo País, 21 % for Blanco Mera and 5.5 % for Vilachán). Referring to these tests, around 90 % of the values fell around the median ±3°, with this higher value explained by the variability of the different rocks. This suggestion of a fourth test, which would not require a large amount of extra work, would thus sensibly enhance the reliability of the results.

The results for the basic friction angle in degrees were also considered and represented in the form of histograms for the two types of granites (Fig. 12). For the grey porphyritic granite (specimens 121 and 122), 384 values were obtained with a mean of 19.32° and a standard deviation of 4.56°. For the pinkish-grey porphyritic granite (specimens 316, 317 and 318), 1,152 values were obtained with a mean of 26.61° and a standard deviation of 5.51°. Even considering the reduced number of samples, these deviations are higher than those for the different tilt tests on different rocks described in Sect. 3.

It is also important to refer that in around 1/3 of tests of the same surface, two repetitions rendered the same tilt angle.

If friction coefficients (tan ϕ_b) rather than degrees were considered, the dispersion would be larger. So it is recommended to analyse results in degrees. Nevertheless, results in degrees still show significant dispersion, even if not higher than other commonly studied representative parameters in rock mechanics, such as the uniaxial compressive strength, orientation of joints and so on.

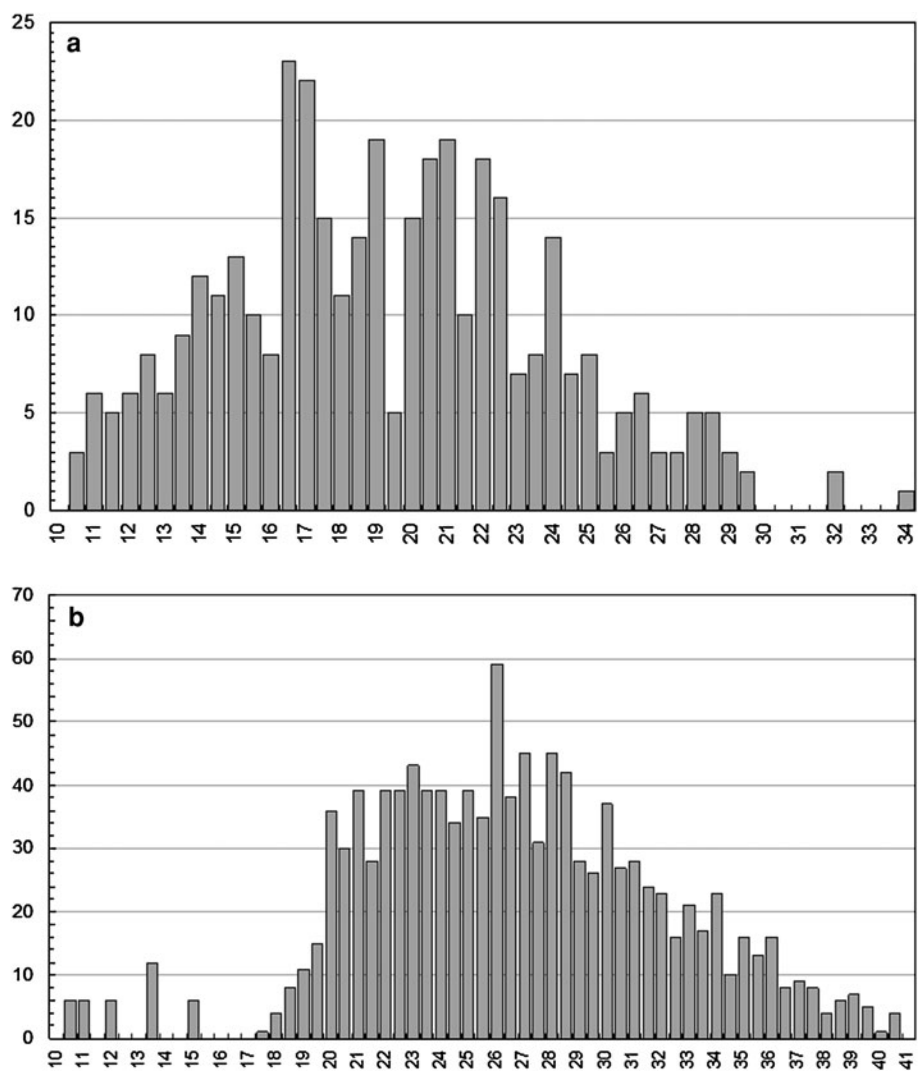

Fig. 12 Histograms representing basic friction angles for three repetitions of tilt tests performed on the different sides of granite prismatic blocks. **a** Results for two samples of grey porphyritic granite (specimens 121 and 122). **b** Results for three samples of pinkish-grey porphyritic granite (specimens 316, 317 and 318)

5 Conclusions

In a number of engineering projects, tilt tests to obtain the basic friction angle of rock discontinuities according to the method suggested by Stimpson (1981) were performed. Apparently, they overestimated ϕ_b when compared with results suggested in the literature. Simple tilt tests with rock discs (Brazilian test specimens) were also performed in a number of engineering projects, and they rendered significantly lower values for the basic friction angle (more than 10° lower than Stimpson test results).

In order to study these differences in more detail, an experiment to perform different types of tilt tests (including Stimpson tests) on four different rocks (three granitic rocks and a dunite) was planned. Results showed that the Stimpson tests tended to consistently overestimate the basic friction angle of rock surfaces, since the mechanisms of sliding along generatrixes of cylinders and along planar surfaces are different and also due to the fact that three core sticks cause a slight wedging problem, and exaggerate ϕ_b because the normal stress is greater than the shear stress applied. Therefore, the first conclusion of this experimental work is that sliding tests performed on generatrixes are not suitable for obtaining reliable basic friction angle values for rock discontinuity planes.

The experimental results also showed that tests using small specimens are also not recommended, as problems may arise related to the curvature of the cut surfaces. Not recommended are also disc-shaped samples cut from drill cores ($d = 54$ mm and $h > 27$ mm), since they have small surfaces and they do not usually fulfil minimal stress distribution conditions.

Results also allowed to conclude that tests in lengthwise-cut cylinder specimens ($d = 54$ mm and $l > 108$ mm) provided more reliable results, though they are not commonly available for standard engineering projects. Since results from the tests performed with slabs measuring 100 mm × 100 mm × 40 mm were also quite reliable, it is suggested to run tilt tests using rock slabs with at least 50 cm^2 surfaces and a length to height ratio of at least 2 (larger length to height ratios would be even more favourable), in order to use a large enough tilt surface and to assure that contact stresses are compressive when sliding occurs.

Extensive testing consisting of tilting granite prisms along the height for all possible combinations of block faces were also performed. Each test consisted of three repetitions. Since deviations from the median had approximately null means and standard deviations of around 1.5°–2°, the median value of the three repetitions should be used as the basic friction angle. This suggestions deal with the discussion regarding average values of the angles or average values of the friction coefficients, which seem to be more adequate from a theoretical point of view. Considering that around 95 % of the values fell around the median ±3°, it seems wise to recommend also that a fourth supplementary repetition should be performed when the maximum deviation between one of the results and the median is larger than 3°. The result of the basic friction angle would still be the median, but in this case of all four repetitions.

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