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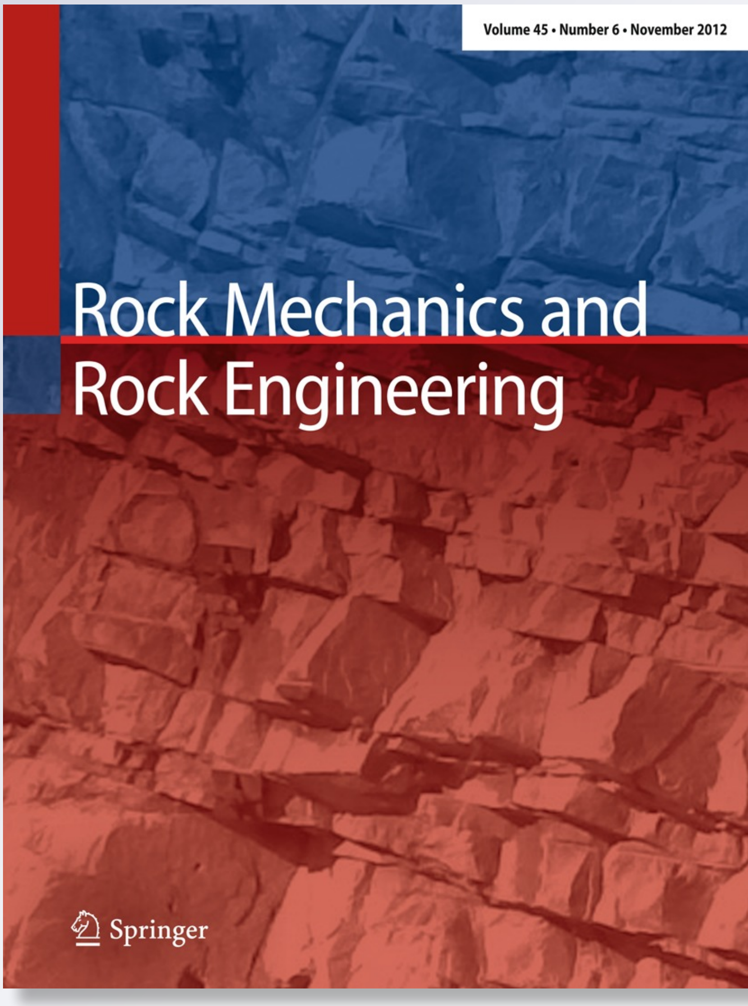

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DISCUSSION

Discussion of Alejano, Gonzalez and Muralha (2012)

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This is a useful contribution serving to illustrate the difficulties in defining a "basic friction angle" for rock joints. The fact that the authors find that the sliding angle of planar surfaces of rock in tilt tests can vary between 10° and 40° for a single granite block (their Fig. 12b) may come as a surprise to some engineers and researchers. Many textbooks and papers lead one to believe that there is a unique friction angle, $ø_b$, for a planar joint in "fresh" rock that can be taken as a lower bound for estimating the shear strength of natural joints empirically.

Similar variability has perplexed many authors such as Nicholson (1994) who found that friction angles for saw-cut Berea sandstone in direct shear tests varied by 12.5° despite great attention to sample preparation and reproducibility. Kveldsvik et al. (2008), in their investigations of the Åknes rock slope, found that the "basic friction angle" derived from tilt testing of core varied between 21° and 36.4°.

Coulson (1971) demonstrated that the friction angle of planar surfaces of rock varies with surface finish. Krahn and Morgenstern (1979) reported similar variation for surfaces prepared in different ways and with different surface finishes. Hencher (1976, 1977) showed how repeated tilt testing of saw-cut and lapped rock sliders could reduce the sliding angle from over 30° to almost 10° after metres of displacement where rock flour was removed between runs. Continuing tests and allowing sliding debris to accumulate between runs, the sliding angle increased again. The results from two such tests using sliders of Darleydale sandstone weighted with steel blocks are presented in Figs. 1 and 2. Similar results were obtained using slate and limestone. All these data are valid strengths for planar rock surfaces; the sliding angle at each stage simply reflects different conditions of surface finish, wear and the presence and nature of any debris.

As Harrison (2008) noted in his review of 60 years of papers in *Géotechnique:* "Unfortunately, these valuable contributions seem to have been ignored by the rock mechanics community in its subsequent development of tilt tests. Furthermore, the principle that friction angle may reduce as the shear displacement continues to increase up to very large values is probably—and erroneously—not accounted for in the majority of analyses undertaken by geotechnical engineers."

The test data presented above simply illustrate that there is no single and simple "basic friction" angle for planar rock joints. Most planar rock surfaces can be roughened to the point where the friction angle approaches 40°; natural rock joints often have such strength even without dilation (Papaliangas et al. 1995). Much of the frictional strength is derived from ploughing and deformation of surface textural components (Engelder and Scholtz 1976). The same surfaces could be polished so that the strength reduces towards the purely adhesional contribution to friction, which, for many rocks seems to be about 10°.

Slopes sometimes fail at sliding angles lower than that of a saw-cut surface, which belies the concept of a lower-bound basic friction angle measurable by simple tilt tests on saw-cut or cored samples. One example investigated in detail was reported in Hencher (1982) and is summarised in Hencher (2012). Similarly the extensive, naturally polished surfaces in the Coal Measures of South Wales have been associated with large landslides. The friction angle of these natural discontinuities can be as low as 10° whereas a saw-cut sample through the parent rock gives more than twice

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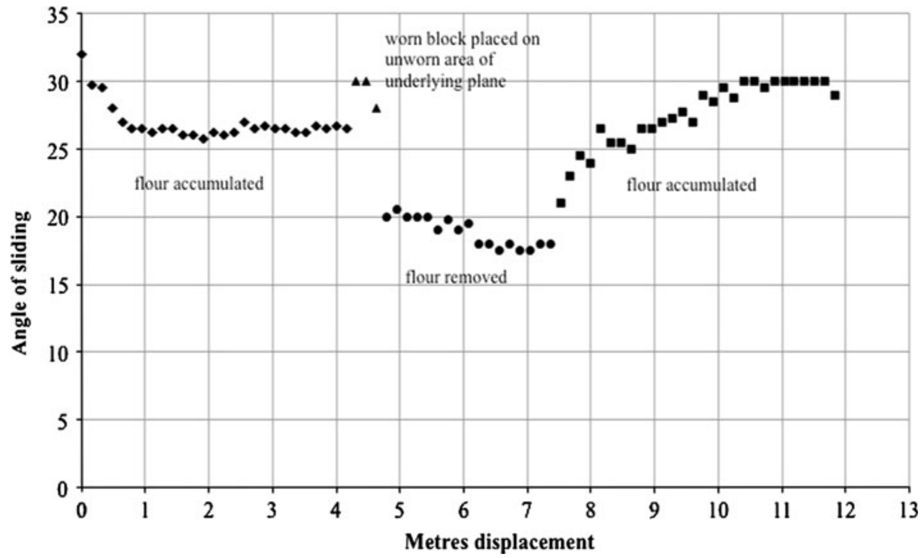

Fig. 1 Repeated tilt tests on saw-cut and lapped sliders of Darleydale sandstone, weighted by steel blocks. For the initial runs, rock flour was allowed to accumulate

that strength (Swales 1996). A large, deep seated landslide currently being remediated in Australia (Starr et al. 2010) is sliding with an operative angle of friction of 8° in mudstone which is much lower than would be anticipated from "basic friction angles" listed in Table 1 of the paper by the authors.

Finally, it should be noted that the strength for saw-cut surfaces or other artificially smoothed surfaces is usually considerably lower than the "basic" friction angle measured from direct shear tests on natural joints where corrections are made for sample-specific roughness causing dilation (Hencher and Richards 1989; Hencher 1995). Dilation-corrected data from shear tests on real joints should not be substituted as the "basic friction angle" within the Barton-Bandis model. For many rough joints, to do so would often be unsafe by perhaps 10°. Instead the roughness and true cohesion contributions to field strength over and above the natural, non-dilational friction need to be judged based on the field characterisation. This is discussed further in Hencher et al. (2011) and Hencher (2012).

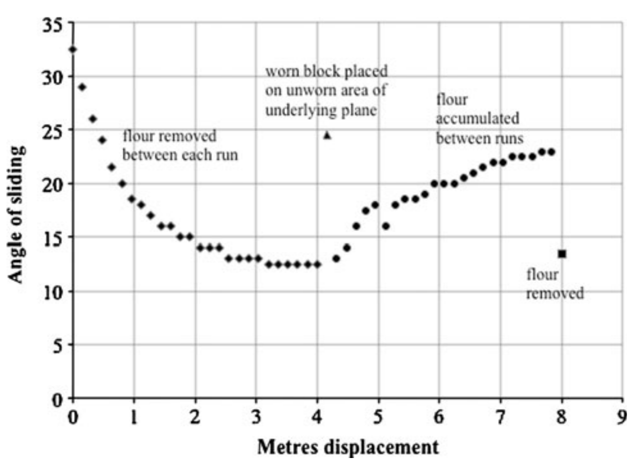

Fig. 2 Repeated tilt tests on saw-cut and lapped sliders of Darleydale sandstone, weighted by steel blocks. Between the initial runs, rock flour was removed by blowing using a lens cleaner

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