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Stability of a block resting on an inclined plane—A classical problem revisited

J. Meier [a,*], H. Bock [b]

[a] Gruner AG, Gellertstrasse 55, 4020 Basel, Switzerland
[b] Q+S Consult, Bad Bentheim, Germany

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ABSTRACT

Blocks of granitic rock, resting on inclined exfoliation planes, show evidence of a downward movement despite the fact that the friction angle of the contact planes is significantly higher than the inclination of the planes. In a pilot study an approximately 0.5 m thick slab of rock with a volume of about 2.6 m^3 resting on a plane inclined by 22° was monitored on its displacement and temperature behaviour. The measurements revealed that the block is subject to distinct cyclic distortions due to temperature effects from solar radiation. The problem was modelled in 3-D by means of the finite element (FE) code Abaqus/Standard. It was possible to qualitatively reproduce the essential thermo-mechanical features of the rock block under consideration. It is shown that intermittent slip of discrete contact points at the base of the block is a key factor in the downward movement of the block. The shear strength of the contact points is sequentially exceeded due to cyclic reaction forces imposed by thermally-induced expansion/shortening and warping of the block.

1. Introduction

The stability of a block resting on an inclined plane is one of the most elementary problems in rock mechanics, and in applied mechanics generally. For centuries, it appeared that that problem had been resolved, not least because of its elementary geometry (Fig. 1) and the simplicity of the equations describing its state of stability. The block is supposed to be in a stable state, and remains in that state, if the following condition holds

$$|F_a| \le |F_r| \quad (1)$$

where F_a is the force acting in direction of the inclined plane, and F_r is the resisting force mobilised in the block/plane contact.

In the case that there are only gravity-induced forces acting on the block, the stability condition can also be denoted by the following criterion

$$\beta \le \phi \quad (2)$$

where β is the inclination angle of the plane, and ϕ is the angle of friction of the block/plane contact. Eq. (2) is the basis for virtually all stability considerations in geo-engineering, and is well established in theory and practice. The equation has to be adjusted if, besides gravity-induced forces, forces acting in non-vertical directions are to be considered, e.g. those stemming from water thrust or earthquakes.

In contrast to the above, field observations made some thirty years ago bear evidence of some downward movements of rock blocks even in cases where Eq. (2) is satisfied. An example of such evidence is presented in Section 2. From the setting of the field example, it is anticipated that solar radiation and associated cyclic temperature changes in the block are connected with the observed downward movement and, thus, somehow responsible for the lack of the long-term stability of the block. Progress in FE software which, nowadays, makes it feasible for coupled thermo-mechanical 3-D modelling to be carried out on standard PCs, allows for new appraisal of the field example. A mechanism for the long-term instability of the block is suggested in Section 3, and numerical results are presented in Section 4.

2. Field observations

2.1. Location and general setting

The site investigated is located at Cape Ferguson in the Coral Sea, latitude 19°16′22.07″S and longitude 147°3′27.55″E, in the immediate vicinity of the Australian Institute of Marine Science, situated some 50 km east of Townsville, Queensland, Australia. Geologically, the site is characterised by a coarse-grained granite which shows a high degree of exfoliation. Such exfoliation is

* Corresponding author. Tel.: +41 61 317 62 53.
E-mail addresses: joerg.meier@vint.de (J. Meier), qs-consult@t-online.de (H. Bock).

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a physical weathering process that is quite common in granitic rocks, particularly in tropical climates. In course of this process, near-surface rocks are de-stressed by developing surface-parallel fractures, thus forming peels of rock in an onion-like pattern [19]. The outer peel subsequently breaks up along joints oriented about normal to the exfoliation plane leading to the situation, shown in Fig. 2, where numerous well-defined rock blocks are resting on an inclined exfoliation plane.

Mechanically, the exfoliation planes are extensional fractures. They are clean fractures without any gouge or other types of infilling. From inspection, the joint roughness coefficient *JRC* [3] is in the range of between 8 and 10.

2.2. Block selected for further studies and monitoring

A single block was selected for further studies (Fig. 3a). The selection was made in view of the hypothesis that solar radiation and associated cyclic temperature changes may be connected with the downward movement of the rock block. The plane on which the block is resting dips exactly towards geodetic north. Considering the inclination of the block ($\beta \approx 22^\circ \pm 1^\circ$) and the latitude of the site (19° South) this means that, at noon and on average throughout the year, the sun stands about normal to the top surface of the block. The block is almost perfectly rectangular in the dimensions length L=6.70 m, width W=0.80 m and height H=0.48 m.

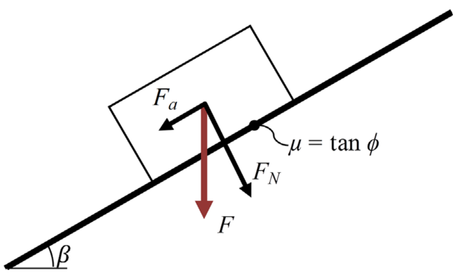

Fig. 1. Block resting on a plane, inclined by the angle β, with gravity acceleration force F and its components F_N and F_a acting normal, respectively, parallel downward to the plane.

Fig. 2. Several granitic blocks resting on an inclined exfoliation plane location: Cape Ferguson, Queensland, Australia.

Laterally, the block is well detached from adjacent parts of the exfoliated rock slab. In its upper part the contour of the block matches perfectly with the boundary of the adjacent rock abutment (Fig. 3b) thus indicating a certain downhill displacement of the block of some 1.50 m, which must have occurred in the past. That downhill displacement is also documented by a series of striae which are visible on top of the free surface of the base plane (Fig. 3c). A departure from the almost ideal setting was that the west side of the block is partly shielded by the undetached rock and thus receives less sunlight than the opposite eastern side.

As can be seen in Figs. 2 and 3, the exfoliation planes, and thus also the base and the top of the block, are smooth in the 10 m - range, planar in the 1 m - range, undulated in the 0.1 m – range and rough in the cm- to mm-range (terminology after [3]). With regard to the dimension of the block under consideration this means that the block will rest on its base on a limited number of contacts, ideally in a statically determinate mode on three (3) contact points. Even in heavy rain, there will be no water pressure built-up as the base plane has interconnected mm- to cm-sized apertures and acts as a perfect drainage.

Evidently, the block has already been sheared along the base plane by an amount of at least 1.50 m. Thus it can be anticipated that the shear strength of the block/base plane contact has passed its peak and may be approaching the residual strength. For plane, unpolished and dry shear surfaces of coarse-grained granitic rock, [4] specified a residual friction angle ϕ_{res} of between 31° and 35°, a value which is generally accepted in rock mechanics. Note that, even when conservatively estimated, it is $\beta \lll \phi_{res}$.

The above field observations do not provide any evidence on the style (intermittent or continuous) or velocity of the downward movement. Therefore a monitoring programme was instigated where the displacements of the four (4) corners of the rock block were measured relative to the base plane. Monitoring was restricted to that displacement component which is of particular interest for the case considered, i.e. the component in downhill direction parallel to the base plane. The uncertainty range of the measurements was ± 0.01 mm.

Fig. 4 shows a monitoring example over a 24-h period. Within that period the corners of the rock block are subject to displacements in the order of several tenths of a millimetre. Clearly, there is a tendency for an extension/shortening of the block in

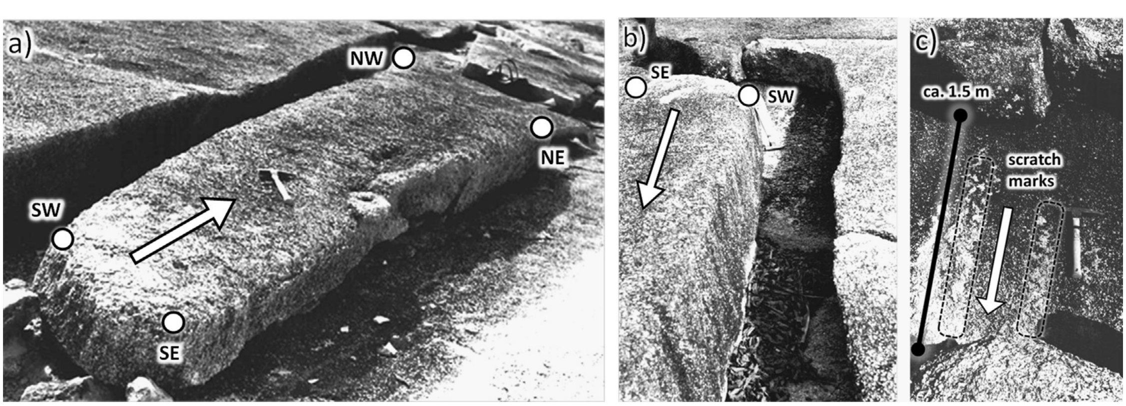

Fig. 3. Rock block considered (L=6.70 m; W=0.80 m; H=0.48 m; direction of the four edges indicated; arrows: direction of overall downhill movement of rock block).