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INSTRUMENTS AND METHODS

A FIELD TEST TO ASSESS SNOW-SLOPE STABILITY

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ABSTRACT. A simple field test of snow-slope stability is proposed, which allows decisions about a number of factors recently described by Conway and Abrahamson (1984). These include spatial variation of snow strength along a slope, and progression of failure from a localized initial failure. Strength within the snow slab is considered as well as that at its base. A snow saw is required for the test and, because a number of tests can be made in a few minutes, much information on the state of the slope can be obtained in a practical time.

RÉSUMÉ. *Un test de terrain pour éprouver la stabilité du manteau neigeux.* On propose un test simple de la stabilité du manteau neigeux qui permet une prise de décision à propos d'un certain nombre de facteurs récemment décrits par Conway et Abrahamson (1984). Cela inclu la variation spatiale de l'état de tension le long du manteau neigeux et la propagation d'une fracture à partir de sa localisation ponctuelle initiale. L'état de tension à l'intérieur du manteau neigeux est envisagé de même que celui à sa base. Une scie à neige est nécessaire pour le test et grâce au nombre de tests possibles en quelques minutes, de nombreuses informations sur l'état de la couche peuvent être obtenues en ce court laps de temps.

ZUSAMMENSFASSUNG. *Ein Feldtest zur Abschätzung der Stabilität verschneiter Hänge.* Es wird ein einfacher Feldtest für die Stabilität von verschneiten Hängen vorgeschlagen, der Urteile über eine Reihe von Faktoren erlaubt, wie sie jüngst von Conway und Abrahamson (1984) beschrieben wurden. Dazu gehört die räumliche Schwankung der Schneefestigkeit längs des Hanges sowie das Fortschreiten einer Störung von einem bekannten Ausgangspunkt aus. Die Schneefestigkeit wird sowohl innerhalb der Schneedecke als auch am Untergrund betrachtet. Für den Test wird eine Schneesäge benötigt. Da eine Mehrzahl von Tests in wenigen Minuten durchgeführt werden kann, lässt sich viel Information über den Zustand des Hanges in vertretbarer Zeit gewinnen.

INTRODUCTION

Most techniques used for snow-stability assessment rely on some interpretative skills of the observer as well as special equipment (for example, snow-stratigraphy tests, a ram penetrometer, explosives, shear tests as outlined by Sommerfeld (1984) or Conway and Abrahamson (1984), the wedge test of LaChapelle and Ferguson (1980)). The "shovel test" (described by Sommerfeld (1984)) provides an estimate of the extra down-slope force required to overcome basal resisting forces and requires only simple equipment to perform (a snow shovel and saw).

Conway and Abrahamson (1984) measured significant spatial variability of snow strength, and this has been confirmed by further measurements made by us across avalanche crown-walls. Such variability indicates that a single test at only one location may give a misleading estimate of slope stability.

To allow for the variability we have combined a simple force-excess criterion (imposed forces minus a combination of resisting strengths acting together on a certain section of the slope) with a probabilistic description of the variables (Conway and Abrahamson, in press). A "local" failure was considered to occur when the forces driving a localized section of the snow slab (the down-slope component of gravitational weight plus any extra forces such as a skier) exceeded the forces resisting the loads (the resistance around the peripheries, including the base of the section of slab). Using measurements made over five slopes which had avalanched and analysing the values of strength and their spatial distribution, the most likely failure area was found to be about 1 m × 1 m in size. Furthermore, on large slopes with moderate snow strengths, such a "local" failure was found likely to occur at least once and so occurrence of such a failure appears not to be a sufficient criterion for slope instability.

Because the most likely failure area was found to be small compared with observed sizes of avalanches, an initial failure needs to propagate in order to become an avalanche. It follows that the probability of a local failure propagating to adjacent snow should be a primary consideration for slope-failure assessment.

Scales of spatial variability

We think wind may strongly influence the patterns of distribution of both snow strength and snow depth – and hence driving force. We have noted surface ripples left after winds, and measured wavelengths (peak to adjacent peak distance) in the wide range of 10 mm to about 15 m. Commonly, however, the spacing was less than 5 m. Because we believe that the basal shear strength depends on the conditions of local deposition of the snow forming that layer, we expect the basal shear strength may vary with wavelengths of similar range to those of snow ripples. In fact, for six completed sets of spatial measurements of snow strength across slopes, the average wavelength of the shear strength ranged from 0.3 m to 4.6 m (the "wavelength" here was taken to be 2.5 times the correlation length; see Conway and Abrahamson, in press).

Slope-risk assessment depends on adequate estimates of both the mean and the variation of strength. It is clear that, with a semi-periodic variation, measurements should be made over at least one entire wavelength for a reasonable estimate. In the absence of knowledge of the wavelength, the test should ideally be made over 15 m, but often a series over a smaller distance (about 5 m) will give an adequate description. If snow loads or mean snow strength changes considerably over a slope as might be expected in

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drifts behind obstacles, the slope can be subdivided into sections which are regarded as closely similar, and sets of tests on each section will be necessary.

An unequivocal test which can satisfy the above requirements, uses simple equipment, and can be done with a minimum expenditure of energy and time, is described below.

THE PROPOSED "SAW TEST"

This test requires the use of a saw with appreciable thickness and longer than most snow saws. The thickness is required to leave a gap in the snow to enable observation of block movement and to prevent an isolated block from fouling surrounding snow when sliding parallel to the cut. We found that a saw made from 10 mm thick plywood, 1 m in length to the handle, with teeth made by cutting 50 mm diameter semi-circular notches, was a satisfactory tool.

The steps of the test are:

(1) Choose a position close to a potential crown zone and make a single saw cut about 1.5 m long, across the slope to a depth greater than the suspected shear plane.

(2) 1 m above the centre of the single saw cut, simulate a failed critical area by saw-cutting the four boundaries of a square column 1 m × 1 m to a depth greater than the suspected failure plane (see Fig. 1). The saw cuts are best

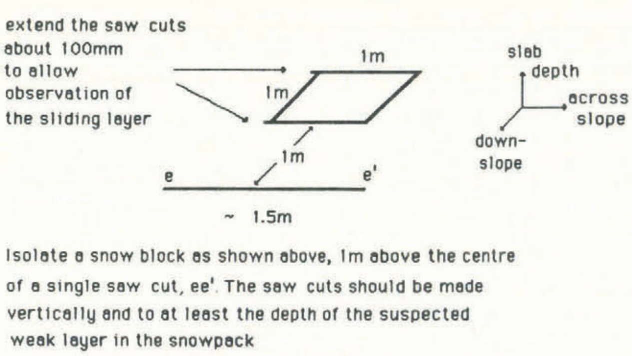

Fig. 1. Preparation of snow columns for the proposed saw test.

made vertically (to avoid bending of the column). Continue the cross-slope cuts out to the side by about 100 mm to allow observation of the plane of slip.

(3) (a) Note whether the column has failed in basal shear. (b) If the column has failed, note whether the extra weight of the failed column has caused the snow immediately below it to fail in side shear (i.e. whether the lower saw cut has closed).

(4) Ski on to the top of the column, note any failure, and then jump (to simulate a turn or a fall), and note whether fracture has occurred and whether it has propagated and caused the lower saw cut to close.

(5) If the failure has still not progressed to the lower snow, an assessment of the level of stability is possible by making saw-cuts from the extremities of the lower saw cut (e and e'), towards the column until failure occurs (see Fig. 1).

(6) To allow for any spatial variability of strength, a number of such tests should be made contiguously (see Fig. 2). In most cases five such tests should be sufficient to determine a reasonable stability estimate, but more may be needed in some situations. To avoid disrupting adjacent tests when isolating blocks and still make contiguous measurements, it is best to work down a slope with succeeding tests, as shown in Figure 2. The horizontal cuts can be made first as the experimenter moves down one side, and the vertical cuts made after each jump test.

If the first three tests show failure progression, the slope should be considered unstable. In fact, if one-half or more of the total number of tests (with extra load applied) show failure progression, the slope should be considered unstable. If snow strengths or loadings are likely to differ considerably at another location on the slope, a further series of tests at that location is desirable.

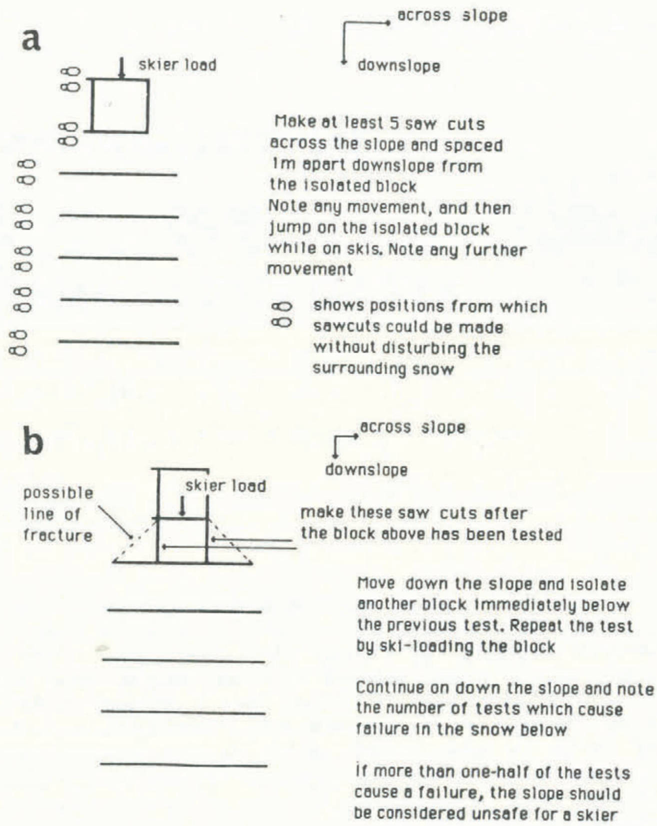

Fig. 2. (a) Method of testing for propagation of failure with skier loading. By repeating the test (b), an indication of the spatial variability of strength down the slope can be ascertained.

DISCUSSION OF THE TESTS

The test allows for several factors which are expected to influence slope stability:

(1) Especially for hard slabs, the strength within the slab may be sufficient to prevent progressive failure, and we think this strength in addition to basal shear strength should be included in a stability assessment. On the other hand, for soft slabs the upper snow layers may compress rather than transmit forces to adjacent snow, and cause "point release" rather than "slab"-type avalanches. The behaviour of both hard and soft slabs will be shown up in the progression part of the above test.

After a small movement, the shear strength of snow may drop from its original value to a "residual" value (McClung, 1977). Cutting of the four boundaries of a column (step (2) above) does not strictly simulate a "local" failure unless the column moves and the basal strength takes its residual value. We have found, however, that when a skier loads an isolated column, the column generally slips and thus simulates a local failure. The shear strength of the basal surface of this 1 m^2 column will in many instances have assumed a lower residual value before the column transmits load to its down-slope neighbour.

(2) The forces driving the slab down-slope are influenced by: (a) slope angle, (b) slab depth and density, and (c) an external load such as a skier. All of these factors are implicit in the test. We are particularly interested whether a skier will cause an avalanche by standing or jumping on a slope. A skier may make a significant contribution to the forces driving the avalanche in situations when the slab consists of low-density snow and is shallow. Several skiers

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on a slope not only increase the total load but also, by traversing a larger area, increase the probability of causing an initial local failure and progression.

Provided the saw cuts are sufficiently deep to penetrate the sliding layer, it is not important to know the location of the layer prior to the tests. However, after the test, the depth to the layer most likely to slide under the weight of a skier can be easily measured. If fracture depths for a region are typically greater than 1 m, a saw longer than 1 m would be required. Alternatively, a shovel may be used gently to cut out narrow troughs so that one can work the handle of the 1 m saw down to the length of one's arm.

A cutting edge could be made by clipping some plastic teeth on to a ski-edge or to ski-poles. This would save carrying a saw and would also increase the depth to which one could isolate columns.

At the present time we have not made sufficient tests using the described technique to set confidently limits which might differentiate potential avalanche slopes from stable slopes. Our suggested "half-failure" rule is largely derived from previous experimental work (Conway and Abrahamson, in press) and will be improved by experience with this test. Also, we cannot accurately predict the location of the weakest and therefore most critical zone on a slope but, because the series of tests can be made rapidly (five snow columns took about 5 min to isolate using the saw mentioned above), it is possible to make several series of tests with a minimum expenditure of energy and time. The tests also do not disrupt a slope for skiing, should it be judged stable.

In the tests described above we have considered propagation of the failure down-slope but a similar set of experiments could be made to study failures progressing across slopes.

CONCLUSIONS

Analysis of strength measurements by considering a static force-balance model, combined with a statistical model of failure probability, has shown that the spatial variability of snow strength should be an important consideration when assessing the stability of a snow-pack (Conway and Abrahamson, in press). The proposed simple field test is derived from this work and is a test for failure progression rather than one for an initial failure. The test is easily and quickly made and, with experience, should yield unequivocal information about the stability of slopes likely to be triggered by skiers.

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