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Stress measurements from common snow slope stability tests

Scott Thumlert *, Bruce Jamieson

Department of Civil Engineering, University of Calgary, Calgary, Alberta, Canada

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ABSTRACT

In the majority of fatal snow avalanches, skiers and snowmobilers trigger the avalanche by applying load to the snow cover. The snow cover is often tested to learn information about its stability on surrounding slopes. This testing is normally performed by digging down into the snow cover, isolating a column of snow, dynamically loading the top of the column and observing fractures that occur in the column due to the loading. Understanding how stress from dynamic surface loads and from loading in common stability tests transmit through the snow cover can help people avoid situations in which they can trigger avalanches. Capacitive sensors were used within the mountain snow cover to measure peak stress below dynamic surface loads and in common stability tests. The sensors were used on 21 field days to collect over 1,605 measurements. We present measured stress data illustrating the effect of isolating a column in stability tests compared to skiing and snowmobiling over a largely undisturbed snow cover. We observed that adjusting the depth of stability tests to account for the penetration depth of snowmobiles loads the snow cover more similarly to the loading applied by snowmobiling. We found that the stress profile in stability tests more closely matched skiing and snowmobiling when the snow cover was softer compared to when the snow cover was harder. Similarly, the differences between the skier and snowmobile loading compared to the stability test loading were increased for a harder snow cover. Finally, in the Extended Column Test, a modern stability test, stress was only measured directly below the loading and not on the opposite side of the column.

1. Introduction

Most snow avalanche fatalities result from people triggering the avalanches themselves (Harvey et al., 2012; Jamieson et al., 2010; Tremper, 2008). Backcountry skiing, snowmobiling, snowboarding, etc., result in localized dynamic loading (LDL) applied to the snow cover, which can initiate failures in weak layers and possibly trigger avalanches. Jamieson et al. (2010) showed that individuals on foot or snowmobiles rarely initiate failures in layers deeper than 100 cm. The transmission of stress below LDL through the mountain snow cover is much more complicated than that in continuous materials as snow is a porous layered material. Energy and momentum are transferred away from the LDL in the form of waves, or in the case of a single loading event, a pulse. Various types of particle motion develop beneath the LDL as the pulse passes:

Primary motion—this is motion parallel to the propagation direction causing stretching or compressing of the material (P-motion)

Secondary motion—this is motion perpendicular to the propagation direction of the wavefront. Sometimes called the "shear wave" (S-motion).

Surface waves (Rayleigh and Love)—the interaction of P-motion and S-motion with a free surface causes the formation of surface waves.

Biot (1956) developed a theory for stress wave propagation in porous materials based on the coupling of stress waves in the skeleton and air space. Johnson (1982) and Albert (1993) have applied Biot's theory to the mountain snow cover and their results imply that three main waves develop beneath LDL: a P-wave and an S-wave in the ice skeleton and a slower P-wave in the air space. The complicated interaction between these waves in the air space and the ice skeleton leads to rapid scattering and attenuation. The interaction of LDL and the snow cover results in plastic deformation of the surface layers followed by an elastic stress pulse consisting of P-wave and S-wave motions in the ice skeleton and a P-wave in the pore space. The mechanics are further complicated by the non-homogeneous nature of a layered snow cover. Stress pulses interact with layers of varying density, crystal shape, and bonding regime. Thus, the complicated nature of stress transmission through the mountain cover results in large uncertainty when analyzed theoretically.

Despite the challenges in understanding the interaction between LDL on the snow cover, finite element modeling and buried load sensors have been used to show some important concepts. Schweizer (1993) used finite element modeling to show how stiffer layers concentrate stress from localized loading and also form "sort of a bridge," which

* Corresponding author.
E-mail address: thumlert@ucalgary.ca (S. Thumlert).

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reduced how deep the stress would penetrate the snow cover. More recently, Jones et al. (2006) and Habermann et al. (2008) used finite element modeling to investigate the static stresses in a layered snow cover. Their work showed that stiffer layers reduce stress at a given depth in the snow cover and concentrate stress, specifically for soft-over-hard interfaces (greater stiffness below).

Load cells buried in the snow have been used to measure the dynamic stresses induced by skiers (Camponovo and Schweizer, 1997; Schweizer et al., 1995a,b; Thumlert et al., 2013). Results from these studies confirmed that stress decreases with depth, hard layers caused a bridging effect by distributing the stress over a larger area and that dynamic loading imparts more stress than static loading. Schweizer and Camponovo (2001) used the same load cells as in their 1997 (Camponovo and Schweizer, 1997) study to measure the skier's zone of influence, defined as the area where a skier is capable of initiating fractures in weak layers. It was found to be relatively small, approximately 0.3–0.5 m^2, for depths relevant to skier triggering. These data supported, in accordance with the earlier finite element calculations, the theory that skiers are able to trigger slab avalanches by directly initiating a brittle fracture within a weak layer or interface. Thumlert et al. (2013) compared the dynamic stress induced into the snow cover by snowmobiles and skiers. They found that the increased penetration of snowmobiles compared to skiers was the main factor contributing to greater added stress by snowmobiles at specific depths.

Modern snow slope stability tests are used to assess the semi-quantitative stability of the snow cover on a given slope. Common tests, such as the Compression Test (Jamieson, 1999; Jamieson and Johnston, 1997), the Extended Column Test (Simenhois and Birkeland, 2006), and the Rutschblock test (Föhn, 1987), involve dynamic surface loading of an *isolated column* of snow. These tests load the column with hand-on-shovel tapping or with skis which results in variation in the applied loading. To overcome some of this human induced variation, the Drop Hammer Test (Stewart, 2002) and the Stuffblock Test (Birekland and Johnson, 1999) were developed and used in scientific studies. The Drop Hammer Test is very similar to the Compression Test because both involve repeatedly loading an isolated column. The difference is that the loading is applied by dropping a specific weight from a fixed height as opposed to tapping with one's hand. Column isolation changes the configuration of the snow cover compared undisturbed snow that is loaded by skiing or snowmobiling. The stress from surface loading above an isolated column focuses the stress to the isolated column and prevents lateral dispersion outside the column.

It is unknown how the stress beneath LDL, such as skiing and snowmobiling, relates to stress applied in isolated column stability tests. In this paper, we present the first stress measurements from common stability tests and LDL performed on the same snow cover. We show stress measurements from standard Compression Tests, adjusted depth Compression Tests, Extended Column Tests, and Drop Hammer Tests. These measurements are related to stress measurements from skiing and snowmobiling.

2. Methods

2.1. General experimental procedure for field measurements

To investigate the additional stress applied to a mountain snow cover in isolated column stability tests and by human-induced LDL, we used single point capacitive sensors. Measurements were performed in the Columbia mountains near Blue River, British Columbia, Canada, in the winters of 2012, 2013, and 2014. The data from the C-500 sensors made by Pressure Profile Systems were recorded with a Campbell Scientific CR5000 data logger at approximately 160 Hz for the skiing and snowmobiling measurements and with a Campbell Scientific CR1000 data logger at approximately 105 Hz for the stability test measurements. The sensors can reliably measure to 0.1 kPa, which is limited by noise in the signal and the signal processing methods.

The experimental procedure involved digging into the snow cover and performing a manual snow profile, including density measurements for layers thicker than 4 cm (Canadian Avalanche Association, 2007). The snow profile was used to quantify the snow cover stratigraphy for the area of the experiments. The experiments were performed on sloped terrain ranging between 16° and 33°. The snow cover was mostly undisturbed soft snow on the surface with harder layers composed of rounded grains below (Fierz et al., 2009). The sensors were then inserted into the snow cover through an exposed wall in the profile. Dynamic loading was applied to the surface of the snow cover while the sensors recorded stress in the underlying snow.

To obtain a stress measurement for each LDL over the individual sensor, the difference between the baseline quasi-static stress measurement per sensor (before arrival of the dynamic load) and the peak stress recorded for the dynamic load was extracted. This ensured that only the additional stress due to the LDL was measured and not the initial compression on the sensors from insertion into the snow cover.

2.2. Skiing and snowmobiling measurements

For the skiing and snowmobiling measurements, the sensors were mounted on narrow aluminum sheets and inserted 1 m into one of the sidewalls of the snow pit. We used between six and ten sensors per pass of the LDL, depending on equipment functionality. The sensors were angled so that they recorded slope normal

Fig. 1. Skier performing an experiment loading the snow surface above the buried sensors.

(compressive) stress. The loading was performed on the snow surface by either of the following:

1) skier sliding straight downhill pushing down with their legs over the sensors to simulate the increase in loading during a typical ski turn (Fig. 1)
2) snowmobile driving uphill over the sensors

2.3. Drop hammer measurements

The drop hammer instrument used was similar to the Rammrutsch device used by Schweizer et al. (1995a) except with a smaller base plate (Stewart, 2002). The drop hammer equipment consisted of a 30 cm × 30 cm × 1 cm stiff base plate with a 15 cm diameter × 1 cm thick stainless steel striking plate bolted to the base plate. A 60 cm guide rod was fixed perpendicular to the centre of the striking plate, which directed a 3 kg brass weight to impact the striking plate. The drop hammer was used as reference for loading because of its repeatability.

Two types of experiments were performed with the drop hammer device; isolated column and not isolated. The first involved loading (10 hammer drops from 60 cm) the top of a 30 cm × 30 cm × 120 cm deep column of snow with stress sensors inserted at two different depths in the column. One sensor was always inserted at 40 cm deep and the other sensor was inserted at 60 cm, 80 cm, or 100 cm. The sensors were inserted 15 cm laterally into the column wall but offset along the slope so that any interference on the stress pulse from the higher sensor was reduced for the lower sensor. The experiment was repeated three times until stress measurements were recorded at all four depths.

The second experiment involved loading a less disturbed snow cover (not isolated). Only the front wall of the snow profile was exposed with undisturbed sides and back around the drop hammer. The sensors were inserted at similar depths to the isolated column experiments and measurements were acquired for all four depths (40 cm, 60 cm, 80 cm, and 100 cm). In both experiment types, the sensors were oriented parallel to the slope so that they recorded slope normal (compressive) stress. Fig. 2 shows the two different drop hammer experiments being performed.

Fig. 2. The drop hammer test experiments being performed. The top shows the test configuration where the column is isolated, whereas the bottom shows the less disturbed snow cover test configuration.

2.4. Compression Test and adjusted Compression Test measurements

The stress measurements from Compression Tests were done similarly to the Drop Hammer Tests. The Compression Tests were performed according to Canadian Avalanche Association (2007) with a sensor inserted at 40 cm below the surface and either 60 cm, 80 cm or 100 cm below the surface. The loading in the Compression Tests was performed by manual hand-on-shovel tapping on top of the isolated column. Thirty taps were performed in increasing force: 10 “easy” taps using the finger tips, then 10 “moderate” taps initiated from the elbow and finally 10 “hard” taps initiated from the shoulder. The data presented in this paper are measurements from the “hard” taps. Compression of the soft upper layers of the snow cover occurred during the tapping.

The adjusted depth Compression Test measurements were performed in a manner analogous to the Compression Test, except that the average penetration depth of the snowmobile, as measured in the field, was removed from the top of the 30 cm × 30 cm column. The column was isolated deeper into the snow cover by this same distance. For example, if the average penetration of the snowmobile into the snow cover was 40 cm, then 40 cm would be removed from the top of the 30 cm × 30 cm column, and the column would be dug 40 cm deeper. Sensors were again inserted at depths 40 cm, 60 cm, 80 cm, and 100 cm from the original surface of the snow unless the penetration depth was more than 40 cm in which case the 40 cm stress measurements were not recorded. The adjusted depth Compression Test measurements presented in this study were performed on days where skiing, snowmobiling and regular Compression Test measurements were also performed.

2.5. Extended Column Test measurements

The Extended Column Test (Simenhois and Birkeland, 2009; Simenhois and Birkeland, 2006) experiments were performed similarly to the above experiments. The Extended Column Test involves the isolation of a 90 cm across slope × 30 cm upslope × 120 cm deep column of snow, which is then loaded on one end of the rectangular surface by the same hand-on-shovel tapping as the Compression Test (Fig. 3). Stress measurements were recorded at depths of 40 cm, 60 cm, and 80 cm directly under the side of the column being loaded and at 60 cm depth on the side opposite to the loading.

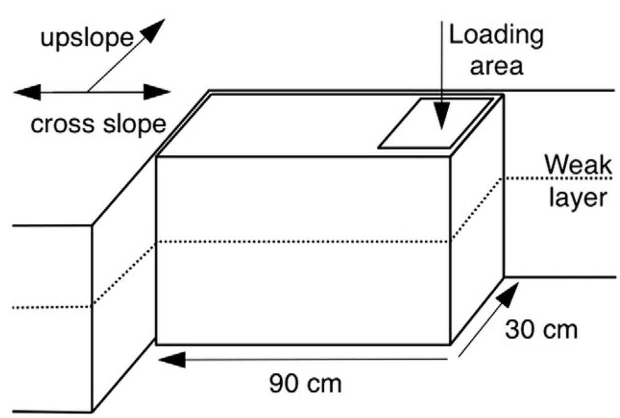

Fig. 3. The preparation of the ECT involves isolating a column 90 cm across the slope by 30 cm upslope. The column is then loaded from one side using the same technique as the compression test. Adapted from Simenhois and Birkeland (2006) and Simenhois and Birkeland (2009).

2.6. Visualization of field stress measurements

To visualize the impact from skiing, snowmobiling and stability test loading, the dynamic stress measurements were coupled with calculated static stress. The data displayed in the stress contour plots (Figs. 5 through 11) start with calculated stress values (σ_z). for any point below the LDL calculated from the well-known Boussinesq equations (Das, 1985) with the LDL approximated by an infinite strip load on the surface of a semi-infinite elastic mass:

$$\sigma_z = \frac{q_{\text{nor}}}{\pi}\left[\tan^{-1}\frac{z}{x-b} - \tan^{-1}\frac{z}{x+b} - \frac{2bz\left(x^2-z^2-b^2\right)}{\left(x^2+z^2-b^2\right)^2+4b^2z^2}\right] + \left[\frac{4bq_{\text{par}}xz^2}{\pi\left[\left(x^2+z^2-b^2\right)^2+4b^2z^2\right]}\right] \quad (1)$$

where q_{nor} was the component of load normal to snow surface defined for a 38° slope, q_{par} was the component of load parallel to snow surface defined for a 38° slope, b was half the width of the surface loading strip, x was the slope parallel coordinate and z was the slope normal coordinate as defined in Fig. 4.

We extracted the median stress values for each depth in which measurements were made for each type of loading experiment. The calculated values from Eq. (1) were scaled so that they approximated the median measured stress values. A power law smoothing function was applied to the scaling factors to create smooth transitions between the medians. Note that the data displayed in Figs. 5–11 are based on calculations that assume a homogeneous, elastic, and isotropic snow cover.

3. Data

We analyzed 1,605 measured localized loading events by skiing, snowmobiling, or from stability tests on 21 different field days. The data presented include 121 measurements of peak compressive stress from Extended Column Tests, 582 from Drop Hammer Tests, 330 from standard Compression Tests, 273 from adjusted depth Compression Tests, 128 from skiing, and 164 from snowmobiling. We measured and analyzed the vertical depth of each sensor below the undisturbed surface of snow, type of LDL (e.g., skier, snowmobile, stability test), penetration depth of trigger into the snow cover, effective depth (defined as penetration depth subtracted from depth of sensor), snow cover density, and snow cover hand hardness (Fierz et al., 2009). Table 1 describes the characteristics of the data set.

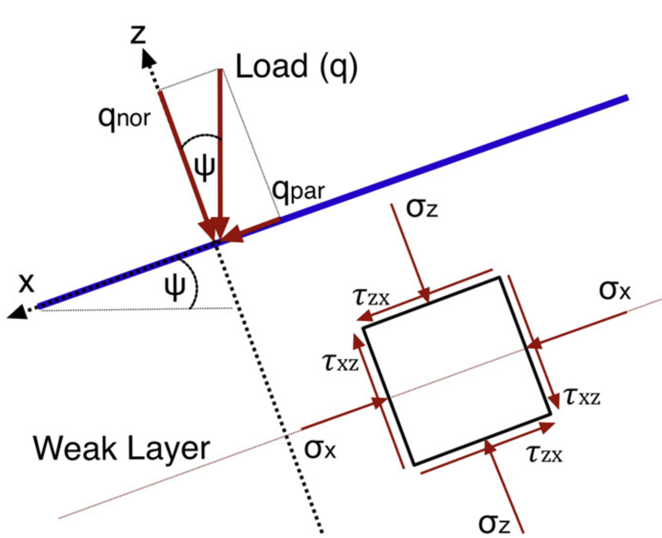

Fig. 4. Definition of stress components.

4. Results

4.1. Effect of isolating column

Isolating a column in the snow cover confined the stress from the loading to the column and the stress reached deeper into the snow cover compared to skier or snowmobile loading (Figs. 5–10). At 40 cm depth, Fig. 5 shows no significant difference between a median value of 2.34 kPa for 60 data in the Compression Test measurements (a) compared to the median value of 2.38 kPa for 32 data for the skier measurements (b) (Mann–Whitney $p = 0.67$). However, deeper into the snow cover at 80 cm depth, Fig. 5 shows a median value 0.82 kPa for 26 data from the Compression Test measurements (a) compared to the median of 0.45 kPa for 143 data from the skier measurements (b) (Mann–Whitney $p < 10^{-4}$). The similar stress levels measured at 40 cm have attenuated more in the undisturbed snow cover beneath the skier compared to the isolated column in the Compression Test. This result is also shown when observing similar applied stress at 40 cm attenuating more by 80 cm in the undisturbed snow in Fig. 5(c) and (d) as well as in Figs. 6 and 7. This result of similar applied stress attenuating more in undisturbed snow compared to the isolated columns is also observed in the drop hammer experiment data displayed in Figs. 8, 9 and 10.

The data in Fig. 5 were fit with a power law using the non-linear least squares method (Bates and Chambers, 1992) according to the following equation:

$$\sigma = (a * \text{Depth})^b \quad (2)$$

with $\sigma =$ measured normal stress, and the constants a and b evaluated by the function. The fitted equations were as follows:

- CT data: $\sigma = (-0.012 * \text{Depth})^{-1.4}$, $R^2 = 0.34$, $n = 330$.
- skier data: $\sigma = (-0.012 * \text{Depth})^{-1.2}$, $R^2 = 0.22$, $n = 128$.
- adjusted depth CT: $\sigma = (-0.007 * \text{Depth})^{-1.4}$, $R^2 = 0.33$, $n = 273$.
- snowmobile: $\sigma = (-0.009 * \text{Depth})^{-1.7}$, $R^2 = 0.30$, $n = 168$.

A more subtle effect from column isolation is observed in the drop hammer experiment data when comparing a harder snow cover (Fig. 9) to a softer one (Fig. 10). The harder snow cover (Fig. 9) attenuates the applied stress more than the softer snow cover (Fig. 10) shown in the not isolated tests. At a depth of 40 cm, we see a median measured stress of 0.56 kPa for 30 data (Fig. 9b) compared to a median of 2.35 kPa for 18 data (Fig. 10b) (Mann–Whitney $p < 10^{-7}$). This result was consistent for the deeper measurements at 60 cm. The opposite effect is observed in the isolated column data. The harder snow cover (Fig. 9a) is more effective at transmitting the applied stress deeper into the snow cover compared to the softer snow cover (Fig. 10a). At 40 cm into the harder snow cover, the median stress is 2.99 kPa for 27 data (Fig. 9a) compared to a median of 1.44 kPa for 5 data (Fig. 10a) (Mann–Whitney $p = 0.025$). This result was also observed in the deeper measurements at 60 cm and 80 cm. Thus, we observe a greater difference between isolated and not isolated loading on a harder snow cover compared to a softer snow cover. At 40 cm, the harder snow cover had a median isolated column stress of 2.99 kPa, and a median not isolated stress of only 0.56 kPa, a difference of 2.43 kPa. However, at 40 cm, the softer snow cover had a median isolated stress of 1.44 kPa, and a median not isolated stress of 2.35 kPa, a difference of −0.91 kPa. This exaggerated difference of applied stress at specific depths between hard and soft snow covers is also shown in the grouped drop hammer data from many days of experiments (Fig. 8).

The exaggerated difference of applied stress between hard and soft snow referenced above was also observed in Compression Test and skiing measurements (Figs. 6 and 7). The data in Fig. 6 were measured from an earlier season day in January with a softer profile, and Fig. 7 shows data from a more settled snow cover in March with a hard thicker

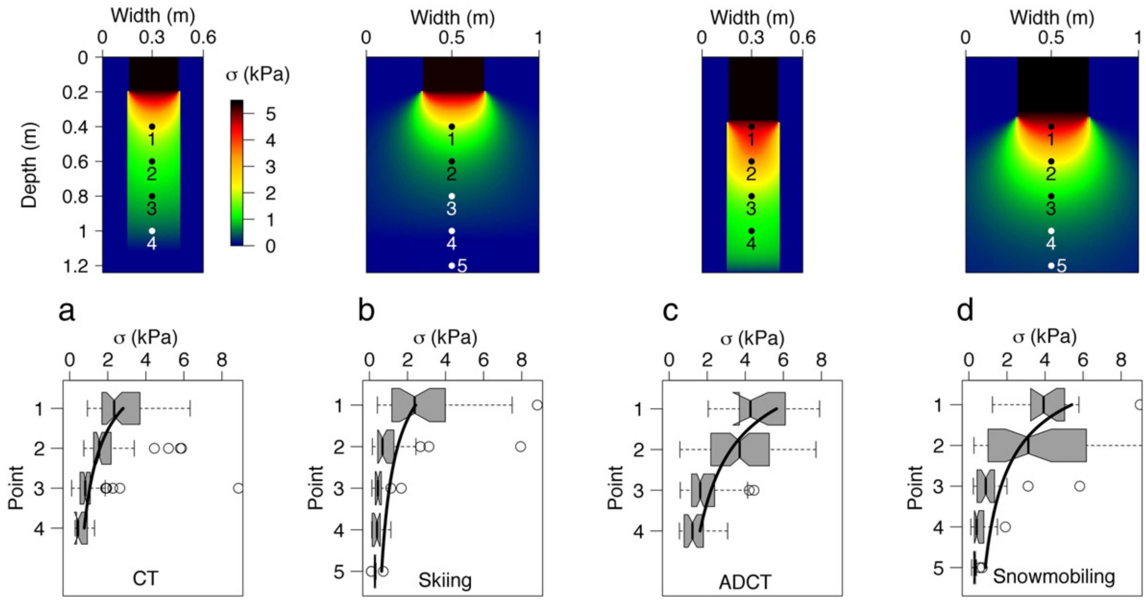

Fig. 5. Visualizations and box plots of (a) the loading of the isolated column in compression tests (CT), (b) skiing, (c) the loading of the isolated column in the adjusted depth compression tests (ADCT), and (d) snowmobiling. Boxes span the interquartile range. Whiskers extend to the data point closest to 1.5 times the interquartile range. Open circles indicate outliers. The stress bulbs observed are calculated normal stress values for the loading of an elastic homogeneous snow cover. The values were calibrated to match measured displayed in the box plots. The data presented are from multiple days of experiments. The curved lines indicate the fitted models.

crust layer near the surface. Fig. 6 (softer snow) at 60 cm shows similar median stress of 1.44 kPa for 6 skier data compared to the median stress of 1.15 kPa from 7 Compression Test data, a difference of 0.29 kPa (Mann–Whitney $p = 1$). However, Fig. 7 (harder snow) at 60 cm shows a median stress of 0.69 kPa for 3 skier data compared to median stress of 2.1 kPa for 2 Compression Test data, a difference of 1.41 kPa (Mann–Whitney $p = 0.2$). Thus, these differences between median applied stress from the Compression Test and skier measurements suggest that there is a greater difference on the day with the harder snow cover (Fig. 6) compared to the day with the softer snow cover (Fig. 7). This result is not statistically significant due to the small sample sizes but is presented to support the results from the drop hammer experiments and because it is expected due to the increased attenuation of stress from harder snow.

4.2. Effect of deeper stability tests

The stress measurements shown in Fig. 5 show more stress at specific depths for the adjusted depth Compression Tests compared to the standard Compression Tests. The data observed in Fig. 5 from many different experiment days shows a median stress of 2.34 kPa for 60 data at 40 cm for the Compression Test measurements (a) compared to median stress of 5.54 kPa for 17 data from the adjusted depth Compression Test

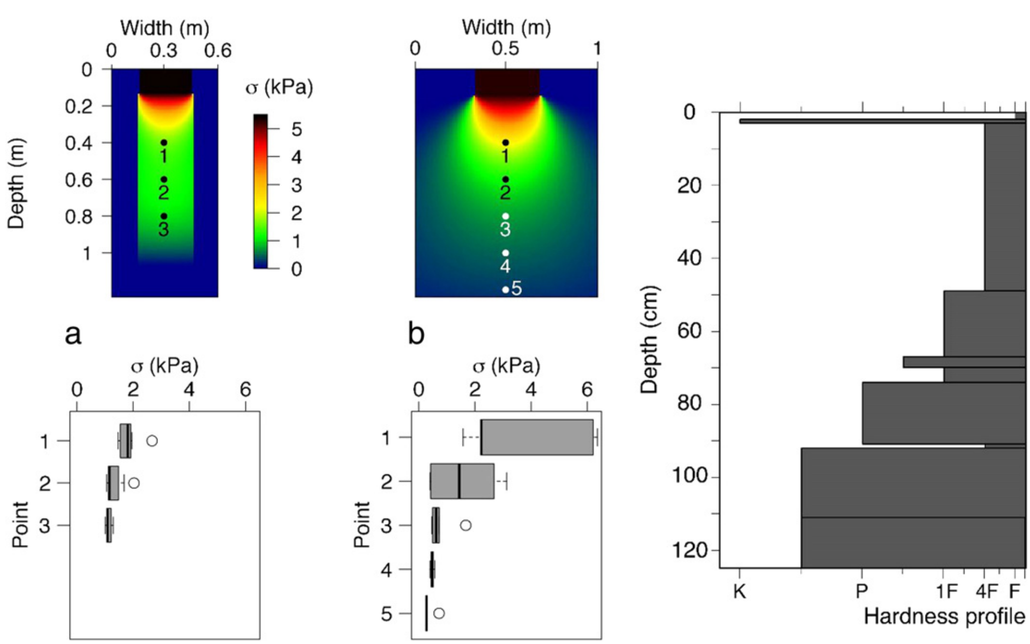

Fig. 6. Visualizations and box plots of (a) the loading of the isolated column in compression tests and (b) skiing. Data presented are only from January 4, 2012, are shown. The hand hardness profile is shown on the right of the visualizations and box plots.

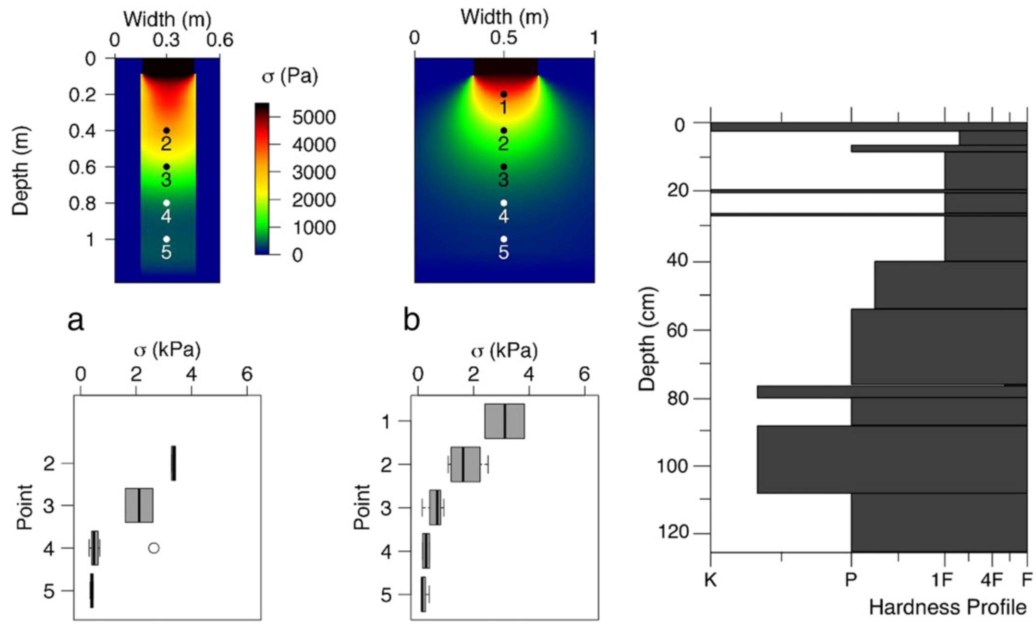

Fig. 7. Same as Fig. 6, but with data from March 26, 2012.

(c) (Mann–Whitney $p < 10^{-7}$). This result is consistent for deeper depths into the snow cover where we performed measurements.

Snowmobiles applied more stress down to depths of 60 cm into the snow cover than the Compression Test, but the measured stress was more similar at depths of 80 cm and 100 cm (Fig. 5). At 40 cm depth in Fig. 5, we observe median stress of 3.92 kPa for 17 snowmobiling data (d) compared to 2.34 kPa for 60 Compression Test data (a) (Mann–Whitney $p = 0.001$). This result is consistent at 60 cm into the snow cover (Mann–Whitney $p = 0.003$), but at 80 cm and 100 cm, the stress levels are more similar. At 80 cm into the snow cover, we observe a median stress of 0.89 kPa for snowmobiling compared to 0.82 kPa for the Compression Test (Mann–Whitney $p = 0.72$).

Adjusting the depth of the Compression Test to account for snowmobile penetration resulted in more stress applied to the snow cover than snowmobiling at depths deeper than 60 cm and similar stress at shallower depths (Figs. 5–7). At 40 cm into the snow cover, we observe a median stress of 3.92 kPa for 17 snowmobiling data (Fig. 5d) compared to 5.54 kPa for 17 adjusted depth Compression Test data (Fig. 5c) (Mann–Whitney $p = 0.54$). Similarly, at 60 cm, we observe median stress of 3.12 kPa for 46 snowmobiling data compared to 3.70 kPa for 97 adjusted depth Compression Test data (Mann–Whitney $p = 0.33$). At 80 cm into the snow cover, we observe median stress of 0.89 kPa (Fig. 5d) for 38 snowmobiling data compared to 1.63 kPa (Fig. 5c) for 113 adjusted depth Compression Test data (Mann–Whitney

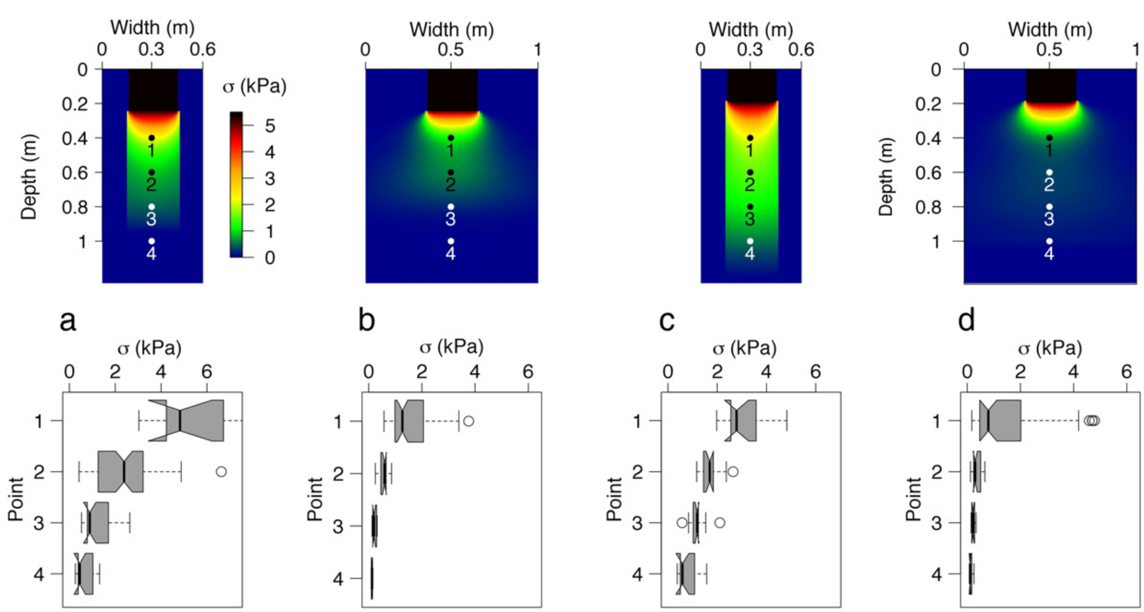

Fig. 8. Similar to Fig. 5, but grouped data from the drop hammer experiments on multiple days are shown. (a) Data from the isolated column configuration (4 side walls) for days classified as having a softer snow cover are shown. (b) Data from the same softer snow cover profile days, but from the unisolated snow cover test configuration (1 side wall) are shown. (c) Data from the isolated column configuration for days classified as having a harder snow cover are shown. (d) Data from the same harder snow cover profile days, but from the unisolated snow cover test configuration are shown.

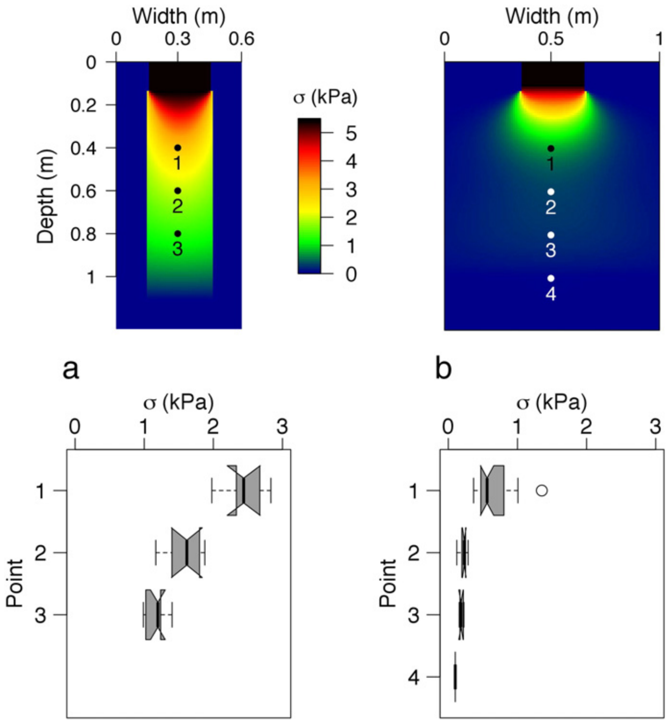

Fig. 9. Same as Fig. 8, but with data from February 3, 2014.

$p < 10^{-7}$). Finally, at 100 cm, we see median stress of 0.41 kPa for 46 snowmobiling data compared to 1.22 kPa for 46 adjusted depth Compression Test data (Mann–Whitney $p < 10^{-7}$).

The adjusted depth Compression Test resulted in more stress applied to the snow cover at all measured depths compared to skiing (Fig. 5). At 40 cm into the snow cover, we observe median stress of 2.38 kPa for 32 skier data compared to 5.54 kPa for 17 adjusted depth Compression Test data (Mann–Whitney $p < 10^{-7}$). This result

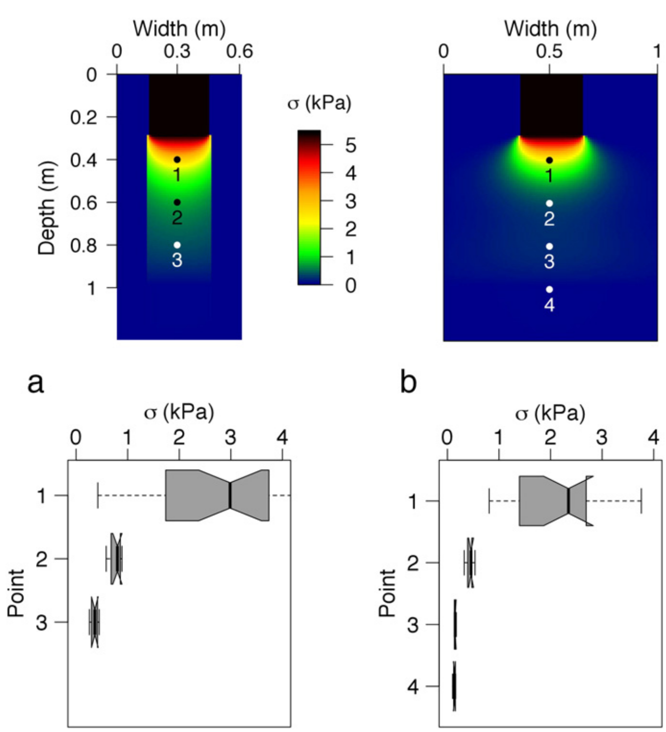

Fig. 10. Same as Fig. 8, but with data from January 24, 2013.

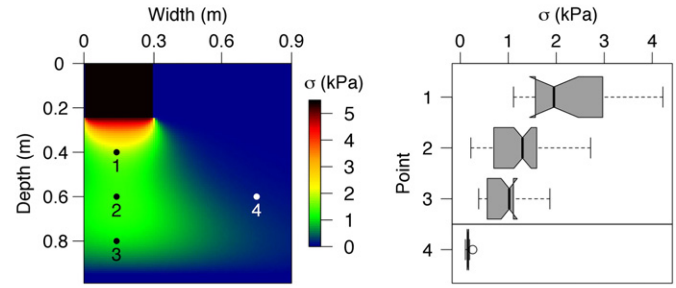

Fig. 11. Similar to Fig. 5, but measured stress data from the extended column test are shown.

is consistent for all measured depths shown in Fig. 5 as well as in the data shown in Figs. 6 and 7.

4.3. Extended Column Test

Fig. 11 shows stress measurements from within the 30 cm × 90 cm column of an Extended Column Test. Median stress values from directly below the hard tapping were 1.95 kPa, 1.30 kPa, and 1.02 kPa for depths 40 cm, 60 cm, and 80 cm, respectively. The sensors placed at the opposite end of the column from the loading did not record measurable stress (depth 60 cm).

5. Discussion

5.1. Column isolation

Correlating the results from stability tests to natural and human triggered avalanche activity has received much attention from practitioners and researchers (e.g., Schweizer and Jamieson, 2010; Simenhois and Birkeland, 2009; van Herwijnen and Jamieson, 2007a; Winkler and Schweizer, 2008). The importance of accurate interpretation and appropriate application of the information provided from point slope stability testing is critical for reducing the risk associated with snow avalanches. The effect of isolated columns on stress transmission in slope stability testing focused the stress and generally allowed it penetrate deeper in the snow cover (Figs. 5 through 10).

The unmodified Boussinesq equations used to create Figs. 5–11 show a decrease of stress proportional to *1*/depth based on assumptions

Table 1
Descriptive statistics of stress measurements. "Effective depth" is the depth of the sensor from the surface of the snow minus the penetration of the skier/snowmobile. Penetration depth shows data from both skiers and snowmobiles. "ECT" stands for Extended Column Test. "DH" stands for Drop Hammer Test. "Deep Compression Test" is the compression test that was adjusted for depth of snowmobile penetration. *n* indicates the sample size of the data.

	Median	Min	1st quartile	3rd quartile	Max	*n*
Depth (cm)	60	20	40	80	120	1605
Effective depth (cm)	40	0	20	60	111	1605
Penetration depth (cm)	20	0	0	30	60	1605
Slope angle (°)	24	16	21	26	33	1605
Hand hardness above sensors	1F	F-	4F	1F+	P+	21
Density above sensors (kg/m^3)	172	80	151	192	300	21
ECT stress (kPa)	1.1	0.1	0.6	1.6	5.8	121
DH stress (kPa)	0.7	0.1	0.3	1.2	3.8	338
Isolated DH stress (kPa)	1.5	0.3	1.0	2.6	10.8	244
Compression Test stress (kPa)	1.2	0.1	0.8	1.9	8.9	330
Deep compression test (kPa)	2.2	0.5	1.3	3.7	12.0	273
Skier stress (kPa)	0.7	0.1	0.4	1.5	11.2	128
Snowmobile stress (kPa)	0.9	0.1	0.4	2.5	12.7	164

of an elastic semi-infinite mass. The calibrated Boussinesq stress fields that show the field measurements (Fig. 5) show the decrease of stress proportional to approximately $1/\text{depth}^{-1.5}$. We postulate that the reason for this increased dissipation of stress compared to the model to be the viscoelastic response of the snow cover to the loading and due to snow being a porous material. The fitted models from Fig. 5 are in the expected range compared to previous experimental results (Schweizer and Camponovo, 2001; Thumlert and Jamieson, 2014; Thumlert et al., 2013).

The data showed that harder snow covers increased the difference between the stress profiles from skiing and isolated column tests (Figs. 6, 7). This exaggerated stress profile difference between isolated columns and undisturbed snow cover was also observed in the drop hammer experiments (Figs. 8–10). Avalanche practitioners in Canada have observed situations where sudden fractures, often associated with avalanching (van Herwijnen and Jamieson, 2007b), occur in stability tests below hard layers, but no avalanches occur nearby on the same layer (S. Davis, 2013, personal communication). This observation is supported by the greater stress differences for harder snow between the isolated column tests and the less disturbed snow (Figs. 6–10). The harder not isolated snow cover was more effective at spreading out the stress under LDL, thus reducing the depths to which it penetrated. However, the harder snow cover was also more effective at transmitting stress deeper into the snow cover in the isolated column stability tests (Figs. 6–10).

5.2. Deeper stability tests

The importance of penetration depth into the snow cover by the skier on applied stress, and thus slope stability, has been recognized (Camponovo and Schweizer, 1997; Jamieson and Johnston, 1998). Further, Thumlert et al. (2013) showed that the penetration depth while snowmobiling was the main factor for increased stress being added to the snow cover compared with skiing. The data presented here showed that adjusting the isolated column stability tests for deeper triggers (i.e., snowmobiling) applied more stress to the snow cover than the simplified skier and snowmobile loading performed in the experiments. We must clearly understand the limitations of the loading experiments. In the experiments, the skier loading was performed by a single skier sliding downhill in a straight line with a knee push over the buried sensors, and the snowmobile loading was performed by driving the snowmobile straight uphill over the buried sensors. Clearly much more stress is applied to the snow cover in a typical day of skiing or snowmobiling. Further, the spatial variations of the snow cover across the mountainous terrain results in areas of thin and thick slab above a weak layer. Thus, performing an isolated column stability test in a thick area may yield results implying a more stable snow cover compared to a test performed where the slab is thin. Therefore, the greater stress applied at given depths in stability tests adjusted for penetration depth may favor more cautious interpretation of snow stability testing.

5.3. Extended Column Test

The results from the Extended Column Test showed no measurable stress down 60 cm on the end of the 90 cm column away from the tapping (Fig. 11). This is in agreement with van Herwijnen and Birkeland (2014), who used particle tracking to measure snow displacement during Extended Column Tests. They showed no observable displacement from tapping on the opposite end of the column. These results support the theory that fractures initiated in the Extended Column Test result from a sudden fracture and not from progressive accumulation of damage in the weak layer.

6. Conclusions

Measurements of stress beneath localized dynamic loads (skiers and snowmobiles) and from common isolated column stability tests were performed within a variety of mountain snow covers. The effect of loading isolated columns when performing common stability tests compared to the dynamic loading of an undisturbed snow cover by skiing and snowmobiling was shown to concentrate stress and allow it to penetrate deeper into the snow cover. Adjusting the depth of the Compression Test to account for the penetration depth of snowmobiles stressed the snow cover similarly to the loading applied by snowmobiling. A more similar stress profile occurred in stability tests for skiing and snowmobiling when the snow cover was softer compared to when the snow cover was harder. The differences in stress under skiers and snowmobiles compared to stability tests were exaggerated when the snow cover was harder. Stress was only measurable directly below the loading (tapping) in the Extended Column Test and not on the opposite side of the column.

How can an avalanche practitioner use and interpret the results presented in this paper? Penetration depth has been proven to be very important for how deep specific stress levels penetrate into the snow cover. Therefore, adjusting the depth of stability tests to account for ski or snowmobile penetration should produce more accurate results when forecasting slope stability specifically for skier/snowmobile loading. The results in Fig. 5 support this. Further, harder snow covers exaggerated the difference in applied stress at specific depths for isolated column tests and skiing or snowmobiling on an undisturbed snow cover (Figs. 6, 7, 9, and 10). Therefore, there may be situations where results from isolated column stability test indicate slopes are prime for triggering, but in fact, the stress from skiing does not affect the weak layer. Accounting for these concepts when interpreting the results from stability tests can improve the application of the data provided from the testing.

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References

Albert, D., 1993. Attenuation of outdoor sound propagation levels by a snow cover. Cold Regions Research and Engineering Laboratory Report, p. 93-20.
Bates, D., Chambers, J., 1992. Nonlinear models. Chapter 10 In: Chambers, J.M., Hastie, T.J. (Eds.), Statistical Models. Wadsworth & Brooks/Cole.
Biot, M., 1956. Theory of propagation of elastic waves in a fluid-saturated porous solid. J. Acoust. Soc. Am. 28, 161–198.
Birekland, K., Johnson, R., 1999. The stuffblock snow stability test: comparability with the Rutschblock, usefulness in different snow climates, and repeatability between observers. Cold Reg. Sci. Technol. 30 (1–3), 115–123.
Camponovo, C., Schweizer, J., 1997. Measurements on skier triggering. Proceedings of the 1996 International Snow Science Workshop ISSW, Banff, Canada, 6–10 October 1996, pp. 100–103.
Canadian Avalanche Association, 2007. Observation Guidelines and Recording Standards for Weather, Snow Cover and Avalanches. Canadian Avalanche Association, Revelstoke, BC, Canada.
Das, B., 1985. Advanced Soil Mechanics, 3rd edition. McGraw Hill, pp. 87–111.

Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K., Sokratov, S.A., 2009. The International Classification for Seasonal Snow on the Ground. IHP-VII Technical Documents in Hydrology 83, IACS Contribution 1. UNESCO-IHP, Paris.

Föhn, P., 1987. The Rutschblock as a practical tool for slope stability evaluation. Int. Assoc. Hydrol. Sci. Publ. 162, 223–228.

Habermann, M., Schweizer, J., Jamieson, B., 2008. Influence of snow cover layering on human-triggered snow slab avalanche release. Cold Reg. Sci. Technol. 54 (3), 176–182.

Harvey, S., Rhyner, H., Schweizer, J., 2012. Lawinenkunde. Praxiswissen für Einsteiger und Profis zu Gefahren, Risiken und Strategien . Bruckmann Verlag GmbH, Muenchen, p. 192.

Jamieson, B., 1999. The Compression Test—after 25 years. Avalanche Rev. 18 (1), 10–12.

Jamieson, B., Johnston, C., 1997. The Compression Test for snow stability. Proceedings of the 1996 International Snow Science Workshop ISSW, Banff, Canada, 6–10 October 1996, pp. 118–125.

Jamieson, B., Johnston, C., 1998. Refinements to the stability index for skier-triggered dry-slab avalanches. Ann. Glaciol. 26, 296–302.

Jamieson, B., Haegeli, P., Gauthier, D., 2010. Avalanche Accidents in Canada, Volume 5: 1997–2007. Canadian Avalanche Association, Revelstoke, BC, Canada.

Johnson, J., 1982. On the application of Biot's theory to acoustic wave propagation in snow. Cold Reg. Sci. Technol. 6, 49–60.

Jones, A.S.T., Jamieson, J.B., Schweizer, J., 2006. The effect of slab and bed surface stiffness on the skier-induced shear stress in weak snow cover layers. International Snow Science Workshop, Telluride, CO, USA, 1–6 October 2006, pp. 157–164.

Schweizer, J., 1993. The Influence of the layered character of the snow cover on the triggering of slab avalanches. Ann. Glaciol. 18, 193–198.

Schweizer, J., Camponovo, C., 2001. The skier's zone of influence in triggering slab avalanches. Ann. Glaciol. 32, 314–320.

Schweizer, J., Jamieson, B., 2010. Snowpack tests for assessing snow-slope instability. Ann. Glaciol. 51, 187–194.

Schweizer, J., Schneebeli, M., Fierz, C., Föhn, P., 1995a. Snow mechanics and avalanche formation: field experiments on the dynamic response of the snow cover. Surv. Geophys. 16, 621–633.

Schweizer, J., Camponovo, C., Fierz, C., Föhn, P., 1995b. Skier triggered slab avalanche release—some practical implications. In: Sivardiére, F. (Ed.), Les apports de la recherché scientifique a la sécurité neige, glace et avalancheActes de Colloque, Chamonix 30 mai – 3 juin 1995. Association Nationale pour l`Étude de la Neige et des Avalanches (ANENA), Grenoble, pp. 309–315.

Simenhois, R., Birkeland, K., 2009. The Extended Column Test: test effectiveness, spatial variability, and comparison with the Propagation Saw Test. Cold Reg. Sci. Technol. 59, 210–216.

Simenhois, R., Birkeland, K., 2006. A field test for fracture initiation and propagation. Proceedings from the 2006 International Snow Science Workshop, Telluride, CO, pp. 79–85.

Stewart, K., 2002. Spatial Variability of Slab Stability within Avalanche Start Zones. (M.Sc. Thesis) University of Calgary, Calgary AB, Canada.

Thumlert, S., Jamieson, B., 2014. Stress measurements in the snow cover below localized dynamic loads. Cold Reg. Sci. Technol. 106–107, 28–35.

Thumlert, S., Exner, T., Jamieson, B., Bellaire, S., 2013. Measurements of localized dynamic loading in a mountain snowpack. Cold Reg. Sci. Technol. 85, 94–101.

Tremper, B., 2008. Staying Alive in Avalanche Terrain. The Mountaineers Books, Seattle, WA, USA.

van Herwijnen, A., Birkeland, K., 2014. Measurements of snow slab displacement in Extended Column Tests and comparison with Propagation Saw Tests. Cold Reg. Sci. Technol. 97, 97–103.

van Herwijnen, A., Jamieson, B., 2007a. Fracture character in Compression Tests. Cold Reg. Sci. Technol. 47, 60–68.

van Herwijnen, A., Jamieson, B., 2007b. Snowpack properties associated with fracture initiation and propagation resulting in skier-triggered dry snow slab avalanches. Cold Reg. Sci. Technol. 50, 13–22.

Winkler, K., Schweizer, J., 2008. Comparison of snow stability tests: Extended Column Test, Rutschblock test and Compression Test. Cold Reg. Sci. Technol. 59 (2–3), 217–226.