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1. Introduction

1.1 Motivation

Statistics for avalanche fatalities in the USA are recorded by the Colorado Avalanche Information Service (CAIC). Their results show that there has been a spike in avalanche-related deaths in unregulated back-country zones which began some two decades ago. "Prior to 1990, the number of avalanche deaths hovered well below 10 per year. Since then, avalanche deaths have averaged 24 annually but show an increasing trend, the 2011-12 total rose to 36." CAIC 2013. Similar results have been seen in Europe.

As equipment improves and extreme sports become more and more popular, the adventure of skiing outside the controlled ski areas is luring many more and often inexperienced skiers. Even experienced skiers can be killed after being caught in an avalanche as existing snow analysis methods take time, require testing equipment and lots of experience in reading the test results.

To ensure that even novice skiers can use the backcountry areas safely a new method to analyse the snow needs to be developed. It needs to be quicker, require less equipment and give easier to understand results. Measures should be taken to encourage all backcountry skiers to improve awareness in the community of dangerous slopes. Hopefully this will lead to a dramatic decrease in the annual list of fatalities.

1.2 Aims of Project

The aims of the project are:

- Analyse previous ideologies for analysing the strength of the snowpack
- Design and test a device which improves on previous work
- Ensure the device is accurate and reliable
- Formulate ideas to ensure easy and early visibility of results
- Formulate ideas to encourage community awareness of dangerous backcountry areas

2. Literature Review and Design Theory

2.1 Science of Slab Avalanches

The snowpack on a mountain will not always be isotropic. It forms when layers of snow falling at various times build up on the mountain or when more snow is blown across the mountain in snow drifts. These layers will not all have uniform strength, some layers can be significantly weaker than others. Slab avalanches occur when a connected weak layer, which can span an entire mountain face, shears. This allows a slab of the stronger snow above the failed layer to slide down the mountain. These weak layers are most commonly caused by depth hoar or a buried layer of surface hoar under new snowfall. The crystals of both these layers are feathery and form due to the difference in the ability of warm and cold air to hold water vapour. Colder air holds less water vapour which means that temperature gradients will create vapour pressure gradients. When water vapour is more pressurised in some areas than in others it will diffuse from the areas of high concentration to areas of low concentration across the pressure gradient.

While this temperature gradient persists, the ice sublimes from concavities on the snow crystals and condenses on convexities resulting in the formation of sharp needle like cones within the snowpack. The snow crystals will be changed from rounded, strong bonding crystals to faceted crystals which bond poorly to the rounded crystals, creating a weak layer. Condensation typically occurs at a single level within the snowpack creating a uniform layer which can be continuous across many acres. When these connected faceted crystals fail in shear or compression the entire layer across the mountain surface can fail. This transformation is a reversible process; removing the temperature gradient will turn needle like faceted crystal layers back into strong bonding round crystal layers, but this takes much more time. The high energy requirements to create faceted crystals are driven by the temperature gradient, which once removed causes the reverse diffusion to be much slower.

2.2 Depth Hoar

Commonly the ground under a layer of snow will remain warm due to the insulating effects of snow as long as it isn't in a permafrost area which occurs at very high elevations or in arctic latitudes. The air temperature will be cold, creating a strong temperature gradient and vapour pressure gradient across the snowpack. While this gradient persists a layer of faceted crystals will form as water vapour diffuses along the pressure gradient. This form of weak layer causes the most deaths as it is harder to observe its presence without historical weather data and digging out a snow pit.

2.3 Surface Hoar

At night when temperature drops, under a clear sky or even in areas of shade during the day, snow radiates away heat energy. The layer of air just above the snow surface will warm up creating a temperature gradient and a vapour pressure gradient, causing the water vapour to condense onto the snow surface. The higher the relative humidity of the air the more surface hoar can form, this means that areas near streams can be very susceptible to this type of weak layer forming. Wind blowing over the surface can sublimate the layers away; this causes patchy areas where wind has more effects than others across the surface, creating difficulties in detecting surface hoar. Even worse, a very light breeze can encourage surface hoar with a steady supply of moisture.

2.4 Protection of Property and Infrastructure

The long term protection of property and infrastructure has required that both constructional and land-use measures are taken in mountainous regions. In a case study on the village of Galtür in Austria, Keiler (2004) showed that damage to property and infrastructure has been drastically decreased since the hazard mapping of the area which took place in 1986. The region was divided into areas where new buildings are prohibited and those where building can take place as long as suitable snow dams have been constructed. Snow damming constructions include a range of possible designs such as flexible snow nets or rigid steel frames. Their main goal is to prevent connected weak layers which could allow the mountain face to avalanche with the aim of allowing only much weaker avalanches to occur. They also act to slow down or to hold snow in place preventing it from rupturing. The problem is that these structures have to withstand very high dynamic pressures when avalanches occur, so need to be very strong and consequently expensive, often prohibitively so. The classification for absolutely no building is where the dynamic pressures would reach above 10kPa BMLF (1999). Obviously areas showing large pressures up to this point may need to be dealt with. Individual buildings can have built in reinforcements such as concrete damping walls but this offers no protection to the public or those outside the building. These hazard maps only really exist for towns, so individual skiers will need to be able to identify where is safe or unsafe to ski.

2.5 Backcountry Skiers

The adventure of going off the piste is becoming increasingly attractive, and with more newcomers coming to the sport it is essential that knowledge of how to ski there safely is improved. A skier's weight alone can cause a weak layer buried in the snow beneath them to shear. While not turning, the skier's mass is distributed across two skis heading into the snowpack. The force on the snow will be even greater if they are turning or stopping which requires much more effort from the skier.

Ski patrols monitor ski resorts and provide avalanche control in these areas. They will close off areas within the resort boundaries which are unsafe. Outside of the resorts there is no avalanche control but some bulletins will have been produced with information on areas where suspected weak layers are in existence. This snow can change with time so these are not always reliable and there is spatial variability across the regions, so skiers will need to check the constituents of the snowpack themselves.

Backcountry skiers analyse the snow through digging a snow pit followed by extra tests such as the column shear test or a compression test. This testing is time consuming and requires knowledge of other factors including the crystal structure of the layers. Without also bringing a thermometer to measure a temperature gradient the test will not tell the skier everything there is to know about the snow. In the hands of an expert these tests should give the skier a good overview of the snow properties but could be dangerous when performed by someone inexperienced. This project looks at ways to allow even an inexperienced novice to get a good indication for the safety of the slope to ski on.

2.6 Snow Pits

This test involves digging a pit into the snow surface with one perfectly flat wall. This wall then needs to be mapped out and the following readings are taken at 5cm intervals. First the skier measures the temperature at this point and then they tries to identify the type of crystal by inspection. Finally they perform the hand hardness test which involves judging how easy it is to insert various objects into the snow pack, starting with a closed fist. If this doesn't penetrate the snow the person should try three fingers, then one finger, on to a pencil then finally a blade. If the blade does not penetrate, the snow is classed as ice. Recording the hardness in this way allows the tester to build up a profile of the snow strength.

Approximations of the snow shear strength are provided in the Avalanche Handbook as follows:

Very Low	0-1	(kPa)	Fist
Low	1-10	(kPa)	Three Fingers
Medium	10-100	(kPa)	1 Finger
High	100-1000	(kPa)	Pencil
Very High	>1000	(kPa)	Blade

Table 1 - Approximate snow strength from hand hardness test

A snow pit of concern would contain a very weak layer between other much stronger layers

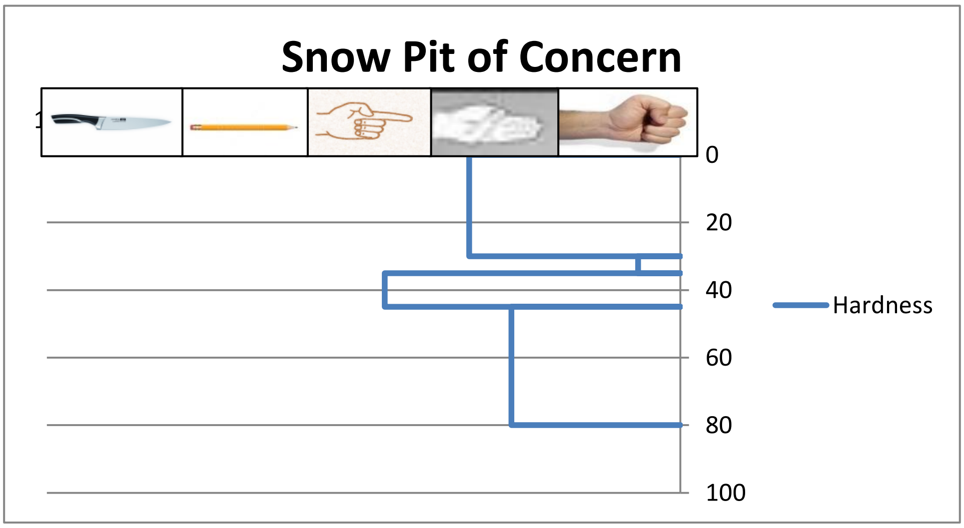


Figure 1 - Snow pit of concern

3. Previous Design Ideologies

Three methodologies from previous years for analysing the snowpack to give clearer results to the inexperienced novice were devices measuring the permeability of the snow, the light scattering effects of the snow and the compression shear strength of the snow.

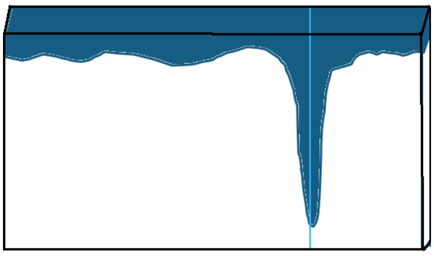


Figure 2 - Device measuring snow permeability.

3.1 Permeability of Snow. R Firth(2008)

This device removes a cuboid block of the snow in a perspex box, which is then turned onto its side. The snow sample is therefore rotated 90^{o}. The test involves coloured antifreeze dispensed in liquid droplets across the top and the displacement of the coloured liquid through the snow is measured. The weaker layers have a higher permeability and so show up as a peak in the block. The light blue line here shows a weak layer.

- Pros: Visible and easy to read results.
- Cons: Time consuming testing, not very portable, requires removing sample from snowpack, and most importantly difficult to use droplet dispensing device while wearing gloves.

3.2 The Effects of Light Scattering. K Salter (2011)

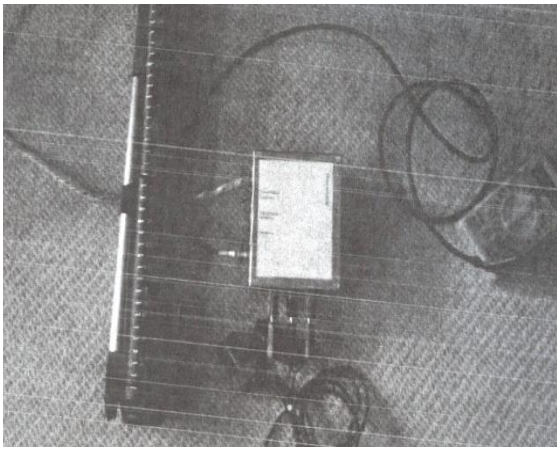


Figure 3- Device analysing light scattering. K Salter (2011)

A probe is inserted into the snow shining a beam of light down and measuring the scattering effects on the returned light.

- Pros: Showed apparent detection of weak layers and their depth in-situ
- Cons: Requires batteries

3.3 Compression Shear Test on Snow. P Kirkwood (2011)

This test simulates a mass on top of the snow surface. It measures the force on a sample taken from 45 degrees to the snow surface required to cause the sample to shear as shown in the image. The simulated mass on the snow represents a skier passing by or even extra snowfall.

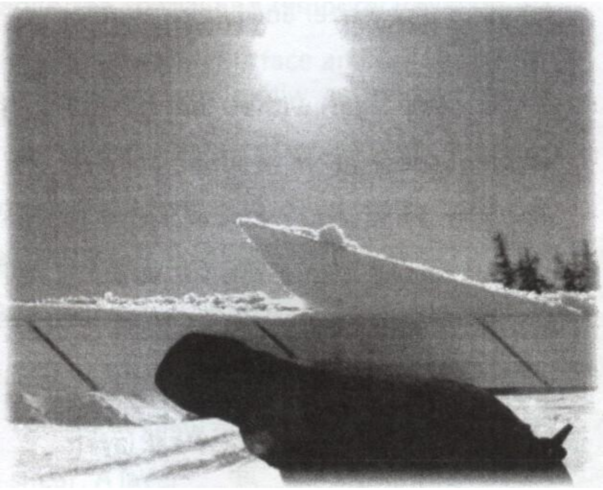


Figure 4 - Shear profile from compression shear test. Clarke (2009)

- Pros: Reliable detection of weak layer, its location and the failure stress.
- Cons: Requires removing a sample from the snowpack

3.4 Comparison of Previous Methods

The device which measures the permeability of the snow gives a really nice way to view the results. This is an important feature in the device to be taken forward, allowing the inexperienced novice to easily read the result. The main downside was the difficulty in using the device to add liquid droplets to the snow sample when wearing bulky ski gloves. An effective new device needs to be much easier to operate during all stages of testing, in setting up the device, taking measurements and packing it up again.

The light scattering detection device had the ability to detect weak layers in-situ, without disturbing the snowpack. Again this is a useful feature with regards to the reliability and repeatability of the results. The need for batteries extends the long term costs of the device and the danger of unreliable readings if the batteries are close to flat.

Finally the compression shear test device showed very reliable detection of the weak layer and the depth could be calculated. Standalone compression and shear tests already existed but combining the two involved the idea of inserting the probe into the ground at 45 degrees to the slope surface. The design progression in started with Clarke. (2009) who used a box section with a removable side to take a sample from the snow by friction alone. Kirkwood (2011) expanded on this with a mechanism to slice the snow sample at the base allowing removal from the snowpack.

4. Theory of Compression Shear Test

The test applies a compression force to one end of a snow sample. The key to this test is to take a sample at 45 degrees to the snow surface. The test assumes that the whole sample will be under the same compression stress and will fail in shear at the weakest point. Measuring the compressive stress required to make the sample to fail can be used to find the maximum shear stress experienced in the sample using a Mohr's circle.

Figure 5 - Compressive and shear stresses acting in a block

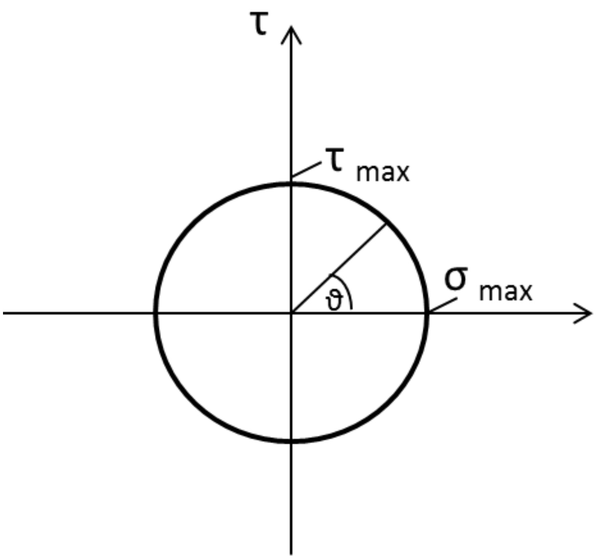


Figure 6 - Mohr's circle

A Mohr's circle shows that as the angle is changed at which the stresses are to be analysed within the block, the compressive and shear stresses interact. To find values for the compressive or shear stresses for a certain sub-section within the sample orientated at ϑ to the application line of the compressive stress one reads off the plot at an angle of 2ϑ. This circle assumes no acting external shear stress on the block, only an external compressive stress. Other acting compressive stresses or shear stresses changes the radius length and moves the centre away from the origin.

To ensure that the device is measuring the weakest layer in the snow pack and finding the absolute minimum shear stress, it is necessary that the suspected weak layer would be at 45^0 to the snow sample centre line. This is achieved by entering the probe into the snow surface at 45^0 to snow slope surface. This ensures that the compressive force can be used to determine the minimum shear strength of any layers in the snowpack.

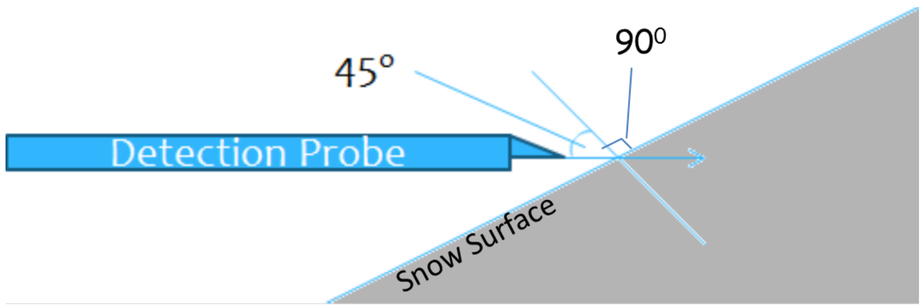


Figure 7 - Image showing probe entering at a 45 degrees angle to the slope surface

5. Design Progression

The original design of the previous project Kirkwood (2011) was taken and improved to incorporate the useful features seen in the other two previous devices.

The key features of the device which were focused upon as areas to improve were:

- The mobility of the device.
- The reliability and accuracy of the snow sample.
- The ease of use especially to make the results clear to inexperienced novices.

5. 1 Snow Blade Feature

One of the earliest criticisms of the earlier probe was that it involved the removal of the sample out of the snow, which would cause the core to be put under stresses during the removal process, from the contact between the snow and the probe wall. The snow blade on half the probe allows a sample space to be created within the snowpack. This allows the test to take place in-situ with an undisturbed sample as can be seen in the figure. This improves both the reliability of the sample and the ease of use, as the removal of the sample (required prior to measurements being made in the previous device, Kirkwood (2011)) could be difficult for those with less dexterity in their hands.

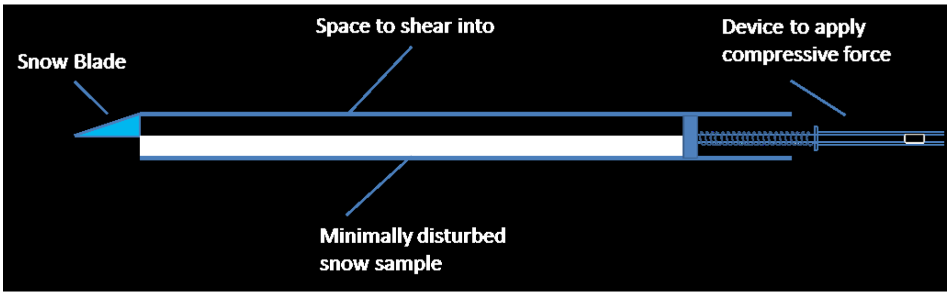


Figure 8 -Image showing how snow blade forms a snow sample on bottom leaving an empty space on top

The optimal design of the snow blade in two dimensions is a triangle, so to bring this into three dimensions (factoring in that the probe is a cylinder) the optimal three dimensional shape was half of a cone.

Figure 9 - Snow blade cone

The snow blade design also allows the user to rotate the sample while in the ground, causing the snow at the end of the probe to shear due to torsion. This allows the user to remove the probe, once testing has been done, to visually inspect the failure planes. The inspection would be to check for the needle like crystals which would be seen from a buried layer of surface hoar. A removed sample in the transparent casing helps the ease of use, making the results visibly clear to all users to aid their understanding of the snowpack.

5.2 Shape of Probe

The earliest ideas and designs for the new probe used the tested shape of a rectangular probe from the year before Kirkwood (2011) but with the addition of a snow blade on the bottom of the device. To improve upon these designs and ideas a cylinder was used which could be easily included with other skiing equipment, allowing it to take up less space in their backpacks. This was to improve the ease of the devices use, mainly with regards to its transport, hopefully encouraging skiers to take the probe with them when leaving the piste.

Another reason for using the cylinder design is that it is the easiest to slide into the ground to get a sample which will cause the minimum disruption due to friction as the probe is inserted into the snow pack. This shape maximises the sample area to probe wall length ratio, giving the least affected snow sample. This also improves the reliability of the snow sample.

The diameter of the device would be determined by testing, using inner probe diameters of 21mm, 35mm and 45mm. An extra probe of 60mm was used to certify that the results from the more mobile probes were accurate. The aim was to balance the mobility of smaller diameter probes with the expected greater reliability of the readings produced by larger diameter probes.

After the first period of testing it was noticed that the base of the cylinder, opposite to the snow blade side, would be acting against the force pushing the probe into the snow. This would have caused issues in allowing the probe to be pushed into the snow. The solution to this was to round the end into a sharp point to help with the insertion into the snow.

Figure 10 - Image showing curved, cutaway base

For testing, the snow down to a vertical depth of 50cm should be checked. A skier's weight will act over the snow and this force dissipates with depth. A weak layer less than 50cm deep in the snow will still have the skiers mass acting upon it potentially failing in shear. The probe is inserted at 45^0 which means that to ensure that snow up to a depth of 50cm in analysed, the probe needs to be:

$$\frac{50cm}{\cos 45^o} \approx 70cm$$

To improve the mobility of this 70cm long probe it was required to split it into two, a few mechanisms where considered:

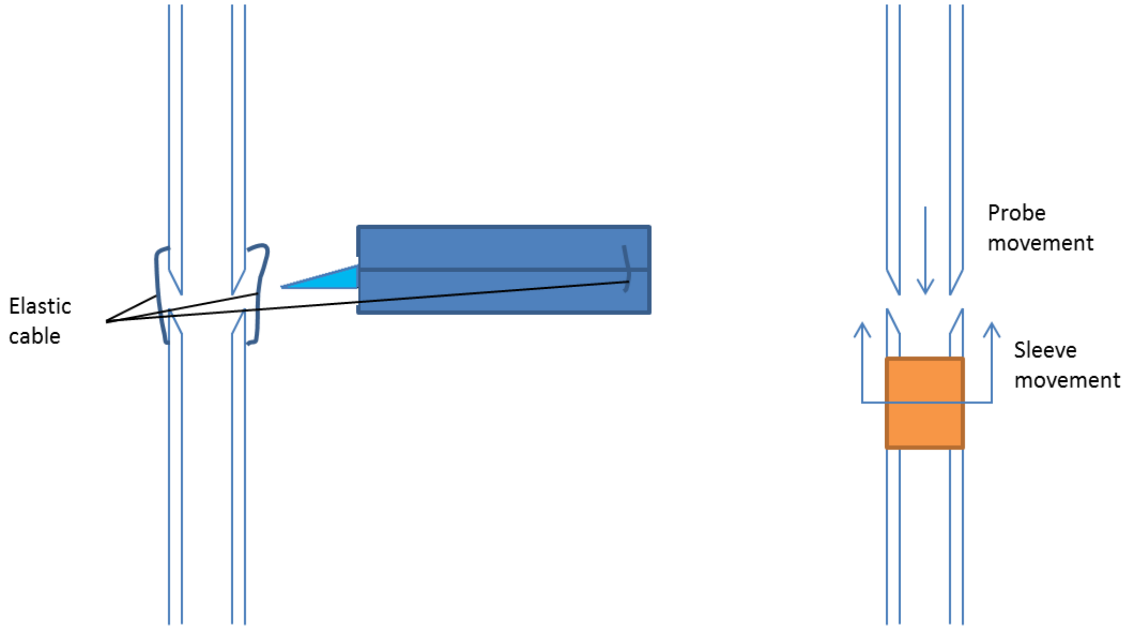


Figure 11 - Elastic cable design is shown on the left. Sleeve design is shown on the right.

The first two mechanisms involved bungee elastic cables or a sleeve to hold the device together. The bungee cables were useful as they would hold the probe together while broken down into its more storage friendly form. The sleeve would require friction alone to hold the probe together. While the elastic cable device looks the more promising of the two, both would require the probe wall to be cut at an angle to encourage the segments to join together and ensure the inside wall is undisturbed.

This would require a thicker probe wall, adding to its weight and cost. The final mechanism was a simple lock and key mechanism, which did not require the probe wall to be cut. A brass band had a vertical, then horizontal inlet cut, which could lock itself to bolts pierced into the outside of the probe. Simply pushing the cylinders together then rotating them forms a solid connection.

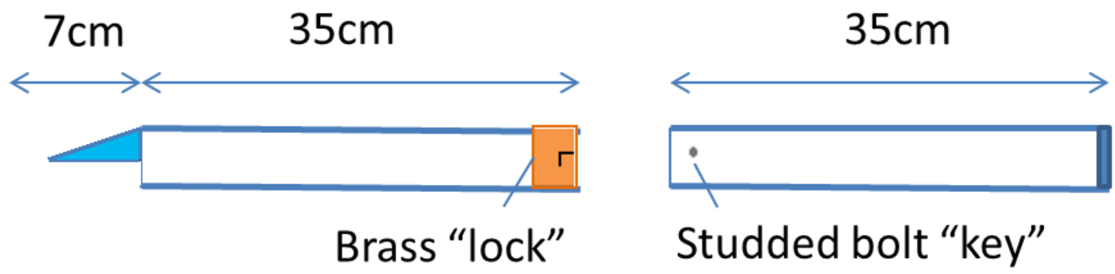


Figure 12 - Image showing lock and key mechanism for joining

The lock and key joining mechanism was the simplest and thought to be most reliable with the least moving parts. With an aim for the design of the probe to ensure as cheap a manufacture as possible this was the chosen solution.

Figure 13 - Close up picture of lock and key mechanism

5.3 Device to Apply and Measure Force

The forcemeter used in the previous project was reused in the testing of the new device.

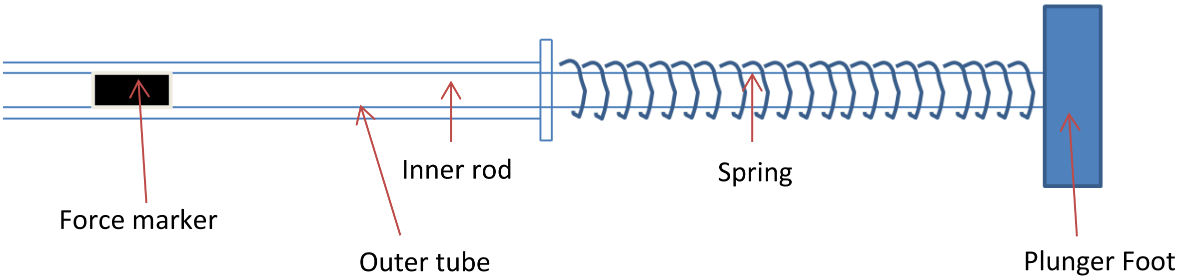


Figure 14 - Labelled image of forcemeter

When the plunger foot is placed onto the snow sample and a force is applied to the top of the outer tube, the spring will compress as the force is increased. The inner rod moves up inside the outer tube pushing along the force marker. When the sample shears the spring will decompress. The maximum compression is recorded by the black marker. Measuring the black marker's displacement allows the maximum compression stress to be recorded. From this, using a Mohr's circle, one finds the failure shear stress.

Two springs were used for testing, the first with a Young's modulus of 2.77 N/cm to test with high accuracy low strength readings. The second spring had a Young's modulus of 88.5 N/cm to measure a range of strengths to insure the probe was reading the strength values of even strong snow. Both readings were verified with a simple experiment.

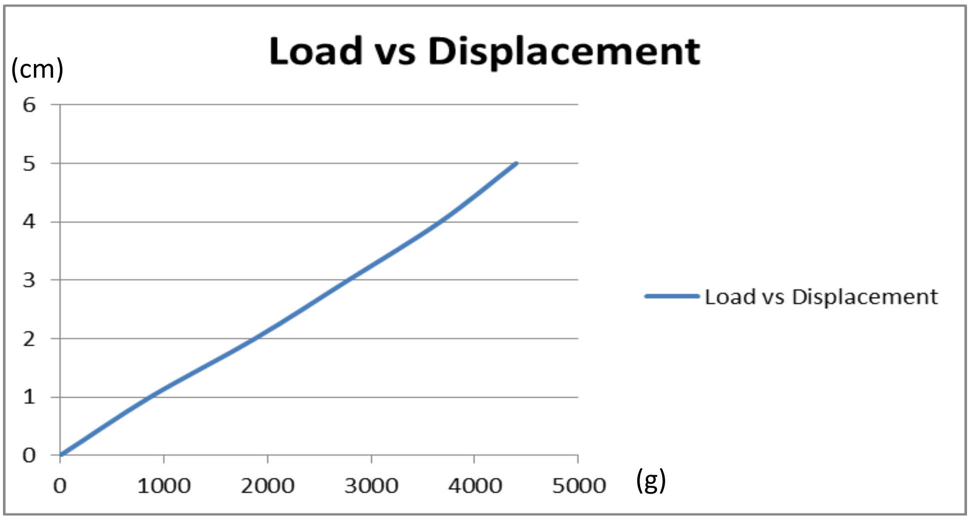


Figure 15 -Experiment to check the manufacturer's values for Young's modulus of springs, k = 88.5 N/cm graph shown.

5.4 Probe Material

When deciding which material to use, the strength to density ratio must be balanced so as to achieve the lightest probe that is strong enough to be pushed into any type of snow. While this would normally lead to choosing a metal, the transparent properties of perspex lead to its choice as the material for the probe wall. This meant that during testing it was easy to see how well the snow sample formed inside the probe. It also meant that with all readings the user could look at the failure profile within the snow to ensure it was failing in shear with a nice 45^0 ridge.

5.5 Verification Device with 60mm Inner Diameter

To act as a benchmark for comparing results from the test probes a verification device was developed. This has a large 60mm diameter, which is bigger than the testing devices and has no joints. It is far too large to be carried around by a skier but gives very accurate readings which the smaller more mobile devices were then tested against.

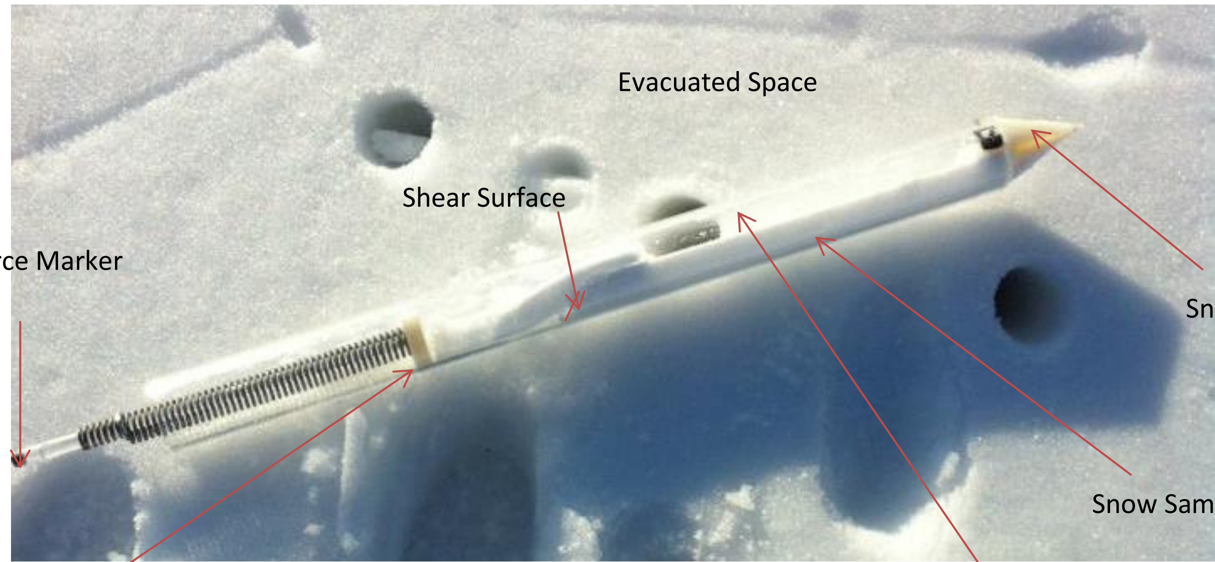


Figure 16 - Image of device used to verify results on mountain

5.6 Final Probe Design

This has the same design and use as the verification probe but with smaller diameters. It also utilises the lock and key mechanism to allow the probe to be split into two and carried in a normal sized backpack for mobility.

Figure 17 – Dugout view of probe

Figure 18 - View of device used for the testing

Figure 19 - View of probe sitting on snow surface

Figure 20 – Collapsed compact probe

6. Preliminary Testing of Device – Aviemore January 2013

6.1 Aims

The first set of testing was to look at the functionality of the snow blade; see how well the snow sample formed within the tube and to get an indication of how the different diameters of inner tube would affect the results. Test mobility and ease of use.

6.2 Location

The testing took place over the Christmas at the top of Cairngorm Mountain near Aviemore in Scotland.

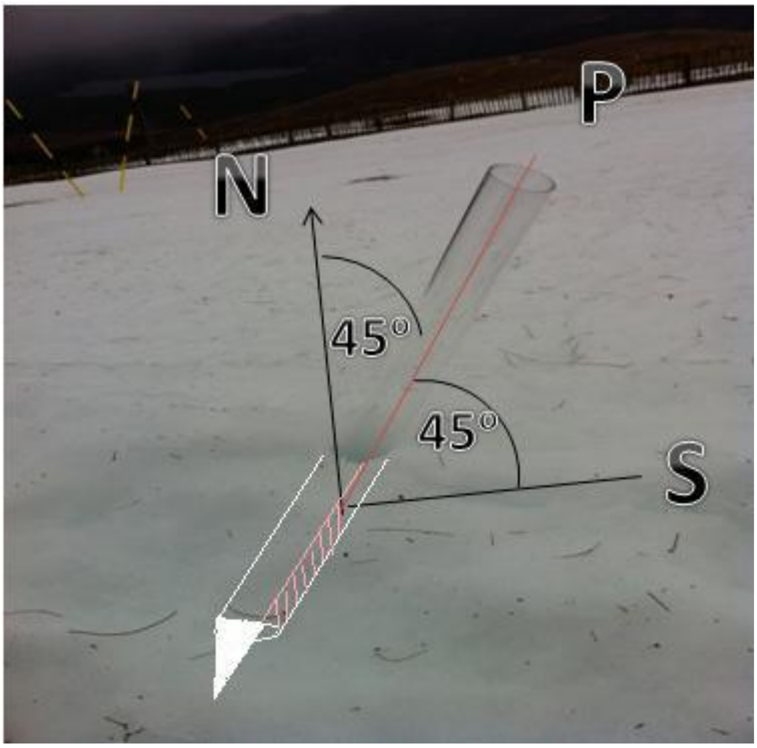


Figure 21 - View of probe in snowpack

KEY:

N is the normal line, at 90° to the slope surface, S is the slope line, parallel to the slope surface. P (red line) is the centre line of the probe, should be 45° to both N and S

The white lines show the probe in the snow, with the blade on the top side, so snow core is on bottom of probe tube. The pink lines show the snow sample which has been formed.

	Displacement	with spring	k=2.767N/cm						
Reading	21mm	35mm	45mm	Force 1 (kN)	Force 2 (kN)	Force 3 (kN)	Pressure 1 (kPa)	Pressure 2 (kPa)	Pressure 3 (kPa)
1	195	148	262	5.39565	4.09516	4.09516	4.29	1.97	0.71
2	140	89	216	3.8738	2.46263	2.46263	3.08	1.18	0.43
3	72	227	300	1.99224	6.28109	6.28109	1.58	3.02	1.09
4	194	299	224	5.36798	8.27333	8.27333	4.27	3.98	1.43
5	69	212	241	1.90923	5.86604	5.86604	1.52	2.82	1.02

Table 2- Compressive stress failure values for snow in Scotland

6.3 Discussion of Results

The snow was mainly melting, it was really just a matrix of water and ice due to the unseasonably warm weather at the time. This meant that the strength readings could not be tested reliably with the snow failing quickly in compression rather than shearing as was expected of a healthy snow sample.

The snow was still useful for seeing how the snowblade worked in action and it performed perfectly. The blade created the space for the in-situ experiment and the cylinder allowed a sample to form undisturbed on the other side. Here light blue shows the probe walls, where the pink lines show the sample within the probe.

Figure 22 - An image of the dugout probe showing the snow sample

This was the 35mm inner diameter probe, which formed a nice sample as did the 45mm probe. The 21mm inner diameter probe did not form a nice sample, with the core crumbling in on itself as the probe was pushed into the snowpack, so this ruled out its use. Whilst light and mobile any results from it would not be reliable.

The probe was large and difficult to carry around, especially with the end sticking out of an already large backpack. Knowing exactly how everything worked it was possible to operate the device with gloves in the extreme conditions and high wind.

This testing showed that the snow blade worked well and that the 21mm diameter probe will not be feasible. Further testing was required to fill in the areas of uncertainty

Inner Diameter	Formation of good snow sample	Snow fails in shear at weakest point	Reliable and repeatable readings
21mm	⊘	?	?
35mm	✓	?	?
45mm	✓	?	?

Table 3 - Decision table on selection of inner diameter design

7. Final Testing of Device – North Antrim, March 2013

7.1 Aims

To make judgements on the existence of weak layers from weather data; get probe readings and measure reliability of readings against snow pit data. Test mobility and ease of use. Determine the optimal inner diameter of probe

7.2 Location

The testing of the final prototype of the device took place in March this year. The map below shows the testing sites and the local weather stations.

Figure 23 - Map showing Testing Sites and Weather Stations

7.3 Historical Weather Conditions, Data and Analysis

The following graphs are from the Met Office's historical records for the month of March, the values giving for daily and maximum temperature have been plotted.

7.3.1 Ballypatrick Forest Weather Station

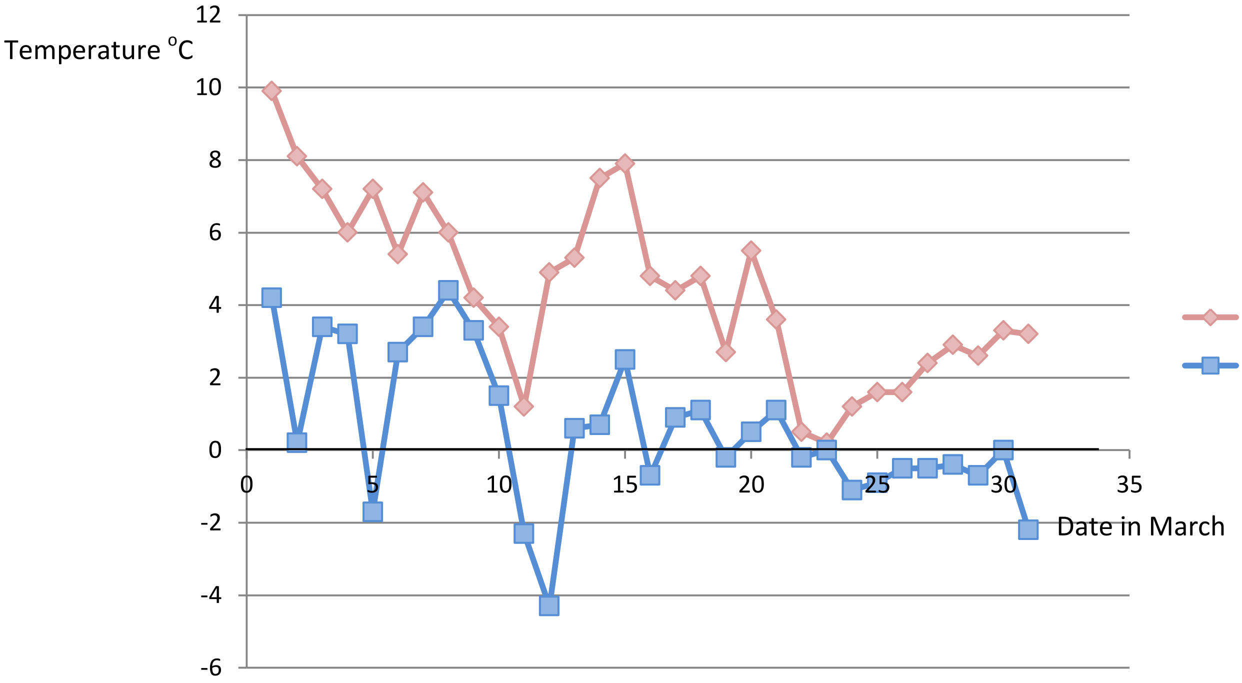


Figure 24 - Temperature data from Ballypatrick Forest weather station

7.3.2 Altnahinch Filters Weather Station

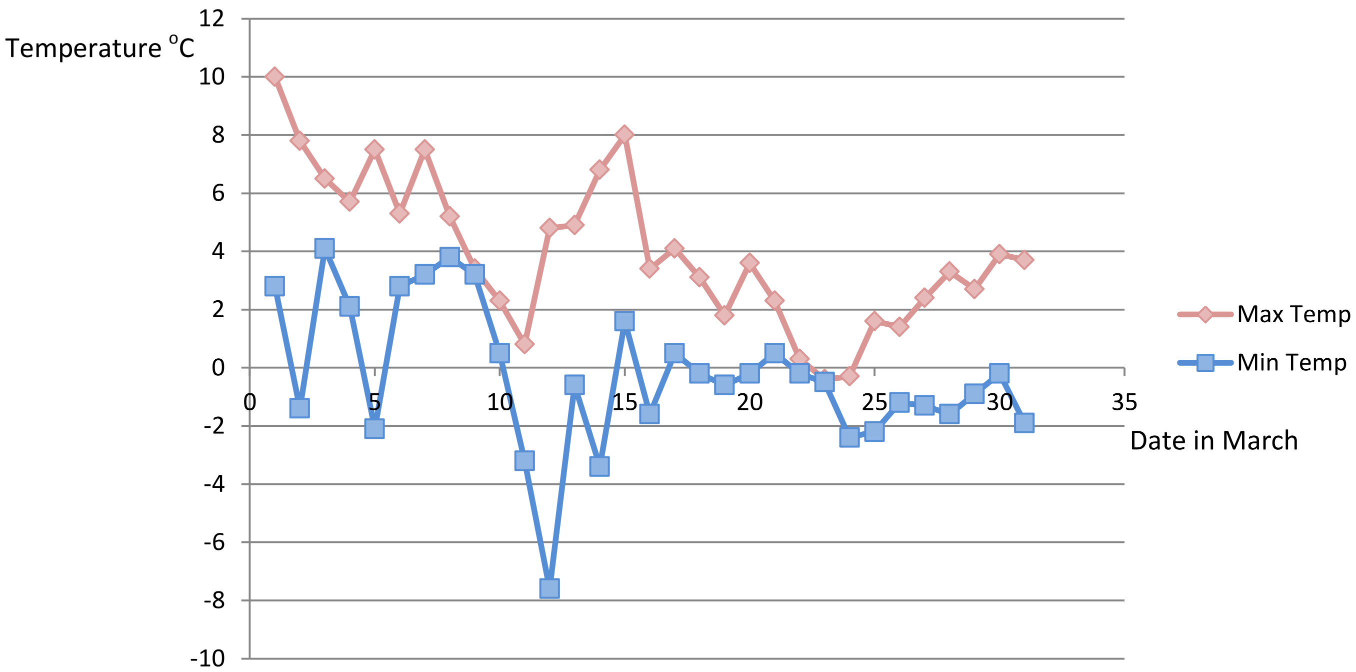


Figure 25 - Temperature data from Altnahinch Filters weather station

The precipitation data is available for both sites. Using the temperatures recorded it is possible to make an estimate for when the snow had fallen, how much had fallen and also make an estimate of how much extra snow would have been drifted onto the site. The below freezing temperatures begin on the 10th of March.

To estimate the amount of snowfall conservative approximated multiplication factors of 2 and 2 were used to factor that the density of snow is only approximately $400kg/m^3$ and that some snow will be from snow drift due to the wind. While the density of water is $1000kg/m^3$ suggesting a factor of 2.5, 2 was used as much of the snow would consolidate under its own weight. Estimated snow shown below.

Date	B'patrick, mm	A'hinch, mm
01-MAR-13	0.2	0.2
02-MAR-13	0	0
03-MAR-13	0	0.2
04-MAR-13	0	0
05-MAR-13	0	0
06-MAR-13	5.2	2.8
07-MAR-13	12.6	4.8
08-MAR-13	7.6	1
09-MAR-13	5	7.6
10-MAR-13	0	0
11-MAR-13	0	1.8
12-MAR-13	0	1.4
13-MAR-13	0.8	1.2
14-MAR-13	1.6	2
15-MAR-13	4.6	0.6
16-MAR-13	8.2	6.6
17-MAR-13	9.2	3.6
18-MAR-13	6.2	7.4
19-MAR-13	4.4	12.8
20-MAR-13	0	0.2
21-MAR-13	7.9	2.8
22-MAR-13	31.6	10.7
23-MAR-13	0.6	0.4
24-MAR-13	0.1	0
25-MAR-13	0	0
26-MAR-13	0	0
27-MAR-13	0.2	0
28-MAR-13	0	0
29-MAR-13	0	0
30-MAR-13	0	0
31-MAR-13	0	0

Table 5 - Precipitation values for weather stations

09-MAR-13	B'patrick, mm	A'hinch mm	Average mm
10-MAR-13	0	0	0
11-MAR-13	0	7.2	3.6
12-MAR-13	0	5.6	2.8
13-MAR-13	3.2	4.8	4
14-MAR-13	6.4	8	7.2
15-MAR-13	18.4	2.4	10.4
16-MAR-13	32.8	26.4	29.6
17-MAR-13	36.8	14.4	25.6
18-MAR-13	24.8	29.6	27.2
19-MAR-13	17.6	51.2	34.4
20-MAR-13	0	0.8	0.4
21-MAR-13	31.6	11.2	21.4
22-MAR-13	126.4	42.8	84.6
23-MAR-13	2.4	1.6	2
24-MAR-13	0.4	0	0.2
25-MAR-13	0	0	0
26-MAR-13	0	0	0
27-MAR-13	0.8	0	0.4
28-MAR-13	0	0	0
29-MAR-13	0	0	0
30-MAR-13	0	0	0
31-MAR-13	0	0	0

Table 4 - Estimates for snow at stations and average value

The weather stations are approximately equidistant from the site of testing so an average value is used as the assumed weather at the sites. While there appears to a small amount of snowfall, the total adding to only 253.8mm, there was considerably more snow in some parts of the mountain face than others. Some areas had almost no snow while other areas were more than 3m deep. The average snow height was by inspection around 20cm.

There is a noticeable difference in some of the expected snowfall in both locations and this is down to the irregular behaviour of weather in mountainous areas. The snow seems to fall in two series of continuous precipitations, first across the 15th-19th March period, then again 21st-22nd March.

The large temperature gradients required to create depth hoar would not have been present as the lowest reading of temperature was -8^{o}C which persisted for only one night and there was no snow according to this weather data. News articles from the time suggest that there were snow drifts of up to 18ft in some areas during the period, BBC News (2013).

Figure 26 - An image displaying deep snow in some areas and little snow in other areas

7.4 Testing Site 1

For safety reasons the testing began on a reasonably flat slope on the eastern side of the mountain which is where the bulk of the snow would have been deposited upon. Moving some distance away from the road a first snow pit was dug in order to get an idea of what the constituents of the snowpack was. The properties of the 2m deep snowpack were a complete unknown before this step.

Figure 27 - View downhill from site 1

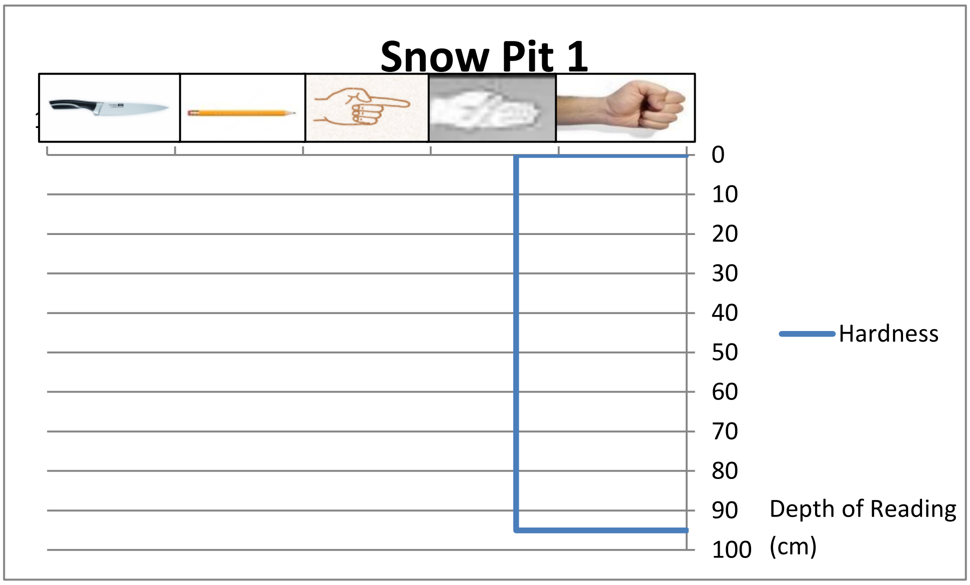


Figure 28 - Snow Pit from site 1

Figure 29 - Image showing attempt at continuous testing

The results show that there was a fairly uniform hardness profile through the entire depth of the snow. The hardness was measured in 5cm intervals. To check that there were no tiny layers between these the test involved running a finger down the wall to get an idea of what a continuous test would give.

The observation was that there seemed to be boundary layers with slightly different hardness than the rest of the snow and when testing was done this was where failure layers were from, as it was a very slight difference in hardness these were not signifantly weak layers. When measured, the strength was within the expected range in accordance with the snow pit results suggesting that these were simply three layers of snow probably arriving at different times.

Measuring the displacement of the black marker on the forcemeter required for shearing to occur and knowing the spring constant allows the force applied onto the snow sample to be calculated. The force is divided by the contact area with the snow to find the compressive stress. A mohr's circle is used to find the maximum shear stress in the sample and this is the value of interest.

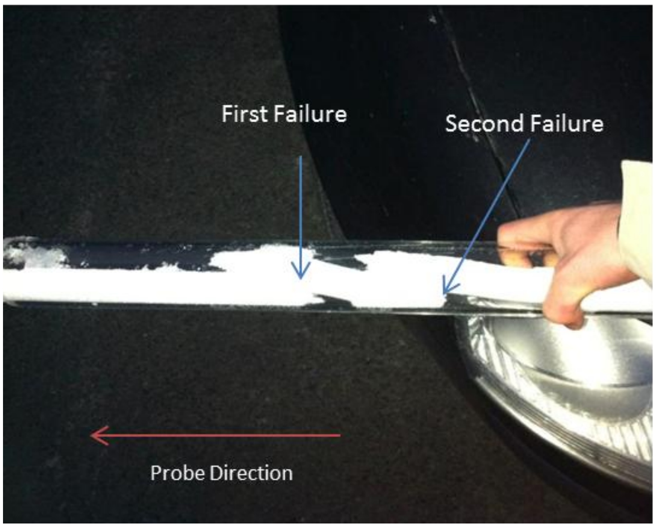
Reading	τ failure (kPa)	Mean (kPa)	Stand Error
1	13.91	14.38	1.35
2	15.30		
3	13.91	Confidence Intervals (kPa)	
4	12.52	99.00%	18.44
5	15.30		10.32
6	16.69	95.00%	17.09
7	12.52		11.67
1	14.87	Verification probe results	
2	13.30		
3	13.30		

Table 6 - Probe results from site 1

This table is for the 45mm inner diameter probe as well as the verification probe results. The confidence intervals show the percentage certainty that the true mean lies within a range of the multiples of standard errors. The 99% confidence interval is the range adding or subtracting three standard errors to be 99% the true mean lies within the range. The 95% confidence interval adds or subtracts two standard errors.

Figure 30 - View of readings sites and verification sites

Here all the results were within the 95% confidence interval showing good reliability and repeatability of results. These readings were performed with the 45 inner diameter probe, repeats were made with the 60mm probe which gave matching readings and showed failures at the same depth with same profiles.



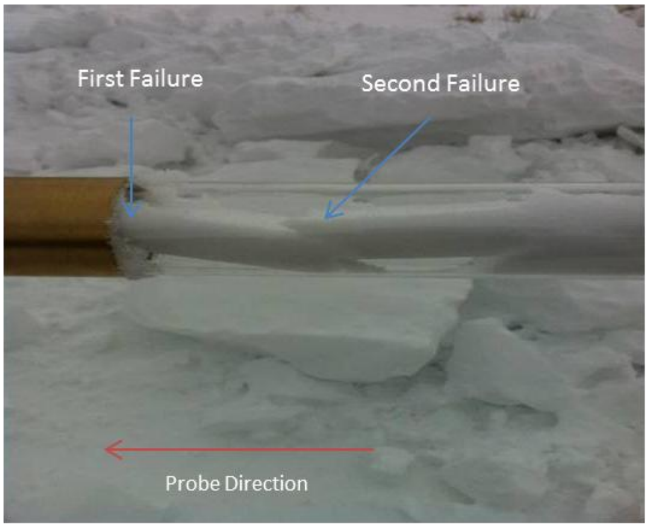


Figure 31 - Side by side view of verification device (left) and testing probe (right)

An unexpected bonus with this device is its ability to indicate the next weakest point in the snowpack and its properties. When the snow sheared it was expected to slip down further but this did not happen. Instead it forms a new surface allowing the snow below to have a greater force exerted on it until another shear occurs at the second weakest point. Only the first shear readings have been shown as the contact surface area of the snow on snow interaction is not going to be constant so the extra readings could not be guaranteed to be reliable. This does however allow the user of the probe to get an indication of the next weakest point in the snowpack and its properties.

The sources for error in the testing are mainly parallax errors in reading the force marker on the force tube. It is difficult to read the results accurately beyond the milimetre readings on the ruler and measuring tape used for measuring the displacement of the marker. Another source of error is not putting the probe in at exactly 45^0 to the surface, however due to trigonmetric function graphs an error of up to 5^o should not cause a significant difference in the Mohr's circle shear strength calculations.

This site was also chosen for its location right next to a mountain river as shown in this picture from earlier in the year, the hope being that with the running water, humidity would be higher allowing for possible surface hoar formation. Unfortunately there were also very strong winds present according to the weather data and this would have caused any surface hoar layers to sublime if they managed to form at all.

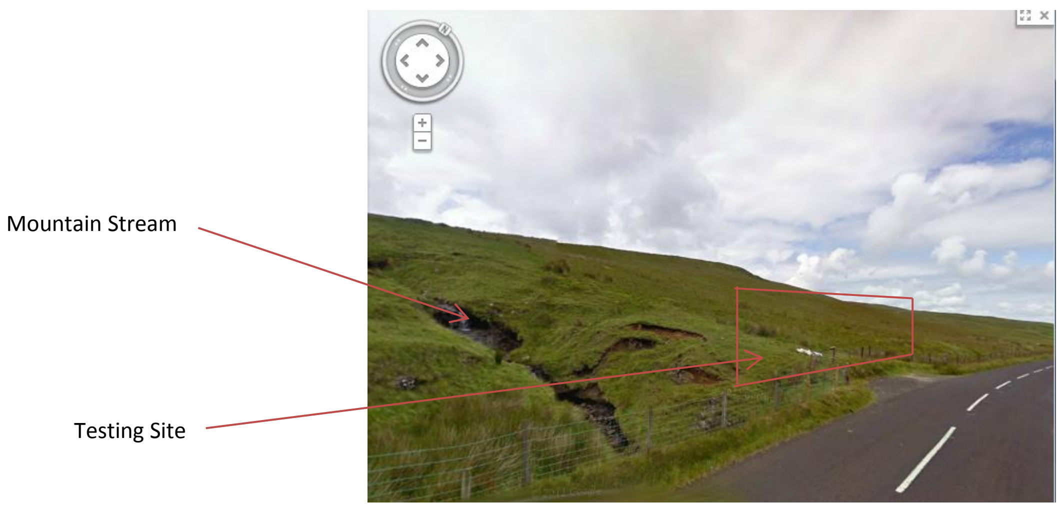


Figure 32 - View of testing site 1 next to stream

7.5 Testing Site 2

Sites 2 through 4 are spaced out about 100m from one another, all behind mounds facing east, this led to large scoured snow deposits, giving ample testing snow again on a safe flat surface to ensure there wasn't risk of the probe and other equipment being buried.

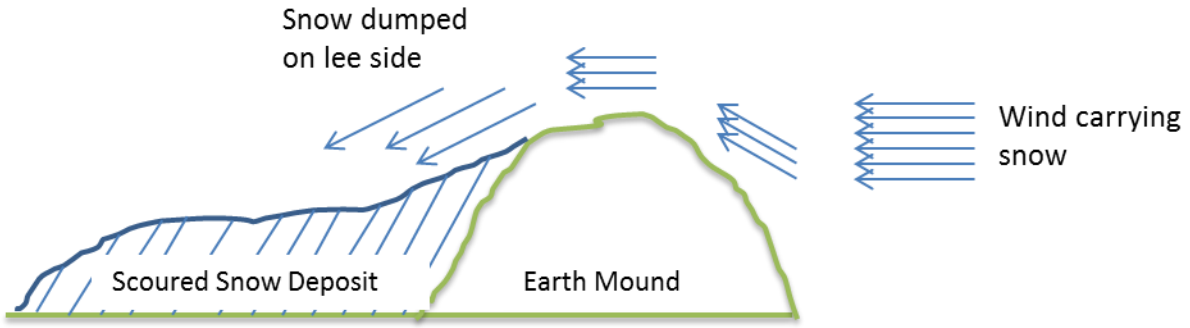


Figure 33 - Explanatory diagram of scoured snow

The snow pit from this location shows weaker snow between from 30cm to 45cm depth, this snow was right on the hand to three fingers boundary. Again the readings from the probe measured strengths close to the approximated hardness values from the snow pit.

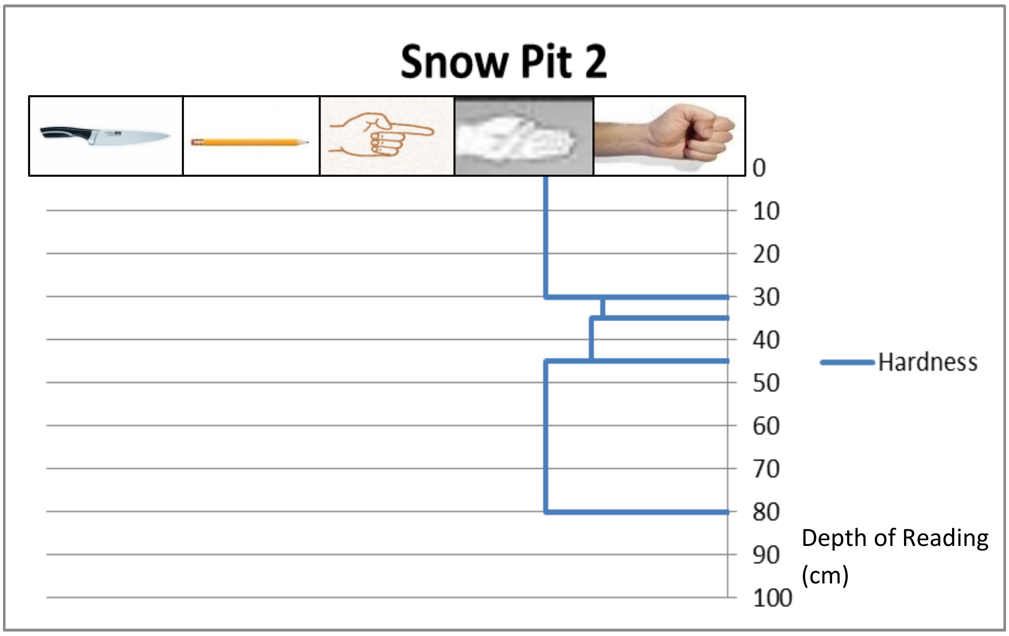


Figure 34 - Snow Pit from site 2

Reading	τ failure (kPa)	Mean (kPa)	Stan Error
1	13.91	12.52	1.49
2	9.74		
3	11.13	Confidence Intervals	
4	13.91	99.00%	16.98
5	13.91		8.06
6	12.52	95.00%	15.49
7	12.52		9.55
1	10.17	Verification probe results	
2	11.74		
3	12.52		

Table 7 - Probe readings from site 2

Interestingly the failure stresses found with the 45mm probe show what the snow pit shows with regards to the weakest layer being on the strength boundary between fist hardness and three finger hardness, the approximate boundary being 10kPa. 9kPa is still well above the strength of faceted layers and was in no way means for concern for safety.

This shows that the probe was accurately reading the actual minimum strength of the snowpack. Again the standard deviation of the sample is low and all results were within the 95% confidence intervals suggesting reliable and repeatable results.

Figure 35 - Scoured snow used for testing

7.6 Testing Site 3

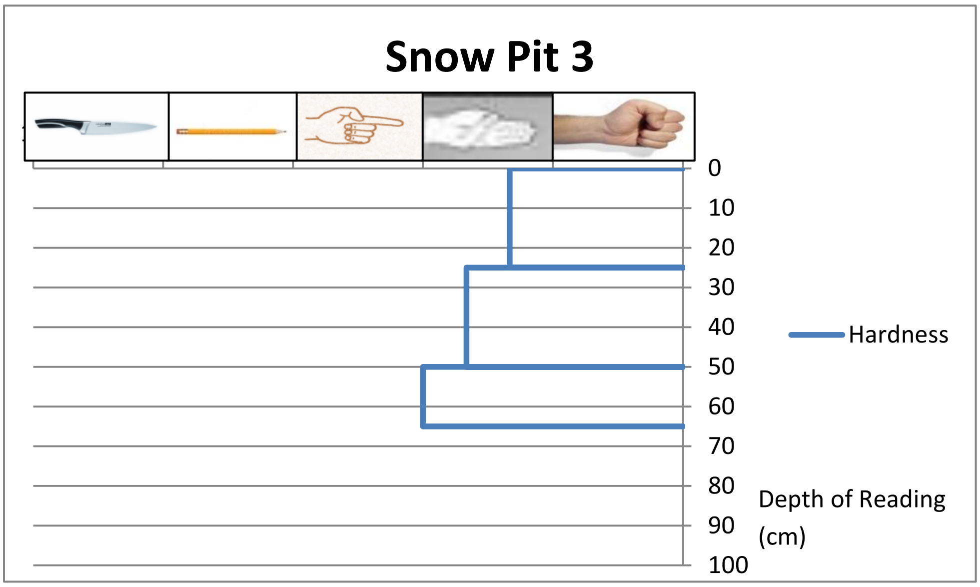


Figure 37 - Snow Pit from site 3

Figure 36 - Confirmation of results with 60mm probe

The third site was 100m across the mountain from the second, again behind a mound. The snow pit differences show the variability that is possible with scoured snow even on the same mountain face. All values were found to be in the three fingers category or the one finger category of hardness lower down in the snowpack.

Reading	τ failure (kPa)	Average (kPa)	Stand Error
1	18.08	16.89	1.38
2	15.30		
3	15.30	Confidence Intervals	
4	18.08	99.00%	21.02
5	18.08		12.76
6	15.30	95.00%	19.65
7	18.08		14.14
1	18.00	Verification probe results	
2	17.22		
3	17.22		

Table 8 - Table showing 45mm probe results from site 3

Again the values are all within two standard deviations showing good reliability and repeatability. The higher mean here corresponds well with the higher strengths throughout the snowpack. The probe here is measuring the strength of the three finger hardness segment between the surface and 25cm deep which was shown by the snow pit to be the weakest point. The failure was occurring close to the top of the probe each time as seen in the image. Again the snow layers can be explained by snow coming in three main blocks over the two weeks of snow and high winds.

7.7 Testing Site 4

This final site gave the most interesting hardness profile of all of those sites tested. Again this was behind an eastern facing mound giving a scoured snow profile, but this was much deeper than the others had been, up to 3m deep.

Figure 39 - Picture of the complex analysis

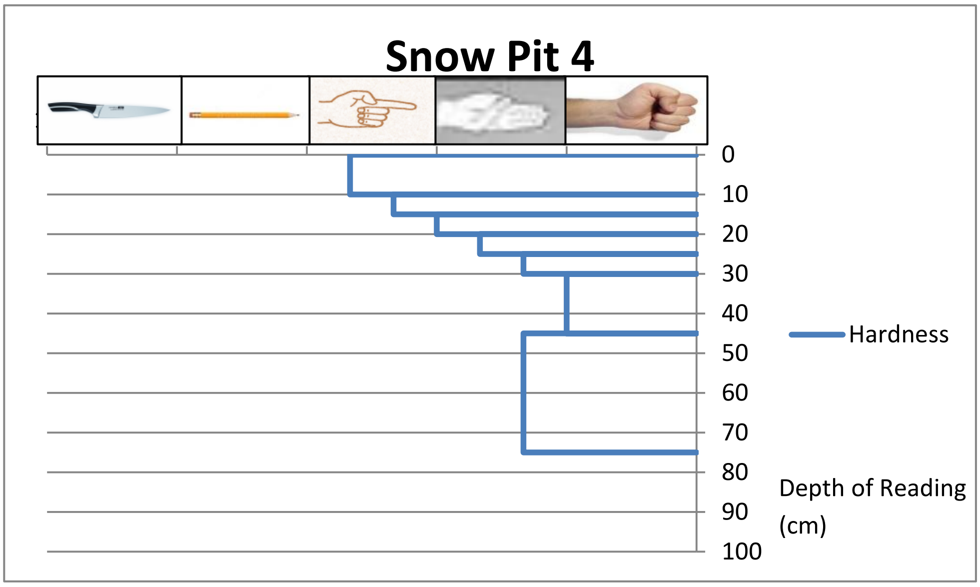


Figure 38 - Snow Pit from site 4

The slope of this ridge made measuring the snowpack in specific layers possible. As the ridge was at 45^0 already it was possible to input the probe horizontally, into just one area of the hardness profile. The other option was a vertical input which gave readings that matched up with strength profiles seen from the snow pit.

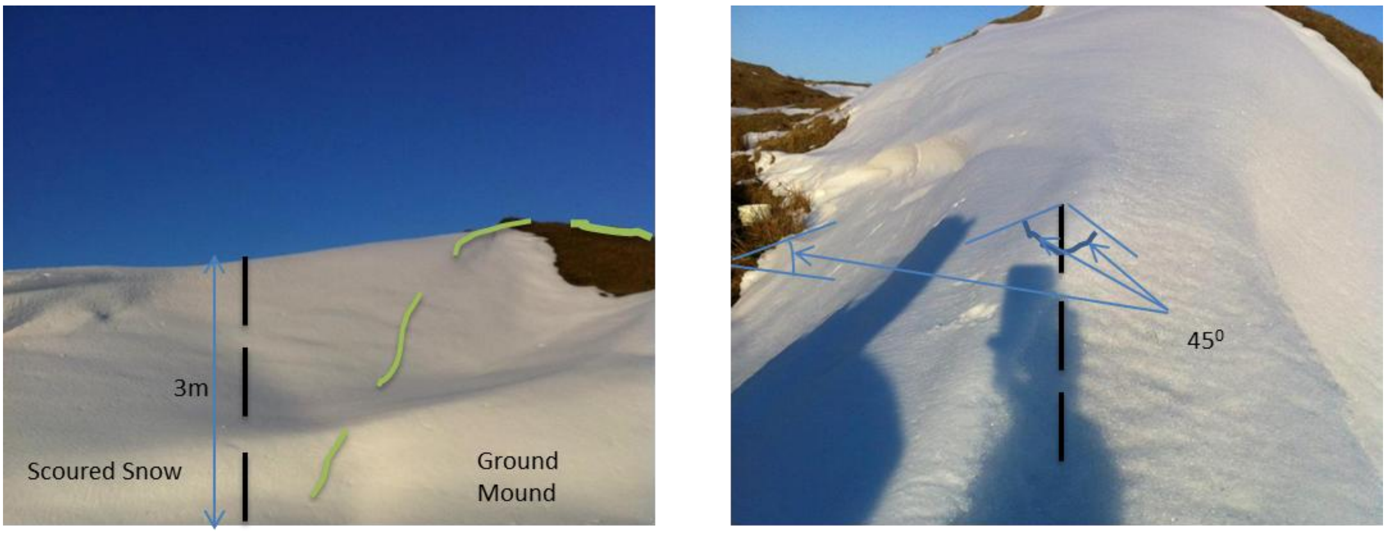


Figure 40 - Side view of deep scoured snow (left). Length view from top of snow ridge (right)

Reading	τ failure (kPa)	Average (kPa)	Stan Error
1	11.13	23.09	1.11
2	12.52		
3	22.26	Confidence Intervals	
4	22.26	99.00%	26.43
5	25.04		19.75
6	23.65	95.00%	25.32
7	22.26		20.87
1	24.26	Verification probe results	
2	24.26		
3	22.69		

Table 9 - Results from site 4

The top two values in the table were from the vertical test and the remainder were from the horizontal tests into the very hard snow at the top of the ridge corresponding to one finger in the snow pit hardness test. This meant it was possible to see how well the probe was measuring the much stronger snow, the weakest layer of which was still quite strong and make sure the difference could be seen in the results.

The average and standard deviation are for the five horizontal readings made with the 45mm diameter probe. The very low standard deviation here shows good repeatability of the readings and as the mean is considerably higher the probe says that the snow is considerably stronger than the earlier snow, showing the reliability of the probe.

7.8 Discussion of Results

In each individual case of testing there were small standard_deviations from the mean, a sign of good repeatability of the readings. The probe consistently showed failures at the same lengths along the probe for each different site, meaning it picked up the weakest layer to be at the same depth in the snow each time. The weather records for the time suggest no way for faceted snow to have formed in the snowpack, there was not a strong enough temperature gradient for depth hoar nor could surface hoar form and be buried due to the strong winds. This meant that the weakest layers that the probe measured should be that of the least hard layers from the snow pits and this consistently is shown in the results. The ability of the probe to reliably measure the lowest shear strength layer in the snowpack has been displayed.

It is important to ensure that users of the probe are aware that whether they are choosing to insert the probe 45^0 from normal towards horizontal or towards vertical will affect how deep into the snow surface they are actually measuring. Testing site four showed how different the readings could be between the horizontal and vertical samples. Weak layers could have existed that would only have been detected if the probe was put in at 45^0 from normal towards vertical. This suggests that both should be measured to give an appreciation of what lies within the snowpack. Most slope gradients will be much lower than this 45^0, closer to 20^0 so should not be a huge concern for skiers but would be relevant for climbers using the device.

The unexpected feature of measuring multiple weakest layers is useful and this is taken into the final suggested designs for the finished probe. The readings of shear strength of these extra layers will not be reliable as mentioned earlier due to the uncertainty of the surface area the compression force is acting upon, but it is useful information. If there is more than just one failure at a low stress, the whole depth should be checked with a snow pit as this suggests a highly layered complex and possibly dangerous snowpack containing multiple weak layers.

A problem with snow pits, which was highlighted in the tests for the second testing site, was that the result is a discrete reading at 5cm intervals, which will not necessarily show up a much thinner layer which could be only 1cm thick. This probe does not have this issue and measures continuously letting the user be confident that the probe has tested every point in the snow sample.

7.9 Conclusions

The following table summarises the capabilities of each different inner diameter of probe:

Inner Diameter	Formation of good snow sample	Snow fails in shear at weakest point	Reliable and repeatable readings
21mm	⊘	⊘	⊘
35mm	✓	⊘	⊘
45mm	✓	✓	✓

Table 10 - Decision table on selection of inner diameter design

The 21mm inner diameter probe could not form a good snow sample as seen during experimentation in Scotland. When the diameter increases so too does the area to diameter ratio, therefore to form a good snow sample the requirement is an inner diameter of 35mm and upwards. During the testing in Northern Ireland it was seen that the wall friction was preventing the shear profile developing in the 35mm device, the walls holding it in place and causing the snow sample to fail in compression. The 45mm inner diameter device was shown to form a good snow sample and achieve accurate reliable and repeatable results.

The probe was reasonably easy to use and the lock and key detachability worked very well allowing the probe to be carried in the backpack. This lightweight probe had simple construction keeping the cost much lower than other devices. With no electric components no batteries are required and there aren't any small parts which require taking off gloves on ski slope. The probe continuously measured the snowpack rather than giving a discrete output for depths like the snow pit, improving on that technique.

8. Suggestions for Future Work

The probe had proven to be reliable when measuring the strength of the weakest layer in a snowpack. The finished probe was sent off to an expert from the Scottish Avalanche Information service with the hope to get their expert opinion on the device, the response was as follows:

“In practice the probe is too complex for us to use in the environmental conditions that we are often in. As a tool for measuring failure and possible relationship to avalanche probability it may have value only in micro areas. Very limited in providing overall hazard or the hazard of a slope because of the issues of spatial variability. It may be of use in a controlled evaluation of a whole slope with multiple samples taken throughout a slope to establish spatial variability.”

From this feedback there are three steps that should be taken to improve on the usability of the device, which was one of the main aims:

- Minimise external moving parts, place forcemeter inside probe.
- Additional modules to increase probe length for deeper analysis.
- Social network app to encourage mapping of backcountry ski area, to overcome issues of spatial variability

8.1 Minimising External Moving Parts

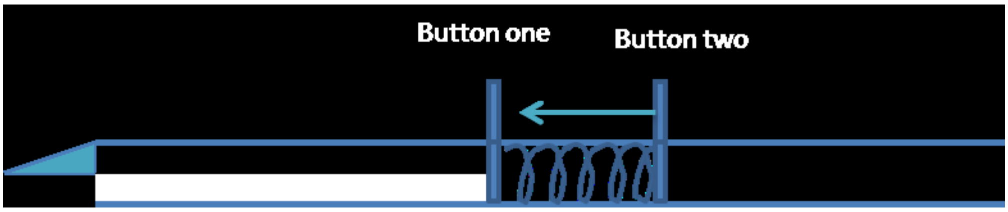


Figure 41 - Buttons and spring design

Initially the idea was to place a button feature within the tube, which would then rest on the snow sample. The 'buttons' are discs with a side arm sticking out of the tube. A spring between the discs would allow a force to be applied to the top of the snow sample equivalent to a maximum shear stress within the sample at 45^0 of 5kPa. 'Button one' will rest on top of the snow sample after the snow enters, with the uncompressed spring attaching the two discs. Pressing 'button two' down towards 'button one' will compress the spring between the two buttons. If they could not meet as button one appears to move, the snow sample would definitely contain a weak layer and is it unsafe to proceed without further analysis.

The problems identified with this design are three fold, it would require a cut all the way down the tube wall, for the button handles to sit out, seriously affecting the torque capacity of the tube. Secondly the spring's Young's modulus and required displacement lengths presented problems. The design could use a high Young's modulus spring and short displacement distance but this would be harder for some people to use if they had limited dexterity in their hands, due to injury or even just age. To counter this with a lower Young's modulus would mean a much longer displacement length so the probe could not be operated easily with just one hand. Finally there is the issue of the mechanism falling out each time the probe is broken down into its constituent parts.

The solution was to place the entire spring and plunger foot closed within the device, allowing it to all fit within the top half of the broken apart probe, removing the issue of it falling apart. As the probe is pushed into the snow surface in the same manner as before, the plunger foot is forced upwards as the snow sample fills the probe, - this action compresses the spring in the same manner as the buttons. The snow sample will in effect have a force again equal to that required to cause a maximum shear stress within the sample at 45^0 of 5kPa.

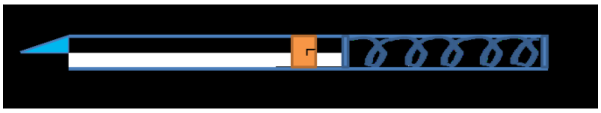


Figure 42 - Compression spring stored within device

A simple traffic light system as shown in these figures will be used to tell the user the properties of the snow sample. If the probe shows amber or red slope it means the slope is not safe until further analysis such as a snow pit shows otherwise and should not be skied upon, while green would show that the sample does not fit the criteria of orange or red samples where failure has occurred once or multiple times. The distinction between orange and red is important to ensure that when red the skier checks for more than one weak layer sign in their further testing. There are two mechanisms for this, simply putting a coloured rod onto the plunger which sticks out the top. If the probe is pushed all the way into the snowpack and doesn't fail the exposed part of the rod will show all three colours. If the snow fails it will only show red or red and orange, both show signs of concern and should not be skied upon.

Figure 43 - Coloured rod sitting on plunger design

The other possibility is using a spring based circular display which would be flat on the top of the probe, the display spins as the spring compresses. First showing red, then orange and finally green as the probe fills if no failure occurs. This method is preferable as gives a clearer result. This approach will require a mechanism to convert the vertical movement of the plunger and spring into a rotational displacement.

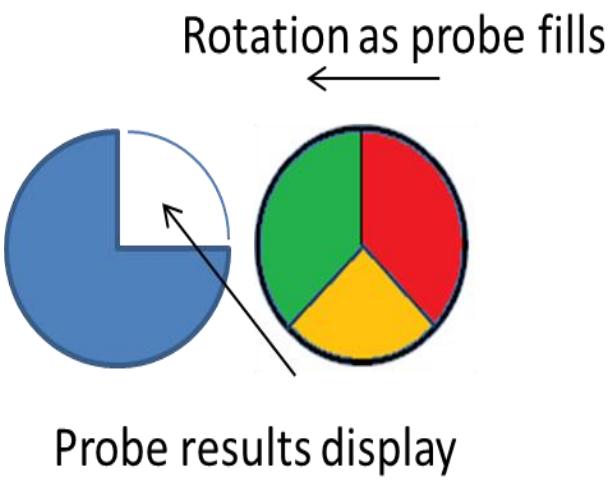


Figure 44 - View from top of probe, window shows red, orange or green as spring compresses

8.2 Additional Modules

Using the lock and key mechanism for breaking the probe into two pieces has the additional benefit of allowing extra probe modules to be added to extend the probes length. This allows the user to analyse as much of the snow depth as they require. This would also allow the snow blade feature to be attached or removed from the probe for its safe storage. A final device should have as sharp a snow blade as possible to ensure it can easily penetrate even very strong snowpacks which may still contain depth hoar. This would need to be stored carefully so that it does not pose a health risk should the skier fall.

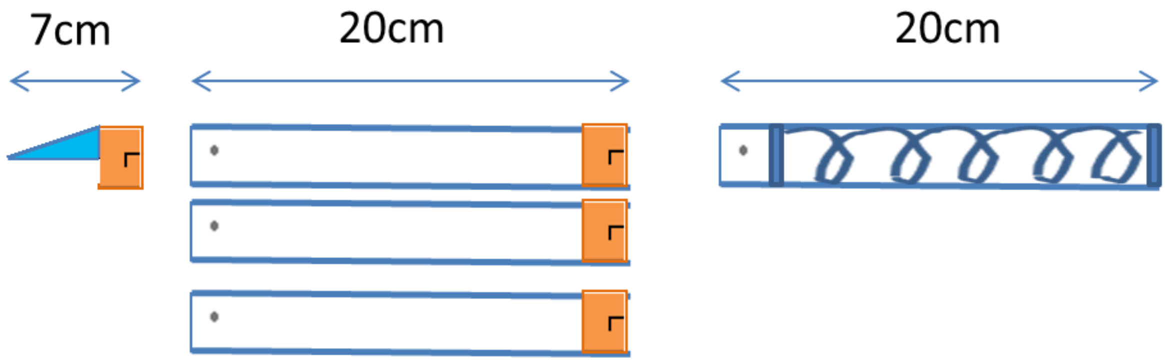


Figure 45 - Design of extra modules

8.3 Social Media Application

The expert feedback suggested that the probe would be useful in a controlled evaluation of a whole slope, taking many samples. An application on smart phones which would use existing maps of the resort, allowing users to update their traffic lights results from specific points could allow the community to monitor the areas themselves. The result would be a traffic light guide to the entire backcountry area.

A feedback system could be used to monitor that users were giving reliable results. The map would also have to take into account the length of time since previous readings had been made, suggesting that more tests should be performed if there had been a period of very low temperatures which could have led to the creation of a depth hoar layer.

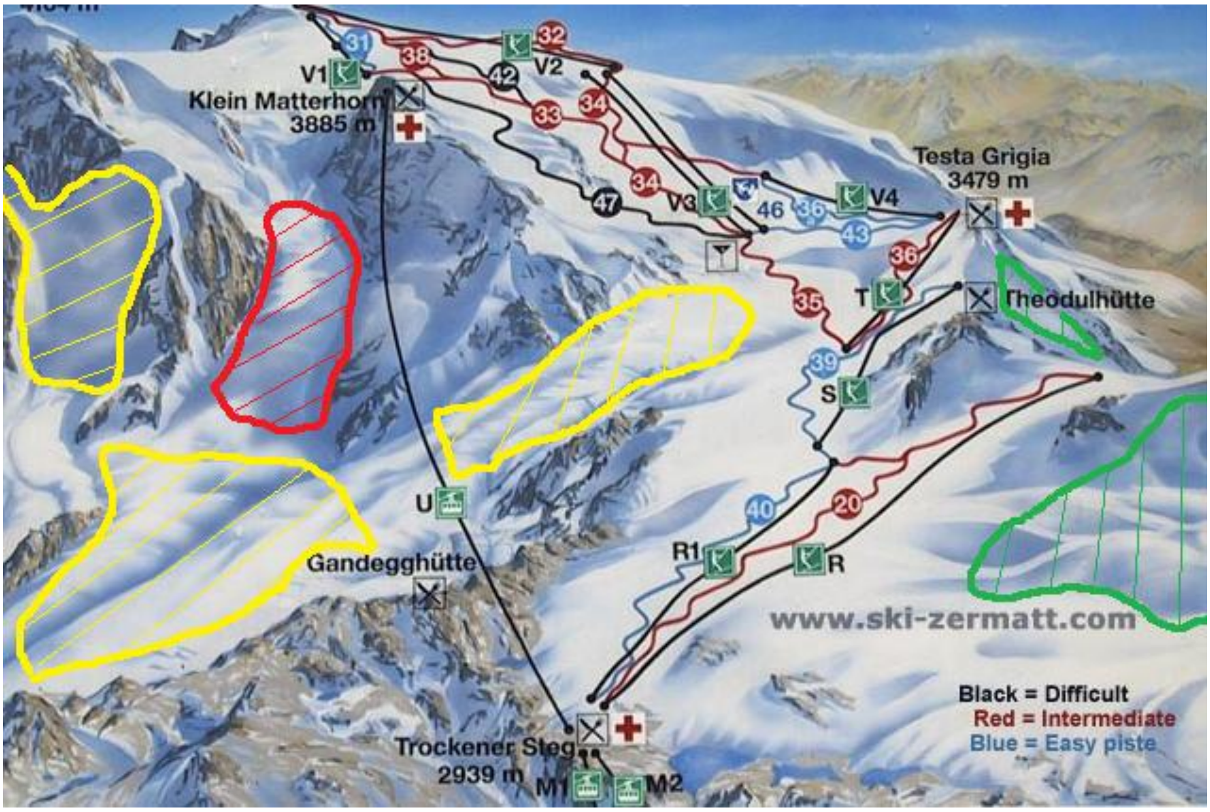


Figure 46 - View of how the app's hazard maps would look

8.4 Change of Material Used

Perspex was used for its transparent properties but an issue existed with regards to travelling, it could not always put up with the abuse it experienced when in transit from one site to another, even when bubble wrapped. A main area of concern with using perspex was in the connection of the snowblade to the probe wall, this will be solved by the addition of lock and key modules. A commercial form of the device needs to be stronger as it will be expected to be regularly in transit and should not require bubble wrap and other protective packaging each time.

A commercial product should offer both transparent and opaque devices. The transparent material could be a stronger but more expensive material such as Corning® Gorilla® Glass which is used on smartphones for protection. This would allow users to visually inspect the snow sample to look for the crystals on the shear surface. Other users may prefer a device with a smaller outer diameter. The 45mm inner diameter is still required so the wall thickness is the only scope for changing the design. Using metal the required wall thickness is reduced and inspection windows could still be cut into the probe at regular intervals to give an insight to the shear profile.

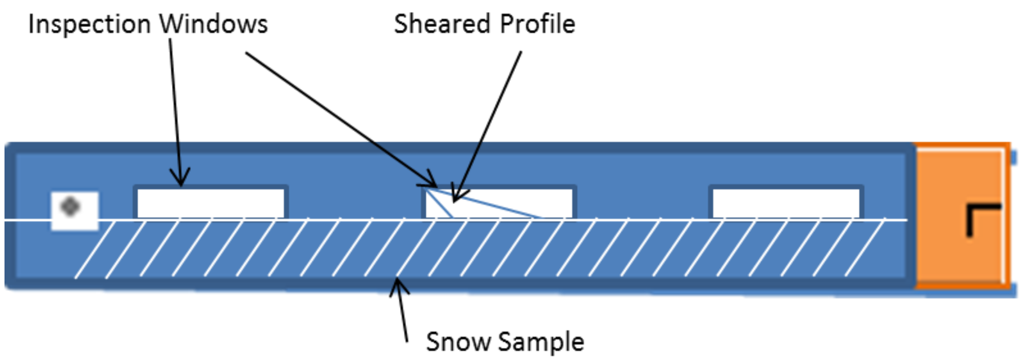


Figure 47 - Design of opaque probe with viewing windows

9. Acknowledgments

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10. References

BBC News. (2013), http://www.bbc.co.uk/news/uk-northern-ireland-21917589, accessed 24th March.

BMLF 1999 - Bundesministerium für Land- und Forstwirtschaft 1999. Richtlinien für die

Gefahrenzonenabgrenzung idgF. (Federal Ministry of Agriculture and Forestry, 1999. Guidelines for hazard zones designation.)

CAIC. (2013) https://avalanche.state.co.us/index.php, Statement by Colorado Avalanche Information Centre.

Clarke. (2009) A possible Technique for Avalanche Prediction, Fourth year project report, CUED

Firth. (2008) A Possible Technique for Avalanche Prediction, Forth year project report, CUED

Keiler, M. 2004. Development of the damage potential resulting from avalanche risk in the period 1950- 2000, case study Galtür. Natural Hazards and Earth Systems Sciences 4, 249–256.

Kirkwood. (2011) A Possible Technique for Avalanche Prediction, Forth year project report, CUED

Salter. (2011) A Possible Technique for Avalanche Prediction, Forth year project report, CUED

11. Appendix

As a note on the risk assessment, this project had quite a complex assessment. With regards to testing in cold weather, appropriate clothing and gloves were worn at all times. The steps taken to ensure safety when testing on possibly dangerous slopes involved testing on flat surfaces and testing behind mounds on scoured snow. Following these ensured safe testing. The steps taken for the manufacturing of the probe were all followed and resulted in the safe assembly of all the testing device probes.