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Feasibility of Seismic Monitoring to Identify Avalanche Activity: Snoqualmie Pass, WA

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FEASIBILITY OF SEISMIC MONITORING TO IDENTIFY AVALANCHE ACTIVITY: SNOQUALMIE PASS, WA

A Thesis

Presented to

The Graduate Faculty

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In Partial Fulfillment

of the Requirements for the Degree

Master of Science

Geology

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by

Kathryn Johnston

June 2013

CENTRAL WASHINGTON UNIVERSITY

Graduate Studies

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ABSTRACT

FEASIBILITY OF SEISMIC MONITORING TO IDENTIFY AVALANCHE ACTIVITY: SNOQUALMIE PASS, WA

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June 2013

Avalanches across the Interstate-90 corridor over Snoqualmie Pass, in Washington State, are a concern for winter travelers and backcountry recreation. The temporary closure of the interstate for avalanche mitigation work also affects commerce by delaying transportation of merchandise. The study of seismic signals associated with snow avalanches could allow for greater understanding of avalanche properties, while remote sensing of avalanche activity could help established avalanche control programs and regional avalanche centers with forecasting and mitigation efforts. Two seismic stations were installed near the Alpental ski area on Snoqualmie Pass and recorded seismic activity throughout the winters of 2009-2010 and 2010-2011. During the winter of 2010-2011, two avalanches were successfully recorded, one artificially released with explosives and one naturally during a rain on snow event. These results show that it is possible to record avalanche activity over the traffic noise of the interstate and that avalanche activity can be distinguished from other seismic sources. Similarities in the seismic signals with previous research show distinct characteristics associated with avalanches, however, no further conclusions on the seismic characteristics unique to this avalanche path can be made with such a small sample size; more research is necessary.

ACKNOWLEDGMENTS

I would like to acknowledge all the people who have helped me complete my graduate studies at Central Washington University. John Stimberis with the Washington Department of Transportation and Alpental Pro-Patrol for his extraordinary help with field equipment and access to field locations. Dr. Charles Rubin for advising me in the first two years of study. Dr. Tim Melborne, Dr. Susan Kaspari, and Paul Winberry for support and assistance with my thesis. Also, Dr. Lisa Ely for all her help with graduation requirements.

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CHAPTER I

INTRODUCTION

Snow avalanches are a frequent hazard during the winter months in mountainous regions and avalanche mitigation work is necessary to alleviate some of the hazard. This is an obvious concern for winter recreationalists venturing out into avalanche prone terrain, however, it is also an concernfor transportation corridors, land use planning and development. Avalanche hazard also has economic consequences to regions specifically road closures due to avalanche mitigation, avalanche fatalities, and search and rescue costs. Recently, seismic monitoring of avalanches has shown potential for assisting avalanche professionals in forecasting and mitigation efforts.

Although avalanche forecasting techniques are well established, it is still hard to predict the exact timing and spatial distribution of avalanche activity. Detailed information of avalanche activity on a large spatial scale is difficult to obtain because backcountry travel is unsafe during periods of high avalanche danger. The spatial extent of many avalanche forecasts combined with the transient nature of the instability and the likelihood that, in maritime climates, most periods of instability occur during storms often do not allow for wide-ranging detailed observations of avalanche activity (McClung and Schaerer, 2006). Most avalanches occur in remote areas where real time information cannot be obtained, and a seismic array would provide information on spatial extent of avalanche activity in these remote areas, including slope aspect, and elevation. Understanding the spatial extent and variability of avalanche activity would benefit avalanche forecasters in focusing the first mitigation efforts to areas of the highest hazard.

In operations such as ski areas and transportation corridors, seismic monitoring of avalanche paths could provide verification of small avalanches that may negate the need for avalanche control and impacts to operations. An array of seismic sensors would also benefit regional avalanche centers by assisting in verifying their avalanche forecasts. The development of seismic techniques has wide-reaching benefits for avalanche control programs and as the technology continues to improve, more of these will become evident.

Previous Research

Efforts to monitor avalanches using seismic methods were first successful in 1976, when scientists used a vertically mounted geophone to record naturally occurring avalanches in the Bridger Range of south-western Montana (Lawrence and Williams, 1976). They successfully distinguished avalanche seismic signalsfrom other sources by collecting seismic data during the summer months when snow is not present. By comparing those signals to the winter seismic data, the signals associated with avalanche activity could be isolated. Using these seismic data, preliminary seismic characteristics of avalanche activity were also determined. Their data suggested that a slab avalanche initiates with a characteristic spike that relates to the slab fracture.

In 1996, the National Snow and Avalanche Research Association developed a prototype for an automatic detection system in France. The system was largely successful at detecting an increase in avalanche activity in an isolated region of the French Alps (Leprettre et al 1996, 1998). However, it requires a low seismic noise background, which is not possible along interstates with established avalanche mitigation programs due to heavy traffic volumes. This research from France produced the first prototype for an automatic detection of avalanches using seismic signals, and produced some general seismic characteristics for snow avalanches. They determined that avalanches generally produce long-duration signals with smooth amplitude variations (Leprettre et al. 1996, 1998), which distinguishes them from impulsive seismic sources.

In the eastern Pyrenees of Spain, seismic data were taken from multiple control avalanches and examined to improve the understanding of avalanche-generated seismic signals (Suriñach 2000, 2001). Their results showed that slope angle, geometry, and impacts with obstacles indicate changes in the avalanche path that correspond to changes in the seismic signal. Using video imagery of avalanches, the different waveforms can be attributed to these changes in the avalanche path. They also proposed that since avalanche size could be correlated with amplitude, seismic signals could be used to estimate the size of the avalanche. However, even with an established relationship between thesize of an avalanche its amplitude, the general seismic signatures of avalanches are dependent on the location of the geophone and the slope geometry (Suriñach 2000, 2001).

Further research was conducted by the Universidad de Barcelona at the ski resort Vall de Nùria in Switzerland from 1998-2000 to understand how the seismic response changes under a variety of snow and avalanche types and sizes and the frequency content evolution was analyzed (Biescas et al. 2003). Previously, seismic research had only been focused on monitoring purposes; however, with current research, seismic signals may provide additional information on avalanche dynamics. Avalanches that were large enough to be detected showed a distinct triangle pattern in the spectrogram, a three-component plot showing time versus frequency content with amplitude displayed as a color gradient (Biescas et al. 2003). Spectrograms are essential to identifying and analyzing a seismic event that could be attributed to a snow avalanche. Depending on the placement of the geophone with respect to the avalanche path, spectrograms showed either increasing frequency content and increasing amplitude if the starting zone is a significant distance away from the sensor, or decreasing frequency and decreasing amplitude content where the geophone is near the starting zone of the avalanche, and with either situation the triangular pattern can be identified. When results were compared to that of the seismogram of an earthquake there are distinct differences. High frequency waves attenuate faster than lower frequencies; therefore, in the spectrogram of an earthquake there is a significantly smaller frequency range than that of an avalanche. As an avalanche passes over the geophone the frequency increases greatly and then decreases as the avalanche moves on; this is known as the Doppler Effect and is not evident in the seismogram of an earthquake. This Doppler Effect is caused because of the movement of an avalanche (Biescas et al. 2003).

It is also possible to use seismic sensors to determine avalanche velocity and this has many practical applications in land use planning and development. Research from Oslo, Norway has investigated avalanche speed using multiple seismic sensors located on avalanche paths. Using avalanche speed information can allow avalanche forecasters and land use planners to determine runout distance, and then plan developing ski areas and communities in mountainous regions around areas of potential avalanche hazard. (Vilajosana et al. 2006).

Recently, research conducted in Davos, Switzerland confirmed that avalanches can be detected using geophones for a distance up to 2km (van Herwijnen, 2011). Avalanche activity was confirmed using automatic cameras and microphones to identify erroneous seismic sources, allowing for seismic classification of aircraft, ski lift, and snowcat noise. Seismic characteristics for avalanche activity cannot be fully classified because impacts with terrain features and slope characteristics affect the seismic signals and therefore the seismic data can only be considered on a slope-specific scale (van Herwijnen, 2011). Once the typical seismic signal for a specific slope is determined, natural stabilization due to avalanche activity can be determined during times of limited visibility, reducing the amount of necessary mitigation work.

Research Objectives

The focus of this thesis is to assess the feasibility of using seismic techniques to streamline avalanche forecasting and control efforts for a highway avalanche control program, and my research was conducted in close association with a large-scale highway avalanche control program run by the Washington State Department of Transportation (WSDOT). Seismic signals associated with snow avalanches could provide new information on avalanche dynamics and provide a new useful tool in forecasting and control efforts. Signals can assist avalanche professionals in the documentation of avalanche activity, which is important during avalanche control work when explosives are used to trigger an avalanche and reduce the hazard. Also, seismic monitoring could help to confirm when the avalanche activity has naturally occurred and more control work is no longer necessary.

The area of study in this thesis is Snoqualmie Pass, Washington and the details of the seismic instrumentation site and associated avalanche paths are discussed in Chapter 3. Snow avalanche mitigation along the Interstate-90 (I-90) corridor, East of Seattle, Washingtonis mostly successful, though unexpected avalanches do occur and threaten the safety of travelers and highway workers. Highway delays and closures for scheduled avalanche control work amount to numerous hours of traffic delay and a significant economic impact to the region. Avalanche control during the 2007-2008 winter resulted in nearly 400 hours of delay to travel; one storm resulted in a 28-hour closure and economic impacts were estimated to have totaled nearly 28 million USD (Ivanov et al. 2008). Currently no remote avalanche monitoring system is in use at Snoqualmie Pass.

The WSDOT avalanche forecasters monitor the weather and snowpack structure to forecast snow instability and perform avalanche control as needed. Documentation of natural avalanches is largely dependent on visibility, weather, and availability of observation staff. Alternate methods of observation and forecasting will reduce the threat of naturally occurring avalanches and improve forecasting accuracy during times of low visibility at night or during heavy snowfall. During times of heavy snowfall, the danger to highway workers may increase and a remote monitoring system would be useful in risk assessment. An avalanche detection system would increase the ability to confirm that avalanche activity has occurred during control work and therefore, the hazard is being reduced.

Several avalanche paths along the I-90 corridor may benefit from remote seismic avalanche detection because small order avalanches may represent a decrease in the potential hazard from the particular path, thus reducing the need for avalanche control activities. This would reduce some of the uncertainty associated with avalanche control work for the WSDOT and shorten the length of road closures, which would benefit the regional economy by reducing the restriction of transportation of goods and materials. Verification of the size and timing of the avalanches could provide a benefit to operations by confirming the size of a natural avalanche, which provides information to assess the need for additional control work later during a heavy storm. The need for avalanche control could be postponed to a period of low traffic volume, thus reducing the impact for the regional economy (Stimberis, personal communication, 2012).

A significant amount of research on avalanche seismicsignals has been done in Europe, but research on this subject has been less extensive in the United States (Biescas, 2003, Surinach, 2000, 2001, Leprettre, 1996, 1998, Navarre, 2009). Conditions of the avalanche paths in my research from Snoqualmie Pass, WA are different because the avalanche paths are located within the tree line and are much smaller in spatial extent, while the researchconducted in Europe was above the tree line and located on large open slopes. Different slope conditions and snow types affect the seismic signals and therefore more preliminary research is necessary studying different types of avalanche paths (Biescas, 2003, Surinach, 2000,2001, Leprettre, 1996, 1998, Navarre, 2009).

This thesis details seismic research conducted near Snoqualmie Pass, WA. Throughout the winters of 2009-2010 and 2010-2011, I investigated the reliability of using seismic techniques to monitor avalanche activity and the difficulties with using electronic seismic systems in the harsh winter environment. The seismic signals were also studied for characteristics specific to avalanches. The results of this study are presented here, as well as the implications for future work and the potential for seismic monitoring of avalanche activity in the future.

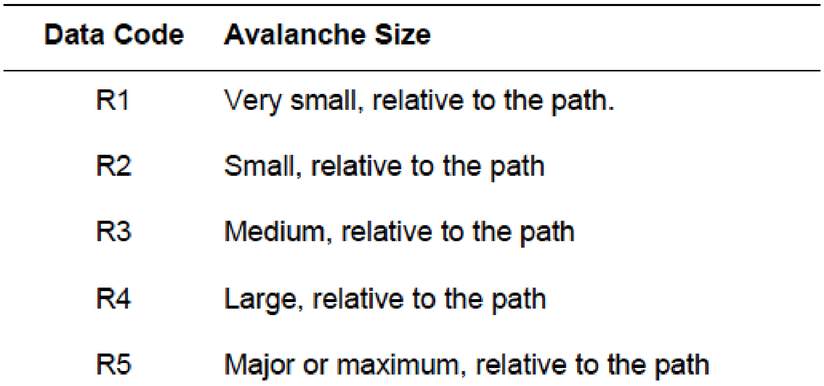
CHAPTER II

BACKGROUND

A snow avalanche occurs when a mass of snow releases and slides down a slope. Of Earth’s surficial materials- including soils, rock, ice, and snow- snow is the weakest. This fact makes the frequency of snow avalanches much greater than landslides, rock avalanches, or ice avalanches (McClung and Schaerer 2006). On a global scale, snow avalanches do not have as large an effect on human life or economics in relation to other natural disasters. In regions with avalanche activity, however, avalanches do have a significant impact. In Washington State, avalanche deaths far outnumber deaths from other natural disasters.The United States averages 24 avalanche fatalities per year, while in Washington state alone avalanches have killed 58 people since 1986, an average of 2.1 per year (NWAC, 2013). A seismic avalanche monitoring system could assist professionals working for regional avalanche centers, highway control programs, and ski areas with forecasting and mitigation efforts. Mountainous regions also rely heavily on winter tourism and recreation; therefore, avalanche safety, forecasting, and mitigation are very important. Forecasting and mitigation techniques are especially important for transportation corridors through mountain regions to ensurethe safety of travelers and highway workers (McClung and Schaerer, 2006). The ability to better-forecast avalanche conditions can decrease the effect of avalanches on human life and economic loss.

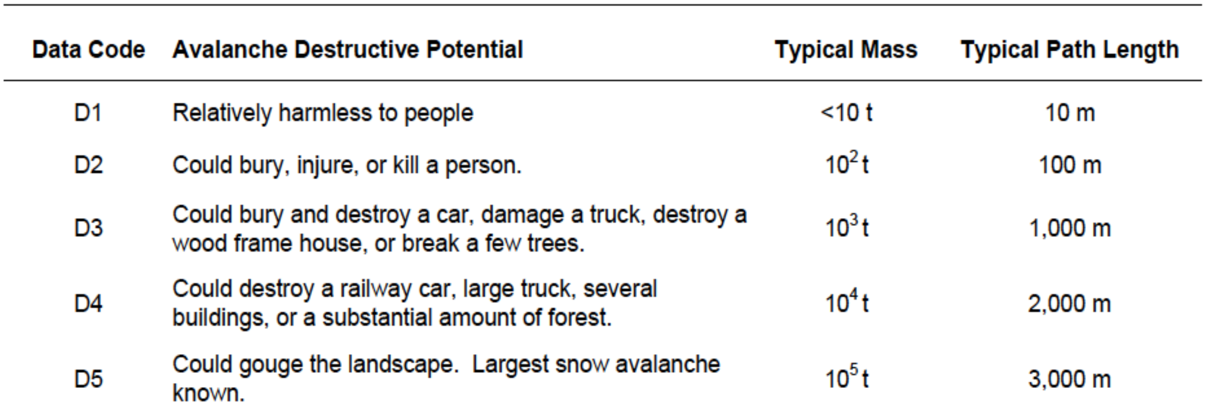
On a small scale, avalanche determination using seismic methods can assist highway control programs in mitigation efforts by decreasing cost and length of road closure. While on a regional scale daily recreational avalanche reports could be assisted by a large spatial scale seismic array providing information on elevation, aspect, and area of current avalanche activity (Stimberis, personal communication, 2012).

Most snow avalanches form by a load that is added to the top of the snowpack when a storm deposits snow or wind transports snow at the surface (McClung and Schaerer, 2006). Avalanches are usually categorized as either loose snow or slab avalanches. These categorizations are further qualified as involving either dry-snow or wet-snow. Either type of avalanche can have an adverse effect on transportation, but slab avalanches have the biggest impact on recreationalists, and dry-snow slab avalanches have the biggest effect on property and resources due to the potential for enormous impact forces depending upon the size. Both size (Table 1) and destructive forces (Table 2) are recorded following a logarithmic scale of mass and path length (Greene et al. 2010). Using this scale the size of an avalanche is considered relative to its path, so an avalanche could be an R2 but have a destructive potential of D4. This makes it important to consider both classifications when analyzing an avalanche event.



Data Code	Avalanche Size
R1	Very small, relative to the path.
R2	Small, relative to the path
R3	Medium, relative to the path
R4	Large, relative to the path
R5	Major or maximum, relative to the path

Table 1: Avalanche size scale from the Snow, Weather, and Avalanche Guidelines handbook. The size of the avalanche in this scale is relative to the avalanche path (Greene et al. 2010).



Data Code	Avalanche Destructive Potential	Typical Mass	Typical Path Length
D1	Relatively harmless to people	<10 t	10 m
D2	Could bury, injure, or kill a person.	10^2 t	100 m
D3	Could bury and destroy a car, damage a truck, destroy a wood frame house, or break a few trees.	10^3 t	1,000 m
D4	Could destroy a railway car, large truck, several buildings, or a substantial amount of forest.	10^4 t	2,000 m
D5	Could gouge the landscape. Largest snow avalanche known.	10^5 t	3,000 m

Table 2: The scale for the destructive potential of an avalanche from the Snow, Weather, and Avalanche Guidelines handbook (Greene et al. 2010).

The prediction or forecasting of when and where avalanche conditions will occur is challenging due to the dynamic nature of the seasonal snowpack and inconsistency in snow layering and deposition on a slope-scale. Recreation based avalanche forecasts are developed on a regional scale, whereas established avalanche control programs tend to produce forecasts based on a slope scale, or basin/sub-basin scale.

Avalanche initiation is categorized as natural, occurring without anthropogenic influence, or human-triggered, initiated by backcountry travelers or explosives. (Greene et al. 2010). Avalanches release when certain conditions are present, loose snow avalanches are triggered when a loss of cohesion in surface snow occurs, and slab avalanches are triggered when shear stresses reach a critical point and a fracture is initiated and the snow slab fails. For either type of avalanche, a snowpack of ample height to cover anchors and terrain roughness must exist (McClung and Schaerer 2006).

To understand how the slab avalanche is initiated, it is first critical to understand how the snowpack develops over the winter and on a smaller temporal scale during a storm. During the winter, meteorological variables (e.g. temperature, humidity, and wind) drive the precipitation to change either drastically from rain to snow or changesoccur on a molecular scale affecting the type of crystal structure of the falling snow. These meteorological changes create a stratified snowpack. For example, the typical star shaped snow crystal, known as a dendrite or stellar, will form at -12 to -16°C at supersaturation, while needle-like snow crystals will form at warmer temperatures of -3 to -5°C at supersaturation (Fierz et al. 2009). Another example of how weather creates stratigraphy within the snowpack is that high winds during a storm lead to more cohesive snow, resulting in slab avalanche conditions. Because the stratigraphic layers within the snowpack have different bonding properties, they also have different friction coefficients, and when a layer has a small friction coefficient it can be considered a weak layer. The small friction force can be overcome by the shear stress of loading snow and a slab avalancheoccurs. Over time, if no avalanche occurs, the snow undergoes settlement and crystal metamorphosis occurs, and the threat of avalanche is decreased. Persistent weak layers are those that metamorphose slowly and create an avalanche hazard for a long duration of time (McClung and Schaerer, 2006).

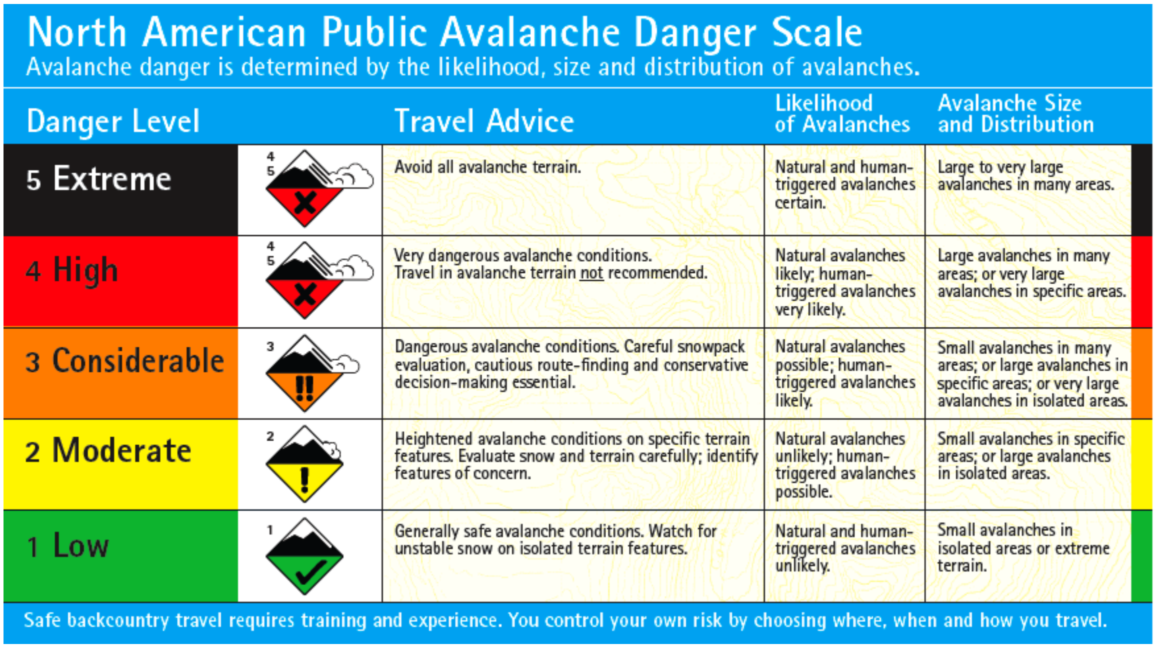
Snow crystals can also undergo metamorphosis within the snowpacktocreate weak layers, which is known as faceting. This occurs when there is a significant temperature gradient in the snowpack, which happens when the temperature in the snowpack changes by at least 10°C/m. This promotes fast crystal growth rates due to high vapor pressure and the crystals tend to be angular and have low bonding properties which create an avalanche hazard (McClung and Schaerer, 2006).

Another type of slab avalanche, known as a glide avalanche, occurs when the entire snowpack slips down a smooth slope. This slip is related to the roughness of the snow-ground interface and the presence or absence of liquid water at this interface. As the snowpack begins to glide, the tensile stress on the stationary part of the snowpack is greatly increased and a glide crack forms. Often this is associated with an increase in glide speed of the snowpack below the crack. This glide effect often results in full-depth avalanches where the entire snowpack is involved (McClung et al. 1994). These full-depth avalanches due to glide can be dangerous and difficult to predict and control, unlike normal avalanche conditions. If no free water is present at the snow- ground interface at the time of control work it is likely that no avalanche will occur, however, if free water becomes present at the interface at a later time, an unexpected avalanche can occur on the slope (McClung et al. 1994).

Snoqualmie Pass, located in the Washington State Cascade Mountains, has long been a frequently travelled corridor for people, goods, and recreation. The pass hosts four small ski areas, Alpental, Summit West, Summit Central, and Summit East, and also has a high volume of snowshoe, cross-country, and backcountry recreationalists. It is an avalanche prone area and the interstate has a developed avalanche control program utilizing explosive control work, a snow-shed tunnel, and professional avalanche forecasters to mitigate avalanche hazard to the roadway.

The research I conducted on Snoqualmie Pass, WA focuses on the seismic response to avalanches for monitoring and control purposes. In particular, we study avalanche cycles caused by rain-on-snow events, which are common in maritime climates. Rain-on-snow events occur when winter temperatures rise above 0°C and precipitation turns from snow to rain. The rain moves through the top layers of the snowpack and begins to consolidate the snow crystals and the deformation in the upper snowpack increases. This occurs preferentially through multiple drain channels within the snowpack and the snow surface above these channels deforms at raster rates then the surrounding surfaces, and therefore, the topography of the surface is changed. The different deformation rates of the snow surrounding these drain channels could produce stresses that result in avalanches (Conway and Raymond, 1993).

The accurate prediction of natural and human triggered avalanches is the goal of avalanche hazard forecasts. The North American Public Avalanche Danger Scale utilizes a 5 level rating scale to convey the avalanche hazard from both natural and human triggered avalanches (Table 3). The danger scale takes into account size, distribution, and likelihood of an avalanche. Although it not intended to be a substitute for knowledge of snowpack analysis while traveling in avalanche terrain, it provides a generalized guide for what to expect in the snowpack (American Avalanche Association). Regional avalanche centers produce bulletins using this danger scale to rate the hazard on various aspects and elevations.



North American Public Avalanche Danger Scale

Avalanche danger is determined by the likelihood, size and distribution of avalanches.

Danger Level		Travel Advice	Likelihood of Avalanches	Avalanche Size and Distribution
5 Extreme	4 5	Avoid all avalanche terrain.	Natural and human-triggered avalanches certain.	Large to very large avalanches in many areas.
4 High	4 5	Very dangerous avalanche conditions. Travel in avalanche terrain not recommended.	Natural avalanches likely; human-triggered avalanches very likely.	Large avalanches in many areas; or very large avalanches in specific areas.
3 Considerable	3	Dangerous avalanche conditions. Careful snowpack evaluation, cautious route-finding and conservative decision-making essential.	Natural avalanches possible; human-triggered avalanches likely.	Small avalanches in many areas; or large avalanches in specific areas; or very large avalanches in isolated areas.
2 Moderate	2	Heightened avalanche conditions on specific terrain features. Evaluate snow and terrain carefully; identify features of concern.	Natural avalanches unlikely; human-triggered avalanches possible.	Small avalanches in specific areas; or large avalanches in isolated areas.
1 Low	1	Generally safe avalanche conditions. Watch for unstable snow on isolated terrain features.	Natural and human-triggered avalanches unlikely.	Small avalanches in isolated areas or extreme terrain.

Safe backcountry travel requires training and experience. You control your own risk by choosing where, when and how you travel.

Table 3: The North American Public Danger Scale. This scale provides information for backcountry recreationalists on the avalanche danger for the forecast period (http://avalanche.org/danger_card.php).

CHAPTER III

STUDY AREA

Snoqualmie Pass, WA is located in the heart of the Cascade Mountains approximately 220km west of the Pacific Ocean. Mountain climates located in close proximity to oceans are known as maritime climates and are characterized by heavy snowfall and mild winter temperatures that average near 0°C. The wind patterns that drive local circulation originate from the west between 30ºN to 60ºN, and push moist air masses from the Pacific Ocean onto the west coast of Washington and into the Cascade Mountain range. Precipitation in these regions is dominated by orographic lifting of coastal air into the high elevations of the mountains, resulting in very high precipitation rates. The average precipitation for Snoqualmie Pass is approximately 266cm water equivalent, with 50-80% of this falling in the winter in the form of snow for an average of 1100cm of snowfall per year (WRCC, 2012). Average temperatures for the region during the winter months are approximately -2ºC (WRCC, 2012). Because the mean temperature for the region is close to 0ºC, the region experiences many rain-on-snow events during the winter season. Often this involves the influx of warm air masses from the coast associated with frontal air masses. Warming air temperatures and solar radiation result in speeding the deformation of the surface snow and create stresses the snowpack leading to instability and high avalanche potential. During the spring months, active avalanche conditions and instability are prevalent because of the heavy snowfall characteristic of the Cascade Mountain maritime climate along with high potential for rain-on-snow events, and the increased effect of solar radiation that occurs during the spring, when snowpack is close to maximum and terrain features are covered (McClung and Schaerer, 2006).

There were two seismic site locations in this study, Denny-9 and Rockface; both are accessed from the Alpental Ski Area on Snoqualmie Pass, WA. Continuous seismic data from both field sites were collected throughout the 2009-2010 and 2010-2011 winter seasons. The Rockface location (Figure 1) was chosen because it experiences full-depth glide avalanches, unfortunately, no seismic avalanche data from the Rockface site are used in this study because no avalanche activity was recorded. However, an earthquake was recorded from this site location. Interstate-90 along Snoqualmie Pass has multiple avalanche paths that have the potential to reach the road, and because of this are frequently subject to mitigation efforts. The Denny-9 avalanche path (Figure 2) trends south from the Alpental Ski Area towards the interstate. The South facing slide path has several start zones ranging from 1100-1350m in elevation upslope from the seismic station location, which is at an elevation of 1030m. Average slope angle ranges from 35º-50º in the starting zones and 25º-30º in the avalanche track to the run out zone. The Denny-9 location was chosen because it avalanches frequently and although it has the potential to reach the interstate, frequent avalanching reduces the likelihood for avalanches to reach the full extent of the runout. Avalanches that reach the interstate occur roughly once every three years (WSDOT, 2012). This makes the site excellent for forecasting purposes and is also important to the study because it is frequently artificially controlled.

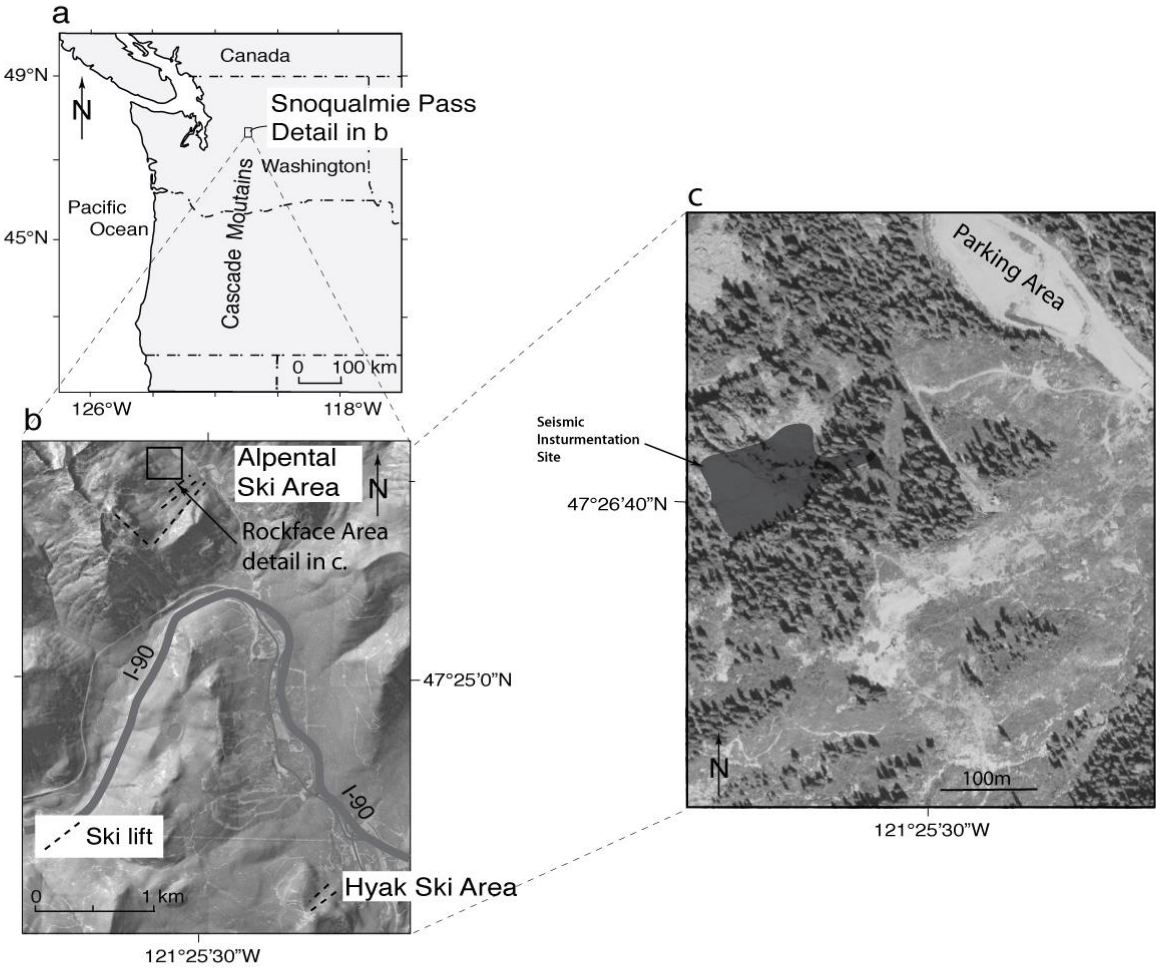


Figure 1: Location of Rockface site (a) Location of Snoqualmie Pass in relation to the Cascade Mountains. (b) Location of Alpental Ski area (976m) (c) Detail of Rockface avalanche path in relation to Alpental Ski Area

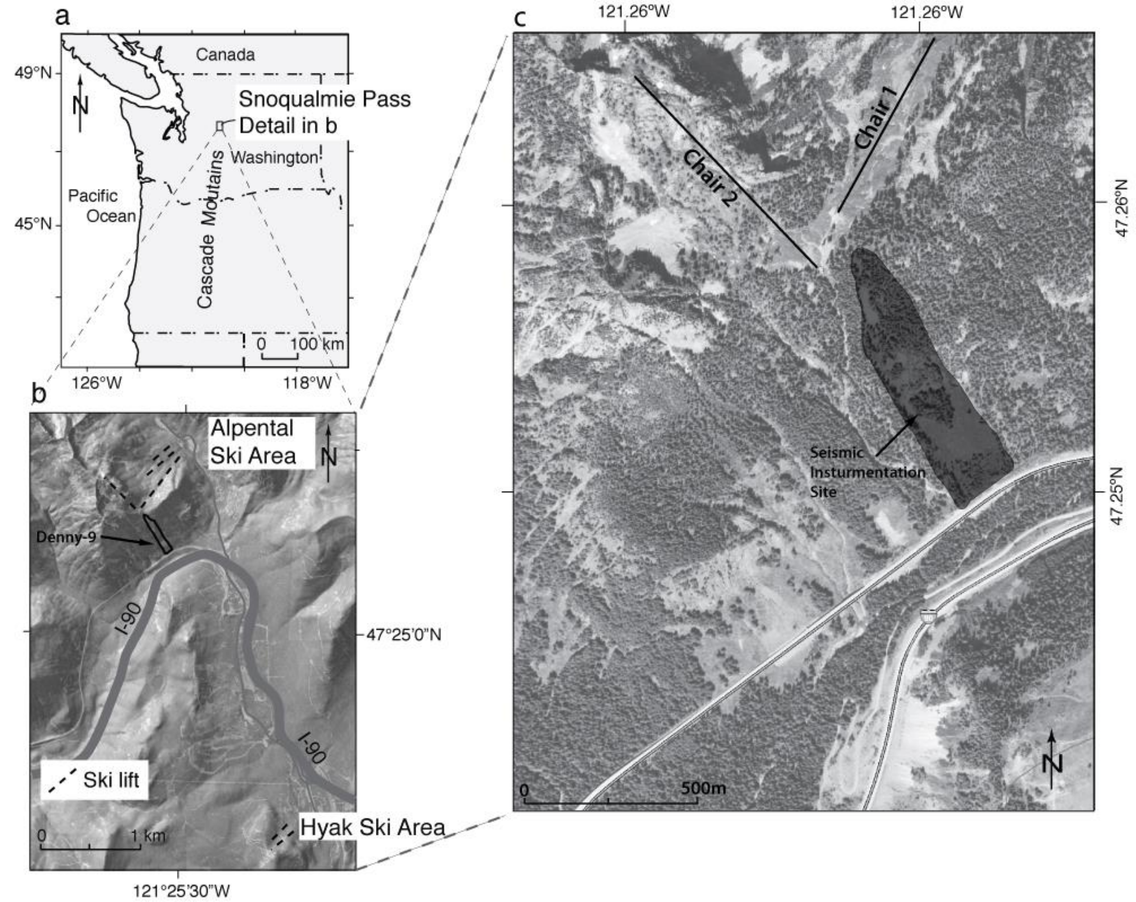


Figure 2: Location of Denny-9 site (a) Location of Snoqualmie Pass in relation to the Cascade Mountains. (b) Location of Alpental Ski area (976m) and Denny-9 slide path in the Interstate-90, WSDOT study site (921m). (c) Denny-9 study site with seismic instrumentation locations.

The ability to determine avalanche activity through seismic data would allow avalanche activity confirmation during times of low visibility. Rockface is located on a smooth rock surface and is also equipped with a glide potentiometer, allowing for the identification of glide events that may result in full depth avalanches. Denny-9, located closer to I-90, determines if it is possible to detect avalanches over the seismic noise from passing traffic. Denny-9 is equipped with a broadband seismometer that records continuously throughout the winter and Rockface is equipped with a three component geophone with a 2Hz natural frequency also recording throughout the season. The Rockface location is also equipped with a weather station that records air temperature, snow temperature, wind speed, and a radiometer. Data from this weather station were used for the meteorological data in this study. Both sites used a Quanterra digitizer sampling at 100 samples per second (sps) and data was stored on a Quanterra Bailer for periodic downloading. They are powered with two 12V deep cycle batteries that are charged with solar panels.

Harsh winter conditions in the Cascade Mountains make it difficult for running electronic equipment in this environment. Wet conditions can lead to electrical shorts and consistent cloud cover makes it difficult to maintain batteries using solar panels. There were many times during these two field seasons that we found the seismic equipment without power.

CHAPTER IV

DATA ANALYSIS

In my study Passcal Quick Look was used to analyze the raw seismic data. Data were analyzed for potential avalanche activity and correlated with meteorological conditions associated with natural avalanche conditions, and compared to direct observations to confirm that the signals were associated with avalanche activity. Meteorological conditions that are associated with natural avalanche activity include rapid temperature increases, heavy snowfall, high winds, and rain-on-snow events. The seismic data associated with the natural avalanche activity in this research focuses on rain-on-snow events. Information on avalanche control from the WSDOT and Alpental Pro-Patrol was also used to correlate avalanche events, both natural and artificially triggered, if avalanche control work was conducted.

The seismic signals associated with avalanche activity are converted into a format readable by Seismic Analysis Code (SAC) using Unix computer code. SAC is then used to run high pass filters to remove noise from the seismogram (Claerbout, 1985). Noise sources include earthquakes, snow falling from trees, highway traffic, skier traffic, and tree-coupled wind noise. Using the Pacific Northwest Seismic Array earthquake catalog, it is relatively simple to eliminate seismic signals generated by earthquakes. Seismograms from avalanche events are identified and SAC is used to isolate avalanche signals and create power spectrums and spectrograms for analysis. Trends over time in seismic data are common and are removed using SAC commands. SAC is then used to run a Fast

Fourier Transform on the seismogram to create spectrograms with distinct characteristics associated with avalanche activity (Figure 3). Figure 3 illustrates the general procedure for data processing from raw data to seismogram and spectrogram time series.

The seismic response to an earthquake was recorded at the Rockface location on March 29th, 2010. The recorded seismogram was compared to a seismic study location in Ellensburg, WA, courtesy of the Incorporated Research Institutions for Seismology and the seismic signal was typical for an earthquake (IRIS) (Figure 4). Although recording the seismic signal of an earthquake was not the goal of my research it confirmed that the seismic instrumentation is working correctly.

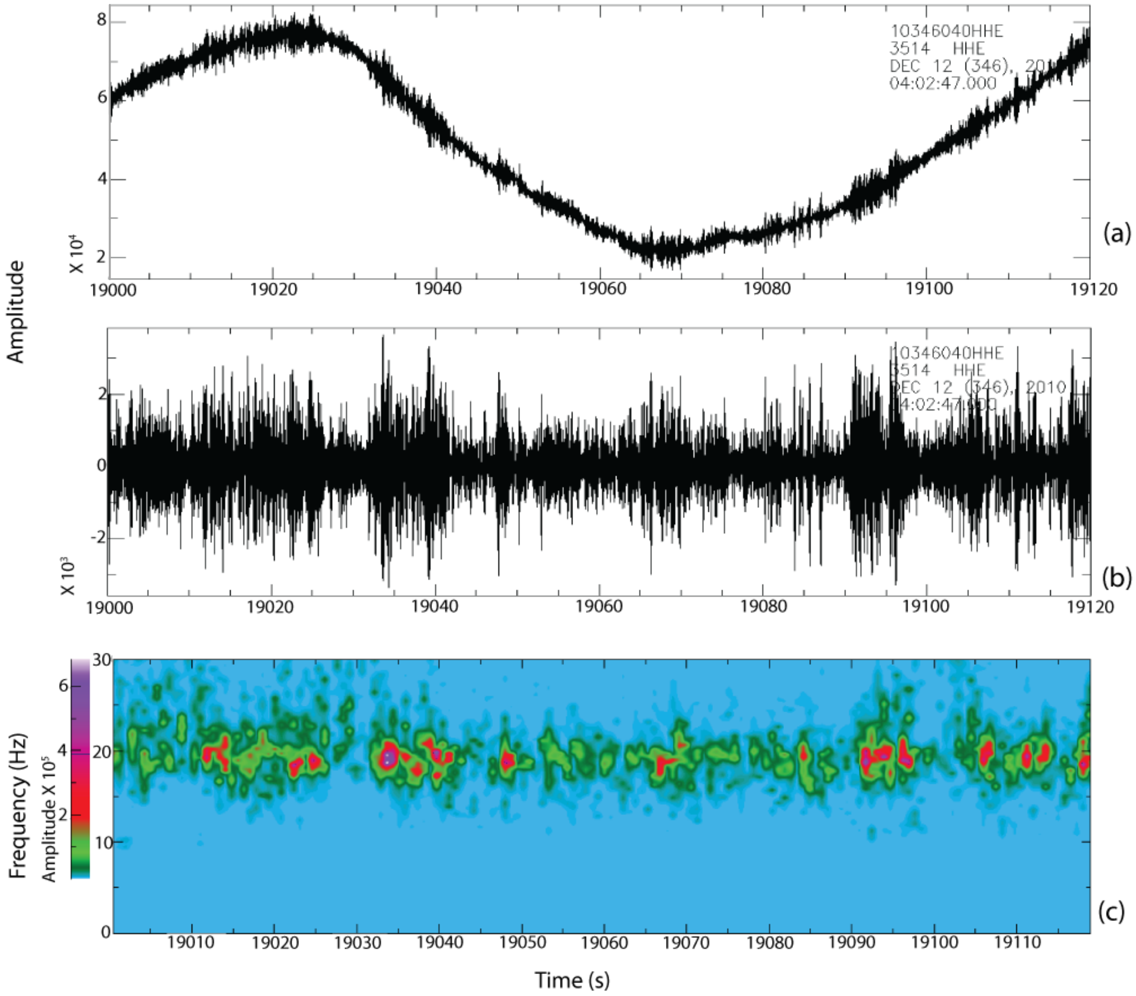


Figure 3: Background seismic noise recorded at Denny-9 site. (a) Raw seismogram (b) Seismogram normalized and high pass filtered at 2Hz (d) Spectrogram of normalized seismic data.

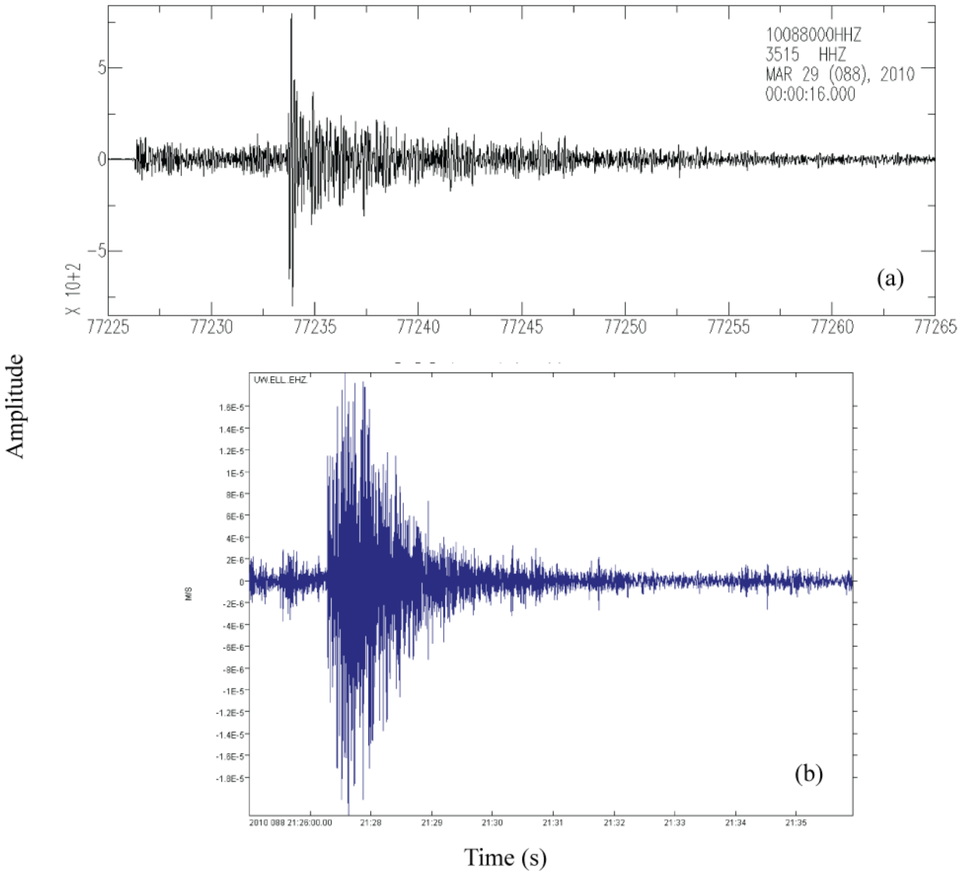


Figure 4: Seismic signals from an earthquake: Magnitude 3.8 located at 46.999°N and 120.995°W at a depth of 4Km. (a) Seismogram from Rockface field site. (b) Earthquake recorded by seismic station ELL located in Ellensburg, WA provided by IRIS.

CHAPTER V

RESULTS

2009-2010 Results

During this research two avalanches were recorded using the seismic equipment. Both avalanches were from the Denny-9 location and occurred during the 2010-2011 winter season. The 2009-2010 winter produced no avalanches on the Denny-9 avalanche path, and a glide avalanche that occurred on Rockface was not registered on our equipment and through the course of my research we did not pinpoint the problem. Van Herwijnen's research in Switzerland used a very similar experimental design and recorded smaller avalanches (van Herwijnen, 2011). The lack of avalanche activity being recorded by the geophone on Rockface could potentially be due to different forces behind glide avalanches and the lubrication of the bed surface limiting seismic wave permeation into the rock.

December 12, 2011

Weather and Snowpack Observations

Significant snowfall and rapid accumulation occurred during the winter of 2010-2011, particularly during November and December. The snow fell at temperatures ranging from -7 to -2ºC, developing an initially cold and consistent snowpack with little initial avalanche activity. On December 11th, 2010 a snow profile showed a potential weak layer 40cm down from the surface consisting of rimed stellar snow crystals of 2mm (Figure 5). The total snow depth was 220cm with an insignificant temperature gradient.

On December 12, 2010 achange to abovefreezing temperatures in the Cascades was seen as a warm air mass moved in at 00:00 hrs and temperatures rose rapidly to 5.5ºC, a temperature increase of approximately 10ºC (Figure 6). The warming event changed precipitation from snow to rain and the first major avalanche cycle of the season began. A cold dry air mass then moved into the Cascade Range bringing only trace amounts of precipitation and snow accumulation, along with a return to cold temperatures. During this time, limited precipitation allowed for snowpack consolidation and stabilization.

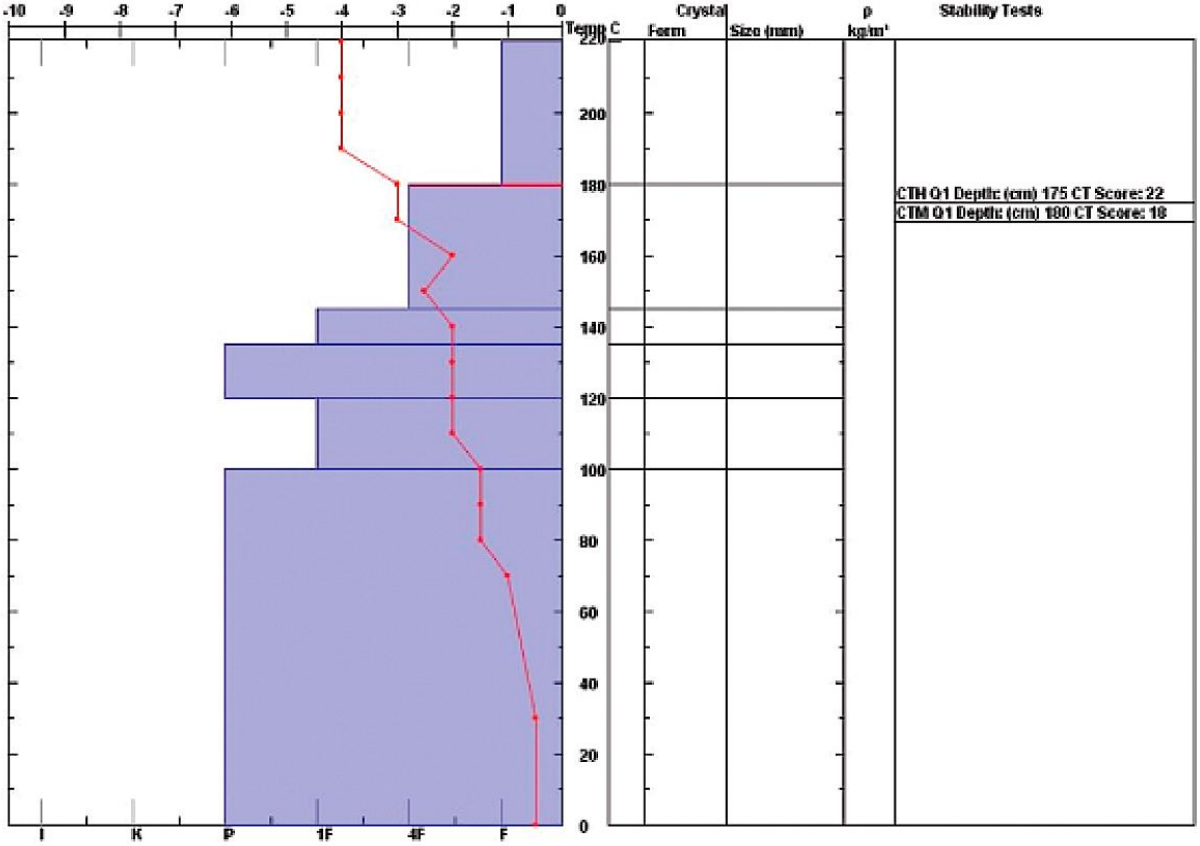


Figure 5: Early Season snow profile: Completed December 11, 2010 at 1300hrs. Indicating instability in the snowpack between 100-220cm.

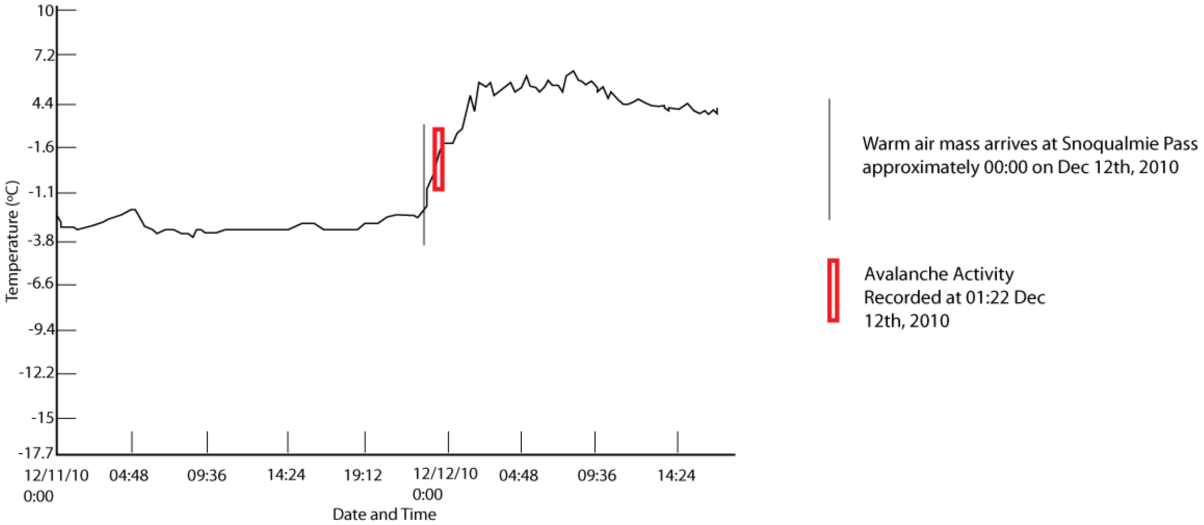


Figure 6: Temperature versus time plot of warm air mass arrival at Snoqualmie Pass:Heavy precipitation from December 11 through December 12, 2010

Avalanche

On December 12, 2011 heavy precipitation quickly added a significant load to the snowpack and warming temperatures initiated a wide spread avalanche cycle. A natural avalanche was recorded at the Denny-9 site location shortly after the arrival of the warm air mass at Snoqualmie Pass. The seismic signal from the avalanche was recorded at 01:22 and a seismogram and spectrogram of the event were created using SAC (Figure 6). There was a delay of 1 hour and 22 minutes from the arrival of the warm air mass to the recorded avalanche activity. During a rain event, avalanche activity responds in two phases; immediate avalanching and delayed avalanching (Conway and Raymond, 1993). It seems that in this case a delayed avalanche had occurred as the surface snow became increasingly dense as liquid water from the rain collected in the upper snowpack. The weak snow underneath the increasingly dense snow could not support the extra weight and therefore an avalanche occurred.

The Washington State Department of Transportation (WSDOT) investigated the avalanche on December 12, 2011 on the Denny-9 slide path and the WSDOT avalanche forecasters reported the conditions of the avalanche as a small wet, loose avalanche with a path size of 1 (out of 5) and a destructive potential of 1 (out of 5), relatively harmless to a person (SWAG). The avalanche started at the flank wall and traveled down slope 60m before stopping at the seismic sensor location (WSDOT, 2012, Stimberis, personal correspondence, 2012).

Seismic Signal

The seismic signal associated with the December 12, 2011 avalanche indicates a small avalanche size because of low amplitudes and a higher dominant frequency. The higher dominant frequency could also be characteristic of the geometry of the Denny-9 slide path being narrow at the starting zones. The smaller the extent of the avalanche fracture area, or crown, will dictate the dominant frequency of the seismic signal. A larger spatial extent will create a lower dominant frequency. In this case the narrow geometry of the avalanche path creates a higher dominant frequency. However, as the avalanche entrains more snow the dominant frequency is subsequently lowered; this is evident in the spectrogram of the December 12 avalanche (Figure 7). The signal also shows that the seismic source was in motion because increasing frequency content is evidence of the Doppler Effect. In our spectrogram, the frequency content shows a steady increase from 15Hz to 25Hz as the avalanche moved down the path towards the study site.

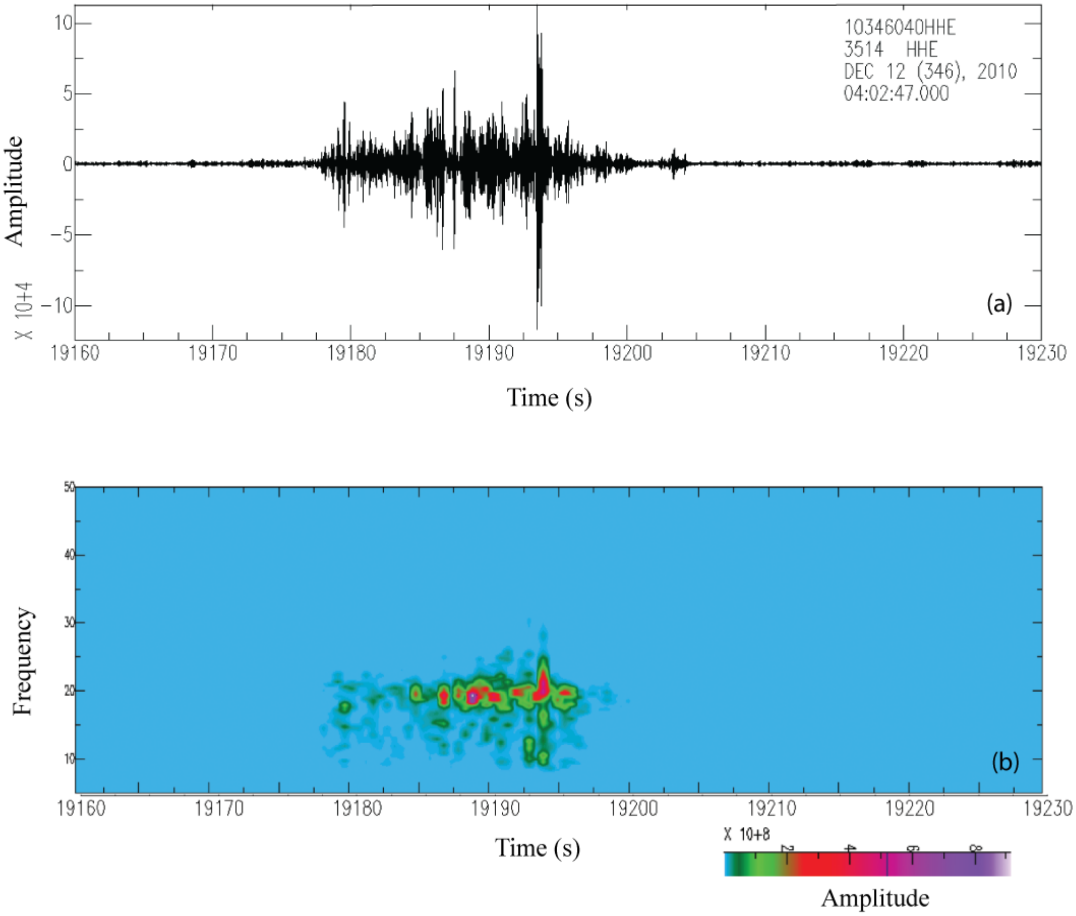


Figure 7: Seismic Signals from avalanche on December 12, 2010(a) Seismogram of natural avalanche on Denny-9 (b) Spectrogram of avalanche.

March 10, 2011

Weather and Snowpack Observations

In spring 2011, the Washington Cascades received above average snowfall and accumulation attributed to La Niña conditions of the El Niño Southern Oscillation in the Equatorial Pacific Ocean. Heavy snowfall during the late winter to early spring often produces significant avalanches as the snowpack is near maximum, thus, anchors are buried and avalanche paths are full.

Heavy snowfall produced several avalanche cycles throughout the month of March, 2012 and the WSDOT was involved in multiple avalanche mitigation efforts on Snoqualmie Pass. Beginning on March 9 temperatures began to increase from -4°C to 2°C and the temperature increase was accompanied by snowfall; 33cm of high-density snow fell in less than 48hrs. The new snow was deposited on top of a melt freeze layer above low-density snow that fell on March 4 and 5 when temperatures were approximately -6°C. Qualitative snow stability tests, such as the compression test, are performed in order to determine slope stability and whether avalanche control is necessary. A compression test (CT) done by the WSDOT on March 10, 2011 produced a CTM13 at 20cm depth with a Q3 shear and a CTH23 at 35cm depth with a Q2 shear. A CT score of M13 and H23 indicate medium and hard failure probability respectively. Shear quality represents the ability of the slab fracture to propagate; Q2 and Q3 shears indicate an average to low propagation prediction. The shallow failure occurred on a melt freeze crust and the deeper failure on another crust below the low-density snow.

A forecaster would consider these results to indicate moderate to considerable avalanche potential on this slope. Although these results do not indicate a highly unstable path, some instability is evident and due to the nature of the storm, heavy high-density snow deposited on low-density snow, control efforts are still necessary for traveler safety.

Avalanche

On March 10 at approximately 12:00am, explosive control efforts produced an avalanche on the Denny-9 path. This avalanche consisted of wet, loose snow and labeled for path size relative to maximum path as R3, the vertical fall was 150m and the avalanche stopped near the location of the seismic instrumentation. The avalanche had a destructive potential of 2, and the released on the new snow/old snow interface. If a natural avalanche could have been confirmed on this avalanche path using seismic data control efforts likely would have been averted (Stimberis, personal correspondence, 2012).

Seismic Signal

On March 10 the broadband seismometer recorded the explosive avalanche mitigation by the WSDOT and the resulting avalanche. The seismogram of this avalanche event shows two explosions and the avalanche signal between the two explosions (Figure 8).

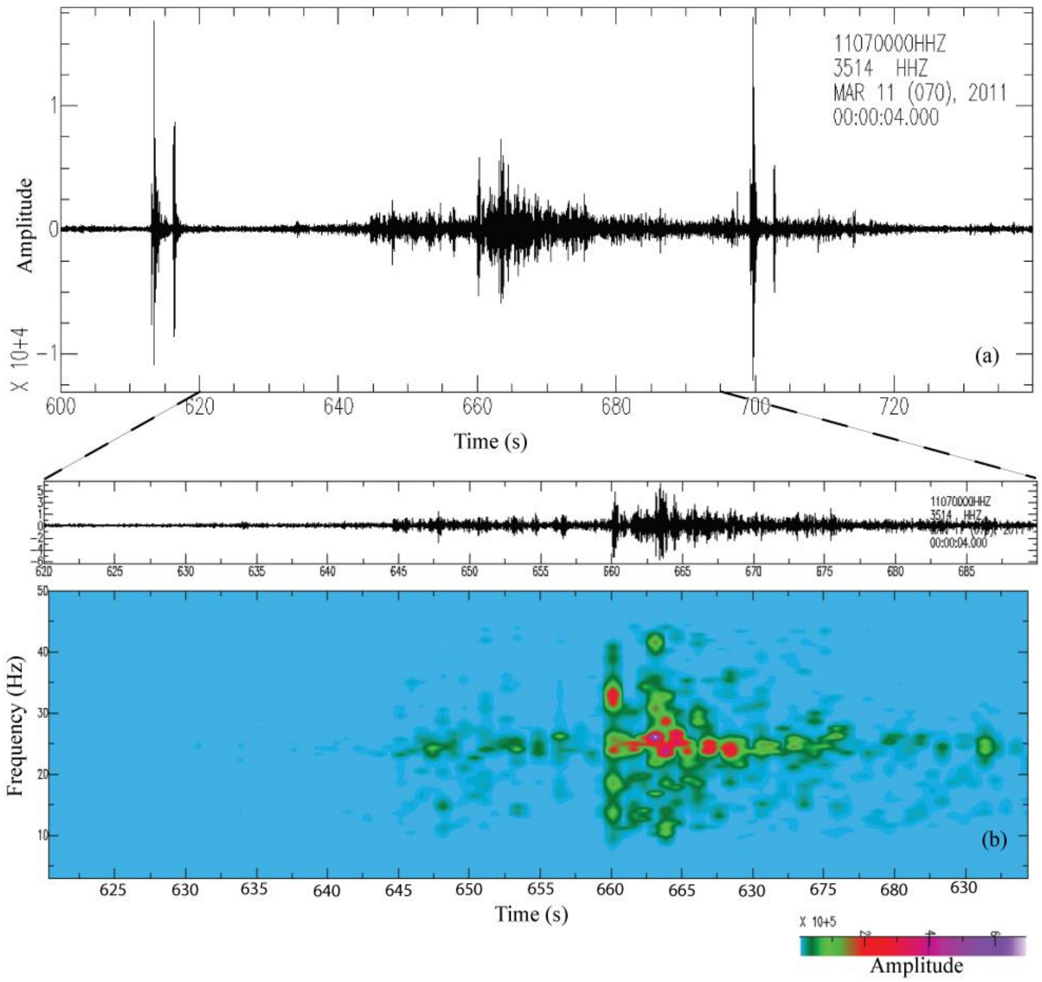


Figure 8: Seismic Signals from avalanche on March 10, 2011 (a) Seismogram of control explosions and resulting avalanche. (b) Spectrogram of artificially released avalanche.

The characteristics of the seismogram from this avalanche show differences from the previous avalanche recorded on December 12, 2010. The amplitude of the avalanche from March 10 was much lower than the December 12 avalanche leading up to the high frequency point where the avalanche crosses the seismic sensor, after which the amplitude increased significantly, while the December avalanche showed decreasing amplitude after passing over the seismic sensor. During the whole duration of the March 10 avalanche the amplitudes were 10^2 orders of magnitude lower, possibly due to velocity differences. Also, the frequency range of the March avalanche was much greater than the December avalanche, 10-45Hz and 10-25Hz respectively. The artificially released avalanche recorded on March 10 was larger with a longer and more complex path length then the December 12 avalanche possibly explaining the differences in the seismic signal.

CHAPTER VI

DISCUSSION AND CONCLUSIONS

These two avalanche events indicate that it is possible to record avalanches using seismic sensors as a tool for avalanche professionals. Due to the difference in frequency range and amplitude evolution, more events are necessary to make any definitive conclusions about the seismic characteristics. I think that because the avalanches had different physical characteristics in mass and path length the dissimilarity in seismic signals could be showing mass disparity or a result of the longer and more complex path length of the event on March 10. It is also important to note that velocity and snow density could have a distinct effect on the seismic characteristics of the avalanche signals. Currently there is nothing in place to measure avalanche velocity at the site locations, however, because the March avalanche traveled further down slope it had probably been moving at a greater velocity, also changing the seismic response. It may also be possible that there is a linear relationship between duration of signal versus size of avalanche with respect to mass of snow and vertical fall. In my data the duration of the signal from the larger avalanche on March 10 was significantly longer, by approximately 25 seconds, then that of the smaller avalanche on December 12. More events are necessary to confirm this idea; however, it may be another method to estimate avalanche size of the seismic signals.

Even though more research is required to develop distinctive seismic avalanche characteristics, my research has shown that avalanches do create seismic waves and these signals can aid in forecasting and avalanche control efforts, especially for avalanche control programs. Implications for control verification are important during times of low visibility, especially during heavy snowfall when access to slide areas is dangerous. Studying the timing of avalanche release after changes in temperature or precipitation is important for verificationof regionalavalanche hazard forecasts, and using seismic signals timing can be studied more accurately. We have determined that it is possible to record these seismic avalanche events, however, nothing more can be extrapolated from the limited data that were collected.

Changes in experimental design could allow for more definitive conclusions on the seismic characteristics. In this experimental seismic site the seismometer is located on the ground surface due to difficulties in installation in the harsh winter environment and rugged, brushy terrain during the summer months and this made it impossible to determine the source of the seismic waves. The wave transfer could have been through the bedrock, the snowpack, or through the air and this is important to the seismic characteristics because the substrate through which the waves are transferred directly affects the seismic properties. For future research, placing the sensor in the ground would provide better results because the travel of seismic waves through rock substrate has been widely researched (Shearer, 1999). Also, the density of snow affects the velocity at which the seismic waves travel, so measuring snow density could provide insight into why some avalanches were observed but not recorded by the seismic sensor. Previous research has indicated that high velocity powder avalanches have no, or insignificant, seismic signals (Biescas et al. 2003).

Successfully recording the seismic signals of two avalanches at Snoqualmie Pass is only the beginning of the use of seismic technology for the study of avalanche activity. I feel another important step in the future would be the use of multiple sensors in avalanche paths which would allow for the determination of avalanche velocity, and using amplitudes from these seismic signals could provide information on the mass of snow entrained in an avalanche. My research indicates that seismic detection of avalanches can be a successful tool to assist avalanche professionals in mitigation efforts.

Although my research does not provide information on distinctive seismic characteristics for avalanche determination using seismic data, it does indicate that it is possible for avalanches to be distinguished between the high seismic background noise of a highway such as I-90. These data could be transferred in real time to avalanche professionals for forecasting and avalanche mitigation purposes. This technique can be especially useful for determining whether control efforts produce an avalanche or if mitigation work needs to be continued. Also, the possibility of determining when natural activity occurred and the size of the avalanche would assist professionals in determining if avalanche control was necessary or if natural avalanche had already stabilized or partially stabilized the slope. Continued research using seismic techniques to study avalanche activity could provide useful tools for avalanche professional and recreationalists.

During the course of this research there were difficulties in maintaining sufficient power in the deep cycle batteries to keep the data loggers recording. This inevitably resulted in the failure to record many of the avalanches during the 2010-2011 season and the 2009-2010 season produced no avalanches at the Denny-9 study. The use of a high bandwidth telemetry system would have allowed for immediate knowledge when the system failed, reducing the length of the power outage. The reason for the failing power system could not be identified during the course of this study. It was possibly due to frequent cloud cover and dense forest not allowing the solar panels to charge the batteries efficiently. In order for the seismic system to provide useful information for avalanche mitigation, the source of the power failure needs to be identified and corrected, allowing the system to run continuously throughout the winter.

During the 2009-2010 winter the Rockface geophone failed to record a full depth glide avalanche and there is no definitive reason why the seismic signals were not picked up. Glide avalanches are not high velocity powder avalanches; therefore, it is not possible that the frequency content was outside of our range of detection. It is possible that the path is too small to create seismic waves detectable with our instrumentation. The geophone at the Rockface site is located very close to where the glide crack usually forms and it is possible that once the glide crack has been formed there is not a significant mass of snow close enough to the sensor to produce a seismic signal.

A relationship between avalanche size and amplitude of the seismic signal can be observed (Suriñach et. al. 2001). The limited amount of recorded events from this study does not allow us to confirm this observation. However, this correlation could assist avalanche forecasters to determine the size of natural or artificial avalanches that have occurred. Small avalanches involving surface layers of snow do not necessarily indicate thata slope has stabilized, and there may be instabilities deeper in the snow pack that may result in larger more destructive avalanches. This is a common phenomenon during rain-on-snow events (Conway et. al. 1993). The identification of an avalanche event may not necessarily be enough to determine that an avalanche path does not need to be artificially controlled and the ability to determine avalanche size from the seismic signal would provide necessary additional information.

The benefits of seismic monitoring techniques for avalanche forecasting have not been fully explored and those that have been investigated have not been developed enough to be implemented. In the future these techniques could be exceedingly useful to avalanche forecasting for highway, resort, and recreational avalanche safety programs.

CHAPTER VII

FUTURE EXPERIMENTAL DESIGN

For seismic observations of avalanche activity to be successful along the Interstate-90 corridor in Washington, changes in the field equipment are necessary. Power supply to the instrumentation needs to be reliable; therefore, it would be important to have either more deep cycle batteries on site or direct power going to the site. It may be possible that an increased number of solar panels could possibly compensate for power uptake from the seismometer and data loggers; however, with the duration of cloud cover during the winter months on the Cascade Mountains this may not be possible.

The ability to have a direct power line to the sites would also allow for enough power to run a high bandwidth FreeWave® modem for real time data transfer. When avalanche hazard is too high, this would allow avalanche professionals to retrieve data from the site and have real time avalanche activity information. Another advantage would be that if there were a problem with the instrumentation it could be discovered immediately and fixed promptly. If significant power or bandwidth were not available it would also be possible to write a program that would relay data only when certain criteria were met, such as particular frequencies or duration of signal. A once or twice daily station report could also provide all the vital information on station health without requiring a transfer of a large amount of data. If the power failure during this study had been discovered earlier then it could have been remedied before the avalanche cycles began.

Previous seismology research has focused on seismic waves travelling through a rock substrate (Shearer, 1999); while there has not been much research on seismic wave propagation through a snow substrate. If two sensors were installed together with one sensor in the snowpack and one sensor in the bedrock, the signals could be compared and the data could offer insight to the velocity and propagation of seismic waves through a snowpack. To research any characteristics of the seismic response to an avalanche it is essential to understand how the waves respond to the substrate, allowing the seismic study of avalanches to be taken farther and possibly provide information on avalanche dynamics.

I feel that in any future experimental design it would be beneficial to install multiple seismic sensors in the same avalanche paths and making avalanche velocity determinations. This would be especially useful when planning future development in and around mountainous regions where avalanche hazards exist. Similarly, I also hypothesize that in developed avalanche control programs the knowledge of avalanche velocities during different snow conditions may be helpful in how avalanche mitigation efforts are performed. By using multiple sensors I believe it may be possible to estimate the mass of snow entrained between each seismic site by determining how much the amplitude has increased, and therefore providing an estimate on the mass difference between the beginning of an avalanche and as the avalanche nears the runout.

I am certain that all of these aspects are necessary for the seismic detection system to run efficiently and reliably, and the problems discussed would need to be addressed in order for the seismic locations on Snoqualmie Pass or other avalanche prone areas to become a useful tool for avalanche forecasting.

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