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The Afternoon Creek rockslide near Newhalem, Washington

Abstract A series of mass wasting events occurred above a Washington, USA, highway in the Cascade Mountains in November and December 2003. The largest event was a rockslide involving approximately 750,000 m³ that occurred on November 9, 2003. The source zone for this event was located at the crest of a ridge. Most of the debris fell to the east of the sharp ridge and was deposited in the relatively shallow sloping Afternoon Creek without causing damage to the highway. Lesser amounts of debris fell to the west of the ridge, sliding 600 m down the steeper Falls Creek and impacting the road. There is an evidence of one or more historical rock avalanches at this location. Displacement of reference points, ground vibration, crack extension, and tilting are being monitored due to concerns that future slope failures or remobilization of debris might again damage or block the highway.

Keywords Rock avalanche · Slope stability · Monitoring – Highway hazard · Newhalem – Washington State

Introduction

On November 9, 2003, a rockslide occurred above Washington State Route 20 (SR 20) near Newhalem, Washington, USA. Rock avalanche debris fell more than 600 m in elevation down Falls Creek, Falls Creek Chute, and Afternoon Creek (Fig. 1). Most of the debris (approximately 750,000 m³) fell to the east of a sharp ridge and was deposited in the relatively shallow sloping Afternoon Creek without causing damage to the highway. Lesser amounts of debris fell to the west of the ridge down the steeper Falls Creek and Falls Creek Chute. Much of this material traveled all the way to SR 20, destroying portions of the roadway and guardrail, and depositing up to 4-m diameter boulders on the road. This rockslide was followed by a series of smaller mass wasting events in November and December 2003.

The slope is composed of orthogneiss of the Skagit Gneiss Complex, and it appears that the instigating factors underlying the rock slope hazard are glacial over-steepening of the slope, multiple cross-cutting faults and fractures, and decreased rock mass strength due to weathering. The November 9, 2003 event was triggered by elevated groundwater conditions created by rainfall events in October, 2003 (URS and Wyllie & Norrish Rock Engineers 2004a). This paper presents the results of a field investigation conducted immediately following the Afternoon Creek rockslide, including a description of the geological setting, history of landslide activity in the area, and its implications with respect to future rockslide hazards that threaten the highway. Details of the ongoing monitoring and hazard mitigation work are also discussed.

Geological and geomorphological setting

The source zone for the Afternoon Creek rockslide is located 600 m above SR 20, the northernmost route through the Cascade mountain range in the USA. Afternoon Creek is located in the heart of these exceptionally steep and rugged mountains (Fig. 2); the peaks near the Afternoon Creek rockslide have nearly 1600 m of vertical relief.

Fig. 1 Afternoon Creek rockslide above SR 20 near Newhalem, WA. Photograph provided by John Scurlock, Concrete, WA

The North Cascades is a complex region of accreted Mesozoic and Paleozoic terrains that were assembled during the early to middle Cretaceous. The geology of the region is further complicated by late Cretaceous through Eocene thrusting, plutonism, regional metamorphism, strike-slip faulting, extensional faulting, and basin development. Quaternary glaciation created the chiseled peaks and open parabolic-shaped valleys that exist today. The most recent Cordilleran

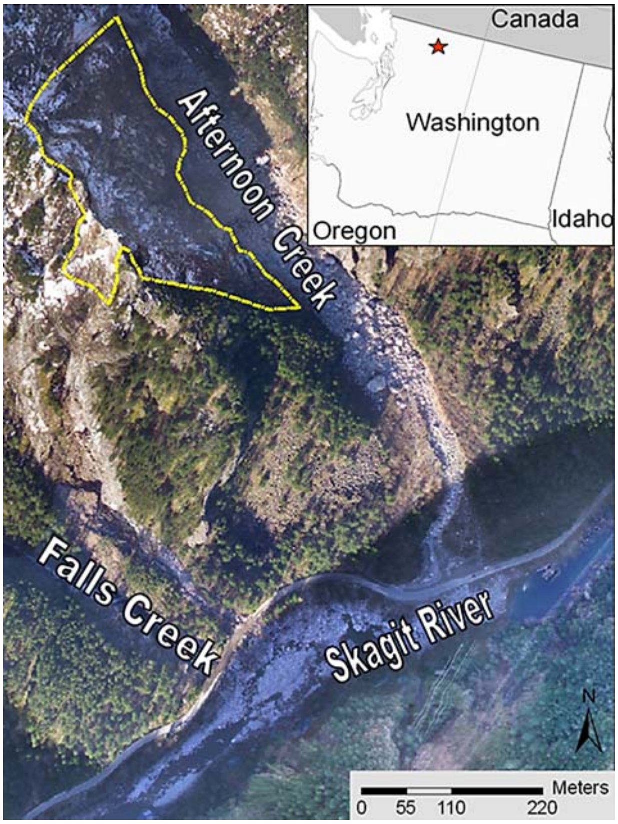

Fig. 2 Location of Afternoon Creek rockslide. Three kilometers east of Newhalem, Washington, USA. Failure area outlined in *yellow*

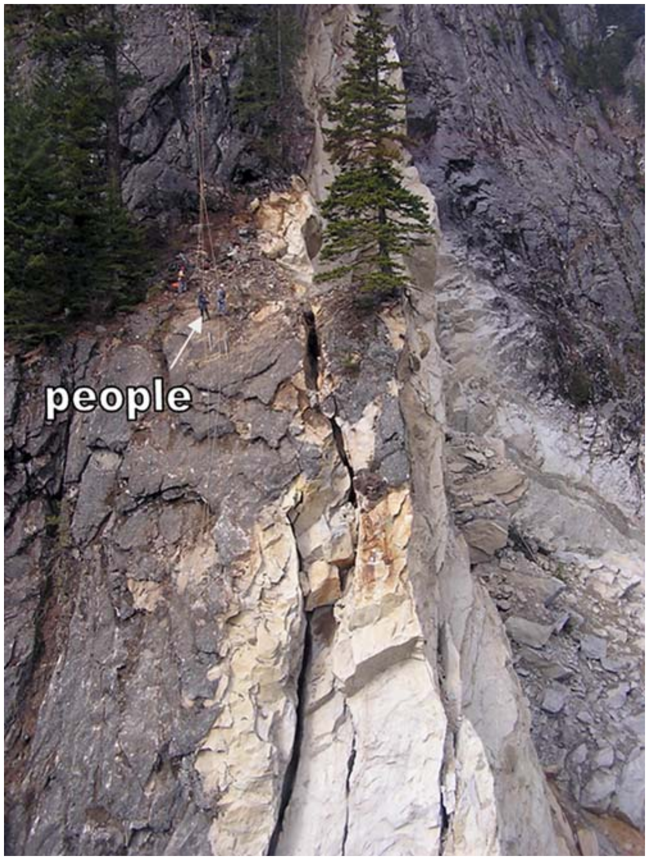

Fig. 3 Plane B joint set. Note open fractures near the top of the Afternoon Creek slope (photograph date, March 1, 2004). Photograph provided by URS Corporation

glaciation covered the area 15,000 years ago with a continuous ice cap (Tabor et al. 2003). The Afternoon Creek slope is oversteepened as a result of this most recent glaciation.

All of the rocks involved in the rockslide are hornblende-biotite tonalite orthogneiss of the Skagit Gneiss Complex (Tabor et al. 2003 map). The tonalite is most likely intrusive igneous material with original igneous crystallization from the late Cretaceous to early Paleocene. The cause of metamorphism is still under debate, but it is agreed that the mechanism is related to some sort of crustal thickening and that ductile deformation ceased by the early Oligocene (Tabor et al. 2003).

The average uniaxial compressive strength (UCS) of the intact orthogneiss is approximately 90 MPa according to UCS tests performed by GeoTest Unlimited, and from point load correlation and field observations (URS and Wyllie & Norrish Rock Engineers 2004a). This corresponds to 'R4-strong rock' according to Brown (1981). Multiple cross cutting fractures and faults divide the slope into several structural zones. The rock mass in each zone ranges from 'disintegrated' with 'fair' surface conditions to 'very blocky' with 'good' surface conditions corresponding to a Geological Strength Index ranging from 30 to 60 (Marinos and Hoek 2000).

Dozens of northeast–southwest trending fracture lineaments that are visible on a regional scale cut across the Afternoon Creek rock slope; additionally, locally persistent fractures trend northwest–southeast, parallel to Afternoon Creek. Near the failed slope, many of these discontinuities are filled with soil and rock rubble debris. Two important joint sets were apparent in the preliminary investigation. The most common set (plane A) dips parallel to the larger Skagit valley (i.e., strikes perpendicular to the Afternoon Creek slope). The second set is sub-vertical and parallel to Afternoon Creek (plane B). Plane B joints are widely spaced and highly persistent. Many are open or filled with soil and rock rubble (Fig. 3).

History of activity

Debris flows and snow avalanches are common to both Afternoon Creek and Falls Creek and have forced road closure on several occasions in the past (e.g. Fig. 4). Although the November 9, 2003 event was the first large rock avalanche on record, undated photographs and aerial photos from 1998 indicate ongoing rock fall activity several years before the event. Significant rock fall scars near the top of the slope and fresh boulder-sized debris in Afternoon Creek can be seen in undated oblique photographs (Fig. 5). Rockfall scars of the same magnitude can be seen in aerial photos taken in 1998. Some of the rock rubble that is now covered by vegetation (Fig. 5) may be debris from a single rock avalanche, or a series of historical rock avalanches that have occurred since deglaciation (late Pleistocene). This evidence indicates that slope instabilities in the form of isolated rockfall and larger rock avalanches are common in Afternoon Creek since deglaciation.

Chronology of recent mass wasting events

The November 9, 2003 Afternoon Creek rockslide, and subsequent smaller mass wasting events that occurred through November and December 2003, were preceded by record rainfall in October. The

Fig. 4 Historical photographs of debris flows that reached the state route 20 highway. **a** Afternoon Creek debris flow material (March 23, 1949). **b** Falls Creek Chute debris flow covered with fresh snow (1990). **c** Afternoon Creek (1999 or 2000). Photographs provided by WSDOT

week of October 16 through 21 was one of the wettest weeks in western Washington history; a rain gauge just 6.5 km from the landslide measured more than 400 mm of rain in these 6 days. The soil and rock rubble filled fractures that cut across the Afternoon Creek slope readily allow surface runoff to enter the fracture system. This water backed up against hydraulic barriers such as clay-rich shear planes, soil and possibly ice, creating high pore-water pressures. It is likely that the increased pore water pressures in the slope due to the influx of water in mid-October triggered the initial collapse of the slope.

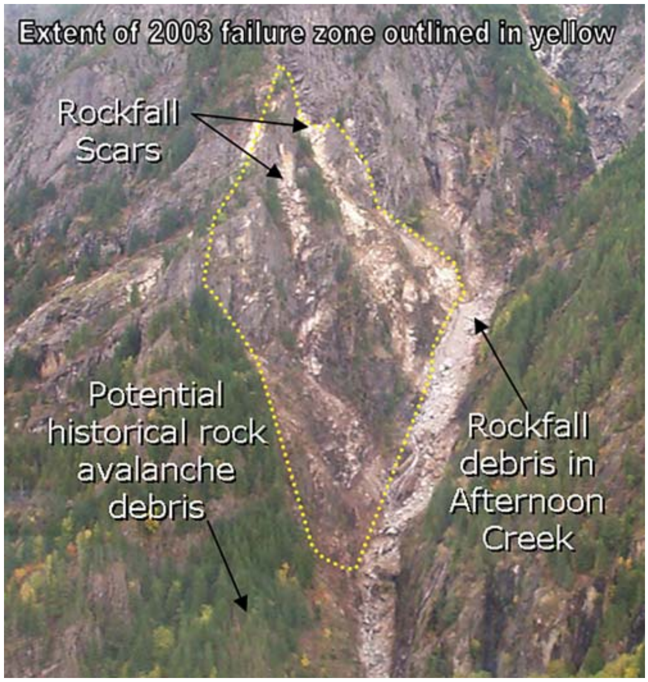

Fig. 5 Afternoon Creek Rockslide slope before the November 9, 2003 event (photograph date unknown). Photograph provided by WSDOT

The failure mechanism of the November 9, 2003 rockslide is complex. A preliminary interpretation is that the initial collapse occurred in the southern half of the failure zone where the rock mass is most highly fractured and dilated. This material collapsed toward Afternoon Creek. The event unloaded the toe of the larger, more competent blocks that slid on plane A, initially in a direction parallel/oblique to Afternoon Creek (Fig. 6). Rockfall and/or toppling in the upper portion of the failure zone followed after the loss of lateral support provided by the large blocks. Plane B (parallel to Afternoon Creek) allowed toppling and provided the lateral release necessary for planar sliding. Given the geometry of the ridge, a small percentage of the total rockslide material (<10%) traveled down the west side of the ridge along Falls Creek and Falls Creek Chute impacting the highway below (Fig. 7).

This initial slope failure was followed by several smaller events during the following weeks. Heavy rain a week later washed smaller rock and debris out of Falls Creek, and on November 19, 2003, a debris flow (approximately 35,000–60,000 m^3 in size) came down Falls Creek Chute and closed the road. Increased rockfall activity in Afternoon Creek was observed beginning in early December and leading up to December 19, 2003. On December 19, 2003, a rockfall of approximately 35,000 m^3 in size occurred. This event deposited boulders up to 15 m in diameter in Afternoon Creek. A series of smaller rockfall events continued during the following week.

Large scale fractures were recognized in the intact bedrock near the failed face following these events. On several occasions workers heard loud explosion-like booms and felt the ground vibrate beneath their feet. Although the sounds emanated from the slide area, they were not followed by rolling rocks or dust clouds. These booms may have been the result of intact brittle rock fracturing in the slope.

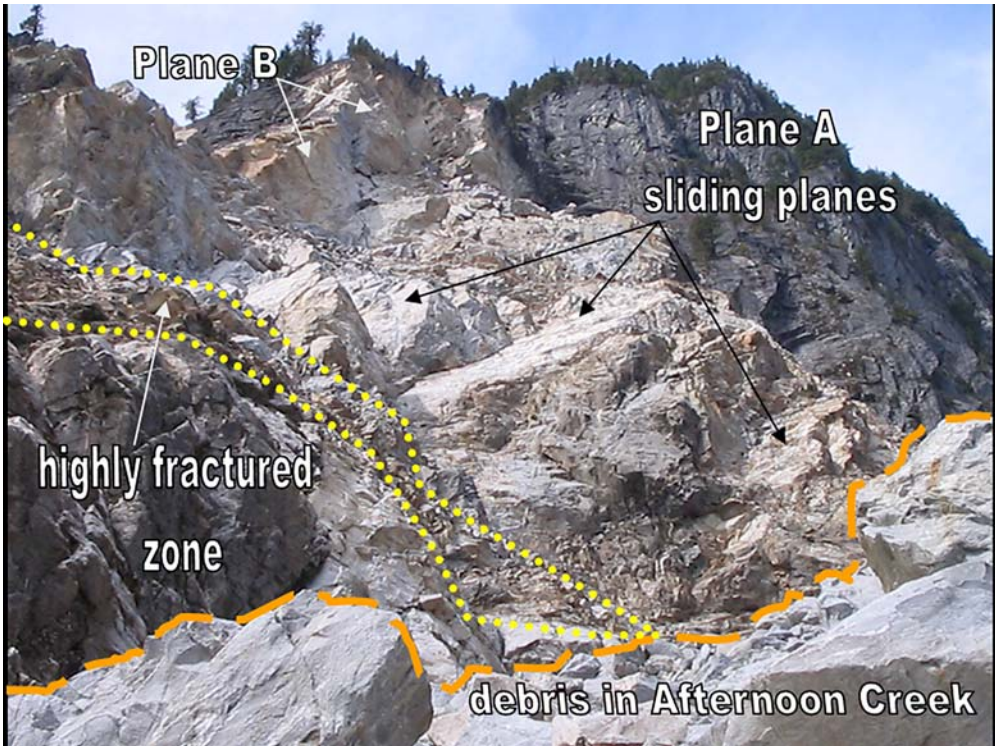

Fig. 6 View of the scarp from Afternoon Creek (photograph date, April 20, 2005). Photograph by Alex Strouth

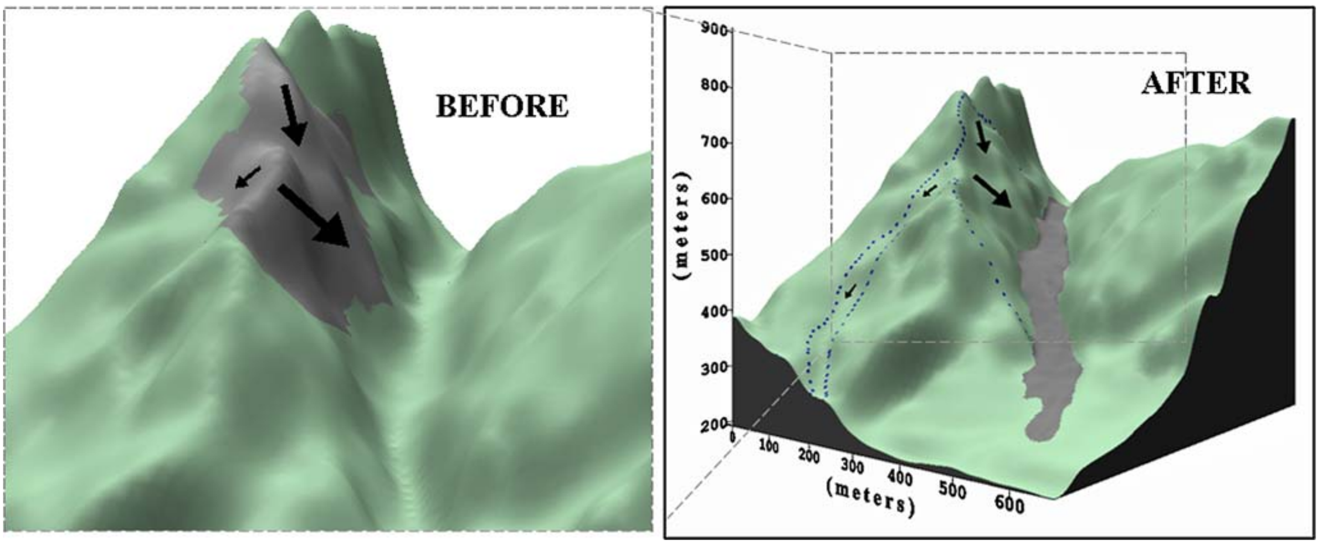

Fig. 7 Digital elevation model of the Afternoon Creek rockslide. Unstable mass is shown in *gray*. *Arrows* indicate direction of movement. *Dotted blue line* indicates the extent of path

Continued monitoring, hazard mitigation, and future work

After the November 9, 2003 collapse, there were concerns that additional slope failures and remobilization of the rock avalanche debris might further damage or block the highway (SR 20). The Washington State Department of Transportation (WSDOT) contracted with URS Corporation and Wyllie & Norrish Rock Engineers to begin a monitoring and investigation program. As part of this investigation, four monitoring techniques were employed to locate areas of ongoing slope movement, measure movement vectors and enable prediction of future slope failures:

1. Displacement monitoring consisted of regularly surveying the location of reference points to track cumulative movement of those points. Fifteen geodetic prisms were placed near or within the area of slope failure as reference points.
2. Vibration monitoring was used to correlate ground vibrations with rockfall activity triggered by precipitation events. Geophones were buried adjacent to Afternoon Creek, in Falls Creek Chute and along the upper head scarp of the failure plane.
3. Displacement monitoring was used to monitor crack dilation to assist in predicting potential rock failure. Two extensometers were

installed across cracks within intact bedrock just above the upper head scarp of the failure.

4. Rock tilt monitoring was used to assist in interpreting if further head scarp development was occurring. Two tiltmeters were installed on intact bedrock faces near the upper head scarp of the failure. The tiltmeters were used to monitor rotation of the bedrock adjacent to the area of rock failure.

Three of the geodetic prisms in the upper slope were destroyed by rockfall and have not been replaced. One of these was lost in the rockfall event of December 19, 2003. Based on the survey data, this prism accelerated to failure, traveling more than 2.5 m prior to failure in a period of 27 days. The remaining prisms in the upper and lower slope show no measurable movements within the error limits of the survey method (URS and Wyllie & Norrish Rock Engineers 2004b).

Geophone background values typically increase slightly during precipitation events. The majority of peak vibrations are two to four times larger than the background values. The rockfall event of December 19, 2003 had a peak vibration 35 times larger than the typical background values. There is a correlation between the rainfall and increased event activity. The extensometer and tiltmeter data show diurnal changes, however, no long-term trends related to movement of the rock has been observed (URS and Wyllie & Norrish Rock Engineers 2004b).

Back analysis of the November 2003 slope failure and stability analysis of the current Afternoon Creek slope through observation and numerical modeling is in progress at the University of British Columbia. The objectives of the analysis are to: (1) advance the current understanding of the operative slope deformation mechanisms, such as the importance of discontinuities on rock mass deformation and landslide volume; (2) investigate how the operative slope deformation and failure mechanisms relate to runout path, distance, and velocity; and (3) use this unstable slope as a laboratory for developing methodologies to optimize the numerical modeling and data collection process.

Conclusions

A series of mass wasting events occurred at Afternoon Creek in November and December 2003. The largest event was a 750,000 m^3 rockslide on November 9, 2003, originating near the top of a sharp ridge. Most of this volume of large boulder debris landed in the Afternoon Creek without causing damage to the highway; however, a very small portion of the material traveled down the backside of the ridge and impacted the Washington SR 20 roadway. Glacial oversteepening of the slope, multiple cross-cutting fractures and shear zones, and decreased rock mass strength due to weathering were key factors in conditioning the slope for failure. Heavy precipitation leading to high joint water conditions triggered the rockslide.

The slope is currently being monitored with a regular survey of reference points, geophones, crack extensometers, and tiltmeters. Back analysis of the Afternoon Creek rockslide event and stability analysis of the current slope configuration are currently in progress to help optimize mitigation strategies.

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