Abstract

Construction of an 8-km-long, multiphase, interstate-widening project on Snoqualmie Pass along Lake Keechelus will require 600,000 m$^3$ of steep side-hill excavations with 0.25H:1V rock cuts up to 40 meters in height. The highly variable condition of the volcanic rock mass includes deeply weathered/altered and very closely fractured basalt; adversely oriented, clay-infilled flow boundaries; and very strong tuffs with extremely persistent, adversely oriented, clay-infilled discontinuities. The latter condition resulted in a catastrophic rock slide in 1957, when construction for the interstate unsuspectingly undercut such structure.

The slope design includes pattern reinforcement concurrent with excavation and real-time monitoring for slope deformation, utilizing 1) automated motorized total stations (AMTS) and survey prisms and 2) strain gages on 30-m-long sacrificial anchors. Data is telemetered to web-based platforms, allowing real-time monitoring with remote access. Periodic ground-based laser scanning supplements the optical survey and strain gage data.

Initial results following the first construction season for the AMTS system demonstrated the importance of stable instrument platforms and back-sights and the vulnerability of the data stream to interruptions from precipitation and road spray. Distance measurements have provided more reliable indication of slope deformation than measured angles, though the latter has proved useful for determining vector direction of movement and evaluating kinematic control. The strain gages have been reliable indicators of stress induced from the excavation, increased pore pressure along discontinuities due to precipitation, and blasting. The laser scanning has augmented monitoring capabilities of slope areas between the widely spaced survey prisms and instrumented anchor bars.

1 Introduction

Interstate 90, within Washington State is the most heavily used east-west crossing of the rugged Cascade Mountains. Currently, average daily traffic is about 27,000 vehicles a day, with weekend and holiday traffic climbing to as high as 58,000 vehicles a day. By 2030, traffic volumes on this facility are expected to grow to an average of 41,000 vehicles per day. I-90 across Snoqualmie Pass is a strategic freight corridor serving local, national, and international markets and shippers. It is estimated that on any given weekday twenty five percent of the traffic consists of trucks, and on annual basis they carry an estimated 35 million tons of freight with an estimated value of $500 billion (US).

The 8–km-long highway corridor between Hyak, located just east of Snoqualmie Pass, and the Lake Keechelus Dam is currently a narrow four-lane highway facility located immediately adjacent to Lake Keechelus and bounded upslope by steep mountainous terrain (Figure 1). Construction of a $551 million (US) infrastructure improvement project to upgrade this highway facility, administered by the Washington State Department of Transportation (WSDOT), was started in Spring 2010. The project will improve this section of I-90 by adding one additional lane in each direction accommodated by about 600,000 m$^3$ of large rock excavations along the uphill side, constructing new bridges, reducing sharp substandard curves, repairing deteriorated concrete.
pavement, construction of a new snow avalanche shed, the installation of snow avalanche fences, and stabilizing unstable slope conditions along the project alignment. When completed in 2016, the highway capacity through this section of Snoqualmie Pass will be increased by 50 percent in each direction of travel, resulting in reduced congestion. In addition, winter closures due to snow avalanches and needed control work will be reduced, and the risk associated with slope instabilities will be lessened. The project has been divided into three construction phases, 1A, 1B, and 1C, ordered from west to east. The major rock excavations occur within 1B and 1C, which are the sections located to the west and east sides of the snow shed, respectively (Figure 1).

The geologic challenges associated with the hill-slope excavations are considerable. During the initial construction of the interstate in the late 1950s, a catastrophic slope failure occurred within a large rock excavation at a location now referred to as Slide Curve (Figure 1). The cause of the rock slide was the undercutting of extremely persistent, adversely dipping structure, which is also present within the existing cuts and natural slopes throughout the project limits. Given the proximity of the planned excavations to the travelled lanes and the requirement to minimize traffic impacts, an aggressive monitoring program was instituted for the rock excavations. Its primary purpose is to provide early warning of excavation-related slope distress, and thereby maximize the available time to employ remedial stabilization, reduce risks to construction personnel and the traveling public, and minimize traffic interruptions.

1.1 Site geology

Bedrock in the western project area consists primarily of basalt flows, local pillow structure; silty sandstones and siltstones are locally interbedded. These rocks also exhibit low-grade metamorphism. The overall rock mass can be characterized as weak to moderately strong.

Bedrock in the eastern project area consists of volcanic tuffs, primarily pyroclastic flows with variable welding and extreme heterogeneity in their chemical and depositional characteristics. Frequency of flows, flow thickness and proximity of sequential eruptive centers affected the cooling rates of both individual flow units and
successive deposits. The variability in the original composition of the tuff, degree of welding and in-situ porosity and permeability throughout the flow deposits is further complicated in the project area by subsequent low-grade metamorphic alteration. The tuffs are characterized as strong with unconfined compressive strengths typically between 35 and 100 MPa, with a few test results exceeding 140 MPa.

The range of discontinuities within the rock mass include faults, shear zones, joints, and lava and pyroclastic flow boundaries. Many of the encountered discontinuities have adverse orientations, high persistence, and/or weak infilling material. They pose significant design concerns due to their potential for day-lighting in the excavations and the fact that they have proven to be sufficiently unpredictable or ubiquitous in nature that they can exist anywhere within the cuts. Joints in the vicinity of Slide Curve exhibit persistence values in excess of 100 meters with adverse inclinations directed out of the proposed cut slopes.

1.2 Slope design

Rock slopes as high as 40 meters are required for the new alignment. Where the basalt rock mass is of lower quality and the natural slopes above the cut are favorable, the cut slopes were designed with inclinations ranging from 1H:1V(45°) to ½ H:1V (63°). However, throughout most of the project, traditional steep ¼ H:1V (76°) slopes were employed with the integration of slope reinforcement and mechanical methods for rockfall control. Slope stabilization design measures include untensioned rock dowels, tensioned rock bolts, drain holes, cable net drapery, reinforced shotcrete, and scaling.

Rock conditions in this volcanic terrain are highly variable and defied accurate characterization, irrespective of drilling and mapping intensity. Provisions were made to make design changes to rock slopes during excavation as actual rock conditions were encountered. Site geotechnical engineering during construction coupled with predictive slope displacement monitoring were included in the project to recognize and mitigate slope instability in a timely manner and to provide for worker and public safety.

2 Slope monitoring

A study of methods to measure the performance of the rock cuts was performed by the authors in 2008, methods that could be installed and operated by the Contractor and data transmitted to WSDOT in near-real-time for evaluation with movement thresholds for response (amber alert protocol). An array of methods for both surface and subsurface monitoring were considered.

Surface methods considered observation stations along the outside shoulder of the roadway or across Lake Keechelus, more than a kilometre in distance. The need for timely data and efficient data collection required robotic theodolite stations (automated motorized total stations, or AMTS) that could be programmed to cover about 50 reflector targets per setup and transmit data in real-time. It was recognized that the instrument stations would have to be protected from the frequent severe weather, air blast from traffic, flyrock, and vandalism. Laser monitoring without prisms and radar monitoring from vantage points across the lake were considered, but not chosen for this project due to both cost and operational issues.

Subsurface displacement monitoring considered borehole instrumentation such as inclinometers installed vertically and extensometers installed sub-horizontally. Inclinometers may be installed a distance behind the cut face prior to excavation, but it does not offer real-time monitoring capabilities. A variation on the vertical inclinometer methodology is the stationary array, or in-place inclinometers, that WSDOT already was using nearby and that can be used to monitor in real-time. However, the accuracy is dependent on the distance between sensors in the array, the mechanical coupling to the ground and the precision of the sensors. For example, sensor spacing of 3 m will not produce accuracy as good as a traversing probe (0.2 mm per m). High accuracy is more critical in rock where magnitudes of displacements are small.

Multi-position borehole extensometers (MPBX) could have been installed from the excavated rock face as the excavations progressed. Cables from each MPBX head would be routed vertically up to the top of the cut and be shielded from flyrock and the like; heads can be recessed behind the face.
Likewise, strain monitoring in un-tensioned bar reinforcement could be installed. Both miniature vibrating wire (VWSG) and weldable resistance gages (WRSG) could be installed at selected points along the bar. However, installation procedures are slow and involve highly specialized work. During insertion there is always some risk of tearing gages off and damaging cables. Like the MPBX, cables from each of the sensors are routed to the top of the slope for real-time monitoring by an automatic data acquisition system (ADAS). Ultimately, sister bars with factory-installed vibrating wire strain gages secured to sacrificial untensioned bars were chosen for subsurface monitoring.

The limited coverage with any of the subsurface methods is an unavoidable short-coming. “Critical” locations have to be selected by judgment and may not coincide with actual movement locations. Contractually, it is necessary to have a working plan for the method with specified locations. Retrofitting with these types of instruments after problem areas are revealed during excavation is usually not practical.

2.1 AMTS/prism system

Under Phase 1B, more than a kilometre of cuts were to be monitored by the AMTS-prism system, utilizing permanently mounted, optical glass prisms (generic term for targets). Approximate installation elevations were listed in a table in the Plans, with the actual locations dependent on field conditions determined by the Engineer. The x, y and z coordinates for each prism were to be measured from monitoring stations along the west (lake) side of the I-90 right-of-way at nominal highway elevation so that the sight distance to any prism would be 100 meters (300 feet) or less. The specified accuracy of the measurements in x, y and z directions was +/- 5mm (+/- 0.2 inches).

Based on favorable experience, a Leica AMTS with IRIS control program (provided by Geo-Instruments) was specified, with an allowance for alternative instruments of equal performance. It is configured to run on the Campbell Scientific Inc, CR800/1000 data logger as a gateway platform to control and store data from the AMTS. It uses PakBus protocol to send data via spread-spectrum radio so that a common ADAS Base Station (also a CR1000) may be used. The geodetic data was to be retrieved by CSI LoggerNet automatic polling of the Base Station and FTP forwarded along with other data tables to an ARGUS or ATLAS web-based database.

Truck traffic is very heavy on I-90 and could interfere with the line-of-sight to the prisms, if the instrument’s telescope was set too low. Suitable stable platforms and pedestals were to be provided for an instrument height of up to 5 meters (15 feet) above the roadway elevation, with the design responsibility left to the Contractor. Depending on the Contractor’s excavation staging, several AMTS instruments would be required to operate at the same time to provide full-face displacement monitoring. Monitoring was not required when the area was under snow cover.

2.2 Strain gage system

Within the Phase 1B portion of the project, five, 30-m-long, instrumented rock dowels were specified to be installed along the crest of the highest rock cuts. The strain gages and their associated monitoring system shown in Figure 2 consisted of the following:

1. Five, 13-mm-diameter, 1.4-m-long sister bars with factory-installed vibrating wire strain gages and thermistors installed on each rock dowel. Each sister bar was to be attached to dowels by four cable clips. The major advantages were that no epoxy coating had to be stripped off the dowels and no attachments of the VWSGs were needed in the field.
2. Lengths of unspliced integral cable from each gage to reach junction box above cut slope.
3. Junction boxes with over-voltage protection.
4. Cabling in conduit from junction-box to data logger.
5. Automatic Data Acquisition System (ADAS) or data logger.
7. Power supply system.
The specified data logger specified was a model CR1000 provided by Campbell Scientific Inc. (CSI). It utilizes CRBasic programming language and PakBus communications protocol compatible with the ATLAS web-based monitoring system. A vibrating wire interface (Model AVW200 provided by CSI) was required to read the strain gages, which employs FFT spectral analysis to measure the frequency output of the strain gages. This was connected to a 16-channel multiplexer (Model AM16/32). A modular autonomous photovoltaic power supply system was to be provided at the ADAS site. The solar power supply system was to be based on a CSI Model SP65 Solar Panel with a 12-volt photovoltaic power module (solar panel) capable of producing minimum 65 Watts of power; a deep cycle type battery with a nominal capacity of 100 AH (amp-hours), and a charge/load controller. The data logger, multiplexers, and other related and necessary components were to be housed in a lockable rainproof enclosure. The ADAS site included necessary components to allow remote communication with the data logger using a model RAVEN XTA digital-cellular telephone package. The data was to be transmitted to an ARGUS or ATLAS web-based database (Fig 3).
2.3 Terrestrial LiDAR

The specified surface and subsurface monitoring above was supplemented with terrestrial light distance and ranging (LiDAR) technology to monitor for surface deformation, using WSDOT's short-range, Leica laser scanner (Fig. 4A). The scanner has a resolution of about 6 mm at 50 m (0.02 ft at 150 ft). The scan data is processed with the software PolyWorks V11 by InnovMetric. A triangular irregular network (TIN) is first created with the initial scan data. The point clouds from subsequent scans are then comparatively analyzed against the initial TIN mesh to identify areas of surficial slope movement (Fig. 4B). Several hundred meters of slope face can be scanned and data transmitted within a few hours, and data processing can usually be completed within an hour. Scans are not regular in occurrence but made upon request, generally after significant exposure of new cut faces or when the strain gages and/or AMTS detect slope distress.

3 Results

3.1 AMTS/prism system

As was allowed in the contract, the Contractor unfortunately selected an alternative AMTS for Phase 1B. In addition, the specifications were not sufficiently explicit about experience requirements with the AMTS system. Instruments and software could only be approved on a trial basis. As a result, the Contractor provided untried equipment, software and personnel without prior AMTS experience. Unstable pedestals were initially provided (Fig. 5A), which resulted in poor data quality; these were later replaced with more stable pedestals (Fig. 5B). During the first construction season, accuracy was never achieved consistently, so that normal high and low alarm limits could not be used. Further, the data contained so much scatter that it made interpretation difficult and data reliability uncertain. This frequently complicated decisions about allowing continued excavation.

The utility of the prism system was best illustrated by the slope deformation experienced near Station 1325. The subsurface investigation indicated the presence of hydrothermally-altered, extremely weak rock that would require stabilization with patterned rock dowels and fibre-reinforced shotcrete. Because the subsurface investigation could not fully define the distribution of this poor quality material, it was necessary to expose a sufficiently large face area before the final stabilization measures could be designed. Furthermore, construction
staging required the deferral of the stabilization until late in the 2010 construction season. Consequently, the
prism system was relied upon to monitor the interim stability.

When the x, y, z movement data showed a lot of scatter and reliability was diminished, the EDM data were
separated out in an attempt to improve it (Fig. 6). For this critical situation the EDM shots proved to be the most
accurate. On occasion, the x, y, z resultant movement proved useful to determine vector direction of movement
where structurally-controlled slope movement was predicted. To confirm compatibility of the movement, these
calculations could then be compared with the orientations of structural features measured from the slope face or
from oriented-borehole logging data. In most cases, however, the change in slope distance typically provided
greater accuracy than did the three dimensional vector movement and yielded superior results for interpretation
of slope behaviour for those cases in which the line-of-sight was nominally orthogonal to the slope face. The
AMTS/prism monitoring also frequently detected slope movements associated with blasting (Fig. 7).

Figure 5. a) Initial contractor-supplied tower consisted of an undersized (0.35 m), flimsily braced, H-pile
section, which was highly susceptible to wind and thermal changes. b) Final tower consisted of 0.6 m
pipe pile section cast into a buried concrete pad, which provided much higher data accuracy.

3.2 Strain gage system

To date, the strain-gage system has consistently provided highly reliable data, with the exception on one
occasion due to wind-related damage. Figure 8A depicts the installation of instrumented dowel #5, which is
located in strong dacite tuff. Oriented-borehole logging of test hole H-202-06 enabled the projection of
adversely-oriented, clay-infilled discontinuities within the planned cut, assuming suitable persistence for these
features. It is noted that the two outermost strain gages (located at 1.5 and 6-meter (5 and 20-foot) depths)
correspond closely to the projected discontinuities. Subsequent to the unsatisfactory production blast on the top
lift which damaged the rock behind the final cut face, two rows of high capacity Type “H” dowels were
proactively installed prior to blast #54 to stabilize the upper portion of the rock cut. The five strain gages exhibit
load increases in response to the blasts (Fig. 8B). Instantaneous load increases as high as 30 kN (7 kips) were
measured followed by a prolonged period of increasing load accumulation. As the depth of cut is increased, the
strain gages will be carefully monitored for indication that the bar loading is migrating deeper into the slope.

An interesting side note to the strain gage system was the observation that certain gages apparently respond to
transient pore water pressure within discontinuities caused by winter storm events (Fig. 9). Using the cross-
sectional areas of the steel, the loads can be calculated from the measured strains. Strain gages at 1.5 and 6 m
below the surface (5 and 20 feet) are currently at 2.27 and 4.55 metric tons (5,000 and 10,000 pounds) respectively. The deeper strain gage at 21-m depth is sensing up to 5.68 tons (12,500 pounds) of transient loading mentioned above.

Figure 6. Resultant displacement and change in distance over 10-day period show a gradual increase to 1.25 mm (0.05 inches) and then a jump to just over 2.5 mm (0.1 inches) of movement on the last day.

Figure 7. Monitoring record for Prism 3005 shows blasting response. Shot #48 resulted in 7 mm (0.023 ft) of resultant slope movement.
Figure 8. a) Design cut section at instrumented dowel #5 showing test boring H-202-06 with projected clay-infilled discontinuities (dimensions and stationing in feet). b) Monitoring record for the five strain gages showing immediate response to blasting followed by gradual load accumulation, presumably related to mucking of lift.

Figure 9. Transient loads on SG20 and SG70 correspond to periods of heavy precipitation.

3.3 Terrestrial LiDAR

The terrestrial LiDAR has proved to be an extremely valuable tool, which has greatly enhanced the deformation-monitoring capabilities that are needed for the construction of the rock cuts. Where the AMTS/prism system
provides point measurements of slope movement, the laser scanning is able to define the areal extent and maximum amount of slope movement with a similar range of accuracy. Additionally, it can identify deformation in non-instrumented areas of the slope between/beyond where prisms and strain gages are located. By identifying areas of slope distress or pending failure, remedial stabilization measures can then be implemented or access restricted if unsafe conditions arise. Figure 10 shows the slope deformation between September 21 and October 5, 2010, which compares well to the monitoring record for Prism P3005 shown in Figure 7. This eventually led to the cessation of rock excavation in the area.

The digital terrain model developed from the scan data has also been used to monitor the progress and create as-builts of the excavation (Fig. 11), extract cross sections for derivative slope analyses, and accurately determine quantities of excavation and surface treatments (i.e., cable net drapery, shotcrete). In addition, digital terrain models have been combined with the excavation sequencing and geo-referenced discontinuity data derived from nearby oriented-borehole logging data to project problematic rockmass structures/conditions into the cuts (Fig. 12). This analysis has allowed for the pre-emptive reinforcement of cuts prior to exposing potentially adverse discontinuities.

Figure 10. Differential analysis of terrestrial LiDAR scans on September 21 and October 5, 2010 (units in feet). Warm colors indicate movement out of slope and depict area of slope distress around Station 1325.

Figure 11. Progressive terrestrial LiDAR scans provide sections for stability analyses and production documentation.
4 Conclusions

As conceived and specified in the initial construction contract for Phase 1B, the monitoring program for the rock excavations has been largely successful in identifying areas of slope deformation, informing necessary modifications for excavation sequencing and for additional slope stabilization, and safeguarding construction personnel and the traveling public. The strain gages and terrestrial LiDAR have proved to be the most reliable and informative monitoring systems. Problems encountered with the AMTS/prism system have been addressed in the pending Phase 1C contract, by requiring more proven equipment and assuming more responsibility for system maintenance. The terrestrial LiDAR has greatly expanded the monitoring capabilities of the AMTS/prism and strain gage systems by providing critically important monitoring redundancy and slope deformation data between in non-instrumented portions of the cuts. Vibrating wire piezometers will also be incorporated on the instrumented dowels to better understand climatic-induced loading on the slope.

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