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ABSTRACT
We used digital outcrop characterization in a rock slope remediation project along Interstate 90 approximately 66 miles east of Seattle. Forty-three photo pairs of rock exposures over a distance of 1600 feet were combined with surveyed camera and control point positions to create 3-D digital outcrop models that can be rotated, panned, and zoomed. The photogrammetry and much of the structural mapping were performed using software created for surface mining applications. Each 3-D model consists of a rectified digital photograph integrated with a cloud of several hundred thousand x-y-z points, with estimated positional errors typically on the order of millimeters to centimeters. Discontinuity orientations are determined by fitting planes to user-selected surfaces or their traces, and the fitted planes can be added to the 3-D model to facilitate visualization of the outcrop-scale structural geology. Discontinuity orientations can be exported and plotted on stereo or equal area nets, and the software calculates surface areas of planes and lengths of traces to characterize discontinuity persistence and spacing. Profiles can be extracted for outcrop-scale joint roughness coefficient (JRC) estimates. We also projected the 3-D models onto a large screen that allowed collaborative structural mapping and interaction among the project team members. The structural data obtained from the digital outcrop characterization were verified with conventional mapping from accessible areas near highway grade. The potential uses of the digital data for slope mitigation projects include kinematic analyses for structurally controlled failure mechanisms, roughness profiles for rockfall simulations, remediation design, and quantity takeoffs for trim blasting and scaling.

INTRODUCTION
Two rockslides along the westbound lanes of Interstate 90 near Snoqualmie Pass, approximately 60 miles east of Seattle, in September and November 2005 prompted a re-evaluation of slope stabilization projects that had previously been deferred in light of anticipated capital improvements to the highway. The September rockslide killed three motorists and the November rockslide caused a short but complete closure and an extended partial closure of the highway while repairs were made. As a result of the re-evaluation process, three rock slopes along a portion of Interstate 90 from milepost 66.00 to milepost 66.58 were slated for immediate remediation on the basis of high rankings in the Washington State Department of Transportation (WSDOT) Unstable Slopes Management System.

Bad weather, snow and ice covered surfaces, winter traffic hazards, and a short time frame for remedial design required an expedited approach to rock slope characterization for this project. There were no known existing surface or subsurface geotechnical data for the project area beyond the information collected for the Unstable Slopes Management System review process. To help meet project deadlines, we used 3-D digital outcrop models for office-
based structural mapping of rock mass discontinuities and extraction of rock slope profiles. This technique, using commercially available software supplemented by custom in-house routines, employs high-resolution digital photogrammetry to create detailed 3-D representations of complicated rock exposures. The digital modeling was supplemented by limited field mapping for verification of the digital results and an aerial man lift survey to allow additional observations of the rock slopes.

GEOLeGIC SETTING

The milepost 66 project site lies along Interstate 90 east of Snoqualmie Pass in the Cascade Range of Washington State and traverses the western slope of Anabilis Mountain, a topographic extension of Keechelus Ridge (Figure 1). The summit of Anabilis Mountain lies at an elevation of 4,554 feet and Interstate 90 lies at an elevation of about 2,535 feet.

![Index map showing the project area in relation to local topography and features. Location is 66 miles east of downtown Seattle.](image-url)
Bedrock exposed in cuts along the westbound lanes consists of early Oligocene to middle Eocene Naches Formation rhyolite, andesite, and basalt, tuff, and breccia with lesser amounts of sandstone, argillite, and laminated siltstone interbeds (1). Bedding generally strikes north-northwest and dips to the west-southwest at 50° to 75°, with anomalies near faults. There is evidence for at least three major alpine glacial advances in the vicinity of the site during the Pleistocene (1). Glacial deposits at and near the site, including moraines near the south end of Keechelus Lake and Kachess Lake, range from till on upland and valley margin surfaces to sand and gravel outwash deposits in lowland areas. Lake Keechelus, which is located approximately three miles from the project, is a moraine-dammed lake raised in the early twentieth century by a man-made dam. Kachess Lake, two miles east of the project site, is a natural lake on which an outlet structure was constructed in 1905 to provide flood control and irrigation storage for the Yakima River project. Holocene material at the site consists of mass wasting, colluvium, and minor fluvial deposits of sand and gravel in nearby drainages.

DIGITAL PHOTOGRAMMETRY, MODELING, AND MAPPING

Fieldwork

Digital photographs for the project were taken on the morning of January 24, 2006, with weather ranging from cloudy to partly sunny. Temperatures were at or near freezing, and ice on parts of the eastbound shoulder made it difficult to walk and mark camera locations. The right eastbound lane of the interstate was closed by WSDOT for safety.

Forty-three pairs of 6.1-megapixel photographs were obtained using a Nikon D70 digital SLR with a Nikkor AF-D 24 mm f2.8 lens. The camera was mounted on a standard camera tripod with a pan head. A plumb bob and a retractable steel tape used to mark each camera station and measure the camera height. Although an infrared remote control was available for the camera, it was not used for most of the photographs because its slight time lag made it difficult to ensure that photographs were taken between passing trucks. The files were saved as native Nikon NEF (also known as RAW) files to allow for greater flexibility if exposure or white balance adjustments were needed and to ensure lossless conversion to the tiff format required by the photogrammetry software.

The approach used in this project requires two surveyed camera positions and one surveyed control point location for each photo pair. Alternative approaches can be used for other situations, for example making use of three or more surveyed control points in cases where it is not feasible to accurately determine the camera location (as would be the case if photographs were taken from a helicopter or boat). Camera stations were marked on the shoulder of the eastbound lane using spray paint and PK nails, and control points were marked on the rock face using spray paint. In the case of the camera stations, the letters A and B were used to denote the eastern and western points in each pair (photography proceeded from east to west). The locations of both the camera stations and control points were later surveyed by WSDOT and the coordinates provided in an Excel spreadsheet. The approximate distance between the camera stations and the outcrop, which is required to establish an appropriate baseline length of 1/6 to 1/8 of the distance to the outcrop, was estimated using a pocket laser distance finder to measure the distance to the median barrier. That distance was doubled and 10 feet were added (to account for the distance between the outcrop and shoulder) to establish the approximate distance to the outcrop. The result divided by 6 to calculate the approximate baseline length of 1/6 the distance between the camera locations and the base of the outcrop. As shown in Figures 2 and 3, the photographs covered three cuts, the easternmost of which consisted of five smaller components.

The WSDOT survey coordinates were based on an arbitrary datum assuming camera station 6A to have (east, north, elevation) values of (10000, 10000, 10000) feet. The WSDOT coordinate system further assumes that the vector from camera station 16A to camera station 6A is aligned due east (090°). Office inspection of plans after the 3-D models had been processed showed that the vector from 16A to 6A has an azimuth of 110°. Therefore, a 20° correction was added to dip directions calculated from the 3-D models.
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Figure 2. Camera and control point layout. Easting and northing measures are given in arbitrary project coordinates supplied by WSDOT with camera location 6A assumed to have a value of (10000 feet, 10000 feet), and the project easting has a true azimuth of approximately 110°. Upper and lower figures overlap each other.

Image Processing and 3-D Model Creation

Sirovision software (version 3.1) from the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) was used to create the 3-D outcrop models (2). The software consists of two programs: Siro3D for 3-D model creation and Sirojoint for structural mapping and analysis. Although the software was originally developed for surface mining applications, it has proven useful for non-mining geotechnical and hydrogeologic rock mass characterization. Additional information about the software is available at www.sirovision.com.

The photograph files were downloaded from the camera to a computer and converted from NEF to tiff format. Each photograph was then corrected to remove lens distortion using the default Sirovision parameters for the lens, which is among the list of those supported by the software, and each pair was combined with the WSDOT survey results to set up the 3-D orientation for the pair. This processes uses the camera station, camera height, and control point locations for each model and requires that the surveyed control point and three other common (but not surveyed) points be identified in each photograph. A 3-D model area was then defined for each pair, using as much of the overlap area as was practical in each case. Irregular topography, trees, and snow along the tops of the road cuts complicated this task and, as a consequence, some of the models are either truncated along their top edge or contain irregularities near the trees and snow. Finally, 3-D models were generated using block matching (the recommended Sirovision option for structurally or geometrically complicated outcrops). Each 3 by 3 block of pixels in the defined overlap area yielded one spatial data point on the outcrop face, which yielded models consisting of approximately 200,000 to 500,000 xyz points each. This process took approximately 30 minutes per photo pair.

Figure 4 illustrates the progression from a photo pair to a rectified orthophoto and then a 3-D outcrop model for outcrop model 18. Figure 5 shows the 3-D geometric framework of outcrop model 18 using both a point cloud and a triangular faceted surface. This outcrop model is typical of the results obtained in this project and contains an interesting variety of structures. It is used as an example throughout the paper.

Once a 3-D model is created, it can be manipulated within Siro3D or saved for further analysis. Outcrop model 18 consists of 425,523 xyz points in the project coordinate system and covers approximately 8,000 square feet of outcrop surface, giving an average linear xyz point spacing of about 1.6 inches. Denser xyz point spacing can be obtained with higher resolution cameras. A 12-megapixel camera, for example, would have produced more than
800,000 points with an average linear spacing of about 1.2 inches. The estimated root-mean-square (RMS) error of the xyz points comprising outcrop model 18, which is calculated by the Siro3D software, was ±0.75 inches.
Figure 4. Results for outcrop model 18 showing progression from the individual left and right photos to the rectified orthophoto and finally the 3-D outcrop model saved in a proprietary enhanced tiff format. The 3-D outcrop model consists of 3.8 million color pixels draped over 425,523 xyz points.
Figure 5. Reduced point cloud and reduced triangular mesh surface for outcrop model 18. Every fifth point was plotted in the point cloud so that individual points can be seen. Note the correspondence between flat facets and snow and trees visible in Figure 4. The mesh was reduced to 23,360 triangular facets for ease of manipulation. Plots were produced by importing Sirovision output into Mathematica and using in-house visualization routines.
As long as a common coordinate system is used for all of the models, two or more models can be combined into a 3-D panorama. Experience has shown, however, that real-time manipulation of the models and structural mapping become slow for models consisting of millions of xyz points. Therefore, the most efficient approach is to use each outcrop model separately.

The models were saved in two formats: special Sirovision rectified tiff files containing 3-D information and an ASCII xyz matrix format for use in profile extraction and visualization. Point density in the ASCII matrices was reduced by factors of 3 to 7 to produce meshes with 20,000 to 25,000 points each. The 3-D meshes can also be exported as ASCII xyz point cloud or dxf files with or without mesh reduction.

INTERPRETATION AND ANALYSIS

Structural Mapping

Digital structural mapping based on the 3-D models was performed at the Golder Associates office. A laptop computer running the Sirojoint component of Sirovision was connected to an LCD projector and used to display the models on a conference room white board, which allowed for collaborative mapping of significant structures by the project team. Sirojoint structural models were created for 3-D outcrop models 1, 2, 3, 4, 5, 11, 13, 18, 20, 24, 27, 30, 32, 36, and 40. Each model includes joint surfaces identified during collaborative mapping, the orientations of which were exported and delivered electronically to Wyllie & Norrish and Golder Associates for further plotting, analysis, and incorporation into slope designs.

Sirojoint allows users to map discontinuities by drawing either polygons outlining visible discontinuity surfaces or 3-D lines that represent the traces of discontinuities intersecting the outcrop face at high angles. The drawing can be done on either the 2-D rectified photograph or the 3-D model, and the latter can be rotated to better expose unfavorably oriented discontinuities. For each discontinuity that is mapped, the software calculates the orientation of a best-fit plane defined by the points within the polygon or comprising the 3-D line. As each orientation is calculated, it can be added to an automatically updated equal area net (with or without contours) or rose diagram. Figure 6 is a screen capture of a Sirojoint session for outcrop model 18, showing the 3-D model, several discontinuities that were mapped as polygons, the planar projection of a fault that was mapped as a three dimensional line, and a contoured equal area net showing poles to the selected planes.

A limited program of field-based manual structural mapping was undertaken to verify and calibrate rock mass discontinuity measurements obtained from the 3-D digital models. Discontinuity orientations were measured at selected locations accessible from the highway shoulder and a limited number of locations accessible with an aerial man basket. The data were collected in general accordance with Golder Associates technical procedures and International Society of Rock Mechanics guidelines, then plotted using the commercial computer program Dips. With the exception of the 20° strike bias arising as a consequence of the WSDOT coordinate system alignment, the manual and digital orientations were in excellent agreement (Figure 7).

Once discontinuity orientations are calculated, they can be displayed within Sirojoint or exported for further visualization and analysis using such computer programs as Mathematica and OpenDX (2-4). Although Sirojoint has some advanced visualization and analysis capabilities, we prefer the flexibility offered by our own in-house visualization routines and commercial stereo-net software. As an example of alternative visualization methods, Figure 8 shows thirteen best-fit planes superimposed on both filled and wire mesh representations of outcrop model 18.

If an outcrop mesh is composed of triangular facets, as in Figure 8, the vertices of each facet can be used to solve a three-point problem that gives the orientation of the facet. The facet orientations can then be assigned to sets using statistical techniques such as cluster analysis or based upon professional interpretation of a smaller number of manually measured orientations (4-6). Each triangular facet in Figure 9 is colored according to its affiliation with the three discontinuity sets shown in the inset stereo net, allowing for visualization of planar features that may not have been identified during the manual measurement phase. A facet was classified as a member of a discontinuity set if its dip direction and dip angle were both within ±20° of the average values for the set. The continuity of each colored patch in Figure 8 reflects the roughness or irregularity of discontinuity surfaces. The blue release plane
surfaces shown in Figure 8, for example, are much rougher and less continuous than the yellow wedge left surfaces. Although we did not do so in this project, directional roughness profiles and joint roughness coefficients (7) can be calculated by exporting the portions of the 3-D model corresponding to specific discontinuity surfaces (8).

Figure 6. Screenshot of the Sirojoint model of outcrop 18 illustrating the capability to measure orientations and sizes of selected discontinuities. Areas outlined in red were mapped as planar polygons. The translucent red plane is the projection of a fault trace mapped as a 3-D line. The inset shows a Kamb-contoured equal area plot of the poles to the mapped planes. Distances are in feet, not meters as shown (this cannot be changed in the Sirovision software).

Figure 7. A) Poles and planes calculated using Sirojoint (n = 171). B) Poles and planes measured manually (n = 49). Sirojoint orientations have been adjusted by 20° to account for the survey coordinate system. Results are from all outcrops modeled for this project.
Figure 8. Reduced mesh for outcrop model 18 showing best-fit planes for selected discontinuities and two vertical cutting planes of the type used for profile extraction. These plots were produced by importing Sirovision results into Mathematica and using in-house visualization routines. A) Shaded surface. B) Wire mesh surface.

Profile Extraction

Vertical profiles of each outcrop model were extracted from the reduced meshes and used in the remedial design. Except for three profiles that were moved to avoid trees, profiles were created by slicing the 3-D mesh with a north-south vertical plane passing through each surveyed control point. Profile extraction was accomplished using in-house Mathematica functions that calculate the intersection of a vertical plane with arbitrary strike and the triangular
facets comprising outcrop model surface. Figure 8 includes two examples of profiles created by the intersection of arbitrarily striking vertical planes with the outcrop mesh.

Each profile was exported converted to an Excel spreadsheet that included the coordinates of the relevant control point and also converted to dxf format as a five foot wide 3-D strip for easier visualization in Golder’s CAD software. A series of annotated jpeg images showing the profiles and control points superimposed on the 3-D mesh was also provided to help visualize the profile locations.

Figure 9. Reduced mesh for outcrop model 18 colored according to discontinuity set affiliation. Individually measured discontinuities are shown in green as in Figure 5B. Orientations shown on the stereo net have not been corrected and azimuths therefore differ from those in Figure 7 by 20°.

REMEDIAL DESIGN

Geologic aspects relevant to remedial design of the rock slope covered by outcrop model 18 include:

- A potentially unstable planar slab of rock near the top of the model. The slab is more than 10 feet thick and rests on a joint surface dipping 50° towards the highway.
- Blocky volcanic rock with a colonnade structure in the upper left hand corner of outcrop model 18. Significant joint apertures and rock mass dilation were noted during fieldwork.
- Zones of weathered and highly fractured rock with random discontinuity orientations and limited persistence. These zones will not be amenable to rock bolting or long term stabilization using only scaling.

Remedial measures for the slope consisted of a combination of hand and mechanical scaling and debris removal, top-down installation of 60 kip tensioned rock bolts and 60 kip non-tensioned rock dowels, placement of fiber-reinforced shotcrete, installation of horizontal drains, and installation of cable netting. The particulars for the area covered in part by outcrop model 18 are shown in Figure 10. Sirovision data were used to obtain discontinuity data used in a plane analysis of the large slab, to estimate slab thickness, and to provide vertical profiles such as the one inset into Figure 10.
Figure 10. Rock slope design for the area covered by outcrop model 18, consisting of a combination of scaling, rock bolts and rock dowels, horizontal drains, shotcrete, and cable rockfall nets. Section S18 (inset figure) illustrates typical rock bolt placement and was based on a vertical profile extracted from a Stirovision 3-D mesh.

<table>
<thead>
<tr>
<th>KEY</th>
<th>STABILIZATION ITEM</th>
<th>EST QTY (Sheet 6)</th>
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<tbody>
<tr>
<td></td>
<td>60 kip tensioned rock bolt</td>
<td>24 x 20 ft = 480 ft</td>
</tr>
<tr>
<td></td>
<td>60 kip untensioned rock dowel</td>
<td>12 x 20 ft = 240 ft</td>
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<tr>
<td></td>
<td>Horizontal drain</td>
<td>3 x 40 ft x 5 x 30 ft = 270 ft</td>
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<tr>
<td></td>
<td>Scaling / Debris removal</td>
<td>40 crew hr &amp; 2 machine day / 2000 cy</td>
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<tr>
<td></td>
<td>Shotcrete</td>
<td>40 ft x 10 ft x 4 in = 5 cy</td>
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<tr>
<td></td>
<td>Cable Net Slope Protection</td>
<td>140 ft x 70 ft avg = 9800 sf</td>
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CONCLUSIONS

High-resolution digital photogrammetry provided a fast, safe, and economical characterization alternative for a fast-track rock slope remediation design project conducted under challenging conditions. Field photography was completed within a day of verbal authorization to proceed and the photographs necessary to characterize 1600 feet of rock slopes were obtained in about four hours. Subsequent processing took about 30 minutes for each of the 43 digital outcrop models, and office-based collaborative structural mapping using 15 of the 43 outcrop models was accomplished in less than one day. Additional time was required for file format translation, data management, graphical output, and report writing. The accuracy of the digital structural data was verified against manually collected discontinuity orientation data, and both the orientation data and outcrop surface profiles provided important information for the remedial design.

Advantages of structural mapping using digital photogrammetry and Sirovision software include:

- Equipment portability. The necessary equipment can be carried in a daypack.
- Complete integration of high-resolution digital photographs with 3-D models.
- The ability to select and measure the orientation of individual discontinuities selected on the basis of professional experience and geological insight (i.e., virtual fieldwork).
- The ability to export results in a variety of formats of direct interest to engineering geologists and amenable to quantitative methods such as cluster analysis or eigenvalue fabric analysis.
- 3-D models can be created using photographs taken from a moving aircraft or watercraft.
- Low cost of readily available cameras and software compared to terrestrial laser scanners.

Complete integration of high-resolution color photographs with the 3-D models, in particular, is extremely useful for geologic interpretation because it can convey information about non-geometric attributes such as the distribution of alteration or weathering, locations of seeps, and some variations in rock type. The result is a virtual outcrop that provides more information for geologic interpretation than an unadorned point cloud or mesh.

Disadvantages associated with digital photogrammetry and Sirovision software include:

- Dependence upon proprietary and single-source software for critical parts of the work.
- A steep learning curve for novice users.
- In common with laser scanners, depicts only those features in the direct line of sight.
- Also in common with laser scanners, an inability to extract information about variables such as joint filling, joint aperture size, small-scale joint roughness, and field-based estimates of rock material strength such as those in the ISRM system (9).

The density of photogrammetric point clouds tends to be less than that for laser scanners, but in practical applications clouds consisting of hundreds of thousands of points provide useful models. Thus, it is not a significant disadvantage. Although it is possible to estimate large-scale directional joint roughness (feet to tens of feet), the data we describe in this paper are inadequate for the estimation of fine-scale roughness (inches to tens of inches). Future improvements may, however, make fine-scale roughness calculation possible.

Our experience has been that structural mapping using digital photogrammetry and 3-D modeling represents a significant advancement in rock slope characterization for engineering purposes by:

- Greatly reducing the need for high-angle rope belay access to slopes.
- Improving the efficiency and reducing the cost of structural mapping,
- Providing a greatly increased number of data points that help to reduce the uncertainty of stability and kinematic analyses.
Regardless of the advantages that digital photogrammetry presents to the rock slope practitioner, and in contrast to claims that technology will alleviate the need for compasses and measuring tapes (10), there will always be a need for trained geotechnical eyes in the field and field-based reality checks to validate digital results.

REFERENCES