ARMA 12-368

Comparison of Standard Structural Mapping Results to 3-D Photogrammetric Model Results: Boundary Transformer Banks Rockfall Mitigation Project, Metaline Falls, Washington

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This paper was prepared for presentation at the 46th US Rock Mechanics / Geomechanics Symposium held in Chicago, IL, USA, 24-27 June 2012.

ABSTRACT: The Boundary Dam hydroelectric power plant on the Pend Oreille River in northeastern Washington has been producing a significant proportion of Seattle's electricity since 1967. Six hydro-generating units are housed in a large machine room within a dolomitic rock massif with individual step-up transformers in rock bays, located at the bottom of a 150 m high cliff above the tailrace. Transmission lines exit the bays on concrete outriggers, run nearly vertically up the rock face to stand-off structures, and then into the power grid. Rockfall has been a constant problem, causing damage to outriggers, power line accessories, and appurtenances. Because of electrical interference and difficult access, traditional mapping of the geologic structure was complemented with close range terrestrial photogrammetric 3-D models on which discontinuities could be mapped remotely. Rock mass discontinuity orientations from historical mapping data, new tunnel mapping, and photogrammetric modeling of the face agreed well and fell into distinct sets. This facilitated evaluation of the rock mass structure and kinematic analyses used in tunnel design and rock face protection. Remote techniques such as photogrammetry are important tools that complement manual rock face mapping. However, they cannot and should not replace traditional hands-on-the-rock geological fieldwork, observation, and interpretation.

1. BACKGROUND

1.1. Boundary Dam Hydroelectric Plant

Seattle City Light (SCL) owns and operates the Boundary Dam and Hydroelectric Power Plant on the Pend Oreille River in the northeast corner of Washington State (Fig. 1) [1]. SCL began producing electricity with one generator in 1967 and now produces over 25% of Seattle's electricity. Presently there are six hydro-generating units all housed in a large machine room within the dolomitic rock massif. The units are coupled with individual step-up transformers in rock bays, at the bottom of a 150 m high cliff above the tailrace. Transmission lines exit the transformer bays horizontally on outriggers, and then run vertically up the face to stand-off structures referred to as "pickleforks" atop the rock massif. From there, the lines tie into the Northwest Power Grid.

The rock massif consists of primarily fair to good quality moderately strong to strong dolomitic rock intermixed in some areas with very poor weak rock and collapse breccias. Major intersecting discontinuities control the shape and structure of the rock massif.

Geotechnical investigation for the project began in about 1962 [1, 2, 3]. Even though the rock face was scaled during construction of the hydroelectric plant, falling rocks have continued to be a problem causing damage to the outriggers and power line accessories.

To assess the kinematics controlling the rockfall, the authors collated and evaluated the original geological data that were collected in 1962 during the original investigation of the rock massif. These data were coupled with detailed geomechanical mapping of the interior of the rock massif, which houses the transformers bays. Because of the high exposure requiring rock climbing and rappelling techniques to access the rock faces above the river and the fact that the overhead power lines interfered with the CLAR compass, mapping of the rock face was facilitated through the use of close-range terrestrial photogrammetry to produce 3-D digital outcrop models on which major discontinuities could be mapped virtually.

Fig. 1. Boundary Dam Hydroelectric Plant on the Pend Oreille River northeastern Washington, USA. Photo displays the northeast face above the transformer bays.

1.2. Photogrammetric Mapping Techniques

Digital outcrop model creation and virtual mapping were accomplished using Sirovision (version 4), a commercially available software package created specifically for geological and geotechnical mapping. Sirovision, like other photogrammetric software, uses overlapping (stereo) digital photographs and survey information to create 3-D digital models that are scaled and oriented within a specified coordinate system. Sirovision was developed and is supported by the Commonwealth Scientific and Industrial Research Organization (CSIRO) Exploration and Mining Division in Brisbane, Australia. The software consists of two applications: Siro3D for 3-D model creation and SiroJoint for rock mass discontinuity mapping, visualization, and analysis.

Comparison of field- and model-derived discontinuity orientation measurements have repeatedly shown close-range digital terrestrial photogrammetry in general, and Sirovision in particular, to be useful and accurate tools for rock mass discontinuity mapping in support of both construction and mining [4, 5, 8]

2. MAPPING METHODS USED

2.1. *COE Exploratory Tunnel*

Initial geologic mapping was conducted by the Army Corp of Engineers (COE) and consultants contracted with the COE and SCL circa 1962 [2, 3]. To collect the geologic data, the COE contractors drilled numerous borings in the vicinity of the footprint of the dam. In addition, COE contractors and SCL constructed an exploratory tunnel within the rock massif on the west buttress of the dam and below the machine room. The purpose of the exploratory tunnel was to assess the engineering geology and structure of the dolomitic rock mass. No oriented rock core was apparently collected, however, COE personnel collected strike and dip discontinuity data on the rock mass in the exploratory tunnel using a traditional Brunton quadrant compass. These data were then converted to conventional standard dip and dip directions by the authors. Geologists recorded about 169 strike and dip measurements of the rock discontinuities along the flanks of the exploratory tunnel [2].

2.2. *Level 6*

Level 6 is the access tunnel for the transformer bays and is a level above the machine room. Additional geologic mapping was conducted by the authors within Level 6 tunnel to evaluate the geology and rock structure. In this case the discontinuity data were collected using present conventional methods. Dip and dip direction values were measured using a Geologic Strata Compass developed by Dr. Clar. The team collected about 131 data points [1].

2.3. Sirovision

In preparation for mapping the northeast face of the rock massif, photographs were taken mid-day on March 2, 2010, with a tripod mounted Nikon D200 (10 megapixels) and a Nikkor 24 mm f/2.8 D lens. Overcast skies produced relatively even and diffuse light during the time the photographs were being taken, although the north facing rock slope was shadowed because of its orientation, time of year, and latitude of the dam. Three control points consisting of bright orange military signal panels, each marked with a large white “X”, where temporarily hung on the rock face by the authors. The control points and camera locations were surveyed and delivered on-site for immediate use. Fig. 2 displays the locations of the control points and the camera.

The 3-D model contained 362,274 x-y-z points in Washington State Plane coordinates (NAD83/NAVD88) distributed over a surface area of approximately 39,388 m^2, yielding an average of 9.2 points/ m^2 with an average linear spacing of 33 cm. Experience has shown that this point density can be used to map major discontinuities with lengths longer than about 3 m. In practice, discontinuities mapped as closed polygons typically have angular standard deviations $\leq \pm 1°$ whereas those mapped as traces typically have angular standard deviations $< \pm 10°$. Those with larger standard deviations were generally discarded and considered unmappable at the resolution of the model.

109 discontinuities were identified and their orientations measured using standard Sirovision procedures [5, 8]. The discontinuities are displayed on Figure 3. Each discontinuity was digitized as either a polygon enclosing a visible discontinuity plane or a 3-D line along a visible discontinuity trace, and its orientation (with supporting statistics) was automatically calculated by the software.

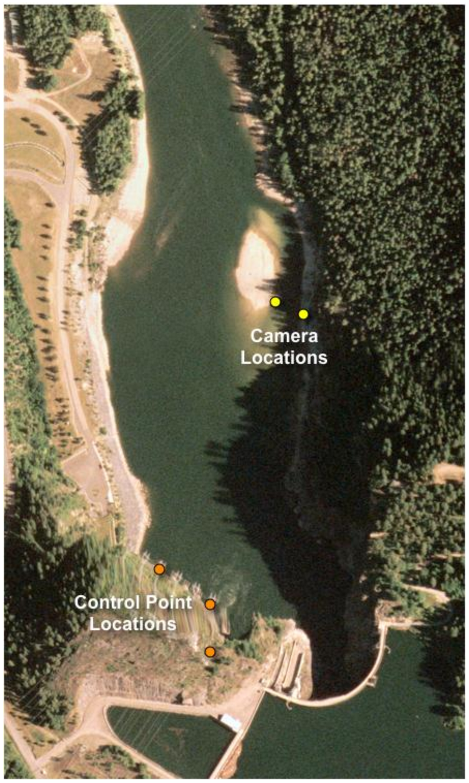

Fig. 2. Orthophoto showing Boundary Dam and its forebay, the Pend Oreille River, the dolomite massif, and the camera locations and control points used for photogrammetric modeling. North is towards the top of the photograph.

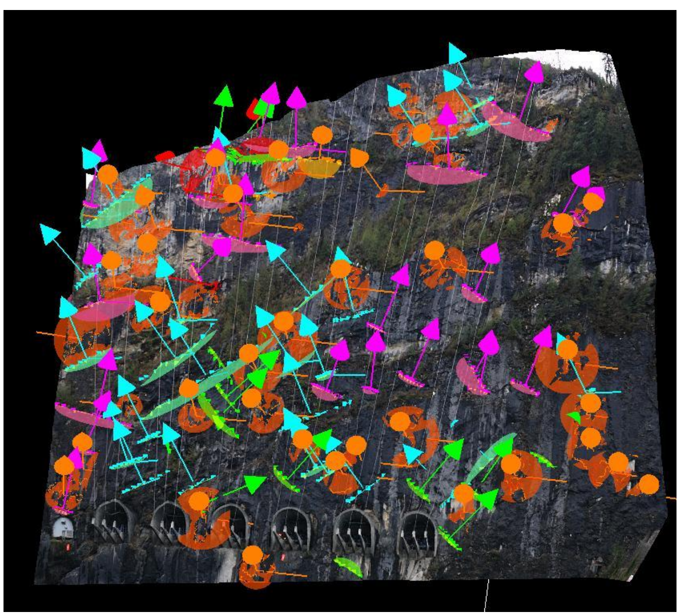

Fig. 3. Screen capture showing the Sirovision 3-D photogrammetric model with 109 mapped rock mass discontinuities. Colors correspond to the sets listed in Table 1 and the arrows represent the normals to the discontinuities.

Based upon on-site discussions among project team members and consideration of existing data sets, five discontinuity sets were delineated using the cluster analysis capabilities in Sirovision. The discontinuity sets are displayed on Table 1. Subsequent sections discuss the relationship between the delineated clusters and the discontinuity sets inferred from manually collected data on the basis of geologic insight and experience.

Table 1. Orientation data for discontinuity sets identified using cluster analysis within Sirovision (also see [8] for additional statistics). N = number of discontinuities, SD = standard deviation, Dip = dip angle, and DDN = dip direction. Set colors are keyed to Fig. 3.

Set	N	Mean Dip	Mean DDN	SD Dip	SD DDN
Red	4	54.6°	183.0°	17.4°	8.1°
Green	14	34.4°	313.3°	17.0°	33.83
Magenta	22	39.6°	17.8°	13.2°	11. 2°
Aqua	25	39.7°	95.6°	8.4°	12.6°
Orange	44	82.6°	35.5°	10.2°	6.9°

2.4. Stereographic Assessment

Discontinuities include beds, faults, joints, shears, foliation and other fractures. With this information, the authors constructed contoured pole plots on equal area stereonets to evaluate the dip and dip direction of the discontinuity sets, their kinematic relationship to each other, the relationship to underground structures and the face of the rock massif. The orientations of the discontinuities collected from the COE exploratory tunnel, Level 6 and Sirovision were collated and plotted as individual sites on equal area lower hemisphere equatorial stereonets using the computer program Dips® Version 5.0 [6]. Pole populations plotted on each stereonet were contrasted and compared for consistency and major population identification.

3. FINDINGS AND DISCUSSION

3.1. COE Exploratory Tunnel and Level 6 Access Tunnel

Figure 4 displays the combined stereographic assessment of the rock structure collected from the COE exploratory tunnel and Level 6 access tunnel. By interpretation of the pole concentrations, the stereonet displays at least four discontinuity sets. Discontinuity sets 1 and 2 display the strongest concentration of poles. Discontinuity set 1 represents bedding planes which dip about 50 degrees to the south and daylight the rock massif above the forebay of the dam (Fig. 2). The beds are prominent below the observation point above the east buttress of the dam. Discontinuity set 2 dips at about 57 degrees to the northeast. This joint set is the main cliff former above the transformer bays. Joint sets 3 and 4 are not as apparent on the stereonet but together with joint set 2 form wedges in the rock mass on the west abutment of the dam.

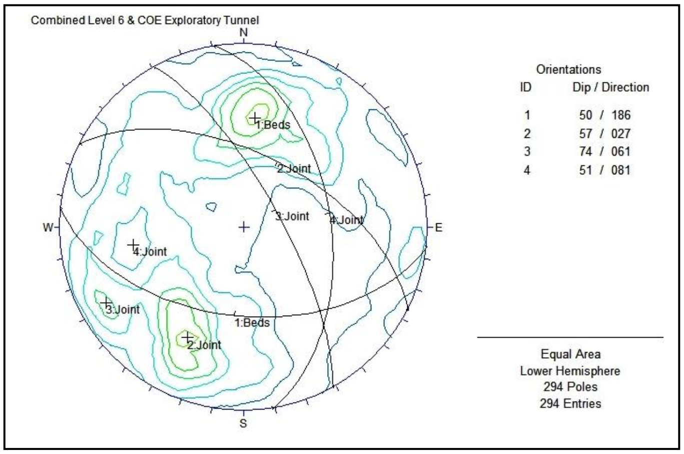

Fig. 4: Combined Level 6 and COE exploratory tunnel equal area stereonet.

3.2. Sirovision

Figure 5 displays the results the Sirovision mapping of the rock mass discontinuities on the northeast face of the rock massif above the transformer bays. Joint set 2 forming the steep northeast face is very strong. Joint sets 4 and 5 are clearly evident. Taken together, the tightly defined sets 2 and 5 on Figure 5 may correspond to the single diffuse set 2 on Figure 4. Discontinuity set 1, representing the beds on Figure 4, is weak but evident. Joint set 3 is not visible on Figure 5. A few joints having orientations that might place them into set 3 were measured on the 3-D model [8]; however, they did not persist as a cluster when the poles were contoured to create Figure 5. This under-representation may have been the result of 1) line-of-sight issues or 2) short joint lengths that made the set 3 joints difficult to identify on the 3-D model.

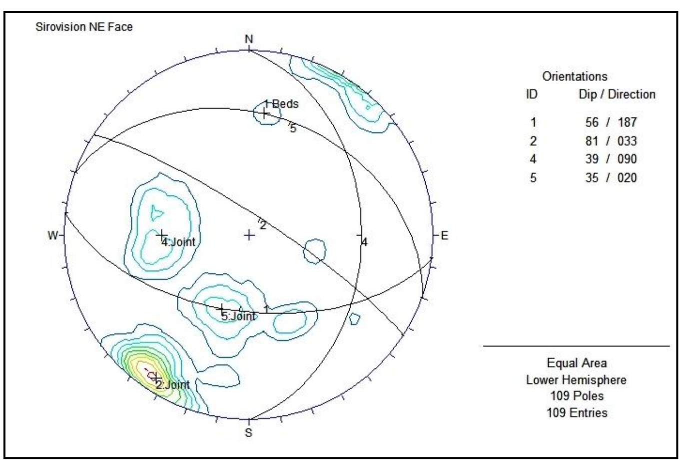

Fig. 5. Equal area stereonet using Sirovision for the northeast face of the rock massif.

3.3. Combined Results

Figure 6 is an equal area polar plot of the mean poles and planes mapped using SiroJoint (red) and manually in the exploratory tunnel (blue) and along the level 6 tunnel (green) [7]. The SiroJoint mean poles were calculated using cluster analysis whereas the other two means were identified visually by engineers from Kleinfelder [1]. The plot displays five sets of discontinuities. In general, the poles of the discontinuities complement each other.

The stereonet displayed on Figure 7 combines the results from all of the mapping and are displayed as sub-Joint Sets 1 through 5. From these joint sets, three supersets can be inferred. These sets are very evident in the rock massif. The beds (Set 1) play a key role in the structure of the rock massif and daylight over the forebay and intersect Joint sets 2 and 3 forming wedges on the west wall above the tailrace of the dam. Joints 2 and 5 appear to be a subset forming Joint set 2 which is the cliff face above the transformer bays. Similarly, Joints 3 and 4 appear to be a subset of Joint set 3 which is a major fault that transects the rock massif.

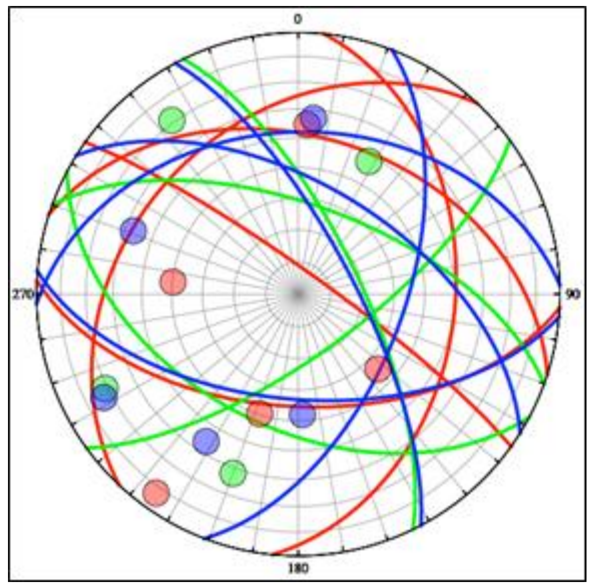

Fig. 6. Equal area polar projection displaying the combined poles with great circles from the different mapping areas [7].

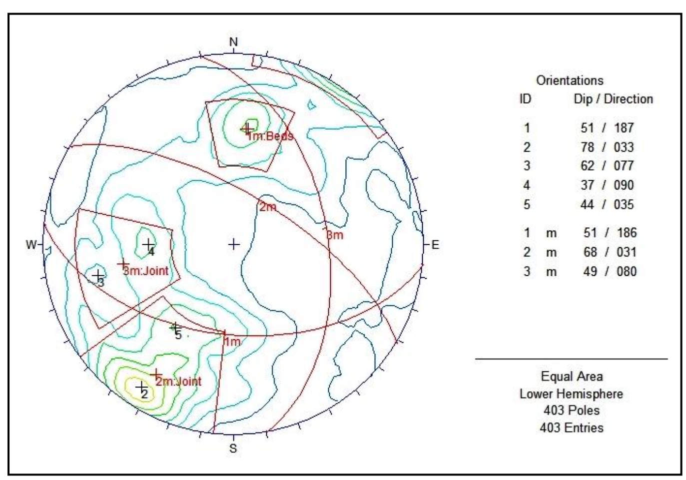

Fig. 7. Equal area equatorial projection of combined discontinuity poles and sets (represented as "m").

4. PRACTICAL ASPECTS

Remote mapping using 3-D photogrammetric models can be an efficient approach in areas where traditional discontinuity mapping is difficult or impossible because of safety issues, limited access to the rock face, or other factors such as electromagnetic interference with the handheld compasses.

Cost is always an issue. Using 3-D photogrammetric models for discontinuity mapping requires a good quality digital camera and lenses, specialized software, survey control, and an operator who knows both how to use the equipment and how to analyze the data [5]. The amount of work necessary to obtain survey control or model orientation and scaling data depends on the required accuracy, and also varies among the commercially available software packages. One advantage of close range photogrammetry is that modern software can use images from off-the-shelf digital SLR cameras, obviating the need for the expensive metric cameras traditionally used in aerial photogrammetry or laser scanners. Thus, the equipment is comparatively inexpensive.

Using information from Carnahan [9], Pate and Haneberg [8] estimated that photogrammetric modeling cost less than one-tenth as much as traditional manual mapping on a per measurement basis. Photogrammetric modeling was also competitive with ground based laser scanning, with photogrammetric results about half the cost of human-interpreted laser scanner results and about twice as much as automated laser scanner results, again on a per measurement basis [8].

Perhaps the most important limitations of any kind of remote mapping—photogrammetric or laser based—are that 1) human interpretation and oversight are essential, 2) the human needs to understand structural geology and engineering geology in order to know if the input data and output data are reliable and geologically realistic, and 3) remote methods do not provide critical geologic information that can be gleaned only by human examination of the discontinuities.

For the Boundary Dam project, field data collection and analysis the traditional mapping techniques and photogrammetric mapping took about one week. A working 3-D model was available within hours of the photogrammetric fieldwork; hence, most of the data analysis took place on site and was followed up with final review and a report.

5. CONCLUSIONS

Rock mass discontinuity orientations from historical mapping data, new tunnel mapping, and 3-D photogrammetric modeling of the face agreed well and complimented each other. The discontinuities fell into three distinct sets with possibly two subsets. Discontinuity set 1 representing a set of prominent dipping beds was weakly observed on the Sirovision mapping because most of the discontinuities of the set were hidden from the camera view or dipping away from the camera. Joint length may also be an issue, as the resolution of the 3-D model precluded confident mapping of joints less than about 3 m long. The results described here clearly show that remote techniques such as photogrammetry are important tools that complement manual rock face mapping. However, they cannot and should not replace traditional hands-on-the-rock geological fieldwork, observation, and interpretation.

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