Rockfall protection along Highway 403 in Hamilton, ON: A recent re-assessment and application of emerging site investigation methods

David F. Wood
David F. Wood Consulting Ltd., Sudbury, ON
Dave Gauthier[1, 2], D. Jean Hutchinson[1]
[1]Dept. of Geological Sciences and Geological Engineering, Queen's University, Kingston, ON; [2]BGC Engineering, Kingston, ON
Stephen Senior
Ontario Ministry of Transportation, Downsview, ON

ABSTRACT
The Niagara escarpment is a unique area of high relief and exposed bedrock in Southern Ontario between Niagara in the south, and Tobermory in the north. Ontario King's Highway 403 transects the escarpment with a long approach along the toe of an active talus slope, and directly adjacent to exposed bedrock near to the crest of the escarpment, within the limits of the City of Hamilton. Engineered rockfall hazard protection extends for approximately 1.5 km through this area, with a combination of a 500 kJ capacity rigid catchment fence and a narrow ditch/clear zone. Following a number of rockfall events in 2012, some of which impacted the fence and reached the shoulder of the eastbound lanes, a detailed assessment of the efficacy of the existing protection was undertaken. In this paper we report on the application of traditional and emerging site investigation methods employed in this assessment. We focus on the use of oblique aerial photogrammetry to generate a detailed 3D terrain model of the 1.5 km long slope, from crest to road, and report on the use of that information in a number of novel ways to evaluate the protection provided, and recommend further risk management measures.

RÉSUMÉ
L'escarpement du Niagara est un espace unique à haut relief et affleurements rocheux dans le sud de l'Ontario entre le sud de Niagara et le nord de Tobermory. L'autoroute 403, reine de l'Ontario, traverse l'escarpement avec une longue approche le long du pied d'un talus d'éboulis actifs et directement adjacente à l'affleurement rocheux à proximité de la crête de l'escarpement, à l'intérieur des limites de la ville d'Hamilton. Les protections contre les dangers d'éboulement s'étendent sur 1,5 km à travers cette zone, avec, en combinaison, une clôture rigide de captage d'une capacité de 500 kJ et une zone de fossé étroite. Après un nombre d'événements d'éboulements en 2012, dont quelques-uns ont heurté la clôture et atterri dans l'accotement des voies en direction est, une évaluation détaillée de l'efficacité des mesures de protection existantes a été effectuée. Dans cet article, nous rapportons l'application des méthodes d'investigation employées lors de cette étude. Nous mettons l'accent sur l'utilisation de la photogrammétrie oblique aérienne pour générer un modèle 3D du terrain de la pente de 1,5 km de long, de la crête à la route, et sur l'utilisation de cette information pour évaluer la protection mise en place et recommander des mesures de gestion des risques futures.

1 INTRODUCTION

The Niagara escarpment is a unique area of high relief and exposed bedrock in Southern Ontario between Niagara in the south, and Tobermory in the north. Its expression varies from vegetated gentle slopes to vertical cliffs tens of metres high, and associated active talus slopes with rockfall and other geohazards recognized at various locations along its length. The City of Hamilton is the focus of much of the risk, given the proximity of a dense population to the steep, rocky escarpment in this area (Figure 1).

Ontario King's Highway 403 (a four-lane divided highway also known as the 'Chedoke Expressway' within Hamilton) transects the escarpment with a long approach along the toe of an active talus slope, and directly adjacent to exposed bedrock near to the crest of the escarpment, within the limits of the City of Hamilton. Engineered rockfall hazard protection extends for approximately 1.5 km through this area, with a combination of a 500 kJ capacity rigid catchment fence and a narrow ditch/clear zone (Figure 2). Following a number of 2-5 m^3 rockfall events in 2012, some of which impacted the fence and reached the shoulder of the eastbound lanes, a detailed assessment of the efficacy of the existing protection was proposed by the Ontario Ministry of Transportation.

In this paper we report on the application of traditional and emerging site investigation methods employed in this assessment. We focus on the use of oblique aerial photogrammetry using high-resolution digital photographs collected from a moving helicopter to generate a very detailed 3D terrain model of the 1.5 km long slope, from crest to road, and report on the use of that information in a number of novel ways to evaluate the protection provided, and recommend further risk management measures.

Figure 1. Map showing approximate study area location, and trace of the Niagara Escarpment through the City of Hamilton.

Figure 2. Typical site conditions at highway level, showing the talus slope, ditch, catchment fence, and travelled lanes.

2 METHODS AND DATA

Along with a traditional reconnaissance-level field visit, in the fall of 2014 we chartered a Robson R44 helicopter for the purposes of collecting a set of oblique aerial photographs of the study area. The intent was to use these to develop the detailed three-dimensional photogrammetric model of the slope, as well as the travelled lanes, fence and ditch, and terrain beyond the crest.

Photogrammetry for rock slopes is typically conducted from the ground (e.g. Haneberg, 2008; Sturznegger and Stead, 2009; Andrew et al., 2012; Wolter et al, 2013; Lato et al 2014), however emerging techniques in 'structure from motion' has made it possible to conduct oblique photogrammetric surveys from the air (UAV or helicopter) for many geological and geotechnical applications (see James and Robson, 2012; Hugenholtz et al, 2012; Westoby et al, 2012). Several other authors in the current volume have applied this technique to rock slopes.

We used a 24 megapixel Nikon DSLR camera, with a 50 mm (75 mm equivalent) lens to capture 567 geotagged photos of the slope. Photogrammetric processing was completed using Agisoft Photoscan Pro (V1.0). Alignment tie were points culled to retain only those with reprojection error < 0.5 pixels, then alignments were optimized. We generated a 53 million-point dense cloud generated for entire length of the project area, for an average of 185 points/m^2 (Figure 3).

For the western portion we also generated a much denser cloud (815 points/m^2). We registered the photogrammetric model using a combination of the geotagged photos and terrestrial LiDAR scan (TLS) data provided by a third-party. Once registered in georeferenced coordinates, 0.5 m and 0.1 digital terrain models (DTM) were generated for the project area (Figure 3).

As part of this study we also reviewed rockfall and rock scaling investigation and supervision reports, aerial photographs provided by the City of Hamilton, design and construction drawings, and Environment Canada's Climate Data Archive.

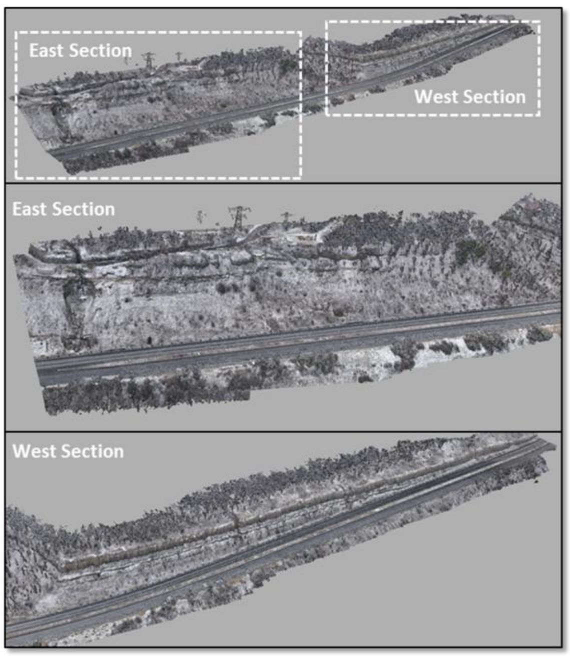

Figure 3. Oblique view of the study area, captured from the 3D photogrammetry model. Scale varies (perspective view).

3 RESULTS

3.1 Rockfall hazard

During rockfall events on March 13 and March 21 2012 rock blocks engaged the protection fence and resulted in its elongation onto the shoulder of the eastbound right lane. There was no intrusion into the travelled lanes.

Block sizes ranged from 1-5 m^3. Numerous blocks were caught in the ditch; however, on both dates individual large blocks ascended the foreslope and reached the fence. In both cases the braking elements in the fence were activated, and from a cursory review of the original design drawings for the fence it appears that it performed as intended, i.e. with low elongation.

The source areas for theses rockfalls was identified within an exposed layer of bedrock, below the ultimate crest of the escarpment. Overlying layers seem to fail in a ravelling mode, while the stratum directly below the rockfall-producing one is know to erode preferentially and undercut the more massive, blocky structure of the layer above, leading to the periodic release of large blocks.

There are no records of other significant rockfall events since the fence was installed in 1998, however the current and previous studies have noted numerous fallen rocks in the ditch – presumably the result of ongoing rockfall activity. None, however, appear to have engaged the braking elements on the catchment fence.

We conducted a back-analysis of these rockfall events, in order to calibrate the rockfall simulation parameters for forward analysis of potential future events. In all cases the detailed photogrammetry-derived DEM was used to generate the 2D cross-sections and to assign slope material and roughness parameters. The simulations showed that:

- The March 13 2012 event was simulated to reach the fence with total kinetic energy of 360 kJ, using conservative slope material and initial velocities in the simulation
- Two other test sections showed similar results, with some proportion of the simulated blocks reaching the fence with maximum total kinetic energy less than 75% of its design capacity
- The ditch was generally effective in stopping and/or attenuating the energy of the simulated blocks.

To evaluate potential conditioning or triggering factors for the rockfalls, we reviewed of Environment Canada's Climate Archive for 2012 at the Hamilton Airport, which is located approximately 7 km south of the study area. We found that:

- By late February 2012 intermittent snow cover had disappeared completely, due to warming air temperatures
- Between February 29 and March 13 2012, at total of 22 mm of rain fell, with a further 4.2 mm prior to March 21 2012
- March 11 2012 marked the onset of an intense period of unseasonably warm weather, with daytime highs exceeding 25°C on March 29 2012, and overnight low temperatures remaining above freezing (except for one night at -0.6°C) over consecutive nights for the first time in 2012, beginning March 11 2012.
- The record high temperature for March (25.6°C) would have been reached on March 29, and exceeded the following day (1981-2010).

This review suggests that several meteorological factors, likely in combination, may have contributed to the occurrence of the rockfalls: snowmelt, wet weather, and unseasonably warm/record high temperatures, and above-freezing overnight temperatures.

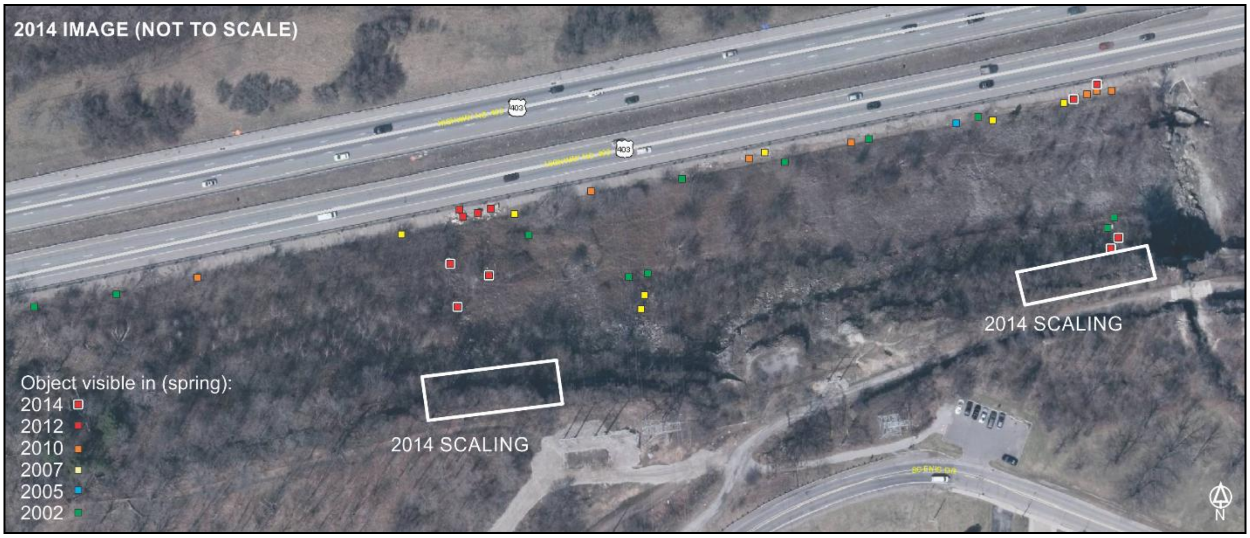

Figure 7. Air photo review, showing approximate location of fallen blocks identified in each photo. Areas of 2012 rockfall and 2014 scaling indicated.

Aerial photography for the project area was gathered for review. We subjectively compared the sequential aerial photographs, and noted the existence of any large (approximately 0.5 m^3 or larger) blocks on the slope or in the ditch. The images were each captured in springtime, so foliage did not obscure visibility. We found a concentration of fallen rocks downslope of the source areas for the 2012 events and the focus of rock scaling effort in 2014, as expected. Otherwise, a minor concentration of fallen blocks was noted below the eastern scaling area between 2007 and 2010, and generally fallen blocks were often found in groups of different age at a similar location. Note that this dataset is almost certainly truncated with the smaller blocks not counted, and the 2002 count would represent a longer record than the other intervals (Figure 4).

With regards to the terrain between the rockfall sources and highway, a subtle bench feature is noted in some locations directly below the main rockfall-producing strata, which are assumed to be protrusions of lower bedrock strata through the otherwise talus-covered slope. Lower on the slope, particularly in the east part, inspection of the photogrammetry-derived fine DEM shows other similar, but more subtle, bench features, assumed to represent similar bedrock control on the form of the slope (Figure 5). These benches serve to break up the slope and provide natural attenuation for rolling blocks, both because of their shape and because of the coarser composition of the talus overlying them (due to previous rocks having stopped there).

4. DISCUSSION

Taken together, the data described here – along with other inputs omitted for space considerations – suggest that the rockfall hazard at this site is mostly governed by the periodic release of large (~5 m^3) or greater blocks; the numerous smaller rockfalls do not pose a threat to the highway or the travelling public. Furthermore, these releases seem to be sourced from a particular 2-3 m thick stratum. The other beds do produce rockfalls, but generally do so in a ravelling or disaggregation mode, and without the volume or potential energy to reach or cause engagement of the catchment fence.

Rockfall observations and simulations at a number of locations demonstrated that the largest of these can approach the design capacity of the catchment fence, although only in the eastern part of the project area, where the lower elevation of the highway grade below the approximately horizontal bedding provides sufficient fall-height.

This study and others found that the rockfall catchment fence had performed as designed, during past rockfall events. However, further risk reduction may be desirable, particularly where public safety is involved. Risk reduction measures are currently being considered, but that is beyond the scope of this paper. However, we can note that since the site is a UNESCO Biosphere Reserve adjacent to a 400-Series highway within the limits of a large metropolitan area, there are some special limitations regarding the practicable approach to any further mitigation or risk management. For example, major construction efforts (e.g. a replacement fence, slope benching, stabilization, etc.) would be difficult given both the sensitivity of the site, and traffic patterns.

Other options (e.g. ditch expansion) may be easier to construct, but could be seen to alter the hydrological character of the site, and any downstream impacts may need to be evaluated prior to implementation.

For these reasons, intrusive or non-esthetic risk reduction measures may be difficult to implement at this site. One advantage of the OAP method presented here is that it is ‘hands-off’, so not subject to limitations related to the sensitivity of the site, yet establishes a 3D baseline to which subsequent surveys could be compared to monitor the slope for development of hazardous blocks in the specific rock formations known to produce them periodically. Change-detection technology between serial LiDAR and photogrammetry surveys is advancing rapidly, and in many cases even small displacements of discrete blocks can be identified, and the location of future rockfalls predicted (e.g. Kromer et al., 2015). Any

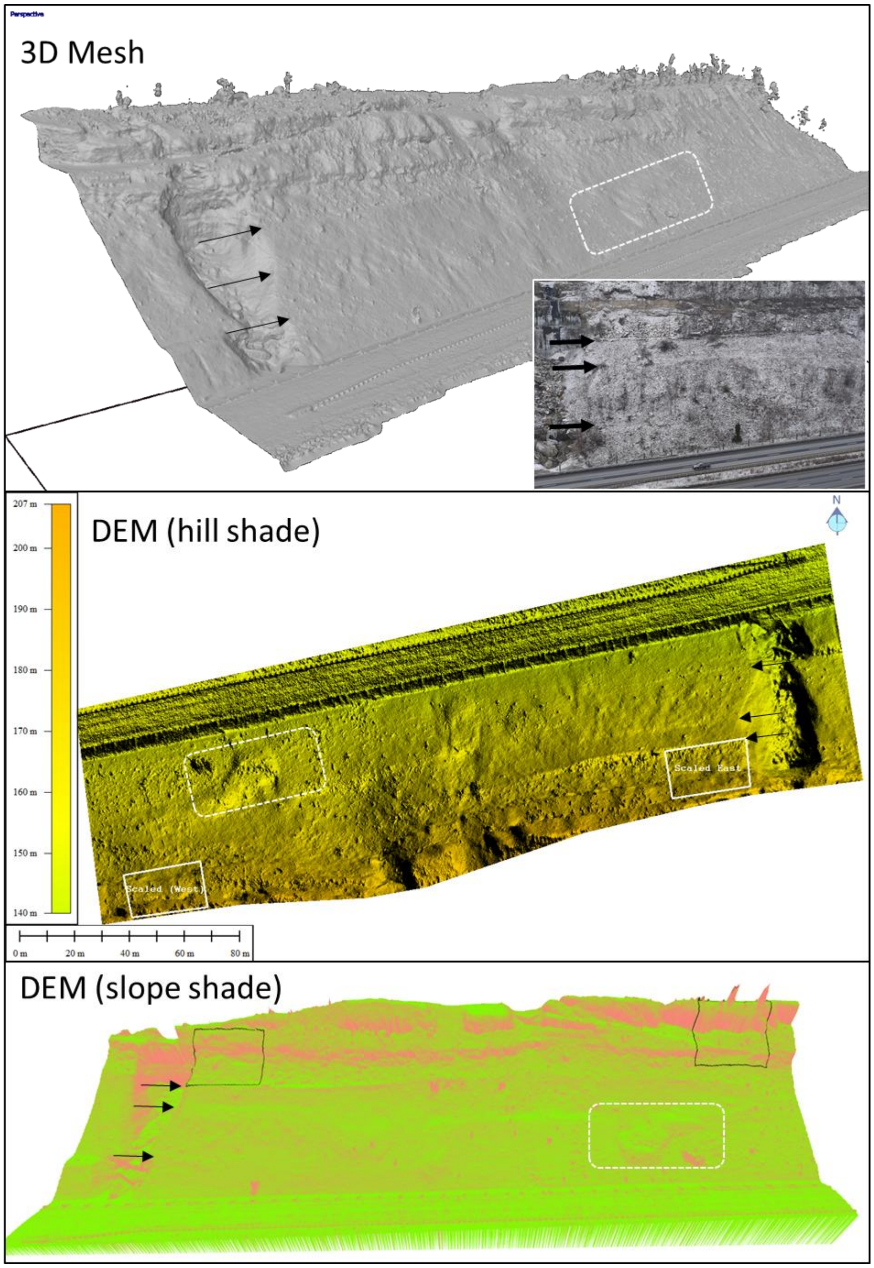

Figure 5. Sample of 3D mesh (oblique view, with inset oblique photo), DEM hill shade (map view) and DEM (slope shade) for the east section, highlighting the bedrock-controlled benches on the lower slope (arrows), and a shallow creep-like feature in the talus (dashed box). The 2012 rockfall source areas are indicated.

developing loose blocks could be managed directly, through small scale scaling or removal operations, in generally controlled circumstances.

4 CONCLUSIONS

For the assessment of rockfall hazard and rockfall protection along highway 403 in Hamilton, we found that the application of oblique aerial photogrammetry, as a supplement to more traditional approaches, was useful, and allowed certain observations and interpretations to be made that would otherwise have been difficult.

We found that the rockfall hazard was governed by the development of large blocks in a particular bedrock stratum, and that these formed and fell periodically, with a concentration of recent activity in a few locations. We also found that while the catchment fence was likely adequate for protection as designed, this site is subject to some limitations in practicable risk reduction measures, given its high profile and UNESCO status.

One of the most useful outcomes related to the OAP 3D slope model was the ability to visualize the terrain in high-resolution 3D and thereby identify the locations of subtle, but rockfall-interrupting benches in the slope, apparently related to the protrusion of underlying beds. The accumulation of fallen material on the upper of these benches resulting from a recent scaling campaign is a testament to their efficacy in this regard. In addition, having collected an initial set of oblique photos in 2014 means that subsequent models could be compared, and changes could be detected on the slope prior to the dislodgment of hazardous blocks. These blocks could be removed, ideally, prior to falling naturally.

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REFERENCES

Andrew, R., Arndt, B., and Turner, K. Instrumentation and monitoring technology. In: Turner, K. and Shuster, R. (eds), Rockfall characterization and control, Transportation Research Board, Washington, DC, pp 56-71, 2012.

Fonstad, M., J. Dietrich, B. Courville, J. Jensen, and P. Carbonneau. Topographic structure from motion: a new development in photogrammetric measurement. Earth Surface Processes and Landforms 38 (4), 2013, pp. 421-430.

Haneberg, William C. Using close range terrestrial digital photogrammetry for 3-D rock slope modeling and discontinuity mapping in the United States. Bulletin of Engineering Geology and the Environment 67(4), 2008, pp.457-469.

Hewitt, D., 1971. The Niagara Escarpment. Industrial Minerals Report 35. Ontario Department of Mines and Northern Affairs. 68 pp.

Hugenholtz, C., K. Whitehead, O. Brown, T. Barchyn, B. Moorman, A. LeClair, K. Riddell, and T. Hamilton. Geomorphological mapping with a small unmanned aircraft system (sUAS): feature detection and accuracy assessment of a photogrammetrically-derived digital terrain model. Geomorphology, 194, 2013, pp 16-24.

James, M. R., and S. Robson. Straightforward reconstruction of 3D surfaces and topography with a camera: Accuracy and geoscience application. Journal of Geophysical Research: Earth Surface 117.F3, 2012, pp. 2003-2012.

Kromer, R., Hutchinson, J., Lato, M., Gauthier, D. and Edwards, T., 2015. Early Warning of Rockfall Hazard from Remote Monitoring. *Proceedings: GeoQuebec 2015*, Quebec, QC, September 20-23, 2015

Lato, M., Hutchinson, J., Gauthier, D., Edwards, T., Ondercin, M. Comparison of ALS, TLS and terrestrial photogrammetry for mapping differential slope change in mountainous terrain. Canadian Geotechnical Journal, 52(2): 129-140, 2014.

Sturzenegger, M., and D. Stead. Close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts. Engineering Geology 106(3), 2009, pp. 163-182.

Westoby, M. J., Brasington, J., Glasser, N. F., Hambrey, M. J., & Reynolds, J. M. 'Structure-from-Motion'photogrammetry: A low-cost, effective tool for geoscience applications. Geomorphology, 179, 2012, pp 300-314.

Wolter, Andrea, Doug Stead, and John J. Clague. A morphologic characterisation of the 1963 Vajont Slide, Italy, using long-range terrestrial photogrammetry. Geomorphology, 206, 2013, pp 147-164.