Geotechnical Challenges Associated with the Design and Construction of the Three Valley Gap Remote Avalanche Control System Project

Michael J Laws, Cevat Catana, & Pete Wittstock,
Ecora Engineering & Resource Group Ltd., Kelowna, BC, Canada
Walter Steinkogler
Wyssen Avalanche Control, Revelstoke, BC, Canada

ABSTRACT

The Three Valley Gap Remote Avalanche Control System project involved the installation of nine permanent Avalanche Towers in steep, rocky terrain above the Trans-Canada Highway to decrease the length of avalanche closures. The towers are up to twelve meters tall, and are inclined to overhang the avalanche release areas. Deployment boxes mounted on each tower hold explosive charges that are detonated individually to remotely triggering avalanches.

Many tower locations are subject to potential rock fall and unstable rock masses that presented challenges in design and construction. An iterative tower location selection methodology was adopted in which rock fall protection measures were evaluated for tower locations, and overall rock fall hazard was assessed. Other site constraints considered in the evaluation process include site access and rock quality at the tower foundation.

This paper presents the geotechnical challenges associated with the project and the approach that the design team utilized for the selection of the tower location relating to the geotechnical hazards.

Le projet du système de contrôle des avalanches à distance de Three Valley Gap impliquait l'installation de neuf tours d'avalanche permanente dans un terrain escarpé et rocheux au-dessus de l’autoroute Trans Canada afin de réduire la durée des fermetures à cause d'avalanche. Les tours mesurent jusqu'à douze mètres de hauteur et ont tendance à surplomber les zones de dégagement des avalanches. Les boîtes de déploiement montées sur chaque tour contiennent des charges explosives qui sont détonées individuellement pour déclencher des avalanches à distance.

De nombreux emplacements de pylônes sont au risque des éboulements de roches et à des masses de roches instables qui posent des problèmes de conception et de construction. Une méthodologie itérative de sélection de placement des pylônes a été adoptée, dans laquelle des mesures de protection contre les chutes de pierres ont été évaluées pour l'emplacement des pylônes, et le risque global de chute de pierres a été évalué. Les autres contraintes du site prises en compte dans le processus d'évaluation comprennent l'accès au site et la qualité de la roche à la fondation de la tour.

1 INTRODUCTION

1.1 Project Description

The Trans Canada Highway (TCH) corridor through the Three Valley Gap (3VG) area is subject to avalanche hazard from ten well defined avalanche pathways throughout the winter months. Avalanche hazard was previously controlled using explosives dropped from a helicopter at the avalanche release areas. However helicopters could not be safely flown at night, or during adverse weather conditions such as snow. Therefore road closures for avalanche control often extended for several hours to allow for safe flying conditions and time to clear the road. In 2016, the British Columbia Ministry of Transportation and Infrastructure (BCMoTI) commissioned the construction of nine Remote Avalanche Control System (RACS) Towers. These towers can be operated remotely at any time, which greatly reduces closure times. However as the towers are permanent, they are also subject to geohazards such as rock fall and avalanche damage. This paper details the methodology used for selecting tower locations to mitigate the avalanche hazard in an area prone to rock fall hazard. The Avalanche hazard at the 3VG site is discussed in "Multi-level avalanche risk reduction on the Trans-Canada Highway - Three Valley Gaps RACS" prepared by Val Visotzky of the BCMoTI, Alan Jones of Dynamic Avalanche Consulting, and Walter Steinkogler of WAC, available in the2018 Canmore Geohazards 7 conference proceedings.

1.2 RACS Tower Description

The Wyssen Avalanche Control (WAC) RACS towers consist of steel tower in two segments resting on a reinforced concrete leveling pad. The tower and leveling pad are secured to the ground using four vertical grouted steel micropiles located on the four corners of the tower base, and one inclined shear relief anchor on the up slope side of the tower. A removable explosive deployment box is placed at the top of the tower. The WAC RACS tower is shown as Figure 1 below.

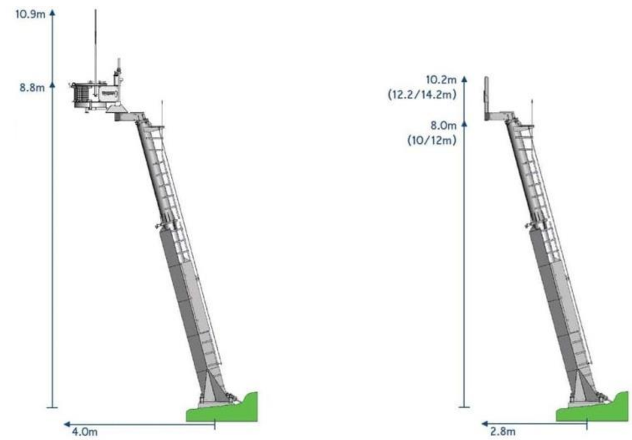

Figure 1. Wyssen RACS Tower Winter Configuration

1.3 Project Location

Three Valley Gap is located approximately 22 km west of Revelstoke BC, along the TCH. The avalanche paths described in this report are located along the south side of the highway adjacent to Three Valley Lake.

The locations of the towers, and the angles of the slope are shown on Figure 2 below.

1.4 Site Geology

Reference to the BC Geological Survey Map "The Geology of the Thompson Okanagan Mineral Assessment Region" (Schiarizza and Church, 1996) indicates that bedrock underlying the RACS towers comprises biotite quartz schist. Ecora confirmed the bedrock geology on site, and noted that the rock was highly foliated with local complex folding.

2 HISTORICAL OCCURENCES OF ROCK FALL

The Three Valley Gap area is subject to frequent rock fall from the numerous steep rock cliffs located along the south side of the TCH corridor. These rock fall events are often large enough to cause damage to passing vehicles, or damage the road surface.

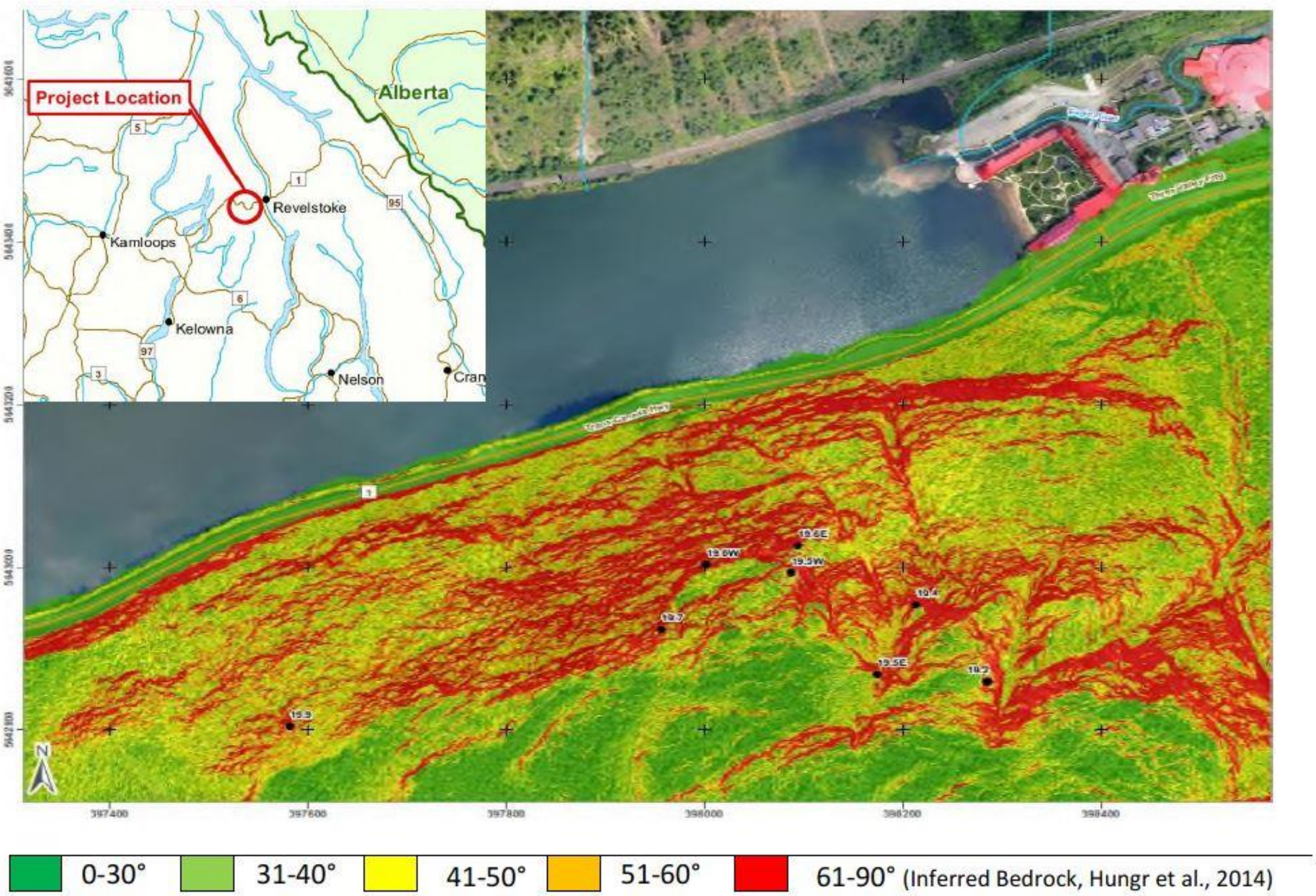

Figure 2. Slope Classes of the Three Valley Gap Area, and Tower Locations

2.1 Maintenance Contractor Rock Fall Reports

A review of the Maintenance Contractor Rock Fall Reports (MCRR) for the period 1994 to 2015 indicates that the Three Valley Gap segment of the TCH has been subjected to 359 reported rock fall events along the approximately 3.2 km of road between the Three Valley to Mabel Lake FSR and the eastern 3VG avalanche gates as summarized in Table 1 below.

Table 1. Volume of Rock Fall Events for the 3 Valley Gap Area from MCRR Reports

Reported Volume (m^3)	Number of Rock Fall Debris Observations	Cumulative %
< 0.03	176	51.2
0.03-0.1	82	75.0
0.1-0.25	30	83.7
0.25-0.5	17	88.7
0.5-0.75	22	95.1
0.75-1.0	2	95.6
1.0-2.5	2	96.2
2.5-5.0	13	100.0

The distribution of the reported rock fall events indicates that the majority of event are concentrated within localized particularly along avalanche paths 19.4, 19.5, 19.7, and 19.9.

2.2 Three Valley Gap Rock Fall Return Period

Ecora calculated the return periods for the rock fall volumes reported in the MCRR rock fall reports using a generalized extreme value (Gumbel) distribution (Wyllie, 2015). The Gumbel distribution is a conservative method of estimating the return periods as the input values are the maximum rock fall volumes per year. Based on the Gumbel distribution, the 20 and 200-year events for Three Valley Gap have volumes of 4.58 m^3 and 8.85 m^3 respectively. The Gumbel distribution for 3VG is shown as Figure 1 below.

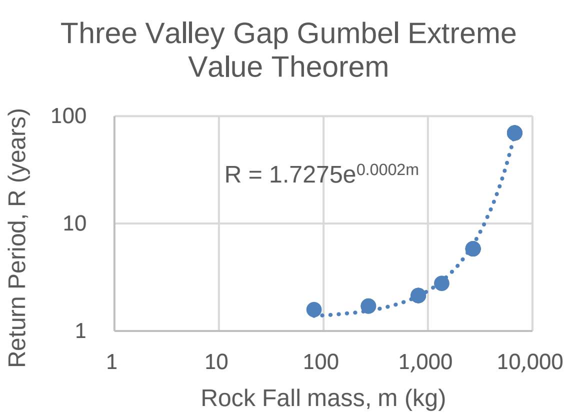

Figure 3. Gumbel Distribution of Rock Fall Mass From MCRR Data for Three Valley Gap

3 ROCKFALL PROTECTION OPTIONS

Ecora considered several rock fall protection options for the RACS tower locations. However all the options were deemed to be unfeasible for construction. The rock fall protection options considered are detailed in the sections below.

3.1 Flexible Rock Fall Barrier

Installation of a flexible rock fall barrier (fence) was not considered technically feasible at six of the RACS tower locations as it would not be possible to install lateral anchors for the bottom & top support ropes within the geometric criteria of the system manufacturer. In addition, all tower locations are subject to avalanche loading in excess of the capacities of any cost-effective rock fall barriers considered.

Clearing of trees would be required for the fence installation, and is expected to increase the hazard to the RACS towers from avalanches, and increase the rate of erosion across the slope contribution to greater rock fall hazard to the TCH corridor.

3.2 Rock Bolting

Installing rock bolts was not considered to be a feasible rock fall protection strategy at any of the tower locations as the foliation of the quartz biotite schist bedrock are roughly perpendicular to the rock face across the site, and rock bolts would not mitigate failures along these foliation planes.

3.3 Drape Mesh

A draped mesh may be effective in mitigating the rock fall hazard at several tower locations. However it is not considered to be feasible as it would require all trees to be cleared within 5 m of the crest of the rock fall source zone on which it is installed which would increase the overall avalanche and rockfall hazard. In addition, rock control mesh strong enough to withstand the expected rock falls and avalanches without tearing would cost substantially more than the replacement cost of the RACS tower, and would still require maintenance.

3.4 Tower Foundation Protection

Tower foundation protection through options such as construction gabion baskets around the tower leveling pad or covering the exposed portions of the tower support micropiles with steel pile caps would reduced the rockfall hazard to the tower and was considered to be constructible. However the gabion baskets would increase the avalanche load on the tower during early and late season avalanche when the snowpack is shallow. Both options would also result in increased corrosion of the steel micropiles and shear relief anchors by restricting airflow and sunlight to the tower base, slowing the evaporation of moisture.

4 TOWER LOCATION SELECTION

As none of the rock fall protection options considered were deemed to be both constructible and beneficial to the RACS towers, Ecora reviewed the likelihood that rock fall would strike any of the tower locations over the 75 year design life.

Based on eight RACS towers located in the main 3VG area, with a width of 0.5 m, and 359 rock fall events along a 3.2 km long stretch of road over 22-year period noted in the MCRR reports, there is a 2.03% chance that any of the eight towers would be struck each year. Applying a 16.3% chance that the rock fall would be large enough to damage the tower, there is a 0.33% chance that a rock fall would damage a tower, which corresponds to a return period of 301 years for tower damaging events.

With such a low probability of rock fall strikes damaging a RACS tower and the unfeasibility of installing rock fall protection, the focus of the project shifted to identifying the tower locations with the lowest hazards which still effected the avalanche release areas.

4.1 Avalanche Release Areas

The general avalanche release areas were identified in the BC MoTI T.C.HWY West of Revelstoke Area Snow Avalanche Atlas, updated August 2015, and refined by WAC in conjunction with Dynamic Avalanche Consulting Ltd. based on site reconnaissance and GIS analysis.

4.2 Site Reconnaissance

Final tower locations were selected in collaboration with WAC in order to be within effective explosive range of the avalanche release areas, while minimizing the Towers' exposure to geohazards such as rock falls and other avalanches by utilizing terrain features and observing the trajectory of rock falls on site during scaling.

The RACS towers have an effective range of 130 to 150 m, compared to approximately 80 m for RACS systems using gas mixtures for explosions. Therefore, there were numerous options available for the locations of each tower.

4.3 Rock Fall Observations

The rock fall hazard across the project area was assessed using a combination of rock fall debris observations made on site, observations of rock fall trajectory during scaling of potentially hazardous rocks, and discontinuity mapping of potential rock fall source zones.

4.3.1 Rock Fall Debris Survey

Ecora carried out a survey of rock fall debris volumes and tree strike heights between rock fall source zones and proposed RACS tower locations prior to construction. Due to time constraints, the survey method involved taking geo-reference photos of rock fall with a survey staff present for scale, and analyzing the photos later. As rock fall volume decreases with distance from the rock fall source zone, the observed volumes are considered to be larger than rock fall volume at the tower locations. Observed rock fall volumes are presented in Table 2 below.

Table 2. Estimated Volume of Rock Fall Debris for the 3 Valley Gap Area

Estimated Volume (m^3)	Number of Rock Fall Debris Observations	Cumulative %
< 0.03	258	38.9
0.03-0.1	124	57.6
0.1-0.25	107	73.7
0.25-0.5	63	83.2
0.5-0.75	48	90.5
0.75-1.0	30	95.0
1.0-2.5	18	97.7
2.5-5.0	15	100.0

The heights of rock fall tree strikes near tower locations are presented in Table 3 below.

Table 3. Summary of Rock Fall Tree Strike Heights for the 3 Valley Gap Area

Strike Height (m)	Number of Observations
<0.2	3
0.02-0.4	3
0.4-0.6	4
0.6-0.8	6
1-1.2	6
1.2-1.5	3
1.5-2.5	2

The rock fall size and the height of tree strikes were used to calibrate rock fall simulations discussed in Section 5 below.

4.3.2 Rock Scaling Observations

Ecora observed the scaling of potential rock fall source zones located above the proposed RACS tower locations and worker access routes. The scaled rocks served as full scale rock fall tests, showing the expected trajectory of anticipated rock fall from the source zones, and were used to identify areas with lower rock fall hazard for tower placement. Figure 5, located at the end of this report shows the expected rockfall trajectories for RACS Tower 19.6W, and identifies the terrain features which directed rock fall away from the chosen tower location. Potential tower location 1 shown on Figure 5 was selected as having the lowest overhead rockfall hazard. Location 3 was affected by a rock fall originating near the base of RACS tower 19.7 during the 2017 construction season, as shown on Figure 6.

4.3.3 Discontinuity Mapping

Ecora carried out discontinuity mapping of the rock fall source zones, and the rock outcrops supporting the RACS towers. The discontinuity mapping data was used to determine if rock faces were kinematically stable, and determine the maximum possible block size for rock fall.

5 ROCK FALL RETURN PERIOD ASSESSMENT

The project specifications required that the RACS Towers be protected from all likely hazards, corresponding to a return period of 200-years (AGS, 2007) over their 75 year design life.

qualitative measures of likelihood are shown in Table 4 below.

Table 4. Qualitative Measures of Likelihood

Likelihood Descriptor	Return Period (Years)
Almost Certain	2 to 20
Likely	20 to 200
Possible	200 to 2000
Unlikely	2000 to 20,000
Rare	20,000 to 200,000
Barely Credible	> 200,000

Modified from (AGS, 2007) and (Lee, 2014).

5.1 Tower Site Rock Fall Return Period

Ecora developed site specific Gumbel distributions for each RACS tower by spatially scaling the return periods of the 3VG Gumbel distribution to the width of the rock fall source zone area above each tower location. The width of the rock fall zone was determined from 1 m contour topographical maps by extending a 70° cone up slope of the tower location to the nearest rock fall source zone, and directly up slope above the nearest rock fall source zone until a sufficiently low angle slope or topographical feature restricts rock fall from above, resulting in rock fall source zone widths of 7.8 to 27.6 m. The width of the rock fall source zone was then multiplied by a factor of 1.3 to account for bounces off trees and uncertainty in the topography. The scaled Gumbel distribution for Tower 19.6W, the location with the largest rock fall source zone is shown as Figure 3 below. Based on the Gumbel distribution, a maximum Likely rockfall mass of 531 kg, corresponding to approximate 0.197 m^3 is expected at Tower 19.6W.

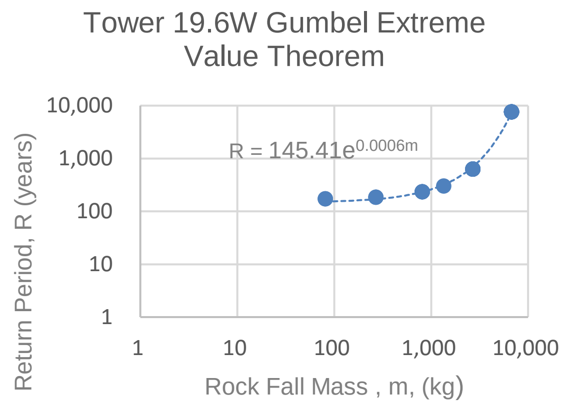

Figure 4. Gumbel Distribution of Rock Fall Mass From MCRR Data for Tower 19.6W

6 ROCK FALL ANALYSIS

Ecora analyzed the anticipated velocities, trajectories and bounce heights of rock fall at each of the tower locations. The analysis utilized the maximum likely and expected rock fall volumes based on discontinuity mapping and the Gumbel distributions, and was calibrated with tree strike heights.

Based on the rock fall analysis, it was possible to determine where rolling behaviour would allow topographical features to deflect rock fall away from tower locations, and the maximum velocities of rock fall passing through the proposed tower locations.

6.1 Rock Fall Simulation

The rock fall simulations were carried out using commercial available software. Material and rock properties for the simulation were based on field observations and published values as summarized in Table 5 below (Wyllie, 2015). To account for the influence of the rock fall impact angle on the normal coefficient of restitution (Rn) a velocity scaling factor (K) of 9.14 was utilized in the analysis (Wyllie, 2015). The simulations were run with the rock fall originating in the identified major source zones above the tower locations, with 1000 rock release to account for statistical uncertainty in material parameters. Standard deviations of 0.04 were utilized for Rn values, and 2° for friction angle values.

Table 5. Rock Fall Simulation Material Properties

Material	Normal Restitution (Rn)	Tangential Restitution (Rn)	Friction Angle (°)
Vegetated Soil[1]	0.25	0.55	17
Talus / Shallow Rock	1	0.72	19.49

Rock	1	0.59	8.53

[1](Giana, 1992)

6.2 Rock Fall Volume Loss

This decreasing volume of rock fall debris over horizontal distance is discussed in "Rock Fall Engineering" by Wyllie (2015). The loss of volume in falling rock can be expressed as a function of the Unconfined Compressive Strength (UCS) of the rock, and the horizontal distance from the rock fall source zone. This relationship is shown as Equation 1 below (Wyllie, 2015).

$$\frac{\Omega}{\Omega_0} = \frac{1}{(1+\lambda x)} \qquad [1]$$

Where Ω_0 is the initial rock fall volume, Ω is the rock fall volume at horizontal distance x (m) from the rock fall source zone, and λ (m^{-1}) is a reduction coefficient defining the loss of mass over a horizontal distance (Wyllie, 2015). Based on Ecora's scaling observations detailed in Section 2.3.3 above, λ values ranging from 0.009 to 0.024 were calculated.

6.3 Rock Fall Hazard to Towers

Combining the results of the rock fall simulation, the rock fall volume loss calculations, and the maximum anticipated rock fall size, it is possible to determine maximum rock fall energy at each tower location. The maximum rock volumes and velocities are presented in Table 6 below.

Table 6. Rock Fall Volume and Velocity at Tower Locations

Tower Location	Velocity (m/s)[1]	Maximum Volume (m^3)
11.7	-	0.389
19.2	-	0.164
19.4	5.6	0.122
19.5E	3.5	0.127
19.5W	3.0	0.140
19.6E	6.7	0.190
19.6W	7.5	0.248
19.7	6.3	0.230
19.9	5.4	0.050

[1]Where no velocities are reported, rocks deflected away from tower location.

Comparing the calculated volume and velocity values to Table 2 from Mavorulli and Corominas (2010) indicates that no structural damage will occur to the reinforce concrete tower base due to rock fall impacts.

It is unclear if rock fall may damage the steel tower itself. However, in the event the tower is damaged beyond repair, the replacement cost is considered to be low, and replacement could be accomplished within one working day.

7 TOWER PERFORMANCE

Four of the nine towers were installed in the Fall of 2016, and were operational in the 2016/2017 winter season. With less than half of towers operational, road closure times for avalanche control were reduced by an average of 50%. Data is not yet available for the 2017-2018 winter season, but additional reductions in closure time are expected.

8 CONCLUSIONS

Construction of permanent infrastructure in areas with multiple overlapping geohazard areas can create many challenges. However, with appropriate use of statistic models, and suitably conservative input parameters, it may be possible to reduce certain hazards to acceptable levels.

9 ACKNOWLEDGEMENTS

The authors wish to acknowledge the BC MoTI and Wyssen Avalanche Control for authorizing use of the information to prepare this paper.
They also wish to acknowledge the assistance of Sean and Neil Alexander with Canadian Rescue Systems Inc. for providing roped access to the tower locations.

10 ADDITIONAL FIGURES

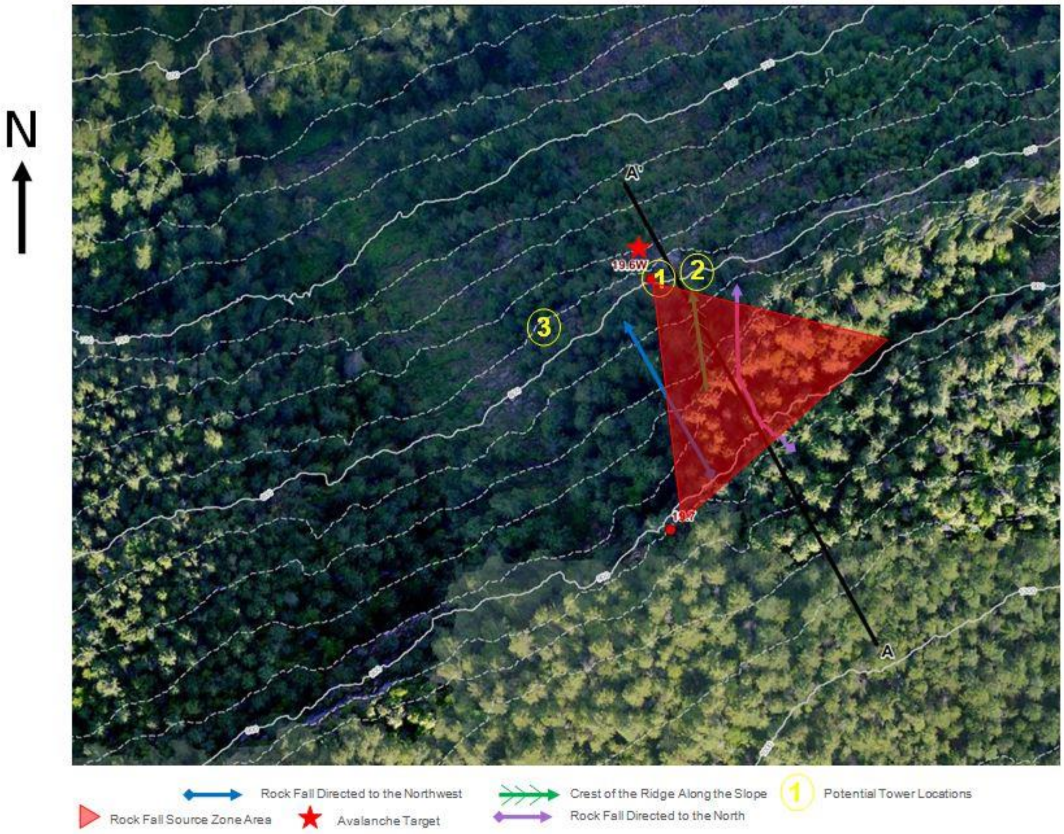

Figure 6. Damage Caused by Natural Rockfall at Tower 19.6W Location Option 3

11 REFERENCES

Wyllie, D. 2015. *Rock Fall Engineering*, CRC Press, Boca Raton, FL, USA.

Giani, G.P. 1992. *Rock Slope Stability Analysis*, CRC, Boca Raton, FL.

Australian Geomechanics Society, 2007, Practice Note Guidelines for Landslide Risk Management 2007, Journal and News of the Australian Geomechanics Society, Volume 42, No. 1, March 2007.

Lee. E. M. and Jones. D. K. C., 2014, Landslide Risk Assessment Second Edition, Institute of Civil Engineers Publishing, London, UK.

Hungr, O., Lerouli. S., and Pacarelli. L., (2014). "The Vanes Classifcation of Landslide Types, and Update", Landslides, Volume 11, Ussue 2, pp 167-194.

Schiarizza, P. and Church, N., 1996, The Geology of the Thompson Okanagan Mineral Assessment Region, BC Geological Survey Open File 1996-20.

Mavrouli, O. and Corominas, J., 2010. Rockfall vulnerability

Figure 5. Rockfall Runnout and Terrain Features at RACS Tower 19.6W

assessment for reinforced concrete buildings, *Natural Hazards and Earth Sciences*, Copernicus Publications, 10: 2055-2066.

Hungr. O., Lerouil. S., and Pacarelli. L. (2014). "The Varnes Classification of Landslide Types, an Update", Landslides, Volume 11, Issues 2, pp 167-194.