Safe blasting near rock glaciers

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ABSTRACT

Large mining projects have been developed and operated in glacial and periglacial environments around the world for decades. This leads to the inevitable fact that certain mining operations are located in close proximity to glacial and/or periglacial cryoforms such as glaciers or rock glaciers, respectively. In response to an increase in public awareness of these projects and climate change, regulatory bodies in various jurisdictions have heightened their focus on potential anthropogenic impacts to these cryoforms. Mining-induced blasting in close proximity to these cryoforms is considered to potentially impact these landforms. It therefore becomes of operational, regulatory and environmental importance to be able to design blasting patterns that do not cause any impact on these geological features for mining operations near such cryoforms. A critical component when designing production blasts in such settings is to determine the so-called Charge Weight per Delay Interval (CWPDI) of an acceptable blast. This paper outlines a simplified method for determining the maximum acceptable CWPDI for blasting as a function of the distance to the selected cryoform. The procedure requires knowledge of the type and weight of explosive per blast hole, the time delay pattern, in situ Peak Particle Velocity (PPV) and frequency measurements at varying distances from the blast, and a basic understanding of the cryoform's geometry and strength properties. Recognizing that not all projects will have access to such extensive data, some parameters and simplified equations are suggested to guide the assessment in those situations. This work serves to highlight the significance of responsible, informed mining practices within a vulnerable environment.

1 INTRODUCTION

Large mining projects have been developed and operated in glacial and periglacial environments around the world for decades. This leads to the inevitable fact that certain mining operations are located in close proximity to glacial and/or periglacial cryoforms such as glaciers or rock glaciers, respectively. Some mining operation activities, such as mining-induced blasting, are considered to potentially impact these landforms. It therefore becomes of operational, regulatory and environmental importance to be able to design blasting patterns that do not cause any impact on these cryological landforms.

Assessing the stability of glacial or periglacial cryoforms is complex due to the complex mechanical properties of the ice present within them (Paterson 1994; Arenson et al. 2014). In the case of a glacier, the instabilities typically evolve with time or in response to changes in temperature (air and ice) or subglacial water pressure. A creep failure (accelerated deformation under constant loading) is another mechanism of instability, and it occurs when the ice goes from a secondary to a tertiary creep stage, associated with an acceleration in cryoform deformation (Glen 1955; Duval et al. 2010). The instability and potential failure of a glacier or a rock glacier, as a whole body, is atypical unless one of the boundary conditions changes dramatically.

Regarding the morphological characteristics of rock glaciers, which are the main focus of this work, the most abrupt possible instabilities are in the form of debris flows or landslides, which are very rare because these cryoforms would simply lose their volume in response to permafrost degrades.

The most critical natural dynamic loading conditions for rock glaciers near tectonic active zones come from earthquakes. However, no evidence was reported on earthquake-induced failures of rock glaciers. Independent on this observation, dynamic loads from other sources, such as production blasting in the vicinity of rock glaciers due to exploitation of natural resources, could potentially generate rock glacier instabilities.

This work outlines a simplified method for assessing the potential impact on global slope stability to rock glaciers as a result of the mining blasting-induced vibrations. The maximum blast Charge Weight per Delay Interval (CWPDI) at different distances from the rock glacier are calculated.

2 APPROACH

The analysis of a potential impact on a glacial and/or periglacial cryoform in response to production blasting induced vibrations in an open mining context is composed of determining the cryoform's resistance to seismic induced displacements (k_y). The overall strategy is outlined in Figure 1.

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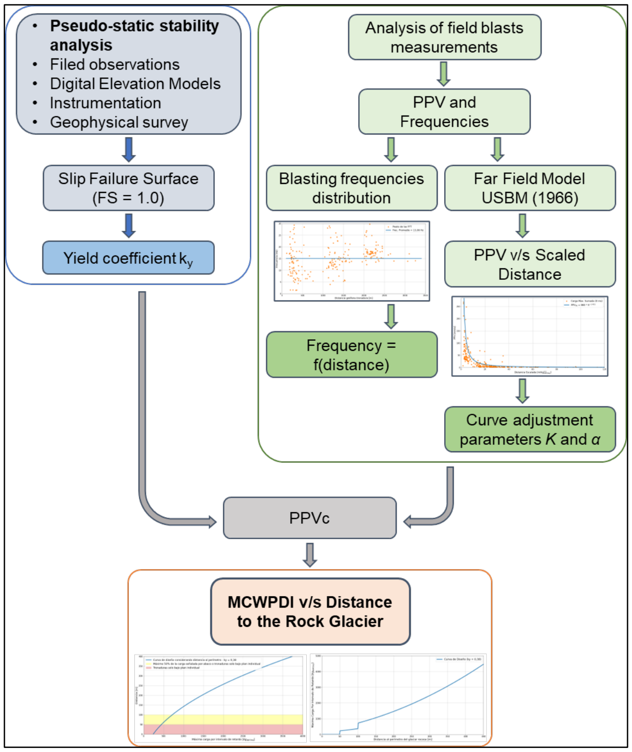

Figure 1. Analysis general strategy.

2.1 Rock Glaciers Stability

The first step is to assess which conditions are critical for a rock glacier to be stable – in traditional slope stability terms.

As previously mentioned, the instability and potential failure of a glacial or a rock glacier, as a whole body, is unusual unless one of the boundary conditions changes dramatically. Dynamic loading originating from earthquakes or, for the purpose of this work, blasting activities may have the potential to affect the overall stability of the entire cryoform.

In this work, the dynamic stability of a rock glacier is assessed using the so-called pseudo-static approach, typically used for simplified seismic stability analyses (Jibson 2011). This approach considers modeling the dynamic loading as a horizontal force acting on the gravitational center of the sliding mass (cryoform), equal to the mass of the frozen soil multiplied by the acceleration of gravity and a horizontal seismic coefficient, k_h.

The minimum value of k_h for which the disruptive forces magnitude is larger than the resisting forces is called *seismic yield coefficient* and is denoted as k_y. The yield coefficient k_y can be estimated from considering a *Factor of Safety* (FS) to sliding equal to 1.0. Hence, the k_y coefficient characterizes the maximum horizontal acceleration that the cryoform can theoretically sustain before the entire mass is failing as a rigid body.

2.1.1 Yield coefficient k_y estimation

The k_y coefficient can be estimated from typically used engineering stability software such as Slope/W (Geoslope International, Calgary AB, Canada) or can be estimated in more simple ways (Figure 2) for simple geometries analytically, as follows:

$$k_y = \frac{\cos(\alpha)\tan(\varphi) - \sin(\alpha)}{\sin(\alpha)\tan(\varphi) + \cos(\alpha)} \quad [1]$$

Where φ is the friction angle acting on the slipping surface. Equation 1 assumes zero cohesion.

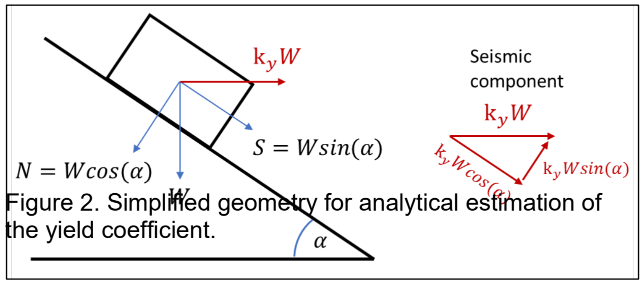

Figure 2. Simplified geometry for analytical estimation of the yield coefficient.

2.1.2 Critical Peak Particle Velocity (PPVc) and yield coefficient (k_y)

Once the blast is detonated, the explosive energy is released in the form of seismic waves thorough the soil and rock media. Historically, the US Bureau of Mines (USBM) has characterized the impacts of vibrations produced by blasting based on the pulse (or seismic wave) that generate the largest particle velocity. This is known as the peak particle velocity or PPV. As the wave travels away from the seismic source, it propagates as an elastic wave through the media. This wave can be modeled as a sine pulse of uniform amplitude and certain frequency. According to USBM (1980), for the wave associated with the pulse having the largest PPV, it is possible to obtain its acceleration from its velocity magnitude and wave frequency as follows:

$$a_{max} = 2\pi f \cdot PPVc \quad [2]$$

Where a_{max} and f are the acceleration and pulse frequency generated by the wave with the largest PPV.

As introduced earlier, the stability of the cryoform can be characterized by its yield coefficient k_y. The acceleration equivalent to that k_y can be calculated via multiplying k_y with the acceleration of gravity:

$$(a_{k_y} = k_y g) \quad [3]$$

Using Equation 2, the value of the PPV that would result in an acceleration that can produce a cryoform instability, which is called PPV critical (PPVc), can then be obtained as:

$$PPV_c = \frac{g}{2\pi f} k_y \qquad [4]$$

Where f is the frequency of the wave that generated the PPV, g is the acceleration of gravity and k_y is the yield coefficient of the sliding mass. Equation 4 provides a limiting PPV such that if a PPV exceeds that threshold an instability of the cryoform could be triggered.

2.2 Analysis of Field Blasts

Once the stability conditions of the cryoform have been defined, the second stage is to determine the loading conditions (defined in terms of velocities and accelerations) generated by the blasting activity near the rock glacier of interest.

The intended outcome of this stage is to measure several Peak Particle Velocities (PPV) generated by the production blasting activity and then establish a relationship between the generated frequency (which is also measured in the field) and the distance between the location of blasting and the measurement point.

For this work, a series of geophones and a vibrations sensor were available to monitor the blasting activity at a mine site for several weeks (see Section 3 for more details). These instruments record velocity histories in three orthogonal directions: longitudinal, transversal, and vertical. From each of these records, the maximum value of the PPV per channel and its associated frequency is obtained. The *PPVsum* is subsequently determined as the maximum value of the norm of the velocity time vector during the entire recording:

$$PPVsum = max\left(\sqrt{V_{lon}^2 + V_{tra}^2 + V_{ver}^2}\right) \qquad [5]$$

Since the PPVsum is always greater than or equal to each of the PPVs per channel, this work conservatively uses the PPVsum as an input for the USBM (1966) model. Therefore, from now on the PPVsum will be referred to as PPV only.

2.2.1 PPV and Frequency

The first objective of the analysis of field measurements is to obtain the distribution of blast wave frequencies versus the distance to the rock glacier of interest. This can be done just by plotting the frequency associated to the maximum PPV and the distance of the blast to the perimeter of the cryoform.

As described above, the PPVsum corresponds to the maximum value of norm of the velocity vector, and as such it does not have an associated frequency. In order to assign a frequency, we considered the frequency value associated with the channel of the maximum individual PPV, which is considered a conservative approach.

2.2.2 PPV and Scaled Distance

The far field vibrations model commonly used for the determination of PPV levels was initially developed by USBM (1966). The model was derived from a statistical analysis of multiple blasts in their three particle velocity components: radial, vertical, and transversal. Blasting registered by the USBM (1966) methodology allowed for establishing a relationship between the so-called *Scaled Distance* and the PPV:

$$PPV = K\left(\frac{D}{\sqrt{W}}\right)^{\alpha} \qquad [6]$$

Where *PPV* is the peak particle velocity (in mm/s), *K* and α are local regression constants, *D* is the distance between the blast and the point of interest (in meters), and *W* is the Maximum Charge Weight Per Delay Interval (MCWPDI, in kilograms ammonium nitrate/fuel oil equivalent - kg ANFOeq). The Scaled Distance is defined as the product between the distance and the square root of the MCWPDI, $D/\sqrt{W}$.

The objective is to determine parameters *K* and α from a curve fit of the blasting measurements obtained during a field campaign. We recommend adjusting the data to a 90% confidence level, as will be shown in the applied case described in Section 3.

2.3 Maximum Charge Weight Per Delay Interval

ANFO is a high explosive, consisting of a mixture of ammonium nitrate and fuel oil. The relative power by weight mass refers to the energy yield of an explosive expressed as a percentage of the energy yield of an equivalent weight in ANFO. For example, a widely used explosive is Blendex 950, which has a power by weight equivalent to 88% of the ANFO (1 kg of Blendex 950 has 88% of the power of 1 kg of ANFO). The sum of the amount of ANFO explosive and the ANFO equivalent of any other explosive used during the blasting is called ANFO equivalent.

Regular production blasting activity consists of a grid composed of dozens (and even hundreds) of blast boreholes, which detonate at different times in sequences that depend on the specific objective of the blasting in question. Each of the blast holes contain bottom charges and column charges, which may use different type of explosives. For this method, it is necessary to determine the ANFOeq charge (in kg) for each borehole. The maximum charge per blasting hole is known as the Maximum Charge Weight Per Delay Interval (MCWPDI) and is an input parameter for the regression of Equation 6 (parameter *W* in the equation).

It is possible that for boreholes that detonate at similar delays their shockwaves will couple (Persson et al. 1994). If this is the case, the MCWPDI is estimated as the sum of the induvial charges of those blast. The current practice considers the superposition of ANFOeq charges for a detonation interval of 8 ms (Hoshino 2000; Singh 2006; Kuzu 2008).

2.4 Blasting Design Chart

Three key inputs have been obtained from this methodology: (1) Yield coefficient k_y; (2) Frequency distribution as a function of the distance to the rock glacier; and (3) Peak Particle Velocity (PPV) as a function of the Scaled Distance ($D/\sqrt{W}$). From these three inputs it is possible to develop a relationship between the distance and MCWPDI, for a given k_y.

For a blast to generate a PPVc in the rock glacier of interest for this study, the PPV must satisfy Equation 4 and Equation 6 at the same time. Then, by eliminating W from both equations, the following relationship is obtained:

$$W = \sqrt[\alpha/2]{\frac{KD^{\alpha} \cdot 2\pi f(D)}{g \cdot k_y}} \quad [7]$$

Where:

- W: Maximum Charge Weight Per Delay Interval.
- K and α: calibrated parameters for the PPVc and the Scaled Distance.
- D: Distance to the centroid of the rock glacier under study.
- f(D): Blast wave frequency as a function of the Distance to the cryoform.
- g: acceleration of gravity.
- k_y: yield coefficient.

From Equation 7, it is now possible to determine the maximum charge of the blast (W, in kg ANFOeq) that will generate the PPVc at a distance D (in meters) to the centroid of the rock glacier of interest. For practical operational use, it is recommended to define the maximum allowed charge of the blast (W) as function of the distance to the perimeter of the rock glacier. To do so, it is necessary to move the abscissa axis (distance) by the distance between the centroid of the slip surface with a yield coefficient k_y, and the perimeter of the rock glacier. Then, a Blasting Design Chart can be defined for the MCWPDI as a function of the distance D (from now on defined as the distance to the perimeter of the rock glacier).

Also, for practical operational use, and based on the limitations described in Section 4, the methodology presented in this paper proposes the use of two buffers for the Blasting Design Chart:

- Buffer 1 – For distances less than 50 m: No blasting unless individual blasting plans are developed.
- Buffer 2 – For distances between 50 m and 100 m: Use a maximum of 50% of the MCWPDI estimated from Equation 7 unless individual blasting plans are developed as necessary.
- Buffer 3 – For distances greater than 100 m: Use the MCWPDI obtained from Equation 7.

Based on these considerations, Figure 3 presents a general schematic of a Blasting Design Chart that would have to be developed for individual geological and topographic settings.

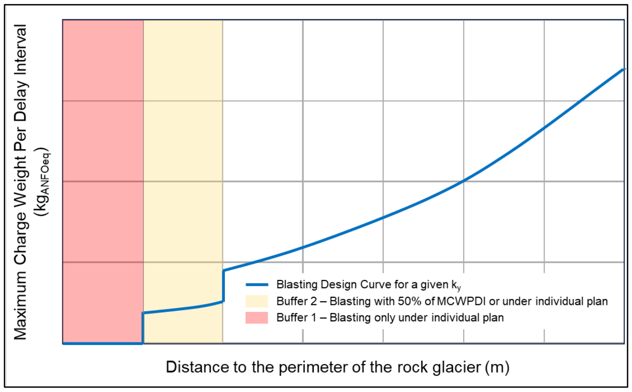

Figure 3. General schematic of the final Blasting Design Chart for a rock glacier with a yield coefficient k_y.

3 APPLIED CASE

A case study has been assessed using the methodology described in this paper. The case is a rock glacier located in the nearby areas of an active mine pit. For confidentiality reasons, no location nor operation details will be shared, and the cryoform will be referred to as "Rock Glacier".

The Rock Glacier of interest is located approximately 600 m from the eastern edge of the active mine pit. Figure 4 shows a schematic of the open pit and the Rock Glacier location.

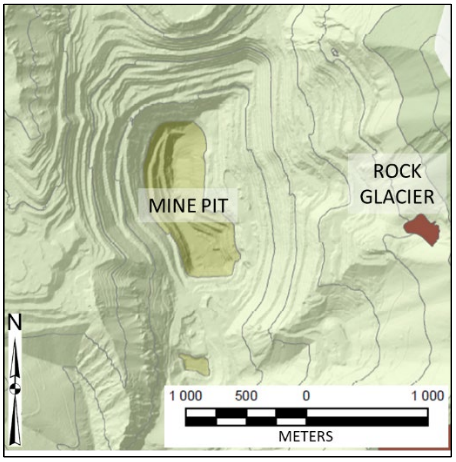

Figure 4. Mine Pit and Rock Glacier locations of the study case.

3.1 Stability and yield coefficient k_y

The first step is to assess the Rock Glacier stability and to determine the yield coefficient k_y at which the cryoform shows a global instability. A series of pseudo-static limit equilibrium slope stability analyses were carried out for a 2D section of the Rock Glacier, using Slope/W 2018 software (Geoslope International, Calgary AB, Canada).

The 2D critical profile analyzed was defined based on the maximum slope of the Rock Glacier. The geotechnical characterization of the cryoform (friction angle and cohesion of ice-rich material) was chosen based on Arenson and Springman (2005) and was based on the estimated ground ice content of the Rock Glacier. The base of the Rock Glacier was modeled as impenetrable rock.

The yield coefficient was determined for different slip surfaces at different distances from the toe of the Rock Glacier. The minimum k_y value of 0.38 was obtained for a global failure surface. Figure 5 shows the resulting slip surface for that global failure.

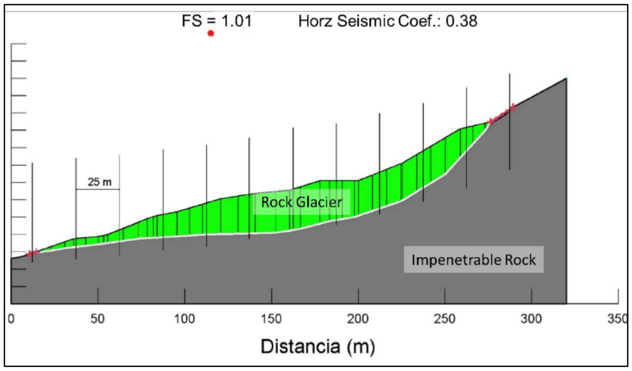

Figure 5. Resulting global slip surface with a yield coefficient k_y of 0.38 (source: Slope/W software).

3.2 Field Blasting Data

Three different sources of PPV and associated frequency measurements coming from the production blasting at the mine site were considered:

- A field monitoring campaign with two seismic monitoring systems consisting of an eight-channel datalogger and two triaxial geophones.
- A vibration sensor installed close to the Rock Glacier, that automatically measures the PPV and frequencies of the blasting activity.
- Internal recordings measured by the blasting contractor.

Figure 6 shows the location of all blast holes and sensors considered in the dataset.

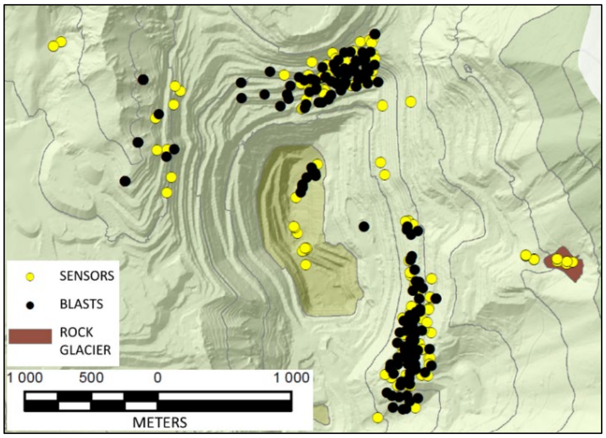

Figure 6. Location of dataset blast holes and sensors.

The complete dataset used in this study consists of 272 vibration records from 141 blasts. The distances to the measurement sensors range from approximately 100 m to ~3500 m. Figure 7 shows the histogram of the detonation distances to the measurement points for the total number of records used.

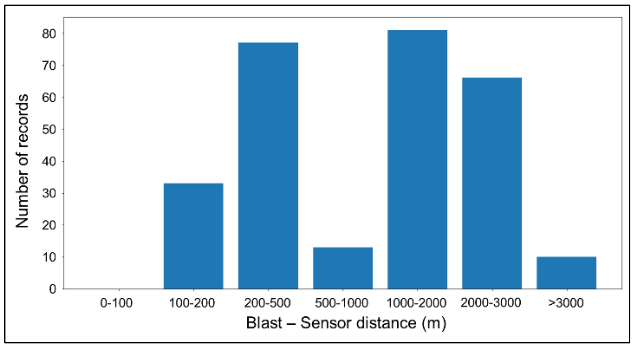

Figure 7. Histogram of distances from the blasts to their corresponding measurement sensor.

3.2.1 PPV Frequency Distribution

For several of the recorded blasts, the PPV was less than 1 mm/s. Such low PPV values are generally considered to produce no damage even in case of sensitive structures (FTA 2006; DIN 4150-3 (1999)). Therefore, frequencies associated with the highest PPV channel for PPV greater than 1 mm/s were used for the estimation of the PPV frequency as a function of distance from the blast. This eliminates records with a high noise component and improves the estimation of the frequency generated by the blast itself.

Figure 8 shows the frequencies obtained as a function of the distance to the measurement point, and their fitting curve. No trend between frequency and distance can be identified. Therefore, we considered a constant average frequency equal to ~15 Hz for the development of our Blasting Design Chart. It is important to note that this step of the methodology needs to be adjusted for each particular site.

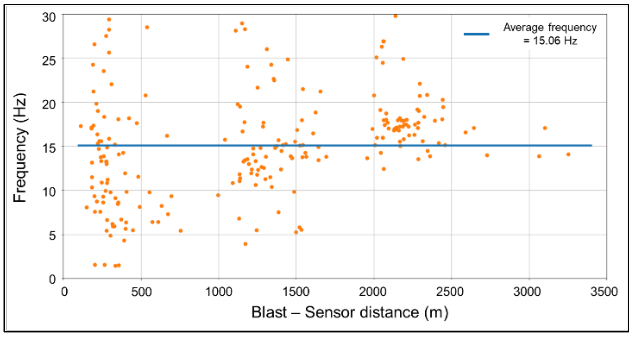

Figure 8. PPV associated frequency distribution as a function of the blast-sensor distance.

3.2.2 *PPV and Scaled Distance*

Figure 9 shows the PPV decay curve as a function of the Scaled Distance. As described in Section 2.3, the MCWPDI is considered as a superposition of individual charges for an 8 ms time interval. The regression of the data is in the form indicated in Equation 6. Conservatively, a 90% confidence level was used to determine the curve fit to the PPV. This means that there is a 90% probability that the recorded PPV would be less than the predicted PPV. From these, we derived the resulting, site-specific adjustment equation of:

$$PPV_{90\%} = 860\left(\frac{D}{\sqrt{W}}\right)^{-1.421} \qquad [8]$$

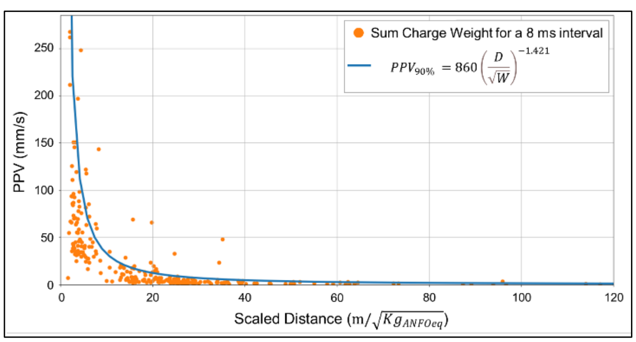

Figure 9. PPV decay curve as a function of the Scaled Distance. The fitting curve is selected such that at least 90% of the data fall under the curve.

3.3 Final Blasting Design Chart

Using the results developed in Sections 3.2.1 and 3.2.2 it is now possible to replace the values in Equation 7 and obtaining the following relationship:

$$W = \sqrt[-0.711]{\frac{8{,}295 \cdot D^{-1{,}421}}{k_y}} \qquad [9]$$

By replacing the critical yield coefficient value estimated for a global stability of the Rock Glacier (see Section 3.1), it is possible to determine the final relationship between the MCWPDI (W) and the distance between the location of the blast and the centroid of the Rock Glacier slip surface (D). As described in Section 2.4, it is recommended to present these results in terms of the distance to the perimeter of the Rock Glacier and not the centroid of the failing mass. The distance between the centroid of the global slip surface (see Figure 4) and the perimeter of the Rock Glacier is ~150 m for this case. Hence, the final curve can be obtained via shifting the origin of the distance axis by 150 m to the right.

Figure 10 shows the resulting design chart for this case study, considering the shift of the x-axis and the inclusion of buffers as recommended in Section 2.4. As an example, the results show that at a distance of 350 m to the perimeter of the Rock Glacier the maximum blast charge (MCWPDI) that can be used is 3000 kg ANFOeq.

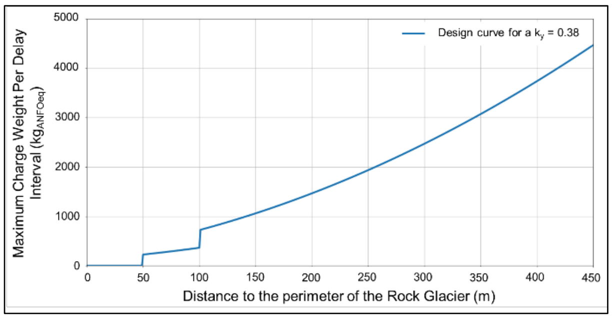

Figure 10. Final Design Chart for the MCWPDI as a function of the distance to the perimeter of the Rock Glacier.

4 Study Limitations

It is important to note that there are several limitations to the methodology and analysis described in this paper. Some specific limitations are:

- The base case from which the methodology was defined has 272 PPV and 224 frequency measurements from 141 blasts. From the frequency associated with the PPV, records are only starting from ~100 m, which results in some uncertainty in the extrapolation of the data at smaller distances. This is why a 50% decrease in the charge is recommended for distances between 50 and 100 m to the perimeter of the rock glacier.
- The analysis assumes that the motion recorded at the surface is the same as the motion that would be recorded at the center of slipping mass of the cryoform. The conservative simplification that the center of mass corresponds to the centroid determined from a plan view was also used for this analysis.
- Each blast generated a wide spectrum of vibration frequencies. Nonetheless, for each of these, the motion generated by blasting is assumed to be a simple harmonic motion with a single frequency corresponding to the predominant frequency at the instant the PPV occurs. In this way, the analysis determined the acceleration generated by the PPV at the instant when the PPV occurs.

5 FINAL COMMENTS AND CONCLUSIONS

A simplified method for assessing the potential impact to the stability of rock glaciers in response to production blasting induced vibrations for open pit mine sites has been outlined. The proposed method seeks to determine the Maximum acceptable Charge Weight Per Delay Interval (MCWPDI) for blasting as a function of the distance between the blast and the cryoform, avoiding the generation of an instability/slope failure. We developed a Design Chart that correlates the MCWPDI with the distance to the perimeter of a rock glacier.

Three important inputs are needed in our method for developing such a design chart: (1) A yield coefficient, k_y, which represents the maximum horizontal acceleration that ensures the cryoform stability; (2) the distribution of Peak Particle Velocities generated by the blasting-induced waves as a function of the Scaled Distance; and (3) the distribution of blasting waves predominant frequencies as a function of the distance between the blast and the point of interest.

The intent of the proposed methodology is to serve as an additional guideline to enable the safe designing of blasting near glacial and periglacial cryoforms as part of a mine operations in mountainous terrain. In response to local geological and topographic settings, and the characteristics of the glacial/periglacial cryoform(s) in question, site specific design charts must be developed using local measurements of PPVs and associated frequencies.

It is also important to note that blasting activities and procedures are subject to local and/or mine operation regulations. The proposed method should be considered as one of the factors in the decision-making process, but not the sole determining factor.

Finally, more research is required to better understand the impact of dynamic load from nearby blasting on glaciers and rock glaciers (frozen soil), specifically the absorption such cryoforms may exhibit.

6 REFERENCES

Arenson, L.U. and Springman, S.M. 2005. ‘Mathematical descriptions for the behaviour of ice-rich frozen soils at temperatures close to 0°C’, *Canadian Geotechnical Journal* 42(2). https://doi.org/10.1139/t04-109.

Duval, P., Montagnat, M., Grennerat, F., Weiss, J., Meyssonnier, J., and Philip, A. 2010. ‘Creep and plasticity of glacier ice: a material science perspective’, *Journal of Glaciology* 56(200), pp. 1059–1068.

Glen, J.W. 1955. ‘The creep of polycrystalline ice’, *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences* 228(1175), pp. 519–538.

Hoshino, T., Mogi, G., and Shaoquan, K. 2000. ‘Optimum delay interval design in delay blasting’, *Fragblast* 4(2), pp. 139–148.

Jibson, R.W. 2011. ‘Methods for assessing the stability of slopes during earthquakes-A retrospective’, *Engineering Geology* 122(1–2), pp. 43–50. https://doi.org/10.1016/j.enggeo.2010.09.017

Kuzu, C. 2008. ‘The importance of site-specific characters in prediction models for blast-induced ground vibrations’, *Soil Dynamics and Earthquake Engineering* 28(5), pp. 405–414.

Paterson, W.S.B. 1994. *The physics of glaciers*, 3rd edition. Oxford, New York and Tokyo: Pergamon Press.

Singh, P.K., Sirveiya, A.K., Babu, K.N., Roy, M.P., and Singh, C.V. 2006. ‘Evolution of effective charge weight per delay for prediction of ground vibrations generated from blasting in a limestone mine’, *International Journal of Surface Mining, Reclamation and Environment* 20(01), pp. 4–19.

U.S. Bureau of Mines 1966. Effect of charge weight on vibration levels from quarry blasting. Report of investigation 6774.