Proceedings of the 17th Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVII PCSMGE), and 2nd Latin-American Regional Conference of the International Association for Engineering Geology and the Environment (IAEG), La Serena Chile, 2024.

Challenges in assessing the impact of blasting-induced vibration on glaciers

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ABSTRACT: This works seeks to establish the challenges in assessing the impacts of blasting-induced vibration on glaciers. There are few experiences on the latter, most of them in Central Chile. So far, all of the performed analysis, in the context of environmental evaluation, seeks to established both a secure radius and a maximum Particle Peak Velocity (PPV) in order to avoid any abnormal behavior of glaciers nearby. Nonetheless, none of the published experiences considers the heterogeneity of glaciers in terms of glacier type and their main characteristics. We propose that prior to the installation of geophones, a general glacier baseline must be performed, oriented to a preliminary stability assessment and to a qualification of all available and used data. The latter should take into account parameters such as glacier's dynamics, thickness, ice content and stratigraphy, all of them on an undisturbed scenario. Then, a glacier mechanical stability model is proposed in terms of peak acceleration and saturation scenarios. Finally, a series of recommendations are given in order to minimize the potential impacts both on nearby glaciers and their surroundings. These include the number and distribution of geophones, and how to analyze the obtained data, plus a series of good measures on glacierized mining prospects.

KEYWORDS: Glacier, vibration, blasting, Andes, Chile.

1 INTRODUCTION

The Andes, one of the largest mountain ranges in the world, is well known for the presence of glaciers and of massive mining deposits, which often coexist. In the case of Chile, top copper producer of the world with 24% of global copper production[1], there are more than 26,000 glaciers accounted on its whole territory (DGA, 2022). Although there aren't any glaciers near the large open pits located in northern Chile (north of -31.5, i.e. Chuquicamata, Escondida, and others), it is on the central region where a vast variety of glacier are found nearby large mining operations such as Los Bronces (Anglo American), Andina and El Teniente Divisions (CODELCO), Los Pelambres (Antofagasta Minerals) and other projects currently on environmental evaluation. All the latter are emplaced on the Mio-Pliocene metallogenic belt of central Chile, -31.5 to -34.5 (Camus & Castelli, 2020; Piquer et al., 2024).

Due to the proximity of glaciers, mining companies must assess the environmental impacts before, during and after their operations. Common impacts on glaciers are mostly associated to a reduction in albedo because of light absorbing particles deposition, such as dust and black carbon (usually linked to debris-free glaciers, Barandun et al., 2021; Cereceda-Balic et al., 2021) and the effect of wave propagation due to blasting-induced vibrations (SEA, 2019).

This works seeks to establish the challenges in assessing the impacts of blasting-induced vibration on glaciers. There are few experiences on the latter, most of them in Central Chile. So far, all the performed analysis, in the context of environmental evaluation, seeks to established both a secure radius and a maximum Peak Particle Velocity (PPV) in order to avoid any abnormal behavior of the glaciers nearby. Nonetheless, most of the published experiences in the Environmental Evaluation System (Andina, Los Bronces, El Teniente, Pascua Lama and Rubí operations) doesn't consider the heterogeneity of glaciers in terms of the glacier type and thickness, debris content and distribution, ice temperature, glacier bed materials (till, bedrock), roughness, intraglacial water levels and glacier's dynamics. More important, the glacier behavior at the time of analysis may be very stable, or on the limit of glacial instabilities, such as ice avalanches or sudden large glacier detachments (Pralong & Funk, 2005; Kääb et al., 2021; Ugalde et al., 2024) or landslides triggered in the frontal talus of rock glaciers (Deline et al., 2021), so that any specific induced PPV value may be of no significance for glacier stability or, on the contrary, the cause of a disaster.

In this work we propose that prior to the installation of geophones to measure vibrations, a general glacier baseline must be performed, oriented to a preliminary stability assessment and to a qualification of all available and useful data. The latter should take into account parameters such as glacier's dynamics, glacier depth, glacier ice content stratigraphy, all of them on an undisturbed scenario. Following the baseline, a glacier mechanical stability model is proposed in terms of peak acceleration and saturation scenarios.

Finally, a series of recommendations are given in order to minimize the potential impacts both on nearby glaciers and their surroundings. These include the number and distribution of geophones, and how to analyze the obtained data, plus a series of good measures on glacierized mining prospects.

2 SCHEME OF FORCES AT THE GLACIER BED

At a glacier bed there are both perturbing and resisting forces, as is shown in Figure 1. Perturbing forces (FP) are W sin σ, where W is the glacier weight and σ is the bed slope. The resisting forces (FR) (or friction) are N tan φ, where φ is the friction angle at the

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[1] https://www.trade.gov/country-commercial-guides/chile-mining

interface and N is the force opposing glacier weight, which is W cos σ. K is the safety margin, or the difference between the tangent of friction and slope angles. So, the resisting forces are defined as Equation 1 shows:

$$FR = W\cos\sigma\tan\varphi \tag{1}$$

For a stable condition FR should be larger than FP, in other terms FR-FP > 0, meaning that the safety margin is defined by Equation 2:

$$W\cos\sigma\tan\varphi - W\sin\sigma = KW\cos\sigma \tag{2}$$

The friction angle must be larger than the slope angle. Then the safety margin is defined by Equation 3.

$$K = \tan\varphi - \tan\sigma \tag{3}$$

It follows that the Safety Factor (FS) is defined by the expression FR/FP.

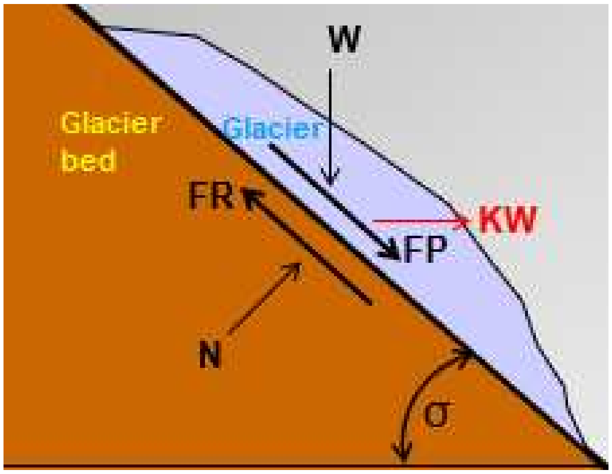

Figure 1. Simplified scheme showing the distribution of resisting forces (FR) and perturbing forces (FP) at a glacier with a bed slope of σ. N is the normal force opposing the glacier weight (W) whereas K is the safety margin between resisting and perturbing forces.

However, on a glacier there are some other aspects which also affect stability and differs from those presented on Figure 1. Also, it must be remarked that the sudden sliding of an ice mass may affect the whole glacier, or just a part of it. In cold glaciers with high slopes usually glacier wedges are affected by sliding. Then, important aspects to consider when evaluating glacier stability are those shown on Figure 2. A brief description is given of the key-aspects as follows:

- Ice mechanical properties. Ice is a viscous-plastic material which deforms under its own weight. Its resistance, and the internal friction angle, vary much with its temperature and density (Cuffey & Paterson, 2010).
- The material at the glacier bed, the basal moraine, it is not only ice, but also contains rocks, in a proportion of about 50% each. Then the friction is not only of ice against the bed, but ice and rocks against the bed material (Marangunic & Marangunic, 2010).
- The temperature of a glacier at its bed. If the glacier base is at negative temperatures (cold ice), the glacier is "welded" to its bed and the ice flows only by internal deformation. If the temperature is at 0ºC, the ice is temperate and with water at its base, and the glacier flows permanently over its bed.
- Water within the glacier. In temperate glaciers, with ice porosity of about 1% to 2% and essentially at 0ºC temperature, the water storage is quite variable. In summer times it is 50% to 70% of the maximum pore pressure, while in winter times it is 15% to 20%. The effective pressure (N) at the glacier bed is the ice pressure (or cryostatic pressure, Pi) minus the water pressure (Pw) which varies between the atmospheric pressure and the cryostatic pressure). When PW is 0, the effective pressure is the cryostatic (Pi) and N partly controls the glacier movement and deformations at the bed. If Pw=Pi (meaning N=0, downstream from protuberances at the glacier bed, or at a subglacial lake, or in a saturated glacier), the water can support the whole glacier weight, and even lift the glacier from its bed.
- Anchor effect. If only part of the glacier slides, a stress is required for a tension or shear fracture to develop between the stable and the sliding part of the glacier. If there is no pre-existing fracture (because of glacier deformations), the stress required to break the glacier is larger.
- Glacier path sinuosities. A glacier with a path (or trajectory) with curves, is more stable than one with a straight path, as there is increased friction at every curve.
- The material of the bed and its distribution. It may be rock, or till, or a mix of both with till occupying bed depressions down-stream from the projection of the glacier equilibrium line, with or without water at the interface. The geotechnical properties of these material are quite different; the till at the bed of a glacier has a very low cohesion (0 to less than 10kPa) and a friction angle usually below 11º.
- The changes from cold to temperate ice masses induced by climatic changes tend to reduce stability.

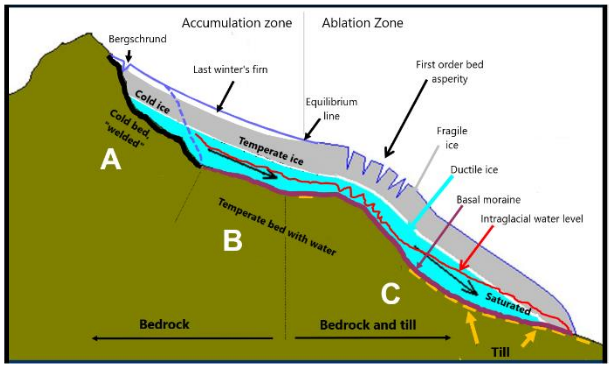

Figure 2. A real-glacier cross section, showing various key-aspects related to glacier stability.

3 PREVIOUS EXPERIENCES

3.1 *El Teniente and Andina Divisions – CODELCO (2018-2023)*

These analyses are based on the studies carried out for the Environmental Impact Assessment of the "Optimización Minera División Andina" project of CODELCO Andina Division. The study estimates the distance required to attenuate vibrations caused by blasting from the Southern Pit at a Peak Particle Velocity (PPV) of 70 mm/s, a value considered by the analyzes as that which does not mechanically affect the nearby rock glaciers. From this distance, it can be discerned which glaciers would be affected by vibrations depending on its intensity. The 70 mm/s threshold is derived from an analysis of historical earthquakes recorded by instruments in a series of rock glaciers located in the Andina Division of CODELCO, on which the vibrations generated by these earthquakes did not produce any recorded changes in the displacement of the glaciers. Therefore, the maximum admissible particle velocity threshold is defined in the form of a PPV corresponding to a subduction earthquake of Mw7.9 that occurred on the coast of the latitude of the Andina Division (CODELCO, 2018).

In the case of El Teniente Division, to estimate the blast attenuation ratio in the Southern Rajo, 10 blast monitoring records, measured between 2019 and 2020, were considered (GS3, 2023). From the PPV identified in each record, and together with the intermediate peaks, the vibration attenuation relationship between the PPV and the distance to the source is established. Finally, a safety distance is estimated to be 84 m on which the analyzed rock glacier obtains PPVs of 3 mm/s in 90% of the cases. It is necessary to mention that the relationship found is based on data obtained for a particular type of vibration: interplate subduction earthquakes. The analysis leaves aside other multiple sources of vibration, starting with other types of earthquakes such as, cortical earthquakes with an epicenter located in the mountain range and continuing with other local sources such as vehicle traffic, blasting, among others. As a result of the above, it is estimated that this threshold is not accurate and should be used only for reference purposes.

3.2 *Los Bronces – Anglo American (2018)*

In the glacier stability analysis proposed as part of Anglo American's LBI Project (Anglo American, 2018), two models were used to obtain a critical distance between the glacier and the source of vibrations such that the first is possibly impacted.

The first models correspond to a Newmark or Whitman Newmark analysis, which relates the stabilizing and destabilizing forces that act on the glacier, where the forces that act are the forces due to gravity and the contact forces between the block and the plane (normal and shearing). The physical analysis allows to know the PPV for a relative movement to occur between the interface of the glacier with the bedrock or moraine, which depends on the frequency of blasting, the inclination of the interface and the resistance parameters of the materials that make up the glacier, the bedrock, moraines, among others. It is important to note that the frequency of blasting depends on parameters such as the type of explosive and the charge. Likewise, the model analyzes the stability in the center of the block, which does not necessarily represent the most vulnerable fraction of the glacier.

The second model corresponds to the Devine's far-field model, which allows estimating the PPV as a function of the scalar distance to the source of the vibration. This relationship is obtained by comparing different particle velocity measurements resulting from different types of blasting in the area. The model has certain restrictions such as its validity that applies only in the medium-far field. It is recommended for distances greater than two or three times the length of the load, it is not recommended for highly fractured rock masses, and it does not consider the output sequence. of the shots. Additionally, it assumes explosive charges of cylindrical geometry and 100% coupled.

Both models come together to determine the critical distance of the particle from the source of the vibration such that it reaches the PPV, allowing the glacier to destabilize. In the same way, it is possible to know through measurements what the acceptable proportion of PPV experienced by rock glaciers in relation to critical velocity. For example, it is concluded in this analysis that, for glaciers in the area nearby Los Bronces operation, the PPV experienced by the glacier cannot exceed 80% of the critical particle velocity. It should be noted that, for the rock glaciers analyzed, the critical particle velocity is mostly between 20 and 30 mm/s. By knowing these parameters, it is possible to design the blasts based on their distribution and delay load levels, such that they do not reach the previously defined threshold.

3.3 *Rubí – Knauf (2023)*

The Rubí district consists on a gypsum quarry located in the Estero Parraguirre creek, a tributary of the Colorado River, Metropolitan Region, less than 4 km of two rock glaciers. The evaluation of potential effect of seismic vibrations generated by blasting on the stability of both rock glaciers was carried out by measuring the environmental noise and vibrations for 139 days using a triaxial geophone (SGA, 2023). The latter was emplaced in front of each rock glacier. The vibration prediction model used was based on the experiences of Andina Division and Los Bronces operations (sections 3.1 and 3.2), specifically the Devine model, which considers the amount of explosive per charge. The obtained results estimated that the maximum PPV would be less than 1 mm/s, significantly lower than the maximum PPV of registered ambient noise (6.82 mm/s).

Although a limit equilibrium analysis was applied to calculate the critical PPV that could destabilize the glaciers, assuming a case without cohesion and with low friction (friction angles between 20° and 35°), the authors didn't provide the detailed assessment on their report. It is concluded that the critical PPV shouldn't be less than 20 mm/s, considering that the analyzed blasting records reported frequencies below 20 Hz, with critical vibration levels unreachable at distances greater than 100 m from the blasting site.

3.4 *Pascua Lama – Barrick (2023)*

The Pascua Lama District, a gold epithermal ore located 5,000 m a.s.l. on the border with Argentina in the Atacama Region (Camus & Castelli, 2020) has its operations suspended on 2018. Nonetheless, currently an environmental assessment is being carried out due to the Project's Closure Phase. In this context, a vibration analysis was carried out to evaluate the impact of potential blasting on the District due to adequation measures concerning the Closure Phase (GAC, 2023). A limit equilibrium methodology was employed along with data from previous blasting in the sector. A PPV prediction model was developed in order to avoid potential instabilities (such as tensile cracks and partial detachments) on glaciers. The maximum blasting power and the amount of explosive were determined for 6 nearby glaciers. The results stablished a minimum blasting distance of 150 m to each glacier .

The two-dimensional pseudostatic limit equilibrium analysis assumed a block slide on a flat failure surface. The destabilizing action of blasting was included on its horizontal component. As a secure threshold, a Safety Factor of 1.0 was considered to determine the seismic acceleration necessary to cause instability. Also, a numerical relationship was generated between the expected PPV and the blast power at different distances. Combining both methods and modeling the vibration generated by blasting as a pulse of uniform amplitude, the values of Critical Peak Particle Velocity (PPVc) and the maximum acceptable blasting power were determined.

It is worth noting that this experience along with the Los Bronces analysis were the only two cases that considered physical properties (both measured and estimated through literature) for the modelled glaciers after a general glacier baseline was performed.

4 PROPOSED METHODOLOGY

4.1 *Glacier baseline*

Following the Chilean Environmental Evaluation System decree DS40/2012, the following mandatory aspects must be assessed for each glacier baseline:

I. Geographical location and glacier's delineation
II. Surface area and surface topography
III. Glacier thickness
IV. Glacier surface characteristics (debris cover)
V. Ice-core characterization and glacier's temperature
VI. Flow rates and hydrological contribution
VII. Hazard assessment

As section 2 indicates, for a complete stability analysis it is relevant to know most of the aforementioned aspects, however, a detailed study for each glacier tends to be expensive and must have at least a year of monitoring considered. In the case of Chile, we propose the extraction of key-aspects from the Public Glacier Inventory published by the Chilean General Water Directorate (DGA) in 2022. For other regions, local glacier inventories must be considered. Specifically, the following attributes should be considered for the stability assessment:

a. Glacier classification
b. Average depth
c. Minimum and maximum elevation (on m a.s.l.)
d. Glacier extension (in the form of outlines provided by the local Water Directorate)

Local geological conditions must be considered for the evaluation. Nearby outcrops, the distribution of strata (if existing) below and surrounding the glacier to interpolate on a more realistic way the longitudinal profile of the glacier. Considering the latter, it is possible to interpolate a longitudinal profile for each analyzed glacier either on Google Earth Pro platform or on a GIS software using the more detailed topography possible. A sub-metrical elevation model is recommended, nonetheless, in case of lacking information, JAXA'S ALOS PalSAR digital elevation model (12.5 m resolution) should be considered. The maximum depth should be estimated as the 2-times the average depth reported by the local glacier inventory, whereas the till level's thickness is estimated according to the stratigraphy model described in the following section 4.2.1. The glacier bed can be inferred parallel to the surface topography and considering the geological conditions surrounding the glacier.

Glacier classification is relevant to estimate the ice proportion for the glacier main body. For a mountain of valley glacier, a glacier-debris ratio should be between 4:1 to 9:1 to even 100% of pure ice. However, in the case of a rock glacier, this ratio decreases significantly reaching proportions of 3:7, although is more common to consider a 1:1 ratio (Marangunic & Marangunic, 2010).

4.2 *Glacier stability model*

In this section we describe two complementary assessments for the glacier's stability prior to the integration of the registered vibrations due to blasting. It is important to remark that this is a preliminary assessment to the natural condition of the glacier and, thus, it should be considered as a first order approximation.

4.2.1 *Non-circular failure*

The principal glacier stability model is based on physical principles and incorporating estimated parameters for each material that makes up the glacier in question. The analysis is carried out following a mass movement event, in which a portion, or the totality of the glacier, is detached from its bed It is necessary to considered at all times that glaciers and rock glaciers, like any mass of heterogeneous unconsolidated material, can move totally or partially and in one or more sectors of the deposit simultaneously or sequentially.

The methodology proposed to evaluate the stability of the glacier is based on a limit equilibrium analysis which is executed using the slice method, or slices. As an object of the evaluation, and similar to the Los Bronces experience (see section 3.2), a Newmark analysis is carried out in which the stabilizing and destabilizing forces acting on the glacier are related.

To carry out the analysis, a computational modeling program should be used to obtain a Safety Factor representative of the stability conditions in the glacier. The chosen software should allow the analysts to to calculate the safety factor on a slope in which it is possible to divide the sliding plane into successive sections of slope and different geotechnical characteristics. The glacier is modeled as a block sliding down an uninclined/inclined plane.

The assumptions for the parameters used in the glacier stability analyzes are listed below according to the key-aspects listed in section 2 and illustrated on Figure 2.

- Density of materials: Cold or temperate ice, snow, snow deposits from avalanches, rocky debris such as in rock glaciers and possible natural or anthropogenic overloads, depending on the stratigraphy of the corresponding glacier.
- Areas of each section of the glacier profile: obtained from recognizable topographic surface in plans, DEMs, measurements or estimates (Figure 3).
- Extent of failure: Detachment of the entire glacier mass, the possibility of a fracture towards the front or in the central area of the glacier, whose location is given by an inflection point on the surface, or by the existence of cracks on the surface.
- Static or pseudo-static case: Assuming scenarios with or without seismic accelerations. In the pseudo static case, the

seismic acceleration used corresponds to that reported by the geophones located near the glacier, as well as by the inclusion of a design earthquake (0.1 to 0.3 g) in the analysis.

- Saturation level: Conditions of partially or fully saturated material.
- Shear resistance parameters: Cohesion and internal friction angle of the material in each modeled layer (bedrock, till, glacial column and surface debris) and according to their topographic conditions (slope). It should be noted that these parameters are obtained both from literature, such as the case of bedrock (González de Vallejo et al., 2002) and the till (Marangunic and Marangunic, 2010) and from the field characterization (in the case of the glacial column and surface debris). Table 1 illustrates an example of materials and properties as were considered by Geoestudios (2023) for the CL106007013 Rock Glacier in El Teniente Division.
- Distribution of different materials within the glacier: Detrital deposits, moraines, bedrock, cold ice, warm ice, among others.

Furthermore, to simulate the greatest number of possible scenarios, the analysis incorporates the longitudinal stress necessary for the formation of a fracture in ice, which is taken into consideration for scenarios that simulate a failure surface towards the front of the glacier.

In this way, with the acceleration measurements captured on the surface of the glacier, the physical analysis of stabilizing and destabilizing forces of the safety factor (FS) is carried out, which given the uncertainty places the equilibrium at a value of 1.5. This is a precautious scenario where unstable conditions are considered if the FS is less than 1.5.

Table 1. Glacier materials and geotechnical properties for the mechanical stability assessment of the CL106007013 Rock Glacier in the Central Andes of Chile (Geoestudios, 2023).

Layer	*Cohesion ($kg\ cm^{-2}$)*	*Internal friction angle (°)*	*Density ($t\ m^{-3}$)*
Bedrock	100	45	2.85
Subglacial till	0.1	21	1.8
Ice level	9.2	38	0.86
Debris cover	0.1	36	1.7

Geoestudios (2023) provide a clear example of the application of the aforementioned methodology.

4.2.2 *Glacier's front stability*

In the context of climate change and its impacts on still considered stable glaciers, the glacier's front stability must be assessed on a complementary basis after the whole glacier's stability is evaluated following section 4.2.1. This particular analysis is relevant in the case of both hanging glacier (slopes over 30°) or active rock glaciers with a steep talus over a 35° slope. Although it also considers a limit equilibrium analysis, the main difference remains at the type of modelled fracture. In this case a circular failure should be assessed for the glacier's front on a non-exclusively form because the glacier's margins could also be analyzed given certain geometric conditions such as a steep slope. The geotechnical properties for the layers of the model should be the same as for the non-circular whole glacier evaluation.

4.3 *Example of application: CL106007013 Rock Glacier*

The present section shows an example of application of the proposed methodology for the CL106007013 Rock Glacier (-34.102/-70.339) following the non-circular failure model. The analysis considers both a static and a pseudo-static case with a 0.2g acceleration for the latter. Also, a fully saturated scenario is modelled with a pore pressure ratio equivalent to 90%. Figure 3 illustrates the case of a simplified scenario prior to the performance of a glacier base line, whereas Figure 4 illustrates the case for a full-detail glacier baseline after Geoestudios (2023). Table 2 resumes the obtained Safety Factors for each modelled scenario on both profiles for CL106007013 Rock Glacier.

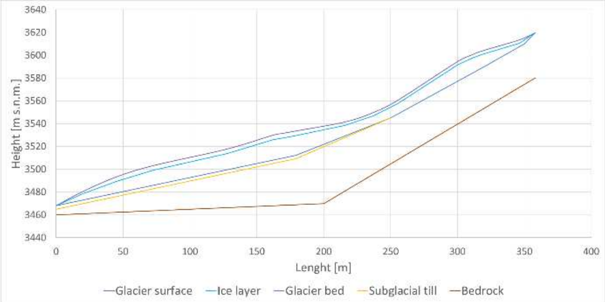

Figure 3. Simplified longitudinal profile generated for the CL106007013 rock glacier in the central Andes of Chile. Top

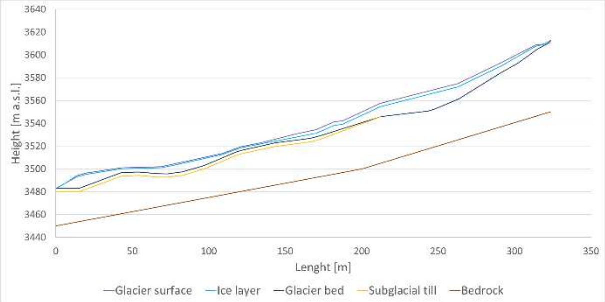

Figure 4. Detailed longitudinal profile generated for the CL106007013 rock glacier in the central Andes of Chile. Modified after Geoestudios (2023).

Table 2. Safety Factors for simplified and detailed stability assessment on CL106007013 Rock Glacier following a non-circular failure model.

Saturation	*Seismic case*	*Simplified model*	*Detailed model*
Non-saturated	Static	6.5	12.5
	Pseudo-static	4.1	8.2
Saturated	Static	5.4	11.2
	Pseudo-static	3.4	7.3

5 DISCUSSION

The lives of many people may depend on proper assessment of glacier stability. Thousands of people have died on a single glacier mass movement event (Evans et al., 2009). Therefore, the selection of methodologies to study these phenomena should be the strictest one. Nevertheless, the so far applied ones are based on extremely simplistic models, far away from what real glaciers are and, introduce a large question mark on the meaning of the resulting Safety Factor and what should be the maximum PPV at certain distance from blasting.

It is evident that simple models that do not consider all the complicate characteristics of glaciers should not be used for real life cases of glacier mechanical stability analysis, but only for a preliminary assessment in order to direct the necessary detailed study. And for a proper preliminary stability analysis a glacier baseline must contain data on glacier materials properties (ice, debris, mixtures, water) such as density, cohesion and internal friction angle of each type, glacier geometry (area, thickness, inclinations, path sinuosities), glacier temperature (temperate, polythermal, cold), glacier bed materials (rock, til), glacier structures (fracture, folds, compression rings, lineations, etc.), eventual anthropic overloads. Most of the glacier baseline studies contain these data (e.g. Los Bronces and Pascua Lama assessments and Geoestudios, 2023, report), or can be inferred from published information such as the example illustrated on Figure 3. Then for the final analysis of glacier stability an essential task is to complete the information and obtain additional needed data, such as bed roughness and asperities, local seismicity and events intensity and frequency, variations of water conditions and gradients, variations of glacier movements, and others. It is expected that the uncertainty of the stability analysis become smaller once a detailed glacier study is performed. An example of the latter is the significant difference of Safety Factors obtained for the CL106007013 Rock Glacier evaluation (see Table 2) which shows a difference 2:1 for the detailed versus simplified comparison.

There are too few cases where an extensive stability analysis has been performed, and comments on results and associated costs are so far meaningless. But until such studies are produced, we can simply assume that safety should come in hand with the model nearer the real glacier conditions, such as those proposed for this work.

6 RECOMENDATIONS

6.1 *Alternatives to rock breaking by blasting*

In mining and constructions sites distant from populated areas, blasting is the preferred rock breaking method because of its high efficiency and relative low cost. But it also has negative effects such as vibrations, gas and particles emissions to the atmosphere, noise, and safety issues, especially in the case of glaciers existing nearby the operations. Alternatives exist to the explosive means to break rock, such as hydraulic splitting, the use of expanding chemical agents, the use of high-pressure gas expansion and plasma blasting.

The hydraulic splitting technique takes advantage of the fact that the tensile strength in rocks is much smaller than the compressive strength, and uses hydraulic splitters, cylinders with pistons and wedges, which apply pressure into a drilled hole, generating a stress pushing the rock into the free-face direction. It is used mainly where the rock masses to break are of limited volume.

Among chemical agents, lime which expands with hydration reaction, is perhaps the most used agent. There is no vibration, no emissions, and a very simple operation, but its efficiency is very low. Carbon dioxide is also used, mainly in coal mines, because it generates a supressed blasting effect at low temperature conditions and low vibrations; but its efficiency on harder rock is reduced, although recent development in hard rock is promising.

Plasma blasting uses electrical energy to excite an electrolyte solution to become a plasma, to produce high temperature and high pressure, forming a shock wave that breaks rock. Successful experiments were performed two decades ago, but the method still requires simplicity of equipment and improvements in power supply. The development of electronics may help making this method the preferred non-blasting rock breaking.

6.2 *Geophones network*

To measure vibrations emitted by sources in the vicinity of glaciers and that may affect them, a network of geophones should be installed. There is no norm related to the number, location, and characteristics of the geophones to be installed. Our experience indicates that the preferred location should be outside off, but near, the glaciers under analysis. At least one geophone per glacier and preferably two. In the case that only one instrument is to be installed, it should be located ideally in rock outcrops nearest to the front of the glacier, usually the most sensitive part of the glacier in respect to vibrations. If a second geophone is available, its location should be ideally in rock outcrops that are nearest to the margin of the glacier that is less distant from the source of the vibrations.

If more than two geophones are available, convenient locations should be at the margin of the glacier distant from the vibrations source, to assess the decaying within the glacier of the vibrations with distance from source and, for similar reason, a geophone located half-way between glacier and source.

The geophone location should be in the vicinity of a seismic station, on a sector free from the risk of avalanches, falling rocks debris flows and similar, and distant or protected from vehicle traffic. The location must be properly signalled and properly identified.

Once collected the data, the peak accelerations registered by the geophones should be incorporated into both stability models in the form of fraction of g. Then, the obtained results of the Safety Factors must be compared to those of the pseudo static scenario evaluated prior to the vibration's monitoring.

7 CONCLUSIONS

We propose a stability assessment for glaciers and rock glaciers nearby mining prospect which should be performed prior to the design of blasting and to the installation of a geophone monitoring network. The stability model consists in a limit equilibrium analysis following the slices method and considers both static and pseudo static scenarios along with saturated conditions. It also considers glacier-related parameters (average thickness, glacier elevation and extension) reported by local glacier inventories such as the Chilean Public Glacier Inventory. Both total and partial evaluations must be performed, being the latter focused on the glacier front in case of steeper (over 30°) slopes.

We also recommend the potential distribution of a geophone network with special attention to the outcrops located near the glacier's front. Once collected the vibrations data from the geophones, we proposed a second stability assessment considering the acceleration values reported by the instruments.

8 ACKNOWLEDGEMENTS

The authors acknowledge the organization for letting the ongoing glaciological problems to be exposed and discussed. The authors also acknowledge the two anonymous reviewers for their valuable comments.

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INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 17th Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVII PCSMGE) and was edited by Gonzalo Montalva, Daniel Pollak, Claudio Roman and Luis Valenzuela. The conference was held from November 12th to November 16th 2024 in Chile.