Back-analysis modelling of the catastrophic avalanches in Sewell, Central Chilean Andes

Marc Janeras[1,*] Pere Oller[2], Rodrigo Arancibia[3], Judit Pons[1], Olga Costa[2], Danilo Asensio[3]
[1] GEOCAT Gestió de Projectes SA, Barcelona, Catalonia, Spain
[2] IGC – Institut Geològic de Catalunya, Barcelona, Catalonia, Spain
[3] APM Ltda. – Asistencia Profesional en Materias de Montaña, Santiago de Chile, Chile

ABSTRACT: In the Chilean Andes, avalanche risk is often related to mining industry, due to its presence in this mountain range, comparing to other activities. A paradigmatic case is El Teniente mine, the largest underground copper mine in the world, located at southeast of Santiago de Chile, VI Region of Chile. Although the most part of mineral extraction is underground, a lot of facilities and associated devices are placed on surface, like the town of Sewell at 2.100 m a.s.l., that grew up to 15.000 inhabitants during the first half of the XX century, increasing the risk with the exposure. As corresponds to the climate in the central Chilean Andes, Sewell has a highly variable precipitation regime, depending on the ENSO effect, what determines the conditions for major avalanches. Taking into consideration all available information (photographs, chronicles, nivological data) an accurate scenario was recreated to fit each 1914, 1926, 1941 and 1944 catastrophic events. Two of them are wet dense flow, and the other two are dry snow avalanches with a powder part. It is clearly seen the different behavior at the run-out zone where deflection is imposed by the main valley and run-up occurs for the powder. To perform the dynamics calculation, Aval-1D and RAMMS software were used on the basis of the Voellmy – Salm formulation. The friction parameters are reviewed and, from these and other experiences, a modification for the altitudinal limits is proposed.

KEYWORDS: Back-analysis calculation, avalanche dynamics, Chilean Andes.

1 INTRODUCTION

As a result of several experiences of technical assistance in avalanches risk for different mines in the central Andes of Chile and Argentina in the past seven years, we have performed avalanche modeling under several snow-climate conditions between 30º and 35º south and both sides of the range (east and west).

To deal with these projects, Voellmy – Salm formulation has been applied for practical purposes assessing the hazard and designing protection measures. To validate the results, calibration works were mandatory and were carried on wherever it was possible. An especially interesting case is Sewell settlement at El Teniente mine, which will be analysed below.

There are only few previous references of such calibrating analysis (Naaim et al., 2002; Casteller et al., 2008) for the large mountainous range of Andes, despite its wide nivoclimatic variability.

1.1 Central Chilean Andes

In the Chilean and Argentine Andes touristic and sportive activity in the mountain range is relatively limited, with a few ski resorts and some scattered practice of mountain climbing (Arancibia, 2006 and Vásquez, 2011). On the contrary, it highlights an important industrial activity, mainly mining, penetrating to the mountainous terrain up to high elevations and remote places. This activity involves road infrastructures, complex and extensive facilities and the presence of people not used to high mountain conditions. The mining investments are very high, like their economic weight in the Chilean economy and progressively also in Argentina.

In this context, a clear risk arises in relation to snow avalanches, which was manifested along the years by several catastrophes. For illustrative purpose it can be quoted the cases compilation done by René León in 2003, which only in the VI Chilean region accounted 211 avalanche deaths throughout the twentieth century. From León, 2003 and Baros, 1996, the cases relating to the surroundings of El Teniente mine can be summarized totaling 193 fatalities associated with snow avalanches, 91% of the region's account. These data highlight the weight of the mining industry on the human exposure to avalanches in this region. Worth noting the phenomenological map for avalanches in El Teniente mine designed in 1910 (León, 2003), as a sign of the concern caused by avalanches from the beginning of the mining projects.

Corresponding author address: Marc Janeras, Geocat Gestió de Projectes SA, Barcelona, Catalonia, Spain;
tel: +34 932 289 253; fax: +34 934 252 001;
email: mjaneras@ggp.cat

1.2 El Teniente and Sewell

El Teniente mine is located in the VI Region of Chile, near Rancagua town, at 80 km south from Santiago de Chile. This section of the mountainous range can be called as Central Chilean Andes. Currently, the mine is under exploitation by Codelco, the main mining public company in Chile. The extracted mineral is mainly copper, with a production of about 400,000 tons yearly. It turns out the largest underground copper mine in the world, with more than 3000 km long galleries and tunnels. However, from the start of the project in 1904 there was intensive auxiliary activity on surface, decreasing after several decades. Nowadays new projects in open pit raise the issue again of exposure to avalanches.

The facilities of this mine extend from 1,500 to 3,100 m a.s.l. One of the main cores is Sewell (34°5' S; 70°23' W), a historic mining settlement where up to 15,000 people lived during several decades at about 2,100 m a.s.l. At present, Sewell is declared industrial heritage for humanity by UNESCO.

All along the history of Sewell, the avalanche activity has taken a crucial role, through several accidents. In 1944 the largest avalanche catastrophe known in Chile occurred in Sewell killing 102 people. After all these fatal experiences, the population was moved to more comfortable villages in the plain, reducing the activity on terrain surface at high altitude, and its overall exposure.

From these major avalanche catastrophes we selected 4 remarkable episodes occurred in a period of 30 years in the first half of the twentieth century, from which we have observational data of the extent, whether from photographs or description about damages. They all occurred at the same avalanche path, affecting northwest flank of Sewell and Rebolledo Bridge, a very valuable infrastructure for the mineral transportation.

Historical information allowed a back-analysis of avalanches with a dynamic calculation. The absence of vegetation in this context avoids other kind of terrain analysis, like it was done further south in Patagonia (Casteller et al., 2008). Section 3 presents the four avalanches considered in the calculation, and section 4 the results obtained by two models.

2 NIVOLOGY AND CLIMATIC CONDITIONS

1.3 Chilean Andes and ENSO

The climate varies widely along the Andes. Throughout the Chilean geography, precipitation has a strong trend to increase with latitude, resulting for the middle section (about 34º) intermediate values, but highly irregular and influenced by the *El Niño* Southern Oscillation (ENSO) phenomenon.

Precipitation is concentrated in winter, and the highest snowfall source is the front al advections with dominance from NW. Under these conditions it is crucial the orographic effect of the mountain range, so there are significant differences in the amount of precipitation between the Chilean and Argentine side by the blocking effect of precipitation from the Pacific perturbations. Moreover, there are very severe wind conditions at highest elevations and plateaus on the leeward side of the range (Oller et al. 2008).

Besides these general characteristics, in many cases, the effects of local conditions can be determinant, and they are still not sufficiently known. The snow precipitation records in El Teniente show an abundant snowfall, though with high interannual variability. Some climatic and hydrographic studies (Escobar & Aceituno, 1998) have shown the influence of ENSO in snow fall regime. Furthermore, data registered at different nivometeorological stations of the mine show a strong contrast between years with *El Niño* effect (abundant snowfall) respect to other situations.

1.3 Snow height

In the centennial nivo-meteorological register at Sewell highlights some significant snowfall records compared to other sites, but coherent with the nearby Andina mine (León, 2003 and Arancibia, 2006). The average annual snow precipitation is 614 cm, with a standard deviation of 282 cm, and a maximum value of 1500 cm. Based on a continuous record of daily snowfall along 17 winter seasons (from 1980 to 2004) with a maximum value of 398 cm in 72 h, it was adjusted to an extreme values Gumbel distribution, obtaining the values shown in Table 1 (Janeras et al. 2013).

Return period (years)	Recent snowfall in Sewell	
	In 24 h (cm)	In 72 h (cm)
10	161	315
30	201	409
100	244	510

Table 1. Fresh snow depth at Sewell for 24 and 72 hours.

From Burkard & Salm, 1992 the usual criterion for defining representative avalanche scenarios is based on values from recent snowfall in 72 h as unstable snow depth. Although the genesis of snowpack instability is not necessarily only derived from snowfall, exceptional avalanches are strongly linked to certain weather conditions also exceptional, so that this criterion is harmonized in practice around the world for the calculation of avalanches. By this way it becomes easier the correspondence with return periods, and it allows estimating a frequency – magnitude relationship quite consistent with the observations of real situations

The values of new snow depth in 72 hours obtained for El Teniente (Table 1) are inapplicable for avalanche calculation, either hazard zoning or protection design. It is not plausible to conceive so thick slab avalanches on the full extent of potential release area, which leads us to reinterpret the criterion of 3-day precipitation standard generating instability in the snowpack. For this amount of precipitation one of the following facts must be considered: either there is a consolidation of new snow in the mantle by the weight and metamorphism to more stable state, or avalanches are triggered before the total 3-day snow depth accumulation is reached. Actually, several historical texts referring to situations of catastrophic avalanches under heavy snowfall situations in this area, describe the occurrence of successive avalanches in the same avalanche path during the storm. So in the chronicles there are several cases of rescuers surprised by secondary avalanches during the rescue. This key point should be contrasted with other experiences and new data more in depth, checking if the influence of other factors inherent to the data itself, either procedure or any local effect on the measurements is plausible.

3 CATASTROPHIC AVALANCHES

From the historical register of avalanches in Sewell, 4 episodes in the same avalanche path were selected to build up a back-analysis. The singularity of this avalanche area stems from its affectation to Sewell buildings and facilities, and in particular to Rebolledo Bridge, the tailings pipeline, crucial for the mining process. Table 2 summarizes the reference avalanches and interpreted and adjusted volume calculation and assigned return period.

Year of occurrence	Avalanche properties	Estimated volume (m^3)	Assigned return period (years)
1914	Dense flow and wet snow	55,000	10
1926		72,000	30
1941	Dry snow flow with powder	66,000	30
1944		120,000	100

Table 2. Avalanche summary in Sewell-Rebolledo path selected for back analysis.

3.1 Avalanche in 1914

According to chronicles, the disaster occurred when a second larger avalanche buried twenty people taking part in the rescue of a worker cached by a previous small avalanche. In the picture (Figure 1) we assume all the deposit as the result of the second avalanche.

This avalanche affected the railway in its curve at the bottom of the valley Quebrada Coya (Figure 7), just before its entrance to Sewell. According to historical data, the damages on railway caused by snow and avalanches were quite frequent. Only ten years after the start of the mine, this curve has been equipped with a protection shed against snow and avalanches. At that time, Rebolledo Bridge was not yet built, but the avalanche did not reach its position.

Consequently, this scenario is supposed similar to an avalanche situation of return period T = 10 years. Each year there may be several avalanches in this path; those arriving just at the bottom of Coya valley can be assumed as a T = 1 to 3 years scenario. In 1914 the volume of the avalanche and its extent over the valley were already remarkable, therefore lower recurrence was assigned to it. To reach the position of the bridge with enough intensity to cause damage, it seems required conditions of return period of about 30 years, as it happened later.

Figure 1. Deposit of 1914 avalanche (source: Sewell Museum).

Based on the photograph of the deposit (Figure 1), an estimate of the volume was made with a precise assessment of the area occupation, but with greater uncertainty in the snow depth, because it is highly variable. According to its nature of dense flow of wet snow, it can be considered a relationship between the density in the release and the deposit, but unknowing the entrainment effect along the route. It is estimated this avalanche with a release volume of about 55.000m^3, under the threshold of medium to large sized avalanche in the sense of the friction parameters.

3.2 Avalanche in 1926

This avalanche is quite similar to the precedent behavior; it is also a dense flow of wet snow undergoing a strong deflection when reaches the bottom of the valley and takes the direction of Quebrada Coya following their hydrological axis. But unlike the 1914 case, the volume and run-out are considerably higher. At this time, Rebolledo Bridge was already built in its initial latticework structure, resulting opaque to the avalanches (Figure 2). Destruction occurs in the half right of the bridge, near the west abutment. With a larger volume, this avalanche can certainly be considered in the group of large avalanches for frictional parameters. 1926 has the record of annual snowfall for the whole century, and recorded many large avalanches. But there was no fatality, although the use of space and activity in the mine had highly increased. Maybe the previous disasters had prepared an adequate awareness for the hazard, and a good risk management was applied with temporary protection, occurring only damage to the facilities.

Figure 2. Run-out of the 1926 avalanche, damaging the old Rebolledo Bridge (source: Sewell Museum).

3.3 Avalanche in 1941

This avalanche has a run-out similar to the precedent in the longitudinal direction of Quebrada Coya, as it caused a partial damage of similar intensity to Rebolledo Bridge, which had been rebuilt on the same structural type. But in this case it destroyed the left half and the east abutment. This was due to the difference in the type of avalanche, in this case a mixed dynamics of dense flow of dry snow and powder. Consequently, there was not the same degree of deflection in the valley, but there is a run-up on the opposite slope. The dense flow affected only the bottom of this side (Figure 3), but the powder had more capacity to climb up damaging the first line of houses, placed at 2095 m a.s.l., which means a run-up height larger than 21 m, after the lower point of the central axis of avalanche at 2074 m a.s.l.

Figure 3. Damages on buildings and Rebolledo Bridge caused by the avalanche of 1941 (source: Sewell Museum).

3.4 Avalanche in 1944

This avalanche is similar to the previous one, but larger. It is also a mixed type of dry snow dense flow and powder, which means less deflection and a stronger run-up effect on the opposite slope, where it is located Sewell. Although the affected buildings in 1941 had been demolished after the catastrophe, this time the run-up was significantly higher and affected the next line of buildings located at an elevation around 2108 m, and also partially a second level placed at 2122 m, what means a run-up height of about 48 m.

Figure 4. Damages on Rebolledo bridge caused by the avalanche of 1944 (source: León, 2003).

The old Rebolledo Bridge had been replaced again by a new big metal arch, with an opening of 100 m wide offering such a large section for the torrential and snow avalanches dynamics. But the avalanche pressure in run-up destabilized in the left abutment, dropping the entire arch (Figure 4). This was a very cruel fact for a bridge designed so elegant just newly opened (Faiguenbaum, 2000). But the worst were the consequences for the inhabitants of Sewell: the avalanche caused a total of 102 fatalities, the worst tragedy known for snow avalanches in Chile. According to the extent and intensity of damage in 1944 we associated a centennial return period. Vergara & Baros, 2002 conclude that snowfall in August of 1944 corresponds to a return period of 180 years.

The damage to buildings is given in two separate areas: one upstream of the bridge, similar to 1941 but with greater extent, and the other one about 200 m downstream of the bridge where most buildings were destroyed (Figure 5). These damages placed downstream from Rebolledo Bridge do not seem compatible with the same avalanche, but that would be caused by an avalanche coming from the front slope, called Quebrada Chica, and which occurred within few hours of difference. This interpretation is consistent with a witness reported in chronicles, which describe two avalanches, although they do not clearly locate their origin.

Figure 5. Damages on buildings caused by the avalanche of 1944 (source: León, 2003).

Figure 6. Rebolledo bridge current situation and protection dikes for Sewell.

Afterwards protection dams were built for this bridge footboard and for Sewell perimeter against such avalanches (Figure 6). Finally, according to all this information, it was mapped the most reasonable interpretation of the extent for the four avalanches (Figure 7).

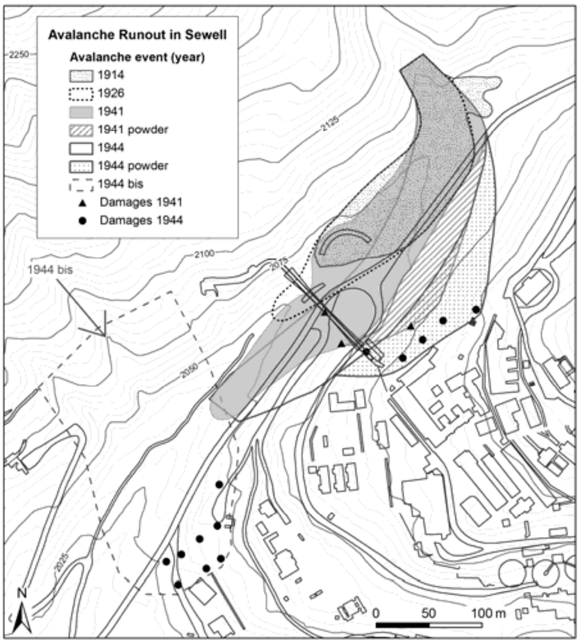

Figure 7. Interpretation of run-out and run-up for the 4 avalanche events under back-analysis based on historical data.

4 AVALANCHE CACULATIONS

In the context of a new project for an open pit at the end of 2011 – beginning of 2012 we carried out a review of the historical avalanches to validate calculation models. At that time Aval-1D software (SLF, 2005) was used. Recently, we have checked the results using the RAMMS model, the 2D evolution of the previous one (SLF, 2011).

Only dense flow was modeled for the avalanches. It will be interesting for further and deeper analysis to perform powder simulation with the SL-module on Aval-1D, or also to compare with analytical calculation of the run-up comparing lumped-mass and leading-edge formulations (McClung & Mears, 1995).

4.1 Aval-1D

Using Aval-1D we observed that adopting the frictional parameters in the same way that had been proposed for the Alps by SLF on the user manual (SLF, 2005), the run-out was too large for the reasonable volume estimations, or alternatively, the release volume must be set underestimated to get agreement with real cases. After some tests, we achieved good results for the ensemble of occurred avalanches (Figure 8) applying a translation of the altitudinal thresholds by an increase of 900 m high and the volumes presented in the Table 2. The resulting limits to consider the change in the behavior were set to 1,900 m and 2,400 m. Case examples are situated over 2,000 m altitude, therefore the lower limit could not be tested, but we assumed the same displacement.

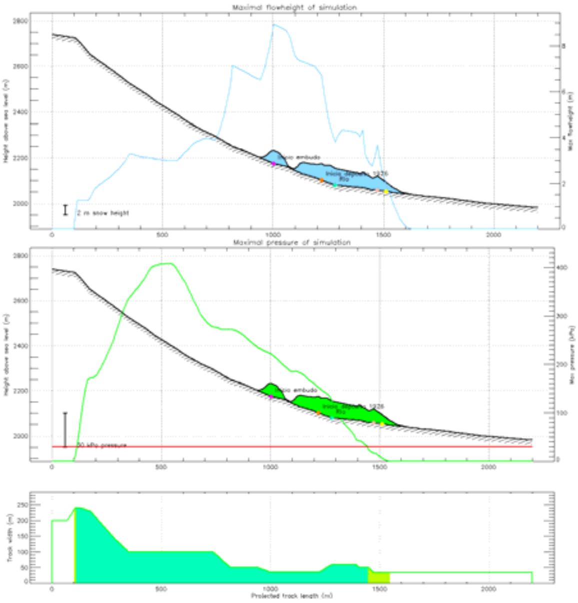

Figure 8. Run-out fitting for the 1926 avalanche according to damages against the bridge.

These tests have shown again the consistency of a simple model, but it obviously involves many simplifications. We have not imposed any additional condition in friction terms for the hard deflection experienced by both flows in 1914 and 1926, which could be an effect to consider in future improvements.

4.2 RAMMS

This model only reproduces the dense flow, without a specific modeling for powder dynamics. But also reproduces the fact that during the deflection at the bottom of the main valley the bulky mass at high speed experiences a run-up on the opposite side. But it would lack to introduce a greater differentiation between two types of motion to be distinguished:

- In wet snow dense flow (like in 1914 and 1926) it prevails deflection under the confinement effect caused by the compressive regime (like Rankine passive state) resulting from the depositional process on the front and flank side.
- In dry snow flow with powder (like in 1941 and 1944) it prevails the component of inertial motion over the smoother deposition of dense flow, resulting unable to confine it.

Despite this limitation, RAMMS appears like a valuable tool to analyze the dynamics on plant layout as a 2.5-dimentional result.

For 1914 avalanche a release volume of 55,000 m^3 is necessary to fit the run-out (Figure 9), but maintaining parameters of medium-size avalanche. This case is the less sensitive to the changes in altitudinal limits.

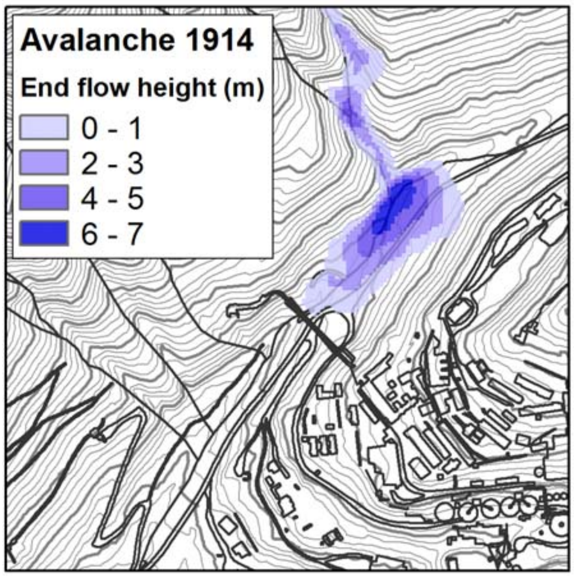

Figure 9. Deposition snow height result for the 1914 avalanche.

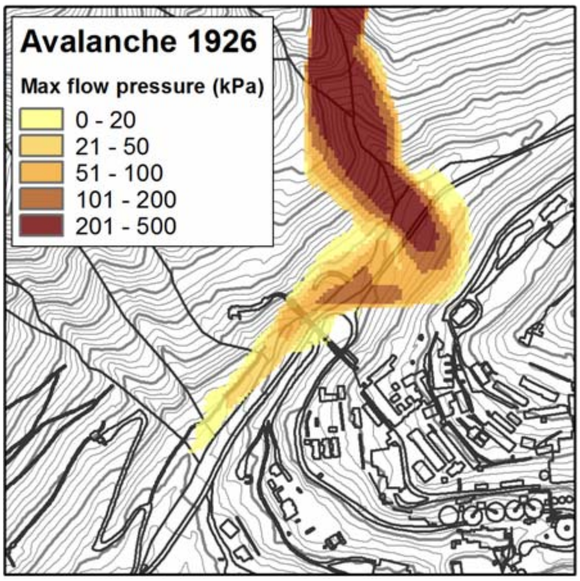

Figure 10. Maximum flow pressure result for the 1926 avalanche.

On the contrary, the 1926 avalanche is more sensitive to these limits. Its size is clearly large, and under this condition it is necessary to rise the upper limit to 2,400 m. However the terminal velocity reaching the bottom valley is too high or an additional condition for deflection should be imposed artificially to reduce the unrealistic run-up on the opposite slope (Figure 10). Further refinements like Christen et al., 2010 should be done to fit better the results. The blocking effect of the bridge is not considered in the model, so the run-out results larger.

All calculations are performed with a spatial resolution of 5m of cell and in second order of numerical iteration. For avalanche 1926 also a 10 m cell calculation was done, maintaining good results, but the maximum values for pressure were smoothed. After some tests for the stopping criteria, it is fixed by 3% for the total momentum.

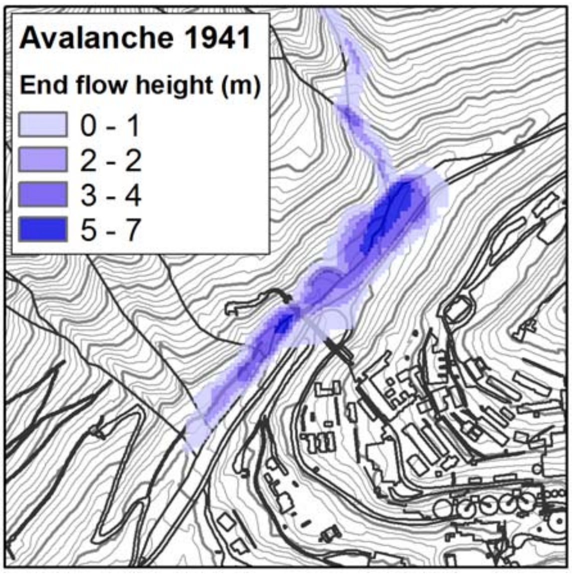

Figure 11. Deposition snow height result for the 1941 avalanche.

For 1941 and 1944 bigger difficulties were found, to reproduce a partial run-up of the dense flow and resulting deflected direction to the left abutment of the bridge. RAMMS reproduces a frontal run-up followed by a return back to the bottom and the central axis of the valley (Figure 11). To liberate the flow of the final channelized section of the path, and let it attack the front slope not so orthogonal, it was performed a calculation for 1941 avalanche using the terrain elevation model modified by a previous small avalanche deposit, but not much improvement was found. More tests should be done in this way, because it seems realistic to smooth the channel by snow cover.

For the 1944 avalanche, a volume of 120.000 m^3 justifies a run-out along the Coya valley large enough to get to the second area of destroyed buildings. But by no means, the damages distribution fits to the incidence direction (Figure 11). Accordingly, we conclude that there are two separate avalanches at different paths, as some historical data were suggesting. Damage downstream of the bridge corresponds to an avalanche coming from the front slope (Quebrada Chica) as it is also suggested by the disposal of a protective dike built shortly thereafter.

If we unlink both avalanches, the scenario might fit better for Rebolledo Bridge according to RAMMS results would be a release volume of about 105,000 m^3. Under these conditions we obtained pressure values of about 100 kPa for the first line of buildings, and 130 kPa for the abutment of the bridge. But it results unclear the distinction between dense flow and powder effects.

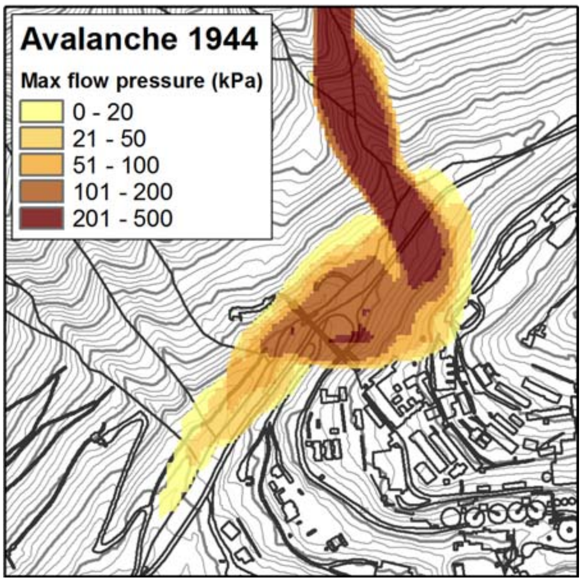

Figure 12. Maximum flow pressure result for the 1944 avalanche and 105.000m^3 released.

4.3 Model calibration

In this way, it was possible to calibrate the modeling of avalanches in this Andean environment, reviewing the Voellmy-Salm model parameters. The conclusion was that the reference parameters tabulated by the SLF for the Alps could be taken in the same terms with respect to the magnitude and return period of avalanches, as well as terrain features, but its altitudinal variation had to be changed. The back-analysis of the 4 Sewell-Rebolledo avalanches concluded a proposed modification of the limits with a translation of about 900 m, increasing from the limit of 1,500 m to 2,400 m. This approach is observed valid in the study area and for the purpose of the project in curse, but must be contrasted with regional climatic differences between mountain ranges to be finally validated. But it is in agreement with other experiences around the world, also in Chile (Stoffel, 2012).

Similarly, the precedent study checking the applicability of the SLF parameters for the model Voellmy-Salm in the Pyrenees (Oller, et al., 2010) for zoning purposes (Janeras et al., 2011), noted that the possible adjustment in the transposition to other ranges would be in the first instance by means of altitudinal limits. In the Pyrenees, being smaller the climatic differences regarding the Alps (simplifying, those derived of 4° of latitude difference) this altitudinal adjustment of the parameters would be much smaller and could not be set, because even may be negligible compared to the uncertainty that may exist on other key variables in the dynamics of avalanches for those study cases.

5 CONCLUSIONS

The friction parameters are reviewed and, from these and other experiences, an adjustment for the altitudinal limits is proposed for the recommended values by SLF. Specifically for this case, an increase of 900 m in the altitudinal thresholds was adopted as the best approach. More cases must be back-analysed and other kind of approaches must be performed, like from climatic perspective, to ensure the value for this shifting. But what is appearing clear is that this is the easiest and most reliable way to adjust the frictional parameters for each mountainous range and the specific nivoclimatic context.

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