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Study of lahar hazards at Villa la Angostura

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Secondary lahar hazard assessment for Villa la Angostura, Argentina, using Two-Phase-Titan modelling code during 2011 Cordón Caulle eruption

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Abstract

This paper presents the results of lahar modelling in the town of Villa La Angostura town (Neuquén-Argentina) based on the Two-Phase-Titan modelling computer code. The purpose of this exercise is to provide decision makers with a useful tool to assess lahar hazard during the 2011 Puyehue-Cordón Caulle Volcanic Complex eruption. Possible occurrence of lahars mobilized from recent ash falls that could reach the city was analized. The performance of the Two-Phase-Titan model using 15 m resolution DEMs developed from optical satellite images and from radar satellite images was evaluated. The output of these modellings showed inconsistencies that, based on field observations, were attributed to bad adjustment of DEMs to real topography. Further testing of results using more accurate radar based 10 m DEM, proved more realistic predictions. This procedure allowed us to simulate the path of flows from Florencia, Las Piedritas and Colorado creeks, which are the most hazarddous streams for debris flows in Villa La Angostura. The output of the modelling is a valuable tool for city planning and risk management especially considering the glacial geomorphic features of the region, the strong urban

development growth and the land occupation that occurred in last decade in Villa La Angostura and its surroundings.

[Introduction] After decades of quiescence, the Cordon Caulle volcanic complex in the Chilean Southern Andes began an eruptive process at 14.45 LT on 4 June 2011 (Elissondo et al., 2011) from the new vent named We Pillan (New Crater in Mapuche language) (Collini et al., 2012). This vent is located in the Southern Volcanic Zone (SVZ) at 40.58 S and 72.13 W, and 2240 m a.m.s.l. (above mean sea level) (Lara and Moreno , 2006). The sub-plinian eruption produced a large plume of gases and ash particles that reached 12 km in height (Figure 4) which eventually circled the Southern Hemisphere disrupting air travel on several continents. As typically occurs in mid-latitude Central and South Andean eruptions (Villarosa et al., 2006; Folch et al., 2008; Collini et al., 2012), the dominant regional winds directed the ash clouds over the Andes and caused abundant ash fallout across the Argentinean provinces of Río Negro, Neuquén and Chubut (affecting the more proximal areas in Chile as well). Large quantities of ash fell in the nearby regions until the end of July, causing major problems in villages and cities of the Patagonian Andes and permanent closure of airports. Villa la Angostura, one of the most touristic areas of Patagonia , located near the Argentine-Chilean border and a short distance from the new vent, was one of the most affected cities by this eruption.

As a consequence of these ash fall events, thick deposits of tephra and snow accumulated during the winter covering extensive areas surrounding Villa La Angostura. This resulted in a lahar hazard for the town, as the snow began to melt during the spring ans summer seasons. This paper analyzes the hazard posed by the snow-ash deposits/pack that could contribute to lahars formation potentially affecting Villa La Angostura.

1 VOLCANIC EVENT AND DEPOSITS

On April 27, 2011 the argentinean OVDAS-SERNAGEOMIN institute (OVDAS-SERNAGEOMIN, 2011a) reported that a swarm of volcano-tectonic earthquakes, centered on the Cordón Caulle fissure zone, were detected. These earthquakes continued to increase in magnitude and frequency until Saturday 4th of June, when the eruption sequence began (OVDAS-SERNAGEOMIN, 2011b). At 13 LT, an earthquake followed by a strong blast surprised neighbors at Villa La Angostura, 45 Km East-South-East of the vent, and a 5 Km-wide ash and gas plume rose to more than 12 km height (Figure 4). Then, coarse ash fall occurred soon after in the villa and by 16:30 LT the plume reached San Carlos de Bariloche, located 100 km SE of the vent producing a dense coarse ash seized pyroclastic fall. A sampling network was set up to collect direct fall tephra from the beginning of the eruption, covering a transect from Paso Puyehue, at the Chile-Argentina border, Villa La Angostura, Bariloche and to the steppe as far as Ingeniero Jacobacci in Río Negro province.

Over 400 thickness data were plotted to make an isopach map (Figure 4). The most relevant characteristic of the first pulses of the eruption that comes up clearly from the map is a distribution pattern showing three main deposition axes that correspond to the dispersion directions of the main plumes at 90^o, 110^o and 130^o. Deposited materials during the period June - October 2011, affected more than 1450 Km2 with at least 10 cm thick ash and 170 Km^2 were covered by more than 30 cm thick tephra.

Direct tephra fall in the basins of the streams draining towards Villa La Angostura accumulated more than 15 cm (up to 30 cm in some cases) forming thick deposits along the dispersion axis. Soon after deposition, remobilization of tephra by wind and rain in high slopes was evident.

Tephra deposited during the first eruptive pulse was characterized by well-sorted coarse ash and lapilli layers composed of high vesicular pumice with subordinated lithics. The deposit formed during the first days of the eruption was coarse-grained, mainly composed of lapilli and coarse ash with the main fraction in the range 500 µm

to $1,5$ mm. By June 8 samples was finer-grained with almost 50% of particles between 500 µm and 63 µm. The grain size distribution of samples collected during 12-14 June was even finer, with almost 40% of particles < 63 µm.

Subsequent explosive pulses produced several coarse to fine ash tephra deposits, frequently separated by thin compact, very fine ash layers. This alternation of thick, coarse unconsolidated and well-sorted tephra with thin, fine, compacted ash showed different degree of stability in high slopes and differential behavior when exposed to erosion.

The eruption occurred during the austral winter that is the rain season in the Andean North Patagonia region (average rainfall between 4.000 to 2.500 mm/yr, Barros, et-al. (1983). Important masses of unconsolidated ash deposits were remobilized by rain and wind and were covered by snow soon after the deposition, conforming a snowpack characterized by several centimeters to tens of centimeters thick snow layers intercalated with subcentimeter to 5 cm thick ash/lapilli layers. According to traditional snow avalanche tests performed in the field, (shovel shear and stability tests Villarosa, et-al. (2012) these snow/tephra deposits proved to be very unstable. Well-sorted coarse ash and lapilli tephras are low cohesive layers that frequently work as failure layers in the snowpack, producing snow avalanches that carry and deposit downhill important masses of tephra. The instability of the ash and snow deposits in the upper basins, characterized by high slope valley-walls of glacial origin, was later confirmed by several snow and ash avalanches that were recorded in the area during July and August 2011. In those environments, mobilization of tephra occurred rather quickly, accumulating reworked materials on the valley floor, 2 or 3 times thicker than the original deposits. On the other hand, fine ash frozen layers were identified as low permeability horizons that prevent infiltration and enhance surface runoff. These factors could result in a combination of processes that lead to the generation of secondary lahars triggered by intense rainfall events. Rainfall accelerates snow melting; increased runoff produces high volumes of running water in the high fluvial basins; snow/ash avalanches and re-deposited tephra in the valley floor make solid phase available for mass mobilization.

By the end of the spring most snow disappeared, the pyroclastic material contained in the snowpack was almost completely transported downhill into the floor of the valleys and the finer fractions were intensely reworked by wind. As a result, thicknesses varied significantly compared to the original deposit, particularly in the heads of these U shaped valleys, determining a change in the original conditions used for the modeling. The resulting isopach map using data collected up to November 2012 shows these variations (Figure 4).Therefore, results presented here are only valid for the dominating conditions during 2011 winter and spring, when secondary lahars were considered as a real hazard.

2 LAHAR HAZARD ASSESSMENT

In order to provide the decision makers with a reliable forecast of possible lahars from Florencia, Piedritas and Colorado creeks, we chose a modeling method, which accounts for the current topography and uses geological records as initial conditions.

Due to the two-phase characteristics of debris flows, the chosen model must account for the two phase behavior of lahars (Iverson, 1997). In this case we used the Two-Phase-Titan model (Cordoba, et-al., 2015) (*this issue*) which was developed at SUNY University at Buffalo. For the solids phase, this model is based on the early work of Savage and Hutter (1989), Iverson (1997) and Iverson and Denlinger (2001), who arrived at the insight that very large dense granular flows could be modeled as incompressible continua governed by a Coulomb failure criterion (Coulomb, 1773). The fluid phase uses the typical hydraulic approach (Chow, 1969; Guo, 1995) together with the Colebrook-White equation (Colebrook and White, 1937) for the basal friction. The phases interact through a phenomenological interphase drag and a buoyancy term.

Further, the equations of motion are depth averaged, by assuming that the flow depth is very small in comparison to the runoff. This mean that the resulting equations neglect vertical accelerations in similar way to shallow water approaches. By scaling the problem stating that $\epsilon = H/L$, where L is runout length to the pile front, and neglecting higher-order terms in ϵ, the correspondent equilibrium equations become (only x direction are shown):

1. Conservation of Mass:

$$\partial_t \hat{h} + \partial_x(\hat{h}(\overline{\varphi v_x} + \overline{\varphi^f u_x})) + \partial_y(\hat{h}(\overline{\varphi v_y} + \overline{\varphi^f u_y})) \; = \; 0 \; . \tag{1}$$

2. Conservation of Solid Phase Momentum:

$$\begin{aligned}
& \partial_t(\hat{h}\overline{\varphi}\overline{v^x}) + \partial_x(\hat{h}\overline{\varphi}\overline{v^x v^x}) + \partial_y(\hat{h}\overline{\varphi}\overline{v^x v^y}) \qquad (2) \\
= \quad & -\frac{\epsilon}{2}(1-\frac{\rho^f}{\rho^s})\partial_x(\alpha_{xx}\hat{h}^2\overline{\varphi}(-g^z)) \\
& -\frac{\epsilon}{2}(1-\frac{\rho^f}{\rho^s})\partial_y(\alpha_{xy}\hat{h}^2\overline{\varphi}(-g^z)) \\
& +(1-\frac{\rho^f}{\rho^s})(-\epsilon\alpha_{xx}\partial_x b - \epsilon\alpha_{xy}\partial_y b + \alpha_{xz}) \\
& \hat{h}\overline{\varphi}(-g^z) - \frac{\epsilon}{2}\frac{\rho^f}{\rho^s}\overline{\varphi}\partial_x(\hat{h}^2(-g^z)) \\
& -\epsilon\frac{\rho^f}{\rho^s}\hat{h}\overline{\varphi}(-g^z)\partial_x b + (\frac{\overline{D}}{\rho^s})(\overline{u^x} - \overline{v^x}) + \hat{h}\overline{\varphi}g^x \; .
\end{aligned}$$

3. Conservation of Fluid Phase Momentum:

$$\partial_t(\hat{h}\overline{\varphi^f}\overline{u^x}) + \partial_x(\hat{h}\overline{u^x}\overline{\varphi^f}\overline{u^x}) + \partial_y(\hat{h}\overline{\varphi^f}\overline{u^x u^y}) \tag{3}$$

$$\begin{aligned} = \quad & -\frac{1}{2}\epsilon\partial_x\hat{h}^2\overline{\varphi^f}(-g^z) - (\frac{\overline{D}}{\rho^s})(\overline{u^x} - \overline{v^x}) \\ & + \hat{h}\overline{\varphi^f}g^x + \overline{\varphi^f}C_f u^x||u|| \,. \end{aligned}$$

Where $\overline{\varphi}$ is the solids volumetric concentration, and $\overline{\varphi^f} = 1 - \overline{\varphi}$. ϕ_{int} and ϕ_{bed} represent basal and internal friction angles, $\alpha_{xy} = -sgn(\partial_y v)$, $\alpha_{xx} = k_{ap}$, $\alpha_{xz} = -v^* tan(\phi_{bed})/||\mathbf{v}||$, where k_{ap} relates the normal and tangential stresses. $\hat{h}$ represents the depth of the flow, $\overline{v}^x$ and $\overline{v}^y$ the solids velocity field, $\overline{u}^x$ and $\overline{u}^y$ the fluid velocity field, ρ^s and ρ^f the solids and fluid densities. ϵ is the ratio flow depth to flow length, g is the gravity, C_f is the friction factor, and D is the interphase drag coefficient. The solids and fluid momentum equations in y direction have a similar form. Note that if $\overline{\varphi^f} \rightarrow 1$ equation 3 becomes the typical shallow water approach of hydraulics (Chow, 1969). This mean that the program can be used in both extremes, from a maximum pack concentration of $\varphi^s = 0.65$ to concentrations as low as $\varphi^s = 10^{-8}$ (almost pure water).

The model has the additional advantage of saving computer power, because it is a pseudo-3D approach, which is also due to its mesh adapting capabilities. Through the extended use of this program in real scale problems, it has shown its reliability and robustness (Córdoba et al., 2010; Sheridan et al., 2011; Cordoba, et-al., 2015). Thus, in this work we use Two-Phase-Titan as the computational tool to study and forecast the lahar hazard in Villa la Angostura.

2.1 Initial conditions

We analyzed the lahar hazard at Villa La Angostura from three drainages whose streams flow directly toward the urban area of the town. As can be seen in Figure 4 they are Las Piedritas creek, which have a catchment area of 7.75 Km^2, Colorado creek, with a catchment area of 3.8 Km^2 and Florencia creek, with a catchment area of 1.3 Km^2 (Baumann et al., 2011). The program Two-Phase-Titan needs the location of the piles, their initial volumes, the pile height and initial concentration of solids as initial conditions.

In order to set the initial volumetric fraction of solids, we used the actual ratio of snow and ash deposits from the eruption. Figure 4 shows several interlayered ash-snow deposits from the Cordón Caulle eruption. They show that almost 30% of them consist of the deposited ash. However, water rain and water of the streams added to the lahar reduce this fraction, but later erosion incorporates solid particles to the lahar, resulting in the opposit effect. Thus, we postulate that these effects become balanced or negligible which allow us to use as initial solids volumetric concentration $\varphi_s = 0.3$ for all the initial piles.

The needed data to set the initial volumes was taken from the Elissondo et al. (2011) andBaumann et al. (2011) reports, which analyzes the deposits of the ash fall from the 4 of July 2011 eruption of Cordón Caulle volcanic complex on the nearby mountains. Elissondo et al. (2011) estimated the amount of deposited material at each basin and Baumann et al. (2011) estimated the depth of the respective deposits. Two cases where analyzed for each creek, a high and a medium volume. As it is unlikely that all of the deposited material to instantaneously become a lahar in large catchments, we assumed different fractions of the total deposited volumes as initial volumes for each catchement. In the case of Las Piedritas basin, we assumed as high initial volume the 50% of the total deposited material, and the quarter of all the deposited material as a medium volume. In case of medium size catchment areas like Colorado, 75% of the deposited material is assumed as high volume. Finally, we assume that from the material deposited on small catchment areas, 90% could become part of the lahar. An other initial condition is the pile height. In this paper we use the reported material deposited depth, which are less than 1 m in all the basins (Elissondo et al., 2011; Baumann et al., 2011). However, we increased these values by a security factor, in order to account for other uncertainties. Table 4 summarize the high and medium volumes, as well as the pile height used as initial conditions in our modeling.

The location of the initial piles of material were chosen at great distances from each outlet basin. In the case of Las Piedritas, we tested several initial locations. One from the farthest place on the basin, others from the lateral walls. All of them resulted in almost the same pile height and flow velocity at the basin outlet. The basin of Colorado received the Florencia-North stream as well. Thus, we locate piles both at the top of the Colorado basin and at the top of the Florencia-North stream. In the case of Florencia-South, the initial pile was located at the top of its basin.

An additional pile was located at the top of the La Ponderosa basin, just to test if lahars can reach the town. However, this site has no collected data about the deposited ash volumes. We assumed the same volumes as in Florencia creek due to the size of this basin is similar.

3 Results

In order to run Two-Phase-Titan, a Digital Elevation Model (DEM) is needed. The Argentine Comisión Nacional de Actividades Espaciales (COANE) initially provided us with two 15 m resolution DEMs. One of them was developed from optical satellite images and the second one from radar satellite images.

In order to test the DEMs, we used the initial data set for Florencia creek. Orange contours in Figure 4, shows the predictions of Two-Phase-Titan using the DEM based on optical sensors, and the red contours shows the prediction using the DEM build

from radar sensors. The Google-Earth image shows a widespread forest that hides the Florencia stream from view. The optic DEM reproduces this effect showing the terrain flatter than it actually is. For this reason the model predicts that the lahar will be widely spread from the beginning. In contrast, using the radar sensor based DEM, the flow follows the actual natural channel hidden by the trees. In addition, the boundary of the forest is represented in the model as an abrupt change in the topography. This is the case for some locations in Villa la Angostura, where patches of more than 30 m high forest have been cleared to allow human settlements. Thus, the program predicts a diversion of the flow where such a barrier is reached (see the arrow in Figure 4), while the flow just follows the natural channel in the prediction done by the program using the radar based model.

Therefore, the optic sensor based terrain model was replaced by the more accurate radar sensor based DEM. As explained above, we use two initial conditions. One with high volumes and the second one with medium volumes (see values in Table 4). Figure 4 shows the prediction of Two-Phase-Titan for the medium volumes. In this case, none of the flows reach the urban area. Nevertheless water treatment facilities and spare living houses could be inundated. For the volume used in La Ponderosa creek, Two-Phase-Titan predicts that the flow could inundate the main road and structures built near it. It is informative to see that the flow from Piedritas creek inundates part of a planned urban expansion zone. However, the flow is diverted in an almost 90^o angle seemingly by a topographic barrier.

In the case of high volumes, the urban area is shown to be reached by the flows from Florencia creek (see Figure 4). We should pay special attention to the possibility that the school named School 186 might become affected, as shown by the circle filled in blue. Based on such prediction of the program, we advised the local governmental authorities of the city to take appropriate decisions about that possibility. Then, the

Mayor ordered to temporary relocate the children to another school located in a safer place. In the cases of Colorado and La Ponderosa, the runout of the flow is almost the same of the medium volume case. Nevertheless, they tend to inundate in a more expanded way, showing larger inundation areas than in the case of medium volumes. Fortunately, these increase in the inundation area occur in low population zones.

In the case of Las Piedritas creek, we located the initial pile at the highest place of the basin. The flow shows a meandering behavior until it reaches the middle of the basin. From that point, its behavioral characteristics become similar to the case of medium volumes but with greateer depth at each point. Then, despite of the high volume used, the program shows that the flow apparently diverted in the same fashion as in the medium volume case. Field inspection of the place where the modeled diversion occcurs we found that there is no such topographic barrier. Instead, there is a narrow opening in the hills. Thus, the prediction of Two-Phase-Titan about the path followed by the flow was mistaken, probably because the 15 m DEM was flattening the representation of the terrain.

We decided to test if by using a more accurate DEM, the prediction would become more realistic. For this purpose the Comisión Nacional de Actividades Espaciales (CONAE), developed a 10 m resolution DEM, which was used to repeat the medium volume predictions. Figure 4 shows a Google-Earth image of Villa la Angostura with the medium size modeled lahars using that DEM. The initial piles ware located at the top of the basins of Las Piedritas, Colorado and Florencia creeks. In this case the flow from Las Piedritas followed the narrow path, predicting that the flow could reach the outskirts of the urban area. The prediction for Colorado creek is similar to the correspondent prediction done using the 15 m DEM. In the case of Florencia creek, the prediction shows that the flow could go through the whole School 186 neighborhood, even reaching the highway.

[Conclusions]

Though Villa La Angostura is located in a mountainous environment and conditions for secondary lahars were present, only minor mass waste events were recorded. Destructive mass waste events involving tephra deposits triggered by intense precipitations were reported in distal locations in the Patagonian steppe (100 km east of Villa La Angostura) where annual average rainfall is less than 600 mm (Wilson et-al., 2013).

This work draws the attention to secondary lahars as a real hazard not only in volcanic proximal areas, but also in broad regions of Andean Patagonia under the influence of explosive volcanic activity, even though from the volcanological and the tephra deposits perspective, they are considered as medial to distal facies. It also proposes a valid method to evaluate critical hazardous areas in dense forested urban environments that are typical in the region.

Although at this point this is not a probabilistic tool, results of the presented modelling provide a good evaluation of lahar susceptibility and have set the basis for future development of a probabilistic approach.

The output of the modelling is a valuable tool for city planning and risk management especially considering the physical characteristics of Villa La Angostura area, the strong urban development growth and the land occupation tendencies observed in the last decade.

In forested areas, the availability of a DEM produced from good radar data is critical in order to get the minimal resolution required for the modelling. In addition, through our numerical experiment results, we support the work of (Capra et-al., 2011) and (Stefanescu et-al, 2012) related to the importance of the precision of the DEM in forecasting the spread and runout distances of modeled flows.

4 Authors contribution

Gustavo Córdoba and Michael Sheridan developed the program TWO-PHASE-TITAN. In addition, Dr. Córdoba worked in the modeling with Gustavo Villarosa and Debora Beigt. Gustavo Villarosa conducted field work and contributed with the geological background and data interpretation. Debora Beigt cooperated with photo-interpretation and GIS mapping. Jose Viramonte helped in the geologic interpretation. Graciela Salmuni developed the Digital Elevation Models at CONAE.

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Table 1. Calculated total volumes of deposited ash-snow material at each basin, and volumes used in the modeling, as well as the used pile height.

Creek	Total volume (m)	Large volumes (m)	Medium volumes (m)	Pilel height (m)
Piedritas	600.000	300.000	150.000	1
Colorado	270.000	200.000	70.000	1
Florencia	55.500	50.000	20.000	1.5

fall3d_pred.jpg

Fig. 1. Fall3D program ash dispersion modeling of the Cordón Caulle complex 2011 eruption. The colored representation shows its subplinian plume dispersion for 9th of June (After Collini et al. (2012)).

layers2_villarosa.jpg

Fig. 2. Interlayered ash-snow deposit at the nearby mountains of Villa la Angostura. The total deposited thickness is less than 1 m. The ash corresponds to almost 30% of such a thickness.

isopach1_villarosa_gus.jpg

Fig. 3. Isopach and affected area by the end of October 2. The yellow lines are the isopach contours. The dots are the sampling sites. (After Villarosa and Outes (2013))

isopach2_villarosa.jpg

Fig. 4. Distribution of tephra deposits modified by erosion and remobilization by November 2012, thicknesses expressed in centimeters (after Villarosa and Outes (2013))

three_basins_2.jpg

Fig. 5. Satellite view of the area of Villa la Angostura, showing the three streams that enter the urban part of the town. (Image courtesy of Comisión Nacional de Actividades Espaciales, CONAE)

dem_comp_arrow.jpg

Fig. 6. Two-Phase-Titan predictions using two DEMs on a Google-Earth image. The orange contours shows the prediction of the lahar inundation using the DEM based on optical sensors. The red contours shows the prediction of the lahar inundation using a DEM developed from radar sensors. The white arrow points to a beginning of the forest that seems to divert the flow, because it is seen by the optic sensor based DEM as a wall.

flujos_medios.jpg

Fig. 7. Predictions of Two-Phase-Titan for medium size volumes.

flujos_altos.jpg

Fig. 8. Predictions of Two-Phase-Titan for large size volumes.

prediction-10m-dem.jpg

Fig. 9. Prediction of Two-Phase-Titan using the 10 m resolution DEM built by the CONAE