Rheology of hail-debris flow and implications in flow mobility

Santiago Aguilar, Alex Tupper, Jorge Carcés, Germán Tamburrino, Aldo Romero

Abstract. Triggered and hail bearing debris flows are underreported in the literature. In this work, Using the FLO2D model, we study the effects of hail in the mixture rheology and its consequences reducing frictional stress.

1 Introduction

Debris flows are water sediment mixtures, in roughly similar proportions, flowing downs slopes due to gravity [1]. In debris flows, friction is dominated by fluid stress (viscous stress, the same as water flows), and fluid-particle (drag) and particle-particle interactions (Coulombic friction and collisions) [1, 2]. Apparent flow friction angles are significantly lower than typical repose angles, resulting in larger run-out distances than expected [3,4]. Friction reductions are attributed to different mechanisms, as particles interacting with bottom roughness or particle-fluid interactions causing fluidization [1,4]. Single phase numerical models introduce friction mechanisms in as part of the use resistance law by ad-hoc rheological formulation.

An extreme storm event during 29-31 January 2021 (austral summer) triggered several catastrophic debris flows in central Chile (33-36°S) [5]. In the rural commune of Malloa (34°S), several hail-debris flows caused 200 injured individuals and 73 damaged houses in small and precarious settlements located at the alluvial fan of steep small catchments (~0.4 km²). Hail-triggered and hail bearing debris flows are underreported in the literature [3]. Coppus and Imeson [7] give a qualitative description of hail erosion capacity. However, to our knowledge, there no literature regarding the effects of hail in debris flows rheology.

In this work, Using the FLO2D model, we study the effects of hail in the mixture rheology and its consequences reducing frictional stress.

2 Study area and storm event characteristics

The study area corresponds to four small catchments (~<1.4 km², Table 1) at the north face of the Cerro Negro hill (CR1 to CR4, Table 1 and Fig. 1), located in the rural settlement of Cantarrana. They are characterized by steep-slope hillside covered by herbaceous shrubby undergrowth, historically degraded by livestock [6]. Settlements are mainly in the alluvial fans, since lower lands are used for agriculture, increasing its commercial value.

Table 1. Catchments characteristic and hydrology

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area km²</th>
<th>Conc. time min</th>
<th>Max. water flow rate m³/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR1</td>
<td>0.18</td>
<td>6.2</td>
<td>2.49</td>
</tr>
<tr>
<td>CR2</td>
<td>0.12</td>
<td>6.1</td>
<td>1.32</td>
</tr>
<tr>
<td>CR3</td>
<td>0.16</td>
<td>7.0</td>
<td>1.25</td>
</tr>
<tr>
<td>CR4</td>
<td>0.36</td>
<td>6.7</td>
<td>3.79</td>
</tr>
</tbody>
</table>

Precipitation was recorded by four meteorological stations surrounding the study area: San Vicente (4.5 km SW), El Tambo (8.6 km SE), Quinta de Tilcoco (7.7 km NE), and El Arenal (6.3 km NE). The event developed in four main rain pulses, accumulating near 40 to 65 mm. Antecedent wet conditions were dry because of the summer period and the unprecedented long-lived drought affecting central Chile from 2010, with annual rainfall deficits of 20%−40% [8].
The rainfall event started with a first intense pulse of near 10 h precipitation, accumulating 23-35 mm, with maximum intensities about 6 mm/h. After 22-24 h, a second rainfall pulse of ~4 h duration, accumulating near 0.6-3 mm, occurred. Few hours later, a short pulse (~2 h) of intense precipitation (~4 mm/h) accumulated ~1.4-5.8 mm. This third pulse was accompanied by 5 to 9 min of intense hail precipitation, with hailstones diameter ~2-3 cm, rapidly generating a 5-10 cm white deposits over land [6]. At the same time, hail-debris flows were triggered in northern slopes, affecting rural settlements in alluvial fans (Figure 2). A final fourth intense rainfall pulse, accumulating between 7 and 24 mm occurred. However, no debris flows were triggered at this time.

According to grain size analysis in the deposits, clays to medium sand matrix represented 16-20% by weight. Original deposits contained near ~15% of hailstones mostly concentrated on top of the deposits, apparently because of segregation process during flow motion.

3 Methods

3.1 Hydrology

As hail-debris flows occurs during the third rainfall pulse, and because of small catchments, we estimate the flow hydrograph using the synthetic unit hydrograph method, SCS, assuming soil saturated conditions due to the antecedent precipitation pulses. The catchments concentration times were estimated in near 6-7 min, obtaining peak water flows ranging from 1.25 to 3.79 m³/s (Table 1).

3.2 Post-event topography

After the event, a 1.65 km² high resolution topography was obtained covering the four studied catchments. Topography was performed, by the aerophotogrammetry technique using a drone. The drone flight was made at fixed 150 m height from the ground, obtaining a digital elevation model (DEM) with 13.5 cm/pixel resolution. Topographical data was used for configuring channel and alluvial fan geometry in the numerical model, and to compute flooded areas for model calibration.

3.3 Debris flow modelling

We use the two-dimensional FLO-2D model to solve the flood wave progression for water and debris flows in complex topographical terrains [9]. FLO-2D solves two-dimensional depth-averaged continuity and momentum equations, known as Saint-Venant equations, for water and debris flows. Frictional stress \( S_f \) are calculated using the so-called quadratic rheology model, Eq. (1), which combines different terms accounting for yield and coulomb, viscous, and turbulent and dispersive stresses [9].

\[
S_f = \frac{\tau_y}{\gamma_m h} + \frac{K\eta V}{8\gamma_m h^2} + \frac{n_d \tau_s^2 V^2}{h^3}
\]  

(1)

Where, \( \tau_y \) is the yield stress, \( \gamma_m \), the specific weight of the solid–liquid mixture, \( h \) the element (cell) flow depth, \( K \) a resistance parameter for laminar flow, \( \eta \) the dynamic viscosity of the fluid phase, \( V \) the element (cell) flow velocity, and \( n_d \) a pseudo-Manning coefficient corrected by the sediment concentration. O’Brien and Garcia (2009) suggest the following empiric relationships, Eq. (2 -4), for estimating the parameters \( \eta \), \( \tau_s \), and \( n_d \) as functions of sediment volume concentration, \( C_v \) (O’Brien and Garcia, 20).

Fig. 1. Study area. Coloured polygons define each catchments limits.

Fig. 2. A) Hail-debris flows deposits around houses. B) Fresh hail-debris flows mixture near the top of the deposit.
\[ \eta = \alpha_1 e^{\beta_1 C_v} \]  
(2)

\[ \tau_y = \alpha_2 e^{\beta_2 C_v} \]  
(3)

\[ n_{td} = n b e^{m C_v} \]  
(4)

where \( \alpha_{1,2} \) and \( \beta_{1,2} \) are empirical coefficients that must be calibrated, \( n \) is the conventional Manning coefficient, \( b=0.0538 \), and \( m=6.0896 \).

4 Results

FLO2D models were configured for the four catchments using obtained topographical data and water hydrographs. Detrital flow rates were computed assuming 45\% to 47\% of sediment volume concentrations.

As starting point, we used typical rheological parameters obtained by different authors for debris flows mixtures in laboratory tests (see references in [10]), and by calibrating debris flows models using field post-event data [2,11,12]. However, this set of rheological parameters overestimate frictional stress, resulting in lower flow velocities and flooded areas compared to observation.

Thus, rheological model parameters were calibrated against observed flooded areas following Zegers et al. [2] and Garces et al. [12] and validated against flow velocities estimations obtained from videos recorded by inhabitants. Results are shown in Figure 3 and Table 2.

Table 2. Calibrated Rheology and comparison between modelled and observed velocities (video records)

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Viscosity (Pa s)</th>
<th>Yield Stress (Pa)</th>
<th>Max. Velocity (m/s)</th>
<th>Obs. Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR1</td>
<td>4.7</td>
<td>54.8</td>
<td>3.5</td>
<td>3</td>
</tr>
<tr>
<td>CR2</td>
<td>3.0</td>
<td>33.6</td>
<td>5.5</td>
<td>-</td>
</tr>
<tr>
<td>CR3</td>
<td>3.7</td>
<td>42.1</td>
<td>4.6</td>
<td>4</td>
</tr>
<tr>
<td>CR4</td>
<td>4.5</td>
<td>52.4</td>
<td>2.4</td>
<td>2</td>
</tr>
</tbody>
</table>

After calibration, we obtained values for viscosity and yield stress in the order of \(~4\) Pa s and \(~50\) Pa, respectively, and maximum flow velocities in the same order than estimated from video records. Viscosities are in the lower limit compared to the debris flow literature, and probably near one order magnitude below expected values for similar debris mixtures [12]. Calibrated yield stress values are in the range of 30-50 Pa, that is one or two order magnitude lower than reported in the literature.

5 Discuss and Conclusions

During a rainfall event accompanied by 5-10 min intense hailstorm, catastrophic hail-debris flows occurred in the commune of Malloa, central Chile, affecting precarious rural settlement located at alluvial fans. The presence of hails as part of the granular mixture, 2-3 cm diameter and \(~15\)% volume concentration, significantly increases flow mobility by reducing frictional stress. We conclude that hail interacting with sediment-water mixture appears as new friction reduction mechanisms for debris flows.
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