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# Influence of bottom roughness and ambient pressure conditions on the emplacement of experimental dam-break granular flows

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Santiago Montserrat, Lady Ordoñez, Aldo Tamburrino, Olivier Roche. Influence of bottom roughness and ambient pressure conditions on the emplacement of experimental dam-break granular flows. *Granular Matter*, 2021, 23 (3), 10.1007/s10035-021-01125-2 . hal-03254037

**HAL Id: hal-03254037**

**<https://uca.hal.science/hal-03254037v1>**

Submitted on 16 Jun 2021

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1 **Influence of bottom roughness and ambient pressure**  
2 **conditions on the emplacement of experimental**  
3 **dam-break granular flows**

4 **Santiago Montserrat · Lady Ordoñez ·**  
5 **Aldo Tamburrino · Olivier Roche.**

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7 Received: DD Month YEAR / Accepted: DD Month YEAR

8 **Abstract** Geophysical granular flows occur at the surface of the Earth and  
9 other planets with reduced atmospheric pressure. In this paper, we investigate  
10 the run-out of dam-break flows of particle-air mixtures with fine ( $d = 75\mu m$ )  
11 or coarse ( $d = 150\mu m$ ) grains in a flume with different bottom roughness ( $\delta$ )  
12 and vacuum degrees ( $P^*$ ). Our results reveal an increase of the flow run-out  
13 as  $d/\delta$  decreases for fine  $d = 75\mu m$ -particles, and run-out decreases with the  
14 dimensionless ambient pressure ( $P^*$ ) for a given  $d/\delta$ . In contrast, the run-out

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15 for coarser  $d = 150\mu m$ -particles, is almost invariant respect to  $P^*$  and  $d/\delta$ .  
 16 These results show that autofluidization of fine-grained flows demonstrated  
 17 by earlier works at ambient pressure also occurs at reduced pressure though  
 18 being less efficient. Hence, autofluidization is a mechanism, among others, to  
 19 explain long run-out of geophysical flows in different environments.

20 **Keywords** Dam-break · Granular flows · Pore pressure · Ambient pressure ·  
 21 Fluidization · Substrate roughness

## 22 1 Introduction

23 The run-out distance of dense geophysical granular flows is commonly larger  
 24 than expected because the apparent friction angle is significantly reduced with  
 25 respect to the repose angle of same geological materials Legros (2002); Iver-  
 26 son (1997); Delannay et al. (2017). Friction reduction mechanisms have been  
 27 attributed for instance to the formation of a low density bottom layer, caused  
 28 by grains interacting with the bottom Cleary and Campbell (1993); Bartelt  
 29 et al. (2006); Brodu et al. (2015), and/or to particle-fluid interactions caus-  
 30 ing fluidization Iverson (1997); Roche et al. (2008). However, long run-outs  
 31 have been observed for flows at the surface of the Earth and celestial bodies  
 32 with different gravity, substrate roughness and atmospheric conditions, the lat-  
 33 ter including the ambient atmospheric pressure, density and viscosity Legros  
 34 (2002); Lajeunesse et al. (2006); Lucas and Mangeney (2007); Singer et al.  
 35 (2012); Lucas et al. (2014). However, based on the analysis of Martian flows  
 36 deposits, Lucas et al. Lucas and Mangeney (2007) show that flow run-out is  
 37 independent of gravity.

38 It is argued that friction reduction can arise because moving grains inter-  
 39 act with the substrate, increasing random grain-velocity fluctuations at the  
 40 base of the granular flow. Thus, the bulk dense flow slides over a highly ag-  
 41 itated and low concentrated basal layer reducing the apparent basal friction  
 42 Campbell (1989); Cleary and Campbell (1993); Iverson (1997); Bartelt et al.  
 43 (2006); Brodu et al. (2015). Recent numerical experiments shows that the  
 44 basal agitated layer can reach a height of some particles diameters and has  
 45 a volume concentration as low as 0.2 Brodu et al. (2015). However, friction  
 46 reduction through this mechanism seems to occurs only for high speed flows on  
 47 relatively steep substrates and bounded by lateral walls on which significant  
 48 friction occurs.

49 Goujon et al. Goujon et al. (2003) showed experimentally that for flows of  
 50 relatively large particles of size  $d > 150\mu m$  and propagating on an inclined  
 51 rough plane, the main parameter controlling flow friction was the ratio be-  
 52 tween the size of the flowing particles ( $d$ ) and the size of roughness ( $\delta$ ). They  
 53 found that flow friction was maximum at  $d/\delta \sim 0.5$ . They also argued that the  
 54 increase in the flow run-out for  $d/\delta < \sim 0.5$  was probably because the particles  
 55 filled the substrate interstices, thus reducing the effective roughness. However,  
 56 changes in flow run-out with  $d/\delta$  was almost negligible for slope angles lower

57 than  $\sim 18^\circ$ . The negligible dependence of the flow run-out with  $d/\delta$  on hori-  
58 zontal planes was confirmed by experiments of Lube et al. (2004)  
59 for  $d > 300\mu m$  and maximum values of  $d/\delta \sim 1$ .

60 The presence of an interstitial fluid can be a key factor for friction reduction  
61 in granular flows, especially those containing high amounts of fine particles  
62 ( $\sim 100\mu m$ ) that confer low hydraulic permeabilities Iverson (1997); Iverson  
63 and Denlinger (2001); Roche et al. (2010); Montserrat et al. (2012, 2016);  
64 Chédeville and Roche (2018); Breard et al. (2018). Excess pore fluid pressure,  
65 naturally arising from upwards fluid fluxes and/or particle settling, reduces  
66 interparticle friction by locally decreasing contact forces Iverson (1997); Iver-  
67 son and Denlinger (2001); McArdell et al. (2007); Montserrat et al. (2012).  
68 Excess pore fluid pressure, high above hydrostatic levels, was measured both  
69 in laboratory experiments and in natural flows in the field Iverson (1997); Iver-  
70 son et al. (2010); Roche et al. (2010); McArdell et al. (2007). Chédeville and  
71 Roche Chedeville and Roche (2014); Chédeville and Roche (2015) found that  
72 flows of fine particles on a rough substrate experienced autofluidization. This  
73 occurred as the flow particles settled into the interstices of the substrate and  
74 forced the air to escape upwards and to percolate through the flow. Autoflu-  
75 idization thus increased the flow run-out compared to a smooth substrate, and  
76 this effect was enhanced as the substrate roughness increased because more air  
77 was available for autofluidization. On the same principle, autofluidization occurs  
78 also in collapsing beds of fine particles released from some height above a solid  
79 surface, as demonstrated by numerical simulations Breard et al. (2018) and  
80 laboratory experiments Chédeville and Roche (2018). Fine-grained mixtures  
81 can also be fluidized through mechanical vibrations that cause fluid-particle  
82 relative oscillations and related high pore fluid pressure, a phenomenon called  
83 acoustic streaming Valverde and Soria-Hoyo (2015); Soria-Hoyo et al. (2019).

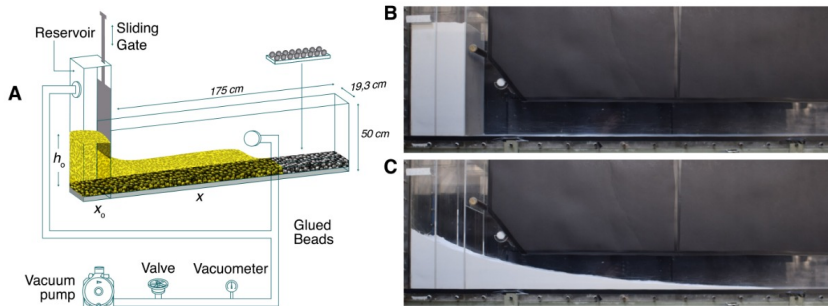
84 Fluidization of granular flows rich in fine particles, however, is uncertain in  
85 case the atmospheric pressure is significantly lower than on Earth, as it is the  
86 case on Mars for instance ( $4 \times 10^{-3}$  to  $9 \times 10^{-3}$  bar). Therefore, we experimen-  
87 tally explore the effect of the ambient air pressure and substrate roughness on  
88 the run-out of granular flows. We perform dam-break type experiments involv-  
89 ing different particle sizes, substrate roughness, and degrees of vacuum. To this  
90 end, we constructed a sealed channel that allowed us to make experiments up  
91 to  $\sim 99\%$  of vacuum relative to the ambient atmosphere. To our knowledge,  
92 this is the first investigation conducted under vacuum conditions and using  
93 fine particles. Previous granular flow experiments under high vacuum condi-  
94 tions were performed with coarser particles and showed no significant effects  
95 of the vacuum degree on flow emplacement Börzsönyi and Ecke (2006). Our  
96 results highlight the importance of the ambient fluid and bottom roughness  
97 in increasing flow-run out of fine particles ( $d \sim 75\mu m$ ) even at low vacuum  
98 degrees, while for coarser particles ( $d \geq 150\mu m$ ) both effects are negligible.

## 99 2 Materials and Methods

100 We conducted dam-break experiments in a sealed lock-exchange channel 180  
 101 cm-long, 19.3 cm-wide and 50 cm-high (Figure 1). A sluice gate separates the  
 102 channel from the reservoir at the upper end, where the particles are retained.  
 103 This section is 100 cm high, so that the gate can be opened inside the device.  
 104 The reservoir has a length  $x_o = 20\text{cm}$ . We generate granular flows by a rapid  
 105 vertical release of the sluice gate ( $< 0.1\text{s}$ ). The experimental device is made  
 106 of a 30 mm-thick transparent plexiglass to permit flow visualization and to  
 107 resist high degrees of vacuum. It is also equipped with a vacuum pump to  
 108 reduce ambient air pressure, and the degree of vacuum is measured using a  
 109 *EdwardsAPG100 – XM* vacuummeter. The maximum degree of vacuum that  
 110 can be reached in the channel system is of the order of  $\sim 1\%$  of the atmo-  
 111 spheric pressure. For the range of ambient pressures we use (1% to 100% of  
 112 the atmospheric pressure), air viscosity remains constant Börzsönyi and Ecke  
 113 (2006); Bello (2017).

114 The bottom of the channel is covered by a 10 mm-thick aluminum sheet  
 115 over which the granular flow propagates. Different roughnesses were obtained  
 116 by gluing a single layer of particles of diameter  $\delta$  to the aluminum base. We  
 117 tested three different bottom roughness conditions: i) aluminum roughness,  
 118 ii)  $\delta = 1\text{mm}$  roughness and iii)  $\delta = 3\text{mm}$  roughness. Onward, the smooth  
 119 aluminum roughness condition will be denoted as  $\delta = 0$ .

120 We used two different types of near spherical glass beads (Ballotini, Potters  
 121 Industries) with characteristic diameters  $d_1 \sim 75\mu\text{m}$  ( $\sim 40\mu\text{m}$  to  $\sim 140\mu\text{m}$ )  
 122 and  $d_2 \sim 150\mu\text{m}$  ( $\sim 70\mu\text{m}$  to  $\sim 300\mu\text{m}$ ), repose angles  $\theta_1 = 27.1^\circ \pm 0.4^\circ$   
 123 and  $\theta_2 = 27.7^\circ \pm 0.3^\circ$ , and both with a particle density of  $\rho_p = 2500\text{kg/m}^3$ .  
 124 Particles were carefully poured inside the reservoir in order to achieve near  
 125 constant mixture densities,  $\rho_1 = 1360 \pm 15\text{kg/m}^3$  for  $d \sim 75\mu\text{m}$ -particles and  
 126  $\rho_2 = 1412 \pm 6\text{kg/m}^3$  for  $d \sim 150\mu\text{m}$ -particles, resulting in initial particle



**Fig. 1** A) Sketch of the experimental device.  $h_o$  and  $x_o$  denotes the initial height and length of the column of particles inside the reservoir, respectively, while  $x$  is the flow-front position measured from the gate, B) Side view of the experimental channel before removing the gate. Particles (in white) are in the reservoir. C) Side view of the final deposit

127 volume concentrations  $c_{v1} = 0.54 \pm 0.01$  and  $c_{v2} = 0.56 \pm 0.01$  (i.e. particle-  
 128 mixture porosity  $\phi_1 = 0.46 \pm 0.01$  and  $\phi_2 = 0.44 \pm 0.01$ ). Particles bed heights  
 129 in the reservoir where varied from  $h_o \sim 20cm$  to  $h_o \sim 40cm$  (in terms of mass,  
 130 from  $\sim 10.5kg$  to  $\sim 22.5kg$ ).

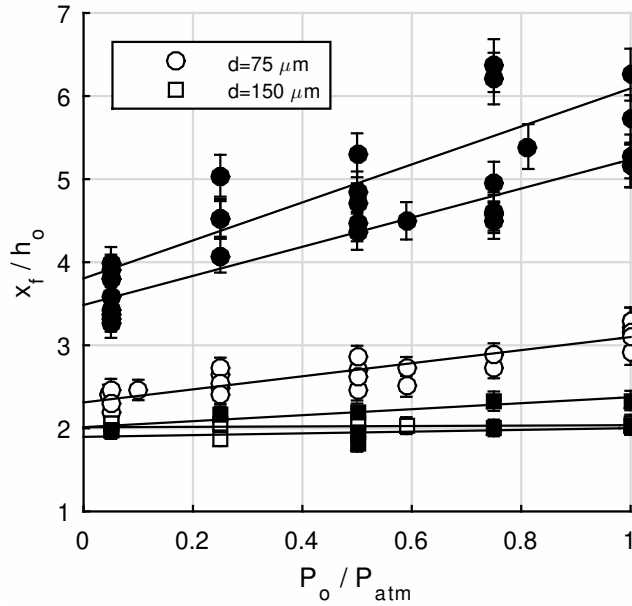
131 In our experiments, and due to the relatively narrow grain size range of  
 132 the materials, we did not expect significant particle size segregation in the  
 133 reservoir, flow or deposit. Thus, segregation was neglected in our analysis. In  
 134 addition, the channel width to particle size ratio was of the order of  $\sim 2550$   
 135 and  $\sim 1280$  for fine and coarse particles respectively, so that negligible sidewall  
 136 effects were expected. However, side wall effects seem to be responsible in  
 137 reducing flow run out in case of initial high column aspect ratios ( $h_o/x_o > 1.5$ )  
 138 respect to low column aspect ratios Roche et al. (2011); Montserrat et al.  
 139 (2016). Nevertheless, these differences are less than the observed experimental  
 140 variability and we assumed that sidewall effects had a negligible influence on  
 141 our flows.

### 142 3 Results

#### 143 3.1 Flow run-out distance

144 The run-out distance of flows of particles of size  $d = 75\mu m$  shows an important  
 145 increase with both ambient pressure and substrate roughness. Figure 2 shows  
 146 that, for these particles, the dimensionless flow run-out ( $x_f^* = x_f/h_0$ ) increases  
 147 fairly linearly with the dimensionless ambient pressure  $P^* = P_o/P_{atm}$  (where  
 148  $P_o$  denotes for the ambient pressure inside the channel and  $P_{atm}$  is the at-  
 149 mospheric pressure in the laboratory). The dimensionless flow run-out under  
 150 vacuum conditions (i.e.  $P^* = 0$ ), inferred from the best linear fits shown in  
 151 Figure 2, increases from  $x_f^* = 2.3$  to  $x_f^* = 3.5$ , and  $x_f^* = 3.8$  for smooth, 1 mm  
 152 and 3 mm-substrate roughnesses, respectively. This corresponds to a flow run-  
 153 out increase of 52 % and 65 %, for 1 mm and 3 mm roughnesses, respectively,  
 154 compared to the smooth case in the absence of an interstitial fluid. In addi-  
 155 tion, the substrate roughness increases the growth rate of the dimensionless  
 156 flow run-out with the ambient pressure. While the slope of the fitted straight  
 157 lines for the case of the smooth surface is 0.79, it increases to 1.75 and 2.29  
 158 for 1 mm and 3 mm-substrate roughnesses, respectively. This results in values  
 159 of  $x_f^* = 3.1$ ,  $x_f^* = 5.2$  and  $x_f^* = 6.1$  for smooth, 1 mm and 3mm-substrate  
 160 roughnesses, respectively, at laboratory ambient conditions ( $P^* = 1$ ). This  
 161 corresponds to an increase of the flow run-out of 68% and 97% for 1 mm and  
 162 3 mm-roughnesses, respectively, compared to the smooth case.

163 The flow run-out distance for particles of size  $d = 150\mu m$  shows to be  
 164 independent of both the ambient pressure and surface roughness (Figure 2),  
 165 except for the case of  $\delta = 3mm$ , where a slight increasing tendency of the  
 166 flow run-out is observed with  $P^*$ . The dimensionless run-out for  $d = 150\mu m$   
 167 particles is always significantly lower than that of flows of  $d = 75\mu m$  particles  
 168 for the same range of ambient pressure and channel roughness. Note that at



**Fig. 2** Dimensionless flow run-out,  $x_f/h_o$ , as a function of the dimensionless ambient pressure  $P_o/P_{atm}$  (with  $P_o$  the ambient pressure inside the channel and  $P_{atm}$  the atmospheric pressure in the laboratory). White, gray and dark symbols represent smooth, 1 mm and 3 mm bottom roughness respectively. Note that symbols may be larger than error bars.

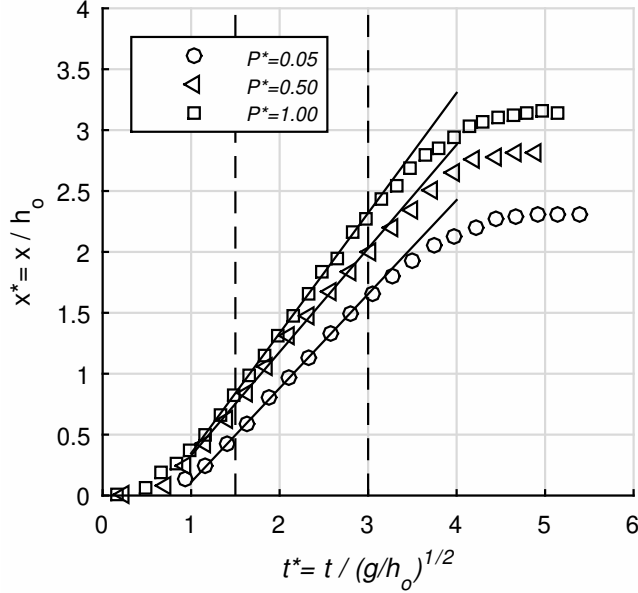
169 vacuum conditions, the dimensionless flow run-out for  $d = 75\mu m$  ( $x_f^* = 2.3$ )  
 170 on a smooth substrate is slightly higher ( $\sim 15\%$ ) than that for  $d = 150\mu m$   
 171 ( $x_f^* = 2$ ).

### 172 3.2 Flow-front dynamics and flow morphology of fine particle mixtures

173 In this section, we examine fine particles mixtures as no significant changes in  
 174 the flow front dynamics and flow morphology are observed for coarser particles  
 175 ( $d \sim 150\mu m$ ), neither with  $P^*$  nor  $\delta$ . In addition, and to simplify the analysis,  
 176 we only compare the obtained results between the two roughness extremes  
 177 used in the experiments (i.e.  $\delta = 0$  and  $\delta = 3mm$ ).

178 Figure 3 shows the dimensionless flow front position,  $x^* = x/h_o$ , for  
 179  $d = 75\mu m$ -particles, as a function of the dimensionless time,  $t^* = t/(h_o/g)^{1/2}$   
 180 Roche et al. (2008), where  $x$  denotes the horizontal flow front position mea-  
 181 sured from the gate,  $t$  is time, and  $g$  is the gravitational acceleration, for dif-  
 182 ferent vacuum conditions and for a smooth substrate ( $\delta = 0$ ). The flow front  
 183 propagates in three different phases, as known for flows under atmospheric  
 184 pressure conditions Lajeunesse et al. (2005); Roche et al. (2008); Xu et al.  
 185 (2016); Lube et al. (2005). Under atmospheric conditions ( $P^* = 1$ ), Figure  
 186 3 shows a first phase for which the flow front accelerates (first phase) until  
 187 it reaches a constant front velocity  $U$  equal to  $\alpha(gh_o)^{1/2}$ , where  $\alpha$  is a pro-

188 proportionality constant close to  $\sim 1$  Roche et al. (2008). The constant velocity  
 189 phase occurs for  $\sim 1.5 < t^* < \sim 3.0$ . A second transition occurs at  $t^* \sim 3.0$ ,  
 190 where the flow starts decelerating until it comes to halt at  $t^* \sim 5 - 5.5$ .



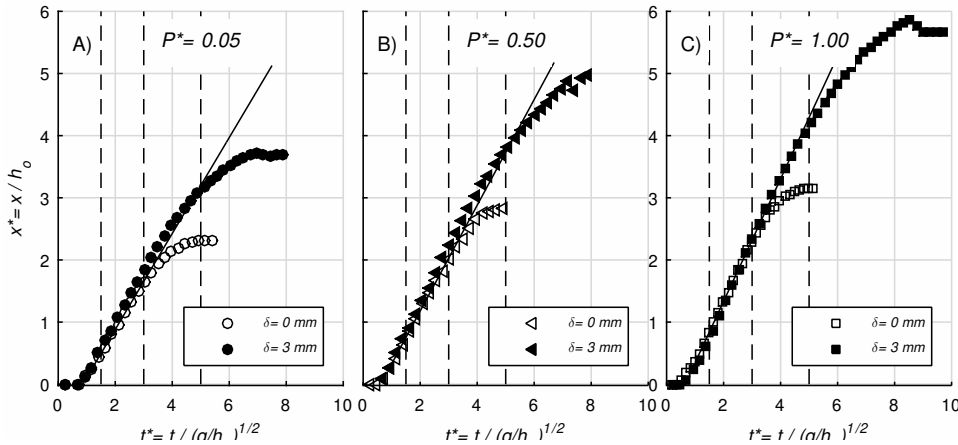
**Fig. 3** Dimensionless flow front position  $x^*$  for different values of  $P^*$  and  $\delta = 0$

191 The same trend is observed at reduced atmospheric conditions (Figure 3),  
 192 with the transitions between phases occurring at the same values of  $t^*$  than  
 193 for laboratory ambient pressure (i.e.  $P^* = 1$ ). The main effect of the ambient  
 194 pressure is a velocity decrease in the constant-velocity phase, with  $\alpha$  decreasing  
 195 from  $\alpha = 0.99$  at laboratory atmospheric conditions to  $\alpha = 0.85$  and  $\alpha = 0.77$   
 196 at  $P^* = 0.50$  and  $P^* = 0.05$ , respectively.

197 Figure 4 shows that the front position for fine particles flows ( $d = 75\mu m$ )  
 198 at  $\delta = 0$  and  $\delta = 3mm$  and different vacuum degrees are almost identical  
 199 until  $t^* \sim 3.0$ . However, for rough substrates ( $\delta = 3mm$ ), the constant veloc-  
 200 ity phase lasts longer. For example, for  $\delta = 3mm$ , the transition between the  
 201 second and third phase occurs at  $t^* \sim 5$ . In addition, increasing roughness sig-  
 202 nificantly reduces the front deceleration, thus increasing the flow run-out and  
 203 duration Chedeville and Roche (2014); Chédeville and Roche (2015). While  
 204 flows on a smooth substrate stop at  $t^* \sim 5 - 5.5$ , almost independently of  $P^*$ ,  
 205 at  $\delta = 3mm$  flow duration last up to  $t^* \sim 7$ ,  $t^* \sim 8$  and  $t^* \sim 9$  for  $P^* = 0.05$ ,  
 206  $P^* = 0.50$  and  $P^* = 1.00$ , respectively.

207 These kinematics can be complemented considering the flow morphology,  
 208 which varies very little with the channel roughness until the end of the constant  
 209 velocity phase for smooth surfaces ( $t^* \sim 3$ ), regardless of  $P^*$  (Figure 5). For  
 210  $t^* > 3$ , the flow length increases with the substrate roughness and this is



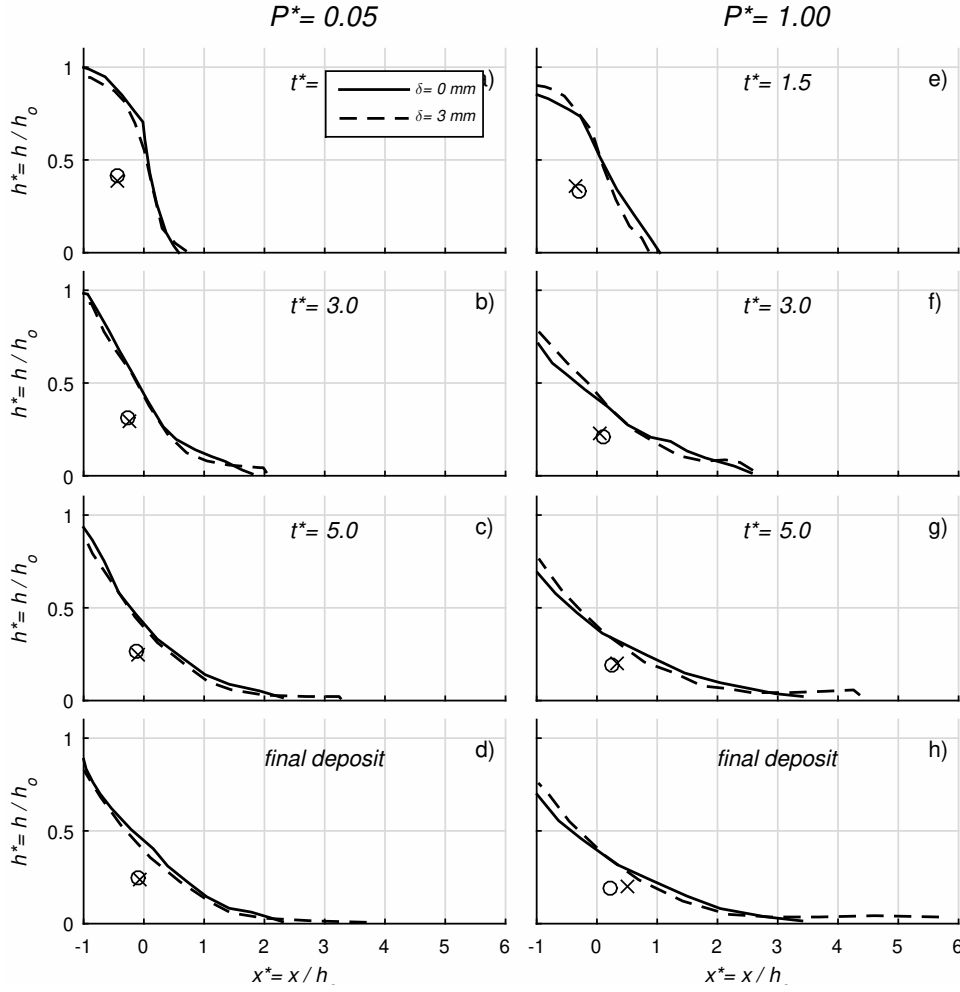


**Fig. 4** Dimensionless flow front position,  $x^*$ , for different values of  $P^*$  and  $\delta$ , for fine  $75\mu\text{m}$  particles

211 mainly because a thin flow head arises from the flow body, even after the latter  
 212 has stopped Chedeville and Roche (2014). Slight differences in the position of  
 213 the center of area (equivalent to the center of mass in 3D) of the flow for  
 214 smooth and 3 mm rough surfaces confirm that the increasing flow length with  
 215 roughness is due to the very thin frontal part of the flow that propagates  
 216 downstream and causes long run-out.

#### 217 4 Discussion

218 Sustained high pore fluid pressure has been pointed out as one of the primary  
 219 friction reduction mechanisms in experimental flows of initially fluidized fine  
 220 ( $< \sim 100\mu\text{m}$ ) granular materials propagating on smooth or rough surfaces at  
 221 earth atmospheric conditions Roche et al. (2008, 2010); Montserrat et al. (2012,  
 222 2016); Chedeville and Roche (2014); Chédeville and Roche (2015); Breard et al.  
 223 (2018); Chédeville and Roche (2018). Notice that initially non-fluidized flows  
 224 with shorter run-out distances have the ability to self-generate excess pore  
 225 fluid pressure to near  $\sim 15\%$  of the weight of the particle, possibly because of  
 226 granular mixture compaction Roche et al. (2010) or by air incorporation at the  
 227 flow front Bareschino et al. (2008). However, this last mechanism has shown  
 228 to be negligible in experimental flows Chédeville and Roche (2015). Recent  
 229 dam-break experiments show that the mixture porosity is correlated with flow  
 230 velocity as it decreases during flow acceleration (i.e. mixture dilation) and  
 231 increases during flow deceleration (i.e. mixture compaction) Xu et al. (2016).  
 232 In case of granular compaction, pore pressure rises by the compression of air  
 233 trapped in the interstices if the time scale for particles rearrangement ( $T_R$ ) is  
 234 small compared with the time scale for vertical pore pressure diffusion ( $T_D$ )  
 235 Homan et al. (2014). The opposite occurred in case of mixture dilation (i.e.  
 236 pore pressure drops when the mixture and pores dilate). For a given change in



**Fig. 5** Flow morphology for different  $\delta$  and  $P^*$ .  $\circ$  and  $\times$  denotes for the center of area of the flowing mixture for  $\delta = 0$  and  $\delta = 3\text{mm}$ , respectively.

237 air volume ( $\Delta V_a$ ), and assuming isothermal air compression, the upper limit  
 238 for pore pressure variations ( $\Delta P$ ) respect to the ambient pressure ( $P_o$ ) can be  
 239 approximated as Homan et al. (2014):

$$\Delta P = -P_o \frac{\Delta V_a}{V_a} \quad (1)$$

240 where  $V_a$  is the volume of air in the interstices and  $\Delta V_a$  is defined positive for  
 241 air dilation and negative for air compression. In equation (1), non linear terms  
 242 have been neglected Homan et al. (2014).

243 As  $P_o = P^* P_{atm}$ , equation (1) shows that for similar changes in the air  
 244 volume between grains,  $|\Delta P|$  linearly decreases with the degree of vacuum

( $\Delta P \sim P^*$ ). Thus, autofluidization is possible even under reduced atmospheric conditions, and decreasing the ambient pressure will linearly decrease the amount of pore pressure changes. This can explain the observed linear trends between the flow run-out and the degree of vacuum ( $x_f/h_o \sim P^*$ , see Figure 2), at least for the case  $\delta = 0$  and  $d = 75\mu m$ -particles. In this sense, reducing  $P_o$  increases the effective flow friction, which also agrees with the observed reductions in flow duration and flow-front velocities during the constant velocity phase.

For flows over rough substrates ( $\delta = 1\text{ mm}$  and  $\delta = 3\text{ mm}$ ), fluidization can arise because of particles falling into the substrate interstices and forcing the air to percolate upwards through the granular flow Chedeville and Roche (2014); Chédeville and Roche (2015). The amount of pore fluid pressure due to drag interactions ( $\Delta p$ ) increases with air velocity and can be accounted in packed beds by the semi-empirical Ergun equation Gibilaro (2001), here expressed in terms of the degree of fluidization ( $\Delta p^* = \Delta p/P_L$ ) of a granular column of height  $h$  and bulk density  $\rho$ :

$$\Delta p^* = \frac{\Delta p}{P_L} = 150 \frac{\mu_g U_g}{\rho g d^2} \frac{(1 - \phi)^2}{\phi^3} + 1.75 \frac{\rho_g U_g^2}{\rho g d} \frac{1 - \phi}{\phi^3} \quad (2)$$

where  $\mu_g$  is the gas dynamic viscosity,  $U_g$  is the superficial gas velocity (defined as the flow rate per unit cross sectional area),  $\rho_g$  is the gas density and  $\phi$  is the particle-mixture porosity (defined previously). We assumed that changes of porosity was negligible during flow emplacement, making the Ergun equation relevant for describing fluidization. The first and second terms at the right-hand of equation 2 accounts for viscous and inertial fluidization, respectively.

$\Delta p^* = 1$  means that the entire weight of the particle bed is supported by air drag, which occurs at a minimum value of  $U_g$  called the minimum fluidization velocity,  $U_{mf}$ . Solving equation 2 for  $\Delta p^* = 1$  results in  $U_{mf} = 11\text{ mm/s}$  and  $U_{mf} = 32\text{ mm/s}$  for  $d = 75\mu m$  and  $d = 150\mu m$ -particles, respectively. These values scale with previous experimental measurements done on similar materials Roche et al. (2004). Chédeville and Roche Chedeville and Roche (2014) estimate that particles falling into the interstices generate upward air fluxes above  $U_{mf}$ -values due to the high settling velocities of the particles. For the estimated values of  $U_{mf}$ , the first term on the right hand side of equation 2 is  $\sim 1$ , while the second term is  $\sim 10^{-3}$ , meaning that fluidization is mainly due to viscous drag. Thus, for the range of  $P$ -values used for this experiments, for which  $\mu$  is constant, autofluidization related to a rough substrate is always possible, even at high vacuum conditions. This explains the increasing run-out of  $d = 75\mu m$ -particles mixtures compared to a smooth substrate even at very low ambient pressure conditions ( $P^* \sim 0.05$ ).  $U_{mf}$  for  $d = 150\mu m$ -particles is larger than for  $d = 75\mu m$ -particles. As both types of particles fall into the interstices as about the same velocity, then the interstitial air velocity should be in the same order in both cases. However, this result in smaller  $\Delta p^*$  for  $d = 150\mu m$ -particle mixtures, explaining the almost null effect of  $P^*$  in the run-out of these flows. The slight increase of  $x_f^*$  with  $P^*$  observed for  $\delta = 3\text{ mm}$ , suggests that higher volumes of air trapped into the interstices

288 are able to sustain vertical air fluxes for longer periods, promoting a weak  
 289 fluidization compared with  $d = 75\mu\text{m}$ -particles flows.

290 An alternative (or complementary) friction reduction mechanism, consist-  
 291 ing in the development of a low density layer at the flow bottom because  
 292 of flow particles colliding with those of the bottom roughness, may also be  
 293 considered. In this context, the flow run-out is expected to be a function of  
 294  $d/\delta$  Goujon et al. (2003). In the case of a smooth surface (aluminum sub-  
 295 strate) we assume  $d/\delta = 1$ , as it has been observed that the flow rides over a  
 296 thin layer of the same particles deposited after the passage of the flow-front  
 297 Lube et al. (2004). Thus, for  $d = 75\mu\text{m}$ -particles  $d/\delta = 1 - 0.025$ , while for  
 298  $d = 150\mu\text{m}$ -particles  $d/\delta = 1 - 0.05$ . Although  $d/\delta$  varies in a similar range  
 299 for both types of particles, the flow run-out with  $d/\delta$  for  $d = 150\mu\text{m}$ -particles  
 300 does not vary significantly. This suggests that viscous fluidization controls the  
 301 flow mechanism of fine granular mixtures and confirms that, in the absence of  
 302 autofluidization,  $d/\delta$  does not control the flow run-out in horizontal channels.

## 303 5 Conclusions

304 Our results confirm that viscous air-particle interactions are an important fric-  
 305 tion reduction mechanism for fine-grained granular flows. In our experiments,  
 306 the relative increase of flow run-out with the substrate roughness is reduced as  
 307 the ambient pressure decreases, but such increase is still significant (65%, from  
 308  $\delta = 0$  to 3 mm) even at  $P^* = 0.05$  (Figure 2). This suggests that the autoflu-  
 309 idization mechanism acting in flows of fine particles on rough substrate and  
 310 at atmospheric pressure Chedeville and Roche (2014); Chédeville and Roche  
 311 (2015) operates as well at lower pressures. This can be explained because vis-  
 312 cosity remains constant for the range of vacuum conditions explored in this  
 313 study and because, for particles of this size range, fluidization is dominated  
 314 by fluid viscosity Bello (2017); Roche et al. (2008).

315 The above-mentioned friction reduction mechanisms does not act for coarser  
 316 particle materials ( $d \sim 150\mu\text{m}$ ). This can be explained as the air initially  
 317 present in the substrate interstices is expelled upwards at lower velocities  
 318 compared with the minimum fluidization velocity ( $U_{mf}$ ) of the coarse par-  
 319 ticles (see Chédeville and Roche Chedeville and Roche (2014) for experiments  
 320 at  $P^* = 1$ ) or because the amount of air trapped in the interstices is not  
 321 enough to fluidize the particle mixture over a significant duration. An excep-  
 322 tion occurs for  $\delta = 3\text{mm}$ , where a slight influence of  $P^*$  in the flow run-out is  
 323 observed. In addition, for coarser  $d \sim 150\mu\text{m}$ -particles, the increasing rough-  
 324 ness does not have significant effects on the flow run-out, even for a similar  
 325 range of  $d/\delta$  compared with  $d = 75\mu\text{m}$ -particles flows. Thus, in the absence of  
 326 fluidization capacity of the flowing mixture, increasing roughness shows not to  
 327 be an important friction reduction mechanism in granular flows. However, this  
 328 mechanism could become important for high-velocity flows on steep substrates  
 329 Brodu et al. (2015).

330 Regarding the motion of the flow front of fine-grained mixtures, decreasing  
331 the ambient pressure mainly results in a decrease in velocity and duration of  
332 the constant velocity phase. This is a consequence of the reduction of the aut-  
333 offluidization capacity, proportional to  $|\Delta P|$ , which causes increasing friction.  
334 Increasing  $\delta$  increases the flow run-out by increasing the time of the constant  
335 velocity phase and the stopping phase. This is because, for larger  $\delta$ , the air is  
336 expelled from the substrate for longer duration as more air is trapped initially  
337 in their interstices. However, the increase in flow run-out is due to a thin flow-  
338 ing frontal layer that spreads from the flow body at  $t^* \sim 3$ , which represents a  
339 little amount of the total mass. Thus, the run-out of the bulk flow, represented  
340 by the run-out of the center of area of the avalanche (see Figure 5), is almost  
341 independent of  $d/\delta$ .

342 Our findings have implications for granular mass flows on extraterrestrial  
343 planets with reduced atmospheric pressure. They suggest that fluidization  
344 caused by viscous drag may occur through vertical gas fluxes within the gran-  
345 ular flow, even at low ambient pressure. This is likely to occur when flows  
346 propagating on rough substrates contain high amounts of fine particles that  
347 settle into the substrate interstices. However, fluidization may also arise from  
348 air compression (i.e. increasing pore pressure) during fast contraction of the  
349 particle network. This second mechanism decreases when reducing the atmo-  
350 spheric pressure, thus increasing flow friction and reducing the flow run-out.  
351 This is likely to be important for fine particle flows, where the time for particle  
352 rearrangements is small compared with the time for pore pressure diffusion

353 **Acknowledgements** This work was supported by the Advanced Mining Technology Cen-  
354 ter (AMTC) and Departamento de Ingeniería Civil, from Universidad de Chile, the French  
355 National Research Institute for Sustainable Development (IRD, France) and the Chilean Na-  
356 tional Commission for Scientific and Technological Research, CONICYT, through Fondecyt  
357 Projects 1130910 and 11130254 and PIA Project AFB180004. We thank P. Mendoza and  
358 two anonymous reviewers for helpful comments on our work. We also thank C. González  
359 for his assistance with graphics. This is Laboratory of Excellence ClerVolc contribution No  
360 XXX.

361 **Compliance with Ethical Standards** The authors declare that they  
362 have no conflicts of interest. The study was supported by the Advanced Min-  
363 ing Technology Center (AMTC) from Universidad de Chile, and the Chilean  
364 National Commission for Scientific and Technological Research, CONICYT,  
365 through Fondecyt Projects 1130254.

## 366 References

- 367 Bareschino P, Lirer L, Marzocchella A, Petrosino P, Salatino P (2008)  
368 Self-fluidization of subaerial rapid granular flows. *Powder Technology*  
369 182(3):323–333, DOI 10.1016/j.powtec.2007.12.010
- 370 Bartelt P, Buser O, Platzer K (2006) Fluctuation dissipation relations for  
371 granular snow avalanches. *Journal of Glaciology* 52(179):631–643, DOI  
372 10.3189/172756506781828476

- 373 Bello I (2017) Vacuum and Ultravacuum. CRC Press, DOI  
374 10.1201/9781315155364
- 375 Börzsönyi T, Ecke RE (2006) Rapid granular flows on a rough incline: Phase di-  
376 agram, gas transition, and effects of air drag. *Physical Review E* 74(6):61,301
- 377 Breard ECP, Dufek J, Lube G (2018) Enhanced Mobility in Con-  
378 centrated Pyroclastic Density Currents: An Examination of a Self-  
379 Fluidization Mechanism. *Geophysical Research Letters* 45(2):654–664, DOI  
380 10.1002/2017GL075759
- 381 Brodu N, Delannay R, Valance A, Richard P (2015) New patterns in  
382 high-speed granular flows. *Journal of Fluid Mechanics* 769:218–228, DOI  
383 10.1017/jfm.2015.109
- 384 Campbell CS (1989) Self-lubrication for long runout landslides. *The Journal*  
385 *of Geology* pp 653–665
- 386 Chédeville C, Roche O (2014) Autofluidization of pyroclastic flows prop-  
387 agating on rough substrates as shown by laboratory experiments. *Journal*  
388 *of Geophysical Research: Solid Earth* 119(3):1764–1776, DOI  
389 10.1002/2013JB010554
- 390 Chédeville C, Roche O (2015) Influence of slope angle on pore pressure gen-  
391 eration and kinematics of pyroclastic flows: insights from laboratory exper-  
392 iments. *Bulletin of Volcanology* 77(11):96, DOI 10.1007/s00445-015-0981-4
- 393 Chédeville C, Roche O (2018) Autofluidization of collapsing bed of  
394 fine particles: Implications for the emplacement of pyroclastic flows.  
395 *Journal of Volcanology and Geothermal Research* 368:91–99, DOI  
396 10.1016/j.jvolgeores.2018.11.007
- 397 Cleary PW, Campbell CS (1993) Self-lubrication for Long Runout Landslides:  
398 Examination by computer simulation. *Journal of Geophysical Research:*  
399 *Solid Earth* 98(B12):21,911–21,924, DOI 10.1029/93JB02380
- 400 Delannay R, Valance A, Mangeney A, Roche O, Richard P (2017) Granular  
401 and particle-laden flows: from laboratory experiments to field observations.  
402 *Journal of Physics D: Applied Physics* 50(5):053,001, DOI 10.1088/1361-  
403 6463/50/5/053001
- 404 Gibilaro LG (2001) *Fluidization dynamics*. Elsevier
- 405 Goujon C, Thomas N, Dalloz-Dubrujeaud B (2003) Monodisperse dry granular  
406 flows on inclined planes: Role of roughness. *The European Physical Journal*  
407 *E* 11(2):147–157, DOI 10.1140/epje/i2003-10012-0
- 408 Homan T, Gjaltema C, van der Meer D (2014) Collapsing granular beds:  
409 The role of interstitial air. *Physical Review E* 89(5):052,204, DOI  
410 10.1103/PhysRevE.89.052204
- 411 Iverson RM (1997) The Physics of Debris. *Review of Geophysics* 35(97):245–  
412 296, DOI 10.1029/97RG00426
- 413 Iverson RM, Denlinger RP (2001) Flow of variably fluidized granular  
414 masses across three-dimensional terrain: 1. Coulomb mixture theory.  
415 *Journal of Geophysical Research: Solid Earth* 106(B1):537–552, DOI  
416 10.1029/2000JB900329
- 417 Iverson RM, Logan M, LaHusen RG, Berti M (2010) The perfect debris flow?  
418 Aggregated results from 28 large-scale experiments. *Journal of Geophysical*

- 419 Research: Earth Surface 115(F3):n/a—n/a, DOI 10.1029/2009JF001514
- 420 Lajeunesse E, Monnier JB, Homsy GM (2005) Granular slumping on a hori-  
421 zontal surface. *Physics of fluids* 17:103,302, DOI doi.org/10.1063/1.2087687
- 422 Lajeunesse E, Quantin C, Allemand P, Delacourt C (2006) New insights on the  
423 runout of large landslides in the Valles-Marineris canyons, Mars. *Geophysical*  
424 *Research Letters* 33(4), DOI 10.1029/2005GL025168
- 425 Legros F (2002) The mobility of long-runout landslides. *Engineering Geology*  
426 63(3):301–331, DOI 10.1016/S0013-7952(01)00090-4
- 427 Lube G, Huppert HE, Sparks RSJ, Hallworth MA (2004) Axisymmetric col-  
428 lapses of granular columns. *Journal of Fluid Mechanics* 508(1):175–199, DOI  
429 10.1017/S0022112004009036
- 430 Lube G, Huppert HE, Sparks RSJ, Freundt A (2005) Collapses of two-  
431 dimensional granular columns. *Physical Review E* 72(4):041,301, DOI  
432 10.1103/PhysRevE.72.041301
- 433 Lucas A, Mangeney A (2007) Mobility and topographic effects for large Valles  
434 Marineris landslides on Mars. *Geophysical research letters* 34(10):L10,201,  
435 DOI 10.1029/2007GL029835
- 436 Lucas A, Mangeney A, Ampuero JP (2014) Frictional velocity-weakening in  
437 landslides on Earth and on other planetary bodies. *Nature communications*  
438 5, DOI 10.1038/ncomms4417
- 439 McArdell BW, Bartelt P, Kowalski J (2007) Field observations of basal forces  
440 and fluid pore pressure in a debris flow. *Geophysical Research Letters* 34(7),  
441 DOI 10.1029/2006GL029183
- 442 Montserrat S, Tamburrino A, Roche O, Niño Y (2012) Pore fluid pressure  
443 diffusion in defluidizing granular columns. *Journal of Geophysical Research*  
444 117(F2):F02,034, DOI 10.1029/2009JB007133
- 445 Montserrat S, Tamburrino A, Roche O, Niño Y, Ihle CF (2016) Enhanced run-  
446 out of dam-break granular flows caused by initial fluidization and initial  
447 material expansion. *Granular Matter* 18(1):1–9, DOI 10.1007/s10035-016-  
448 0604-6
- 449 Roche O, Gilbertson MA, Phillips JC, Sparks RSJ (2004) Experimental study  
450 of gas-fluidized granular flows with implications for pyroclastic flow em-  
451 placement. *Journal of Geophysical Research: Solid Earth* 109(B10), DOI  
452 10.1029/2003JB002916
- 453 Roche O, Montserrat S, Niño Y, Tamburrino A (2008) Experimental observa-  
454 tions of water-like behavior of initially fluidized, dam break granular flows  
455 and their relevance for the propagation of ash-rich pyroclastic flows. *Journal*  
456 *of Geophysical Research* 113(B12):B12,203, DOI 10.1029/2008JB005664
- 457 Roche O, Montserrat S, Niño Y, Tamburrino A (2010) Pore fluid pressure and  
458 internal kinematics of gravitational laboratory air-particle flows: insights  
459 into the emplacement dynamics of pyroclastic flows. *Journal of Geophysical*  
460 *Research* 115:B09,206, DOI 10.1029/2009JB007133
- 461 Roche O, Attali M, Mangeney A, Lucas A (2011) On the run-out distance  
462 of geophysical gravitational flows: Insight from fluidized granular collapse  
463 experiments. *Earth and Planetary Science Letters* 311(3):375–385, DOI  
464 10.1016/j.epsl.2011.09.023

- 465 Singer KN, McKinnon WB, Schenk PM, Moore JM (2012) Massive ice  
466 avalanches on Iapetus mobilized by friction reduction during flash heating.  
467 Nature Geoscience 5(8):574–578, DOI [doi.org/10.1038/ngeo1526](https://doi.org/10.1038/ngeo1526)
- 468 Soria-Hoyo C, Valverde JM, Roche O (2019) A laboratory-scale study on the  
469 role of mechanical vibrations in pore pressure generation in pyroclastic ma-  
470 terials: implications for pyroclastic flows. Bulletin of Volcanology 81(2):12,  
471 DOI [10.1007/s00445-019-1271-3](https://doi.org/10.1007/s00445-019-1271-3)
- 472 Valverde JM, Soria-Hoyo C (2015) Vibration-induced dynamical weak-  
473 ening of pyroclastic flows: Insights from rotating drum experiments.  
474 Journal of Geophysical Research: Solid Earth 120(9):6182–6190, DOI  
475 [10.1002/2015JB012317](https://doi.org/10.1002/2015JB012317)
- 476 Xu X, Sun Q, Jin F, Chen Y (2016) Measurements of velocity and pres-  
477 sure of a collapsing granular pile. Powder Technology 303:147–155, DOI  
478 [10.1016/j.powtec.2016.09.036](https://doi.org/10.1016/j.powtec.2016.09.036)