



**HAL**  
open science

## Experimental Insights on the Propagation of Fine-Grained Geophysical Flows Entering Water

Alexis Bougouin, Olivier Roche, Raphael Paris, Herbert E Huppert

► **To cite this version:**

Alexis Bougouin, Olivier Roche, Raphael Paris, Herbert E Huppert. Experimental Insights on the Propagation of Fine-Grained Geophysical Flows Entering Water. *Journal of Geophysical Research. Oceans*, 2021, 126 (4), 10.1029/2020JC016838 . hal-03192290

**HAL Id: hal-03192290**

**<https://hal.science/hal-03192290v1>**

Submitted on 7 Apr 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1                   **Experimental insights on the propagation of**  
2                   **fine-grained geophysical flows entering water**

3                   **Alexis Bougouin<sup>1</sup>, Olivier Roche<sup>1</sup>, Raphaël Paris<sup>1</sup> and Herbert E. Huppert<sup>2</sup>**

4                   <sup>1</sup>Université Clermont Auvergne, CNRS, IRD, OPGC, Laboratoire Magmas et Volcans, F-63000  
5                   Clermont-Ferrand, France

6                   <sup>2</sup>Institute of Theoretical Geophysics, King's College, University of Cambridge, Cambridge, CB2 1ST,  
7                   United Kingdom

8                   **Key Points:**

- 9                   • Gas-fluidized granular flows down an inclined plane entering water are investigated  
10                  experimentally and compared to those propagating in air  
11                  • The presence of the water body promotes the generation of a granular jet above  
12                  the free surface and a particle-driven gravity current underwater  
13                  • The granular jet and the current are well described by ballistic motion theory and  
14                  the physics of gravity currents, respectively

---

Corresponding author: A. Bougouin, [alexis.bougouin@univ-lehavre.fr](mailto:alexis.bougouin@univ-lehavre.fr)

## Abstract

Granular flows that propagate down a mountainside, then reach the sea, a lake or a river and finally, travel underwater, is a common event on the Earth's surface. To help the description of such events, laboratory experiments on gas-fluidized granular flows entering water are performed, analyzed, and compared to those propagating in air. The originality of this study lies in the fluidization process, which improves the laboratory modelling of geophysical flows by taking their high mobility into account. Qualitatively, the presence of the water body promotes the generation of a granular jet over the water surface, a leading and largest wave, and a particle-driven gravity current underwater. Hydrodynamic forces mainly play a dissipative role by slowing and reducing the spreading of the granular mass underwater, but a low amount of grains are still transported by the turbulent fluid as a gravity current far away. The temporal evolution of the granular jet and the particle-driven gravity current are well described by ballistic motion theory and scaling laws of homogeneous gravity currents, respectively. Most currents propagate with a constant flow-front velocity along the horizontal bottom, which is controlled by the flow height depending on the water depth. In contrast, the bulk volume concentration of particles in the current is estimated to be nearly constant, interpreted as a critical concentration above which the excess of particles cannot be maintained by the turbulent fluid. This experimental study highlights the complexity of the dynamics and deposits of granular masses when they encounter a water body.

## Plain Language Summary

Geophysical granular flows driven by gravity occur frequently on the Earth's surface, as a result of climatic, tectonic or volcanic events. When they occur near the sea, a lake or a river, the granular flows may enter water, generate tsunamis, and propagate underwater. This study presents laboratory experiments on gas-fluidized granular flows entering water, which are performed in a 7 m-long channel and recorded by high-speed cameras. The fluidization process ensures dynamic similarity for modelling of highly mobile geophysical flows composed of fine materials, which are predisposed to reach the coast and generate turbidity currents underwater. The main contributions of this study are summarized as follows: (i) we show that fine-grained flows entering a water body generate both a granular jet over the water surface and a particle-driven gravity current underwater; (ii) we highlight the dissipative role of water in slowing and reducing the spreading of the granular mass underwater, while a low amount of grains is still transported as a gravity current far away; and (iii) we describe the dynamics of the granular jet and gravity current using simple theoretical models including major physical processes.

**Keywords:** laboratory experiments, granular media, fluidization process, geophysical flows, gravity currents, tsunamis.

## 1 Introduction

Geophysical granular flows driven by gravity occur frequently on the Earth's surface, as a result of climatic, tectonic, or volcanic events (Delannay et al., 2017). Granular flows contribute significantly to the global sediment cycle and the shape of landscapes. When they occur near the sea, a lake or a river, these solid-fluid mixtures may enter water, generate tsunamis, and propagate underwater (Løvholt et al., 2015). The subaqueous flows are known to be more highly mobile compared to subaerial flows and they may cause severe damage to submarine facilities (De Blasio et al., 2006). To predict their potential impact offshore, it is essential to understand the flow dynamics of subaerially-initiated granular flows after impacting water.

Many field observations reported the situation of submarine landslides evolving to turbidity currents (e.g., Heezen & Ewing, 1952, 1955; Mulder et al., 1997; Talling et al.,

2007; Hsu et al., 2008). There are different ways to define these currents, but they broadly consist of very dilute particle-laden flows in which grains are mainly suspended by the turbulent water (Kneller & Buckee, 2000). In some cases, the dilute clouds can overlay dense near-bed layers, as recently shown by field measurements (Paull et al., 2018; Simmons et al., 2020; Wang et al., 2020). It is more difficult to find such reports about the transformation of a subaerial granular mass after entering water, because interest has mainly focused on the wave generation (e.g., Weiss et al., 2009). However, it is expected that granular flows composed of fine materials (e.g., fine-grained landslides, ash-rich pyroclastic flows) are particularly predisposed to generate subaqueous turbidity currents when they enter water because particles have low settling velocity and they can be easily suspended by the turbulent water. To the best of our knowledge, such an event has never been observed and only field works on volcanoclastic deposits have discussed turbidity currents formed by pyroclastic flows entering water. During the 12-13 July 2003 paroxysmal dome collapse of Soufrière Hills volcano, more than  $200 \times 10^6 \text{ m}^3$  of hot pyroclastic material entered the ocean. Phreatic explosions were observed and a cloud surge, decoupled from the main flow, travelled 2 to 3 km over the water surface (Edmonds & Herd, 2005). This phreatic activity promoted the ingestion of sea water by the pyroclastic flow that evolved as a cool and dense water-saturated granular flow underwater (Trofimovs et al., 2008). Additionally, a grain-size sorting process occurred within the subaqueous flow, which led to a fine-particle overload in the upper part and the formation of distal turbidity currents that propagated for more than 30 km on gentle slopes of the sea floor (Trofimovs et al., 2006, 2008). Similar transformation of a subaerially-initiated pyroclastic flow into a subaqueous turbidity current was proposed by Whitham (1989) for explaining Roseau Ash submarine deposits (Dominica Island, Lesser Antilles). The volcanoclastic turbidite deposit was found up to 250 km from the source, at 3000 m water depth. Cas and Wright (1991) reported the possible scenarios when hot pyroclastic flows interact with the sea, and most of them highlight the formation of turbidity currents.

Most experimental studies on granular masses entering water considered dry, heavy, and coarse grains leading to dense granular flows depositing rapidly underwater (e.g., Fritz et al., 2003b; Viroulet et al., 2014; Miller et al., 2017). The generation of particle-driven gravity currents by initially-subaerial fine-grained flows has therefore been poorly investigated. Mcleod et al. (1999) first considered different grain-fluid mixtures, initially maintained above the free-surface and released over an inclined plane, which entered fresh water. They concluded that both negatively and positively buoyant gravity currents can be obtained separately or together, by varying the grain and fluid densities of the mixture. These different flow dynamics have also been reported for homogeneous gravity currents released into a two-fluid layer (Monaghan et al., 1999; Legros & Druitt, 2000; Monaghan, 2007; Wells & Wettlaufer, 2007; Cortés et al., 2014). Freundt (2003) focused on the thermal effects of volcanic ash heated up to  $400^\circ\text{C}$ , entering water at ambient temperature. Steam explosions and major ash-cloud surges propagating above the water surface were obtained with increasing temperature. By contrast, the dynamics of particle-driven gravity currents was mainly controlled by the mass flux of the granular flow and the water depth, while it was not significantly affected by the temperature. In fact, heat transfers mainly modified the early stages of the gravity currents, which propagated dominantly along the water surface at high temperature. Despite these studies, there is still a lack on the description of the granular dynamics after such flows enter water, which is the focus of the present study.

Most works on the propagation of particle-driven gravity currents considered simple configurations using laboratory experiments, numerical simulations and theoretical descriptions. One of the most famous configurations corresponds to the propagation of a fixed volume of a heavy fluid released into a lighter fluid on a horizontal plane, the so-called lock-exchange problem (e.g., Huppert & Simpson, 1980; Huppert, 1982; Rottman & Simpson, 1983). In this case, the motion of homogeneous gravity currents is driven by the density difference between the current and the surrounding fluid. Depending on

118 the dominant forces, the flow dynamics of the current in the two-dimensional configu-  
 119 ration is usually described in three distinct stages, well predicted by shallow layer/lubrication  
 120 models: (i) a slumping regime dominated by inertia during which the flow-front veloc-  
 121 ity remains constant; (ii) an inertial self-similar regime characterized by a buoyancy/inertia  
 122 balance for which the front position scales with time as  $x_f \propto t^{2/3}$ ; and (iii) a viscous  
 123 regime controlled by a balance between buoyancy and viscous dissipation in which the  
 124 front evolves as  $x_f \propto t^{1/5}$  (Huppert & Simpson, 1980; Huppert, 1982; Rottman & Simp-  
 125 son, 1983). This configuration has been extended to gravity currents propagating down  
 126 an inclined plane, for which the gravity current is described by an acceleration phase fol-  
 127 lowed by a deceleration phase (e.g., Beghin et al., 1981; Monaghan et al., 1999; Dai &  
 128 Garcia, 2010; Dai, 2013, 2014). When the current decelerates, the front position scales  
 129 as  $x_f \propto t^{2/3}$  or  $x_f \propto t^{1/2}$  according to the preponderance of inertia or viscous effects,  
 130 respectively (Dai, 2014). The motion of these gravity currents is also well predicted by  
 131 the thermal theory based on the mass and momentum conservation by considering the  
 132 entrainment of the ambient fluid (Beghin et al., 1981). Finally, for gravity currents down  
 133 an inclined plane produced by a continuous inflow, the currents evolve with a constant  
 134 front velocity depending mainly on the buoyancy flux, while the effect of the slope angle  
 135 is insignificant (e.g., Britter & Linden, 1980; Baines, 2001, 2005). We recall that other  
 136 simple configurations have also been considered, in which the above-mentioned stages  
 137 were observed despite a modification of the scaling laws (e.g., Huppert, 1982; Zgheib et  
 138 al., 2015; Zhu et al., 2017). The particle-driven gravity currents are fundamentally grav-  
 139 ity currents whose density is greater than that of the surrounding fluid because of their  
 140 suspended grains (Meiburg & Kneller, 2010; Wells & Dorell, 2020). However, the flow  
 141 dynamics of these currents are more complex than those of homogeneous gravity cur-  
 142 rents, i.e. the intrusion of a pure fluid into another fluid, because the particle concen-  
 143 tration evolves with time and position due to the erosion/deposition of grains (e.g., Bon-  
 144 necaze et al., 1993, 1995).



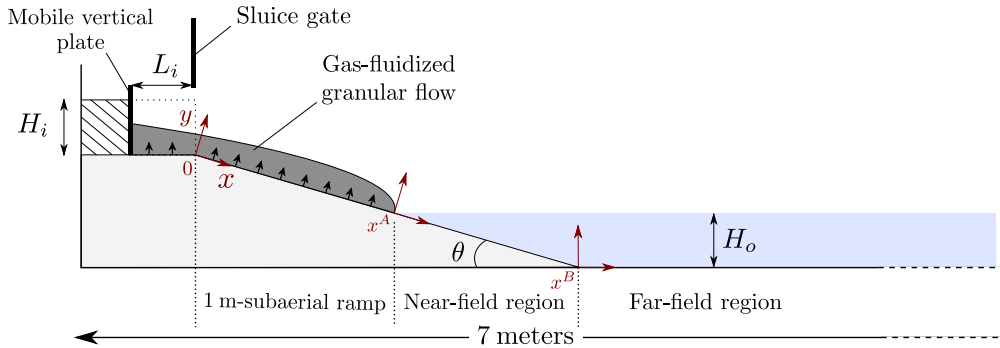
**Figure 1.** Oblique view of a particle-driven gravity current, generated by a gas-fluidized granular flow down an inclined plane entering water. The dashed line indicates the bottom of the inclined plane above the level of the undisturbed water surface. On the left, the subaerial granular flow is relatively thin, dense and rapid before evolving to a thick and dilute particle-driven gravity current underwater. An impulse wave is also generated on the water surface, which has already been studied in Bougouin et al. (2020).

145 In the present work, laboratory experiments on gas-fluidized granular flows enter-  
 146 ing a body of water are performed to understand better the dynamics of geophysical flows  
 147 after they reach the sea, a lake or a river. More specifically, it focuses on granular flows  
 148 composed of fine materials, which are predisposed to generate particle-driven gravity cur-

149 rents underwater, as illustrated by the oblique view of Figure 1. The questions raised  
 150 in the present contribution are the following. What is the effect of a water body on the  
 151 propagation of subaerially-initiated fine-grained flows along an inclined plane? Does the  
 152 water body play a dissipative or a driven role on the granular material? Can the gen-  
 153 eral evolution of the granular material be described using simple theoretical models? In  
 154 order to provide some answers, the paper is organized as follows. In Sec. 2, the exper-  
 155 imental setup and materials used are presented. Sec. 3 highlights the influence of the  
 156 presence of a water body on the granular dynamics through qualitative observations and  
 157 a comparison between gas-fluidized granular flows propagating only in air and entering  
 158 water. Finally, the evolution of the granular material, i.e. the initial granular jet above  
 159 the water surface and the particle-driven gravity current underwater, is described using  
 160 theoretical models (Secs. 4 and 5).

## 161 2 Experimental setup

### 162 2.1 Apparatus



**Figure 2.** Sketch of the experimental setup with the initial parameters (the height  $H_i$  and the length  $L_i$  defining the initial dimensions of the granular column, the slope angle  $\theta$  of the inclined plane, and the water depth  $H_o$ ). Black arrows represent the air flux through the  $12 \mu\text{m}$ -porous bottom plane for the fluidization process. The streamwise coordinates  $x^A$  and  $x^B$  indicate the transition from the 1 m-subaerial ramp to the immersed ramp, and the end of the inclined plane that connects to the horizontal bottom, respectively. The zones containing the immersed inclined plane and the horizontal bottom are referred to as the near- and far-field regions, respectively.

163 Laboratory experiments are conducted in a horizontal transparent channel of rect-  
 164 angular cross-section with dimensions of  $7 \times 0.8 \times 0.2 \text{ m}^3$  in the longitudinal, vertical  
 165 and spanwise directions, respectively. A sketch of the experimental setup is given in Fig-  
 166 ure 2. One side of the channel is equipped with a reservoir delimited by a sluice gate and  
 167 a mobile vertical plate to vary the initial length  $L_i$  of the granular column. In this study,  
 168 the length and the height of the initial granular column are varied in the range  $L_i =$   
 169  $[9 : 34] \pm 0.5 \text{ cm}$  and  $H_i = [10 : 42] \pm 0.5 \text{ cm}$ , respectively. The reservoir is connected  
 170 to an inclined plane composed of a 1 m-subaerial ramp and an immersed ramp. Both  
 171 the bottom of the reservoir and of the 1 m-subaerial ramp are equipped with a  $12 \mu\text{m}$ -  
 172 porous plate to fluidize the granular flow by a vertical air flux before entering water (see  
 173 black arrows, in Figure 2). Here, the granular material is fluidized with an air velocity  
 174 of  $U_f \sim 4.7 \pm 0.1 \text{ mm.s}^{-1}$ , larger than the minimum fluidization velocity  $U_{mf} \sim 3.8 \pm$   
 175  $0.1 \text{ mm.s}^{-1}$ , which ensures that the granular flow is fully fluidized when it impacts wa-  
 176 ter. The minimum fluidization velocity  $U_{mf}$  is estimated prior the experiments as the  
 177 minimum velocity for which the gas pore pressure counterbalances the pressure of a static

178 granular column. The length of the immersed ramp varies as  $H_o/\sin\theta$ , where the slope  
 179 angle is set to  $\theta = 5^\circ, 10^\circ, 15^\circ, 20^\circ$ , and  $30^\circ$  and the water depth is varied up to  $H_o =$   
 180  $38.5 \pm 0.1$  cm. In the following, the zones containing the immersed ramp and the hor-  
 181 izontal bottom are referred to as the near- and far-field regions, respectively. On the op-  
 182 posite side of the channel, a wave breaker is used to limit the reflected waves, which could  
 183 affect the granular flow dynamics underwater. Indeed, the wave velocity is still much larger  
 184 than that of the particle-driven gravity current.

185 As discussed by Bougouin et al. (2020), the initial conditions of the experiment con-  
 186 trol the flow parameters, namely the volume, the velocity, and the height of the gran-  
 187 ular flow. The volume per unit width is estimated as  $v = (H_i - h_r)L_i$ , where  $h_r$  is the  
 188 residual height of grains in the reservoir at the end of the experiment. The height pro-  
 189 file of the granular flow is non-uniform along the inclined plane, and the front-height  $h_f$   
 190 at the impact is therefore chosen as the flow height at 10 cm behind the front (more in-  
 191 formation is provided in the Bougouin et al. (2020)'s Supporting Information). The con-  
 192 stant front velocity  $u_f$  of fluidized granular flows is estimated at the impact, from the  
 193 slope of the linear trend between the front position and time. Finally, as both  $h_f$  and  
 194  $u_f$  vary together with  $H_i$ , the flow rate per unit width  $q = h_f u_f$  is also defined. In this  
 195 study, the control parameters are varied in the range  $v = [1.5 : 13.2] \pm 0.1$  dm<sup>2</sup> (with  
 196  $1$  dm<sup>2</sup> =  $10^{-2}$  m<sup>2</sup>),  $h_f = [0.9 : 2.8] \pm 0.4$  cm,  $u_f = [2 : 3.7] \pm 0.1$  m.s<sup>-1</sup>, and  $q = [1.8 :$   
 197  $8.5] \pm 1$  dm<sup>2</sup>.s<sup>-1</sup>, respectively.

198 At the initial time  $t = 0$ , the sluice gate is rapidly and entirely removed with a  
 199 velocity of about  $2$  m.s<sup>-1</sup> by releasing a suspended weight, which triggers the collapse  
 200 of the granular column on the inclined plane. The flow dynamics of the granular mate-  
 201 rial is recorded using a classical shadowgraph method with two Photron Fastcam  $1024 \times$   
 202  $1024$  pixel cameras and LED panels on the back side of the channel. This optical method  
 203 allows visualization of the interface between fluids due to different light absorptions. Here,  
 204 the granular material, the water layer, and the ambient air are represented in black, gray  
 205 and white, respectively (see Figure 3, for instance). The first camera records a large view  
 206 of the experiment, while the second camera focuses on the flow dynamics of currents in  
 207 the far-field region. The resolution obtained is  $4$  mm/pixel and  $0.8$  mm/pixel, respec-  
 208 tively, and the acquisition rate is  $250$  Hz. Finally, the extraction process is performed  
 209 using a Matlab routine based on a threshold method.

## 2.2 Materials

210  
 211 The granular material used corresponds to quasi-monodisperse spherical glass beads  
 212 manufactured by Wheelabrator, with a diameter of  $d = 65 \pm 10$   $\mu$ m and a density of  
 213  $\rho_p = 2550 \pm 50$  kg.m<sup>-3</sup>, respectively. Before each experiment, the grains are weighted,  
 214 poured into the reservoir, fluidized and then the height of the initial column is measured.  
 215 The particle concentration of the initial granular column is  $\phi_i = V_{grains}/V_{column} \sim$   
 216  $0.56 \pm 0.01$ , where  $V_{grains}$  and  $V_{column}$  denote the volume of grains and the total vol-  
 217 ume of the initial column, respectively. This corresponds to an initial bulk density of  $\rho =$   
 218  $\phi_i \rho_p + (1 - \phi_i) \rho_a \sim 1400$  kg.m<sup>-3</sup>, where  $\rho_a \sim 1.2$  kg.m<sup>-3</sup> is the density of ambient air.  
 219 Both the particle concentration and the density are expected to remain constant in the  
 220 reservoir and during the flow propagation on the  $1$  m-subaerial ramp because of the sus-  
 221 tained gas flow from the bottom.

222 Some experiments of dense liquid flows entering water are also performed to com-  
 223 pare the propagation of homogeneous gravity currents with that of particle-driven gravi-  
 224 ty currents. Sodium Chloride (NaCl) is therefore added to dyed water with a concen-  
 225 tration of  $325$ g/kg of water, leading to a dense saline liquid of  $\rho \sim 1200$  kg.m<sup>-3</sup> mea-  
 226 sured by a DMA 35 Anton Paar electronic densimeter. In Sec. 5, we will show that the  
 227 density of homogeneous gravity currents is roughly similar to that of particle-driven gravi-  
 228 ty currents, and their dynamics can therefore be compared together depending on the

229 flow conditions at the impact. It should be remembered that no gravity currents would  
 230 be generated by the entrance of a fluid into another fluid of the same density (Bullard  
 231 et al., 2019; Clous et al., 2019), while reversing buoyancy of currents would be observed  
 232 with a lighter fluid into a heavy fluid (Monaghan et al., 1999; Monaghan, 2007). For dense  
 233 liquid flows, the initial parameters are  $H_i = [16 : 40]$  cm,  $L_i = 34$  cm,  $H_o = 26.4$   
 234 cm and  $\theta = 15^\circ$ , while the flow parameters at the impact are found in the range  $v =$   
 235  $[5.2 : 12.5]$  dm<sup>2</sup>,  $u_f = [2.4 : 3.2]$  m.s<sup>-1</sup>,  $h_f = [0.9 : 2.5]$  cm, and  $q = [2.2 : 8.0]$   
 236 dm<sup>2</sup>.s<sup>-1</sup>.

### 237 2.3 Scaling issues of geophysical granular flows

238 In this section, we propose to discuss the relevance and limitations of the exper-  
 239 iments, which aim to help the understanding of fine-grained geophysical flows propagat-  
 240 ing down a mountainside, entering the sea, a lake or a river, and then propagating un-  
 241 derwater far away.

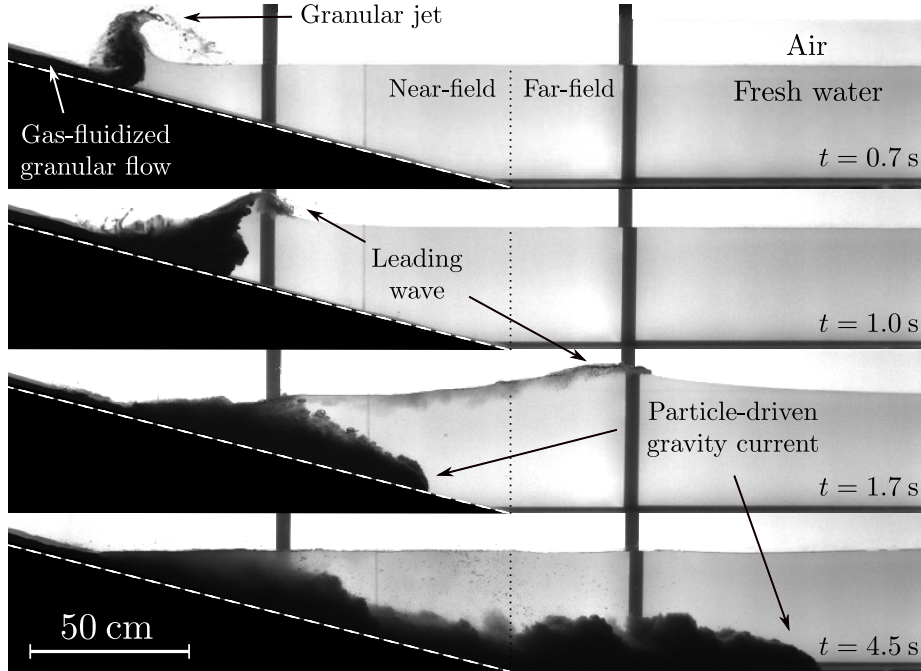
242 The novelty of this study lies in the consideration of gas-fluidized granular flows,  
 243 which ensures a more suitable modelling of geophysical flows taking their high mobil-  
 244 ity into account. Indeed, natural granular flows are known to exhibit energy dissipation  
 245 lower than at the laboratory scale, for which several physical mechanisms have been pro-  
 246 posed, i.e. basal lubrication (e.g., Bowden & Hughes, 1939; Shreve, 1968; Goren & A.,  
 247 2007), acoustic or mechanical fluidization (e.g., Melosh, 1979; T. R. H. Davies, 1982; Collins  
 248 & Melosh, 2003), high gas pore pressure (e.g., Major & Iverson, 1999; Sparks, 1976), dy-  
 249 namic fragmentation (e.g., T. R. Davies & McSaveney, 2009), and material entrainment  
 250 (e.g., Hungr & Evans, 2004; Sovilla et al., 2006), among others. At the laboratory scale,  
 251 a granular flow fluidized at the source propagates faster and farther than a non-fluidized  
 252 granular flow with the same initial conditions (Roche et al., 2008). In case of fluidiza-  
 253 tion along the flow path and for gentle slopes, the fluidization process also prevents the  
 254 deposition of grains along the bottom plane, and the entire volume of the granular flow  
 255 thus enters water (Bougouin et al., 2019). This behavior is attributed to the high gas  
 256 pore pressure generated by the fluidization process, which reduces the internal friction  
 257 within granular flows and therefore promotes the high mobility. The dynamics of exper-  
 258 imental and natural granular flows can be compared through the Froude number  $Fr =$   
 259  $u_f/(gh_f)^{1/2}$ , which is found in the range  $Fr = [6 : 9]$  corresponding to the upper range  
 260 of natural flows (Delannay et al., 2017). Moreover, the bulk flow to water density ratio  
 261 is about  $\rho/\rho_f \sim 1.4$  which is consistent with that of most natural flows (Delannay et  
 262 al., 2017), even if ash-rich pyroclastic flows and dry snow avalanches may be less dense  
 263 than water. This experimental configuration seems therefore to be a relevant modelling  
 264 for investigating most geophysical granular flows entering water, despite some limitations.

265 In the present configuration, the fluidization process is facilitated using fine, spher-  
 266 ical, and monodisperse beads, which is a crude assumption about natural flows usually  
 267 composed of different grain sizes, densities, and shapes. In this way, some physical mech-  
 268 anisms such as the grain-size sorting process in or out of the water, the reversing buoy-  
 269 ancy and the coarse grain spreading underwater cannot be reproduced here. The grain  
 270 size to flow length ratio of natural flows cannot also be maintained at the laboratory scale,  
 271 because the grain size used in the experiments is usually similar to those found in the  
 272 field. Moreover, natural pyroclastic flows can have high temperatures up to 500–600°  
 273 when they enter the sea. Freundt (2003) concluded that the main consequence of high  
 274 temperature was the generation of phreatic explosions and major ash-cloud surges prop-  
 275 agating over the water surface, while particle-driven gravity currents were slightly affected  
 276 close to the shoreline. However, an open question still remains about the formation of  
 277 welded deposits, which could not be addressed here (Sparks et al., 1980; Cas & Wright,  
 278 1991; Kokelaar & Busby, 1992). In summary, the present setup ensures a suitable mod-  
 279 elling of dense, cold or moderate-heated, fine particle-rich geophysical flows entering wa-  
 280 ter.



### 3 Gas-fluidized granular flows entering water

#### 3.1 Preliminary observations: Role of the water body



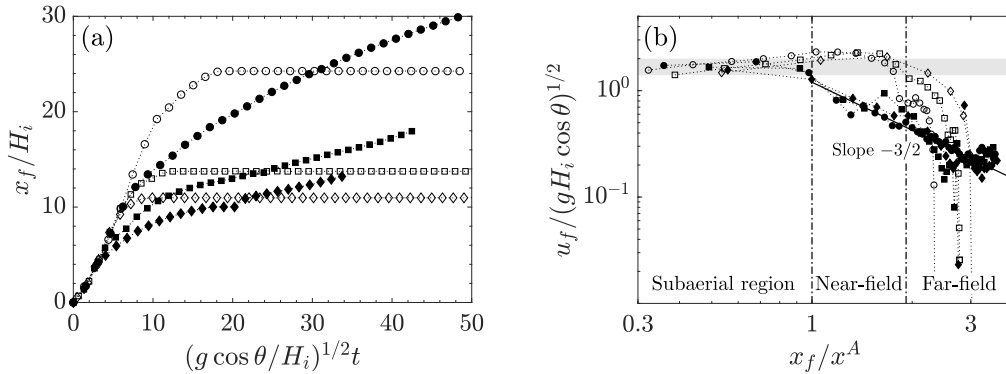
**Figure 3.** Snapshots of the entrance of a gas-fluidized granular flow into water, for  $H_i = 22$  cm,  $L_i = 34$  cm,  $H_o = 38.5$  cm, and  $\theta = 15^\circ$ , at four different times from the opening of the sluice gate. A movie of the same experiment and a compilation of experimental movies from different camera viewpoints are also available in the Supporting Information.

At the initial time  $t = 0$ , the initial column of grains is released, collapses and forms a gas-fluidized granular flow on the subaerial inclined plane until reaching water. The impact between the granular flow and the water body generates (i) an initial granular jet corresponding to grains ejected above the water surface, (ii) a leading and largest wave, and (iii) a turbulent mixing zone from which a particle-driven gravity current is spontaneously formed (Figure 3). These observations are direct consequences of the presence of a water body, which have already been observed for fine particle-fluid mixtures entering water (McLeod et al., 1999; Freundt, 2003; Allen et al., 2012; Bougouin et al., 2020). By contrast, both the granular jet and the gravity current have never been reported in the literature for coarse granular materials [i.e.,  $d > \mathcal{O}(10^{-3})$  m] under similar flow conditions (e.g., Fritz et al., 2003a; Heller et al., 2008; Viroulet et al., 2014; Zitti et al., 2016; Miller et al., 2017). It suggests therefore that both the granular jet and the particle-driven gravity current are mainly controlled by the grain-fluid interaction. In fact, the flow dynamics of particle-driven gravity currents along the bottom plane looks more like that of homogeneous gravity currents penetrating a two-fluid layer (Monaghan et al., 1999; Legros & Druitt, 2000; Monaghan, 2007; Wells & Wettlaufer, 2007; Cortés et al., 2014). In this configuration, a splitting of the homogeneous gravity current can even be obtained, which could be related to the formation of the granular jet above the water surface and of the particle-driven gravity current underwater. However, some caution has to be exercised here because the splitting of homogeneous gravity currents was attributed to lighter fluid incorporated into the current by turbulent entrainment (Wells & Wettlaufer, 2007;

304 Cortés et al., 2014), which is not expected to occur for gas-fluidized granular flows prop-  
 305 agating in air.

306 **3.2 Comparison with gas-fluidized granular flows in air**

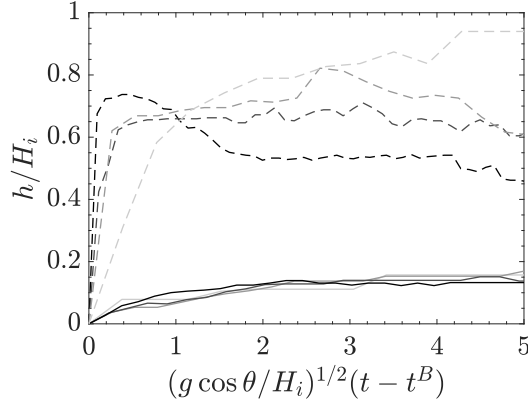
307 In this section, we highlight the effect of a water body on the granular dynamics  
 308 and the associated deposits by comparison of gas-fluidized granular flows propagating  
 309 only in air and entering water, under the same initial conditions.



**Figure 4.** (a) Front position  $x_f/H_i$  as a function of normalized time  $(g \cos \theta/H_i)^{1/2}t$  for gas-fluidized granular flows propagating in air (opened symbols) and entering water (closed symbols), with  $H_i = 10$  cm (diamonds),  $H_i = 22$  cm (squares) and  $H_i = 30$  cm (circles). The other initial parameters are set to  $L_i = 34$  cm,  $\theta = 15^\circ$ , and  $H_o = 26.6$  cm (in the presence of water). (b) Front-velocity  $u_f/(gH_i \cos \theta)^{1/2}$  as a function of the front position  $x_f/x^A$ , where  $x^A$  is the streamwise coordinate of the shoreline. The gray area corresponds to  $u_f/(gH_i \cos \theta)^{1/2} = [1.4 : 2]$ ; the solid line is a slope  $-3/2$ ; and the dotted-dashed lines delimit the subaerial, near- and far-field regions.

310 One of the relevant macroscopic analyses to compare the dynamics of granular flows  
 311 is the tracking of the front position  $x_f$  and the front-velocity  $u_f$  with time and position  
 312 (Figure 4). The presence of a water body significantly affects the temporal evolution of  
 313 the flow front beyond the initial height  $H_i$ , the latter being already reported for water  
 314 dam-break flows (e.g., Ritter, 1892; Laubert & Hager, 1998; Ancey et al., 2008) and sub-  
 315 aerial granular flows (e.g., Roche et al., 2008; Mangeney et al., 2010; Farin et al., 2014;  
 316 Bougouin et al., 2020). At early times, all curves collapse together corresponding to the  
 317 propagation of granular flows down the subaerial inclined plane. During this stage, the  
 318 flow front slightly accelerates along the plane, as predicted by the theory for a friction-  
 319 less fluid flow down an inclined plane (Ancey et al., 2008). We recall that the acceler-  
 320 ation phase of channeled granular flows is expected to end when the gravity is balanced  
 321 by sidewall friction (Brodu et al., 2015). For the sake of simplicity, the averaged front  
 322 velocity can also be defined in the range  $u_f/(gH_i \cos \theta)^{1/2} = [1.4 : 2]$  [gray area, in  
 323 Figure 4(b)], in agreement with values found in the case of dam-break flows on a hori-  
 324 zontal plane (Dressler, 1954; Jánosi et al., 2004; Leal et al., 2006; Roche et al., 2008; Bonometti  
 325 et al., 2008; Bougouin et al., 2017). During the second phase, gas-fluidized granular flows  
 326 either enter water and then propagate in the form of subaqueous particle-driven gravi-  
 327 ty currents, or they continue to flow down the subaerial inclined plane without the sus-  
 328 tained gas flow from the bottom. The main consequence of the water body is to slow down  
 329 the spreading of the granular material. A gross estimate of the normalized front veloc-  
 330 ity with the normalized front position gives  $u_f/(gH_i \cos \theta)^{1/2} \propto (x_f/x^A)^{-3/2}$  [solid line,

331 in Figure 4(b)]. However, the flow dynamics of the currents will be more fully investi-  
 332 gated in Sec. 5. Finally, the gas-fluidized granular flows in air stop rapidly on the hori-  
 333 zontal bottom, while the gravity currents continue slowly to propagate underwater [Far-  
 334 field region, in Figure 4(b)].



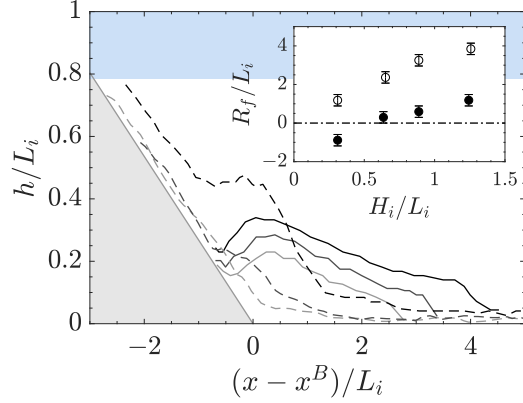
**Figure 5.** Temporal evolution of the flow height  $h/H_i$  at the slope break  $x - x^B = 0$ , for gas-fluidized granular flows propagating in air (—) and entering water (- - -), with  $H_i = 10, 22, 30$  and  $42$  cm (from light to dark gray). The other initial parameters are set to  $L_i = 34$  cm,  $\theta = 15^\circ$ , and  $H_o = 26.6$  cm (in the presence of water).

335 The morphology of the granular flow can also be investigated here, because it is  
 336 particularly modified by the presence of the water body (Figure 5). More specifically,  
 337 the major effect of water is to generate thick and dilute particle-driven gravity currents  
 338 underwater compared to dense and thin gas-fluidized granular flows in air. Moreover,  
 339 the inertial dimensionless form used here allows the collapse of the height profile of gas-  
 340 fluidized granular flows obtained for different  $H_i$ , which does not hold true for subaque-  
 341 ous particle-driven gravity currents.

342 Finally, at sufficiently long times (i.e., from a few seconds to tens of seconds), the  
 343 granular material stops forming a final deposit along the bottom surface (Figure 6). Again,  
 344 the morphology of the granular deposit strongly differs for gas-fluidized granular flows  
 345 propagating in air and those entering water. The presence of the water body leads to  
 346 a thick and voluminous granular mass along the inclined plane probably due to a dense  
 347 granular flow, while a thin layer of grains, initially suspended in the gravity current, is  
 348 deposited on the horizontal bottom. By contrast, the subaerial granular flows form only  
 349 a massive deposit at the end of the inclined plane. The inset of Figure 6 shows that the  
 350 presence of water reduces significantly the runout of granular flows, as already reported  
 351 for coarse grains falling into water (Mazzanti & De Blasio, 2011; Viroulet et al., 2014;  
 352 Miller et al., 2017). The runout is defined here as  $h(x - x^B = R_f) = H_i/10$  to be free  
 353 of the thin and very elongated granular layer deposited by the current. Overall, the pres-  
 354 ence of the water body therefore plays a dissipative role by slowing and reducing the spread-  
 355 ing of the granular material, even if a low amount of grains are still transported by the  
 356 turbulent fluid far away.

### 357 3.3 Discussion of results

358 Our laboratory experiments on fine-grained granular flows entering a water body  
 359 have revealed the following results. Overall, the presence of water promoted the forma-  
 360 tion of a granular jet, corresponding to grains ejected above the water surface and then



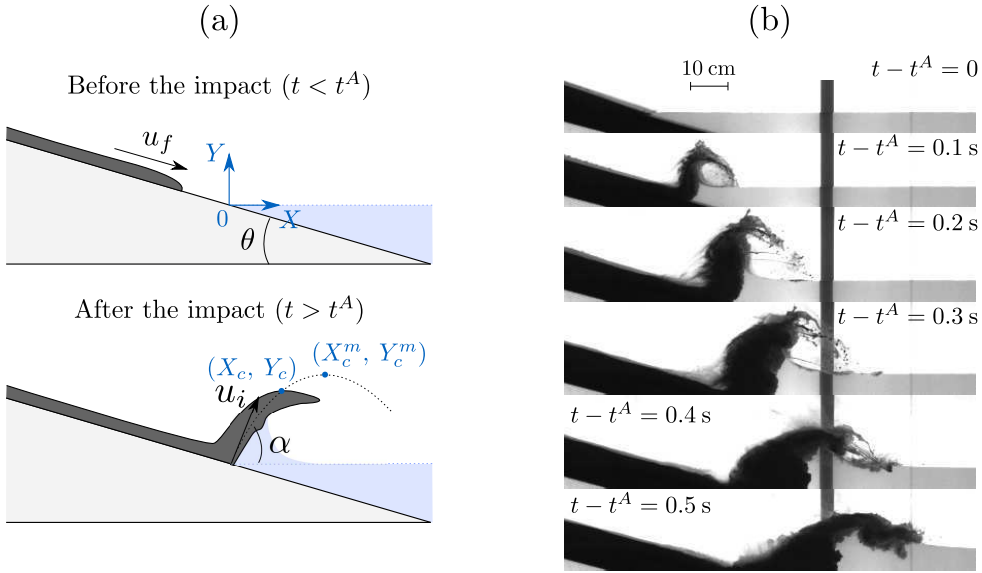
**Figure 6.** Morphology of granular deposits along the bottom surface, for gas-fluidized granular flows propagating in air (—, opened circles) and entering water (- - -, closed circles), with  $H_i = 22, 30$  and  $42$  cm (from light to dark gray). The other initial parameters are set to  $L_i = 34$  cm,  $\theta = 15^\circ$ , and  $H_o = 26.6$  cm (in the presence of water). Inset: Runout  $R_f/L_i$ , defined as  $h(x - x^B = R_f) = H_i/10$ , as a function of the aspect ratio  $a = H_i/L_i$  of the initial column.

361 falling onto it, and a particle-driven gravity current underwater. Moreover, hydrodynam-  
 362 ics forces mainly played a dissipative role by slowing and reducing the spreading of the  
 363 granular mass underwater, even if a low amount of grains were still transported by the  
 364 turbulent fluid as a gravity current far away. These observations highlight the complex-  
 365 ity of granular flows impacting water, with in particular, a splitting of granular masses.  
 366 These results are now discussed to help the interpretation of some submarine deposits  
 367 in the natural environment.

368 In the field, both the morphology and the internal structure of deposited material  
 369 represent a suitable marker of the dynamics of granular flows. In the case of fine-grained  
 370 geophysical flows entering water, it is expected from our experiments to obtain distinct  
 371 submarine deposits, recording successively gravity currents, dense basal flows, and gran-  
 372 ular jets. The 1995-2010 eruption of Soufrière Hills volcano represents an invaluable case  
 373 study of pyroclastic flows entering the sea with volcanic activity having been intensively  
 374 documented (e.g., Young et al., 1998; Trofimovs et al., 2006, 2008; Le Friant et al., 2009,  
 375 2010; Trofimovs et al., 2012; Wadge et al., 2014, among others). A large part of volcani-  
 376 clastic materials was transported into the sea, and associated submarine deposits have  
 377 been particularly well described through bathymetric survey data and core samples. Over-  
 378 all, massive coarse-grained deposits were observed close to the slope break, which was  
 379 interpreted as the sign of dense granular flows propagating slowly underwater (Le Fri-  
 380 ant et al., 2009, 2010; Trofimovs et al., 2012). A grain-size sorting process also promoted  
 381 the formation of dilute turbidity currents composed of fine materials, which deposited  
 382 as thin and elongated masses far away from the shoreline (Trofimovs et al., 2006, 2008,  
 383 2012). Our experimental observations of submarine gravity currents and deposit mor-  
 384 phologies are consistent with those reported from the field. Additionally, they highlight  
 385 that grain-size sorting processes are not needed to form both proximal massive deposits  
 386 and distal turbidites. Finally, deposits of granular jets have never been mentioned in the  
 387 literature, suggested that they were probably hardly recognized.

#### 4 Spatio-temporal evolution of the granular jet

The entrance of a gas-fluidized granular flow into a water body generates first a granular jet above the water surface, before falling onto it. Here, we propose to describe the spatio-temporal evolution of the position of the jet crest  $(X_c, Y_c)$  considering a ballistic trajectory. A sketch of this issue is shown in Figure 7(a), with the flow parameters before entering water (upper) and the granular jet after the impact (bottom). It can already be anticipated that both the initial length  $L_i$ , which only controls the volume of the granular flow, and the water depth  $H_o$  could be disregarded here, as the granular jet is rapidly generated near the shoreline. The control parameters for this problem are therefore the slope angle  $\theta$  of the inclined plane and the front velocity  $u_f$ , the latter being controlled by the initial height  $H_i$  of the column and the slope angle  $\theta$ . Figure 7(b) shows snapshots of the typical evolution of a granular jet over the free-surface at different times from the impact. Note that the granular jet could also contain some water, but the proportion is expected to be low compared to those of grains and the ambient air.



**Figure 7.** (a) Sketch of a gas-fluidized granular flow before (upper) and after (bottom) the impact with water. The trajectory of the granular jet is characterized by the crest position  $(X_c, Y_c)$  reaching a maximum height at the position  $(X_c^m, Y_c^m)$  and the time  $T^m$ , and described by ballistic motion theory considering an initial velocity  $u_i$  and an initial angle  $\alpha$ . (b) Snapshots of the typical evolution of a granular jet for  $u_f = 3.0 \text{ m.s}^{-1}$  and  $\theta = 15^\circ$ , at different times from the impact.

##### 4.1 Frictionless ballistic motion theory

For the purpose of describing the trajectory of the granular jet crest, let us first consider a single grain ejected with an initial velocity  $u_i$  and an initial angle  $\alpha$  (with respect to the horizontal plane), i.e.  $(X_c, Y_c) = (0, 0)$  and  $t - t^A = 0$  with  $t^A$  the time at the impact [see Figure 7(a)]. To first order, the drag force of the ambient air on the grain motion can be neglected. Hence, the single grain is only subject to its own weight and momentum conservation reduces to  $(d^2 X_c/dt^2, d^2 Y_c/dt^2) = (0, -g)$  in the hori-

410 zontal and vertical directions, respectively. Then one can simply obtain the temporal evo-  
411 lution of the horizontal and vertical positions of the grain as

$$X_c = u_i \cos \alpha (t - t^A), \quad (1)$$

$$Y_c = -\frac{g}{2}(t - t^A)^2 + u_i \sin \alpha (t - t^A). \quad (2)$$

412 Additionally, the spatial evolution can also be expressed by combining equations  
413 (1) and (2), which leads to

$$Y_c = -\frac{g}{2u_i^2 \cos^2 \alpha} X_c^2 + \tan \alpha X_c. \quad (3)$$

414 It can also be useful to predict the position  $(X_c^m, Y_c^m)$  and the time  $T^m$  at which  
415 the maximum height is reached as discussed later in Sec. 4.3. This is obtained when  $dY_c/dt =$   
416  $dY_c/dX_j = 0$ , at  $t = T^m$  and  $X_c = X_c^m$ . Using equations (1), (2) and (3), we obtain

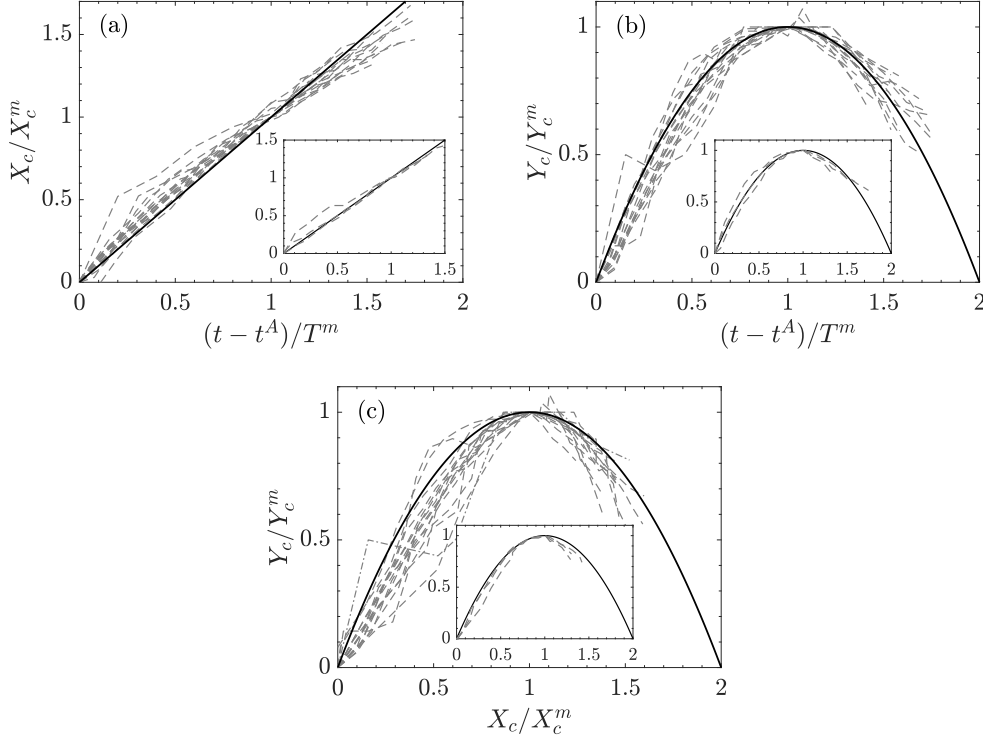
$$X_c^m = \frac{\cos \alpha \sin \alpha}{g} u_i^2, \quad Y_c^m = \frac{\sin^2 \alpha}{2g} u_i^2, \quad T^m = \frac{\sin \alpha}{g} u_i. \quad (4)$$

417 It should be noted that each quantity depends only on the initial conditions of the  
418 ballistic trajectory, i.e. the initial velocity  $u_i$  and the initial angle  $\alpha$ . Now, we assume  
419 that the grain motion of the jet crest can be related to that of a single grain with a bal-  
420 listic trajectory, which can be anticipated to be a crude assumption in view of dense gran-  
421 ular flows impacting the water body. In fact, this suggests that grain-grain interaction  
422 can be neglected, at least in the upper region of the granular jet. In the following, it will  
423 be shown that this model captures most of the physical mechanisms, giving a fairly good  
424 description of the spatio-temporal evolution of the granular jet.

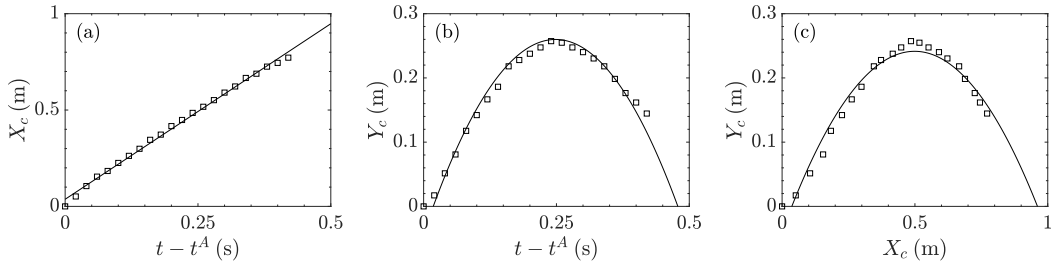
## 425 4.2 Application to the experiments

426 The validity of the predictive model is now assessed from experimental data. Fig-  
427 ure 8 shows a fairly good collapse of the spatio-temporal evolution of the granular jet  
428 crest, using  $(X_c^m, Y_c^m)$  and  $T^m$  as length and time scales. The duration of the jet is  $(t -$   
429  $t^A)/T^m \sim 1.5$  here, from which the jet falls down the generated leading wave. More-  
430 over,  $X_c/X_c^m$  and  $Y_c/Y_c^m$  have a quasi-linear and a 2-polynomial trend with the time  
431  $(t - t^A)/T^m$  [solid lines, in Figs. 8(a)-(b)], which is consistent with the form of the the-  
432 oretical predictions given by equations (1) and (2), respectively. Similar conclusions can  
433 also be drawn from the spatial evolution of the granular jet [Figure 8(c)] in comparison  
434 with equation (3). This supports the idea that the trajectory of the jet crest could be  
435 simply described from a frictionless ballistic trajectory of grains. Finally, the insets of  
436 Figure 8 show the spatio-temporal evolution of the jet crest generated by dense liquid  
437 flows impacting a water body (salt water into fresh water, here). In this case, the jet cor-  
438 responds to a volume of dense liquid ejected above the water surface. The dynamics of  
439 liquid jets is equivalent to that of granular jets, as shown by the collapse of the exper-  
440 imental data and the solid lines. In the present configuration, the jet dynamics is there-  
441 fore mainly dependent on the flow conditions (e.g., flow velocity, slope angle), regard-  
442 less of the rheology of the flowing material (e.g., Newtonian fluid, granular material).

443 In order to describe the spatio-temporal evolution of the granular jet, the initial  
444 parameters  $(u_i, \alpha)$  of the model have to be quantified from the flow conditions. The tem-  
445 poral evolution of the horizontal and vertical positions of the granular jet crest, i.e.  $X_c(t)$   
446 and  $Y_c(t)$ , are fitted by equations (1) and (2), respectively, for which  $u_i$  and  $\alpha$  can be



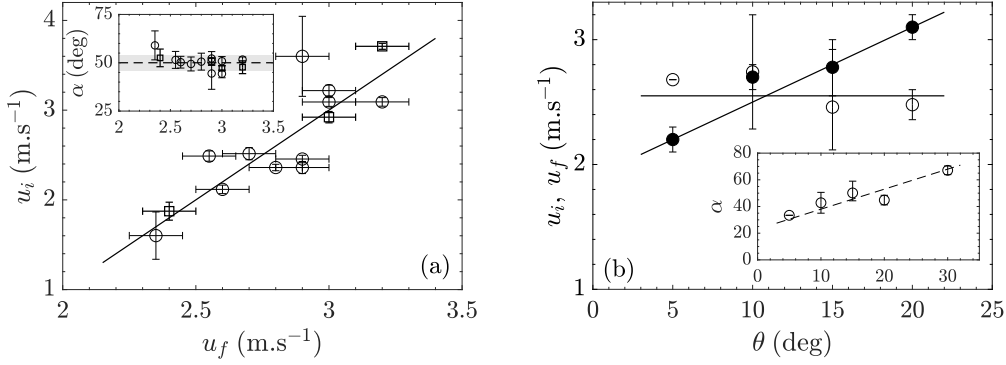
**Figure 8.** Evolution of (a) the horizontal position  $X_c/X_c^m$  and (b)-(c) the vertical position  $Y_c/Y_c^m$  of the jet crest generated by gas-fluidized granular flows (insets: dense liquid flows) impacting a water body, as a function of (a)-(b) the time  $(t - t^A)/T^m$  and (c) the horizontal position  $X_c/X_c^m$ , where  $(X_c^m, Y_c^m)$  and  $T^m$  are the position and the time at which the maximum height of the jet crest is reached. The solid lines correspond to (a)  $X_c/X_c^m = (t - t^A)/T^m$ , (b)  $Y_c/Y_c^m = -[(t - t^A)/T^m]^2 + 2(t - t^A)/T^m$ , and (c)  $Y_c/Y_c^m = -(X_c/X_c^m)^2 + 2X_c/X_c^m$ , respectively.



**Figure 9.** Spatio-temporal evolution of the granular jet crest, with  $u_f = 3.0 \text{ m.s}^{-1}$  and  $\theta = 15^\circ$ . Squares and solid lines correspond to the experimental data and the theoretical predictions [equations (1), (2) and (3)] with (a)-(b)  $u_i \sim 3.0 \text{ m.s}^{-1}$  and  $\alpha \sim 53^\circ$ , and (c)  $u_i \sim 3.1 \text{ m.s}^{-1}$  and  $\alpha \sim 48^\circ$ , respectively. To overcome the problem of time and space offsets, the fitted relations are not set to  $(X_c, Y_c) = (0, 0)$ , at  $t - t^A = 0$ .

447 adjusted. To overcome the problem of time and space offsets, the fitted relations are not  
 448 set to  $(X_c, Y_c) = (0, 0)$ , at  $t - t^A = 0$ . A similar method is also realized with the spatial  
 449 evolution of the granular jet crest, i.e.  $Y_c(X_c)$ , using equation (3). Figure 9 shows

450 an example of the good agreement between the experimental data and the fitted theo-  
 451 retical predictions. Here, the initial parameters of the model are equal to (a) and (b)  $u_i \sim$   
 452  $3.0 \text{ m.s}^{-1}$  and  $\alpha \sim 53^\circ$  and (c)  $u_i \sim 3.1 \text{ m.s}^{-1}$ , and  $\alpha \sim 48^\circ$ , respectively. As two dif-  
 453 ferent values of  $u_i$  and  $\alpha$  are obtained by the extracted method, the values and error-  
 454 bars used in the following correspond to the averaged value and the standard deviation,  
 455 respectively.



**Figure 10.** (a) Initial velocity  $u_i$  (inset: initial angle  $\alpha$ ) as a function of the front-velocity  $u_f$  of gas-fluidized granular flows (circles) and dense liquid flows (squares) at the impact with water, with  $\theta = 15^\circ$ . The solid line is  $u_i = 2u_f - 3$ , and the dashed line and gray area correspond to  $\alpha = 50 \pm 4^\circ$ . (b) Initial velocity  $u_i$  (opened circles) and front-velocity  $u_f$  (closed circles) as a function of the slope angle  $\theta$  of the inclined plane, with  $H_i \sim 22 \text{ cm}$ . The solid lines are  $u_i = 2.55 \text{ m.s}^{-1}$  and  $u_f = 0.06\theta + 1.9$ , respectively. Inset:  $\alpha$  as a function of  $\theta$ , with  $\alpha = 1.5\theta + 23$  (dashed line).

456 The estimated parameters of the model, i.e. the initial velocity  $u_i$  and the initial  
 457 angle  $\alpha$ , are plotted as a function of the relevant parameters of the problem, i.e. the flow-  
 458 front velocity  $u_f$  before entering water and the slope angle  $\theta$  of the inclined plane [Fig-  
 459 ure 10]. As expected, the initial velocity  $u_i$  is related to the flow-front velocity  $u_f$  be-  
 460 ing the relevant velocity scale of the problem [Figure 10(a)]. By contrast, the initial an-  
 461 gle  $\alpha$  is not affected by  $u_f$ , which is found equal to  $\alpha = 50 \pm 4^\circ$ , for a given slope an-  
 462 gle of  $\theta = 15^\circ$  [dashed line and gray area, in the inset of Figure 10(a)]. Additionally,  
 463 Figure 10(b) shows the effect of  $\theta$  on the initial parameters ( $u_i, \alpha$ ) of the model. Sur-  
 464 prisingly,  $u_i$  remains broadly constant, while  $u_f$  increases for increasing  $\theta$  (opened vs.  
 465 closed symbols). Here, the variation of  $u_f$  is only attributed to the slope angle  $\theta$ , as the  
 466 initial height of the column is kept constant. This observation seems to be inconsistent  
 467 with the conclusions drawn from Figure 10(a), for which  $u_i$  and  $u_f$  increase together.  
 468 In fact, this could suggest that the driving effect of  $u_f$  on the initial velocity  $u_i$  is here  
 469 counterbalanced by a dissipative effect of  $\theta$ . In the inset of Figure 10(b), it is shown that  
 470  $\alpha$  increases with  $\theta$ . This means that grains sustain a change of their direction more abrupt  
 471 at larger  $\theta$  (i.e., from  $\alpha + \theta \sim 40^\circ$  to  $\alpha + \theta \sim 100^\circ$  with  $\theta = [5 : 30]^\circ$ ) which could  
 472 strongly promote dissipation in the system.

### 473 4.3 Discussion of results

474 Experiments showed that the spatio-temporal evolution of the position of the granu-  
 475 lar jet crest above the water surface can be well described using the theoretical predic-  
 476 tion of a frictionless ballistic motion. This simple model requires only two parameters,  
 477 i.e. the initial velocity  $u_i$  and the initial angle  $\alpha$  of the ballistic trajectory, which are di-



478 rectly related to the flow-front velocity  $u_f$  and the slope angle  $\theta$  of the inclined plane.  
 479 In the following, the predictive model is applied to a recent natural event to assess its  
 480 accuracy for geophysical applications.

481 Stromboli volcano (Italy) has persistent explosive activity with several hundreds  
 482 of moderate-intensity events per day, and some notable paroxysmal phases. The 03 July  
 483 and 28 August 2019 paroxysmal explosions produced eruptive columns of more than 5  
 484 km height, whose collapse generated pyroclastic density currents travelling rapidly along  
 485 the northern flank of the volcano and entering the Mediterranean Sea (Giudicepietro et  
 486 al., 2020). Recorded images of the impact of pyroclastic density currents into water showed  
 487 the generation of volcanoclastic jets above the sea level, from which the maximum height  
 488 of a granular jet crest could be approximately estimated as  $Y_c^m \sim 200$  m. In the present  
 489 case, equation (4) can therefore be reversed to provide an estimate of the impact veloc-  
 490 ity of the pyroclastic flow, knowing that the values of both  $u_f \sim 70$  m.s<sup>-1</sup> and  $\alpha \sim$   
 491  $50^\circ$  are also extracted from videos of LBZ webcam of Laboratorio Geofisica Sperimen-  
 492 tale (lgs.geo.unifi.it). The predictive model gives an impact velocity of  $u_i \sim 68$  m.s<sup>-1</sup>,  
 493 with  $Y_c^m = 200$  m and  $\alpha = 50^\circ$ , which is in excellent agreement with the direct mea-  
 494 surement of the flow velocity  $u_f \sim 70$  m.s<sup>-1</sup>. It should be mentioned, however, that  
 495 recorded images suggest a lower streamwise position  $X_c^m$  of the maximum crest height  
 496 compared to the vertical position  $Y_c^m$ , unlike the prediction of the model, but the esti-  
 497 mate of  $X_c^m$  is poorly constrained. In any case, this result suggests that the theoretical  
 498 prediction of a frictionless ballistic motion could be successfully used for granular jets gen-  
 499 erated by fine-grained geophysical flows entering water to provide an estimate of their  
 500 impact velocity, which is invaluable for the hazard assessment of tsunami generation.

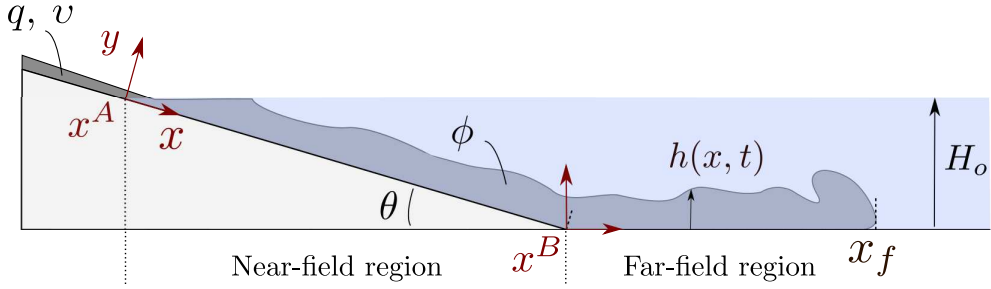
## 501 **5 Flow dynamics of the particle-driven gravity current**

502 In this section, we focus on the propagation of particle-driven gravity currents along  
 503 the inclined plane and the horizontal bottom underwater, referred to as the near- and  
 504 far-field regions, respectively (Figure 11). The current is characterized by the height pro-  
 505 file  $h(x, t)$ , the front position  $x_f$ , and the bulk volume concentration of particles  $\phi$  as  
 506 a function of the flow rate per unit width  $q$  and the volume per unit width  $v$  of the gran-  
 507 ular flow, the slope angle  $\theta$  and the water depth  $H_o$ . It should be remembered that the  
 508 gas-fluidized granular flow enters the water body at  $x_f = x^A$  and  $t = t^A$ , and then  
 509 the current reaches the slope break at  $x_f = x^B$  and  $t = t^B$ .

### 510 **5.1 Near-field region: gravity current over an inclined plane**

511 The first stage of the flow dynamics of particle-driven gravity currents underwa-  
 512 ter corresponds to the flow propagation along the inclined plane in the near-field region.  
 513 It can already be anticipated that the water depth  $H_o$  could be disregarded here, being  
 514 sufficiently far from the inclined plane. This is supported by results (Figure S1, in the  
 515 Supporting Information) and the present configuration is therefore reduced to three con-  
 516 trol parameters here, i.e.  $q$ ,  $v$  and  $\theta$ .

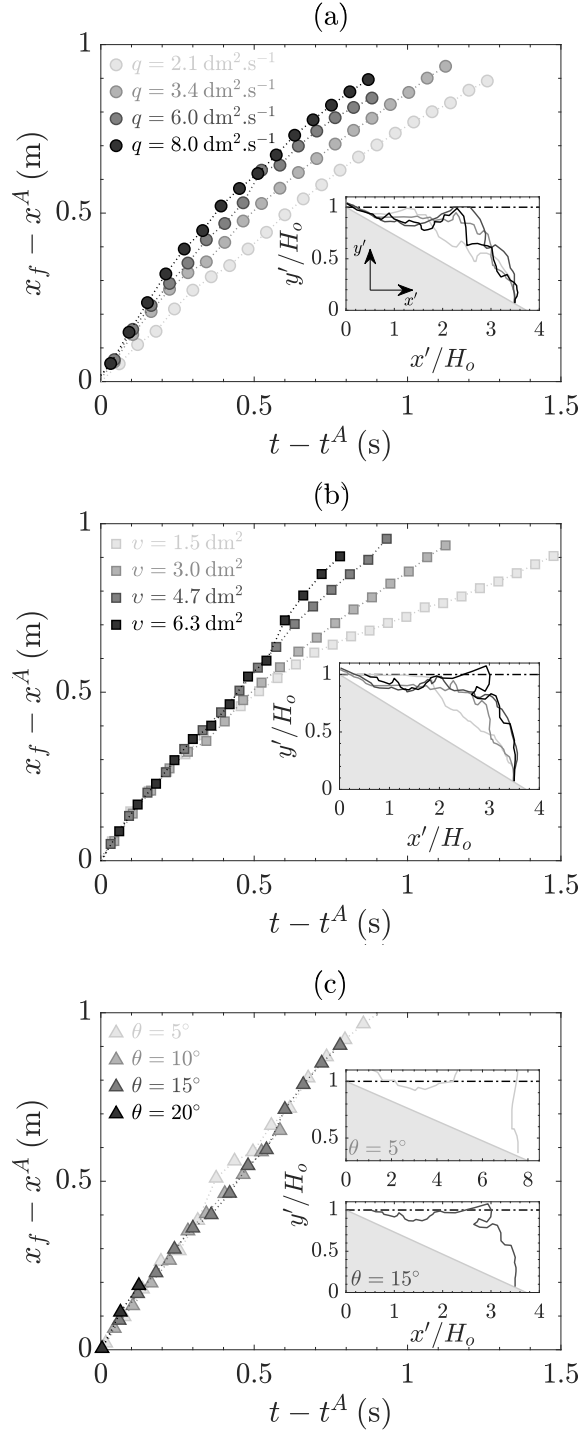
517 Figure 12 shows the temporal evolution of the front position  $x_f - x^A$  varying (a)  
 518 the flow rate per unit width  $q$ , (b) the volume per unit width  $v$ , and (c) the slope an-  
 519 gle  $\theta$  of the inclined plane. In the first two cases, other control parameters are strictly  
 520 kept constant while, in the latter case, the flow-front velocity  $u_f$ , and therefore the flow  
 521 rate  $q$ , varies with the slope angle  $\theta$  of the inclined plane. First, it can be clearly observed  
 522 that both  $q$  and  $v$  affect the propagation of the front position, while  $\theta$  can be disregarded  
 523 here. More specifically,  $q$  modifies the whole propagation of the current, with in particu-  
 524 lar, a front propagation slower at lower  $q$  than at larger  $q$  [from light to dark gray, in  
 525 Figure 12(a)]. By contrast, the influence of  $v$  is only clear for  $t \gtrsim 0.5$  s, from which all  
 526 data deviate from the master curve. In this case, the flow front of currents propagates  
 527 slower at lower  $v$  than at larger  $v$  [from light to dark gray, in Figure 12(b)]. This tran-



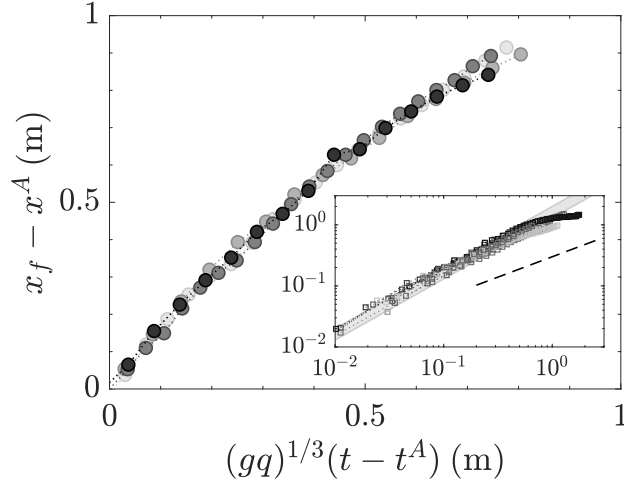
**Figure 11.** Sketch of the propagation of a particle-driven gravity current along a bottom plane with its macroscopic quantities [height profile  $h(x, t)$ , front position  $x_f$  and bulk volume concentration of particles  $\phi$ ], and the control parameters (flow rate per unit width  $q$  and volume per unit width  $v$  of the granular flow, slope angle  $\theta$ , and water depth  $H_o$ ) of the problem. The streamwise coordinates  $x^A$  and  $x^B$  indicate the transition from the 1 m-subaerial ramp to the immersed ramp, and the end of the inclined plane that connects to the horizontal bottom, respectively. The zones containing the immersed inclined plane and the horizontal bottom are referred to as the near- and far-field regions, respectively.

528 sient behavior can probably be attributed to the end of the granular inflow. Finally, the  
 529 influence of  $q$  and  $v$  is hardly observed from the height profile of currents (insets of Fig-  
 530 ure 12), which supports the idea that the front position evolution is more relevant to quan-  
 531 tify the flow dynamics of currents in the near-field region.

532 These results show that, as long as the entire granular volume has not yet entered  
 533 the fluid layer, the flow rate per unit width  $q$  mostly controls the front dynamics of the  
 534 gravity current beneath the free-surface. This observation can be related to a homoge-  
 535 neous gravity current produced by a constant flux over an inclined plane, for which the  
 536 front position scales as  $x_f \propto (g'Q)^{1/3}t$ , with  $g' = 2g(\rho - \rho_f)/(\rho + \rho_f)$  the reduced  
 537 gravity,  $\rho$  and  $\rho_f$  the densities of the current and of the surrounding fluid, respectively,  
 538 and  $Q$  the flow rate per unit width (Britter & Linden, 1980). It is difficult to consider  
 539 this scaling in the present configuration, given that the flow rate per unit width  $Q$  be-  
 540 neath the free-surface and the bulk density  $\rho$  of currents are unknown. However, we make  
 541 the somewhat crude assumptions that the flow rate per unit width  $q$  at the impact is re-  
 542 lated to the flow rate per unit width  $Q$  beneath the free-surface, and that the bulk vol-  
 543 ume concentration of particles  $\phi$ , and therefore the reduced gravity  $g'$ , do not vary sig-  
 544 nificantly in the range of parameters considered here. The latter issue will be more fully  
 545 discussed in Sec. 5.2. Under these assumptions, the front position  $x_f - x^A$  is plotted  
 546 as a function of  $(gq)^{1/3}(t - t^A)$  in Figure 13, for the same set of experiments shown in  
 547 Figure 12(a). Surprisingly, a very good collapse of the experimental data is obtained for  
 548 different flow rates per unit width  $q$ , which supports the use of this scaling. More specif-  
 549 ically, it is not necessary to consider the reduced gravity  $g'$ , which means that the par-  
 550 ticle concentration  $\phi$  of currents is fairly constant here. The inset of Figure 13 shows that  
 551 all experimental data are included in a low interval delimited by two scaling laws, i.e.  
 552  $x_f - x^A = \lambda(gq)^{1/3}(t - t^A)$  with  $\lambda = 1.3$  and 2 (gray area). At large times, the front  
 553 position deviates from the linear trend, which is probably caused by the end of the gran-  
 554 ular inflow. The dynamics could tend towards the power-law evolution  $x_f \propto t^{2/3}$  of a  
 555 finite volume released over an inclined plane (Dai, 2013, 2014), represented by the dashed  
 556 line in the inset of Figure 13. However, the inclined plane is not long enough in this study  
 557 to fully support this interpretation.



**Figure 12.** Near-field region: temporal evolution of the front position  $x_f - x^A$  of the particle-driven gravity currents by varying (a) the flow rate per unit width  $q$  ( $v \sim 3.1 \text{ dm}^2$ ,  $\theta = 15^\circ$ ), (b) the volume per unit width  $v$  ( $q \sim 3.3 \text{ dm}^2 \cdot \text{s}^{-1}$ ,  $\theta = 15^\circ$ ), and (c) the slope angle  $\theta$  ( $q = [2.6 : 4.3] \text{ dm}^2 \cdot \text{s}^{-1}$ ,  $v \sim 6.2 \text{ dm}^2$ ). Insets: Height profile of currents along the inclined plane, at  $x_f - x^A \sim 1$  m.



**Figure 13.** Near-field region: front position  $x_f - x^A$  of the particle-driven gravity currents as a function of  $(gq)^{1/3}(t - t^A)$  [based on Britter and Linden (1980)], for the same set of experiments shown in Figure 12(a) (inset: for the whole set of experiments, in a log-log representation). Gray area:  $x_f - x^A = \lambda(gq)^{1/3}(t - t^A)$  delimited by  $\lambda = 1.3$  and  $2$ ; (---)  $x_f - x^A \propto (t - t^A)^{2/3}$ .

558

## 5.2 Far-field region: gravity current over a horizontal bottom

559

560

561

562

563

564

565

566

567

568

The front of the particle-driven gravity current reaches the slope break, at  $x_f - x^B = 0$  and  $t - t^B = 0$ . Then, it propagates on the horizontal bottom until it reaches the end of the channel, referred to as the far-field region. Figure 14 shows  $x_f - x^B$  as a function of  $t - t^B$  for different flow rates per unit width  $q$  and volumes per unit width  $v$  of the granular flow, while the water depth and the slope angle are set to  $H_o \sim 26.5$  cm and  $\theta = 15^\circ$ , respectively. Additionally, the front dynamics of homogeneous gravity currents generated by the impact of dense liquid flows into water is shown, for different  $q$  and  $v$  (blue circles, in inset of Figure 14). Note that, at early times of the propagation, the partial mixing between the dense liquid and water prevents the tracking of the invisible front of the currents.

569

570

571

572

573

574

575

576

577

578

579

At early times, the front position  $x_f - x^B$  increases faster for larger  $v$  (from light to dark gray symbols), due to the flow dynamics of the current in the near-field region. Then, at sufficiently long times, all experimental data collapse on a master curve with a linear trend (dashed line), regardless of  $q$  and  $v$ . In contrast, at sufficiently low  $v \lesssim 2.3$  dm<sup>2</sup> (cross symbols, in inset of Figure 14), the front position deviates from the linear trend and tends towards a slope of  $2/3$  (solid line). Surprisingly, the constant front-velocities of both particle-driven gravity currents (black symbols, in Figure 14) and homogeneous gravity currents (blue circles, in inset of Figure 14) are similar for different  $q$  and  $v$ . More specifically, one obtains  $dx_f/dt \sim 0.35$  m.s<sup>-1</sup> (dashed lines), which suggests that both currents have similar densities, and this point will be further discussed in the following.

580

581

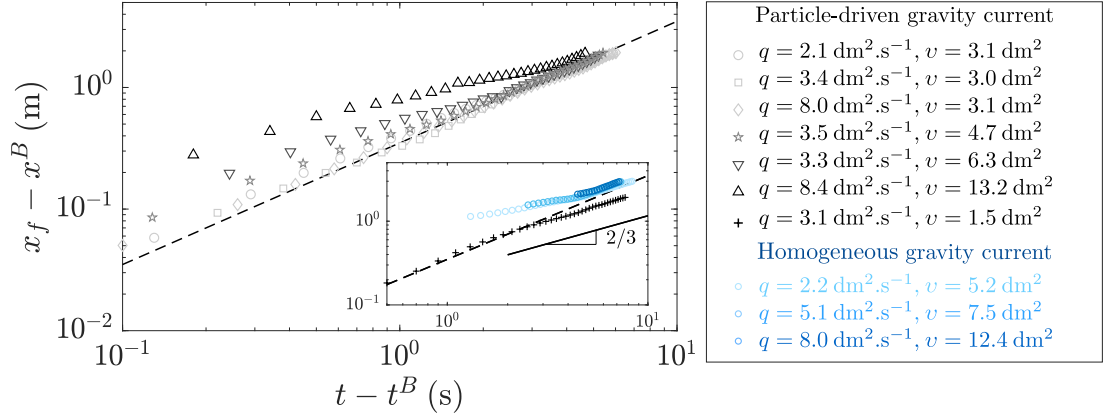
582

583

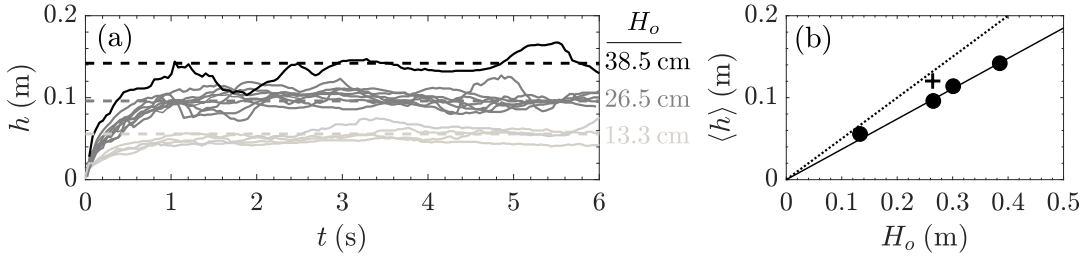
584

585

Figure 15(a) shows the temporal evolution of the height  $h$  of particle-driven gravity currents at  $x \sim 3.5$  m. The height  $h$  increases rapidly at the front and then remains roughly constant over time (dashed lines), despite Kelvin-Helmholtz instabilities at the interface. Moreover, the constant height of the current behind the front, noted  $\langle h \rangle$ , is only dependent on the water depth  $H_o$ , while the flow rate per unit width  $q$ , the volume per unit width  $v$ , and the slope angle  $\theta$  are varied. In Figure 15(b),  $\langle h \rangle$  increases linearly



**Figure 14.** Far-field region: temporal evolution of the front position  $x_f - x^B$  of the particle-driven gravity currents (gray symbols) and homogeneous gravity currents (blue circles) as a function of time since arrival at the slope break, for different flow rates  $q$  and volumes per unit width  $v$ . The water depth and the slope angle are set to  $H_o \sim 26.5 \text{ cm}$  and  $\theta = 15^\circ$ , respectively. The dashed line is  $x_f - x^B = 0.35(t - t^B)$  and the solid line represents a slope of  $2/3$ .



**Figure 15.** Far-field region: (a) Temporal evolution of the height  $h$  of particle-driven gravity currents at  $x \sim 3.5 \text{ m}$ , for different flow rates per unit width  $q$  and volumes per unit width  $v$  of the granular flow, water depths  $H_o$  and slope angles  $\theta$ . Here, the time  $t = 0$  corresponds to the arrival time of the current front at the given position. The dashed lines indicate the constant height  $\langle h \rangle$  of currents behind the front. (b)  $\langle h \rangle$  as a function of  $H_o$ , for particle-driven gravity currents (full circles) and homogeneous gravity currents (cross). The lines are  $\langle h \rangle = \gamma H_o$ , with the best fit  $\gamma = 0.37$  (solid line) and the theoretical value  $\gamma = 0.5$  (dotted line) for homogeneous gravity currents in the full-depth lock-exchange, respectively.

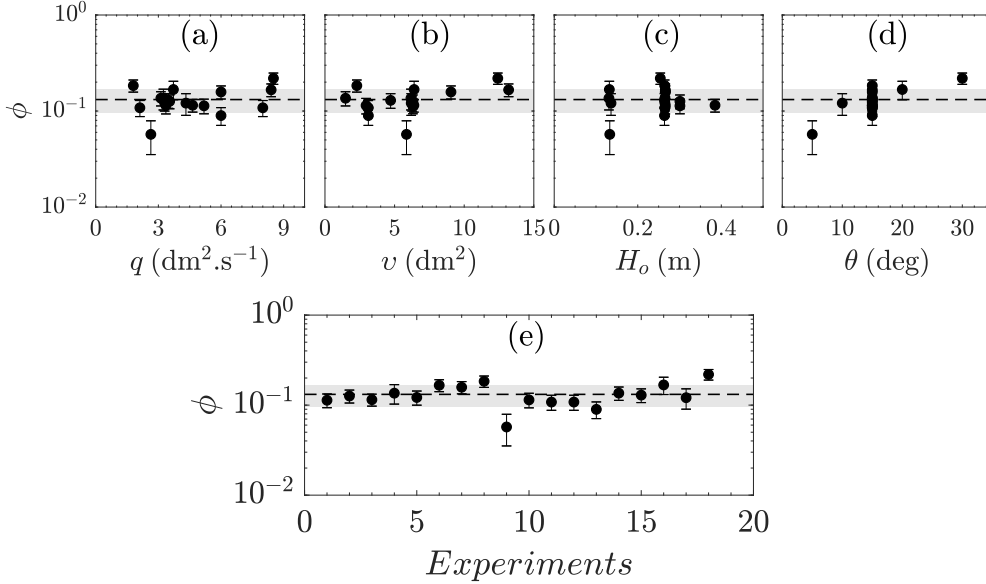
586 with  $H_o$ , and in particular, it is found that  $\langle h \rangle \sim 0.37H_o$  (solid line). Note that  $\langle h \rangle$  is  
 587 slightly lower for particle-driven gravity currents (full circles) than for homogeneous grav-  
 588 ity currents (cross), which could be attributed to the different mixing efficiencies at the  
 589 interface. Finally, the dotted line represents the theoretical value  $\langle h \rangle = 0.5H_o$ , for ho-  
 590 mogeneous gravity currents in the full-depth lock-exchange (Ungarish, 2007; Bonometti  
 591 & Balachandar, 2010). Experimental data of both particle-driven and homogeneous grav-  
 592 ity currents are lower than the theoretical prediction, which is partly consistent with other  
 593 experimental studies (Rottman & Simpson, 1983; Lowe et al., 2005). In particular, Lowe  
 594 et al. (2005) showed that the decrease of the density ratio  $\rho_f/\rho$  between the surround-  
 595 ing fluid and the current could decrease the parameter  $\gamma$  (see their Figure 12), but it can-  
 596 not fully explain the values obtained here.

597 In view of these results, the motion of particle-driven gravity currents in the far-  
 598 field region can be roughly related to that of homogeneous gravity currents in the full-  
 599 depth lock-exchange, far enough from the shoreline where the propagation in the near-  
 600 field region does not affect yet the front dynamics. In the present work, most of currents  
 601 exhibit a constant height and velocity of the front similar to the slumping regime while,  
 602 at low  $v$ , the front position evolves as  $x_f \propto t^{2/3}$  according to the inertial self-similar  
 603 regime. In both regimes, the preponderance of inertia over viscous effects can be quan-  
 604 tified by the Reynolds number  $Re = (\rho \langle h \rangle / \mu)(dx_f/dt)$ , where  $\rho \sim \rho_f$  and  $\mu \sim \mu_f$  are  
 605 the density and the viscosity of currents estimated as those of water given that the bulk  
 606 particle concentration remains sufficiently low [see Figure 16(e)], and  $\langle h \rangle$  and  $dx_f/dt$  are  
 607 the height and the front velocity of currents in the far-field region. The Reynolds num-  
 608 ber is in the range  $Re = [10^4 : 6 \times 10^4]$ , much larger than one. Now, let us consider  
 609 that the theoretical relation of the constant flow-front velocity, i.e.  $dx_f/dt = 0.5(g''H_o)^{1/2}$   
 610 with  $g'' = g(\rho - \rho_f)/\rho_f$ , can be used here (Ungarish, 2007). It should be remembered  
 611 that this relation is applicable as long as the settling of grains is sufficiently slow along  
 612 the time and the particle concentration is not too high, i.e.  $\phi \lesssim 0.3$  (Hallworth & Hup-  
 613 pert, 1998). These assumptions seem to be reasonable here because the constant front  
 614 velocity of currents is broadly maintained until  $x_f - x^B \sim 2$  m corresponding to the  
 615 tracked propagation, and the bulk particle concentration of the currents is thereafter es-  
 616 timated of the order of  $\mathcal{O}(0.1)$  [Figure 16(e)]. Now, the above-mentioned equation of the  
 617 front velocity can be reversed to estimate the bulk concentration of particle-driven grav-  
 618 ity currents because the density and the concentration are related by  $\rho = \phi\rho_p + (1 -$   
 619  $\phi)\rho_f$ , where  $\rho_p = 2550 \text{ kg.m}^{-3}$  and  $\rho_f = 1000 \text{ kg.m}^{-3}$  are the densities of grains and  
 620 water, respectively. Recall that the bulk particle concentration of currents corresponds  
 621 to  $\phi = V_{grains}/V_{current}$ , where  $V_{grains}$  and  $V_{current}$  denote the volume of grains and the  
 622 total volume of the current, respectively. In this way, one obtains

$$\phi = \frac{4\rho_f}{(\rho_p - \rho_f)gH_o} \left( \frac{dx_f}{dt} \right)^2. \quad (5)$$

623 No clear trend is obtained between the bulk volume concentration of particles  $\phi$   
 624 and the flow rate per unit width  $q$ , the volume per unit width  $v$ , and the water depth  
 625  $H_o$ , which suggests its independency on these different parameters [Figure 16(a)-(c)]. By  
 626 contrast, the slope angle  $\theta$  of the inclined plane seems to affect the concentration of cur-  
 627 rents, in the far-field region [Figure 16(d)]. More specifically, a steeper slope angle  $\theta$  of  
 628 the inclined plane promotes a larger bulk particle concentration of currents. Now, re-  
 629 gardless of the role of  $\theta$ , the bulk concentration of particle-driven gravity currents is roughly  
 630 constant in the set of experiments, with an order of magnitude of  $\phi \sim \mathcal{O}(0.1)$  [Figure  
 631 16(e)]. More precisely, it is found that  $\phi \sim 0.13 \pm 0.035$  (dashed line and gray area),  
 632 but some caution has to be exercised with the obtained value because some crude as-  
 633 sumptions were made through the model. This result suggests, however, that an increase  
 634 of the front velocity, the front height, or the volume of the granular flow do not increase  
 635 the bulk particle concentration  $\phi$  of the currents interpreted as a critical value. This crit-  
 636 ical value of  $\phi$  corresponds to a current density of  $\rho \sim 1.20 \pm 0.09 \text{ g.cm}^{-3}$ , similar to  
 637 that of homogeneous gravity currents in our experiments. This could explain that the  
 638 front-velocity of both particle-driven and homogeneous gravity currents is similar in the  
 639 far-field region (see Figure 14). Moreover, the constant value of  $\phi$  supports the idea that  
 640 the relative gravity can be disregarded using Britter and Linden's scaling in the near-  
 641 field region (see Figure 13). Finally, Freundt (2003) also estimated the density of particle-  
 642 driven gravity currents generated by experimental volcanic ash flows entering water based  
 643 on the front dynamics of the currents. He reported a bulk density of currents evolving  
 644 from  $\rho \sim 1.15 - 1.25 \text{ g.cm}^{-3}$  proximally to  $< 1.01 \text{ g.cm}^{-3}$  near the tank end, corre-  
 645 sponding to bulk particle concentrations from 0.16 - 0.27 proximally to 0.01 distally.  
 646 The strong decrease of the particle concentration along the current propagation is at-

647 tributed to the high settling velocity of the ash material sieved at 4 mm, which is much  
 648 smaller in our experiments with glass beads of 65  $\mu\text{m}$ . In both cases, the bulk particle  
 649 concentration of currents proximally is estimated to be of the same order of magnitude,  
 650 i.e.  $\phi \sim 0.16 - 0.27$  for Freundt (2003)'s experiments and  $\phi \sim 0.13 \pm 0.035$  for our ex-  
 651 periments, while quantitative variations can be probably attributed to the different grain  
 652 properties (e.g., size, density, shape).



**Figure 16.** Bulk particle concentration  $\phi$  (in volume) of particle-driven gravity currents estimated by equation (5) in the far-field region, as a function of (a) the flow rate per unit width  $q$ , (b) the volume per unit width  $v$ , (c) the water depth  $H_o$ , (d) the slope angle  $\theta$  of the inclined plane, and (e) for all experiments of the present study. The dashed line and gray area correspond to the mean value and the standard deviation, i.e.  $\phi \sim 0.13 \pm 0.035$ .

### 653 5.3 Discussion of results

654 In the natural environment, there are few measurements of particle concentration  
 655 in subaqueous particle-laden flows due to the difficulty of predicting them. For turbid-  
 656 ity currents in which grains are mainly suspended by the turbulent fluid, available field  
 657 measurements showed that the volume concentration was usually lower than 0.01 (Talling  
 658 et al., 2013, and references herein). The indirect concentration measurements of subma-  
 659 rine currents caused by the 1929 Grand Banks event, however, give higher values of  $\sim$   
 660 0.03–0.05 (Stevenson et al., 2018). Moreover, recent works reported that the dilute clouds  
 661 of such currents can sometimes overlay dense basal layers (Paull et al., 2018; Simmons  
 662 et al., 2020; Wang et al., 2020). In fact, grains can theoretically be suspended by the fluid  
 663 turbulence up to a volume concentration of about 0.1, above which grains settle due to  
 664 the importance of grain-grain interaction (Bagnold, 1962). This threshold is in line with  
 665 the critical concentration obtained in our experiments, while other experimental stud-  
 666 ies also observed a threshold of the particle concentration in fluid-particle systems.

667 For the purpose of better understanding subaerial dilute pyroclastic density cur-  
 668 rents, Weit et al. (2018, 2019) performed experiments to study the spatial distribution  
 669 of solid grains into a gas-particle turbulent system. In a steady vertical flow in which grains  
 670 were poured gradually, the bulk particle concentration of the dilute gas-particle suspen-

671 sion increased with the added granular mass before it reached a threshold. Then, the ex-  
 672 cess of grains could not be suspended by the turbulent fluid and clusters were formed  
 673 and fell forming a basal concentrated granular bed. The coexistence of dilute and dense  
 674 regions controlled by clustering instabilities has also been observed for gas-particle gravity-  
 675 driven flows, which suggested that the upper dilute part was in its saturated-state (Breard  
 676 et al., 2016). Although clustering is poorly understood, it is usually attributed to dis-  
 677 sipation of the granular temperature by collisional contacts or to hydrodynamic insta-  
 678 bilities caused by the relative motion between the grains and the surrounding fluid (more  
 679 details in Fullmer & Hrenya, 2017, and references herein). In both above-mentioned ex-  
 680 periments, the critical volume concentration of the dilute region was a few percent, much  
 681 lower than in our experiments. Yet, subaerial pyroclastic density currents and subaque-  
 682 ous turbidity currents share common characteristics, such as the turbulent-multiphase  
 683 nature and the potential formation of dense granular regions (Doronzo & Dellino, 2010).  
 684 For grains suspended in water by a vertical oscillating grid, the particle concentration  
 685 also saturated to a critical value depending on the oscillation frequency, but the clus-  
 686 tering instabilities disappeared (Bennett et al., 2013, 2014).

687 In view of these findings, the particle-driven gravity currents in our experiments  
 688 could be related to physical mechanisms similar to those mentioned above. The impact  
 689 between the granular flow and water generated a turbulent mixing zone, in which grains  
 690 were suspended by the turbulent fluid. The bulk volume concentration of particles ex-  
 691 ceeded a critical value, leading to a saturated upper region in which the excess of grains  
 692 probably fell, forming a basal concentrated region. For all experiments, a thick and vo-  
 693 luminous granular deposit was obtained along the inclined plane, which could be inter-  
 694 preted as the final state of the dense granular flow (see Figure 6). Unfortunately, the flow  
 695 dynamics of the dense basal region cannot be observed directly because of the visual lim-  
 696 itations of the optical shadowgraph method. Under the influence of gravity, the upper  
 697 dilute suspension at critical particle concentration collapsed on the inclined plane form-  
 698 ing the particle-driven gravity current. Compared to gas-particle turbulent systems with  
 699 critical volume concentrations less than  $\sim 0.03$ – $0.04$ , the high value of the critical con-  
 700 centration observed here could be attributed to different grain-fluid interaction. It is prob-  
 701 able that the clustering instabilities control the critical concentration of gas-particle flows,  
 702 in response to different settling rates between individual particles and clusters. This phys-  
 703 ical mechanism is mainly controlled by the grain inertia through the Stokes number, which  
 704 is usually defined as the ratio between the particle inertial response time and the tur-  
 705 bulent timescale (Warhaft, 2009). For liquid-particle systems, however, further work will  
 706 be necessary to highlight the physical mechanisms controlling the critical concentration  
 707 of particles.

## 708 6 Conclusion

709 Well-controlled laboratory experiments focusing on the entrance of gas-fluidized  
 710 granular flows into water have been performed, and backed up by theoretical models, to  
 711 understand better the motion of geophysical granular flows going down a mountainside,  
 712 then entering the sea, a lake or a river, and finally propagating underwater for what can  
 713 be a considerable distance. The consideration of fluidized granular flows ensured a more  
 714 suitable modelling of highly-mobile fine-grained geophysical flows, which are predisposed  
 715 to reach the coast and generate turbidity currents. First, the presence of a water body  
 716 promoted the generation of a granular jet over the free-surface, a leading and largest wave,  
 717 and a turbulent mixing zone from which a particle-driven gravity current was sponta-  
 718 neously formed. Overall, hydrodynamic forces played a dissipative role by slowing and  
 719 reducing the spreading of the granular mass along the bottom plane. However, a low amount  
 720 of grains were still transported by the turbulent fluid like a gravity current propagating  
 721 far away, showing both the dissipative and driving role of the fluid. Then, the granular  
 722 jet and the particle-driven gravity current were analyzed by tracking the spatio-temporal



723 evolution of the jet crest and the current front, respectively. The trajectory of the gran-  
 724 ular jet was well described by the theoretical prediction of frictionless ballistic motion,  
 725 for which the initial parameters of the model depended on the flow-front velocity and  
 726 the slope angle of the inclined plane. The flow dynamics of particle-driven gravity cur-  
 727 rents was described in two distinguished regions beneath the water surface, namely along  
 728 the inclined plane and the horizontal plane, referred to as the near- and far-field regions,  
 729 respectively. In the near-field region, the propagation of the current mainly depended  
 730 on the flow rate per unit width  $q$  and the temporal evolution of the front position scaled  
 731 with time as  $x_f \sim (gq)^{1/3}t$ , with  $g$  the gravitational acceleration, in agreement with ear-  
 732 lier findings. Then, the granular inflow was stopped and the finite volume affected the  
 733 motion of the current from the above-mentioned scaling. In the far-field region, the evo-  
 734 lution of the front position was similar to that of homogeneous gravity currents in the  
 735 full-depth lock-exchange configuration. The particle-driven gravity current first evolved  
 736 with a constant-front velocity in the so-called slumping regime, then the front deceler-  
 737 ated and its position scaled as  $x_f \sim t^{2/3}$  in the inertial self-similar regime. During the  
 738 slumping regime, the constant flow-front velocity was only controlled by the height of  
 739 the current depending on the water depth. More specifically, the bulk particle concen-  
 740 tration of the current was roughly constant, i.e.  $\phi \sim 0.13 \pm 0.035$  (in volume), in the  
 741 range of parameters considered. This result is interpreted as a critical concentration reached  
 742 in turbulent fluid-particle flows, above which the excess of particles cannot be maintained  
 743 by the turbulent fluid.

744 This study provides the conclusions that highly mobile fine-grained geophysical flows  
 745 entering water are predisposed to generate granular jets above the free surface and di-  
 746 lute particle-driven gravity currents underwater. Both can be fairly well predicted us-  
 747 ing simple theoretical models capturing most of the physical mechanisms, which are of  
 748 interest for geophysical purposes. Lastly, the bulk particle concentration of gravity cur-  
 749 rents generated by rapid granular flows entering water reaches a threshold, which needs  
 750 further work to investigate the influence of grains properties (e.g., density, diameter) and  
 751 to support this outcome by direct measurements.

## 752 Acknowledgments

753 This work was funded by the ANR RAVEX (ANR-16-CE03-0002) project. The authors  
 754 acknowledge the technical support of the Laboratoire Magmas et Volcans (Marc Nivoix,  
 755 Eric Brut, Jean-Louis Fruquière, Cyrille Guillot) for their contribution in designing and  
 756 constructing the experimental setup. We thank the anonymous reviewers for their con-  
 757 structive comments that helped to improve the initial manuscript. This is ClerVolc con-  
 758 tribution n°470. Data presented in this paper are partly in open access at  
 759 <https://doi.org/10.6084/m9.figshare.12137373>

## 760 References

- 761 Allen, S. R., Freundt, A., & Kurokawa, K. (2012). Characteristics of submarine  
 762 pumice-rich density current deposits sourced from turbulent mixing of sub-  
 763 aerial pyroclastic flows at the shoreline: field and experimental assessment.  
 764 *Bull. Volcanol.*, *74*, 657–675.
- 765 Ancy, C., Iverson, R. M., Rentschler, M., & Denlinger, R. P. (2008). An exact  
 766 solution for ideal dam-break floods on steep slopes. *Water Resour. Res.*, *44*,  
 767 W01430.
- 768 Bagnold, R. A. (1962). Auto-suspension of transported sediment: turbidity currents.  
 769 *Proc. Roy. Soc. London A*, *265*, 315–319.
- 770 Baines, P. (2001). Mixing in flows down gentle slopes into stratified environments. *J.*  
 771 *Fluid Mech.*, *443*, 237–270.
- 772 Baines, P. (2005). Mixing regimes for the flow of dense fluid down slopes into strati-  
 773 fied environments. *J. Fluid Mech.*, *538*, 245–267.

- 774 Beghin, P., Hopfinger, E. J., & Britter, R. E. (1981). Gravitational convection from  
775 instantaneous sources on inclined boundaries. *J. Fluid Mech.*, *107*, 407–422.
- 776 Bennett, S. J., Atkinson, J. F., Hou, Y., & Fay, M. J. (2013). Turbulence modu-  
777 lation by suspended sediment in a zero mean-shear geophysical flow. *Coherent*  
778 *Flow Structures at Earth’s Surface*, 309–321.
- 779 Bennett, S. J., Hou, Y., & Atkinson, J. F. (2014). Turbulence suppression by sus-  
780 pended sediment within a geophysical flow. *Environ. Fluid Mech.*, *14*, 771–794.
- 781 Bonnecaze, R. T., Hallworth, M. A., Huppert, H. E., & Lister, J. R. (1995). Axisym-  
782 metric particle-driven gravity currents. *J. Fluid Mech.*, *294*, 93–121.
- 783 Bonnecaze, R. T., Huppert, H. E., & Lister, J. R. (1993). Particle-driven gravity  
784 currents. *J. Fluid Mech.*, *250*, 339–369.
- 785 Bonometti, T., & Balachandar, S. (2010). Slumping of non-Boussinesq density  
786 currents of various initial fractional depths: a comparison between direct nu-  
787 merical simulations and a recent shallow-water model. *Comput. Fluids*, *39*(4),  
788 729–734.
- 789 Bonometti, T., Balachandar, S., & Magnaudet, J. (2008). Wall effects in non-  
790 Boussinesq density currents. *J. Fluid Mech.*, *616*, 445–475.
- 791 Bougouin, A., Lacaze, L., & Bonometti, T. (2017). Collapse of a neutrally buoyant  
792 suspension column: from Newtonian to apparent non-Newtonian flow regimes.  
793 *J. Fluid Mech.*, *826*, 918–941.
- 794 Bougouin, A., Paris, R., & Roche, O. (2019). Ecoulement granulaire fluidisé impac-  
795 tant l’eau: Application aux tsunamis volcaniques. *24ème Congrès français de*  
796 *mécanique*, Brest, France.
- 797 Bougouin, A., Paris, R., & Roche, O. (2020). Impact of fluidized granular flows into  
798 water: Implications for tsunamis generated by pyroclastic flows. *J. Geophys.*  
799 *Res. Solid Earth*, *125*, e2019JB018954.
- 800 Bowden, F. P., & Hughes, T. P. (1939). The mechanism of sliding on ice and snow.  
801 *Proc. of the Royal Society of London. Series A.*, *172*, 280–298.
- 802 Breard, E. C. P., Lube, G., Jones, J. R., Dufek, J., Cronin, S. J., Valentine, G. A.,  
803 & Moebis, A. (2016). Coupling of turbulent and non-turbulent flow regimes  
804 within pyroclastic density currents. *Nat. Geosci.*, *9*, 767–771.
- 805 Britter, R. E., & Linden, P. F. (1980). The motion of the front of a gravity current  
806 travelling down an incline. *J. Fluid Mech.*, *99*, 531–543.
- 807 Brodu, N., Delannay, R., Valance, A., & Richard, P. (2015). New patterns of high-  
808 speed granular flows. *J. Fluid Mech.*, *769*, 218–228.
- 809 Bullard, G. K., Mulligan, R. P., Carreira, A., & Take, W. A. (2019). Experimental  
810 analysis of tsunamis generated by the impact of landslides with high mobility.  
811 *Coast. Eng.*, *152*, 103538.
- 812 Cas, R. A. F., & Wright, J. V. (1991). Subaqueous pyroclastic flows and ignimbrites:  
813 an assessment. *Bull. Volcanol.*, *53*, 357–380.
- 814 Clous, L., Le Guer, Y., & Abbadie, S. (2019). Génération de vagues par des coulées  
815 liquides : application aux écoulements pyroclastiques. *24ème Congrès français*  
816 *de mécanique*, Brest, France.
- 817 Collins, G. S., & Melosh, H. J. (2003). Acoustic fluidization and the extraordinary  
818 mobility of sturzstroms. *J. Geophys. Res.*, *108*, 2473–2487.
- 819 Cortés, A., Rueda, F. J., & Wells, M. G. (2014). Experimental observations of  
820 the splitting of a gravity current at a density step in a stratified water body. *J.*  
821 *Geophys. Res. Oceans*, *119*, 1038–1053.
- 822 Dai, A. (2013). Experiments on gravity currents propagating on different bottom  
823 slopes. *J. Fluid Mech.*, *731*, 117–141.
- 824 Dai, A. (2014). Non-Boussinesq gravity currents propagating on different bottom  
825 slopes. *J. Fluid Mech.*, *741*, 658–680.
- 826 Dai, A., & Garcia, M. (2010). Gravity currents down a slope in deceleration phase.  
827 *Dyn. Atmos. Oceans*, *49*.

- 828 Davies, T. R., & McSaveney, M. J. (2009). The role of rock fragmentation in the  
829 motion of large landslides. *Eng. Geol.*, *109*, 67–79.
- 830 Davies, T. R. H. (1982). Spreading of rock avalanche debris by mechanical fluidiza-  
831 tion. *Rock Mech.*, *15*, 9–24.
- 832 De Blasio, F. V., Elverhoi, A., Engvik, L. E., Issler, D., Gauer, P., & Harbitz, C.  
833 (2006). Understanding the high mobility of subaqueous debris flows. *Nor. J.*  
834 *Geol.*, *86*, 275–284.
- 835 Delannay, R., Valance, A., Mangeney, A., Roche, O., & Richard, P. (2017). Granular  
836 and particle-laden flows: from laboratory experiments to field observations. *J.*  
837 *Phys. D*, *50*, 053001.
- 838 Doronzo, D. M., & Dellino, P. (2010). A fluid dynamic model of volcanoclastic  
839 turbidity currents based on the similarity with the lower part of dilute pyro-  
840 clastic density currents: evaluation of the ash dispersal from ash turbidites. *J.*  
841 *Volcanol. Geotherm. Res.*, *191*, 193–204.
- 842 Dressler, R. F. (1954). Comparison of theories and experiments for the hydraulic  
843 dam-break wave. *Int. Assoc. Sci. Hydrology*, *3*, 319–328.
- 844 Edmonds, M., & Herd, R. A. (2005). Inland-directed base surge generated by  
845 the explosive interaction of pyroclastic flows and sea water at Soufrière Hills  
846 volcano, Montserrat. *Geology*, *33*, 245–248.
- 847 Farin, M., Mangeney, A., & Roche, O. (2014). Fundamental changes of granular flow  
848 dynamics, deposition, and erosion processes at high slope angles: Insights from  
849 laboratory. *J. Geophys. Res.*, *119*, 504–532.
- 850 Freundt, A. (2003). Entrance of hot pyroclastic flows into the sea: Experimental ob-  
851 servations. *Bull. Volcanol.*, *65*, 144–164.
- 852 Fritz, H. M., Hager, W. H., & Minor, H.-E. (2003a). Landslide generated impulse  
853 waves. 1. Instantaneous flow fields. *Exp. Fluids*, *35*, 505–519.
- 854 Fritz, H. M., Hager, W. H., & Minor, H.-E. (2003b). Landslide generated impulse  
855 waves. 2. Hydrodynamic impact craters. *Exp. Fluids*, *35*, 520–532.
- 856 Fullmer, W. D., & Hrenya, C. M. (2017). The clustering instability in rapid granular  
857 and gas-solid flows. *Annu. Rev. Fluid Mech.*, *49*, 485–510.
- 858 Giudicepietro, F., López, C., Macedonio, G., Alparone, S., Bianco, F., Calvari, S.,  
859 ... Tramelli, A. (2020). Geophysical precursors of the July-August 2019  
860 paroxysmal eruptive phase and their implications for Stromboli volcano (Italy)  
861 monitoring. *Sci. Rep.*, *10*, 1–16.
- 862 Goren, L., & A., E. (2007). Long runout landslides: the role of frictional heating and  
863 hydraulic diffusivity. *Geophys. Res. Lett.*, *34*, L07301.
- 864 Hallworth, M. A., & Huppert, H. E. (1998). Abrupt transitions in high-  
865 concentration, particle-driven gravity currents. *Phys. Fluids*, *10*, 1083–1087.
- 866 Heezen, B. C., & Ewing, M. (1952). Turbidity currents and submarine slumps, and  
867 the 1929 Grand Banks earthquake. *Am. J. Sci.*, *250*, 849–873.
- 868 Heezen, B. C., & Ewing, M. (1955). Orleansville earthquake and turbidity currents.  
869 *AAPG Bull.*, *39*, 2505–2514.
- 870 Heller, V., Hager, W. H., & Minor, H.-E. (2008). Scale effects in subaerial landslide  
871 generated impulse waves. *Exp. Fluids*, *44*, 691–703.
- 872 Hsu, S.-K., Kuo, J., Chung-Liang, L., Ching-Hui, T., Doo, W.-B., Ku, C.-Y., &  
873 Sibuet, J.-C. (2008). Turbidity currents, submarine landslides and the 2006  
874 Pingtung earthquake off SW Taiwan. *Terr. Atmos. Ocean Sci.*, *19*, 767–772.
- 875 Hungr, O., & Evans, S. G. (2004). Entrainment of debris in rock avalanches: an  
876 analysis of a long run-out mechanism. *Geol. Soc. Am. Bull.*, *116*, 1240–1252.
- 877 Huppert, H. E. (1982). The propagation of two-dimensional and axisymmetric vis-  
878 cous gravity currents over a rigid horizontal surface. *J. Fluid Mech.*, *121*, 43–  
879 58.
- 880 Huppert, H. E., & Simpson, J. E. (1980). The slumping of gravity currents. *J. Fluid*  
881 *Mech.*, *99*, 785–799.

- 882 Jánosi, I. M., Jan, D., Szabó, K. G., & Tél, T. (2004). Turbulent drag reduction in  
883 dam-break flows. *Exp. Fluids*, *37*, 219–229.
- 884 Kneller, B., & Buckee, C. (2000). The structure and fluid mechanics of turbidity  
885 currents: a review of some recent studies and their geological implications.  
886 *Sedimentology*, *47*, 62–94.
- 887 Kokelaar, P., & Busby, C. (1992). Subaqueous explosive eruption and welding of py-  
888 roclastic deposits. *Science*, *257*, 196–201.
- 889 Laubert, G., & Hager, W. H. (1998). Experiments to dambreak wave: Horizontal  
890 channel. *J. Hydraul. Res.*, *36*, 291–307.
- 891 Leal, J. G., Ferreira, R. M., & Cardoso, A. H. (2006). Dam-break wave-front veloc-  
892 ity. *J. Hydraul. Res.*, *132*, 69–76.
- 893 Le Friant, A., Deplus, C., Boudon, G., Feuillet, N., Trofimovs, J., Komorowski,  
894 J.-C., . . . Ryan, G. (2010). Eruption of Soufrière Hills (1995–2009) from  
895 an offshore perspective: Insights from repeated swath bathymetry surveys.  
896 *Geophys. Res. Lett.*, *37*.
- 897 Le Friant, A., Deplus, C., Boudon, G., Sparks, R. S. J., Trofimovs, J., & Talling, P.  
898 (2009). Submarine deposition of volcanoclastic material from the 1995–2005  
899 eruptions of Soufrière Hills volcano, Montserrat. *J. Geol. Soc.*, *166*, 171–182.
- 900 Legros, F., & Druitt, T. H. (2000). On the emplacement of ignimbrite in shallow-  
901 marine environments. *J. Volcanol. Geotherm. Res.*, *95*, 9–22.
- 902 Løvholt, F., Pedersen, G., Harbitz, C. B., Glimsdal, S., & Kim, J. (2015). On the  
903 characteristics of landslide tsunamis. *Phil. Trans. R. Soc. A*, *373*, 20140376.
- 904 Lowe, R. J., Rottman, J. W., & Linden, P. F. (2005). The non-Boussinesq lock-  
905 exchange problem. Part 1. Theory and experiments. *J. Fluid Mech.*, *537*, 101–  
906 124.
- 907 Major, J. J., & Iverson, R. M. (1999). Debris-flow deposition: Effects of pore-fluid  
908 pressure and friction concentrated at flow margins. *Geol. Soc. Am. Bull.*, *111*,  
909 1424–1434.
- 910 Mangeney, A., Roche, O., Hungr, O., Mangold, N., Faccanoni, G., & Lucas, A.  
911 (2010). Erosion and mobility in granular collapse over sloping beds. *J. Geo-  
912 phys. Res.*, *115*, F03040.
- 913 Mazzanti, P., & De Blasio, F. V. (2011). The dynamics of coastal landslides: In-  
914 sights from laboratory experiments and theoretical analyses. *Bull. Eng. Geol.  
915 Environ.*, *70*, 411–422.
- 916 Mcleod, P., Carey, S., & Sparks, R. S. J. (1999). Behaviour of particle-laden flows  
917 into the ocean: experimental simulation and geological implications. *Sedimen-  
918 tology*, *46*, 523–536.
- 919 Meiburg, E., & Kneller, B. (2010). Turbidity currents and their deposits. *Annu. Rev.  
920 Fluid Mech.*, *42*, 135–156.
- 921 Melosh, H. J. (1979). Acoustic fluidization: A new geologic process? *J. Geophys.  
922 Res.*, *84*, 7513–7520.
- 923 Miller, G. S., Andy T., W., Mulligan, R. P., & McDougall, S. (2017). Tsunamis gen-  
924 erated by long and thin granular landslides in a large flume. *J. Geophys. Res.*,  
925 *122*, 653–668.
- 926 Monaghan, J. J. (2007). Gravity current interaction with interfaces. *Annu. Rev.  
927 Fluid Mech.*, *39*, 245–261.
- 928 Monaghan, J. J., Cas, R. A. F., Kos, A. M., & Hallworth, M. (1999). Gravity cur-  
929 rents descending a ramp in a stratified tank. *J. Fluid Mech.*, *379*.
- 930 Mulder, T., Savoye, B., & Syvitski, J. P. M. (1997). Numerical modelling of a  
931 mid-sized gravity flow: the 1979 Nice turbidity current (dynamics, processes,  
932 sediment budget and seafloor impact). *Sedimentology*, *44*, 305–326.
- 933 Paull, C. K., Talling, P. J., Maier, K. L., Parsons, D., Xu, J., Caress, D. W., . . .  
934 Cartigny, M. J. (2018). Powerful turbidity currents driven by dense basal  
935 layers. *Nat. Commun.*, *9*, 1–9.

- 936 Ritter, A. (1892). Die fortpflanzung der wasserwellen. *Z. Verein Deutch. Ing.*, *36*,  
937 947–954.
- 938 Roche, O., Montserrat, S., Niño, Y., & Tamburrino, A. (2008). Experimental  
939 observations of water-like behavior of initially fluidized, dam break granular  
940 flows and their relevance for the propagation of ash-rich pyroclastic flows. *J.*  
941 *Geophys. Res.*, *113*, B12203.
- 942 Rottman, J. W., & Simpson, J. E. (1983). Gravity currents produced by instan-  
943 taneous releases of a heavy fluid in a rectangular channel. *J. Fluid Mech.*, *135*,  
944 95–110.
- 945 Shreve, R. L. (1968). Leakage and fluidization in air-layer lubricated avalanches.  
946 *Geol. Soc. Am. Bull.*, *79*, 653–658.
- 947 Simmons, S. M., Azpiroz-Zabala, M., Cartigny, M. J. B., Clare, M. A., Cooper, C.,  
948 Parsons, D. R., ... Talling, P. J. (2020). Novel acoustic method provides first  
949 detailed measurements of sediment concentration structure within submarine  
950 turbidity currents. *J. Geophys. Res. Oceans*, *125*, e2019JC015904.
- 951 Sovilla, B., Burlando, P., & Bartelt, P. (2006). Field experiments and numerical  
952 modeling of mass entrainment in snow avalanches. *J. Geophys. Res.: Earth*  
953 *Surface*, *111*, F03007.
- 954 Sparks, R. S. J. (1976). Grain size variations in ignimbrites and implications for the  
955 transport of pyroclastic flows. *Sedimentology*, *23*, 147–188.
- 956 Sparks, R. S. J., Sigurdsson, H., & Carey, S. (1980). The entrance of pyroclastic  
957 flows into the sea. II. Theoretical considerations on subaqueous emplacement  
958 and welding. *J. Volcanol. Geotherm. Res.*, *7*, 97–105.
- 959 Stevenson, C. J., Feldens, P., Georgiopoulou, A., Schönke, M., Krastel, S., Piper,  
960 D. J. W., ... Mosher, D. (2018). Reconstructing the sediment concentration of  
961 a giant submarine gravity flow. *Nat. Commun.*, *9*, 1–7.
- 962 Talling, P. J., Paull, C. K., & Piper, D. J. W. (2013). How are subaqueous sediment  
963 density flows triggered, what is their internal structure and how does it evolve?  
964 Direct observations from monitoring of active flows. *Earth Sci. Rev.*, *125*,  
965 244–287.
- 966 Talling, P. J., Wynn, R. B., Masson, D. G., Frenz, M., Cronin, B. T., Schiebel, R.,  
967 ... Amy, L. A. (2007). Onset of submarine debris flow deposition far from  
968 original giant landslide. *Nature*, *450*, 541–544.
- 969 Trofimovs, J., Amy, L., Boudon, G., Deplus, C., Doyle, E., Fournier, N., ... Talling,  
970 P. J. (2006). Submarine pyroclastic deposits formed at the Soufrière Hills  
971 volcano, Montserrat (19952003): What happens when pyroclastic flows enter  
972 the ocean? *Geology*, *34*, 549–552.
- 973 Trofimovs, J., Foster, C., Sparks, R. S. J., Loughlin, S., Le Friant, A., Deplus, C., ...  
974 Le Bas, T. (2012). Submarine pyroclastic deposits formed during the 20th May  
975 2006 dome collapse of the Soufrière Hills Volcano, Montserrat. *Bull. Volcanol.*,  
976 *74*, 391–405.
- 977 Trofimovs, J., Sparks, R. S. J., & Talling, P. J. (2008). Anatomy of a submarine  
978 pyroclastic flow and associated turbidity current: July 2003 dome collapse,  
979 Soufrière Hills volcano, Montserrat, West Indies. *Sedimentology*, *55*, 617–634.
- 980 Ungarish, M. (2007). A shallow-water model for high-Reynolds-number gravity  
981 currents for a wide range of density differences and fractional depths. *J. Fluid*  
982 *Mech.*, *579*, 373–382.
- 983 Viroulet, S., Sauret, A., & Kimmoun, O. (2014). Tsunami generated by a granular  
984 collapse down a rough inclined plane. *EPL*, *105*, 34004.
- 985 Wadge, G., Voight, B., Sparks, R. S. J., Cole, P. D., Loughlin, S. C., & Robert-  
986 son, R. E. A. (2014). An overview of the eruption of Soufriere Hills volcano,  
987 Montserrat from 2000 to 2010. *Geol. Soc. Lond. Mem.*, *39*, 1–40.
- 988 Wang, Z., Xu, J., Talling, P. J., Cartigny, M. J. B., Simmons, S. M., Gwiazda, R.,  
989 ... Parsons, D. R. (2020). Direct evidence of a high-concentration basal layer  
990 in a submarine turbidity current. *Deep Sea Res. Part I*, 103300.

- 991 Warhaft, Z. (2009). Laboratory studies of droplets in turbulence: towards under-  
992 standing the formation of clouds. *Fluid Dyn. Res.*, *41*, 011201.
- 993 Weiss, R., Fritz, H. M., & Wünnemann, K. (2009). Hybrid modeling of the mega-  
994 tsunami runup in Lituya Bay after half a century. *Geophys. Res. Lett.*, *36*,  
995 L09602.
- 996 Weit, A., Roche, O., Dubois, T., & Manga, M. (2018). Experimental measure-  
997 ment of the solid particle concentration in geophysical turbulent gas-particle  
998 mixtures. *J. Geophys. Res.*, *123*, 3747–3761.
- 999 Weit, A., Roche, O., Dubois, T., & Manga, M. (2019). Maximum solid phase con-  
1000 centration in geophysical turbulent gasparticle flows: Insights from laboratory  
1001 experiments. *Geophys. Res. Lett.*, *46*, 6388–6396.
- 1002 Wells, M. G., & Dorell, R. M. (2020). Turbulence processes within turbidity cur-  
1003 rents. *Annu. Rev. Fluid Mech.*, *53*, 59–83.
- 1004 Wells, M. G., & Wettlaufer, J. S. (2007). The long-term circulation driven by den-  
1005 sity currents in a two-layer stratified basin. *J. Fluid Mech.*, *572*, 37–58.
- 1006 Whitham, A. G. (1989). The behaviour of subaerially produced pyroclastic flows  
1007 in a subaqueous environment: evidence from the Roseau eruption, Dominica,  
1008 West Indies. *Mar. Geol.*, *86*, 27–40.
- 1009 Young, S. R., Sparks, R. S. J., Aspinall, W. P., Lynch, L. L., Miller, A. D., Robert-  
1010 son, R. E. A., & Shepherd, J. B. (1998). Overview of the eruption of Soufriere  
1011 Hills volcano, Montserrat, 18 July 1995 to December 1997. *Geophys. Res. Lett.*,  
1012 *25*, 3389–3392.
- 1013 Zgheib, N., Bonometti, T., & Balachandar, S. (2015). Dynamics of non-circular  
1014 finite-release gravity currents. *J. Fluid Mech.*, *783*, 344–378.
- 1015 Zhu, S. J., Zgheib, N., Balachandar, S., & Ooi, A. (2017). Front dynamics of ellipti-  
1016 cal gravity currents on a uniform slope. *Phys. Rev. Fluids*, *2*, 064801.
- 1017 Zitti, G., Ancey, C., Postacchini, M., & Brocchini, M. (2016). Impulse waves gen-  
1018 erated by snow avalanches: Momentum and energy transfer to a water body. *J.*  
1019 *Geophys. Res.*, *121*, 2399–2423.