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1 Large mobility of dry snow avalanches: insights from
2 small-scale laboratory tests on granular avalanches of
3 bidisperse materials

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7 **Abstract**

8 This paper reports small-scale laboratory tests on granular avalanches of
9 bidisperse materials made of fine particles and larger ones. These experi-
10 ments were motivated by a recent study on the rheology of dense flowing
11 snow which provided evidence for relevant similarities in flow behavior be-
12 tween bidisperse granular materials and dry cold snow [Rognon and others,
13 J. Rheol., **52**, 3 (2008)]. The mass proportion of fine particles in the initial
14 binary mixture was systematically varied at constant initial released volume,
15 and we measured the resulting flow depth, the avalanche front velocity and
16 the final avalanche runout. In particular, we show that the avalanche mobil-
17 ity is largely increased, about 40% in our tests, when the mass proportion in
18 fine particles reaches a critical value, around 0.25 in our tests. The avalanche
19 deposit is shallow and lengthened for this critical mass proportion in fine par-
20 ticles. The experimental results are interpreted by the existence of different
21 avalanche mobility regimes on the basis on an heuristic model previously re-
22 ported in literature. Finally, we discuss their possible implications for the
23 dynamics of full-scale dry snow avalanches.

24 *Key words:* snow, avalanche dynamics, granular flows, binary mixtures,
25 experiments, mobility

26 **1. Introduction**

27 Snow is a cohesive granular material and granular flows are often consid-
28 ered to model dense avalanches of dry and cold snow (Hutter, 1996; Issler,
29 2003; Naaïm and others, 2004). Dry flowing snow is a granular polydis-
30 perse material as corroborated by recent investigations on some deposits of
31 full-scale snow avalanches (Bartelt and McArdell, 2009). Recent systematic
32 experiments on a decametric snow chute has evidenced the fact that dry,
33 cold and dense flowing snow can be seen as a mixture of snow grains, with a
34 diameter typically smaller than 1 mm, and of larger snow aggregates with a
35 maximum size close to the flow thickness (Rognon and others, 2008). These
36 experiments have been combined with discrete element simulations of bidis-
37 perse granular materials (Rognon and others, 2007). It has been shown that
38 dry, cold and dense flowing snow exhibits a behavior stemming from specific
39 properties of bidisperse granular flows (Rognon and others, 2008). First,
40 Rognon and others (2008) showed that steady and uniform flows are pos-
41 sible in a range of slope between two limit angles θ_{min} and θ_{max} . Further-
42 more, when approaching the critical angle θ_{min} , the velocity abruptly drops
43 to zero. These features are reminiscent of the behavior of granulars materials
44 (GDR-MiDi, 2004; Forterre and Pouliquen, 2008). Second, velocity profiles
45 measured by Rognon and others (2008) suggest that the snow flow is divided
46 into two layers: a highly sheared basal layer of small thickness and made of
47 snow grains is surmounted by a thick and less sheared layer made of snow

48 aggregates. It corresponds to a behavior close to the behavior of bidisperse
49 granular mixtures (Rognon and others, 2007). These recent results suggest
50 that assimilating dry, cold and dense flowing snow to a bidisperse granular
51 fluid is a rather good approximation. Many previous small-scale laboratory
52 tests to model snow avalanches have been carried out using monodisperse
53 granular flows to predict avalanche trajectories (Savage, 1979; Savage and
54 Hutter, 1989) or, more recently, to study the influence of obstacles (Tai and
55 others, 2001; Hákonardóttir and others, 2003; Faug and others, 2004, 2008).

56 In this paper we investigate experimentally flows of bidisperse granular
57 mixtures in order to quantify the influence of the bidispersity on the avalanche
58 dynamics. The thickness and the flow velocity during the propagation phase,
59 as well as the maximum runout distance and the final shape of the deposit in
60 the runout zone, are studied here. Our results show that these macroscopic
61 flow descriptors, of crucial interest for hazard zoning and risk management,
62 are largely influenced by the bidispersity. In particular, it exists a mass
63 proportion in fine particles for which the runout distance is maximum. This
64 result demonstrates that bidispersity may be a good candidate to contribute
65 to enhance the mobility of granular snow avalanches, and more generally, of
66 geophysical granular flows.

67 First, we describe the experimental set-up and procedure with a focus
68 on an advanced experimental technique to catch the shape of the granular
69 mass. The second part presents the results concerning the influence of the
70 binary mixture composition on (i) the granular deposit in the runout zone
71 and (ii) the flow characteristics in the upstream flume. The main result is the
72 observation of an enhanced mobility at a given mass proportion in fine parti-

cles inside the granular mixture. Then, we try to highlight various mobility regimes depending on the mass proportion in fine particles, on the basis of an heuristic model recently proposed by Philipps and others (2006). Finally, the results and their possible implications for snow avalanche dynamics are discussed.

2. Experimental device and procedure

The experimental device we used corresponds to a geometry typically used to study snow avalanches on reduced models (Hákonardóttir and others, 2003; Faug and others, 2003, 2008), and more generally geophysical flows (Hutter and others, 1995). It consists of a system of two inclined planes including: (i) a reservoir to store the material and equipped with a gate to release it, (ii) a steep inclined plane equipped with a flume inside which the granular material propagates, (iii) a downstream plane inclined at a lower slope angle where the granular mass decelerates, spreads and finally stops. A typical granular deposit is thus generated. The slope angle of the flume corresponding to the propagation zone was fixed at 35° and the one corresponding to the runout zone was fixed at 6° for the whole experiments. Fig. 1 shows a sketch of the experimental device with the associated instrumentation.

As already mentioned above, most of the previous studies available in literature deal with monodisperse granular flows. Some recent studies tackle the issue of bidisperse granular flows and the associated enhanced mobility using 2D (channelized flows) small-scale laboratory tests (Phillips and others, 2006) or 2D discrete numerical simulations (Linares-Guerrero and others, 2007). Philipps and others (2006) performed experiments with granular sys-

97 tems made of rectangular (rafter with typical size $75 \text{ mm} \times 25 \text{ mm} \times 2.2$
 98 mm) or spherical (gravel of diameter 10-20 mm) coarse particles mixed with
 99 fine spherical particles (about $100 \text{ }\mu\text{m}$ in size). Their bimodal granular sys-
 100 tems are characterized by a few number of coarse (rafter or gravel) particles.
 101 In this paper, we analyse 3D granular avalanches involving a great number
 102 of fine and large spherical particles using advanced experimental techniques.
 103 It gives us access to a large number of measures to characterize the 3D (lat-
 104 eral extension) avalanche deposit: maximum length, location of the center of
 105 mass, spreading length above the center of mass, mean width, flow depth pro-
 106 file of the deposit, location of the maximum depth in the main flow direction.
 107 Thus, the tests presented here are full 3D flows and the observed enhanced
 108 mobility can be characterized by additional parameters that were not studied
 109 in (Phillips and others, 2006; Linares-Guerrero and others, 2007). The bidis-
 110 perse granular materials consists of glass beads of diameter $d_2=1 \text{ mm}$ mixed
 111 homogeneously (before releasing the whole granular mass) with glass beads
 112 of diameter $d_1=200 \text{ }\mu\text{m}$. The value d_1 is a mean value: a slight polydispersity
 113 characterizes the fine particles whose diameter ranges from 150 to $250 \text{ }\mu\text{m}$.
 114 The ratio $D = d_2/d_1$ is then between 4 and 6.66 being a value sufficiently
 115 large for the occurrence of segregation processes. Indeed, it is known that
 116 segregation starts to occur above 20% in polydispersity (Hirshfeld and Rapa-
 117 port, 1997; Berton and others, 2003) which corresponds to a ratio $D = d_2/d_1$
 118 typically higher than 1.2. The mass initially released was kept constant and
 119 equal to $m=10 \text{ kg}$. The channel roughness was smooth (wooden surface)
 120 relatively to the roughness of the runout zone made of sandpaper glued on
 121 the inclined plane. We will come back to this point when giving an attempt

122 to analyse the typical values of the ratios d_1/λ_r and d_2/λ_r with regard to the
123 recent results on bidisperse granular media (Goujon and others, 2003, 2007),
124 λ_r being the typical size of the roughness asperities (sandpaper). Finally
125 the only initial varying parameter in the experiments is the mass proportion,
126 called r , in fine particles of diameter d_1 :

$$r = \frac{m_1}{m} = \frac{m_1}{m_1 + m_2}, \quad (1)$$

127 where m_1 is the mass of fine particles and m_2 is the mass of larger par-
128 ticles. We carried out many laboratory tests by varying the ratio r between
129 the value 0 (glass beads of diameter d_2 only) and 1 (glass beads of diameter
130 d_1 only).

131 A laser sheet which generates a line parallel to the channel walls and
132 centered on this latter (see the red line in Fig. 1) is projected on the inclined
133 plane. When the granular mass propagates on the channel, this laser line is
134 deflected. Thanks to a video camera placed normal to the channel bottom,
135 we can visualize the shifted laser line (video camera n°1 on Fig. 1). The
136 deviation is directly proportional to the flow thickness. A calibration phase
137 using various rectangular objects of known thickness allows us to determine
138 the proportionality coefficient. Then, the thickness at each time t and at
139 each point X (in the centerline of the channel) can be easily derived. Fig. 2
140 gives a depth-profile in time obtained at various abscissa of the channel in
141 the investigation zone of the laser sheet. This latter is filmed by the video
142 camera n°1, has a length of 1 m and is defined on Fig. 1. Let us note that
143 the zone inside which we measured flow thicknesses is smaller than 1 m. The
144 order of magnitude is 55 cm, which corresponds to the zone between the

145 locations X_1 and X_5 defined on Fig. 1. In this investigated zone and at
 146 a given location X , the typical depth-profile in time presents a maximum
 147 with a plateau more or less pronounced. We observe that the value of this
 148 maximum varies with the location X in the channel but this variation is very
 149 weak in the ending part of the channel. The typical values of gradients of
 150 maximum flow-depth in the ending part of the channel are around 1 mm (see
 151 Fig. 2). The precision of depth measurements has been estimated to 1 mm.
 152 We systematically defined h as the mean value of the three maxima obtained
 153 at locations X_3 , X_4 and X_5 , in the bottom part of the channel, excluding
 154 the maxima obtained at locations X_1 and X_2 in the top part. Locations
 155 $X_{i=1,2,3,4,5}$ are defined on Fig. 1. It is then possible to analyse the influence
 156 of the ratio r on the flow-depth h . These results are presented and discussed
 157 in the following section.

158 The laser line allows us also to determine the locations of the front x_f in
 159 the channel and, consequently, the propagation speed of the granular front
 160 (Lagrangian front speed), in want of the knowledge of the depth averaged flow
 161 speed of the granular avalanche core at a given location X (Eulerian speed).
 162 The point corresponding to the front position is the point downstream which
 163 the laser line is not shifted and upstream which it is shifted. Fig. 3 gives
 164 an example of the front position x_f versus the time. This graph allows us to
 165 calculate the front velocity, called u , and defined by the slope of the straight
 166 line ($u = dx_f/dt$). The precision on front speed was estimated to 0.1 m s^{-1} .
 167 The results about the influence of the ratio r on the front velocity u are
 168 presented and discussed in the following section.

169 Parallel fringes, alternatively black and white, were projected on the gran-

170 ular mass on the runout zone with the help of a projector. Similarly to the
 171 shifted laser line technique, the fringes network is shifted by the granular
 172 mass and the deviation is proportional to the deposit thickness. A video
 173 camera placed normal to the inclined plane (video camera n°2 on Fig. 1)
 174 allows us to visualize the shifted fringes network (Fig. 4b). The calculation
 175 consists in determining with accuracy the phase difference $\Delta\varphi(x, y)$ between
 176 the *reference* signal, without the granular mass, and the *object* signal, in pres-
 177 ence of the granular mass which distorts the fringes. The *reference* signal
 178 can be modelled by the following sinusoidal signal:

$$I_{ref}(x, y) = \bar{I}(x, y) + \bar{I}(x, y)\gamma(x, y) \cos(\varphi_0 + 2\pi f_0 x), \quad (2)$$

179 where $\bar{I}(x, y)$ is the mean intensity of the signal, $\gamma(x, y)$ the lightness
 180 contrast at the point location (x, y) , f_0 is the frequency linked to interfringe
 181 and φ_0 the origin phase. The *object* signal can be modelled by the following
 182 sinusoidal signal:

$$I_{object}(x, y) = \bar{I}(x, y) + \bar{I}(x, y)\gamma(x, y) \cos(\varphi_0 + 2\pi f_0 x + \Delta\varphi(x, y)), \quad (3)$$

183 The phase difference $\Delta\varphi(x, y)$ between the two signals is directly propor-
 184 tional to the local deviation of fringes $\delta(x, y)$:

$$\Delta\varphi(x, y) = 2\pi f_0 \delta(x, y) \quad (4)$$

185 It is possible to derive theoretically the proportionality coefficient relating
 186 the local deviation of the fringes and the object height. For this aim, the
 187 geometrical and optical features of the system formed by the projector, the

188 surface of the inclined plane and the video camera have to be considered
189 (Sansonini and others, 1999; Vincent, 2003). However, in order to avoid errors
190 linked to the determination of these geometrical features and to optics of
191 instruments, we used an empirical calibration thanks to rectangular objects
192 of known height to deduce the deposit thickness at each point (x, y) of the
193 inclined plane. This experimental technique using fringes projection is now
194 currently used to study flows in small-scale laboratory models (Pouliquen
195 and Forterre, 2002; Cochard and Ancey, 2008).

196 Several methods exist to have access to the phase difference (Surrel, 2000;
197 Vincent, 2003). Some methods are based on a single image projection of the
198 fringes network as the Fourier transform method (global approach). Other
199 methods, more accurate, are based on the principle of phase shifting which
200 consists in projecting several images shifted one to each other (local ap-
201 proach). This second approach is not adapted to dynamic problems with
202 rapid changes in time but it brings an increased precision for static (or quasi-
203 static) problems. In the experiments presented here, we use this second ap-
204 proach by projecting four grids shifted of $\pi/2$. The displacement of fringes
205 by the granular mass is interpreted as a fringes phase modulation and can
206 be expressed according to the four intensities $I_i(x)$:

$$\phi(x) = \arctan \left(\frac{I_4(x) - I_2(x)}{I_1(x) - I_3(x)} \right), \quad (5)$$

207 where the four shifted images ($\phi_1 = 0$, $\phi_2 = \pi/2$, $\phi_3 = \pi$, $\phi_4 = 3\pi/2$)
208 are modelled by a sinusoidal signal: $I_i(x, y) = \bar{I}_i(x, y) + \bar{I}_i(x, y) \cos(\phi(x) +$
209 $\Delta\phi_i(x))$. The thickness is then directly proportional to the phase modulation
210 $\phi(x)$ and is obtained by calibration. The calibration procedure consists in

211 projecting the four *reference* shifted images ($\phi_1 = 0$, $\phi_2 = \pi/2$, $\phi_3 = \pi$,
 212 $\phi_4 = 3\pi/2$) on various rectangular objects of known height. Fig. 4 shows
 213 the projected fringes on a deposit as well as the numerical result for the
 214 deposit shape in three dimensions. The precision varies according to the
 215 image quality and is generally smaller than $500 \mu\text{m}$.

216 Experimental tests consisted in releasing a mass of 10 kg and changing
 217 the ratio r at each test. We tested values of r ranging from 0 to 65%
 218 with a 1% step. For values greater than 65%, we did tests with the following
 219 values: 80% and 100%. In the following section, we present results concerning
 220 the influence of the ratio r on (i) the deposit morphology and (ii) the flow
 221 dynamics inside the ending part of the flume.

222 3. Results

223 3.1. Evidence of segregation

224 The qualitative observation of deposits, as displayed in Figs. 5a and 5b,
 225 shows (i) the presence of fine particles at the base of the deposits, and (ii)
 226 the presence of coarse particles mostly at the front and, to a less extent, at
 227 the sides. These observations, previously discussed by Pudasaini and Hutter
 228 (2007, p. 63, figure 2.6), are the proof of size segregation effects, during the
 229 propagation phase and during the stopping phase, where the fine particles
 230 tend to fall (percolation) and large grains tend to go toward the surface.

231 The present paper does not tackle the strickly speaking segregation pro-
 232 cess, largely studied for relatively dense granular flows (Savage and Lun, 1988;
 233 Ottino and Khakhar, 2000; Félix and Thomas, 2004; Gray and Chugunov,
 234 2006) but it rather analyses the consequences of the segregation process on

the granular avalanche, during its propagation and stopping phases. Our experiments show, which is described in detail in this section, that several features of the granular avalanche are influenced by the ratio r : (i) the velocity and the thickness during the accelerating propagation phase, (ii) the final length of the deposit in the runout zone, (iii) the thickness of the final deposit (maximum value and mean value along the main flow direction in the x -axis direction), (iv) the location where the deposit thickness is maximum.

3.2. Deposit in the runout zone

3.2.1. Deposit features influenced by the binary mixture composition

Fig. 6 shows various features of the granular avalanche deposit versus the mass proportion in fine particles r : length L , position x_G of the center of mass, spreading length $x_{spreading}$ above the center of mass, maximum width ℓ , maximum height H_{max} , mean depth along the centerline of the deposit H_x and position $x[H_{max}]$ of the maximum height. Each dimension x has been normalized by the corresponding dimension, x_2 , obtained with the monodisperse mixture of beads with diameter $d_2=1$ mm. In the following, the results are systematically normalized by the values obtained with the monodisperse mixture made of beads with diameter $d_2=1$ mm (reference values with subscript 2). In Fig. 6, for the dimensions L and ℓ , are given the results obtained from the fringes projection technique combined with phase shifting as well as the results from the direct measure with a ruler. Similar results are obtained with both methods, which validates our implementation of the fringes projection technique.

The deposit length is very sensitive to the ratio r . It displays a maximum around $r = 0.2 - 0.3$ and this maximum reaches the value 1.4. It shows

260 that the runout distance with a bidisperse mixture (between 20 and 30%
 261 in mass of fine particles) is increased of nearly 40% in comparison with a
 262 monodisperse mixture of large particles. Let us note that L/L_2 is slightly
 263 smaller than 1 when $r = 1$, which illustrates that the runout with fine par-
 264 ticles only is slightly shorter than the runout with large grains only. This
 265 observation shows that large particles go further than small ones, for fixed
 266 roughness conditions. We can introduce here the critical diameter d_c defined
 267 by Goujon and others (2007), and which depends on the typical size λ_r of
 268 the downstream plane roughness and its compacity C :

$$d_C = \frac{\pi}{6C\sqrt{3}}\lambda_r \approx 0.3\frac{\lambda_r}{C}. \quad (6)$$

269 For monodisperse dry granular flows down inclined planes, there exist a
 270 diameter d_C of particles for which the basal friction is maximum: minimum
 271 in mean velocity, maximum in deposit thickness and minimum in deposit
 272 length (Goujon and others, 2003). The value of d_c is equal to $0.42\lambda_r$ for
 273 a typical roughness compacity of 0.72, mean value between the maximum
 274 compacities in two dimensions ($C_{2D} \approx 0.64$) and three dimensions ($C_{3D} \approx$
 275 0.8). The mean value of λ_r is $250 \mu\text{m}$ (corresponding to the norm FEPA
 276 for the sandpaper P60 used in our tests), which gives the value $d_c \sim 105$
 277 μm . The diameter d_2 is nearly ten times greater than the diameter d_c , which
 278 implies that the 1 mm in diameter beads can not be trapped easily in the
 279 roughness ($d_2/\lambda_r \sim 4$). On the other hand, the diameter d_1 is less than
 280 twice greater than d_c ($d_1/\lambda_r \sim 0.8$), which implies that fine particles of
 281 $200 \mu\text{m}$ in diameter are more easily trapped. It results, at constant initial
 282 mass and slope angles, a runout greater for the large grains of diameter d_2 .

283 However the difference between the two monodisperse deposits is not so large.
 284 We may think it is caused by the very low value of the runout zone slope
 285 angle (6°) in our experiments, which allows the large grains to come at rest.
 286 Goujon and others (2007) investigated flows at higher slope angles on which
 287 grains were less stable and they obtained a larger difference between the two
 288 monodisperse deposits.

289 Thanks to the fringes projection technique, we could determine with ac-
 290 curacy the position of the center of mass x_G (calculated from the beginning
 291 of the runout zone: $x = 0$ in Fig. 1). x_G/x_{G2} (Fig. 6) displays a more
 292 pronounced maximum (value around 1.5) than L/L_2 . This implies that the
 293 center of mass is more sensitive than the deposit front to the proportion in
 294 fine particles. Let us consider a simple model for which the total maximum
 295 runout is the sum of the position of the center of mass (x_G) and a spreading
 296 length above the center of mass ($x_{spreading}$), as previously suggested in (Faug
 297 and others, 2004):

$$L = x_G + x_{spreading}. \quad (7)$$

298 A similar approach was been recently proposed in (Staron and Lajeunesse,
 299 2009) where the runout of a gravity-driven granular flow is decomposed in
 300 two contributions: a so-called sliding along the topography and a so-called
 301 spreading of the unconsolidated mass. From this simple model, we can con-
 302 clude that the segregation process acts differently on the displacement of the
 303 total mass (sliding) and on the way the unconsolidated mass spreads beyond
 304 the center of mass. Indeed, the spreading length is less sensitive to the ratio
 305 r than the position of the center of mass, as shown by Fig. 6.

306 In Fig. 6 is also shown the maximum width being relatively independent
 307 of the ratio r . This result tends to show that the segregation acts mainly in
 308 the prevailing direction of the avalanche propagation (simple shear flow). A
 309 similar effect has been also observed by Zanuttigh and Di Paolo (2006).

310 The fringes projection technique allows us to study other effects on the
 311 deposit shape: the mean depth-profile, H , and the maximum height, H_{max} ,
 312 as well as the point location where the height is maximum, $x[H_{max}]$. The
 313 height H is defined by:

$$H = \frac{S}{\ell_S}, \quad (8)$$

314 where S is the area of the transverse section of the deposit at a given
 315 abscissa x and ℓ_S is the deposit width at the abscissa x . The height H
 316 corresponds to the mean value in the transverse y -axis direction (Fig. 1).
 317 Fig. 7 shows examples of mean depth-profiles obtained from various values
 318 of the ratio r . The segregation is shown to decrease the thickness of the
 319 deposits. At the critical value of the ratio r (around 0.2-0.3), the deposits
 320 are lengthened and thinner. At values greater and smaller than the critical
 321 ratio, the deposits are thicker and shorter.

322 Fig. 6 also shows the maximum deposit height, H_{max} , as well as the mean
 323 depth along the centerline of the deposit, called H_x . Both H_{max} and H_x are
 324 very sensitive to r . The height reduction is maximum (around 35-40%) at
 325 the critical ratio $r_{crit}=0.2-0.3$.

326 If we neglect the changes in volume fraction (we will come back to this
 327 point later in the paper), we can assume that the volume is constant because
 328 we kept the total mass m constant. As the deposit width is independent of

the ratio r , it results that the average depth along the whole profile, H_x , is, in first approximation, inversely proportional to the deposit length L . This result is displayed in insert in Fig. 8.

In Fig. 6 is finally displayed the position of the maximum height, $x[H_{max}]$. The results are more scattered because this parameter is more sensitive to experimental conditions. However, the curve (see the gray trend line reported in Fig. 6) shows that this parameter displays a behavior similar to the one observed for L and x_G . Let us remark that the maximum is very pronounced since the value of $x[H_{max}]$ is nearly double when $r = r_{crit}$, in comparison with large particles only. This result indicates that the deposit morphology is very sensitive to r , and therefore to segregation effects.

3.2.2. *Existence of a critical proportion in fine particles for which the friction is minimum?*

Rognon and others (2007) studied, on the basis of discrete numerical simulations, velocity profiles of 2D bidisperse steady flows of disks with varying the ratio S_g as well as the size ratio $D = d_2/d_1$. S_g was defined as the surface proportion of large disks (Rognon and others, 2007): $S_g = (n_2 d_2^2)/(n_2 d_2^2 + n_1 d_1^2)$, where n_2 is the number of large grains and n_1 the number of small grains. They observed an increase in thickness of the top layer made of large grains when increasing S_g , and for $S_g = 3/4$, the basal layer of fine grains was shown to disappear. By analogy, we can define the dimensionless number V_g representing the volume proportion of large grains (1 mm glass beads): $V_g = (n_2 d_2^3)/(n_2 d_2^3 + n_1 d_1^3)$. Since large and small particles has the same density (glass beads), the volume proportion of large grains is equal to the mass ratio between the large grains and all the grains: $V_g = 1 - r$.

According to Fig. 6, the various parameters defined previously L/L_2 ,
 x_G/x_{G2} , $x_{spreading}/x_{spreading2}$, $x[H_{max}]/x[H_{max2}]$ increase when decreasing r
 (when increasing V_g) and reach a maximum when r is around 0.2-0.3 (V_g
 around 0.7-0.8). These parameters then decrease to tend toward 1, extreme
 value for which there is no more fine grains ($n_1 = 0$). These results appear
 to be compatible with the observations by Rognon and others (2007). In this
 decreasing part of the curves, everything acts as if there was not enough fine
 grains to form a homogeneous basal layer allowing the optimal lubrication
 of the whole granular mass mainly made of large grains. In order to develop
 segregation processes that are able to contribute to avalanche lengthening, it
 is necessary to exceed a given proportion in fine particles inside the mixture.
 Conversely, this proportion should be not too high in order to maintain the
 efficiency of the segregation processes. It is really a challenge to find the
 critical value theoretically. However we can provide a qualitative physical
 explanation to the critical condition. Below $r = 0.2 - 0.3$ (above $V_g = 0.7 -$
 0.8), the lubrication can act but is not optimal. The optimum is probably
 reached when a homogeneous layer of fine particles is formed at the base of
 the flow and, simultaneously, no -or a few- fine particles are present inside the
 voids between the large particles. Above $r = 0.2 - 0.3$ (below $V_g = 0.7 - 0.8$),
 as the basal layer of fine particles is saturated, the added fine particles start
 to fill the voids between the large particles. This process offers additional
 contact surfaces for interparticle friction (the velocity of the large particles
 is decreased) which counteracts the basal lubrication.

These mechanisms can be interpreted by the existence of a critical pro-
 portion for which the friction is minimum. The observed maxima on the

379 curves correspond to this minimum friction. These results are in agreement
 380 with the results from 2D discrete numerical simulations showing that the
 381 friction coefficient versus the proportion in fine particles displays a minimum
 382 (see figure 11 in (Linares-Guerrero and others, 2007)).

383 3.2.3. *Volume of the avalanche granular deposit*

384 The fringes projection technique combined with phase shifting allowed us
 385 to access to the final volume of the deposit. This volume is also a function
 386 of r as shown in Fig. 8. In spite of weak variations, it illustrates that the
 387 assumption made previously on the volume fraction is not correct. Since we
 388 kept the total mass constant ($m=10$ kg), we can deduce the volume fraction
 389 evolution:

$$\phi(r) = \frac{m}{\rho_P V(r)}. \quad (9)$$

390 At constant total mass, the volume fraction is inversely proportional to
 391 the volume. Given that a minimum is shown in the volume variation, the
 392 volume fraction displays a maximum. However, this result is non trivial
 393 to interpret since the initial volume is not perfectly controlled. Rearrange-
 394 ment mechanisms, and consequent variations in volume fraction, may have
 395 taken place before the avalanche release, when setting the granular mixture
 396 up inside the reservoir. Indeed, it is known that the compacity of a bidis-
 397 perse granular in a static state depends on the proportion of large grains
 398 in the mixture (Ben Aim, 1970; Dodds, 1980). Adding particles of different
 399 size (larger or smaller), even in small amount, to a monodisperse medium,
 400 modifies and generally increases the solid fraction when the size ratio D
 401 is sufficiently large. This increase in compacity is explained by two main

mechanisms (Ben Aim, 1970): (i) the insertion mechanism for which small particles fill the voids inside a granular skeleton mainly made of large grains (small r) and (ii) the substitution mechanism for which a large grain replaces a cluster of fine grains and the openings between these fine grains inside a matrix mainly made of fine grains (large r). The mean volume fraction of the deposits depends strongly on the segregation processes during the propagation phase. It may also depend on the initial granular rearrangements and resulting initial compacities (difficult to control) of the granular mixture put in place inside the reservoir. However, the behavior observed in Fig. 8 remains difficult to interpret and cannot be explained simply by initial rearrangements. It probably suggests inherent mechanisms occurring during the flow and stopping phases which need further investigations in the future.

As a first approximation, we can relate the total volume of the deposit to its length L , its width ℓ and its mean thickness H_x by the following equation:

$$V = \alpha L H_x \ell = \frac{m}{\rho_P \phi(r)}, \quad (10)$$

where α is a shape coefficient linked to the deposit. The results show that α is constant (close to 3/4) whatever the value of the ratio r . This result is in agreement with the observations showing, for each test, a mean shape of the deposit similar to the one given in Fig. 4a. Let us note that all the deposits observed during our tests, whatever the r value, are uniforms (see Fig. 5a) in the sense that we do not observe digitation mechanism, similarly to the fingering features analysed by other authors (Pouliquen and others, 1997; Pouliquen and Vallance, 1999), and which can be also observed for some natural snow avalanches.

425 In this section, we showed the influence of the segregation process on the
 426 characteristics of the final deposit. We also observed important effects in the
 427 propagation zone on the flow depth and velocity. This tends to show that
 428 segregation processes can occur at very short times once the avalanche has
 429 been initiated. We discuss this question in the following section.

430 3.3. *Flow in the channel*

431 We remind here that the channel is smooth (wooden bottom), which
 432 implies that the typical size, λ_c , of the channel roughness is very small in
 433 comparison with the diameter d_2 ($\lambda \ll d_2$) and also d_1 ($\lambda \ll d_1$). Contrary
 434 to the runout plane, complex effects due to coupling between the roughness
 435 and the flowing binary mixture (Goujon and others, 2003, 2007) have not
 436 to be considered for the propagation phase in the channel. Fig. 9 shows
 437 the mean flow depth h (defined in section 2) in the channel versus the ratio
 438 r . The flow depth is relatively constant when the mass proportion in fine
 439 particles is weak. It decreases afterwards when the ratio r reaches a critical
 440 value around 0.2-0.3. Then, the flow depth remains relatively constant and,
 441 finally, slightly increases at high r values.

442 In Fig. 9 is also shown the mean front velocity in the channel (defined in
 443 section 2) versus the ratio r . The speed increases when the mass proportion
 444 in fine particles increases, before reaching a plateau when the ratio r reaches
 445 a critical value. The transition is observed around 0.2-0.3, which corresponds
 446 to a order of magnitude similar to the value obtained for h . Let us note that,
 447 in spite of the weak number of available data, the speed tends to decrease at
 448 high r values.

449 The Froude number of the free-surface flows is often considered as an

important similitude criterion which is rather easy to estimate with a prior knowledge of the flow depth h and the velocity u . The Froude number is defined as:

$$Fr = \frac{u}{\sqrt{gh}}. \quad (11)$$

We reported the value of the Froude number versus the ratio r in Fig. 9. The Froude number ranges from 5 to 9 in our tests with granular materials. It corresponds to typical values for rapid snow avalanches (Issler, 2003). The Froude number is shown to increase when increasing the mass proportion in small grains inside the mixture and it reaches a relatively constant value when the ratio is above a critical value around 0.3. Let us note that above a certain value of r (around 0.6-0.7), the Froude number decreases. This observation results from the decrease in velocity and the increase in flow depth. Segregation generates thinner and more and more rapid channelized flows. These results are the proof that the segregation and the induced lubrication can be active even if the bottom surface is smooth. The trapping of fine particles is limited here. The large velocity gradients (between the basal layer of fine particles and the large particles above) needed to lubricate the flow are more due to the high inclined slope of the channel. This latter makes the large particles (high inertia) above the small moving ones ($r = r_{crit}$) flowing down faster than the small ones alone ($r = 1$). These results are compatible with the fact that the granular avalanche covers a greater distance and the deposits are thinner and lengthened thereafter in the downstream runout zone.

472 4. Data interpretation

473 On the basis of the study by Philipps and others (2006), we can interpret
 474 experimental data by distinguishing three mobility regimes identified in Fig.
 475 10. Fig. 10 gives the deposit length, L , normalized by the deposit length,
 476 L_2 , obtained for $r = 0$ (large grains only) versus the mass proportion in fine
 477 particles, r .

478 The regime (*I*) is characterized by a mixture made of a majority of large
 479 grains with a few fine particles ($0 < r < r^{I-II}$, where r^{I-II} is the proportion
 480 corresponding to the transition toward to the regime (*II*) defined below).
 481 In the regime (*I*), the fine particles, located at the base of the flow (as a
 482 consequence of segregation effects in the channel), can play the role of a
 483 rolling plane for the incoming larger grains. The limit between regimes (*I*)
 484 and (*II*) is close to the maximum observed on Fig. 10. It is then taken
 485 identical to the critical value r_{crit} : $r^{I-II} = r_{crit} = 0.25$. Philipps and others
 486 (2006) proposed a similar value based on their experiments.

487 The regime (*III*) corresponds to a mixture made of a dominant part of
 488 fine particles with a few large grains ($r^{III-II} < r < 1$, where r^{III-II} is the
 489 proportion corresponding to the transition toward to the regime (*II*) defined
 490 below). As soon as the proportion in fine particles becomes dominant, their
 491 effect becomes more complex and they do not play the simple role of lu-
 492 bricating the mass of large grains. In the regime (*III*), we expect that the
 493 interparticle friction is the main source of energy dissipation, which limits the
 494 avalanche mobility. A simple idea to model this regime is to consider that
 495 dissipations by friction are directly proportional to the surfaces involved in
 496 friction contacts (Phillips and others, 2006). Note that this simple approach

497 does not take into account the dissipations due to collisions which are likely
 498 to be important inside the basal sheared layer made of fine particles with
 499 fluctuating velocities. The effect of substituting a large grain for the same
 500 mass of fine particles is to reduce the contact surfaces availables for interac-
 501 tions, which leads to a region weakly effective in terms of friction dissipations
 502 in comparison with regions where fine particles are free to interact. By com-
 503 paring a situation with a binary mixture (mixture *A*) and a situation with
 504 a monodisperse mixture exclusively made of fine particles (mixture *B*), we
 505 can estimate the ratio R_f between the energies dissipated by friction in each
 506 case (Phillips and others, 2006):

$$R_f = \frac{n_1 S_1 F + n_2 S_2 F}{n S_1 F}, \quad (12)$$

507 where $S_1 = d_1^2$ (respectively $S_2 = d_2^2$ for the large grains) is the surface
 508 of the fine particle of diameter d_1 (respectively d_2 for the large grains). The
 509 product $n_1 S_1 F$ is the total dissipation by friction in the mixture *B*, where F
 510 is the friction force by surface unit. For the mixture *A*, at constant surface
 511 unit force F , the fine particles but also the large grains contribute to friction
 512 dissipations, which gives the following total dissipation: $n_1 S_1 F + n_2 S_2 F$.

513 Some calculations allow us to derive the ratio R_f as a function of the
 514 diameters ratio D , the density ratio $\chi = \rho_2/\rho_1$ and the mass proportion in
 515 fine particles r :

$$R_f = \frac{1 + \frac{1-r}{\chi r D}}{1 + \frac{1-r}{\chi r D^3}}. \quad (13)$$

516 Considering that $\chi = 1$ (in our experiments), and that the value of D is
 517 greater than 1, the ratio R_f is necessarily smaller than 1. This prediction is

518 in agreement with the experimental observation showing that adding large
 519 grains in a mixture of fine particles (by keeping the total mass constant)
 520 leads to an increase in avalanche runout. We compared the prediction of
 521 this heuristic model to data on deposit length, L , normalized by the deposit
 522 length, L_2 , for $r = 0$ (large grains only). It is crucial to notice that in Fig.
 523 10 is reported the ratio R_f multiplied by the ratio (L_1/L_2) because the data
 524 are normalized by the reference value for $r = 0$. Yet, by construction, R_f
 525 is defined with regard to a reference situation for $r = 1$. We do not have
 526 many data for high r values corresponding to the regime (*III*) but we can
 527 observe a good agreement between the data and the heuristic model. Figs.
 528 6, 9 and 11 are relatively flat for values r greater than 0.7. Thus the limit
 529 between the regimes (*III*) and (*II*) is $r^{III-II} = 0.7$ in agreement with the
 530 value proposed by Phillips and others (2006).

531 The regime (*II*) is a transition regime ($r^{I-II} < r < r^{III-II}$) where in-
 532 volved mechanisms are more complex than in regimes (*I*) and (*III*). The
 533 regime (*I*) shows that adding fine particles in a mixture of monodisperse large
 534 grains tends to lubricate the mass of large grains. This induces an increased
 535 mobility. The regime (*III*) shows that adding large grains to a mixture of
 536 monodisperse fine particles tends to reduce the contact surfaces available
 537 for energy dissipation by interparticle friction. This induces an increased
 538 mobility. The transition between both regimes is necessarily characterized
 539 by the existence of a maximum. In the regime (*II*), we observe a maximum
 540 in avalanche runout (L and x_G show a maximum) correlated to a minimum
 541 in deposit height (H_{max} and H_x show a minimum). At the critical value
 542 r_{crit} , deposits are thin and lengthened. We reported the ratio $\epsilon^{-1} = L/H_x$

543 versus the mass proportion of fine particles in Fig. 11. ϵ^{-1} is defined as the
 544 ratio between the deposit length L and the mean deposit height H_x . This
 545 ratio, which characterizes the deposit extension, exhibits a maximum at the
 546 critical value r_{crit} . We called it ϵ^{-1} to refer to the ratio $\epsilon = H_x/L$, classi-
 547 cally used in depth-averaged equations models describing shallow avalanche
 548 flows ($\epsilon \ll 1$). The critical value r_{crit} for which the mobility is maximum is
 549 around 0.25 in our experiments and, to our knowledge, it does not exist any
 550 model to predict it. We will come back to this value in conclusion.

551 **5. Discussion and conclusion**

552 The experiments described above show the strong influence of the bi-
 553 nary mixture composition on the averaged characteristics of the granular
 554 avalanche. Our 3D experiments are in good agreement with the experimen-
 555 tal results about 2D, channelized, flows in (Phillips and others, 2006) and
 556 the 2D discrete numerical results in (Linares-Guerrero and others, 2007) con-
 557 cerning the maximum runout. They bring new results on the influence of the
 558 binary mixture composition on (i) the final shape of the full 3D deposit
 559 (maximum flow depth, the location of this latter on the main flow direction,
 560 mean width) and (ii) the dynamics of the 2D, channelized, incident flow.
 561 Apart from these results largely discussed in the paper, we close the paper
 562 by analysing the possible implications of these results on avalanches of dense
 563 and dry snow.

564 *5.1. Dynamics of the incoming flow and runout deposit*

565 We analysed the influence of the mass proportion in fine particles on the
 566 deposit in the runout zone and on the dynamics of the incoming flow. Re-

sults show a strong influence of the mass proportion in fine particles inside
 the binary mixture on (i) the flow dynamics that can be characterized by the
 Froude number of the incoming flow Fr (diamond symbols in Fig. 9) and (ii)
 the shape of the deposit that can be characterized by the ratio $\epsilon^{-1} = L/H_x$
 (Fig. 11). Then, a question arises: can we relate the ratio ϵ^{-1} to the Froude
 number Fr ? Fig. 12 shows the ratio ϵ^{-1} , which will be named “deposit
 lengthening coefficient”, versus the Froude number. No correlation is found
 between these two dimensionless numbers. On the curve displayed in Fig.
 12, we distinguished data for which r is greater than r_{crit} on the one hand
 from the data for which r is smaller than r_{crit} on the other hand. First, two
 distinct groups appear. The “deposit lengthening coefficient” ranges from 40
 to 100 for both groups but with different values of the Froude number of the
 incoming flows: $Fr \approx 5 - 7$ for $r < r_{crit}$ (group A in Fig. 12) and $Fr \approx 7 - 9$
 for $r > r_{crit}$ (group B in Fig. 12). Second, in each group, a same Froude num-
 ber can give a very distinct avalanche extension (see, in Fig. 12, the points
 A_1 and A_2 on the one hand and the points B_1 and B_2 in the other hand).
 This result highlights that not taking into account an internal property of the
 flowing material (the granulometry here) and the induced mechanism (the
 segregation here) can lead to an apparent macroscopic behavior being not
 intuitive. It points at a crucial implication for dry snow avalanches. Indeed,
 when operating avalanche zoning or designing a protection dam in avalanche
 engineering, it is necessary to calculate the maximum avalanche extension
 on the basis of average models: either the simplified analytical models (see,
 for example, the method proposed by (Salm and others, 1990) and largely
 used in avalanche engineering) or the advanced numerical models based on

592 shallow depth-averaged equations (for example (Naaïm and others, 2004)).
 593 These models are based on the basal effective friction coefficient, μ , which
 594 has been to be estimated as a function of the snow type in particular. The
 595 friction coefficient μ drives the runout distance when using these analytical
 596 or numerical models. Given that the small-scale experiments presented in
 597 this paper show the strong influence of the granulometry on the avalanche
 598 runout (a same Froude number but a different r can lead to two different
 599 values of ϵ), μ should be chosen by taking into account the snow granulom-
 600 etry. Future research should be devoted to the determination of the friction
 601 coefficient as a function of the proportion in small snow grains and the mean
 602 diameter of the large aggregates, the ratio between the larger aggregates and
 603 the smaller grains, and also the particle shapes.

604 *5.2. Influence of the diameters ratio and size effect*

605 Our study at small-scale shows that segregation induces an increased
 606 mobility if the fine particles proportion is at a critical value (0.25 in our
 607 experiments). The ratio $D = d_2/d_1$ was fixed between 4 ($d_1^{min}=250 \mu\text{m}$)
 608 and 6.66 ($d_1^{max}=150 \mu\text{m}$) in our tests. Linares-Guerrero and others (2007)
 609 have analysed the effect of this ratio. They have shown that the higher the
 610 difference between the diameter of large and small particles, the more im-
 611 portant the effect of segregation is. We have to keep in mind that all the
 612 effects observed would have been amplified if we would have had a larger
 613 D , and conversely, softened if we would have had a smaller D . The mobil-
 614 ity will be more and more enhanced when the ratio D will be higher. We
 615 can see here a kind of size effect. Indeed, if the avalanche volume is larger,
 616 its flow depth is larger and the maximum size of snow aggregates may be

617 also larger. The idea suggested here relies on the statement that the initial
 618 largest blocks and chunks can keep their size, or some of the blocks or chunks
 619 may grow, during the flow propagation leading to snow aggregates of large
 620 size. It is a challenge to investigate such a statement by well-targeted snow
 621 experiments in the future. However, if this statement is true, it may result
 622 in a large ratio between the typical size of snow aggregates and the size of
 623 small snow grains, and consequently amplified segregation effects. In this
 624 sense, we think that the segregation mechanism may be a relevant candidate
 625 to enhance the mobility of major dry and dense snow avalanches. It could
 626 provide arguments to explain the field measurements showing a decrease of
 627 the effective friction as a function of the volume generally observed for geo-
 628 physical flows (Legros, 2002), and also for snow avalanches (Ancy, 2005). If
 629 we consider a snow avalanche made of snow aggregates of typically 10 cm
 630 in size ($d_2=0.1\text{m}$ (Bartelt and McArdell, 2009)) and millimetric snow grains
 631 ($d_1=10^{-3}\text{m}$), then the ratio D can reach a value extremely high equal to
 632 100! It would result a very low value of the effective friction coefficient if
 633 the proportion in fine particles is close to the value corresponding to a mini-
 634 mum (for $r = r_{crit}$). Coming back to our small-scale experiments, the critical
 635 proportion is $r_{crit} = 0.25$ for $4 < D < 6.66$. From the preliminary results
 636 of Linares-Guerrero and others (2007, figure 12), the ratio r_{crit} is likely to
 637 decrease when D increases. Thus, it can be an additional amplification fac-
 638 tor. At high D values, a weak proportion of fine particles (small r_{crit}) is
 639 sufficient to produce a largely enhanced mobility. In parallel to researches
 640 already mentioned in conclusion of the previous section, it appears crucial
 641 to systematically investigate the granulometry of snow avalanches deposits

when full-scale avalanches are surveyed following the example of Issler and others (2008). A recent study showed that the granular-size distributions in avalanche snow deposits is nearly log-normal (Bartelt and McArdell, 2009). Further investigations on polydisperse granular materials are also a future challenge to corroborate or not the conclusions reported here for simple binary granular mixtures. The segregation mechanism can also take place in many other geophysical flows where the flowing material is polydisperse with the presence of fine particles, with a large difference in diameter between fine and large particles, and with various shape particles.

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Figure 1: Sketch of the experimental set-up and instrumentation. The channel width was $w_c=0.30$ m, its length was $L_c=1.50$ m and its slope inclination was fixed at $\theta_c=35^\circ$. A laser sheet was projected on the channel bottom to visualize, thanks to a digital camera (n°1), the displacement of the granular mass (flow depth h and front velocity u) in the flowing zone. The locations x_1 was at 55 cm from the reservoir exit and the distance between two successive positions x_i was around 13.75 cm. The width of the downstream plane was $w_r=1.20$ m, its length was $L_r=2.50$ m and its slope inclination was $\theta_r=6^\circ$. Alternatively black and white fringes were projected on the bottom of the downstream plane to visualize, thanks to a digital camera (n°2), the boundaries of the granular mass in the runout zone (see Figure 4).

Figure 2: Flow-depth temporal profiles measured thanks to the shifted laser line at different channel locations. Example for $r = 0.26$: the height h retained is the mean value of the maxima at locations X_3 [$h(X_3) = 10$ mm], X_4 [$h(X_4) = 9.3$ mm] and X_5 [$h(X_5) = 8.8$ mm], which gives $h \approx 9.37$ mm.

Figure 3: Granular front position x_f in the channel versus the time. Example for $r = 0.26$. The slope of the straight line allows us to estimate the mean front speed (u) in the investigated flow zone where the granular mass deflects the laser line (see figure 1).

Figure 4: (a) Photograph of a granular deposit in the runout zone, (b) image of a fringes network projected on a deposit on the runout zone and (c) example of a numerical deposit obtained by the phase shifting method (color levels indicate the value of the deposit thickness, from the low heights in blue color to the larger ones in red color (the numerical values given on axis correspond to pixels)).

Figure 5: (top) Visualization of the frontier above which no fine particles are present. The area A is a location where only large particles of diameter $d_2=1$ mm are present. The area B is a location where we can find both fine and large particles with a majority of fine particles, of diameter d_1 , located at the base of the deposit. The frontier between the areas A and B is visible on the photograph and appears to be white colored, which provide evidence of the segregation operating inside the bidisperse granular material. (bottom) Some material has been removed from the deposit to show the evidence of segregation processes: a bed of fine particles is located at the base of the flow while the larger ones are above and go further (in the main flow direction and also laterally).

Figure 6: Various features of the granular avalanche deposit versus the mass proportion r in fine particles: length L (triangle symbols), position x_G of the center of mass (circle symbols), spreading length $x_{spreading}$ above the center of mass (diamond symbols), maximum width ℓ (square symbol), maximum height H_{max} (times symbol), mean depth along the whole profile H_x (cross symbols) and position $x[H_{max}]$ of the maximum height (star symbols). Each dimension, x , has been normalized by the corresponding dimension, x_2 , obtained with the monodisperse mixture of beads with diameter $d_2=1$ mm ($r = 0$). Note that the results from the direct measurements with a ruler are also shown for L/L_2 (red line) and ℓ/ℓ_2 (blue line) to validate the fringes projection technique. Since large and fine particles have the same density, the mass ratio r is equal to $1 - V_g$, where V_g is the volume proportion of large grains.

Figure 7: Evolution of the deposit shape as a function of the mass proportion, r , in fine particles: mean depth profile (H) for various mass proportions in fine particles: $r = 0$, $r = 0.104$, $r = 0.2015$, $r = 0.299$, $r = 0.403$, $r = 0.5005$, $r = 0.6045$ (see Figure 1 for the definition of $x = 0$ corresponding to the flume exit).

Figure 8: Normalized final volume of the deposit, V/V_2 , versus the mass proportion r in fine particles. The laboratory tests were carried out at constant initial released volume ($m = 10$ kg), which results in a solid fraction variation conversely proportional to the volume variation. Insert: Length of the deposit, L , versus the inverse of the mean flow depth all along the profile, $1/H_x$, and the inverse of the maximum deposit height, $1/H_{max}$.

Figure 9: Various dynamic features of the incident channelized flow versus the mass proportion r in fine particles: average flow depth h (circle symbols), average avalanche front velocity u (square symbols) and avalanche Froude number Fr (diamond symbols). h , u and Fr have been normalized by the corresponding value x_2 obtained in presence of large grains only ($r = 0$). Since large and fine particles have the same density, the mass ratio r is equal to $1 - V_g$, where V_g is the volume proportion of large grains.

Figure 10: Length, L , of the deposit normalized by the length, L_2 , of the deposit obtained with the large grains of diameter d_2 only ($r = 0$) versus the mass proportion r in fine particles: definition of the mobility regimes (I), (II) and (III) and comparison of the data to the heuristic model for the regime (III). The transition between the regimes (III) and (II) is around $r = 0.7$. From their experiments, Philipps and others (2006) proposed also a transition around $r^{III-II} = 0.7$. We reported the model predictions, i.e. the value of $R_f(L_1/L_2)$, for $D = 4$, $D = 5$ and $D = 6.66$.

Figure 11: Ratio of the deposit length to the mean deposit height, $\epsilon^{-1} = L/H_x$, versus the mass proportion r in fine particles of diameter d_1 .

Figure 12: Lengthening coefficient of the deposit in the runout zone, $\epsilon^{-1} = L/H_x$, versus the Froude number Fr . The critical value of the ratio r is about $r_{crit} = 0.25$ in our experiments. This value depends on the value of the ratio $D = d_2/d_1$ according to the discrete numerical simulations carried out by Linares-Guerrero and others (2007).