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# Laboratory Landquakes: Insights From Experiments Into the High-Frequency Seismic Signal Generated by Geophysical Granular Flows

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1     **Laboratory landquakes: Insights from experiments into**  
2             **the high-frequency seismic signal generated by**  
3             **geophysical granular flows**

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12     **Key Points:**

- 13     • We conducted novel laboratory experiments to test five existing models for the  
14       high-frequency seismic signals generated by granular flows
- 15     • The ‘thin-flow’ model of Farin et al. (2019) was the most accurate and makes pre-  
16       dictions consistent with empirical observations
- 17     • The ratio between the mean and fluctuating forces exerted by a granular flow varies  
18       greatly, determined by an inertial number of the flow

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19 **Abstract**

20 Geophysical granular flows exert basal forces that generate seismic signals, which can  
 21 be used to better monitor and model these severe natural hazards. A number of empir-  
 22 ical relations and existing models link these signals' high-frequency components to a va-  
 23 riety of flow properties, many of which are inaccessible by other analyses. However, the  
 24 range of validity of the empirical relations remains unclear and the models lack valida-  
 25 tion, owing to the difficulty of adequately controlling and instrumenting field-scale flows.  
 26 Here, we present laboratory experiments investigating the normal forces exerted on a basal  
 27 plate by dense and partially dense flows of spherical glass particles. We measured the  
 28 power spectra of these forces and inferred predictions for these power spectra from the  
 29 models proposed by Kean et al. (2015), Lai et al. (2018), Farin et al. (2019), and Bachelet  
 30 (2018), using Hertz theory to extend Farin et al. (2019)'s models to higher frequencies.  
 31 The comparison of these predictions to our observations shows those of Farin et al. (2019)'s  
 32 'thin-flow' model to be the most accurate, so we examine explanations for this accuracy  
 33 and discuss its implications for geophysical flows' seismic signals. We also consider the  
 34 normalisation, by the mean force exerted by each flow, of the force's mean squared fluc-  
 35 tuations, showing that this ratio varies by four orders of magnitude over our experiments,  
 36 but is determined by a bulk inertial number of the flow.

37 **Plain Language Summary**

38 Landslides, like earthquakes, generate seismic signals: vibrations of the earth that  
 39 can be detected a long way away. Analysis of the most rapid vibrations could provide  
 40 information about how large a landslide is or how damaging it will be, helping emergency  
 41 services respond. But full-size landslides are complex and difficult to study, so the gen-  
 42 eration of these vibrations is not yet sufficiently well understood for this information to  
 43 be reliable. Therefore, in the place of full-size landslides, we studied simplified, small-  
 44 scale versions in the laboratory, testing previous authors' predictions for the seismic sig-  
 45 nals they generate. We find that one set of predictions was particularly accurate and show  
 46 that the corresponding predictions for full-size landslides are consistent with previous  
 47 observations. This implies that a landslide's seismic signal can be used to calculate its  
 48 size, its speed, and the typical size of particles within it.

## 49 1 Introduction

### 50 1.1 Background

51 Landslides and other geophysical granular flows are a major natural hazard, caus-  
52 ing on average 4000 deaths worldwide each year from 2004 to 2016 (Froude & Petley,  
53 2018) and an estimated billions of dollars of annual damage in the United States alone  
54 (Fleming et al., 1980; National Research Council, 1985; Schuster & Fleming, 1986). Many  
55 areas have little or no early warning system in place (Hervás, 2003; Guzzetti et al., 2020)  
56 and a damaging event’s magnitude and effects may remain unknown for hours or days  
57 after it happens (Hervás, 2003; Scholl et al., 2017), hindering the response of emergency  
58 services and preventing those in a landslide’s path from making even last-minute prepa-  
59 rations. Modelling is currently unable to remedy these knowledge gaps, with poorly con-  
60 strained parameters, such as a flow’s basal friction coefficient, being important in deter-  
61 mining a landslide’s runout (van Asch et al., 2007; Lucas et al., 2014; Delannay et al.,  
62 2017; Cuomo, 2020).

63 Better monitoring of landslide-prone areas and better modelling of flows’ evolution  
64 are therefore key to the reduction of landslide hazard, and the use of seismic signals is  
65 a promising tool towards these aims. Geophysical flows exert forces on the ground over  
66 which they travel, resulting in the outwards-propagating seismic waves that Kanamori  
67 and Given (1982) first described in detail, for an event at Mount Saint Helens. These  
68 seismic waves, which we refer to as ‘landquakes’, can be detected by a local or regional  
69 seismic network, permitting continuous monitoring of a wide area. This monitoring sug-  
70 gests the possibility of early warning systems, analogous to those in use and development  
71 for earthquakes (e.g. Given et al., 2018). Furthermore, landquakes encode information  
72 about a landslide’s magnitude and evolution over time, and so these seismic signals can  
73 be analysed to assess damage, to constrain model parameters, and to compare different  
74 models.

75 The low-frequency components of landquakes encode the accelerations of a land-  
76 slide’s centre of mass, and initial work successfully analysed these components both to  
77 detect landslides and to reconstruct their trajectories. Authors first linked known land-  
78 slides to signals in seismic data (e.g. Galitzine (Golitsyn), 1915; Jeffreys, 1923; Peter-  
79 schmitt & de Visintini, 1964; Berrocal et al., 1978; Kanamori & Given, 1982; Hasegawa  
80 & Kanamori, 1987; Eissler & Kanamori, 1987; Weichert et al., 1994) before considering

81 theoretically the low-frequency signals generated by idealised landslides (e.g. Kawakatsu,  
82 1989; Dahlen, 1993; Fukao, 1995). The theoretical framework of a single-force point source  
83 permitted the detection of landslides from seismic signals both locally (Lin et al., 2010;  
84 Chao et al., 2017) and globally (Ekström & Stark, 2013), while inversion for that force  
85 with single-block landslide models allowed their evolution to be reconstructed or their  
86 flow parameters to be constrained (Brodsky et al., 2003; La Rocca et al., 2004; Ekström  
87 & Stark, 2013; Allstadt, 2013; Yamada et al., 2013; Coe et al., 2016). Other authors (e.g.  
88 Favreau et al., 2010; Moretti et al., 2012, 2015, 2020; Yamada et al., 2016, 2018; Zhao  
89 et al., 2020) used a higher-order approximation towards the same aim, simulating land-  
90 slides as continuous mass distributions rather than point masses and calculating the cor-  
91 responding low-frequency synthetic landquakes. Comparison to observed seismic signals  
92 then permitted higher-resolution reconstruction of mass releases and flow trajectories,  
93 and the estimation of spatially varying flow parameters. However, such low-frequency  
94 seismic waves can only be detected for large landslides and, even if detected, cannot pro-  
95 vide information on many properties relevant to landslide modelling and harm assess-  
96 ment, such as the size of individual particles within the flow or the vertical profiles of  
97 flow properties.

98 To extract more information and infer these properties, previous authors suggest  
99 using the high-frequency component of landquakes, associated with the accelerations of  
100 individual particles within the flow. The spectrogram of this high-frequency component  
101 and its envelope have distinctive shapes (Suriñach et al., 2005) which can be used to de-  
102 tect landslides (Hibert et al., 2014; Dammeier et al., 2016; Fuchs et al., 2018; Lee et al.,  
103 2019). Furthermore, the properties of this envelope can be related to those of the land-  
104 slide: the envelope's duration to the landslide's duration and hence its loss of potential  
105 energy (Deparis et al., 2008; Hibert et al., 2011; Levy et al., 2015); the envelope's am-  
106 plitude to the seismic energy emitted by the landslide and hence its volume (Norris, 1994;  
107 Hibert et al., 2011; Levy et al., 2015), its work rate against friction (Schneider et al., 2010;  
108 Levy et al., 2015), and its momentum (Hibert et al., 2015, 2017); and envelope scale and  
109 shape parameters to the landslide's geometry via multilinear regression (Dammeier et  
110 al., 2011). Without a theoretical framework for the high-frequency component of landquakes,  
111 however, both the precision and the range of validity of these relations are unclear, and  
112 it is difficult to use them to assess a landslide's damage or to better predict it. A model  
113 for landquake generation is required.

114 **1.2 Existing Models**

115 Models of the high-frequency component of landquakes rely on the same framework:  
 116 consideration of the total seismic signal as a sum of the uncorrelated signals generated  
 117 by individual, random particle impacts, with the properties of the impacts determined  
 118 by some mean properties of the particulate flow and with a specified Green’s function  
 119 mapping the force of an individual impact to the seismic signal observed at a remote sta-  
 120 tion. This stochastic impact framework arises from Tsai et al. (2012)’s model of seismic  
 121 noise generation from riverine sediment transport, and we discuss its validity in S2. We  
 122 expect that it will be applicable to any extensive flows of stiff particles for which ener-  
 123 getic impacts are more significant than other high-frequency sources, for signal periods  
 124 smaller than the timescales over which the bulk flow varies. Examples may include avalanches,  
 125 debris flows, and rockfalls involving multiple blocks.

126 Assuming the framework’s validity, prediction of a flow’s high-frequency landquake  
 127 signal requires consideration of the locations  $\mathbf{x} \in V$  of signal generation, and the spec-  
 128 ification of just three things at each location: 1) the number  $n_I(\mathbf{x})$  of impacts per unit  
 129 volume and time; 2) the force  $\mathbf{F}_I(\mathbf{x}, t)$  applied by a single, typical impact over its du-  
 130 ration; and 3) the Green’s function  $\mathbf{G}(t, \mathbf{r}; \mathbf{x})$  for the scalar velocity response  $v_{\mathbf{r}}(t)$  to that  
 131 force of the seismic station detecting the signal, located at  $\mathbf{r}$ . Writing  $\tilde{\cdot}$  for Fourier trans-  
 132 forms over time  $\Delta t$ , the landquake signal will then have power spectral density

133 
$$P_{v_{\mathbf{r}}}(f) = |\tilde{v}_{\mathbf{r}}(f)|^2 / \Delta t = \int_V n_I(\mathbf{x}) |\tilde{\mathbf{F}}_I(\mathbf{x}, f) \cdot \tilde{\mathbf{G}}(f, \mathbf{r}; \mathbf{x})|^2 d\mathbf{x}. \quad (1)$$

134 **1.2.1 Direct Use of Tsai et al. (2012)**

135 Kean et al. (2015), Lai et al. (2018), and Farin et al. (2019) consider only impacts  
 136 on exposed bedrock at the base of a flow to be significant in signal generation, and as-  
 137 sume 1) that the rate of impacts is determined by the advection of particles, with the  
 138 mean flow, into basal irregularities of the same scale; 2) that the force a particle exerts  
 139 varies over timescales much shorter than the range of periods to which the seismic sta-  
 140 tion is sensitive; and 3) that the relevant Green’s function is that for Rayleigh-wave prop-  
 141 agation to the far field. Under these assumptions, if a representative impacting parti-  
 142 cle has diameter  $d$  and downslope speed  $u$ , it will have collision rate  $u/d$ , so that a bedrock-  
 143 contacting flow area  $A$  in which impacting particles have a volume fraction  $\phi$  will have  
 144 an approximate integrated collision rate  $\int_V n_I d\mathbf{x} = \phi Au/d^3$ . For all signal periods of

145 interest, the typical force applied by an impact will be approximable as a Dirac delta func-  
 146 tion in time and hence constant in the frequency domain, equal to the impulse transferred,  
 147 so that we may write  $\tilde{\mathbf{F}}_I(f) = \Delta p \mathbf{e}_I$  for a unit vector  $\mathbf{e}_I$  in the direction of the impulse.  
 148 Meanwhile, the relevant frequency-space Green's function for a station at radius  $r$  will  
 149 have magnitude  $|\mathbf{e}_I \cdot \tilde{\mathbf{G}}| = R(f)e^{-\alpha(f)r}/\sqrt{r}$ , for functions  $R$  and  $\alpha$  related to Rayleigh-  
 150 wave propagation and inelastic attenuation, respectively. Consequently, the signal's power  
 151 spectral density is

$$152 \quad P_{v_r}(f) = \frac{\phi Au \Delta p^2}{d^3 r} R(f)^2 e^{-2\alpha(f)r}. \quad (2)$$

153 Kean et al. (2015) suggests that  $u$  scales with the measured surface velocity and  
 154  $\Delta p$  with the base-normal component of the flow's local weight per unit area. The au-  
 155 thors use an empirical, piecewise-continuous function  $\alpha$ , and avoid consideration of scal-  
 156 ing constants,  $\phi$ ,  $R$  and  $d$  by examining only the ratio of  $P_{v_r}(f)$  to that measured dur-  
 157 ing a reference debris flow in the same channel, for which such parameters are assumed  
 158 to be the same. The paper uses this model to estimate the depths of static sediment 'shield-  
 159 ing' the channel centre from impacts, and these estimates correctly remain positive, but  
 160 the paper performs no further evaluation of the model.

161 Lai et al. (2018) suggests that large, flow-depth-spanning particles dominate the  
 162 signal, so that  $d$  should be the 94th percentile of the particle diameter distribution and  
 163  $u$  should be the depth-averaged downslope velocity  $\bar{u}$  of the flow. The authors implic-  
 164 itly take  $\phi = 1$  and further assume that impacts transfer an impulse equal to that for  
 165 elastic rebounds of individual near-spherical particles at vertical velocity  $\bar{u}$ , such that  
 166  $\Delta p = \pi \rho d^3 \bar{u} / 3$  for particle material density  $\rho$ . Equations for  $R(f)$  and  $\alpha(f)$  are taken  
 167 from Tsai et al. (2012), Tsai and Atiganyanun (2014), and Gimbert and Tsai (2015), and  
 168 then applied to a Californian debris flow, to invert the peak frequency of  $P_{v_r}(f)$  for  $r$ .  
 169 However, this inversion relies on the model for signal generation only via the assump-  
 170 tion that  $|\tilde{\mathbf{F}}_I(f)|$  is independent of  $f$  in the frequency range of interest, so this assump-  
 171 tion is the only part of the model that the paper tests.

172 Farin et al. (2019) generalises the model of Lai et al. (2018) to different flow regions  
 173 and regimes and to a continuous particle size distribution. The authors calculate that  
 174 the impacts of particles falling from the flow front or saltating ahead of it are less sig-  
 175 nificant for signal generation than those in the flow's dense snout and body. In these two  
 176 regions, for 'thin' flows of depth  $h$  comparable to the largest particle diameters, the pa-

177 per suggests that the Lai et al. (2018) model will hold, with slight modifications:  $\phi$  is  
 178 explicitly stated; there are extra terms in the equation for  $\Delta p$  to account for inelastic-  
 179 ity and variation in the angle and velocity of impacts;  $R$  is adjusted to account for non-  
 180 vertical  $\mathbf{e}_I$ ; and  $d$  is represented by its appropriately weighted average over the distri-  
 181 bution of particle diameters, which is suggested to be approximately equal to the 73rd  
 182 percentile of that distribution. However, for ‘thick’ flows, where  $h$  is much larger than  
 183 the particles’ diameters, the paper suggests that, in addition to the above slight mod-  
 184 ifications, the relevant advection and impact velocity is that of base-adjacent particles.  
 185 Assuming no basal slip, in the sense that velocities tend to zero towards the flow’s base,  
 186  $u$  is then proportional to  $\bar{u}d/h$  and the representative value of  $d$  is equal to the 86th per-  
 187 centile of the particle diameter distribution. The authors tested neither of the ‘thin-flow’  
 188 and ‘thick-flow’ models.

189 **1.2.2 Model of Bachelet (2018)**

190 In contrast to the above papers, Bachelet (2018) considers impacts between differ-  
 191 ent layers of particles, throughout the depth of the flow, and supposes 1) that the local  
 192 impact rate is the rate at which adjacent layers shear over each other; 2) that the force  
 193 throughout an impact is described by Hertz theory with typical impact velocity equal  
 194 to the standard deviation in particle velocity within each layer; and 3) that the Green’s  
 195 function includes exponential attenuation of the force with the impact’s distance from  
 196 the flow’s base.

197 The use of Hertz theory to describe the contact force between impacting particles,  
 198 detailed in S3, predicts the duration of impacts and so a frequency scale for the spec-  
 199 tral density of the forces they exert. For a collision at relative normal velocity  $u_n$  between  
 200 two spherical particles of diameter  $d$ , consisting of material with density  $\rho$ , Young’s mod-  
 201 ulus  $E$ , and Poisson’s ratio  $\nu$ , Hertz theory predicts a timescale for the impact

202 
$$\tau = \left[ \frac{\pi^2 \rho^2 (1 - \nu^2)^2}{4E^2 u_n} \right]^{1/5} d. \quad (3)$$

203 With this  $\tau$ , the spectral density of the normal force between the particles is

204 
$$|\tilde{F}_I(f)|^2 = \left( \frac{\pi \rho d^3 u_n}{3} \right)^2 \zeta(f\tau) \quad (4)$$

205 for a non-dimensional function  $\zeta(f\tau)$ , plotted in S3, which is approximately equal to 1  
 206 for  $f\tau \ll 1$ , monotonically decreases to  $\zeta(f\tau) = 0.5$  for non-dimensional corner fre-



207 quency  $f_c\tau \approx 0.208$ , and is much less than 1 for  $f\tau > 1$ . Impacts at higher velocities  
 208  $u_n$  apply forces with higher spectral density, over a wider frequency range.

209 This spectral density doesn't appear explicitly in Bachelet (2018), which instead  
 210 uses the integral of  $\zeta$  over all  $f\tau$  to consider the total seismic power generated by a flow.  
 211 However, we can follow the thesis' reasoning to derive from equation (4) a prediction for  
 212 the spectral density of a flow's high-frequency landquake signal, in the form of equation  
 213 (1). First, separating a flow with representative particle size  $d$  and particle volume frac-  
 214 tion  $\phi$  into layers, and writing  $z_j$  for the vertical position of each layer and  $u_j$  for the mean  
 215 horizontal velocity within it, the thesis suggests that the rate of impacts is

$$216 \quad n_I(\mathbf{x}) = \frac{4\phi}{\pi d^3} \sum_j (u_j - u_{j-1}) \delta(z - z_j) \quad (5)$$

217 for Dirac delta function  $\delta$ . Then, writing  $T_j$  for the granular temperature in the  $j$ th layer,  
 218 equal to the variance of individual particles' velocities, the thesis takes the spectral den-  
 219 sity of the force applied by a typical impact to be given by equation (4) with impact ve-  
 220 locity  $u_n = \sqrt{T_j}$ . Finally, the magnitude of the frequency-space Green's function for  
 221 an impact at height  $z$  is taken to be  $e^{-\gamma z/2} |\tilde{G}_b|$ , where  $\gamma$  is an attenuation constant and  
 222  $|\tilde{G}_b|$ , describing a measurement station's velocity response to vertical basal forces, is con-  
 223 stant due to the assumption of an incoherent, diffuse seismic field with constant atten-  
 224 uation. Therefore, a flow of area  $A$  will generate a landquake signal with power spectral  
 225 density

$$226 \quad P_{v_r}(f) = \frac{4\phi A}{\pi d^3} |\tilde{G}_b|^2 \sum_j (u_j - u_{j-1}) \Delta p_j^2 \zeta(f\tau_j) e^{-\gamma z_j} \quad (6)$$

227 for

$$228 \quad \Delta p_j = \frac{\pi \rho d^3 \sqrt{T_j}}{3}, \quad \tau_j = \left[ \frac{\pi^2 \rho^2 (1 - \nu^2)^2}{4E^2 \sqrt{T_j}} \right]^{1/5} d. \quad (7)$$

229 Bachelet (2018) shows this model to be consistent with measurements of the seis-  
 230 mic signals generated by approximately steady and uniform laboratory-scale granular  
 231 flows, but the results are not conclusive. Releasing flows of  $d = 2$  mm-diameter glass  
 232 beads in a channel inclined at angles between  $16.5^\circ$  and  $18.1^\circ$ , accelerometers were used  
 233 to estimate the total seismic power imparted to an isolated plate by overlying flows of  
 234 depths between  $15d$  and  $20d$ , and this power was compared to the prediction of equa-  
 235 tion (6), with flow parameters estimated using high-speed photography through the chan-  
 236 nel's transparent sidewalls. The agreement is reasonable, but is highly dependent on the  
 237 fitted parameter  $\gamma$ , and so the number of estimates, and their range of variation, are too

238 small for conclusions to be definitive. The use of Hertz theory permits predictions for  
239 the frequency-dependence of the power spectral density, but no such predictions are com-  
240 pared with experimental results. Further tests are therefore required.

### 241 **1.3 Aim of This Paper**

242 This paper aims to test the above models of high-frequency landquake signal gen-  
243 eration. Studying a range of granular flows and measuring the parameters used by the  
244 above models, we aim to compare observed landquake signals to the models' predictions.  
245 Because we are concerned with the generation of the signal, rather than its propagation,  
246 we consider predictions for the power spectral density  $P_F$  of the total base-normal force  
247 exerted by the flow, which may be obtained by removing the Green's function in equa-  
248 tion (1), so by dividing equation (2) by  $R^2 e^{-2\alpha r}/r$  and equation (6) by  $|\tilde{G}_b|^2$ .  $P_F$  will  
249 be proportional to the spectral density of the signal at a receiver, with its appropriately  
250 weighted integral proportional to the seismic power transmitted by the flow, but  $P_F$ , un-  
251 like these measurements, is independent of the response of the base on which the flow  
252 propagates.

253 However, it is difficult to use field-scale granular flows to test the models' predic-  
254 tions for  $P_F$ . Natural geophysical flows often occur in remote locations, infrequently and  
255 unpredictably, and so the sites of most flows are not instrumented for measurements of  
256 flow parameters. Where sites are instrumented, the destructiveness of geophysical flows  
257 restricts which parameters can be measured, excluding most used by the above models.  
258 Furthermore, geophysical flows are typically extremely unsteady and heterogeneous, so  
259 that any given landquake signal may be produced by a flow region with parameters very  
260 different from those that have been measured. Finally, the inference from a landquake  
261 signal of the forces that generated it requires inversion of the Green's function, which  
262 is typically poorly constrained at the high frequencies of interest, and to which the in-  
263 version is typically very sensitive at precisely these high frequencies.

264 We therefore conducted laboratory experiments to link the properties of a gran-  
265 ular flow to the seismic signal it generates. In the laboratory, flows can be fully controlled  
266 and instrumented, allowing a wide range of parameter values to be explored and mea-  
267 sured. Apparatus can be designed to produce steady, uniform, homogeneous flows, and  
268 the Green's function can be well constrained over a large frequency range by calibration.

269 Having established the relevant physics, conclusions drawn from laboratory results can  
 270 then be scaled up to describe field-scale flows.

## 271 **2 Methods**

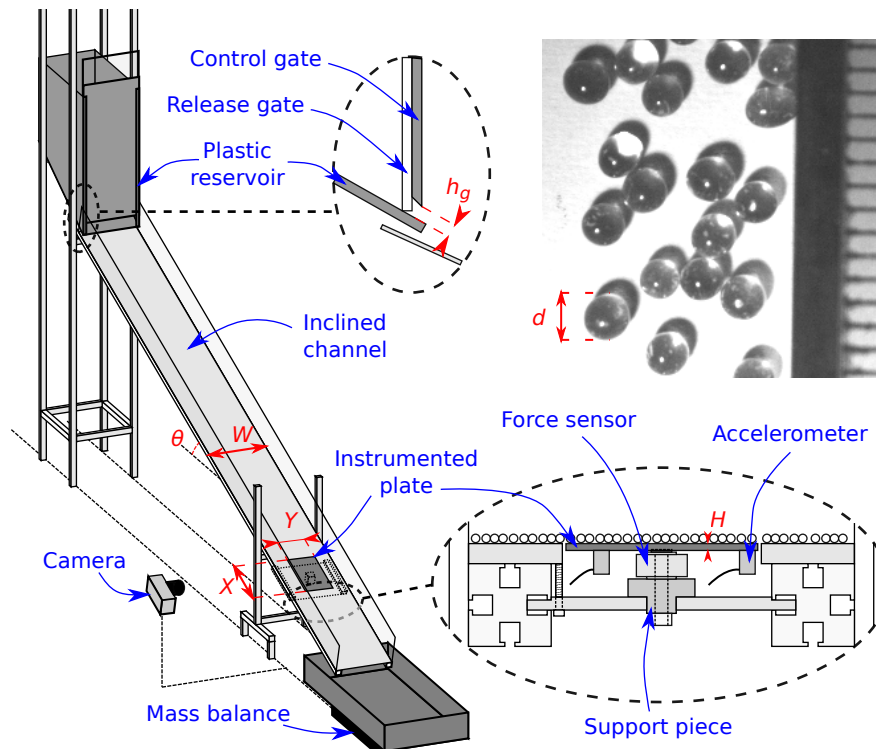
### 272 **2.1 Experimental Apparatus**

273 As the simplest possible analogue of a geophysical granular flow, we studied the  
 274 flow of spherical glass beads,  $d = 2$  mm in diameter, in an inclined channel 2.5 m long  
 275 and  $W = 0.2$  m wide, shown in Figure 1. The beads were 1.7-2.1 mm Type S glass beads  
 276 produced by Sigmund Lindner GmbH and provided by MINERALEX, with material den-  
 277 sity  $\rho = 2500$  kg m<sup>-3</sup> and Young’s modulus  $E = 63$  GPa (Sigmund Lindner, 2018).  
 278 In each experiment, 40 kg of beads were initially stored in a plastic reservoir of volume  
 279 0.08 m<sup>3</sup>, from which they flowed out via a rectangular opening of width 0.18 m and ad-  
 280 justable height  $h_g$ , controlled to within 0.06 mm by a plastic gate which was fixed in place  
 281 during each experiment. A separate plastic release gate blocked this opening before each  
 282 experiment and was manually lifted to start outflow. On leaving the reservoir, beads en-  
 283 tered the separately supported channel, which had an aluminium base; transparent, 0.1 m-  
 284 high acrylic walls; and an incline  $\tan \theta$ , which could be adjusted by changing the heights  
 285 of the braces attaching the channel to its supports. The channel’s base was roughened  
 286 with the same type of glass beads as constituted the flow, fixed in place with extra-strong  
 287 double-sided carpet tape, with an irregular, dense pattern achieved by random pouring.

288 The flow of beads down the channel adjusted to these conditions over a distance  
 289 of 1.92 m, before reaching a rectangular, instrumented steel plate set into a correspond-  
 290 ing hole in the centre of the channel’s base. The plate was  $X = 0.18$  m long,  $Y = 0.1$  m  
 291 wide, and  $H = 2$  mm thick, with its surface flush with that of the aluminium base to  
 292 within 0.02 mm and separated from it by an isolation gap of  $0.04 \pm 0.01$  mm, achieved  
 293 by using strips of plastic film as spacers during emplacement. The plate was supported  
 294 by a force sensor and a support piece, with the three separated by washers and held to-  
 295 gether by a prestressing screw, the head of which was glued into a 0.5 mm-deep recess  
 296 in the centre of the plate’s underside. The support piece, in turn, was attached to the  
 297 channel’s substructure using phenyl salicylate (salol), which was added to the join when  
 298 molten and solidified to form a stiff connection, but could be melted with a heat gun for  
 299 removal of the plate or adjustment of its position. Before the plate’s emplacement, we

300 used the same salol to roughen its surface with glass beads: heating the plate, we added  
 301 salol to form a thin, liquid layer, and we poured beads on top to form an irregular, dense  
 302 pattern, before the salol solidified and fixed them in place.

303 After the plate, the flow of beads continued for 0.4 m, before flowing out of the chan-  
 304 nel and into a plastic outflow tray. Plastic sheeting extended the tray's walls, to prevent  
 305 energetic particles from escaping.



**Figure 1.** *Schematic of experimental apparatus.* Experiments are conducted in the channel represented, to scale, at left, with components of the apparatus labelled in blue and relevant dimensions in red. Expansions at top-centre and bottom-right represent, in cutaway views and not to scale, details of the reservoir and the instrumented plate, respectively. The glass beads used in experiments are shown at top-right, with a mm-unit scale.

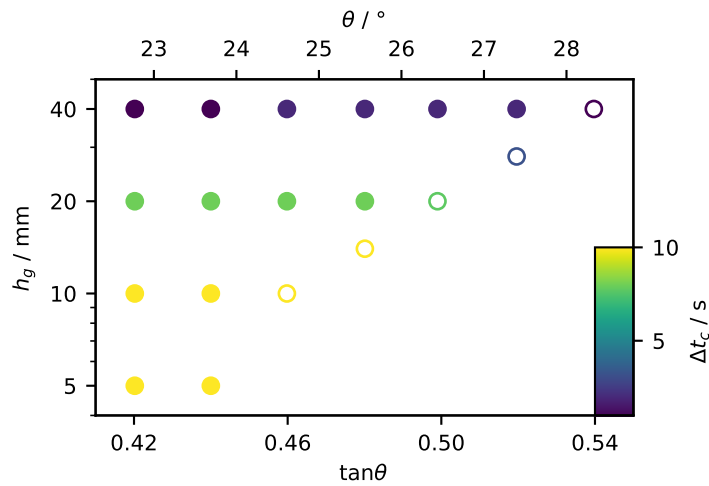
306 Four sets of devices took measurements of the flow: a mass balance beneath the  
 307 outflow tray; the force sensor supporting the instrumented plate; four accelerometers at-  
 308 tached to the plate's underside; and a high-speed camera directed through the channel's  
 309 wall. The mass balance was a Dymo S50 digital shipping scale, which measured in each  
 310 experiment the cumulative mass that had passed through the channel. The force sen-

311 sor was a Kistler 9027C three-component force sensor and was connected to a Kistler  
312 5073 charge amplifier, measuring the normal, downslope, and cross-slope forces exerted  
313 by the flow on the plate. The accelerometers were Brüel and Kjær type 8309 accelerom-  
314 eters, attached with salol to randomly selected positions on the plate's underside and  
315 connected to a Brüel and Kjær Nexus 2692-A-OS4 conditioning amplifier, to measure  
316 the normal vibrations of the plate and hence the seismic energy imparted to it by the  
317 flow. Settings of the force sensor and accelerometer amplifiers are described in S4. The  
318 camera was an Optronis CR600x2, with a Sigma 17-50 mm F2.8 EX DC lense, and was  
319 level with and focussed on the inside of the channel sidewall, directly cross-slope from  
320 the instrumented plate's centre. The camera's inclination was the same as the channel's  
321 and its field of view was 640x256 pixels, corresponding to a region 8 cm long and 3.2 cm  
322 high. The sidewall was lit using a Photonlines H5 LED light, via a white sheet of pa-  
323 per which acted as a reflective diffuser, and we used an exposure of 250  $\mu\text{s}$  and a frame  
324 rate of 2000  $\text{s}^{-1}$ .

325 To control the measurement devices, we used an Arduino Uno R3 microcontroller  
326 board, and we recorded measurements using a Pico Technology Picoscope 4824 oscillo-  
327 scope connected to a Lenovo E530 laptop. Measurements from the mass balance, force  
328 sensor, and accelerometers were recorded from the time  $t = 0$  at which the reservoir's  
329 release gate was lifted until the outflow stopped at  $t = t_e$ , while the camera recorded  
330 footage over a duration  $\Delta t_c$  between 2 s and 10 s, after a delay time  $t_d$  in which the flow  
331 developed into a steady state. Details are in S5.

332 We conducted experiments with six different channel inclinations between  $22.8^\circ$  and  
333  $27.5^\circ$  ( $\tan \theta = 0.42, 0.44, 0.46, 0.48, 0.50$  and  $0.52$ ), with this order randomised to negate  
334 the effect of any systematic variation in atmospheric conditions or measurement sensi-  
335 tivity. For each inclination, we conducted three repeats with the reservoir control gate  
336 at each of four different heights ( $h_g = 5$  mm, 10 mm, 20 mm and 40 mm), with the or-  
337 der of gate heights again selected at random.

338 At channel inclines equal to and greater than  $\tan \theta = 0.46$  ( $\theta = 24.7^\circ$ ), there was  
339 a gate height below which flows were in the gaseous regime of e.g. Börzsönyi and Ecke  
340 (2006) and Taberlet et al. (2007), with all glass beads in saltation and accelerating downs-  
341 slope. We recorded no measurements of such flows, which were energetic and far from sta-  
342 tionary, with a large number of beads escaping across the channel's sidewalls and with



**Figure 2.** Channel inclines  $\tan\theta$  and release gate heights  $h_g$  used in experiments.  $\circ$  indicates an experiment for which the flow was in the transitional regime, while colours indicate the duration of time  $\Delta t_c$  recorded by the camera.

343 the camera’s images unusable for reliable measurements. At each such incline, we instead  
 344 recorded measurements at all gate heights resulting in dense flows and at one gate height  
 345 resulting in a ‘transitional-regime’ flow, with a dense basal flow below a saltating layer.  
 346 These gate heights are plotted in Figure 2, within the full parameter space investigated.

## 347 2.2 Data Analysis

348 For each experiment within the parameter space, we analysed the experimental data  
 349 to calculate dynamic, seismic, and kinematic properties of the flow: the mass of parti-  
 350 cles that lay over the instrumented plate and the effective friction coefficient between the  
 351 two; the mass flux of particles through the channel and their average velocity; the power  
 352 spectrum of the normal force exerted on the plate by the flow; and the vertical profiles  
 353 of particle volume fraction, velocity, and granular temperature at a channel wall. We re-  
 354 call that  $W$  denotes the channel’s width and  $\theta$  its angle of inclination; that  $X$ ,  $Y$ , and  
 355  $H$  denote the length, width, and thickness of the plate; and that  $t_d$  and  $\Delta t_c$  denote the  
 356 delay before and the duration of the high-speed camera’s recording, respectively. These  
 357 and all other variables are listed in S1 and all code used to perform these analyses is avail-  
 358 able at Arran et al. (2020).

359 To infer the mass overlying the plate and its effective friction coefficient with the  
 360 flow, we used the data from the force sensor. Averaging over successive 0.5 ms intervals,  
 361 the net downslope force  $F_x(t)$  and plate-normal, downwards force  $F_z(t)$  applied to the  
 362 plate by the flow were calculated from the voltage output of the force sensor’s charge am-  
 363 plifier, as described in S6. Then, assuming no net plate-normal acceleration of the flow  
 364 overlying the plate, over the period of steady flow recorded by the camera, we calculated  
 365 the average mass per unit area overlying the plate as

$$366 \quad \sigma = \frac{\langle F_z \rangle_{\Delta t_c}}{XYg \cos \theta}, \quad (8)$$

367 where  $\langle \cdot \rangle_{\Delta t_c}$  represents the arithmetic mean over  $t_d < t < t_d + \Delta t_c$  and  $g$  represents  
 368 gravitational acceleration. Similarly, we followed Hungr and Morgenstern (1984) and Roche  
 369 et al. (2020) in calculating the effective friction coefficient as

$$370 \quad \mu = \frac{\langle F_x \rangle_{\Delta t_c}}{\langle F_z \rangle_{\Delta t_c}}, \quad (9)$$

371 with this calculation validated in S6, section S6.3.

372 To calculate the mass flux through the channel, we examined the data recorded by  
 373 the mass balance. Having the cumulative mass  $M(t)$  that had flowed through the chan-  
 374 nel after time  $t$ , we calculated the average flux per unit channel width, over the period  
 375 of steady flow recorded by the camera, as

$$376 \quad q = \frac{M(t_d + \Delta t_c) - M(t_d)}{\Delta t_c W}. \quad (10)$$

377 Assuming this average mass flux to be equal to that across the plate, and having cal-  
 378 culated the mass overlying the plate, we could then calculate the mean depth-averaged  
 379 flow velocity across the plate,

$$380 \quad \bar{u} = q/\sigma. \quad (11)$$

381 To extract the power spectral density of the flow’s basal force, we processed data  
 382 from the accelerometers using Kirchhoff-Love plate theory and assuming perfect isola-  
 383 tion of the plate from the channel and linear attenuation within the plate. On the ba-  
 384 sis of the steel’s technical documentation (John Steel, 2019; Steel SS, 2019), we took its  
 385 density to be  $\rho_p = 7800 \text{ kg m}^{-3}$ , its Young’s modulus to be  $E_p = 200 \text{ GPa}$ , and its Pois-  
 386 son’s ratio to be  $\nu_p = 0.29$ . Then, its bending stiffness was  $D = E_p H^3 / 12(1 - \nu_p^2)$  and  
 387 the mean bandgap between its resonant frequencies was  $\Delta_f = 2\sqrt{D}/XY\sqrt{\rho_p H} \approx 400 \text{ Hz}$ .

388 Assuming that the spectral density of an impact’s force varied little over this frequency  
 389 scale, this spectral density was estimated using  $D$ , the proportion of the plate’s energy  
 390  $\mathcal{P}$  in its steel structure’s vertical displacements, the quality factor  $Q$  describing the at-  
 391 tenuation of energy in the plate, and the accelerations  $a_j(t)$  measured by the four ac-  
 392 celerometers, as

$$393 \quad P_F(f) = \frac{|\tilde{F}(f)|^2}{\Delta t} \approx \frac{(\rho_p H)^{3/2} X Y \sqrt{D}}{\pi \mathcal{P} Q f \Delta t} \left\langle \sum_{j=1}^4 |\tilde{a}_j(f)|^2 \right\rangle_{\Delta f}, \quad (12)$$

394 where Fourier transforms are over a time interval  $\Delta t = 0.2$  s, and  $\langle \cdot \rangle_{\Delta f}$  represents a mov-  
 395 ing average over frequency, with window width  $\Delta f = 2$  kHz. We describe in S7, sec-  
 396 tion S7.1 the derivation of this relation and the calculation of  $|\tilde{a}_j|^2$  from the voltage out-  
 397 put of the accelerometers’ conditioning amplifier; in section S7.2 the calibration we per-  
 398 formed to measure the plate parameters  $\mathcal{P} = 0.25$  and  $Q = 99$  and to extend the flat  
 399 frequency range of the accelerometers to 120 kHz; and in section S7.3 the validation of  
 400 this work.

401 Finally, to extract profiles of kinematic properties at the channel wall, we analysed  
 402 the images taken by the high-speed camera, using particle tracking velocimetry and Gaus-  
 403 sian coarse-graining. Analysing each frame in turn, we detected the positions  $(x_j, z_j)$  of  
 404 particles at the channel walls and, tracking particles between consecutive frames, cal-  
 405 culated their mean velocities over each 0.5 ms interval. Calculating the smoothed veloc-  
 406 ities  $\mathbf{u}_j$  over five frames, or 2.5 ms, we estimated the downslope-averaged and time-averaged  
 407 base-normal profiles at the channel’s wall of relative volume fraction  $\phi_w(z)$ , mean veloc-  
 408 ity  $\mathbf{u}_w(z)$ , and granular temperature  $T_w(z)$  as

$$409 \quad \phi_w(z) = \left\langle \sum_j C(z_j; z) \pi d^2 / 4 \right\rangle_{\Delta t_c}, \quad (13)$$

$$410 \quad \mathbf{u}_w(z) = \left\langle \sum_j C(z_j; z) \pi d^2 \mathbf{u}_j / 4 \right\rangle_{\Delta t_c} / \phi_w(z), \quad (14)$$

$$411 \quad T_w(z) = \left\langle \sum_j C(z_j; z) \pi d^2 \|\mathbf{u}_j - \mathbf{u}_w(z)\|^2 / 4 \right\rangle_{\Delta t_c} / \phi_w(z), \quad (15)$$

412  
 413 where averages are over all frames recorded by the camera, sums are over all particles  
 414 tracked in each frame, and the coarse-graining function  $C$  is localised around  $z$ , with in-  
 415 tegral over the total spatial domain equal to 1. This process is described in detail in S8.

416 While the irregularity of the flow’s base and surface complicate the definition of  
 417 the flow thickness  $h$ , we take the base-normal co-ordinate  $z$  to be zero at the top of the



418 base’s fixed beads, and extract  $h$  as the value of  $z$  at which  $\phi_w(z)$  drops below half its  
 419 maximum value,

$$420 \quad h = \min\{z > \operatorname{argmax} \phi_w | \phi_w(z) < \max(\phi_w)/2\}. \quad (16)$$

421 For a flow with constant particle volume fraction below a level surface, this exactly cor-  
 422 responds to the intuitive flow depth. Whilst other reasonable definitions lead to differ-  
 423 ent specific results, they do not alter our conclusions.

### 424 **2.3 Model Predictions**

425 For each of the models described in section 1.2, for a granular flow’s seismic sig-  
 426 nal, we inferred predictions for the experimental seismic signal. Specifically, we expressed  
 427 a prediction  $\hat{P}_F$  for the power spectrum of the base-normal force applied by the flow to  
 428 the instrumented plate, as a function of the flow properties specified in section 2.2: the  
 429 mean depth-averaged flow velocity  $\bar{u}$ , the mass overburden per unit area  $\sigma$ , the flow depth  
 430  $h$ , and the channel-wall profiles  $u_w(z)$  and  $T_w(z)$  of downslope velocity and granular tem-  
 431 perature. Since previous authors attempted to predict slightly different seismic proper-  
 432 ties and used slightly different flow properties, no directly applicable expressions are in  
 433 the articles introducing the models (Kean et al., 2015; Lai et al., 2018; Farin et al., 2019;  
 434 Bachelet, 2018). We therefore worked from equations (2) and (6); used the models’ meth-  
 435 ods of estimating those equations’ variables, as described in sections 1.2.1 and 1.2.2; and  
 436 removed Green’s functions as described in section 1.3, to predict the basal force’s power  
 437 spectrum rather than the power spectrum of a seismic station’s response. Recalling that  
 438  $g \cos \theta$  denotes base-normal gravitational acceleration,  $d$  the particles’ mean diameter,  
 439 and  $\rho$  their density, and approximating the flow area generating the measured signal by  
 440 the instrumented plate’s area  $A = XY$  and the flow’s mean volume fraction by  $\phi =$   
 441  $\sigma/\rho h$ , these predictions could then be compared to the measured power spectra  $P_F$ .

442 The model introduced by Kean et al. (2015) predicts the seismic signal generated  
 443 by a granular flow covering a certain area, using its surface velocity and the base-normal  
 444 component of its weight per unit area. If the near-base velocity of the flow scales with  
 445 its surface velocity, as Kean et al. (2015) suggests, then both will scale with the depth-  
 446 averaged velocity  $\bar{u}$ , so to calculate predictions we estimated the velocity  $u$  of equation  
 447 (2) with  $\bar{u}$  and the impulse  $\Delta p$  with  $\sigma g \cos \theta$ , the measured base-normal component of  
 448 the flow’s weight per unit area. We may therefore write the model’s prediction for  $P_F$ ,

449 for signal periods  $1/f$  well above the duration of a typical impact, as

$$450 \quad \hat{P}_F^0 = KA\bar{u}(\sigma g \cos \theta)^2/d^3. \quad (17)$$

451  $K$  is a free parameter supposed equal to the product of a constant volume fraction; a  
 452 constant of proportionality between  $\bar{u}$  and the near-base flow velocity; and a squared con-  
 453 stant of proportionality between the mean basal pressure and the typical impulse trans-  
 454 ferred by a basal impact. No indication is given as to its value, so it must be found by  
 455 fitting.

456 In contrast, the model introduced by Lai et al. (2018) requires no free parameter.  
 457 Noting that the experimental particles have a narrow diameter distribution, with 94th  
 458 percentile approximately equal to its mean  $d$ , and using the appropriate substitutions  
 459 for  $u$  and  $\Delta p$  in equation (2), the model's prediction for  $P_F$  is the constant

$$460 \quad \hat{P}_F^0 = \pi^2 \rho^2 A d^3 \bar{u}^3 / 9, \quad (18)$$

461 with the implicit assumption that the volume fraction is equal to 1. Again, this predic-  
 462 tion is expected to be valid only for signal periods  $1/f$  well above the duration of a typ-  
 463 ical impact.

464 The two models described by Farin et al. (2019) are developments of this model,  
 465 with that article's equation (16) developing the definition of the impulse denoted  $\Delta p$  in  
 466 our equation (2). Within the same frequency range as in prior paragraphs, the associ-  
 467 ated predictions for  $P_F(f)$  are the constants

$$468 \quad \hat{P}_F^0 = \pi^2 \rho^2 \phi A d^3 (1 + e)^2 \xi(v) u_b^3 / 36, \quad (19)$$

469 where  $e$  is a constant coefficient of restitution;  $\xi(v) \approx 0.053(1 + 5.6v^2)$  is a non-dimensional  
 470 function accounting for variation in impacts' geometry; and  $v$  and  $u_b$  define the veloc-  
 471 ities of base-impacting particles  $u_b(\mathbf{e}_x + v\mathbf{e}_v)$ , for randomly directed unit vector  $\mathbf{e}_v$ .

472 In the 'thin-flow' model,  $u_b = \bar{u}$ , whereas in the 'thick-flow' model  $u_b = \chi \bar{u} d/h$   
 473 for velocity profile shape factor  $\chi$ , assumed constant and between 1 and 1.5. The model-  
 474 specific parameters are  $e$ ,  $v$  and  $\chi$ , which all contribute to the prefactor and so cannot  
 475 be individually determined via fitting. We therefore take  $e = 0.9$ , consistent with the  
 476 rebound heights of particles dropped onto the instrumented plate; take  $\chi = 1.25$ , con-  
 477 sistent with the velocity profiles measured at the channel's wall; and fit the free param-

478 eter  $v$ , corresponding to the normalised standard deviation of base-impacting particles’  
 479 velocities. Farin et al. (2019)’s derivation of  $\xi$  makes unphysical assumptions (e.g. that  
 480 impacting particles’ velocities differ from  $u_b \mathbf{e}_x$  by an exactly constant magnitude  $vu_b$  and  
 481 that, for each impact velocity, all possible impact locations are equally likely), so the best-  
 482 fit value of  $v$  for an otherwise-accurate model will not exactly equal the true normalised  
 483 standard deviation, but a model cannot be said to be accurate unless this best-fit value  
 484 is a physically reasonable approximation. Specifically, the energy associated with veloc-  
 485 ity fluctuations is drawn from the mean flow and dissipated rapidly, so that we expect  
 486 the typical magnitude of velocity fluctuations to be less than the mean velocity, and hence  
 487 a condition for model accuracy is that  $v < 1$ .

488 To further assess the assumptions of the ‘thick-flow’ and ‘thin-flow’ models, we ex-  
 489 tended each model to higher frequencies. Farin et al. (2019) assumes binary, elastic, nor-  
 490 mal interactions during impacts, with impact velocities such that particle deformation  
 491 in our experiments will be quasistatic and the Hertz theory described in S3 will apply.  
 492 Applying this theory to the impact velocities and geometry assumed by Farin et al. (2019),  
 493 we therefore compute predictions for  $P_F$  over a larger frequency range than that con-  
 494 sidered by the original article, as

$$495 \hat{P}_F(f) = \frac{\int_{S^2} d^2 \mathbf{e}_v \int_{S_{\pi/6}^2} d^2 \mathbf{e}_n (u_n \mathbf{e}_n \cdot \mathbf{e}_z)^2 \zeta(f\tau) \mathcal{H}(u_n)}{\int_{S^2} d^2 \mathbf{e}_v \int_{S_{\pi/6}^2} d^2 \mathbf{e}_n (u_n \mathbf{e}_n \cdot \mathbf{e}_z)^2 \mathcal{H}(u_n)} \hat{P}_F^0 \quad (20)$$

496 for unit sphere  $S^2$ ; unit spherical cap  $S_{\pi/6}^2$  with maximum polar angle  $\pi/6$ ; normal im-  
 497 pact velocity  $u_n = u_b(\mathbf{e}_x + v\mathbf{e}_v) \cdot \mathbf{e}_n$ ; impact timescale  $\tau(u_n)$  as defined by equation  
 498 (3); non-dimensional function  $\zeta$  as introduced in equation (4); and Heaviside step func-  
 499 tion  $\mathcal{H}$ .

500 Finally, the model described in Bachelet (2018) already predicts  $P_F$  over a large  
 501 frequency range. Substituting equations (7) into (6) and moving from the well-defined  
 502 particle layers considered in the thesis to the continuous profiles measured in our exper-  
 503 iments, the predicted power spectral density of the basal force is

$$504 \hat{P}_F(f) = \frac{4\pi}{9} \phi A \rho^2 d^3 \int_0^h u'_w(z) T_w(z) \zeta(f\tau_w(z)) e^{-\gamma z} dz, \quad (21)$$

505 where  $u'_w$  is the derivative of  $u_w$ ;  $\zeta$  is the non-dimensional function in equation (4); im-  
 506 pact timescale  $\tau_w(z)$  is defined with respect to  $T_w(z)$  as  $\tau_j$  is to  $T_j$  in equation (7); and  
 507 constant  $\gamma$  is a free parameter, to be determined by fitting.

508 We compare these predictions to the measured power spectra  $P_F$  in section 3.3, but  
 509 first we define the time period and the frequency-space properties used for the compar-  
 510 ison, by considering the evolution of the flow (section 3.1) and the form of the power spec-  
 511 trum of the basal force (section 3.2).

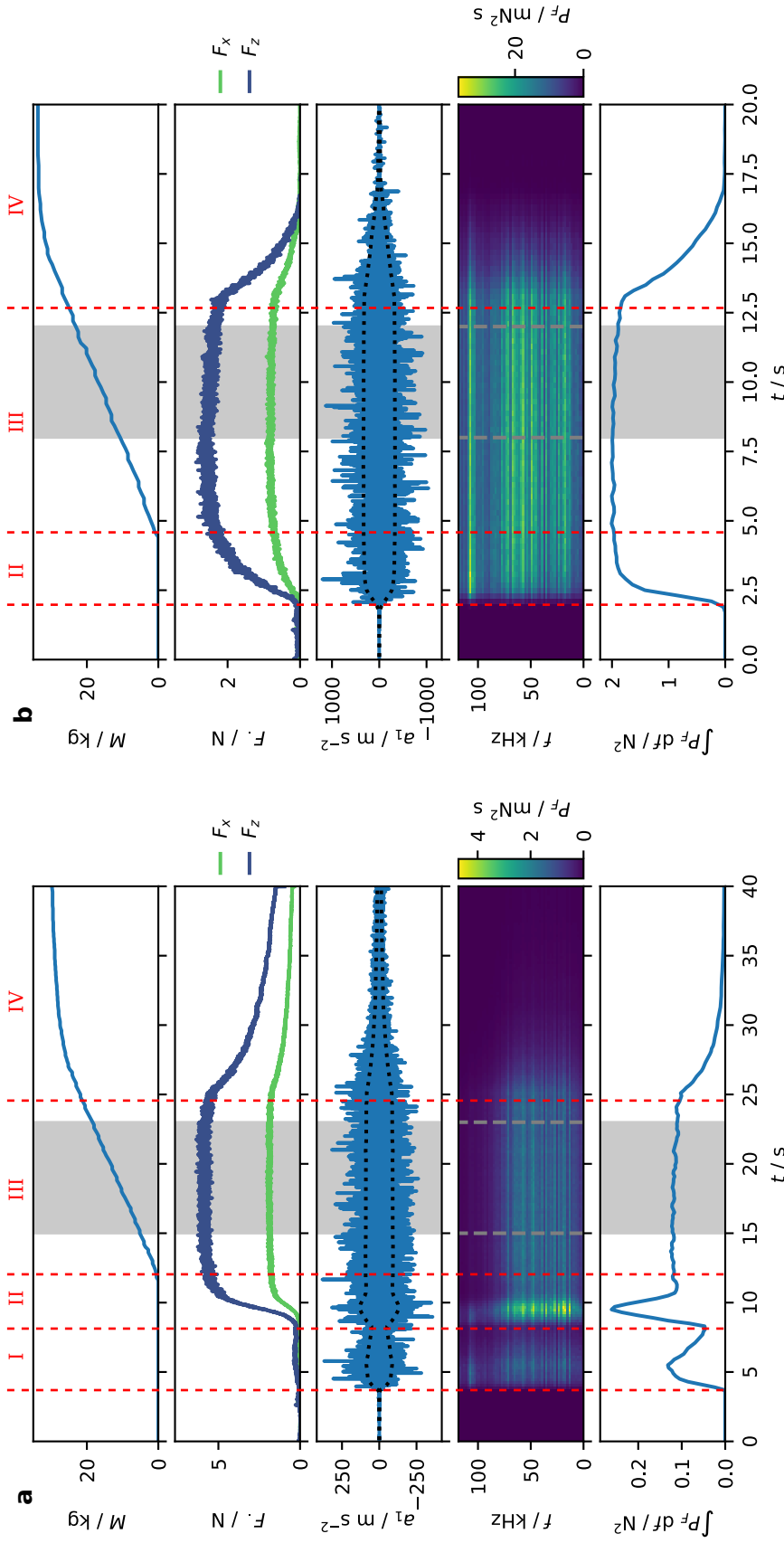
### 512 **3 Results**

#### 513 **3.1 Evolution of the Flow**

514 In each experiment, the flow passing a given point evolved through four distinct  
 515 stages: I) precursory saltation of particles released at the start of the experiment; II) ar-  
 516 rival of the dense flow’s front; III) steady flow; and IV) decay of the flow. These corre-  
 517 sponded to different signals measured at the instrumented plate, as illustrated for two  
 518 different experiments in Figure 3.

519 As Figure 3 illustrates, saltating particles in stage I contributed little to the out-  
 520 flow mass  $M$  and to the net downslope and normal forces  $F_x$  and  $F_z$ , with an implied  
 521 number density of around one particle per  $\text{cm}^2$  of plate surface, but such particles ap-  
 522 plied basal forces with significant spectral density  $P_F$  across a wide frequency range. Sim-  
 523 ilarly, the dense front’s arrival in stage II had a short duration, but was associated with  
 524 an intense, broad power spectrum of basal force, as high-velocity, surficial particles reached  
 525 the front and impacted the plate. In general, as in Figure 3a, the power spectrum at high  
 526 frequencies then dropped during stages III and IV, indicating that impact velocities in  
 527 the dense flow’s bulk were lower than those of high-velocity saltating particles. For ‘transitional-  
 528 regime’ flows, however,  $P_F$  remained the same during stages II and III, as in Figure 3b,  
 529 reflecting the continued saltation within each flow that defines this regime.

530 Such variation of signal properties between different experiments is summarised in  
 531 Table 1. With increasing channel incline  $\tan \theta$  and release gate height  $h_g$ , the duration  
 532 of stage I decreased rapidly and that of stage II decreased slightly, as the speed of the  
 533 dense flow front increased to the speed of saltating particles. Since the same changes greatly  
 534 increased the high-frequency spectral density  $P_F$  of the plate-normal force during stage  
 535 III, which had duration determined by the reservoir’s capacity and decreasing with  $h_g$ ,  
 536 the contribution of stage I to the total generation of seismic energy decreased from around  
 537 70% to less than 0.1%, while the contribution of stage II remained between around 10%  
 538 and 20%, and the contributions of stages III and IV increased. In contrast to this pat-



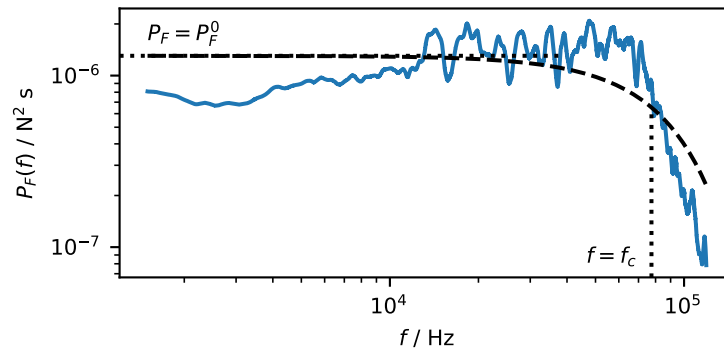
**Figure 3.** *Examples of flow properties' evolution over time.* Plots over time  $t$  of the cumulative outflow mass  $M$ ; the net downslope and normal forces  $F_x$  and  $F_z$  applied to the instrumented plate; a measured normal plate acceleration  $a_1$ , with envelope indicated by dotted lines; the power spectral density  $P_F$  of the plate-normal basal force; and the integral of this power spectrum, which equation (25) shows to be proportional to the seismic power transmitted to the instrumented plate. a) A dense flow at a channel incline  $\tan\theta = 0.44$  ( $\theta = 23.7^\circ$ ), with a release gate height  $h_g = 20$  mm. b) A transitional-regime flow, with  $\tan\theta = 0.52$  ( $\theta = 27.5^\circ$ ) and  $h_g = 28$  mm. Flow stages I to IV are labelled, where present, and the shaded region indicates the period of steady flow recorded by the camera,  $t_d < t < t_d + \Delta t_c$ .

**Table 1.** *Properties of the flow’s stages of evolution.*  $F_z$  and  $P_F$  are as defined in section 2.2, while  $f_c$  is the frequency at which  $P_F$  drops to half its mean value pre-maximum. Arrows ( $\rightarrow$ ) indicate ranges over time in an experiment, while hyphens ( $-$ ) represent the ranges over different experiments.  $\bullet$  indicates the value for dense flows and  $\circ$  for transitional-regime flows, wherever they differed significantly.

Flow stage	I	II	III	IV
Durations / s	0 – 40	2 – 8	4 – 150	5 – 20
$F_z$ / N	$O(0.1)$	0 $\rightarrow$ (1 – 10)	1 – 10	(1 – 10) $\rightarrow$ $O(1)$
$f_c$ / kHz	> 100	> 90	$\bullet$ 70 – 110 $\circ$ > 100	$\bullet$ 70 – 110 $\circ$ > 100
$\int P_F \, df$ / N <sup>2</sup>	$O(0.1)$	0.02 – 2	0.003 – 3	(0.003 – 3) $\rightarrow$ 0

539 tern of variation, the net normal force  $F_z$  increased with  $h_g$  but, for each  $h_g$ , decreased  
 540 with  $\tan \theta$ , as the same flux of particles was maintained by a thinner flow, travelling faster.  
 541 These opposing trends indicate the independence of  $F_z$  and  $P_F(f)$  for  $f \neq 0$ , with the  
 542 former the mean force applied by the flow, and the latter associated with the force’s fluc-  
 543 tuations about this mean.

544 In this article, we restrict our attention to stage III of the flow’s evolution, in which  
 545 the flow’s steadiness ensured that all measurements were of the same flow state. Specif-  
 546 ically, between different  $\Delta t = 0.2$  s time intervals within the duration  $\Delta t_c$  of steady flow  
 547 recorded by the camera, the per-second rate of change of outflow mass  $M$  had a stan-  
 548 dard deviation of around 10% of its mean value, while the standard deviations of  $F_x$  and  
 549  $F_z$  were around 1% and that for  $\int P_F \, df$  around 5%. Similarly, we examined the pro-  
 550 files of kinematic properties at the channel wall, averaged in turn over each decile of time  
 551  $t_d + n\Delta t_c/10 < t < t_d + (n + 1)\Delta t_c/10$  within the period recorded by the camera.  
 552 Within the flow, kinematic properties at the channel wall were steady over time, in the  
 553 sense that the values of  $\phi_w(z)$ ,  $\mathbf{u}_w(z)$  and  $T_w(z)$  varied by at most a few percent over  
 554 time, for each  $z$  satisfying  $\phi_w(z) > \max_z \phi_w(z)/2$ .



**Figure 4.** Example of the plate-normal force’s power spectral density during steady flow.

The power spectrum corresponds to the same experiment as Figure 3a, with channel incline  $\tan \theta = 0.44$  ( $\theta = 23.7^\circ$ ) and release gate height  $h_g = 20$  mm. The dotted lines indicate the corner frequency  $f_c = 77.5$  kHz and the low-frequency amplitude  $P_F^0 = 1.29$  mN<sup>2</sup> s. The dashed line indicates the Hertzian power spectrum fit to these values, corresponding to 4000 Hertzian impacts per second of the experimental particles on the plate’s surface, each at normal velocity  $0.9$  m s<sup>-1</sup>.

555 **3.2 Power Spectrum of the Basal Force**

556 Averaging over this period of steady flow, by taking  $\Delta t = \Delta t_c$  in equation (12),  
 557 we calculated the power spectrum of the base-normal force applied by the flow to the  
 558 plate and find it to be consistent with impacts of short duration. As in the example shown  
 559 in Figure 4, the power spectral density  $P_F(f)$  is approximately constant over a large fre-  
 560 quency range and displays the same decay beyond a given corner frequency as Hertz the-  
 561 ory predicts for a single impact. The fluctuations around this trend with varying frequency  
 562  $f$  are consistent between different experiments, as may be seen in Figure 3, and are sys-  
 563 tematic errors arising from variation in the density of the plate’s resonant modes in fre-  
 564 quency space, as discussed in S7.

565 We described the power spectrum by two quantities: its low-frequency amplitude  
 566  $P_F^0$  and its corner frequency  $f_c$ . We calculated  $f_c$  as the frequency at which  $P_F(f)$  drops  
 567 to half its mean pre-maximum value, so that for a Hertzian impact it would be equal to  
 568 approximately  $0.208/\tau$ , for the timescale  $\tau$  defined in section 1.2.2 and S3. Any such com-  
 569 parison between  $f_c$  and a theoretical corner frequency is unlikely to be exact, due to sys-  
 570 tematic errors in our measured power spectra  $P_F$ , and this is reflected by the mismatch

**Table 2.** *Summary of model testing.* For each of the existing models described in section 1.2, we list those of the flow measurements defined in section 2.2 that are required to predict the flow’s high-frequency seismic signal. We further record the equation for predictions  $\hat{P}_F^0$ ; the free parameter value for which such predictions best fit measurements; and the geometric standard error  $\epsilon = \exp \left[ \sqrt{\frac{1}{N} \sum \ln(P_F^0/\hat{P}_F^0)^2} \right]$  of these predictions.

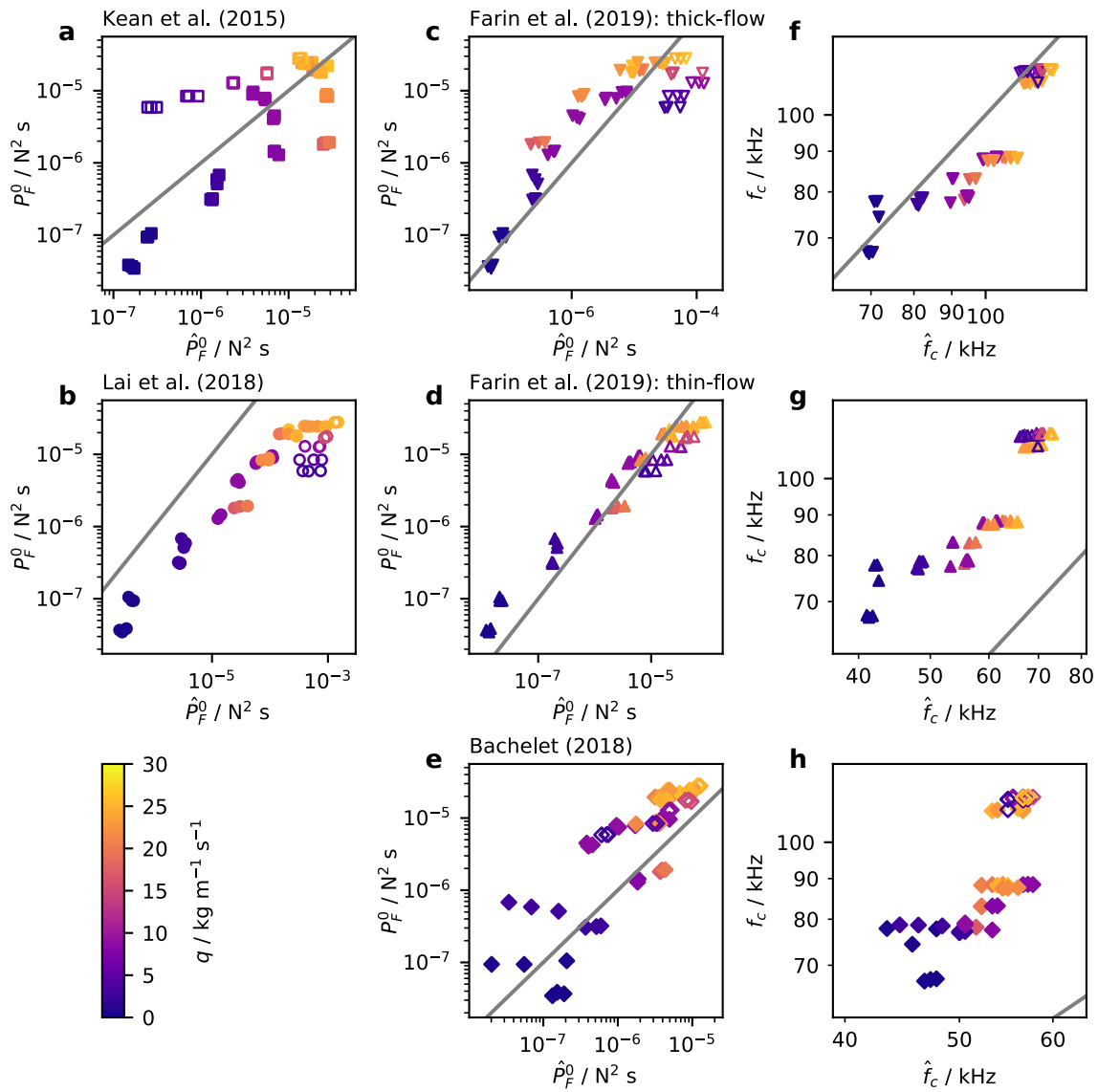
Model	Inputs	Equation	Best-fit parameter	$\epsilon$
Kean et al. (2015)	$\bar{u}, \sigma, \theta$	(17)	$K = 4.0 \times 10^{-16} \text{ m}^4 \text{ s}^2$	4.2
Lai et al. (2018)	$\bar{u}$	(18)	n/a	18.5
Farin et al. (2019)	$\bar{u}, \sigma, h$	(19)		
	‘thick-flow’		$v = 9.8$	3.2
	‘thin-flow’		$v = 0.51$	2.1
Bachelet (2018)	$\sigma, h, u_w, T_w$	(21)	$\gamma = 0 \text{ m}^{-1}$	3.9

571 between theoretical and experimental results in Figure 4. However, our measurements  
 572 of  $f_c$  were sufficiently robust that we calculated  $P_F^0$  as the mean value of  $P_F$  over all fre-  
 573 quencies less than  $f_c/2$ . We could then compare these experimentally measured values  
 574 with the model predictions, computed as described in section 2.3.

### 575 3.3 Tests of Existing Models for Flows’ Seismic Signals

576 To assess the model predictions described in section 2.3, we compared their pre-  
 577 dictions  $\hat{P}_F^0$  for the low-frequency value of the basal force’s power spectrum to the mea-  
 578 sured values  $P_F^0$ . Where possible, we also inferred a prediction  $\hat{f}_c$  for the corner frequency  
 579 of the basal force’s power spectrum, as the frequency at which  $\hat{P}_F(f)$  dropped to half  
 580 its maximum value, and we compared this prediction with the measured value  $f_c$ . Where  
 581 a model had a free parameter, we used the parameter value that minimised the sum over  
 582 all experiments of  $\ln(P_F^0/\hat{P}_F^0)^2$ , which was equivalent to minimising the typical logarith-  
 583 mic error or maximising the model likelihood under the assumption that measurements  
 584 were log-normally distributed about their predicted values (see S9). Table 2 lists these  
 585 best-fit parameter values and Figure 5 shows the results of the comparisons.





**Figure 5.** Comparison between models' predictions (*x-axes*) and experimental measurements (*y-axes*) for the basal force's power spectrum. Plots f, g, and h represent predictions for the corner frequency of the basal force's power spectrum, while all others represent predictions for the power spectral density's value at frequencies well below this corner frequency. In all plots, the grey line represents perfect agreement between predictions and measurements, colours indicate each experiment's mass flux  $q$  per unit channel width, and unfilled symbols represent experiments for which the flow was in the transitional regime.

586 The model introduced by Kean et al. (2015) predicts  $P_F^0$  poorly, due largely to its  
 587 incorrect assumption of proportionality between the pressure fluctuations relevant to  $P_F^0$   
 588 and the mean pressure  $\sigma g \cos \theta$  used as input. To best fit the measurements, the free pa-  
 589 rameter  $K$  had to take a value of  $4.0 \times 10^{-16} \text{ m}^4 \text{ s}^2$ , with a magnitude unforeseeable from  
 590 the model’s assumptions, and even then predictions often differed from measurements  
 591 by an order of magnitude (Figure 5a). Notably, the model’s predictions  $\hat{P}_F^0$  decrease for  
 592 flows at higher channel inclinations or in the transitional regime, for which the mean pres-  
 593 sure is lower, whereas such flows’ higher impact energies in fact resulted in higher pres-  
 594 sure fluctuations and so larger measured values  $P_F^0$ .

595 In contrast, the model introduced by Lai et al. (2018) accurately predicted vari-  
 596 ation in  $P_F^0$  between experiments, with predictions for dense flows consistently 3 to 10  
 597 times larger than the measured values (Figure 5b). For transitional-regime flows, the pre-  
 598 dictions’ errors are larger, due to the model’s implicit assumption that the volume frac-  
 599 tion is equal to one.

600 Surprisingly, of the two models described by Farin et al. (2019), the model derived  
 601 for flows thicker than the largest particles is less accurate than that derived for thin flows,  
 602 with the former requiring an unphysical best-fit value for the ratio  $v$  between the mag-  
 603 nitudes of velocity fluctuations and of the mean velocity. For the ‘thick-flow’ model, we  
 604 required  $v = 9.8$  for predictions  $\hat{P}_F^0$  to be as large as measurements  $P_F^0$  and, in that case,  
 605 the predictions were too large for the transitional-regime flows (Figure 5c). For the ‘thin-  
 606 flow’ model, meanwhile, the best-fit value was  $v = 0.51$ , which is physically reasonable  
 607 and provides an excellent fit of  $\hat{P}_F^0$  to  $P_F^0$  over all experiments (Figure 5d).

608 This difference between the ‘thick-flow’ and ‘thin-flow’ models’ best-fit values of  
 609  $v$  is reflected in the predictions  $\hat{f}_c$  they implied for the corner frequency of the basal force’s  
 610 power spectrum, calculated according to our extensions of these models using equation  
 611 (20). The higher  $v$  required for the ‘thick-flow’ model results in higher predictions  $\hat{f}_c$ ,  
 612 matching the measured values  $f_c$  (Figure 5f), whereas for the ‘thin-flow’ model predic-  
 613 tions are consistently approximately 30% smaller than the measured values (Figure 5g).  
 614 Predicted corner frequencies  $\hat{f}_c$  are as large as measurements  $f_c$  only for typical impact  
 615 velocities six times larger than the flows’ mean velocities, suggesting that our measure-  
 616 ments  $f_c$  were slight, but systematic, overestimates.

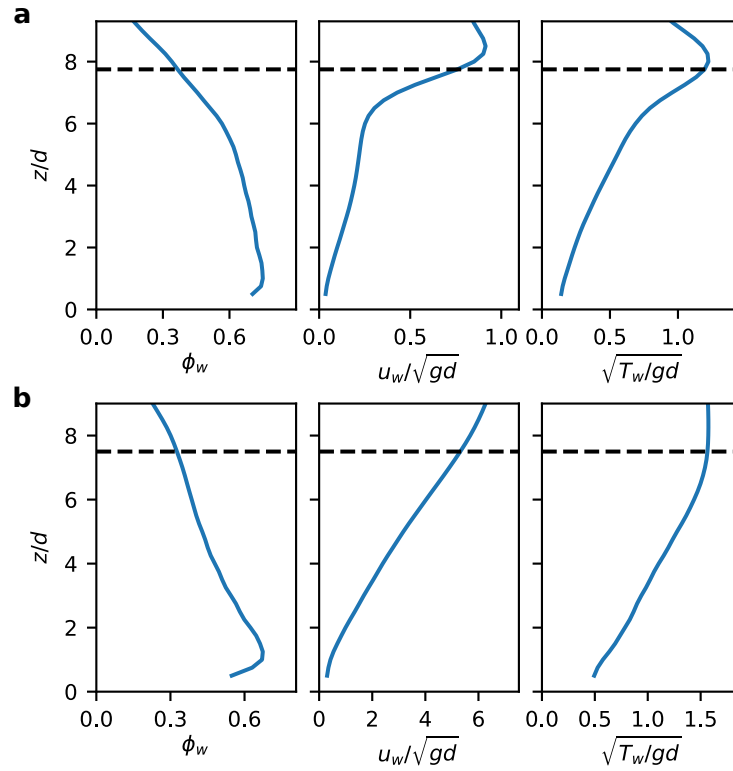
617 Finally, the predictions of the model described in Bachelet (2018) followed the cor-  
 618 rect trend but had a wide dispersion (Figure 5e). The free parameter  $\gamma$ , representing sig-  
 619 nal attenuation within the flow, had best-fit value 0, indicating that the unattenuated  
 620 contributions of all synthetic impacts are necessary for  $\hat{P}_F^0$  to be large enough to com-  
 621 pare to  $P_F^0$ . Even then, the lower energies of synthetic impacts are reflected in predic-  
 622 tions  $\hat{f}_c$  for the power spectrum’s corner frequency that are even lower than those of our  
 623 extension to Farin et al. (2019)’s ‘thin-flow’ model (see Figure 5h).

624 Overall, of the five models, the ‘thin-flow’ model described in Farin et al. (2019)  
 625 best fits the results from our experiments. While the fit is imperfect, the predictions  $\hat{P}_F^0$   
 626 of this model differ from the measured values  $P_F^0$  by a typical factor of 2.1, lower than  
 627 that for the other models, and the model’s accuracy is approximately equal across the  
 628 entire range of experiments, including for the flows in the transitional regime. Construct-  
 629 ing a statistical model for each physical model, by assuming  $\ln P_F^0$  was normally distributed  
 630 about  $\ln \hat{P}_F^0$  with constant variance, the ‘thin-flow’ model is also the preferred model by  
 631 the Akaike information criterion (see S9), indicating that its additional free parameter  
 632 compared to the Lai et al. (2018) model is worthwhile in an information theoretic sense.  
 633 This analysis did not compare models’ predictions to the measured corner frequencies  
 634  $f_c$ , due to the likelihood of systematic error in the latter, but our extensions to the mod-  
 635 els of Farin et al. (2019) both predicted a trend in  $\hat{f}_c$  consistent with measurements.

## 636 4 Discussion

### 637 4.1 Velocity Profiles and the ‘Thin-flow’ Model

638 That the ‘thin-flow’ model best predicts the experimental results is surprising, be-  
 639 cause we do not expect the velocity profile within the flow to be consistent with the model’s  
 640 assumptions. The ‘thin-flow’ model assumes that particles at the flow’s base move across  
 641 the instrumented plate’s surface at approximately the flow’s mean velocity, whereas pre-  
 642 vious authors suggest that the plate’s roughened surface should impose a no-slip con-  
 643 dition on the flow, in the sense that particles’ velocities should tend to zero towards the  
 644 flow’s base (GDR MiDi, 2004; Jing et al., 2016). Furthermore, as the example of Fig-  
 645 ure 6 demonstrates, the velocity profiles we observe at the channel’s wall are consistent  
 646 with this no-slip condition (which we note is distinct from any micromechanical condi-  
 647 tion on rolling or sliding at particle contacts).

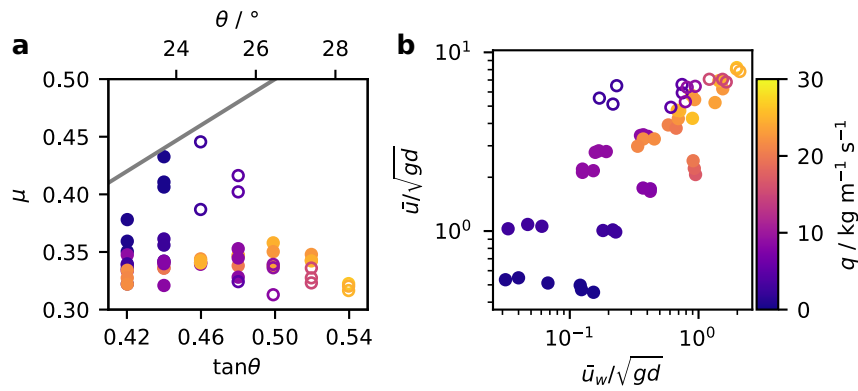


**Figure 6.** *Examples of kinematic properties' steady profiles at the channel wall.* Profiles are estimates from particle tracking velocimetry of the relative volume fraction  $\phi_w$ , the downslope velocity  $u_w$ , and the square root  $\sqrt{T_w}$  of the granular temperature, non-dimensionalised by  $\sqrt{gd} = 0.14$ , while the dashed lines represent the flow thicknesses  $h$  inferred from the profile of  $\phi_w$ . Profiles are taken from the same experiments as for Figure 3: a) a dense flow at channel incline  $\tan \theta = 0.44$  ( $\theta = 23.7^\circ$ ) with release gate height  $h_g = 20$  mm; and b) a transitional-regime flow at channel incline  $\tan \theta = 0.52$  ( $\theta = 27.5^\circ$ ) with release gate height  $h_g = 28$  mm.

648 We propose two possible explanations for the success of the ‘thin-flow’ model. The  
 649 first is that the instrumented plate’s flow-induced vibration reduces the effective friction  
 650 between it and the flow, leading to basal slip and a basal flow velocity closer to the flow’s  
 651 mean velocity. The second is that basal particles have low velocities, but that impacts  
 652 away from the flow’s base make significant contributions to the basal force exerted by  
 653 the flow, in such a way that the total contribution of these impacts scales with the mean  
 654 velocity of the flow.

655 The first explanation is supported by the literature on frictional weakening and by  
 656 measurements of the plate’s effective friction coefficient with the flow. The reduction by  
 657 vibration of a granular medium’s effective friction has been documented in discrete el-  
 658 ement simulations (e.g. Capozza et al., 2009; Ferdowsi et al., 2014; Lemrich et al., 2017)  
 659 and experiments (e.g. Johnson et al., 2008; Dijksman et al., 2011; Lastakowski et al., 2015),  
 660 with suggestions for the necessary vibration amplitude being a particle strain of order  
 661  $10^{-6}$  (Ferdowsi et al., 2014), a velocity of order  $100 \mu\text{m s}^{-1}$  (Lastakowski et al., 2015),  
 662 and an acceleration of order  $0.1g$  (Dijksman et al., 2011). Even in the experiments in  
 663 which the plate vibration amplitudes during steady flow were lowest, the plate had ap-  
 664 proximate root mean square normal displacement  $10 \text{ nm}$ , velocity  $100 \mu\text{m s}^{-1}$ , and ac-  
 665 celeration  $20 \text{ m s}^{-2}$ , so a vibration-induced reduction in friction appears viable. Further-  
 666 more, the effective friction coefficients  $\mu$  that we measure between the plate and the flow  
 667 are too low to prevent basal slip on the surface of the plate, with Figure 7a showing that  
 668  $\mu < \tan \theta$  for all channel inclines  $\tan \theta$ . This implies that basal particles accelerate across  
 669 the plate’s surface, towards the flow’s mean velocity.

670 On the other hand, we do not directly measure any increases in velocity associated  
 671 with basal slip. Over the  $8 \text{ cm}$  distance downslope captured by the high-speed camera,  
 672 averaging over each flow’s depth and each  $4 \text{ cm}$  half-window, the mean downslope veloc-  
 673 ities measured at the sidewall are uniform to within  $10\%$ . Away from the sidewalls, Tsang  
 674 et al. (2019) suggests that a granular flow will adjust to a change in basal boundary con-  
 675 ditions over a lengthscale of order  $\bar{u}^2/g$ , for mean flow velocity  $\bar{u}$  and gravitational ac-  
 676 celeration  $g$ . This lengthscale varies in our experiments from  $0.5 \text{ mm}$  to  $0.1 \text{ m}$ , so that  
 677 we would expect the effects of any basal slip to become evident at the flow’s surface within  
 678 the length of the instrumented plate. However, having conducted particle image velocime-  
 679 try with images captured by an overhead camera, for a flow at a channel incline  $\tan \theta =$   
 680  $0.46$  ( $\theta = 24.7^\circ$ ) and with release gate height  $h_g = 20 \text{ mm}$ , we were unable to distin-



**Figure 7.** *Discrepancies between model assumptions and measurements.* a) Measurements of the effective friction coefficient  $\mu$  between the instrumented plate and the flow fall consistently below the condition  $\mu = \tan \theta$  for zero basal slip (grey line). b) The depth-averaged particle velocity measured at the channel wall  $\bar{u}_w$  is poorly correlated with the mean velocity  $\bar{u}$  calculated from bulk flow properties. Colours indicate each experiment’s mass flux  $q$  per unit channel width, and unfilled symbols represent experiments for which the flow was in the transitional regime.

681 guish whether the flow’s surface’s slight acceleration across the plate was induced by the  
 682 plate, or was simply a continuation of the flow’s acceleration towards a uniform state.  
 683 Similarly, we attempted to detect changes in the velocity of basal particles, via Jop et  
 684 al. (2005)’s method of examining soot erosion from an inserted metal plate, but our at-  
 685 tempts were frustrated by the energetic particles’ rapid erosion of soot during the inser-  
 686 tion and removal of the plate.

687 Consequently, the second explanation remains feasible, with good reasons why the  
 688 model of Bachelet (2018), despite being derived to describe the contributions of impacts  
 689 throughout the flow’s depth, might describe them less well than the ‘thin-flow’ model.  
 690 Firstly, the Bachelet (2018) model uses profiles  $u_w$  and  $T_w$  that are measured at the chan-  
 691 nel’s wall and may not be representative of those in the flow’s interior. In fact, the mean  
 692 particle velocity measured at the channel wall  $\bar{u}_w$  correlates poorly with the mean ve-  
 693 locity  $\bar{u}$  inferred from bulk measurements (see Figure 7), while the monotonically increas-  
 694 ing profiles  $T_w(z)$  differ from the S-shaped profiles that previous authors propose for gran-  
 695 ular temperature profiles in the flow’s interior (Hanes & Walton, 2000; Silbert et al., 2001;  
 696 Gollin et al., 2017). Secondly, Bachelet (2018) may suggest an incorrect dependence of  
 697 the seismic signal on these profiles, with a particularly strong assumption being that of

698 a frequency-independent attenuation constant  $\gamma$ . We were unable to dramatically im-  
 699 prove the predictions of Bachelet (2018)’s model by modifying its inputs, e.g. by mul-  
 700 tiplying the profiles  $u_w(z)$  and  $\sqrt{T_w(z)}$  by  $\bar{u}/\bar{u}_w$ , but, under a different model for the  
 701 contributions of impacts throughout the flow, such contributions could explain the re-  
 702 lationship observed between the mean velocity  $\bar{u}$  and the basal force’s power spectrum  
 703  $P_F$ .

704 To test which explanation accounts for the success of the ‘thin-flow’ model, we sug-  
 705 gest that our experimental conditions be replicated with discrete element simulations.  
 706 In such simulations, a suitably roughened base could be fixed in position to prevent any  
 707 vibration-induced reduction of its effective friction coefficient and any basal slip, as records  
 708 of base-adjacent particles’ velocities could verify. If the ‘thin-flow’ model continued to  
 709 be accurate, then the first, ‘basal slip’ explanation would be disproven. Records of par-  
 710 ticle velocities throughout the flow would then permit variants of Bachelet (2018)’s model  
 711 to be tested and their assumptions examined, using base-normal profiles of velocity and  
 712 granular temperature measured within the flow’s bulk rather than at its edge, to explain  
 713 the ‘thin-flow’ model’s accuracy. If the ‘thin-flow’ model were no longer accurate, how-  
 714 ever, then our first explanation would be proven and the model shown to apply only to  
 715 flows with basal slip. The recorded particle velocities would then permit development  
 716 of a different model, by which a small number of flow parameters could predict the seis-  
 717 mic signal generated by flows without basal slip, analogous to the use of  $\bar{u}$  in the ‘thin-  
 718 flow’ model, or of the inertial number to predict a dense granular flow’s kinematic prop-  
 719 erties.

## 720 **4.2 The Inertial Number and the Seismic Signal**

721 Within a granular flow, the inertial number  $I$  is a local, non-dimensional mean shear  
 722 rate, which previous authors suggest will uniquely determine all other local, non-dimensional  
 723 flow parameters (GDR MiDi, 2004; da Cruz et al., 2005; Jop et al., 2006). This ‘ $\mu(I)$ ’  
 724 framework will not apply where a) the flow’s rheology is ‘non-local’, in the sense that  
 725 the internal stress depends on derivatives of the strain rate rather than on only the strain  
 726 rate’s local value (Clark & Dijksman, 2020), or b) particles are sufficiently agitated that  
 727 kinetic theory describes their motion better than a mean shear rate (Goldhirsch, 2003).  
 728 If, however, the ‘ $\mu(I)$ ’ framework applies within a two-dimensional, steady, uniform shear  
 729 flow above a plate with incline  $\tan \theta$ , a macroscopic force balance implies that  $I$  is con-

stant and can be estimated from bulk measurements of the flow’s mean velocity  $\bar{u}$ , volume fraction  $\phi$ , and depth  $h$  (Jop et al., 2005), as

$$\hat{I} = \frac{5\bar{u}d}{2h\sqrt{\phi g h \cos \theta}}. \quad (22)$$

Even if our experimental flows were uniform, without basal slip, the local inertial numbers within them will have differed significantly from  $\hat{I}$ , with non-locality being particularly significant within slow, thin flows; particles being particularly agitated within transitional-regime flows; and friction at the channel’s walls altering the force balance. We nevertheless calculated  $\hat{I}$  as a descriptor for each flow, with  $\phi = \sigma/\rho h$  for flow mass per unit area  $\sigma$  and particle density  $\rho$  and with other quantities defined in sections 2.1 and 2.2. We see in Figure 8a that the ‘ $\mu(I)$ ’ framework applies for the dense experimental flows, insofar as the local, non-dimensional parameter  $\tan \theta$  is closely related to  $\hat{I}$ .

To examine the relevance to each flow’s seismic signal of this inertial number estimate  $\hat{I}$ , we define a non-dimensional parameter  $\delta\mathcal{F}^2$  expressing the mean squared magnitude of high-frequency basal force fluctuations on the instrumented plate, normalised by the mean basal force. From the low-frequency amplitude  $P_F^0$  and corner frequency  $f_c$  of the basal force’s power spectrum, and from gravitational acceleration  $g$ , inclination angle  $\theta$ , plate length  $X$  and width  $Y$ , and measured mass overburden  $\sigma$ , we calculate for each flow

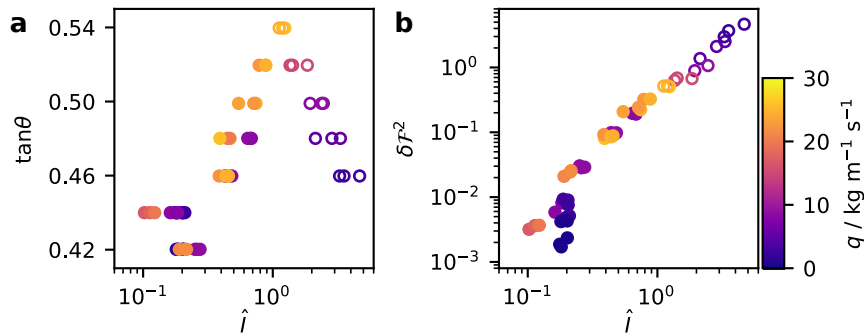
$$\delta\mathcal{F}^2 = \frac{2P_F^0 f_c}{(XYg\sigma \cos \theta)^2}. \quad (23)$$

To understand this definition, we recall from equation (8) that  $XYg\sigma \cos \theta$  is the mean normal force applied by the flow to the instrumented plate, over the time interval  $\Delta t_c$  of steady flow recorded by the camera. Meanwhile, as Figure 4 indicates,  $2P_F^0 f_c$  approximates the integral of the symmetric power spectral density  $P_F(f)$  over all  $f$  with  $|f| > 1$  kHz, this being the lowest frequency accessible to our measurements. Recalling that  $\tilde{F}(f)$  is the Fourier transform over  $\Delta t_c$  of the normal force applied to the plate,  $P_F(f) = |\tilde{F}(f)|^2/\Delta t_c$ . Combining these links and then applying the Plancherel theorem (Plancherel & Mittag-Leffler, 1910) to move to the time domain,

$$2P_F^0 f_c \approx \frac{1}{\Delta t_c} \int_{|f|>1 \text{ kHz}} |\tilde{F}(f)|^2 df = \frac{1}{\Delta t_c} \int_{\Delta t_c} |\delta F(t)|^2 dt, \quad (24)$$

where  $\delta F$  is the fluctuating normal force on the plate, high-pass-filtered above 1 kHz. Assuming that pressure fluctuations are spatially uncorrelated on the lengthscale of the plate, as discussed in S2,  $2P_F^0 f_c$  will be proportional to the plate’s area  $XY$  and  $\delta\mathcal{F}^2$  to  $1/XY$ ,





**Figure 8.** Relations between the inertial number  $\hat{I}$  estimated from bulk flow parameters and a) the channel incline  $\tan\theta$ , b) the normalised mean squared fluctuating force on the plate  $\delta\mathcal{F}^2$ . Colours indicate each experiment’s mass flux  $q$  per unit channel width, and unfilled symbols represent experiments for which the flow was in the transitional regime.

761 but  $\delta\mathcal{F}^2$  can be thought of as a rescaling by  $d^2/XY$  of a local flow parameter, for mean  
 762 particle diameter  $d$ .

763 Plotting  $\delta\mathcal{F}^2$  against  $\hat{I}$  for each flow, in Figure 8b, we see that this measure of the  
 764 high-frequency seismic signal is well determined by the estimated inertial number. This  
 765 relationship between non-dimensional, local flow parameters is in accord with the ‘ $\mu(I)$ ’  
 766 framework, with more energetic flows producing more energetic seismic signals, even for  
 767 flows to which the ‘ $\mu(I)$ ’ framework is otherwise inapplicable.

768 However, it is unclear how it relates to the experimental results of Taylor and Brod-  
 769 sky (2017), in which the mean squared seismic accelerations generated by a torsional shear  
 770 flow were directly proportional to estimates of the flow’s inertial number. Whilst our re-  
 771 sults do not appear consistent with such direct proportionality, with  $\delta\mathcal{F}^2$  increasing much  
 772 faster than  $\hat{I}$ , it is impossible to make a direct comparison without knowing the mag-  
 773 nitude of the Green’s function relating the accelerations discussed by Taylor and Brod-  
 774 sky (2017) to the forces imposed by that article’s shear flow. Such Green’s functions are  
 775 essential in considering the seismic signal generated by a flow, and so in considering the  
 776 application of our results to geophysical flows.

777 **4.3 The Application of Our Results to Geophysical Flows**

778 Our results concern the fluctuating forces exerted by laboratory granular flows upon  
 779 the base on which they travel, so their application to landquake signals necessitates con-  
 780 sideration of two things: the Green’s function that determines a flow’s seismic signal from  
 781 the forces it exerts, and the differences between geophysical flows’ forces and those that  
 782 we’ve studied. We limit ourselves to describing the importance of an accurate Green’s  
 783 function, rather than defining one, and to discussing the adjustments involved in mov-  
 784 ing from laboratory to geophysical flows, rather than validating them, but we neverthe-  
 785 less propose tentative links between our results and the empirical relationships observed  
 786 by previous authors.

787 **4.3.1 The Importance of an Accurate Green’s Function**

788 The forces exerted by a geophysical flow determine a measurable seismic signal only  
 789 via a Green’s function, so an accurate Green’s function is necessary to interpret any landquake  
 790 signal. Here, we use our experimental seismic signals to show that this is true even of  
 791 certain seismic properties that previous authors have used to describe geophysical flows,  
 792 including both the rate of seismic energy emission and the relative amplitudes of differ-  
 793 ent landquake signals with the same source and receiver locations.

794 For our experiments, the Green’s function appears via equation (12), which relates  
 795 the basal forces exerted by the flow to the accelerations they caused and indicates that,  
 796 on a larger, denser, stiffer, or more lossy plate, the same force would result in smaller  
 797 accelerations and hence a smaller seismic signal. Similarly, working from the derivation  
 798 of this equation in S7, the total high-frequency seismic power transferred by the flow to  
 799 the plate is given in terms of the basal force’s power spectral density  $P_F$  by

800 
$$\Pi_s \approx \frac{1}{4\sqrt{\rho_p H D}} \int_{1 \text{ kHz}}^{\infty} P_F(f) \, df, \quad (25)$$

801 dependent on plate density  $\rho_p$ , thickness  $H$ , and bending moment  $D$ . The proportion  
 802 of flow energy dissipated by seismic emission is therefore a function of basal properties  
 803 rather than of flow properties alone, which especially complicates comparisons between  
 804 experimental and geophysical flows, such as Bachelet (2018)’s.

805 Furthermore, the Green’s functions for seismic signals will depend differently on  
 806 frequency  $f$ , so that basal properties will affect even the relative signal amplitudes of dif-

807 ferent flows with the same Green’s function. For illustration, we consider the vertical ve-  
 808 locity response of a surficial receiver to a vertical, surficial point force, on an isotropic,  
 809 homogeneous, perfectly elastic half-space with Poisson ratio 0.25, material density  $\rho_g$  and  
 810 shear wave velocity  $c_s$ . For large source-receiver separation  $r$ , at leading order, Miller  
 811 and Pursey (1954) showed the power spectral density  $P_{v_r}$  of this response to be related  
 812 to the power spectral density  $P_F$  of the vertical basal force by

$$813 \quad P_{v_r}(f) = \frac{1.20f^3}{\rho_g^2 c_s^5 r} P_F(f), \quad (26)$$

814 which we compare to the mean velocity power spectral density over the accelerometers  
 815 in our experiments,

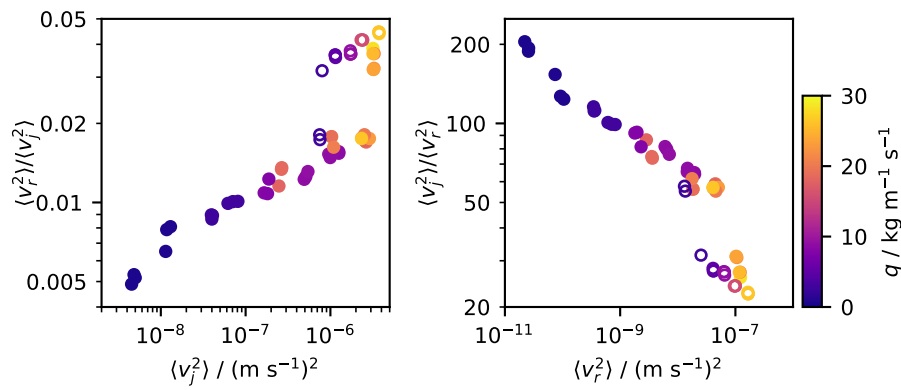
$$816 \quad \bar{P}_{v_j}(f) = \frac{1}{4\Delta t} \sum_{j=1}^4 \left( \frac{|\tilde{a}_j(f)|}{2\pi f} \right)^2 \approx \frac{\mathcal{P}Q}{16\pi(\rho_p H)^{3/2} XY \sqrt{D} f} P_F(f). \quad (27)$$

817 The mean squared velocity at the receiver, being the integral of  $P_{v_r}(f)$  over all  $f$ , will  
 818 clearly be more sensitive to the corner frequency  $f_c$  of  $P_F$  than were the mean squared  
 819 velocities observed in our experiments. Figure 9 shows the consequence: approximating  
 820 mean squared velocities by integrating (26) and (27) between 1 kHz and  $f_c$ , there is no  
 821 constant conversion factor between the mean square velocities observed in our experi-  
 822 ments and those that would be observed if the same flows applied the same forces in an  
 823 idealised geophysical context. Even among signals with the same source and receiver lo-  
 824 cations, the Green’s function determines the ratios between different signals’ amplitudes,  
 825 so that a signal must be properly deconvolved to infer the properties of a flow’s forces.

### 826 **4.3.2 Adjustments to Forces for Geophysical Flows**

827 Returning to consideration of such forces, the application of our results to geophys-  
 828 ical flows involves significant adjustments, firstly to the sizes of the flow and its constituent  
 829 particles and secondly to the flow’s evolution.

830 Clearly, geophysical flows of interest will be more extensive than our experimen-  
 831 tal flows and will involve larger particles, but these changes will not alter the underly-  
 832 ing physics and simply necessitate adjustment of the values of flow area  $A$  and particle  
 833 diameter  $d$  in the models of section 2.3. According to these models, a flow identical to  
 834 those in our experiments, except with particles of radius 1 m, should produce a seismic  
 835 force signal with power spectral density per unit flow area  $\hat{P}_F(f)/A$ , of order  $(10^2 \text{ to } 10^6) \text{ N}^2 \text{ m}^{-2} \text{ s}$   
 836 below a corner frequency  $f_c$  of order 100 Hz. A more difficult adjustment is required to



**Figure 9.** Comparison between the mean squared seismic velocities  $\langle v_j^2 \rangle$  observed in our experiments and the mean squared velocities  $\langle v_r^2 \rangle$  that would be observed in an idealised geophysical context. For the latter, we took  $\rho_g = 2500 \text{ kg m}^{-3}$ ,  $c_s = 1 \text{ km s}^{-1}$ , and  $r = 1 \text{ m}$  in equation (26), but other values would change only the prefactor. Colours indicate each experiment’s mass flux  $q$  per unit channel width, and unfilled symbols represent experiments for which the flow was in the transitional regime.

837 account for the wide particle polydispersity typical of geophysical flows (Takahashi, 1981;  
 838 Nishiguchi et al., 2012), which makes  $d$  hard to define and necessitates consideration of  
 839 the segregation of particles by size that is well-documented within granular flows (e.g.  
 840 Garve, 1925; Gray, 2018). Farin et al. (2019) proposes a promising approach for each given  
 841 model, of dividing the flow into a coarse-grained front and a fine-grained tail and cal-  
 842 culating for each a percentile of the particle size distribution that will be representative,  
 843 but this proposal requires validation.

844 Other necessary changes relate to the flow evolution, stemming from differences in  
 845 particles’ coefficient of restitution and in the mechanism of their release. The glass beads  
 846 in our experiments underwent collisions more elastic than are typical in geophysical flows  
 847 (Kim et al., 2015), resulting in our observations of sustained saltation at relatively low  
 848 channel inclinations. This implies that the precursory saltation of flow stage I, discussed  
 849 in section 3.1, is unlikely to be significant for most geophysical flows, though it may be  
 850 analogous to rock falls at high slope inclinations. Similarly, the energetic, saltating par-  
 851 ticles observed in the steady stage III of transitional-regime flows are likely to be rare  
 852 in geophysical flows, though the coexistence of a dense core and a saltating layer is doc-  
 853 umented in snow avalanches (Pudasaini & Hutter, 2006). In fact, the entirety of the ex-

854 experimental flows’ stage III is atypical of geophysical flows, since particles were released  
 855 from the experimental reservoir over a long period at a constant flux, whilst the release  
 856 of geophysical flows is rarely so steady or protracted. Therefore, our results should only  
 857 apply to individual stages of a geophysical flow, over which flow properties vary little enough  
 858 that the mean quantities we discuss are representative. Determination of quantities that  
 859 are representative of an entire flow requires further work.

### 860 **4.3.3 Comparisons with Empirical Results**

861 Nevertheless, we can tentatively link our measurements of experimental flows’ forces  
 862 to the landquake signals of geophysical flows, by assuming the validity both of certain  
 863 adjustments to those forces and of certain restrictions to the Green’s function linking geo-  
 864 physical forces to landquake signals. Firstly, we assume that any precursory saltation  
 865 of a geophysical flow contributes so insignificantly to the signal as to be negligible. Sec-  
 866 ondly, we suppose that the release mechanism and size distribution of geophysical par-  
 867 ticles significantly affect the signal only by determining the flow’s duration and a rep-  
 868 resentative diameter of its particles. Thirdly, we assume that the signal’s Green’s func-  
 869 tion is constant over time and corresponds to transmission along a single wave path, with-  
 870 out significant dispersion in time. Finally, we consider the signals only at frequencies lower  
 871 than any force’s power spectrum’s corner frequency  $f_c$ , but high enough for the stochas-  
 872 tic impact framework and hence our results to apply.

873 Under these assumptions, the landquake signal  $v_r$  between times  $t_r$  and  $t_r + \Delta t$   
 874 will only depend significantly on the forces exerted by the landslide between times  $t_s$  and  
 875  $t_s + \Delta t$ , for some source-receiver delay  $t_r - t_s$ . Neglecting non-normal components, these  
 876 forces will have a power spectral density within the relevant frequency band that is equiv-  
 877 alent to those that we have studied and is well-described by the constant prediction  $\hat{P}_F^0$   
 878 of Farin et al. (2019)’s ‘thin-flow’ model, for flow properties averaged between  $t_s$  and  $t_s +$   
 879  $\Delta t$ . Writing  $\tilde{G}(f)$  for the relevant frequency-space Green’s function and  $f_0$  and  $f_1$  for  
 880 the minimum and maximum frequencies under consideration, the mean squared ampli-  
 881 tude of the signal will be

$$882 \langle v_r^2 \rangle_{\Delta t} = \frac{2}{\Delta t} \int_{f_0}^{f_1} |\tilde{v}_r(f)|^2 df \approx 2\hat{P}_F^0 \int_{f_0}^{f_1} |\tilde{G}(f)|^2 df. \quad (28)$$

883           Given this link, we can compare our results to the empirical relations discussed in  
 884 section 1.1. Qualitatively, the landquake signal’s envelope will have the same shape as  
 885 the envelope of the time-retarded geophysical force, as Figure 3 shows to be the case for  
 886 our experimental forces and acceleration signals. Adjusting these envelopes by exclud-  
 887 ing the precursory saltation and shortening the artificially prolonged stage of steady flow,  
 888 our results therefore predict the distinctive ‘spindle-shaped’ signal envelopes associated  
 889 with geophysical granular flows (Suriñach et al., 2005). Quantitatively, our results sug-  
 890 gest that a flow’s duration will equal its signal’s, as in the empirical observations of e.g.  
 891 Deparis et al. (2008), though our experiments are unlike those of Farin et al. (2018) in  
 892 that our release mechanism prevents comparison with the observed empirical relation-  
 893 ship between potential energy loss and signal duration. Similarly, we cannot compare  
 894 our results to the observations of e.g. Norris (1994), that the flow volume is correlated  
 895 with the signal amplitude.

          However, we can compare our results with other empirical relationships for the sig-  
 nal amplitude. Substituting equation (19) for  $\hat{P}_F^0$  into equation (28) and assuming both  
 constant particle properties and a constant Green’s function, our results suggest that a  
 flow of area  $A$  in which the particle volume fraction is  $\phi$  and the mean flow velocity is  
 $\bar{u}$  will generate a signal with mean squared amplitude proportional to  $\phi A \bar{u}^3$ . Rearrang-  
 ing equation (22) for flow depth  $h$  and noting that the mean flow momentum per unit  
 area  $q = \rho \phi h \bar{u}$ , for particle density  $\rho$ , we recover that

$$q^3 = \frac{25\rho^3\phi^2d^2\bar{u}^5}{4\hat{I}^2g\cos\theta} \text{ and } \bar{u}^3 = \left(\frac{4\hat{I}^2gq^3\cos\theta}{25\rho^3\phi^2d^2}\right)^{3/5}, \quad (29)$$

896 for bulk inertial number  $\hat{I}$ , representative particle diameter  $d$ , gravitational acceleration  
 897  $g$ , and slope angle  $\theta$ . Among flows with constant  $\hat{I}$  and  $\phi$ , the resulting landquake sig-  
 898 nals will therefore have root mean squared amplitude proportional to  $A^{1/2}q^{9/10}\cos^{3/10}\theta$ .  
 899 Whilst the assumption of constant  $\hat{I}$  is very strong, this quantity is close to those found  
 900 empirically to be approximately proportional to landquake signal amplitude: the work  
 901 rate against friction used by e.g. Schneider et al. (2010), which will be equal to  $\mu Aq\cos\theta$   
 902 for basal friction coefficient  $\mu$ , and the total flow momentum used by e.g. Hibert et al.  
 903 (2015), equal to  $Aq$ . Holding all else constant, the scalings  $A^{1/2}$  and  $A$  correspond to spa-  
 904 tially separated impacts’ signals being perfectly uncorrelated and perfectly correlated,  
 905 respectively, so S2 suggests that  $A^{1/2}$  is likely to be a better approximation, while the  
 906 scalings  $q^{9/10}$  and  $q$  are unlikely to be distinguishable in the field.

## 5 Conclusion

In conclusion, our experimental apparatus and data analysis permitted us to study the normal force exerted by a granular flow upon the base over which it travels, by measuring its high-frequency power spectral density and testing a range of existing models that predict this spectral density from the flow's properties. Figure 5 shows the 'thin-flow' model of Farin et al. (2019) to best predict the spectral density at frequencies well below its corner frequency and demonstrates that our extension of that model to higher frequencies, using Hertz theory, correctly predicts the corner frequency's behaviour. We've proposed that the success of the 'thin-flow' model, despite our experimental flows' thickness compared to their constituent particles, can be explained either by slip at each flow's base or by the contributions to the seismic signal of impacts throughout each flow's depth, and we've discussed the adjustments required to apply our results to the landquake signals generated by the forces of geophysical granular flows. Making such adjustments, under certain restrictive assumptions, the 'thin-flow' model's predictions are consistent with the empirical observation that a landquake signal's amplitude is approximately proportional to the momentum per unit area of the flow region that generated it.

Finally, our results are also relevant to two open questions on geophysical granular flows' dynamics: 1) the relation between the mean and fluctuating forces exerted by a flow; and 2) the low values of effective friction inferred for many geophysical flows. On the first question, previous authors have suggested that the typical magnitude of fluctuations is proportional to the magnitude of the mean force (McCoy et al., 2013; Hsu et al., 2014), but we show in Figure 8b that the ratio between the two,  $\delta\mathcal{F}$ , varies over two orders of magnitude between our experimental flows, dependent on a bulk inertial number. On the second, acoustic fluidisation is one of many possible explanations suggested for the low effective friction necessary to explain many geophysical flows' long runouts (Davies, 1982; Lucas et al., 2014), but we are not aware of it having been previously demonstrated without the application of external forcing. As Figure 7a illustrates, our measurements of  $\mu$  show the effective friction taking values on the plate lower than the channel incline  $\tan\theta$ , which is implied to be its approximate off-plate value by both the downslope uniformity of the flow at the sidewalls and the saturation of flow velocity observed at the surface. Since the base's roughness is identical in each location, we believe it possible that this reduced friction is associated with the strong acoustic vibrations of the plate, induced by the flow itself.

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