

# Potential erosion capacity of gravity currents created by changing initial conditions

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**Abstract.** Gravity currents reproduced in laboratory by the lock-exchange technique are here tested for three initial densities and five lock-lengths, for horizontal and four inclinations of the lock. The main purpose is to quantify the effect of the introduction of an inclined channel reach just upstream from the lock gate, on the hydrodynamics of gravity currents and consequently on its transport capacity. The shape of the current is modified due to the enhanced entrainment of ambient water and the body is the region of the current where this most happens. A range of upstream slopes is tested, going from horizontal to a limit case in which two mechanisms compete, i.e. the current entrainment of water from the upper surface due to the increment of friction and the head feeding by a rear fed current. In particular, bed shear stress and the corresponding erosion potential are analysed. The implications of an inclined reach upstream of the lock gate on the potential entrainment capacity of the flow is here discussed.

## 1 Introduction

Spontaneous in nature or originated by human activities, many are the occurrences of gravity currents. These flows are created by differences in hydrostatic pressures at the surface of contact of two fluids with density differences. In the atmosphere, examples of gravity currents are katabatic winds or sea breeze fronts, in which the density gradient is caused by temperature inhomogeneities. Avalanches of airborne snow, plumes of pyroclasts from volcanic eruptions and sand storms are atmospheric flows where suspended particles play a major role in producing the density gradient. If suspended sediment confer the extra density, gravity currents take the name of turbidity currents. Turbidity currents are given special attention in what concern reservoirs sedimentation, which have important economical costs due to the loss of volume for water storage (Palmieri et al. (2001), Schleiss et al. (2016)). Among gravity currents caused by human actions, the release of pollutants into rivers, oil spillage in the ocean and the desalination plants outflows are of primary importance due to their negative environmental impacts.

Gravity currents have been subjects of research over the last decades. Simpson (1997), Kneller and Buckee (2000), Huppert (2006) and Ungarish (2009) present a comprehensive review of the early work on natural and experimentally reproduced gravity currents. Authors agree on describing the shape of the gravity current as composed by an arising highly turbulent front, called head, followed by, in some cases, a body and a tail. Particularly in the body, that can reach a quasi-steady state, a

vertical structure can be distinguished. A gravity current presents two main interfaces where exchanges concur: at the bottom, generally a solid boundary, and at the top, at the interface with the ambient fluid. These are active boundaries where mass and momentum exchanges are promoted (Ancy, 2012). Ambient fluid is entrained due to shear and buoyancy instabilities at the upper interface (Cantero et al., 2008) resulting in the dilution of the underlying current and modification of the density profile which characterizes a gravity current under stable density stratification (Turner, 1973). If the gravity current travels above an erodible bed, entrainment of material from the bottom can take place, which is conveyed with the current and redeposited sometimes at large distances from their original position (Zordan et al., 2018). High shear stress associated with intense ejection and burst events influence erosion and bed load transport (Niño and Garcia (1996), Cantero et al. (2008), Zordan et al. (2018)). For example, in the shallow shelf region of the lake it is frequently observed that cold water, relatively denser than that in open waters, starts to descend down the slope as a cold gravity current (Fer et al., 2002). The plume is able to transport suspended sediment together with their dissolved components, oxygen, and pollutants into deeper water.

It is therefore evident that gravity currents can originate under different conditions: changes of initial volume of denser fluid and changes of the bottom inclination represent some of the various configurations that can be found in reality. To understand how the initial trigger conditions of gravity currents are linked with their transport capacity is thus of fundamental importance. Gravity currents are here reproduced in laboratory by the lock-exchange technique. Three initial densities are tested in combination with five lock-lengths on horizontal bottom and with four inclinations of the upstream channel reach. The bottom of the channel was designed in order to have a variable slope angle of the lock and a following flat surface. The main purpose is to investigate how the increment of gravitational forces, due to the introduction of a slope in the lock, affect the hydrodynamic of gravity currents and consequently its transport capacity observed downstream in a flat reach.

Britter and Linden (1980) reproduced gravity currents down a slope with no breaks and he found a critical angle, which is typically less than a degree, over which buoyancy force is large enough to counter-act the bottom friction producing a steady flow. At larger slopes, two mechanisms affect the evolution of the current: the current entrains water from the upper surface due to the increment of friction and the head is fed by the rear steady current. Mulder and Alexander (2001) studied slope-break deposits created by turbidity currents. They said that the amount of mixing between flow and ambient fluid is influenced by slope changes which furthermore cause significant changes in turbidite thickness. In the present study the effect of a change in slope is analysed by testing a range of lock-slopes below 16% ( $0^\circ \leq \alpha < 9^\circ$ ). It is expected that the two mechanisms mentioned by Britter and Linden (1980) take place in the lock for the depletion current here formed, due to the incremental gravitational forces, so the transition from a friction governed flow to a flow in which gravitational forces become more and more important happens. The effect on the erosion potential in the downstream flat area where the current propagates is herein studied.

The present paper is structured as such: first the experimental set-up and the process which allows for the noise reduction of the velocity measurements are described. Then, the results are presented: a method for the identification of the shape of the current is described and, by means of the mean streamwise velocity field, both bottom and interface shear stresses are computed. The variation on the shape caused by changing initial conditions (i.e. with different initial buoyancies, various lock-lengths and lock-bottom inclinations) are therefore discussed. The potential water entrainment and bottom erosion capacity are

estimated on the base of the computed shear stresses evolutions. Finally, an overview of the main findings is presented in the conclusions.

## 2 Methodology

### 2.1 Experimental set-up

5 The tests are performed in a channel with a rectangular section, 7.5 m long and 0.275 m wide. The gravity currents are reproduced through the lock-exchange technique by sudden release of a gate which divides the flume in two parts where the fluids of different densities are at rest. Three buoyancy differences are tested in combination with five lock-slopes, ranging from  $S = 0\%$  (horizontal bed) to  $S = 16\%$  (tests S0 to S4). Figure 1 shows the configurations from horizontal bed (S0) to the steepest slope (S4). By introducing a slope on the channel lock reach, the volume of denser fluid is reduced. This lock contraction is also tested separately by performing reference tests with the combination of the three initial densities and the five lock-lengths which correspond to the very same volumes in the lock of the tests under inclined. The experimental parameters are reported in Table 1.  $R_i.S_i$  refer to gravity currents reproduced by different initial density with the presence of a lock-slope while  $R_i.L_i$  indicates the tests with varying initial density and lock-length.

15 The channel is filled with 0.2 m of ambient water in one side and of salty water, up to the same level, in the lock reach. Once the gate is removed, the saline current forms. At 2.5 m from the gate an Acoustic Doppler Velocity Profiler (ADVP) is placed to measure 3D instantaneous velocities along a vertical. The ADVP (Lemmin and Rolland (1997), Hurther and Lemmin (2001), Franca and Lemmin (2006)) is a non-intrusive sonar instrument that measures the instantaneous velocity profiles using the Doppler effect without the need of calibration and was used with an acquisition frequency of 31.25 Hz. The velocity profiles are collected in time along a fixed vertical. The flume is connected to a final big reservoir that allows the current dissipation and avoids its reflection upstream.

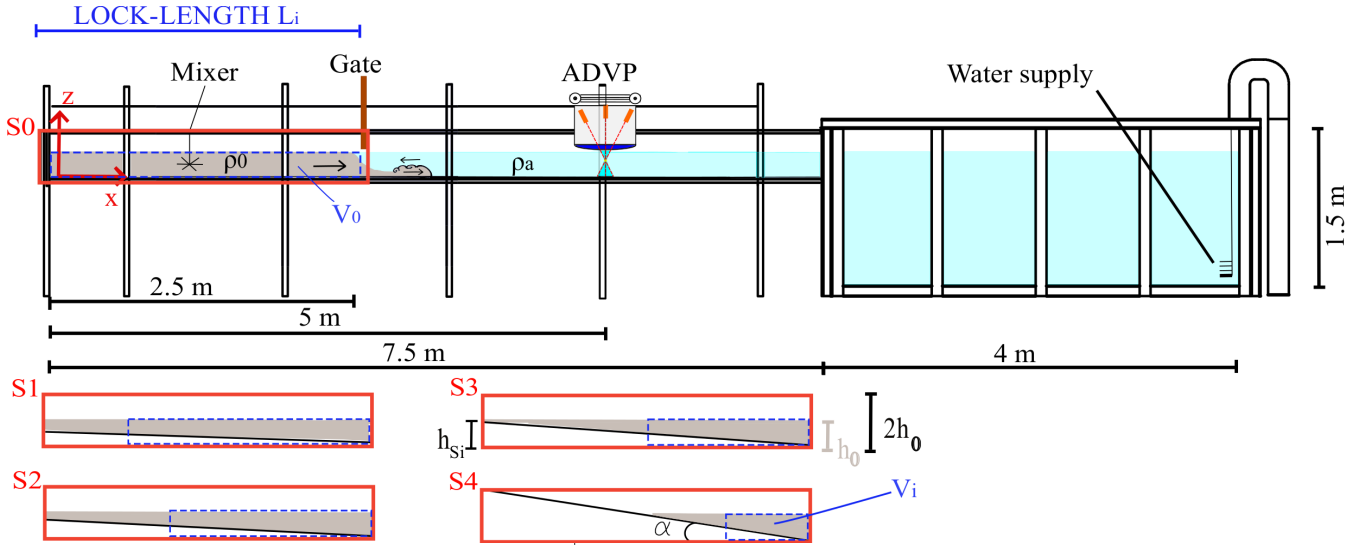
20 Normalization of the time is made using the scale  $t^* = h_b/u_b$ , where  $h_b$  is a vertical geometric scale, here considered as one third of the total height of the fluid in the experimental tank,  $h_0$  ( $h_b = h_0/3$  and  $h_0 = 0.2$  m) and  $u_b = \sqrt{g'h_b}$  is the buoyancy velocity.

### 2.2 Data filtering

25 By means of the analysis of the power spectra of the raw data collected with the ADVP, noisy frequencies were mainly detected below 8 Hz. The instantaneous measurements were thus low-pass filtered with 8 Hz as cut-off frequency (Zordan et al., 2018). The 8 Hz cut-off has been chosen because the signal, for frequencies higher than 8 Hz, showed white noise. The time-series of the mean streamwise and vertical velocities ( $\bar{u}$  and  $\bar{w}$ ) for the unsteady gravity current, were derived after a filtering procedure that consisted in the application of a moving average over a time-window which is chosen by the analysis of the power spectra distribution as in Baas et al. (2005). This analysis showed that for a time window of 0.32 s, the harmonics of all the meaningful frequencies were still recognisable while, increasing the time window, the harmonics of progressively

$S_i$ tests	$\rho_0$ $\left[\frac{kg}{m^3}\right]$	$g'_0$ $\left[\frac{m^2}{s}\right]$	$u_0$ $\left[\frac{m}{s}\right]$	$Re_0$ [—]	$S$ [%]	$\alpha$ [°]	$V_i/V_0$
R1.S0	1028	0.29	0.24	48166	0	0.00	1.000
R1.S1	1028	0.29	0.24	48166	4	2.29	0.750
R1.S2	1028	0.29	0.24	48166	6	3.43	0.625
R1.S3	1028	0.29	0.24	48166	8	4.57	0.500
R1.S4	1028	0.29	0.24	48166	16	9.09	0.250
R2.S0	1038	0.39	0.28	55857	0	0.00	1.000
R2.S1	1038	0.39	0.28	55857	4	2.29	0.750
R2.S2	1038	0.39	0.28	55857	6	3.43	0.625
R2.S3	1038	0.39	0.28	55857	8	4.57	0.500
R2.S4	1038	0.39	0.28	55857	16	9.09	0.250
R3.S0	1048	0.49	0.31	62610	0	0.00	1.000
R3.S1	1048	0.49	0.31	62610	4	2.29	0.750
R3.S2	1048	0.49	0.31	62610	6	3.43	0.625
R3.S3	1048	0.49	0.31	62610	8	4.57	0.500
R3.S4	1048	0.49	0.31	62610	16	9.09	0.250
$L_i$ tests	$\rho_0$ $\left[\frac{kg}{m^3}\right]$	$g'_0$ $\left[\frac{m^2}{s}\right]$	$u_0$ $\left[\frac{m}{s}\right]$	$Re_0$ [—]	$L_i$ [m]		$V_i/V_0$ [—]
R1.L0	1028	0.29	0.24	48166	2.500		1.000
R1.L1	1028	0.29	0.24	48166	1.875		0.750
R1.L2	1028	0.29	0.24	48166	1.563		0.625
R1.L3	1028	0.29	0.24	48166	1.250		0.500
R1.L4	1028	0.29	0.24	48166	0.625		0.250
R2.L0	1038	0.39	0.28	55857	2.500		1.000
R2.L1	1038	0.39	0.28	55857	1.875		0.750
R2.L2	1038	0.39	0.28	55857	1.563		0.625
R2.L3	1038	0.39	0.28	55857	1.250		0.500
R2.L4	1038	0.39	0.28	55857	0.625		0.250
R3.L0	1048	0.49	0.31	62610	2.500		1.000
R3.L1	1048	0.49	0.31	62610	1.875		0.750
R3.L2	1048	0.49	0.31	62610	1.563		0.625
R3.L3	1048	0.49	0.31	62610	1.250		0.500
R3.L4	1048	0.49	0.31	62610	0.625		0.250

**Table 1.** Experimental parameters.  $\rho_0$  is the initial density of the mixture in the upstream tank (measured with a densimeter),  $g'$  is the reduced gravity corresponding to  $\rho_0$ ,  $Re_0 = u_0 h_0 / \nu_c$  is the Reynolds number based on initial quantities with  $u_0 = \sqrt{g' h_0}$  the initial buoyancy velocity,  $h_0 = 0.2$  m the total height of the water column and  $\nu_c$  the kinematic viscosity of the denser fluid,  $\alpha$  is the angle of inclination of the bottom in the lock,  $S$  is the lock-slope expressed in percentage ( $h_{S_i}/L_0$ , with  $h_{S_i}$  the height as in Figure 1),  $L_i$  is the length of the upstream lock-reach,  $V_i/V_0$  the percentage of volume of the upstream lock-reach with respect to the configuration  $L_0$ .



**Figure 1.** Longitudinal view and cross-section of the experimental set-up showing tested slope configurations S0 to S4 of lock volumes  $V_i$ .

smaller frequency gradually lose power and they become impossible to distinguish (Baas et al., 2005). Thus, this window length was chosen for the moving average defining  $\bar{u}$  and  $\bar{w}$ . The turbulent fluctuation time series ( $u'$  and  $w'$ ) is then calculated using the Reynolds decomposition:

$$u = \bar{u} + u' \quad (1)$$

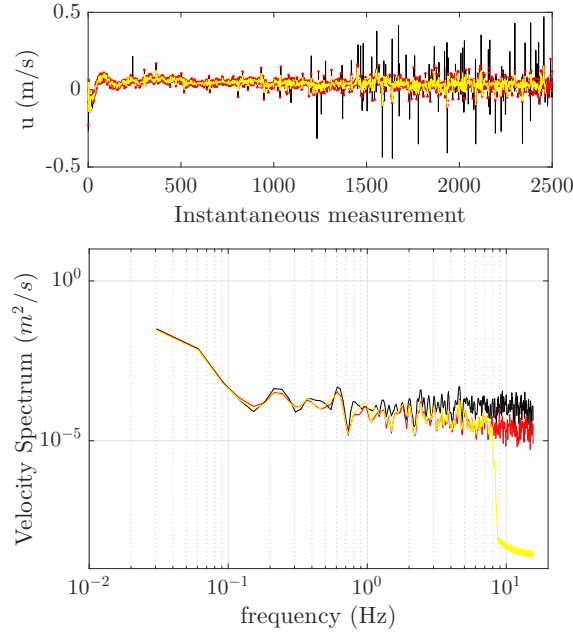
- 5 where  $u$  is the instantaneous velocity. The cleaning procedure with the velocity signals and corresponding spectra is shown in Figure 2.

### 3 Results

#### 3.1 The shape of the current

- A definition that allow to distinguish the head and the body regions of the current is considered in order to analyse the current shape changes due to the presence of the slope in the lock. In particular, a criterion is here established to identify the two main regions of a gravity current: the head and the body. A kinematic function ( $H$ ) is defined and computed as the product between the instantaneous depth averaged streamwise velocity,  $u_d(t)$ :

$$u_d(t) = \frac{1}{h} \int_0^h u(z, t) dz \quad (2)$$



**Figure 2.** Raw velocity data (black) and despiked data (red) obtained with the procedure proposed by Goring and Nikora (2002). Then, through the analysis of the velocity spectra (figure at the bottom), the cut-off frequency of 8 Hz has been identified in order to low pass filter the noisy frequencies (yellow line).

and the current height,  $h(t)$ , that is here identified by the position where the streamwise velocity is equal to zero, as in Zordan et al. (2018).  $H$  is thus defined as:

$$H(t) = u_d(t)h(t) \quad (3)$$

We can moreover notice that, by dimensional analysis, the function  $H$  corresponds to a flow rate per unit width.

- 5 As in Nogueira et al. (2014), where a similar procedure was adopted considering the product of the depth averaged stream-wise velocity by the depth averaged density of the current, the downstream limit of the head ( $L_h$ ) is identified by the first meaningful local minimum of the function  $H$ , starting from the front.  $L_h$  identifies the temporal extension of the head. The conversion from time to length scale may be done by using Taylor frozen hypothesis and considering a reference velocity of the current velocity as advection velocity.
- 10 The body length is instead analysed by using the cumulative sum of the function  $H$ . This is a region where a quasi-steady regime is established for a certain time length. This implies that  $\sum H$  shows a linear increment in time. The limit of the body is therefore here defined by analysing the linear evolution that is fitted by a linear regression with least squares method for progressively longer portion of the accumulated summed data. The analysis of the development of  $R^2$  value, the coefficient

of determination, allows to find the extension of the linear portion which corresponds to the temporal extent of the body region ( $L_b$ ).  $R^2$  is defined as the square of the correlation between the response values and the predicted response values. It is computed as the ratio of the sum of squares of the regression (SSR) and the total sum of squares (SST) as:

$$R^2 = \frac{SSR}{SST} = \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (4)$$

- 5 where  $\bar{y}$  is the average of the response  $y$ ,  $\hat{y}$  is the regression line and  $n$  the number of observations  $i$ . In Figure 3 the development of the function  $H$  is shown for the tests with the lock-slope. The same procedure is adopted for tests  $R_i.L_i$  and the results can be found in Zordan et al. (accepted for publication).

The form of the currents was identified by the zero streamwise velocity contour. In Figure 4 the contours of each test with the lock-slope are compared with the correspondent reference test with lock-length variation. The results are grouped by the  
10 initial density on the lock (columns in the figure), and by pairs of tests with the same volume of the lock but for different slopes. The extension of head and body as identified by the previous methods are also reported with the vertical lines. Dashed lines refers to tests  $S_i$  while continuous lines correspond to  $L_i$  tests.

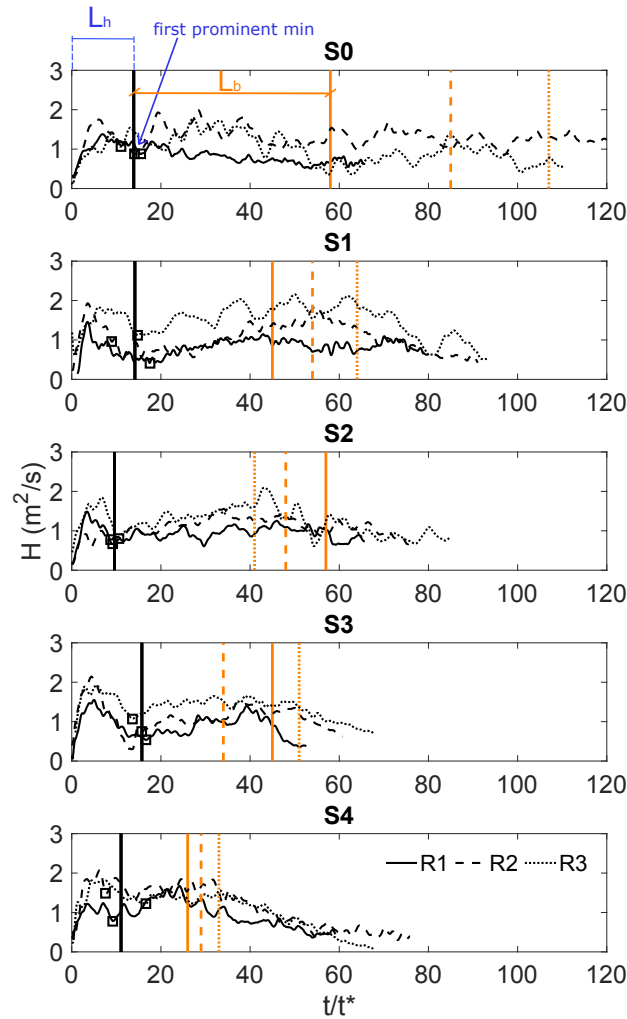
In Figure 4 we can see that the head of the current does not show any relevant change. Instead the extension of the body is affected: it reduces with increasing inclination of the upstream channel reach and the same goes for tests produced by reduced  
15 lock volume. A dependency on the initial density is noticed and in three out of the total five slopes bring to the formation of longer body with greater initial buoyancy. This can be verified in Figure 3 where extensions of the bodies are plotted with the vertical orange lines. R1, R2 and R3 produces progressively longer bodies for tests S0, S1 and S4.

The largest deviation between the two contours of corresponding tests  $L_i - S_i$  is noticed for the last configuration, with the  $R_i.L4$  tests showing a shorter body and a more defined tail while for the correspondent tests with the inclined lock the body is  
20 more extended.

### 3.2 Mean velocity field

In Figure 5 the mean streamwise velocity field on the background and velocity vectors of the components ( $\bar{u}$ ,  $\bar{w}$ ) are shown for all the tests performed. The heads of the currents are indicated by the vertical dashed lines and the zero streamwise velocity contours are marked by the black lines. We can notice that the structures of the currents are quite similar in all configurations.  
25 An arising head is followed by a zone of high mixing, characterized by the presence of billows (due to Kelvin-Helmholtz type of instabilities (Simpson, 1972)) that are due to shear at the rear part of the elevated head. Body and tail are not always well defined regions, mainly for the class of tests down an inclined, and therefore the contour is not drawn. Moreover, tests  $S_i$  show lower streamwise velocities within head and body with respect to correspondent  $L_i$  tests.

By comparing tests  $S_i$  with the correspondent  $L_i$  tests, which have the same lock-volume but are performed without upstream  
30 slope, it is noticed that mean streamwise velocity is slightly higher for tests on horizontal bed. This can appear to some extent contradictory but that behaviour has already been mentioned in literature, in the study of Beghin et al. (1981), who was one

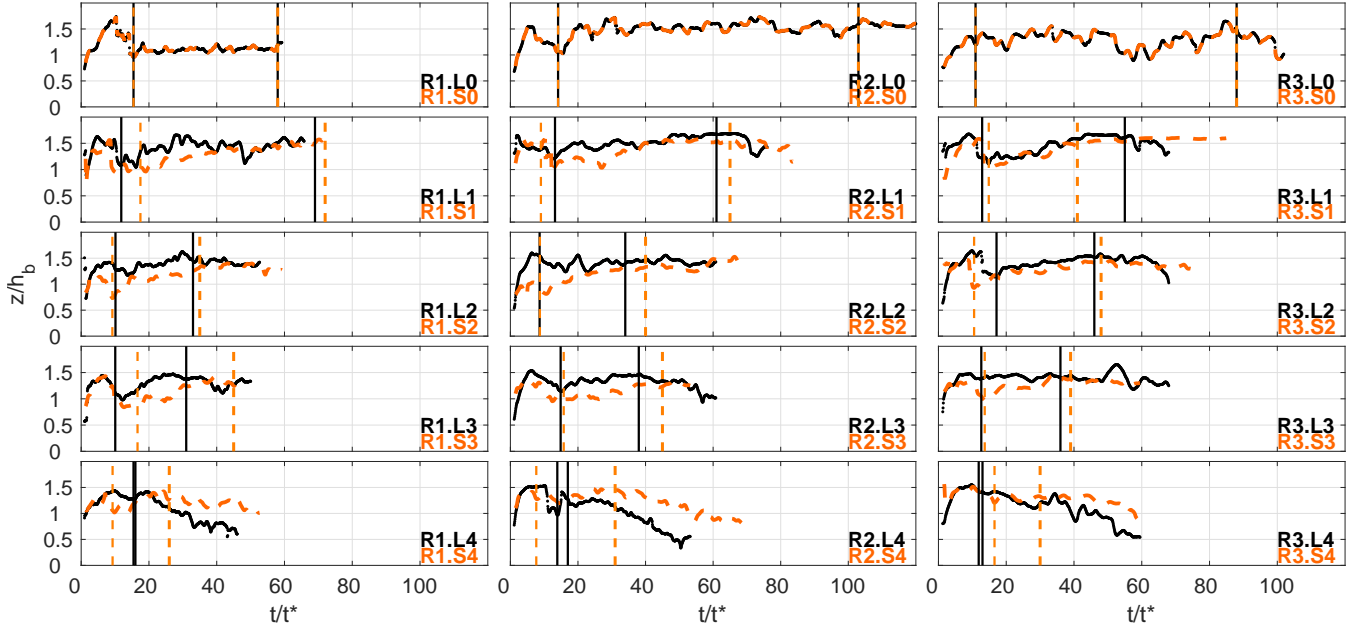


**Figure 3.** Determination of the gravity current head extension from the first prominent minimum of the function  $H$  ( $L_h$ ). The extension of the body ( $L_b$ ), as identified by the cumulative sum of the depth-averaged streamwise velocity, is also traced with the red vertical lines.

of the first to investigate the role of the slope on the physics of a gravity current. He showed that tests which flows on small slopes, for tests where the entire channel was inclined, (typically less than  $5^\circ$ ) experience a first acceleration phase followed by a deceleration phase. This is because of the fact that, although the gravitational force increases as the lock-slope becomes more inclined, there is also increased entrainment, both into the head itself and into the flow behind. This produces an extra

5 dilution of the current with a decrease in buoyancy.





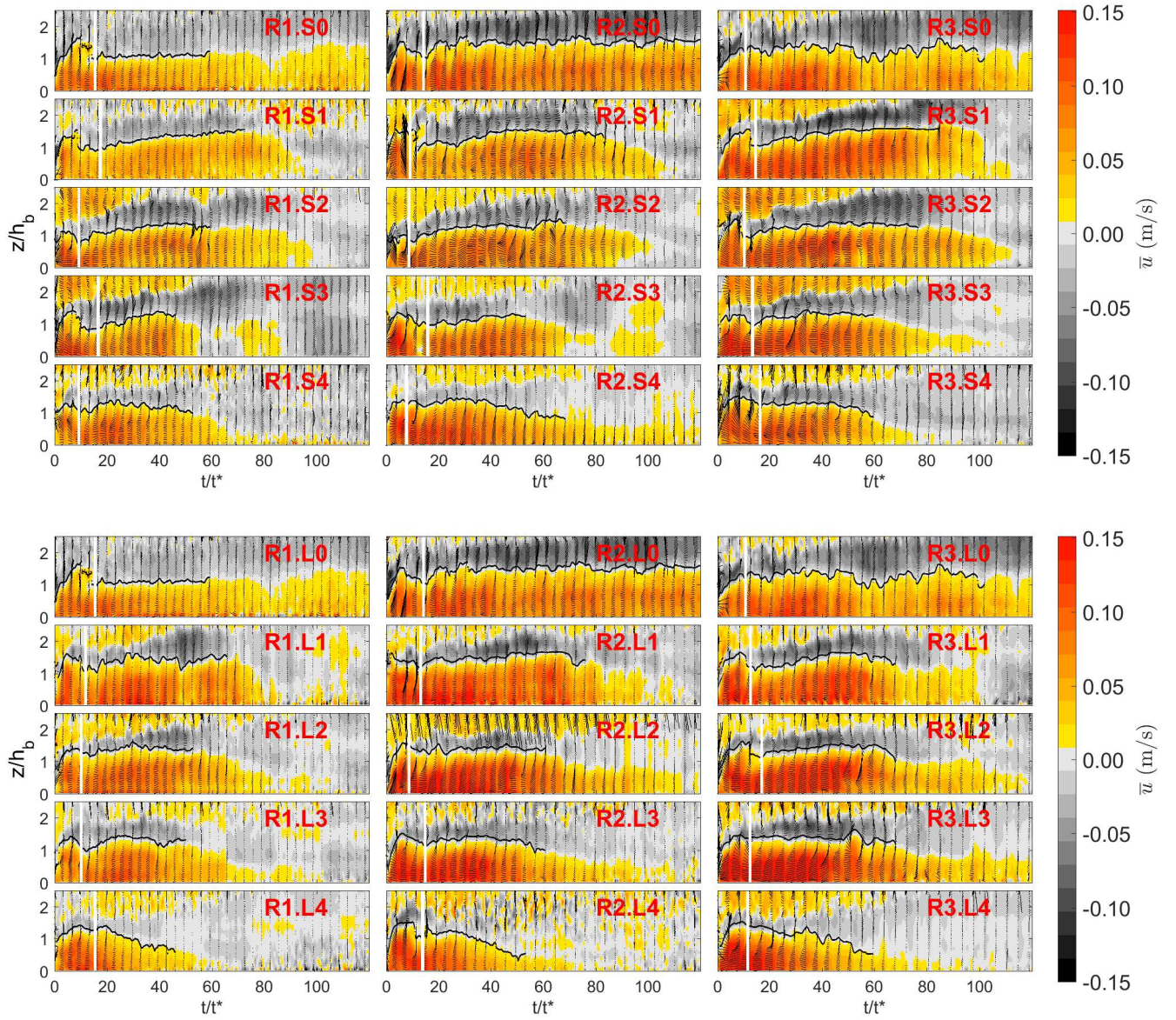
**Figure 4.** Gravity currents contours, as identified by the zero streamwise velocity contour, for tests with the lock-slope and correspondent tests with lock-length variation.

### 3.3 Bottom and upper shear stress

The sedimentological impact of a gravity current is the result of the complex hydrodynamic of this flow. Sediment entrainment is a complex mechanism mainly due to the difficulty in defining the fluctuating nature of turbulent flow (Salim et al., 2017). In Zordan et al. (2018) the transport of sediment within a gravity current is linked to the bed shear stress, that is here considered a "surrogate" measure of it. The form that bed shear stress is affected by the changing initial conditions of the current explains thus how the entrainment capacity of a current is altered. Bed shear stress temporal evolution is calculated by following the procedure in Zordan et al. (2018) where it was assumed that the mean flow met the conditions necessary for the fitting of the overlapping layer by the logarithmic law of the wall as (Ferreira et al., 2012):

$$\frac{\bar{u}(z)}{u_*} = \frac{1}{k} \ln \frac{z}{z_0} \quad (5)$$

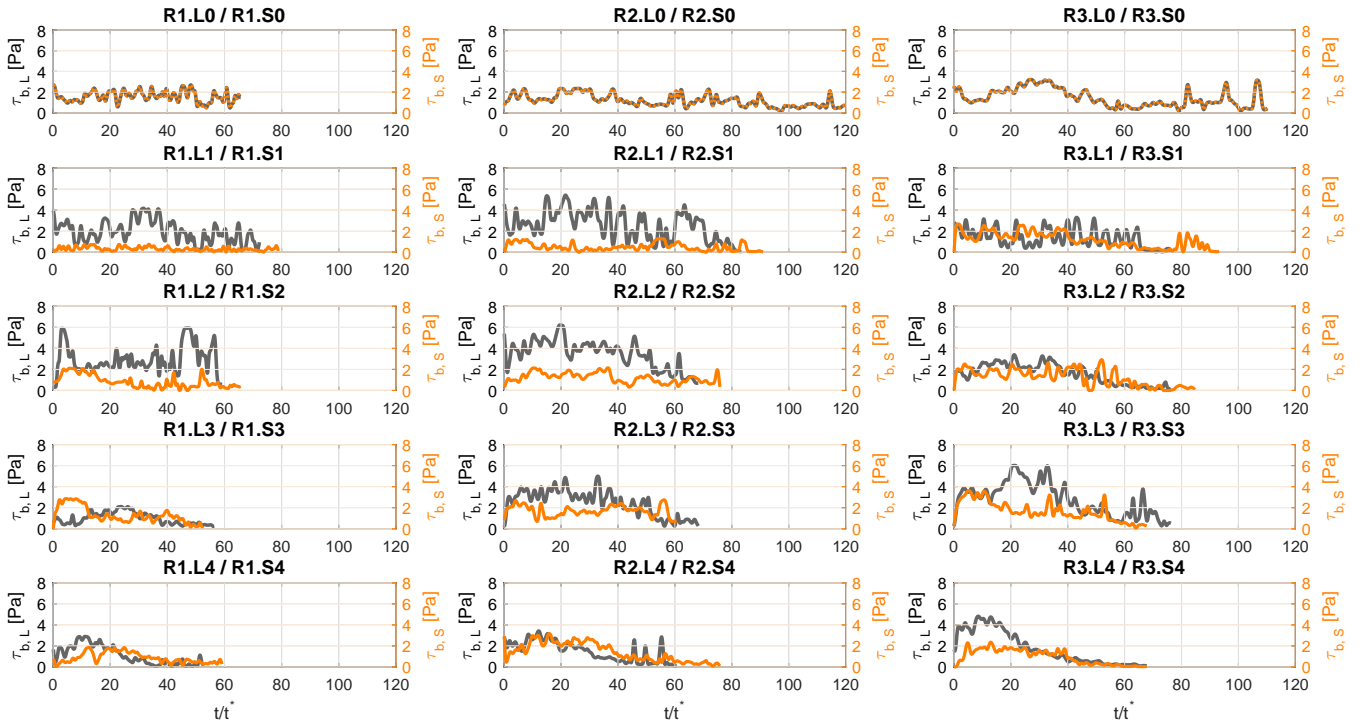
- where  $\bar{u}(z)$  is the mean velocity,  $u_*$  is the friction velocity, which is the velocity scale corresponding to the bed shear stress (Chassaing, 2010),  $k$  is the von Kármán constant,  $z$  is the vertical coordinate and  $z_0$  is the zero-velocity level. The flow boundary is assumed to be smooth, as verified by estimating the shear Reynolds number which is lesser than 5 (Nezu et al., 1994), and the classic value of the von Kármán constant of  $k = 0.405$  is adopted. Discussion on the estimation of  $k$  can be found in Ferreira (2015).



**Figure 5.** Streamwise velocity field on the background and velocity vectors of the components ( $u, w$ ). The head of the current is delimited by the vertical white line. The contour of the current is indicated in black.

The fitting of the logarithmic law of the wall is used to calculate the friction velocity and bed shear stress is afterwards computed by considering a constant initial density that is here equal to the initial density in the lock ( $\rho_c$ ):

$$\tau_b = \rho_c u_*^2 \quad (6)$$

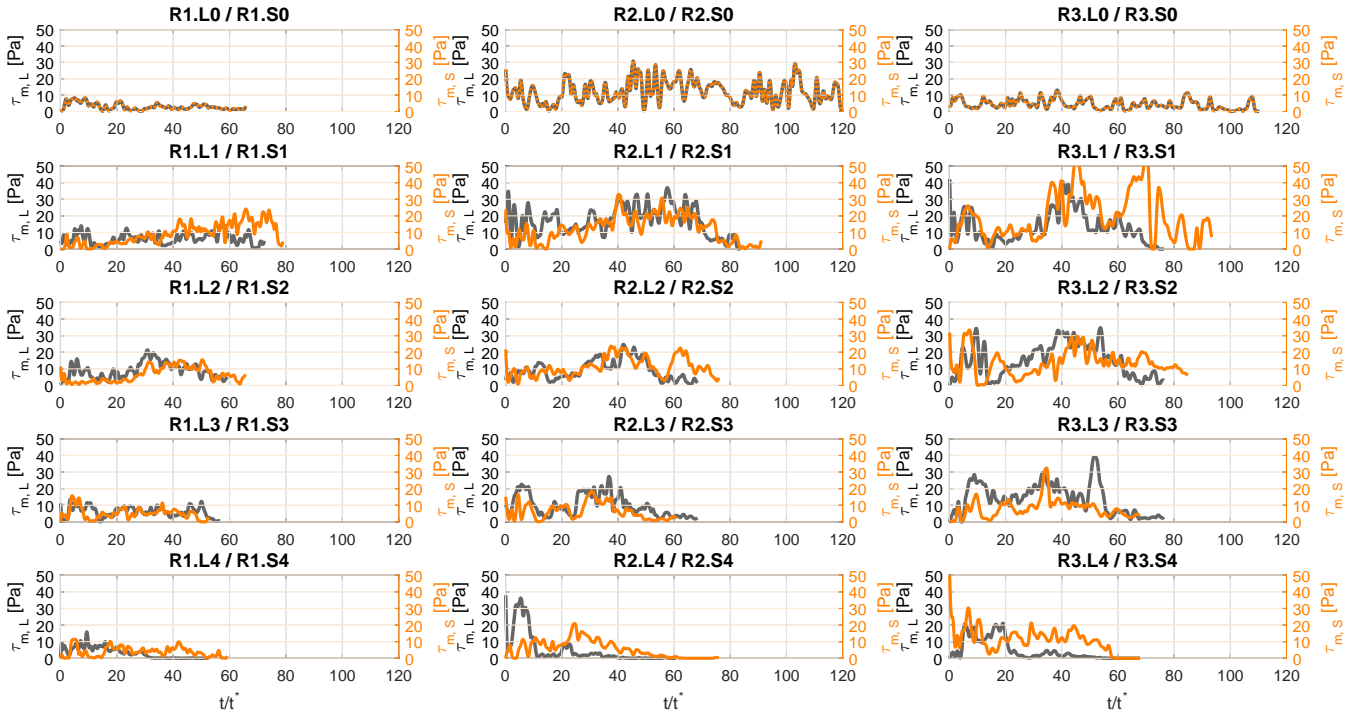


**Figure 6.** Temporal evolution of bed shear stresses calculated by log law fitting for tests with progressively reduced lock-length ( $\tau_{b,L}$ ) and with the lock-slope ( $\tau_{b,S}$ ).

The fitting procedure of the bottom logarithmic layer was determined stepwise, extending a linear least square fitting range (in a semi-logarithmic scale) from the lowest measured point until the maximum velocity vertical position. Then, within this region, the sublayer which provided the best regression coefficient was chosen and considered for the estimation of  $u_*$ , corresponding to the extent of the logarithmic layer as it was shown in Zordan et al. (2016).

- 5 The bed shear stress time-evolution of gravity currents with lock-slope ( $\tau_{b,S}$ ) are compared to the analogous results for tests with decreasing lock ( $\tau_{b,L}$ ) (Figure 6). Tests performed with a slope break at the section of the lock show in average lower values of bed shear stress with the only exception of tests S4, which is the steepest slope condition, where, from normalized time  $t/t^* \simeq 20$ , i.e. in the body region, bed shear stress is slightly higher than in the correspondent  $L_i$  tests.

- 10 At the upper boundary of the gravity currents, i.e. the interface with the ambient water, studies on turbulent flow near a density interface confirmed that under certain conditions, the turbulent boundary layer theory can be applied as well (Lofquist (1960), Csanady (1978)) and that the "law of the wall" can be applied to estimate the shear stress here. By hypothesizing a constant mean value of water viscosity and hydraulically smooth conditions, the estimation of an interface shear stress ( $\tau_m$ ) is made; qualitatively the estimation that will result is enough for the purpose of the present study. The time evolution of interface shear stress is therefore computed following the same procedure as for the bottom shear stress. In this case the fitting



**Figure 7.** Temporal evolution of interfacial shear stresses calculated by log law fitting for tests with progressively reduced lock-length ( $\tau_{m,L}$ ) and with the lock-slope ( $\tau_{m,S}$ ).

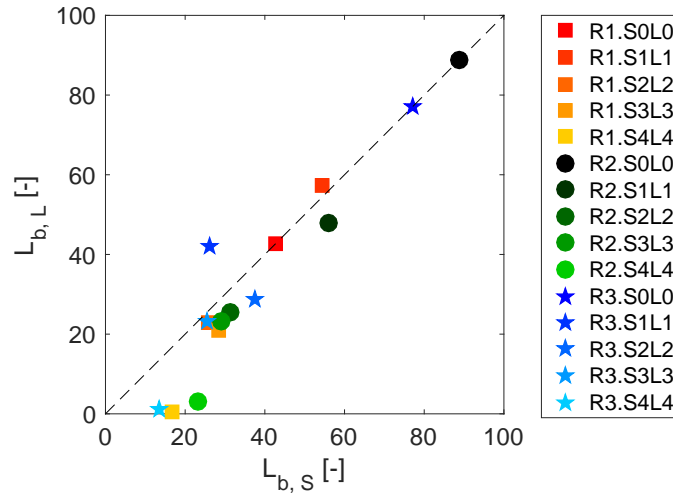
procedure of the logarithmic layer is determined by considering the mixing layer as defined in (Zordan et al., accepted for publication). This layer is delimited at the top by the zero streamwise velocity contour and at the bottom by the height of the current as defined by the Turner's integral scales (Ellison and Turner, 1959). Within this layer the at-least-three consecutive measurement points along the velocity profile which were giving the highest  $R^2$  were considered for fitting. The time evolution of interface shear stress for the two series of tests is shown in Figure 7. Again the main differences between tests with reduced lock and respective tests with lock-slope are for the fourth configuration: the steepest slopes present higher values of interface shear stress in the body region with respect to the correspondent tests with the same initial volume of release but flowing on a horizontal bed.

## 4 Discussion

### 4.1 Shape variation of gravity current with the lock-slope

The extensions of the body of correspondent tests performed with the lock-slope or with horizontal bed, and with varying lock-lengths are compared in Figure 8. For lower lock-slopes the body extension is similar to the currents produced with the





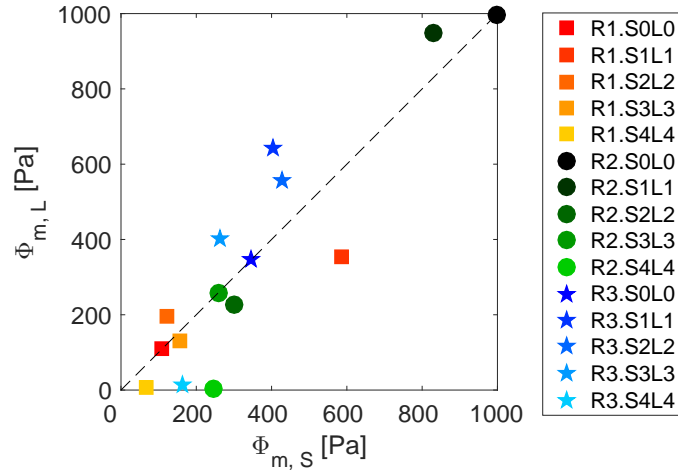
**Figure 8.** Comparison of the length of the body ( $L_b$ ) between tests with progressively reduced lock-length and with lock-slope. The dashed line is the identity line.

same lock-volume but with horizontal bottom. However, for lock-slopes at 16%, the body region for tests  $S_i$  are longer than correspondent tests  $L_i$ . At this point two mechanisms affect the evolution of the current: the current entrains water from the upper surface due to the increment of friction between the denser flow and the counter current progressively advancing upwards the lock, and the head is fed by the rear current. The flow of tests S4 show that these characteristics of the upstream flow in the lock are still influencing the flow at the observation position: (i) an extended body is the result of water entrainment at the upper surface of the current that creates dilution and expansion of the fluid in the current; (ii) the fluid in the body become faster as a result of the gravitation forces as in Britter and Linden (1980) (Figure 5). Britter and Linden (1980) showed that currents flowing along a horizontal boundary the head is the controlling feature. However down a slope, the body becomes more determinant in the gravity current evolution since it is up to 30-40% faster than the head velocity, depending on the slope, being able therefore to move faster fluid into the head. In our study this effect occurring within the inclined lock is still observed in the downstream flat part of the channel but only for lock-slopes of 16%.

## 4.2 Ambient fluid entrainment

A new quantity is defined which account for the potential entrainment capacity of the gravity current on the base of the computed time evolution of the interfacial shear stress ( $\tau_m$ ). It is computed as the non-dimensional time integral of the shear stress which represents, after dimensional analysis, the work done over a determined duration, per unit surface for a given advection velocity, which can be approximated as the initial buoyancy velocity,  $u_0$ . This quantity  $\Phi_m$  is calculated as:

$$\Phi_m = \int_{T_1}^{T_2} \tau_m(t) dt / t^* \quad (7)$$



**Figure 9.** Comparison of  $\Phi_m$ , a surrogate for the entrainment capacity of the mixing region, between tests with lock-slope ( $S_i$ ) and correspondent tests on horizontal bottom ( $L_i$ ). The dashed line is the identity line.

where the limits of integration are  $T_1 = L_h$  and  $T_2 = L_b$ , in order to focus on the body, the region that has been found mostly affected by the variation of the initial conditions. The validity of the use of  $\Phi_m$  as an indicator of the entrainment capacity is supported by the analysis of its relation with the Richardson number  $Ri$  (Zordan et al., accepted for publication). The relation between water entrainment and bulk Richardson number is well known in literature and numerous empirical fits to the experimental data have been proposed since the early work of Parker et al. (1987) and supported by more recent contributions (Stagnaro and Pittaluga, 2014). Therefore, it is here proposed to use this quantity as a surrogate for water entrainment capacity since it benefits from the instantaneous measurements of shear stress and therefore account for the unsteady behaviour of the gravity currents. In Figure 9, the potential water entrainments for gravity currents performed on an inclined and correspondent tests with reduced initial volume of release are compared. The tests S4L4 detach from the identity line, thus a greater water entrainment is expected for the case with the inclined bed with respect to the horizontal bottom.

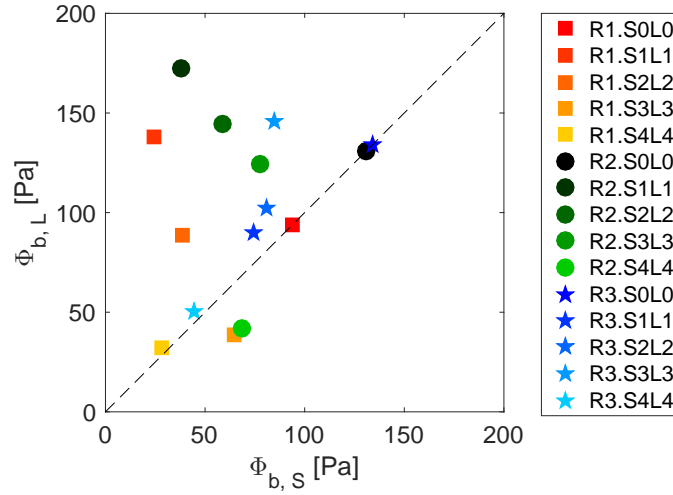
### 4.3 Bottom erosion capacity

Similarly to the interfacial water entrainment capacity, the bottom entrainment capacity, that can also be called the erosion capacity is here computed. This new quantity is computed as:

$$\Phi_b = \int_{T_1}^{T_2} \tau_b(t) dt / t^* \quad (8)$$

where the limit  $T_i$  are  $T_1 = 0$ ,  $T_2 = L_b$ . In Zordan et al. (2018) this quantity proved to be a surrogate of the entrainment capacity of a gravity current produced over a mobile bed.

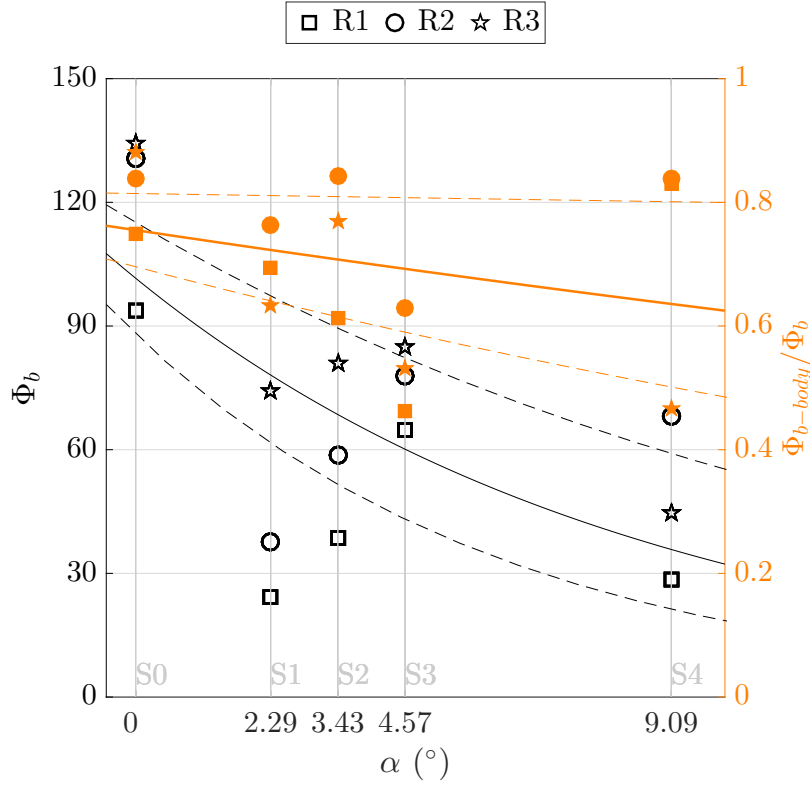
The bottom erosion capacity is compared for gravity currents performed with the lock-slope and correspondent tests on a horizontal bottom. Generally,  $L_i$  tests show a higher erosion capacity with respect to their analogous  $S_i$ . The points in Figure 10



**Figure 10.** Comparison of the bottom erosion capacity  $\Phi_b$  between tests with lock-slope ( $S_i$ ) and correspondent tests on horizontal bottom ( $L_i$ ). The dashed line is the identity line.

are in fact concentrated above the bisect of the first and third quadrants. The effect of an extra gravitational force occurring in the flow upstream the lock, as described above, is proved not to play a role in enhancing the capacity of the current to perform bottom erosion, in the downstream flat reach of the channel, which is instead reduced. This is probably a consequence of the decrease in streamwise velocity which results from the dilution of the gravity current occurring already in the lock. On the other hand, ambient water entrainment causes the expansion of the body region. Longer bodies keep eroding material longer and the erosion potential attributed to this part is therefore increasing. The potential bottom erosion, i.e. the quantity  $\Phi_b$  in Figure 11, shows a tendency to decrease with increasing lock-slope. This is mainly the result of the released volume reduction caused by the presence of the lock-slope, therefore originating shorter current bodies. The role of the body in the total erosion capacity is computed as the ratio  $\Phi_{b-body}/\Phi_b$  (Figure 11) whose limits of integration of  $\Phi_{b-body}$  are  $T_1 = L_h$  and  $T_2 = L_b$ .

The contribution that is ascribed to the body has a similar development as the total erosion capacity. This enforces the hypothesis that the body is determinant in the entrainment capacity of a gravity current. Figure 11 highlights that the importance of the body in the total erosion capacity becomes proportionally higher for tests S4 (the trend lines in Figure 11 deviates more in this configuration). Higher water entrainment was proved in Section 4.2 for this latter case, which was therefore subjected to an expansion of the body region. An influence of the upper surface on the dynamics of the lower bottom boundary is therefore hypothesized. The interaction between the upper layer and the bottom was already pointed out by the numerical investigation of Cantero et al. (2008) and experimental evidences were reported in Zordan et al. (accepted for publication). In this latter the vorticity was analysed showing that residual negative vorticity expands from the upper layer through the bottom with progressively lower intensity.



**Figure 11.** Potential erosion capacity for gravity currents (left axis) developed with different lock-inclinations and rate of potential bottom erosion due to the body of the gravity current on the total bottom erosion capacity,  $\Phi_{b-body}/\Phi_b$ , (right axis). The exponential fitting lines are reported in order to give evidence of the general trend, together with the 85% confidence intervals (dashed lines).

## 5 Conclusion

In most practical situations gravity currents are flowing on different topographies and most of the time travels along inclined but discontinuous slopes (slope breaks). Moreover they are generally originated by the release of a certain amount of a fluid of various densities. The present study analyses all the previously mentioned changing initial conditions which trigger gravity currents that are commonly observed in nature.

In this paper the effect on a downstream flat propagating reach, of incremental gravitational forces induced in the current which is formed still upstream in the lock is tested by reproducing experimentally gravity currents of different initial densities with the presence of an inclined lock. Corresponding tests with a horizontal lock are performed as well in order to have the reference cases with reduced volume. The range of lock-slopes tested varies from horizontal bed to  $S = 16\%$  (which correspond to an inclination of the lock  $\alpha \approx 9^\circ$ ). Gravitational force is the main driving force which directly depends on slope (Khavasi et al., 2012). These within the upstream inclined reach which constitutes the lock, compete with the entrainment that takes place due to higher shear stress at the upper interface and tend to dilute the current. Thus, if on one hand gravitational



- acceleration drives for a faster gravity current, on the other hand water entrainment at the upper interface dilute the fluid of the current which is consequently slowed down and it expands due to incorporation of the ambient fluid. The configurations S4-L4, corresponding to the steepest lock-slope and the shortest lock-length, respectively, exhibit the highest deviations in terms of shape and ambient water entrainment between tests with lock-slopes with respect to correspondent tests on the horizontal bed.
- 5 S4 tests showed a longer body, owing to entrainment of the ambient fluid. Bottom erosion capacity at the downstream flat reach is reduced by the presence of the extra gravitational forces, most probably due to lower streamwise velocities which are consequence of gravity currents dilution occurring on the way of the gravity current along the channel. The limit case of tests S4, with a lock-slope of  $S = 16\%$ , the transient condition as described by previous literature for a continuously sloped channel (Britter and Linden (1980), Beghin et al. (1981), Parker et al. (1987), Maxworthy and Nokes (2007), Maxworthy (2010)). The
- 10 limit given by the experimental set up did not allow to go for steeper lock-slopes, cases for which therefore further investigation should be undertaken.

*Competing interests.* The authors have no conflict of interest to declare.

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