Responses to reviewers

On behalf of all co-authors I would like to thank the editor and the three referees for their constructive comments, which helped improving the quality of the first version of the manuscript.

Note: the comments raised by the referees are listed with numbers and written in italics, the replies are listed accordingly. Changes to the manuscript are yellow-highlighted.

Anonymous Referee #1

This is a nice paper describing a new hydrodynamic model simulating pedestrians' instability during flooding events. The manuscript includes nice figures and is overall well written, but a double check from a English native speaker would help improve readability.

The manuscript has been checked to improve readability.

Yet, I have 2 main major concerns that should be address before publication. (1) The first one is related to the actual usefulness of such a model in risk management. The authors state this point in various parts of the paper, but they do not clarify how such a model can actually be used. I think this clarification is crucial, as its usefulness is one of the selling points of such a model.

(1R) The main contribution of the work is the identification of the most relevant dimensionless actors playing a role in pedestrians instability. The first and most important one is the relative submergence, which accounts for a characteristic of the subject (height) and for a characteristic of the flow (water depth). The second parameter is Froude number, which is an attribute of the flow. Several authors attributed the scatter of experimental pairs (water depth-velocity) to many variables such as body build, psychological conditions, clothing, training levels etc. The aim of the work is to clarify if a limited number of parameters (i.e. shape factor, submergence, Froude number) is capable of explaining most of the variability observed in the experiments. More generally, dimensional analysis allows merging experiments carried out at various scales, highlighting dependencies and relevant factors. Moving from conventional diagrams (water depth versus velocity) to dimensionless diagrams may help in the definition of safety rules for citizens. This doesn't mean that common people should read a dimensional diagram. As an example, teaching people to recognize a level of submergence with respect to their body (knees, ankles, and waist) is easier than refer to absolute water depths, which are more difficult to assess. These points have been clarified in the introduction of the revised manuscript.

(2) The second one is related to the lack of a sensitivity analysis. The current modelling exercise does not allow a proper evaluation of the fact that good results are obtained for the right reasons. The paper describes it only with reference to mesh resolution, but there are numerous parameters affecting model outcomes and, by playing with them, one can get a plethora of different results. Thus, to evaluate the proposed model a comprehensive sensitivity analysis is crucial.

(2R) A sensitivity analysis has been carried out for the dimensionless mobility parameter θ_P and for the goodness of fit between numerical model and experiments to clarify the role of the main parameters and how they affect the results.

For the mobility parameter θ_P, the sensitivity has been evaluated with respect to: length of the foot d, height of the subject H_p and human body density ρ_P. The sensitivity is assessed with a local method i.e. calculating the partial derivative of θ_P with respect to the selected factors X_j. A general form of the mobility parameter with $\rho_P \neq \rho$ has been used for the sensitivity analysis and added to the manuscripts (Eq. 12)

$$\theta_P = \frac{2d}{H_P} \cdot \frac{\frac{\rho_p}{\rho} \cdot H_p - H}{H}$$

The following table (Tab. 1 in the revised manuscript) has been added to the text to summarize the outcome of the sensitivity analysis. The analytical formulas allows calculating the sensitivity for each value of the water depth H thus identifying possible critical ranges.

	Parameter for the sensitivity X_j		
	$X_j = d$ *length of the foot*	$X_j = H_p$ *height of the subject*	$X_j = \rho_P$ *human body density*
Sensitivity function $\frac{\partial \theta_P}{\partial X_j}$	$\frac{2\rho_p}{\rho H} - \frac{2}{H_P}$	$\frac{2d}{H_P{}^2}$	$\frac{2d}{\rho H}$

The units of measurement of the sensitivity function are length^{-1} and length^3/mass for the geometric parameters and density parameter respectively. The sensitivities of θ_P to ρ_P and d decrease with increasing water depth H. The sensitivity to ρ_P and d are of the order of magnitude of 10^{-3} and 10^{-1}-10^1 respectively, for the experimental range of water depths. High sensitivity to d is found particularly for water depths lower than 0.5 m. Thus, d is a more sensitive parameter, although its variation is physically constrained because the foot to height ratio is in the range 0.149-0.169 according to allometry studies (Davis, 1990; Pawar and Dadhich, 2012; Fessler et al., 2004). Consequently, small variations of d can be expected. The sensitivity to H_p is of the order of magnitude of 10^{-1} for height of the subjects between 1 and 2 m.

Therefore, since the sensitivity of the parameter θ_P is the product of the sensitivity function and the variation of the parameter, we can conclude that θ_P is robust enough, although obviously its regression function depends on the experimental data. The above table and comments have been added to section 2.3 of the manuscript.

Regarding the numerical model, a sensitivity analysis to d and friction coefficient μ has been carried out to understand how the goodness of fit between numerical results and experiments is affected by a change in these parameters. The parameters d and μ play a role in the calculation of C_t and C_s respectively (Eqs. 16 and 10). A variation of ± 10% and ± 30% has been applied to both d and μ one at time and the change in the determination coefficient R^2 and RMSE of the fit has been calculated. The results are summarized in Tab. 4, which has been added to the manuscript with the necessary comments (section 4.3).

Exp.	Human subjects	All data	Human subjects	All data	Human subjects	All data	Human subjects	All data	Human subjects	All data
	Base case		d +10%		d -10%		d +30%		d -30%	
R^2	0.82	0.76	0.82	0.73	0.81	0.70	0.81	0.64	0.77	0.62
RMSE	0.28	0.67	0.29	0.67	0.31	0.69	0.31	0.97	0.32	1.26
	Base case		μ +10%		μ -10%		μ +30%		μ -30%	
R^2	0.82	0.76	0.82	0.72	0.82	0.74	0.78	0.69	0.80	0.71
RMSE	0.28	0.67	0.25	0.68	0.32	0.67	0.22	0.71	0.46	0.75

The results of the sensitivity analysis are overall satisfactory since the determination coefficient R^2 does not decrease significantly when modifying the parameters d and μ both considering only experiments on human subjects both considering all the datasets. In fact, the determination coefficient R^2 does not decrease under 0.7. The RMSE tends to increase for larger variations of the parameters especially considering all data, meaning that the scatter plot is sparser but still a high correlation exists between θ_P and numerical results. A more accurate comparison between numerical results and experiments would be possible if friction and length of the foot were measured during experiments, which is strongly encouraged in future research.

Other variables such as position of the body, posture, clothing etc. play a role in the body-flow hydrodynamic interaction, however the effects of these is left for a future research. The aim of the study in fact, is not the exact reproduction of the laboratory experiments but a better understanding of the overall hydrodynamic force variation on a rigid body with respect to a wide range of flow regimes/submergence levels.

Anonymous Referee #2

The authors introduce an interesting topic that has been addressed by several authors before through an experimental point of view. In the paper there is basically a numerical modelling considering a 3D approach, and some hypothesis associated to it.

(1) Some comments of the authors concerning the scatter observed in the experimental studies, must be clarified. Most studies consider different types of individuals to test their problems against urban floods. And it is perfectly logical this scatter, and consider to define hazard criteria as a the lower bound values, not the highest ones. Authors for instance take part of the data of the studied developed by Karvonen, oriented to define hazard criteria, not for the normal people living in the urban area, but for rescue services, people much more trained and strong than aged people or teenagers. So to propose any function including this kind of data, could be biassed not to the normal people. Same comments concerning the message about the tests developed by Foster and Cox, including babies. So it is logical that limiting conditions are not the same for everybody, babies and rescue services, and the scatter must be observed as it is in the real tests. It would be interesting if authors include all the data concerning the previous test developed by other authors (Abt, Takahashi, etc), and their statement that ". . .scatter can be reduced" considering their parameter is fully right or not.

(1R) We absolutely agree with the referee on the first point concerning the scatter of existing experimental data. It is perfectly understandable why experiments carried out on different human subjects (i.e. children or professional stuntmen) differ in the corresponding pairs of water depth and velocity. We also stress these 'dimensional' differences in terms of estimated forces while commenting Fig.5 for instance. In the manuscript, we are not arguing that the scatter is not physically

meaningful, but, given the existing scatter, we investigate the hypothesis that a limited number of dimensionless parameters can explain most of the existing variability. In our opinion, the mobility parameter and the dimensional analysis are capable of identifying two main actors in the phenomenon of instability of pedestrians in floodwaters, which are relative submergence and Froude number. That these two 'actors' may be relevant was of course expected by 'scientific common sense', this study not only clearly confirms that, it also estimates to what extent are they relevant and how much is left as unexplained variance. The contribution of these parameters is then investigated through a 3D numerical model. The discussion on the numerical results also include the effect of other parameters, which were not investigated in this study, but are left for a future research.

Regarding the use of the data by Abt et al. and by Takahashi, in the first case we considered the experimental conditions not fully representative of a 3D flow and limited in the investigated range of flow regimes, in the latter it was not possible to retrieve the heights of the tested subjects to calculate the mobility parameter. In order to clarify these points some paragraphs have been added to the manuscript (sections 1 and 2.3).

(2)Authors have made their choice considering just one orientation, person parallel to the flow. In flood events most of the problems are associated to the crossing of flooding streets. In those cases some of the distances considered in the analysis would be quite different, making more dangerous this condition and not the considered in the paper.

(2R) It is true that we only considered one flow orientation as a simplifying assumption; also most of the existing experimental studies neglects the effect of the angle of flow incidence. We also considered a rigid body thus we neglected the walking condition. As replied to E. M. Gomariz (SC2 available at http://www.hydrol-earth-syst-sci-discuss.net/hess-2016-261/#discussion), the boundary conditions and set up of the 3D numerical model should be completely modified to account for a non-rigid or moving body and this is out of the scope of the manuscript. Accounting for a walking subject would mean to adopt a fully-coupled CFD-CSD model which would require ad hoc experiments for calibration and validation. Some paragraphs have been added to sect.3.3 to clarify this point.

(3)Concerning the application of the 3D code, I would like to get some more details. Authors indicate that no turbulence model has been considered. Especially for local effects, turbulence closures are needed to reproduce properly what really happens. The reason why the authors say they do not consider a turbulence model is not clear for me. Results must be checked with a turbulence model and compare if results change or not. Authors calculate few seconds. Is it fully stable flow? Some authors indicate problems when turbulence models are introduced and forces are calculated, and the process leads to some instabilities. Data about CPU time is welcome for the tests made.

*(3R)*The 3D model aims at investigating the role of the mean flow properties on the phenomenon of instability and a turbulence model was not selected for two main reasons: first, a turbulence model needs the calibration and/or validation of some coefficients and adequate experiments were not available for this purpose; second we are approximating with a rigid body the experimental conditions for subjects which were allowed to move freely. This obviously bears an error in the estimation of the forces on the subject, thus we considered our assumption adequate for the intrinsic uncertainties of the simulated problems. Moreover, as stated in the manuscript, the results of the simplified numerical model were acceptable for a circular cylinder used as a benchmark. The stability of the flow was checked and the parameters were extracted once the simulation reached steady conditions. The flow reaches fast the stability since a wall function is applied (see sect. 3.2) The time required

for simulating 1 s was about 30 minutes with one core and important reductions of the computational time were achieved through parallelization.

The reasons of our hypothesis and the other points have been clarified in the manuscript (sect. 3.1, 3.2)

(4)Another point not fully clear to me is the consideration of the lift force. Authors make the distinction between the buoyancy and lift force (eq. 1). But next they consider density equals between water and humans. What if not? More physical explanations concerning the final orientation are these forces would be welcome. And more interpretation of the results considering the huge variation of drag and lift coefficients is welcome too. Shape of the "person" tested is the same, so for instance drag coefficient can change with a ratio close to ten, for different rates of submergence. At the beginning seems reasonable, but when the shoes/ foot are covered, increase of submergence affects only to legs, so shape is almost the same. The authors present a variation of the Lift force with Froude number, showing a first decrease, then an increase and another decrease. Can they introduce some physical explanation to this point?

(4R) A general form of the mobility parameter with $\rho p \neq \rho$ (Eq. 12) has been added and a sensitivity analysis has been carried out also on this parameter (section 2.2).

 About the lift force orientation we added a clearer explanation in the text (3.2), however the lift force is oriented downward as long as the only horizontal surface involved in the flow is that of the feet, it becomes upward-oriented when the lower part of the body trunk is reached by the flow.

The interpretation of the variation of drag and lift coefficients has been clarified highlighting in the diagrams (Fig. 4) how the reference area for the force coefficients was initially defined. The increase of drag coefficients with submergence is a consequence of the selection of the whole frontal area of the body as reference area. Fig. 4 has been modified adding the geometric scheme of the human body and the definition of the reference area for the force coefficients. This should resolve the ambiguity of the variation of the forces and force coefficients with the submergence and help in the overall understanding of the manuscript and numerical results.

The physical interpretation of lift force in Fig.5 is the compensation of the effects of submergence and Froude number. The decrease of submergence (linear increase of C_l) is counterbalanced by the increase of the square of velocity. This comment has been added to section 4.1.

(5)Errata: Page 13, line 9, there are two consecutive "this".

(5R) corrected.

Anonymous Referee #3

General Comment:

People safety can be compromised when they are exposed to floodwaters that exceed their ability to remain standing, thus leading to a great loss of casualties. Therefore, it is important to study the pedestrian's instability in floodwaters. In order to overcome the scatter of existing experimental data, the authors introduced a dimensionless mobility parameter θP which accounts for both flood and human characteristics. In addiction, a simplified 3D numerical model describing a detailed human geometry partly immersed in water was built to reproduce a selection of the existing experimental

data, which is the first example of numerical investigation on the instability conditions of people in floodwater. In general, the topic of this article is appropriate for this journal, and it should be of interest to researchers in the contexts of flood risk analysis and management. However, there exist some obvious errors in the derivation of the dimensionless coefficients θP, and the current version can not be accepted, but encourage the authors to resubmit the revised version with major revision.

Specific Comments:

*(1)The lift force (**Li**) should not be included in the force analysis. Lift force is generated by pressure difference which results from the flow velocity difference of a completely submerged object. That is to say, the flow velocity at the upper surface of the submerged object is greater than that at the lower surface, so the top pressure is lower than the bottom one (Chien and Wan, 1999). A human body is not completely submerged in floodwaters, and additionally there is little flow water between the bottom surface and the human feet. Therefore it is not necessary to account for the lift force. Chien N and Wan ZH (1999). Mechanics of sediment transport. ASCE Press, Reston VA.*

(1R) "For a stationary body in a moving flow Lift force is the force component acting normal to the mean direction of the undisturbed flow "(Vickery, 1966. Fluctuating lift and drag on a long cylinder of square cross-section in a smooth and in a turbulent stream. Journal of Fluid Mechanics, 25, 03, pp 481- 494). Following this definition, the authors think that the hydrodynamic force component, which is directed vertically in our case, cannot be neglected in a full 3D flow around a human body. Lift force exists also for partly submerged objects as argued by Malavasi and Guadagnini (2003, Hydrodynamic Loading on River Bridges. Journal of Hydraulic Engineering, Vol. 129, No. 11.) who measured drag and lift forces acting on a partly submerged bridge deck through experimental tests. Arslan at al. (2013, Turbulent Flow Around a Semi-Submerged Rectangular Cylinder Journal of Offshore Mechanics and Arctic Engineering, Vol. 135) showed the effect on drag and lift forces of different submergence levels (accounting for partly submerged conditions) on a rectangular cylinder. Arslan et al (2013) used a CFD model to estimate drag and lift forces, which reproduced accurately the experimental data used for validation, where the forces were measured through a dynamometer. Moreover, also Milanesi et al. (2015, A conceptual model of people's vulnerability to floods. Water Resources Research, 51, doi:10.1002/2014WR016172.) in his conceptual model on people's vulnerability to floods accounted for lift force. The definition of lift force as in Vickery (1966) has been added to section 2.1.

(2) The average density of the human body ($\rho p=1062$ kg/m3) is generally assumed equal to the density of muddy water, thus ρp is substituted with ρ in Eq. (2).] Such an assumption is problematic in this derivation.
The expression of $\rho p = \rho$ indicates a human body in floodwater can float, instead of sliding or toppling instability. Therefore it is not appropriate to substitute ρp with ρ in Eqs. (6) and (13).

(2R) $\rho_p=\rho$ is a simplifying assumption which is conservative and thus in favour of stability. If we consider $\rho_p=1062$ kg/m^3 and we do not make any assumption of human body density, we obtain the following mobility parameter which has been added (Eq. 12) to the manuscript

$$\theta_P = \frac{2d}{H_P} \cdot \frac{\frac{\rho_p}{\rho} \cdot H_p - H}{H}$$

It differs from Eq.11 for a constant, which is the ratio between the human body density and water density $\frac{\rho_p}{\rho} = 1.062$. From the point of view of the dimensional analysis nothing changes, but the height of the subject appears increased of about the 6%. If the new mobility parameter is calculated for the experimental data the regression curve of Fig. 1 will be shifted, thus it will have a different representative equation. Moreover, for the range of submergence levels and flow velocities tested in the experiments and reproduced numerically in the manuscript, hydrodynamic forces (especially drag force) are more significant the static forces, thus toppling or sliding prevail over floating. A sensitivity analysis of θ_P to ρ_P has been also carried out and added to the text and demonstrated that small variations of ρ_P are negligible because the sensitivity function $\frac{\partial \theta_P}{\partial X_j}$ when $X_j = \rho_P$ has an order of magnitude of 10^{-3} (section 2.2, table 1).

*(3) The Drag and lift forces are related to the wetted area rather than the total area of the human body. Therefore in the Eqs. (4) and (5), the wetted area projected to the incoming flow should be equal to **H· l** rather than (**Hp· l**). Although the wetted water depth does not coincide with the undisturbed water depth **H**, this slight difference can be neglected. So all the following derivation processes are incorrect. Please see the correct derivation presented … [Equations not reported here].*

(3R)The authors do not agree with the referee on this point. The selection of the reference area for the hydrodynamic forces is a matter of choice among different possibilities. The use of the wetted area is one possibility; the total area is another valid possibility that has been judged as more convenient in the present study. Drag and lift coefficients in the form of Eqs. 19, 20 are derived from dimensional analysis and the reference area is a scale factor with dimensions of (length)[2]. Thus, wetted area and full frontal area are both commonly used in engineering practice, see for instance Fox and McDonald, 1978 (Introduction to Fluid Mechanics, 2nd ed. John Wiley & Sons, N.Y. 684 pp.), Hoerner, 1965 (Fluid dynamic drag, Hoerner Fluid Dynamics ISBN-10: 9993623938), Bertin and Smith, 1979 (Aerodynamics for Engineers, Prentice-Hall, New Jersey, 410pp). Moreover, the difference between actual water depth and undisturbed water depth is not negligible for supercritical flows as clearly visible in Fig. 3 where actual water depth is almost twice the undisturbed one. Obviously, the choice of the reference area significantly affects the magnitude of the force coefficients but not the forces and the essential is the consistency of the definitions between output of the numerical model and the mobility parameter. In order to clarify this point an explanation has been added to sections 2.2 and 3.2 and Fig. 4 has been modified to show the reference area used for the force coefficients evaluation.

4) The dimensionless mobility parameter θ_P indicates that the stability degree of a human body in floodwater is only related to the body height and the flow condition. However, all the previous studies show that the stability degree of a human body is related to both body height and body mass (Abt et al., 1989; Jonkman et al., 2008; Xia et al., 2014; and so on). The difference is attributed by the neglect of the difference between ρp and ρ.

(4R)The dimensionless mobility parameter θ_p actually indicates that the stability of a human body in floodwaters is related to relative submergence and Froude number. The mass does not appear in the parameter definition because with the dimensional analysis the mass becomes a density ρ_p. All human subjects tested in the experiments had different mass/weight but had the same density and the dimensional analysis allows identifying dimensionless combinations of the variables of the system for a given set of independent fundamental units. Also if we do not assume $\rho_p=\rho$ (answer to point 2) we obtain a constant factor 1.062, which virtually increases the height. The height can be also seen as a sort of 'proxy' of the weight for a mesomorphic individual since the mass is the product of body density and body volume (and the body volume depends on the height of the subject). According to the sensitivity analysis to ρ_p the relevance of the body density would be more significant for very small water depths, which require very high velocity to compromise pedestrians' stability. In these conditions sliding instability would prevail, with important role of weight and friction coefficient. However, the influence of body type and build on the occurrence of instability could be a topic on its own for a future research. These comments have been added to section 2.2 to clarify this point.

Hydrodynamics of pedestrians' instability in floodwaters

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Abstract. People safety is the first objective to be fulfilled by flood risk mitigation measures and according to existing reports
10   on the causes of casualties, most of the fatalities is due to inappropriate behaviors like walking or driving in floodwaters. Currently available experimental data on people instability in floodwaters suffer of a large scatter primarily depending on the large variability of physical characteristics of the subjects. This paper introduces a dimensionless mobility parameter θ_P for people partly immersed in flood flows, which accounts for both flood and subject characteristics. The parameter θ_P is capable of identifying a unique threshold of instability depending on Froude number thus overcoming the scatter of existing
15   experimental data. Moreover, a 3D numerical model describing a detailed geometry of a human body and reproducing a selection of critical pairs of water depth and velocity is presented. The numerical results in terms of hydrodynamic forces and force coefficients are analyzed and discussed. Both the mobility parameter θ_P and the numerical results hint the crucial role of Froude number and relative submergence as the most relevant dimensionless numbers to interpret the loss of stability. Finally, the mobility parameter θ_P is compared with an analogous dimensionless parameter for vehicles instability in floodwaters,
20   providing a new contribution to support flood risk management and people education.

Keywords: flood risk, dimensional analysis, Froude number, human-water interaction

1 Introduction

Floods are among the main natural disasters in terms of deadliest events and economic damages (Munich Re, 2015b). The
25   2011 flood in Thailand caused 40 billion dollars of overall damages (Munich RE, 2012), the 2014 flood affecting India and Pakistan caused 665 fatalities (EM-DAT, 2012; Munich Re, 2015a). Although the number of fatalities caused by floods is lower than other hazards (i.e. earthquakes), flood events are those affecting the largest number of people (EM-DAT, 2012). Among the possible human interactions with the hydrological cycle, the loss of life in case of inundation represents a crucial phenomenon where flood and subjects characteristics dynamically interact. The loss of stability of a human body in floods,
30   can be seen as the most direct, tangible and fastest interaction between water and a human system. This topic has been less

studied in recent years with respect to other branches of socio-hydrology, which well conceptualized long-term human-water interactions (Di Baldassarre et al., 2013a; Di Baldassarre et al., 2013b; Di Baldassarre et al., 2015).

Research on loss of life in floods is sparse, and has been so far focusing on dam break catastrophes (Aboelata and Bowles, 2008; Chakraborty et al. 2005), physical experiments (Abt et al. 1989; Karvonen et al. 2000; Jonkman and Penning-Rowsell, 2008; Xia et al. 2014) and conceptual models (Love, 1987; Lind et al., 2004; Milanesi et al., 2015). Most of loss of life models are based on the location of the population at risk measured by its distance from the dam and account for the depth of flooding, population distribution, and effectiveness of warning and evacuation processes (Jonkman et al., 2002; Aboelata and Bowles 2008; US Department of Homeland Security, 2011; Penning-Rowsell et al., 2005). Other models relate the mortality to past flood events (Brown and Graham,1988), which may not be representative anymore of current situation (Jonkman et al. 2002). In the last decade, two approaches to flood fatalities assessment, namely individual and societal risk, have been identified (Tapsell et al., 2002; Beckers et al., 2012; de Bruijn et al. 2014).

The characteristics of the flood and floodwater along with the characteristics and behaviour of the population determine the likelihood of a death due to flooding (Di Mauro et al. 2012). It is widely recognized that, in developed countries, the majority of flood-related fatalities occur as a result of inexperienced people entering floodwater either in boats, vehicles or on foot (Franklin et al. 2014). Many studies (Jonkman and Kelman, 2005; Maples and Tiefenbacher, 2009; Fitzgerald et al. 2010; Kellar, 2010) have shown that the first cause of death during a flood event is related to roads and vehicles (Arrighi et al., 2015). Jonkman and Kelman (2005) reported that in the Netherlands the 33% of deaths for drowning occurs in a vehicle and the 25% as a pedestrian. Many casualties in fact, occur when people try to move in floodwaters (Di Mauro et al. 2012; Chanson et al. 2014), in this case previous experiences may play a role (Siegrist and Gutscher, 2008). Thus, understanding the instability mechanisms and identifying the safest behaviour when a pedestrian or vehicle is unexpectedly facing a flood, might be of crucial importance for management strategies (Franklin et al. 2014; Di Mauro et al. 2012) and emergency planning (Simonovic and Ahmad, 2005).

Two hydrodynamic mechanisms that can cause human instability have been distinguished in existing studies: moment instability (toppling) and friction instability (sliding). Toppling occurs when the mobilising moment caused by the incident flow exceeds the resisting moment caused by the resultant weight of the body (Abt et al., 1989; Jonkman and Penning-Rowsell, 2008). Sliding occurs if the drag force induced by the flow is larger than the frictional resistance between the person's feet and the substrate surface (Keller and Mitsch, 1993).

Foster and Cox (1973) tested the instability perception of children with different physical characteristics (i.e. height and mass combinations) in a laboratory flume and found that also physical, emotional and dynamic factors deeply affect human stability under water flow. They observed that sliding instability prevailed, since the tests were performed with high flow velocities and low water depths. Further tests by Abt et al. (1989) showed that toppling instability is crucial for higher water depths. More recently, several laboratory tests were performed on real adults and children (Takahashi et al., 1992; Keller and Mitsch, 1993; Karvonen et al. 2000; Yee, 2003) considering different training, wearing, environmental conditions and definitions of instability. These studies provide an extensive dataset, which has been used to define inversely proportional

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linear relationships between mean flow velocity and depth (Cox et al., 2010; Smith, 2015), which are often adopted as a reference for flood hazard zoning. These empirical approximating functions are however purely regressive and do not allow linking hazard levels and physical effects. Jonkman and Penning-Rowsell (2008) extended the existing experimental data by testing an adult stuntman in real channel conditions of low depth and significant velocity. Moreover, they calibrated a

5   simplified model for adults which accounts for both slipping and toppling using the data by Abt et al. (1989) and Karvonen et al. (2000). The buoyancy force is however neglected.

Recently, Xia et al. (2014) carried out experiments on a rigid human body model with geometric scale 1:5.54. They developed a parametric scheme, introducing buoyancy force and considering both toppling and slipping failure mechanisms. They derived two formulae for the critical velocity for slipping and toppling instability mechanism.

10   Conceptual models were introduced to describe the human stability as a function of flow velocity and water depth in order to provide an interpretative framework for the experimental activities. These models are based on different assumptions regarding the shape of the body, the involved forces and the failure mechanisms. Love (1987) modelled the human body as a rectangular monolith and recognized the role of the buoyancy force on toppling instability. Lind et al. (2004) tested both conceptual and empirical formulae and calibrated a relation based on the concept of the depth-speed product number (i.e. water depth

15   multiplied by flow velocity). They modelled the human body as a rigid circular cylinder and proposed an equation for toppling instability, which yields the critical depth speed product number as a function of drag coefficient and submergence. Walder et al. (2006), studying a tsunami induced by a debris flow, developed a simplified approach to predict critical velocity for slipping to occur, disregarding toppling instability and the role of the buoyancy force and assuming a fixed drag coefficient. They also supposed that, in waters of some sufficient depth, people could not stand even if the flow velocity is negligible. Milanesi et

20   al., (2015) recently introduced a conceptual model for people instability in a fluid flow also considering the effects of the local bottom slope and the density of the fluid.

Over the last four decades, a number of laboratory-based experimental studies have been undertaken to define the limits of stability under different flow regimes. Moreover, different conceptual models have been developed to derive formulae for these stability limits, usually assuming fixed values for the drag coefficient. The very wide scatter of critical pairs of water

25   depth and velocity is the main evidence of the existing experiments on people instability. A large scatter exists within the same dataset and to a more significant degree, when all datasets are combined (Cox et al., 2010, Russo et al., 2013). In fact, instability conditions are strongly affected by diverse 'non-hydraulic' parameters (Martinez-Gomariz et al., 2016), including the physical characteristics of the subjects (i.e. weight and height), their level of training, clothing and experimental conditions. Thus, a synthetic identification of hazard regimes in dimensional terms is quite difficult.

30   The aim of this work is to overcome the scatter of existing experiments on people instability under water flow introducing a dimensionless criterion capable of accounting for both flood and human characteristics and to understand its dependency on flow regime (Sect. 2). The dimensional analysis is undertaken to clarify if a limited number of parameters (i.e. related to hydraulics and body shape) is capable of explaining most of the variability observed in the experiments or if non-hydraulic parameters are still relevant. The dimensionless criterion also allows comparing the instability conditions of people with the

incipient motion conditions of vehicles (Arrighi et al., 2015), thus providing a framework for societal risk assessment, risk management and education. Particularly for educational purposes, the use of dimensionless quantities may favour the definition of safety rules, e.g. recognizing a level of submergence (water depth reaching knees, ankles or waist) is easier than referring to absolute water depths. Since examples of numerical model can be hardly found in literature, in order to better understand

5   the hydrodynamic interaction between human body and mean flood flow, a simplified 3D numerical model, describing a detailed human geometry partly immersed in water, is introduced (Sect. 3) and used to reproduce a selection of the existing experimental data available in literature.

2 Instability conditions of a human body under water flow

2.1 Geometric representation of the human body and acting forces

10   The shape of the human body is extremely complex, thus leading to different conceptualization schemes of its geometry, such as prisms or cylinders (Abt et al., 1989; Lind et al., 2004; Milanesi et al., 2015). Moreover, relative motion, posture, clothing and physical parameters (i.e. body type, size and build) influence the hydrodynamic interaction between human body and water flow. The two mechanisms by which the stability of people is lost in floodwaters are sliding and toppling (Abt et al., 1989; Lind et al., 2004; Jonkman and Penning-Rowsell, 2008). Incipient sliding on a horizontal bed occurs when drag force

15   on the human body just exceeds the friction force of the feet on the bottom, while motion due to toppling occurs when the moment exerted by drag force just exceeds the weight-induced moment. For a stationary body in a moving flow lift force and drag force are the force components acting normal and parallel to the mean direction of the undisturbed flow respectively (Vickery, 1966).

In order to minimize the number of parameters, the shape of the human body is mechanically schematized as in Lind et al.

20   (2004), with reference to an approximating prism of height H_p, width l and length d (Figure 1, panel a). In the inset of Fig. 1 (panel a), W is the weight, B is the buoyancy, Li is the lift force and D is the drag force. H is the water depth and it is assumed that the resultant drag force acts on one-half the water depth $H/2$ (Lind et al., 2004). The lever arm of the stabilizing force, which is the weight minus buoyancy and lift effect, is d, which is assumed as commutable with the full length of the foot. For a uniform prism, the lever arm of the stabilizing moment should be equal to $d/2$, but here it is preferred to use the length of the

25   foot d in order to partly accounting for the natural adjustment of the posture of the subject observed in the experiments. In the panel (a) in Fig. 1, the rotation point O is placed on the toe for average flow velocity U coming from right to left. Otherwise, for a flow velocity oriented from left to right, the rotation point O would be placed on the heel.

2.2 Dimensionless mobility parameters

The definition of the dimensionless mobility parameter for people instability under water flow follows the procedure adopted

30   for the introduction of the mobility parameter for vehicles incipient motion as in Arrighi et al. (2015). It starts with defining the forces acting on the body and then proceeds with the separation of dynamic and static actions in order to identify relevant

dimensionless groups of variables. The two mechanisms by which the stability of people is lost in dynamic conditions in floodwaters (i.e. sliding and toppling) are separately analysed. For hydrostatic conditions (i.e. zero flow velocity), the hydrodynamic actions are null and the static equilibrium is obtained equalling weight and buoyancy force. Sliding equilibrium is considered first. Incipient sliding on a horizontal bed occurs when drag force D on the human body just exceeds the friction force of the feet on the bottom. Referring to Fig. 1 (panel a), the friction force is equal to the effective weight (weight W minus buoyancy B and lift force Li) multiplied by the static friction coefficient μ. The sliding instability condition is then

$$D > (W - B - Li) \cdot \mu \tag{1}$$

The weight W is the product of constant human body density ρ_p, acceleration of gravity g and body volume $H_P \cdot d \cdot l$. The width of the prism l (Fig. 1, panel b) assumed equal to the waist diameter, has been graphically found as a good proxy for the average width of the human body for a mesomorphic individual (Beashel and Taylor, 1997)

$$W = \rho_P \cdot g \cdot \left(H_P \cdot d \cdot l \right) \tag{2}$$

Buoyancy force B is the product of water density ρ, acceleration of gravity g and the immersed volume of the prism

$$B = \rho \cdot g \cdot \left(H \cdot d \cdot l \right) \tag{3}$$

Drag and lift forces are a function of the square of flow velocity U and are referred to the same total frontal area of the prism, normally projected to the flow $H_P \cdot l$. This reference area has been preferred to the wetted area, because the determination of the actual wet area requires the study of the water profile due to the flow-body interaction, i.e. the wetting water depth does not coincide with the undisturbed water depth H ==(see also section 3.2). In fact, as shown in Fig. 3 the difference between actual and undisturbed water depth is not negligible for supercritical flows.==

$$D = \frac{1}{2} \cdot \rho \cdot U^2 \cdot C_D \cdot H_P \cdot l \tag{4}$$

$$Li = \frac{1}{2} \cdot \rho \cdot U^2 \cdot C_l \cdot H_P \cdot l \tag{5}$$

where C_D and C_l are the drag and lift coefficient respectively. As shown by Arslan et al. (2013), Zhang et al. (2014) and by Arrighi et al. (2015) lift force can play a significant role also for partly submerged objects. The average density of the human body ($\rho_P = 1062$ kg/m^3) is generally assumed equal to the density of muddy water, thus ρ_p is substituted with ρ in Eq. (2). The assumption $\rho_p = \rho$ implies that a human body immersed in water can experience a condition of static equilibrium. Substituting the Eqs. (2), (3), (4), (5) in Eq. (1) and putting equal the left and right term to define the equilibrium condition the following equation is obtained

$$\frac{1}{2}\cdot\rho\cdot U^2\cdot C_D\cdot H_P\cdot l=\left(\rho\cdot g\cdot\left(H_P\cdot d\cdot l\right)-\rho\cdot g\cdot\left(H\cdot d\cdot l\right)-\frac{1}{2}\cdot\rho\cdot U^2\cdot C_l\cdot H_P\cdot l\right)\cdot\mu \qquad (6)$$

The variables l and ρ multiply all the terms of Eq. (6), thus they can be simplified. Separating the dynamic terms ($\propto U^2$) from the static terms Eq. (6) is simplified as

$$\frac{1}{2}\cdot U^2\cdot C_D\cdot H_P+\left(\frac{1}{2}\cdot U^2\cdot C_l\cdot H_P\right)\cdot\mu=\left[\left(g\cdot H_P\cdot d\right)-\left(g\cdot H\cdot d\right)\right]\cdot\mu \qquad (7)$$

5   Collecting U^2 in the left term and d in the right term, then dividing both terms for $1/2\cdot\mu\cdot H\cdot g$ the equilibrium condition yields

$$\frac{U^2}{gH}\cdot\left(C_l+\frac{C_D}{\mu}\right)=\frac{2d}{H_P}\cdot\frac{H_P-H}{H} \qquad (8)$$

Where

$$Fr^2=\frac{U^2}{gH} \qquad (9)$$

is the square of the Froude number of the undisturbed flow,

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$$C_s=\frac{C_D}{\mu}+C_l \qquad (10)$$

and C_s includes the coefficients for drag C_D, for lift C_l and for friction μ forces.

$$\theta_P=\frac{2d}{H_P}\cdot\frac{H_p-H}{H} \qquad (11)$$

is defined as the dimensionless mobility parameter for sliding instability of people standing in floodwaters. θ_P is composed by two factors: the shape factor $2d/H_P$ and the relative dry surface of the body $(H_P-H)/H$. θ_P depends on Froude number and on

15   the dimensionless force coefficients. If the assumption $\rho_p=\rho$ is removed, a factor ρ_p/ρ is introduced in Eq. (11), which turns into the more general form of Eq. (12)

$$\theta_P=\frac{2d}{H_P}\cdot\frac{\dfrac{\rho_p}{\rho}H_p-H}{H} \qquad (12)$$

It should be noticed that with the general form of Eq. (12) the height of the subject appears virtually increased of about the 6% which corresponds to an increased stability of the subject. Moreover, the water density ρ varies with temperature and

20   concentration of dissolved compounds and suspended load, thus Eq. (12) can be used to account for any fluid/body density. Toppling instability occurs when the moment induced by drag force around a pivot point (i.e. the heel or toe) just exceeds the moment of the resultant vertical force (body weight W minus buoyancy B and lift force Li) as shown in Fig. 1 (panel a)

$$(W - B - Li) \cdot d = D \cdot \frac{H}{2} \tag{13}$$

Substituting the forces W, B, Li and D (Eqs. 2, 3, 4, 5) in Eq. (13), the following threshold condition for incipient toppling is obtained

$$\left[(\rho \cdot g \cdot l \cdot H_P \cdot d) - (\rho \cdot g \cdot l \cdot H \cdot d) - \frac{1}{2} \rho \cdot U^2 C_l \cdot H_P \cdot l \right] \cdot d = \left(\frac{1}{2} \cdot \rho \cdot U^2 C_D \cdot H_P \cdot l \right) \cdot \frac{H}{2} \tag{14}$$

5 ρ and l can be dropped on both side of Eq. (14), which after some manipulations and simplifications yields:

$$\frac{U^2}{gH} \cdot \left(\frac{H}{2d} \cdot C_D + C_l \right) = \frac{2d}{H_P} \cdot \frac{H_P - H}{H} \tag{15}$$

This represents a relationship between the square of Froude number $\dfrac{U^2}{gH}$ together with the dimensionless parameter C_t

$$C_t = \left(\frac{H}{2d} \cdot C_D + C_l \right) \tag{16}$$

on the left hand side, and on the right hand side a mobility parameter for toppling instability conditions for a person in

10 floodwaters θ_{Pt}

$$\theta_{Pt} = \frac{2d}{H_P} \cdot \frac{H_P - H}{H} \tag{17}$$

The mobility parameter θ_{Pt} obtained for toppling is equal to the mobility parameter θ_P introduced for sliding (Eq. 11). However, different is the combination of coefficients C_s (Eq. 10) and C_t (Eq. 16) that define the instability limit. In fact, for toppling instability conditions, C_D is multiplied by $H/2d$ in Eq. (16), which can be interpreted as a measure of the relevance of the

15 moment induced by the drag force for larger water depths H. Therefore, although there are two different incipient motion mechanisms, a unique parameter θ_P accounting for a limited number of human body parameters (H_P and d) and flow characteristics is able to represent both mechanisms. It should be noticed that the mobility parameter for people θ_P could be also obtained from the mobility parameter for vehicles θ_V, defined by Arrighi et al., (2015) considering a human body as a 'special' vehicle model with elevation of the planform h_c equal to zero, length equal to d and density ρ_c equal to water density

20 ρ.

For the general equation of the mobility parameter θ_P (Eq. 12), the sensitivity has been evaluated with respect to length of the foot d, height of the subject H_p and human body density ρ_P. The sensitivity is assessed with a local method, i.e. calculating the partial derivative of θ_P with respect to the selected factors X_j. The analytical formulas allows calculating the sensitivity for each value of the water depth H thus identifying possible critical ranges. Table 1 shows the sensitivity functions with respect

25 to the selected parameters. The units of measurement of the sensitivity function are length^{-1} and length^3/mass for the geometric parameters and density parameter respectively. The sensitivities of θ_P to ρ_P and d decrease with increasing water depth H. The

7

sensitivity to ρ_P and d are of the order of magnitude of 10^{-3} and 10^{-1}-10^1 respectively, for the experimental range of water depths. This means that small variations of ρ_P are negligible for θ_P, thus the assumption $\rho_p=\rho$ is not affecting significantly the results. High sensitivity to d is found particularly for water depths lower than 0.5 m. Thus, d is a more sensitive parameter, although its variation is physically constrained because the foot to height ratio is in the range 0.149-0.169 according to allometry studies (Davis, 1990; Pawar and Dadhich, 2012; Fessler et al., 2004). The sensitivity to Hp is of the order of magnitude of 10^{-1} for height of the subjects between 1 and 2 m (i.e. children and adults).

Therefore, since the sensitivity of the parameter θ_P is the product of the sensitivity function and the variation of the parameter, θ_P is robust enough, although obviously its regression function depends on the experimental data used (see Fig.1).

The dimensionless mobility parameter θ_p indicates that the stability of a human body in floodwaters is related to relative submergence and Froude number. The mass does not appear in the parameter definition because with the dimensional analysis the mass becomes a density ρ_p. All human subjects tested in the experiments had different mass/weight but had the same density and the dimensional analysis allows identifying dimensionless combinations of the variables of the system for a given set of independent fundamental units. Also if we do not assume $\rho_p=\rho$ (Eq. 12) we obtain a constant factor 1.062, which virtually increases the height. The height in fact can be seen as a sort of 'proxy' of the weight for a mesomorphic individual since the mass is the product of body density and body volume (and the body volume depends on the height of the subject).

The mobility parameter θ_P is introduced for null bed slope and density of floodwater coinciding with the density of clear water to strictly follow the experimental set-up of the selected studies (Sect. 2.3), however, a further study could also modify Eq. (17) to account for any terrain slope and water density.

2.3 Dimensionless instability threshold from Foster and Cox (1973), Karvonen et al. (2000), Jonkman and Penning-Rowsell (2008) and Xia et al. (2014) flume experiments.

A selection of the existing flume experiments on people instability in flood flows has been made to test the applicability of the mobility parameter θ_P. This selection covers a wide range of Froude numbers and accounts for different subjects characteristics and for a human scale model. The available datasets (Foster and Cox 1973, Karvonen et al. 2000, Jonkman and Penning-Rowsell 2008 and Xia et al. 2014) provide the experimental pairs of water depth and velocity (H, U) in which the subjects lose their stability together with subjects' physical characteristics (i.e. weight and height). The length of the foot d is calculated as a fraction of the height, which is a standard assumption in human allometry (Davis, 1990; Pawar and Dadhich, 2012; Fessler et al., 2004). The dataset by Abt et al. (1989) and by Takahashi et al. (1992) have not been included because in the first case the experimental conditions are considered not fully representative of a 3D flow and limited in the investigated range of flow regimes, in the latter it was not possible to retrieve the heights of the tested subjects to calculate the mobility parameter.

A diagram showing the mobility parameter θ_P against Froude number for the selected experimental data is drawn in Fig. 1. The mobility parameter θ_P evaluated for experimental pairs (*H, U*) (Foster and Cox 1973, Karvonen et al. 2000, Jonkman and Penning-Rowsell 2008 and Xia et al. 2014) defines in the diagram in Fig. 1 a unique dimensionless critical threshold of instability θ_{Pcr} for people under water flow that can be approximated as

$$\theta_{Pcr} = 1.57 \cdot Fr + 0.057 \qquad (18)$$

The determination coefficient R^2 and root mean square error RMSE of the regression curve are 0.98 and 0.21 respectively. Since the regressed critical threshold curve is linear it may appear inconsistent with Eq. (8) or (15) where θ_P depends on the square of Froude number. The 3D numerical model described in Sect. 3 and the numerical results of the parameter study (Sect.

5   4) will help clarifying this apparent inconsistency demonstrating the dependency of C_s (Eq. 10) and C_t (Eq. 16) on the inverse of Froude number.

The critical mobility parameter θ_{Pcr} ranges from 0.3 for low Froude numbers (i.e. sub-critical conditions) up to 6 for super-critical flows and identifies a threshold, which separates stable conditions above the curve from unstable conditions below the curve, with no discontinuity between the two motion mechanisms. While the datasets by Karvonen et al. (2000) and by

10 Jonkman and Penning-Rowsell (2008), represented with circles and diamond symbols respectively, are well aligned, the datasets by Foster and Cox (1973) and by Xia et al., (2014) appear to be more scattered. The first two datasets refer to adult subjects with different age, weight and height, the third refers to children and the latter to the human scale model. Particularly, the selection of points calculated from the data by Xia et al. (2014) are above the threshold curve, i.e. they lie in the stable side of the diagram. This confirms that the experimental instability conditions obtained for a human scale model are more

15 conservative than critical condition for human subjects as argued by the authors (Xia et al., 2014). Some of the data by Foster and Cox (1973) instead are under the curve, thus in the unstable portion of the diagram. A lower estimation of the mobility parameter may be due to the values assigned to the foot length. In fact, the growth of the feet is not proportional to the growth in height for children in the development age and common foot to height ratios are valid for adults (Davis, 1990; Pawar and Dadhich, 2012; Fessler et al., 2004).

20 The mobility parameter θ_P demonstrates that a reduction in the scatter of the existing instability diagrams is possible if the analysis of the instability threshold is done in dimensionless terms and accounts for both flood and subject characteristics. Moreover, a dependence of θ_P on the dimensionless force and friction coefficients has been found (Eqs. 10, 17). The analysis of the force coefficients requires a separate and dedicated analysis through a numerical model, which might help clarifying the hydrodynamics of instability mechanisms (Sect. 3).

25 3 Numerical model

3.1 Model description

The main aim of the numerical simulations is to understand how different mean flow regimes, in which people instability is experimentally observed, affect the drag and lift forces and the motion mechanisms. Thus, the focus is to assess the physical dependencies among the involved parameters (i.e. force coefficients and Froude number) and relate them to the mean flow

30 properties. The study is focused on the estimation of integral quantities such as forces, rather than on the detailed description of the flow properties in terms of local distributions. Thus, the numerical simulations were performed using the 'laminar'

turbulence settings of the numerical code, avoiding the calibration of the turbulence model coefficients, which however could not have been possible with the existing data. Laminar settings of the code do not force a laminar flow simulation, which would not be physically consistent, but they simply refer to the absence of turbulence modelling. A turbulence model was not selected for two main reasons: first, a turbulence model needs the calibration and/or validation of some coefficients and existing experiments were not available for this purpose; second, a rigid body approximates the experimental conditions for subjects allowed to move freely. This obviously bears an error in the estimation of the forces on the subject, thus this simplifying assumption was considered adequate for the intrinsic uncertainties of the simulated problems. As in Arrighi et al. (2015) preliminary tests have shown the substantial independence of the results on the particular choice of the closure model for the selected mesh size. Moreover, the model adequately reproduced the flow around a circular cylinder used as a benchmark test, with a correct estimation of pressures and drag coefficients for the selected range of Reynolds number.

For the numerical simulations, the CFD toolbox OpenFOAM® (www.openfoam.com) is used since it is proven suitable for numerical modelling of wide number of applications in coastal and hydraulics engineering (Leclercq and Doolan, 2009; Seo et al., 2010; Arrighi et al., 2015). The code includes several tools and utilities for wave/current generation/absorption, mesh manipulation and turbulence modelling. The solver waveFoam included within the library waves2Foam (Jacobsen et al., 2012) is selected because it handles two incompressible, isothermal, immiscible fluids with capturing of the fluid-fluid interface through the volume of fluid (VOF) method. It solves the Reynolds Averaged Navier Stokes (RANS) equations implemented in OpenFOAM and applies the relaxation zone technique for current generation together with absorption of its reflection. This 'active sponge' layer is a practical boundary condition, which allows reducing the number of cells of the computational domain. Mayer et al. (1998) and Jacobsen et al. (2012) provide a detailed description of the structure of the relaxation function and of the use of relaxation zones as boundary conditions.

3.2 Numerical model set-up

Among the subjects used in the flume experiments, three subjects (i.e. subjects 2,4 and 5) tested by Karvonen et al. (2000), the subject tested by Jonkman and Penning-Rowsell (2008) and a selection of pairs (H, U) of the scale human model used by Xia et al., (2014) were chosen. This selection has been made in order to cover a wide range of flow regimes (both sub-critical and super-critical) and different subject physical characteristics. To generate the mesh around the human body, a free triangulated geometry of a man (STereo Lithography interface format *.stl), downloaded from www.thingiverse.com was used. The heights of the different subjects were adjusted using the 3D scaling functions available in the code for the triangulated geometries. The mesh domain has a cylindrical shape so that the relaxation zone (with a similar shape and 1.5 m thick) can fully control the generation/absorption of the flood conditions (i.e. water depth and velocity) avoiding possible boundary effects. A mesh sensitivity analysis has been performed with the laminar turbulence model for the numerical simulation of subject 2 (Karvonen et al., 2000) (water depth 0.6 m and velocity 2.0 m/s). Three different mesh sizes around the human surface have been tested: 0.015 m, 0.01 m, 0.005 m. The differences in the estimated drag and lift average coefficients were of the order of a few percent and smaller than the standard deviation of the instantaneous values computed during the simulation. Thus, the 0.015 m mesh

has been preferred for its shorter computational time. The total number of cells is around $4.5 \cdot 10^5$. The snappyHexMesh tool allows refining the mesh close to the human body (cell size is set to 0.015 m), while in the whole mesh domain the maximum size is 0.25 m. The refinement close to the human body can be observed in Fig. 2, where the 3-dimensional view of the mesh in a longitudinal cross section is shown for the whole body (panel a), the legs (panel b) and the feet (panel c). The 3D geometry

5   describes a naked body since clothes are difficult to be represented as soft and flexible, thus rigid clothes could affect the estimation of the forces. The time step is set to be automatically adjusted during the simulation according to the maximum Courant number set to 0.7. The order of magnitude was around 10^{-3}-10^{-4} s to ensure stability. With a time step equal to $2 \cdot 10^{-4}$ s and $4.5 \cdot 10^5$ cells one second of simulation takes 30 minutes without running in parallel (i.e. one core).

The average water elevation H and flow velocity U are initialized in the domain according to the experimental conditions and

10   these values are fixed at the inlet and outlet boundary to a constant value during all the simulation.

The wall function used is the standard nutWallFunction available in OpenFOAM®. The pressure and the velocity fields, needed for the drag and shear forces evaluation, are directly calculated through the continuity and momentum equations (RANS equations) implemented in the model for steady, incompressible and immiscible fluids (Morgan, 2013). The reference 'undisturbed' velocity (U) and an area of reference A_{ref} are set to calculate the instantaneous drag and lift coefficients

15   considering the force acting on the human body in the flow direction, D (Eq. 18), and in the vertical direction, Li (Eq. 18), respectively. Drag force is positive when oriented with the flow and lift force is positive when upward directed. The reference area A_{ref} is the total frontal area of the prism approximating the body normally projected to the flow, equal to $l \cdot H_P$

$$C_D = \frac{D}{0.5 \cdot \rho \cdot U^2 \cdot A_{ref}} \tag{19}$$

$$C_l = \frac{Li}{0.5 \cdot \rho \cdot U^2 \cdot A_{ref}} \tag{20}$$

20   The total frontal area is selected instead of the wet area because the actual wet area is not simply equal to $l \cdot H$. The determination of the actual wet area would require a dedicated analysis of the flow profile for different flow regimes. Moreover, the total frontal area A_{ref} allows better comparing the pushing efficiency for different submergence levels. However, the selection of the reference area for the hydrodynamic forces is arbitrary and the use of the wetted area is optional. Drag and lift coefficients in the form of Eqs. 19, 20 are derived from dimensional analysis and the reference area is a scale factor with dimensions of

25   (length)^2. Thus, wetted area and full frontal area are commonly used in engineering practice (Fox and McDonald, 1978; Hoerner, 1965; Bertin and Smith, 1979).

D and Li include both pressure and viscous forces acting in the flow and vertical direction respectively, although the contribution of the viscous forces is negligible with respect to pressure forces (they differ of six-seven orders of magnitude). To obtain the force coefficients the time average is calculated once the coefficients have reached the steady state, which is

30   confirmed by the absence of a linear trend.

3.3 Tests programme

Three experimental datasets on the instability of people are considered (Karvonen et al., 2000; Jonkman et al., 2008; Xia et al., 2014) because they cover a wide range of flow regimes (i.e. Froude numbers) and include different physical characteristics and a human body model. All simulations account for a frontal impact of the water flow on the human body. Only one flow orientation is considered because most of the experimental studies neglects the effect of the angle of flow incidence. The investigation of a walking condition is considered out of the scope of the manuscript since it would bear different boundary conditions, mesh and working assumptions. The experimental pairs (H, U) recognized as critical in the laboratory tests and used for the numerical simulations are summarized in Table 2 for the different datasets. The experimental data for the human model (Xia et al., 2014) have been scaled to actual size through Froude similarity using the scale ratio $\lambda=5.54$. The total number of numerical simulations is 33.

4 Results

4.1 Forces and force coefficients

The numerical results are analyzed in terms of flow characteristics and hydrodynamic forces. For super-critical flows, a significant splashing area is detected in correspondence of the impact zone (Fig. 3, panels a, c). Figure 3 depicts the simulated flow around the subject tested by Jonkman and Penning-Rowsell (2008) for the pair H=0.35 m, U=2.40 m/s. For this flow condition the free surface elevation decreases downstream after passing the ankles where the flow accelerates, then there is a sudden energy dissipation (behind the ankles, panel b) and the free surface is restored (panel c). The rough aspect of the free surface in Fig. 3 panel a, corresponds to areas with strong mixing between air and water, which has been experimentally observed by Jonkman and Penning-Rowsell (2008).

Panel c in Fig. 3 also shows the distribution of pressures on feet and legs of the subject. Red areas correspond to high pressures located on the inner side of the feet and above the ankles where the flow decelerates. In the external side of the feet depicted in light blue instead, the flow accelerates with a consequent decrease in pressure.

For sub-critical flow condition, the flow is disturbed upstream of the human body, where a slight deceleration occurs. Vortices occur immediately downstream of the obstacle.

Drag and lift forces are integrated over the human geometry during the simulations and the force coefficients are calculated using the frontal reference areas A_{ref} in Table 3, which are evaluated graphically.

Figure 4 shows the drag coefficient and lift coefficients versus Froude number on the right hand side of the figure in the top and bottom panels respectively. Drag coefficient ranges from 0.1 for high Froude numbers, up to approximately 1 for low Froude numbers.

Drag coefficients decrease exponentially with increasing Froude number, i.e. with decreasing submergence. The drag coefficients of all the human subjects (Karvonen et al., 2000; Jonkman and Penning-Rowsell, 2008) are very similar for the

same simulated flow regimes. Drag coefficients for the human scale model (Xia et al., 2014) in the range of Froude number 0.4-1.5 appear lower than the coefficients evaluated for human subjects. In fact, the human model is 'weaker' than the real human subjects in facing the water flow, as demonstrated by the comparison between dimensional thresholds of instability for the model and real humans (Xia et al., 2014). For Froude numbers above 1.5 the drag coefficient for the human model remains almost constant.

Lift coefficients (left and right bottom panels in Fig. 4) range from -0.49 up to 0.06. Except for subject 4, which is represented with a diamond symbol, the lift coefficients are negative. This means that the vertical force contributes to stability because is directed downward. The two positive values for subject 4 (Karvonen et al., 2000) are due to the relative submergence of the subject H/H_P, which is higher than 0.6 (see Fig. 4, bottom left panel). For this level of submergence the water reaches the lower part of the body trunk and thus can exert its action pushing it upward. The negative lift coefficients are the result of the downward directed force acting on the upper boundary of the feet, which is shown in terms of pressures in Fig. 3 (panel c). This occurs because the subject's feet are placed directly on the bottom as a consequence of the assumption of the rigid body. In actual conditions, when a human subject is allowed to move, the pressure distribution and vertical forces would change significantly because also the sole would experience the hydrodynamic forces.

The left hand side panels of Fig. 4 depict drag and lift coefficients versus the relative submergence H/H_P. Drag coefficient increases quadratically as the relative submergence increases since a larger portion of body surface is affected by the water flow, thus increasing the lever arm of the soliciting moment. Moreover, the lift coefficient linearly decreases with increasing relative submergence.

The only surface, which is affected by a vertical force is that of the feet, legs only contribute to horizontal (i.e. drag) forces, assuming the adherence between feet and bottom. Once a threshold level of relative submergence is reached (i.e. around 0.55), the water also surrounds the body trunk, which contributes to the pressure integration.

Figure 5 depicts the lift and drag forces versus Froude number for all the simulated subjects (top and bottom panels respectively). For human subjects, which have been tested in the range of Froude numbers 0.2-2, drag force increases for 0.2<Fr<1, reaching a peak for Fr~1, then it decreases. The values of drag force for human subjects range from 100 N up to 350 N. Subject 2 tested by Karvonen et al., (2000), which is the tallest and heaviest subject of the dataset, is able to face the highest forces with respect to the other subjects. Subject 4 and 5 are weaker according to the diagram, subject 4 is a woman and subject 5 is a 60 years old man. The estimated forces for the human model (Xia et al., 2014) have been scaled according to Froude similarity, using the scale ratio 5.54[3]. This allows comparing the dimensional forces of the human model with the forces acting on the human subjects. The behaviour of the human model, whose drag force values are represented in Fig. 5 (bottom panel) with right-oriented triangles, appear different from the human subjects. In fact, drag force values increase linearly with Froude number without reaching a peak for Froude around 1. The peak of drag force observed for human subjects is the result of a balance between drag-induced moment and immersed weight and ability of actively react to the action of the water flow. Moreover, for Fr=1, where the peak of drag force occurs, the lift force reaches its maximum absolute value (Fig. 5, top panel). Therefore, since the stabilizing effect of the vertical force increases the effective weight, the change of position

of real human subjects, with a consequent change of lever arm d (Eq. 13), increases the resisting moment. Thus, a larger drag force can be faced. This is not possible for the human model, since it behaves passively in the water flow without adjusting its posture.

For Froude number between 0.5 and 1 there is a minimum of the lift force (Fig. 5, top panel), which reaches about -90 N. For low Froude number and relative submergence equal to 0.62 (see Fig. 4, bottom left panel), subject 5 (Karvonen et al., 2000) experiences a positive vertical force since a portion of the lower body trunk is immersed in water. These values correspond in fact, to low values of drag force in Fig. 5 (bottom panel). With the rigid body assumption, for high Froude numbers the human model is protected by an increasing absolute value of the vertical force, which allows resisting to increasing drag forces. For both drag and lift forces there is a compensation of the opposite effects of submergence and Froude number (i.e. velocity), in fact when submergence increases, force coefficients and Froude number increase (in absolute value) and decrease respectively. Unfortunately, only recently human subjects have been tested for highly super-critical flows (Martinez-Gomariz et al., 2016) so a direct comparison between human subjects and human model was not possible for those regimes. While for sub-critical flow regimes, it is clear that the ability of human subject to actively resist to the flow adjusting its position is an advantage in terms of safety with respect to the human model. However, the passive behaviour of the human model can be seen as representative of the weakest class of people like elderly or sick as suggested by Xia et al. (2014).

4.2 Motion mechanisms

Since literature distinguishes two motion mechanisms, namely sliding and toppling (see Sect. 2), the identification of these mechanisms is further investigated in this section. The normalized moment is defined as the ratio of drag induced moment and resisting moment, where the effective weight of the subject is calculated subtracting (adding) the vertical force to the weight.

$$Norm\ moment = \frac{D \cdot H}{2(W - B - Li) \cdot d} \tag{21}$$

The normalized moment is represented against Froude number in Fig. 6. In the diagram, there are two regions identified by the calculated normalized moment. As Froude number increases, the submergence decreases in the diagram. In the left side of the diagram the normalized moment decreases with Froude number until approximately Fr=1.5. Then, for Froude number higher than 1.5 the normalized moment increases slowly. The region with Fr<1.5 is interpreted as the toppling instability area, while for Fr>=1.5 sliding instability occurs. The separation of the two regions, with low values of normalized moment around Fr=1.5 hints that a mix of the two instability mechanism might occur while approaching Fr=1.5 (Jonkman and Penning-Rowsell, 2008). In fact, for low Froude numbers (i.e. high relative submergence) a full toppling instability is expected; vice versa, for high Froude numbers a full sliding instability takes place.

The identification of the two motion mechanisms helps in defining the dimensionless groups C_t and C_s defined in Sect. 2.2 (Eqs. 10, 16), which are used for the comparison between experiments and numerical results.

4.3 Comparison with experimental data

The numerical results obtained from the simulations are compared to the experimental datasets (Karvonen et al., 2000; Jonkman and Penning-Rowsell, 2008; Xia et al., 2014) using the analytical relation between the mobility parameter θ_P, Froude number and the group accounting for the force coefficients (Sect. 2.2). The groups accounting for the combination of the force

5 coefficients is C_s or C_t for sliding or toppling instability respectively (Eqs. 10, 16). Since the two motion mechanisms have been identified in Fig. 6, C_s is calculated for Froude number equal or larger than 1.5 and C_t for Froude number lower than 1.5. Friction coefficient is assumed constant and equal to 0.3, which is in the range used in literature (Milanesi et al., 2015). The mobility parameter θ_P is calculated from the experimental water depth H and Froude number is calculated from the experimental pairs H, U. The length of the foot assumed for the different subjects is shown in Table 3.

10 Fig. 7 shows the scatter plot of experimental and numerical results. On the horizontal and vertical axis there are the mobility parameter θ_P and the product of the square of Fr and C_s or C_t according to the type of motion mechanism. The determination coefficient is 0.76 and the RMSE is 0.63. The comparison is overall satisfactory given the different data sources, however there are some points which are below the 1:1 curve. Thus, the datasets related to human subjects are separately analysed since they have shown a different behaviour in terms of hydrodynamic forces. Different symbols represents

15 human subjects (circles) and human scale model (triangles). As expected, the numerical results of the human model compare less well with the mobility parameter and are in general below the 1:1 curve. This is due to the lower estimated drag coefficient/force for human model. Moreover, since the mobility parameter accounts for the full length of the foot d, which is relevant to calculate the resisting moment, its definition may not be appropriate for a human model, which is not able to adjust its position in order to take advantage of the full length of the foot to react to the instability. If the dataset on the human model

20 is removed, the determination coefficient R^2 is 0.82 and the RMSE is 0.28, thus the comparison between numerical model and experiments improves.

A sensitivity analysis to d and friction coefficient μ has been carried out to understand how a change in these parameters affects the goodness of fit between numerical results and experiments. The parameters d and μ play a role in the calculation of C_t and C_s respectively (Eqs. 16 and 10). A variation of $\pm 10\%$ and $\pm 30\%$ has been applied to both d and μ one at time and the change

25 in the determination coefficient R^2 and RMSE of the fit has been calculated. The results are summarized in Table 4. The results of the sensitivity analysis are overall satisfactory since the determination coefficient R^2 does not decrease significantly when modifying the parameters d and μ both considering only experiments on human subjects both considering all the datasets. In fact, the determination coefficient R^2 does not decrease under 0.7. The RMSE tends to increase for larger variations of the parameters especially considering all datasets. A more accurate comparison between numerical results and experiments would

30 be possible if friction and length of the foot were measured during experiments, which is strongly encouraged in future research.

5 Discussion

Flood hazard and flood risk maps as required by the European Flood Directive 60/2007/EC (European Commission, 2007), should identify the areas which can be affected by floods for different probability scenarios and their potential adverse consequences on the environment, structures and people. Nevertheless, despite the increased capability of hydrologic-hydraulic modelling and damage assessment models, the direct consequences of flood parameters (e.g. water depth and velocity) on human health are often overlooked in hazard and risk maps. This is also due to sparse research on the subject and to the difficulties in identifying precise relationships between flood characteristics and people instability. Usually different hazard zones are classified according to the product number $H \cdot U$ (Cox et al. 2010). The curves so defined attempt to interpret the large scatter observed in dimensional pairs of water depth H and velocity U in which instability occurred in flume experiments. For this reason in the paper, a dimensionless instability criterion for people under water flow has been proposed. The mobility parameter θ_P is a function of the physical characteristics of the human subject (i.e. height and length of the foot). It also shows a strong dependence with Froude number and accounts for the two recognized instability mechanisms, which are sliding and toppling. The evaluation of the mobility parameter for a selection of experiments available in literature (Foster and Cox 1973, Karvonen et al. 2000, Jonkman and Penning-Rowsell, 2008 and Xia et al. 2014) identifies a unique threshold for people instability θ_{Pcr} capable of overcoming the scatter of dimensional critical combinations of water depth and velocity. Since θ_P is dimensionless, it allows comparing the instability conditions for vehicles (Arrighi et al., 2015) and people in the same dimensionless diagram (Fig. 8).

The critical dimensionless threshold curves drawn in Fig. 8 for vehicles (black continuous line) and people (black dashed line) intersect for Froude number approximately equal to 0.6. Thus, four different portions (i.e. hazard zones) can be observed in the diagram. Above both the curves both pedestrians and vehicles can be classified as stable for a given flow regime (i.e. Froude number). Below the curves instead, both people and vehicles are in unstable, and consequently dangerous, conditions. For Froude number between 0.1 and 0.6 moving in floodwaters by car is safer than moving on foot since the θ_{Pcr} threshold curve lies above the θ_{Vcr} curve. For Froude number above 0.6 the θ_{Vcr} curve lies above the θ_{Pcr} curve for people, thus, for these flow regimes moving on foot is better than use a car. In simple words, wading a creek is safer on foot, wading a shallow river is safer by car. In fact, the two curves θ_{Vcr} and θ_{Pcr} show the different dominant modality of instability for vehicles and pedestrians, which depend on the different geometric configuration and mass distribution. For low Froude number the dominant instability mechanism is toppling, to which pedestrians are more vulnerable than vehicles. For high Froude numbers sliding instability prevails, which, in the case of pedestrians is counterbalanced by a lower lift effect, in the case of vehicles instead contributes to a lower adherence. Since higher Froude numbers in the diagram correspond to lower water depths, this result may be not intuitive for a person facing a flood flow. In fact, hazard in low water depths is usually underestimated. In fact, for lower water depths, which can be felt as less threatening, a person can be induced to move by car, which is perceived as a safe shelter. That is why education can be of crucial role.

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A more popular version of this diagram may help supporting people education because it clarifies the instability mechanisms of vehicle and people, which are recognized as responsible of most of the casualties. Moreover, the critical thresholds here proposed can be easily coupled with existing flood maps adding further information on hazard levels to be adopted for mitigation strategies and emergency activities.

5   The 3D numerical model, although very simplified since the human body is modelled as rigid, is the first example of numerical investigation on the instability conditions of people in under water flow. It demonstrates the importance of people ability of counteracting the hydrodynamic forces, through the adjustment of the posture. In fact, the forces evaluated for the instability conditions of the human scale model (Xia et al., 2014) appear lower than those for human subjects. As suggested by Xia et al. (2014) these conservative conditions can be adopted to account for particularly weak categories of people like elderly or sick.

10   Moreover, the numerically evaluated forces show that subjects with larger weight and height are able to resist to higher solicitations confirming the observed experimental variability between the subjects (Cox et al., 2010, Russo et al., 2013). Further experiments on human subjects should investigate the instability conditions in super-critical flow regimes, which have been currently addressed only by Jonkman and Penning Rowsell (2008) and recently by Martinez-Gomariz et al. (2016). The evaluated force coefficients, which are a dimensionless measure of the forces, are strongly similar for the different human

15   subjects and can be adopted in conceptual models, which usually account for standard values for cylinders.

Further studies should better investigate the role of friction coefficient for the occurrence of instability (Martinez-Gomariz et al., 2016), which might be crucial especially for supercritical flow regimes. Moreover, the effect of different physical (i.e. body type, size and build) and psychological human characteristics on the hydrodynamic solicitations should be better understood as well as the role of relative motion, posture, and clothing. Then, more detailed laboratory experiments and numerical model,

20   with turbulence measured and accounted for, could investigate important environmental aspects, such as local turbulence effects (Chanson and Brown, 2015). A more reliable estimation of the hydrodynamic forces on the human body could be achieved removing the strong assumption of rigid body. This would suggest the use of a fully coupled CFD-CSD model capable of accounting for the different hydrodynamic response to changes in posture.

6 Conclusions

25   People safety is the primary objective for flood risk managers in the definition of non-structural risk mitigation measures. Numerous studies demonstrated that most of the casualties for drowning during a flood occurs because of unwise high-risk behaviors like driving and walking in floodwaters. Current hazard zoning rely on the product number H·U, which helps in explaining the large scatter of experimental pairs of water depth and velocity found in the last decades.

This paper provides a new approach for hazard assessment of people in floodwaters. The dimensionless mobility parameter

30   here introduced, calculated for some of the existing experimental datasets, is capable of identifying a unique critical threshold of instability θ_{Pcr} regardless of the type of motion mechanism (i.e. sliding and toppling), which is a function of relative submergence and Froude number. The scatter of dimensional experimental data is overcome because the mobility parameter

accounts for both flood and subject characteristics (height and length of the foot). Thanks to its dimensionless definition, the mobility parameter for people can be easily compared to the existing mobility parameter for vehicles (Arrighi et al. 2015). Thus, it can support the development of behavioral rules conceived for people education. Moreover, it can also be mapped over existing flood hazard maps showing water depth and velocity, for an average subject used as a reference or with a probabilistic distribution of human characteristics. <mark>The sensitivity analysis carried out with respect to geometric and density parameters of the human subjects hints that θ_P is robust since the length of the food d, which is the most sensitive parameter, may vary in a very small range according to allometry observations.</mark>

The 3D numerical model presented in this paper, although simplified, demonstrate through the evaluation of the hydrodynamic forces and force coefficients that relative submergence and Froude number are the most relevant dimensionless parameters for people instability. The human body is modelled as rigid and is described by a detailed 3D triangulated geometry. 33 steady flow numerical simulations have been carried out to reproduce three different experimental datasets (Karvonen et al. 2000, Jonkman and Penning-Rowsell, 2008 and Xia et al. 2014) and subject characteristics, covering a wide range of flow regimes (i.e. Froude between 0.2 and 3.5). The numerical results also clarified the different behaviour of human subjects and human scale model. A further study, both numerically and experimentally, should better investigates the role of other aspects, which affect people instability in flood waters, such as local turbulence effects, friction, relative motion, posture, clothing and water density.

Team list

The team is composed by the three submitting authors.

Author contribution

The research work was carried out by the first author during a PhD program under the joint supervision of the two co-authors.

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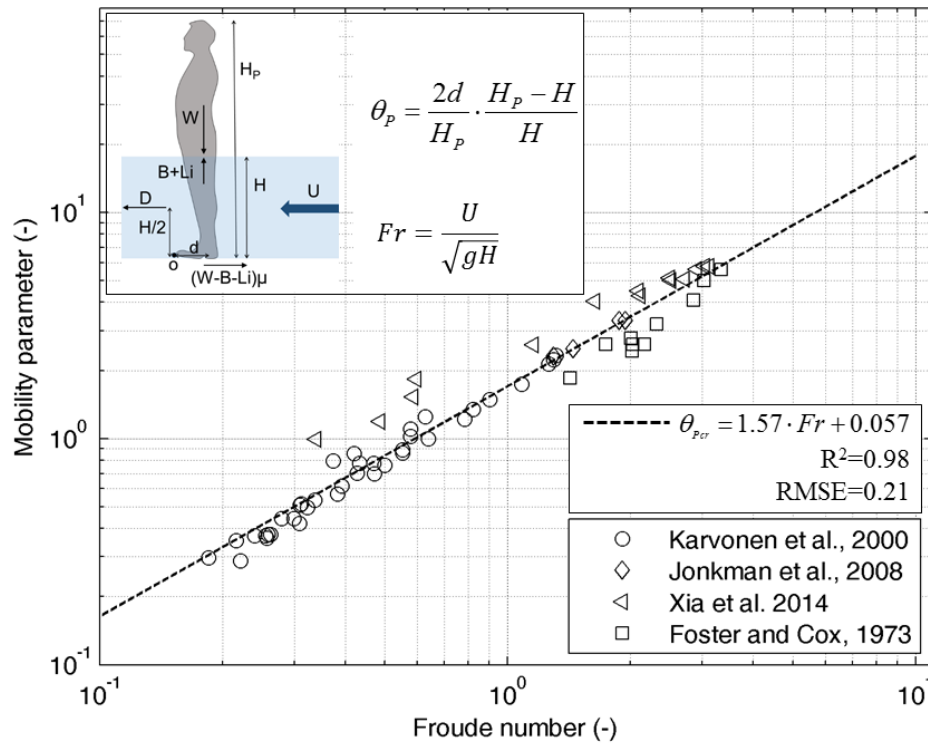
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Figure 1. Instability diagram "Dimensionless mobility parameter θ_P versus Froude number" for the selected studies (Foster and Cox 1973, Karvonen et al. 2000, Jonkman and Penning-Rowsell 2008 and Xia et al. 2014).
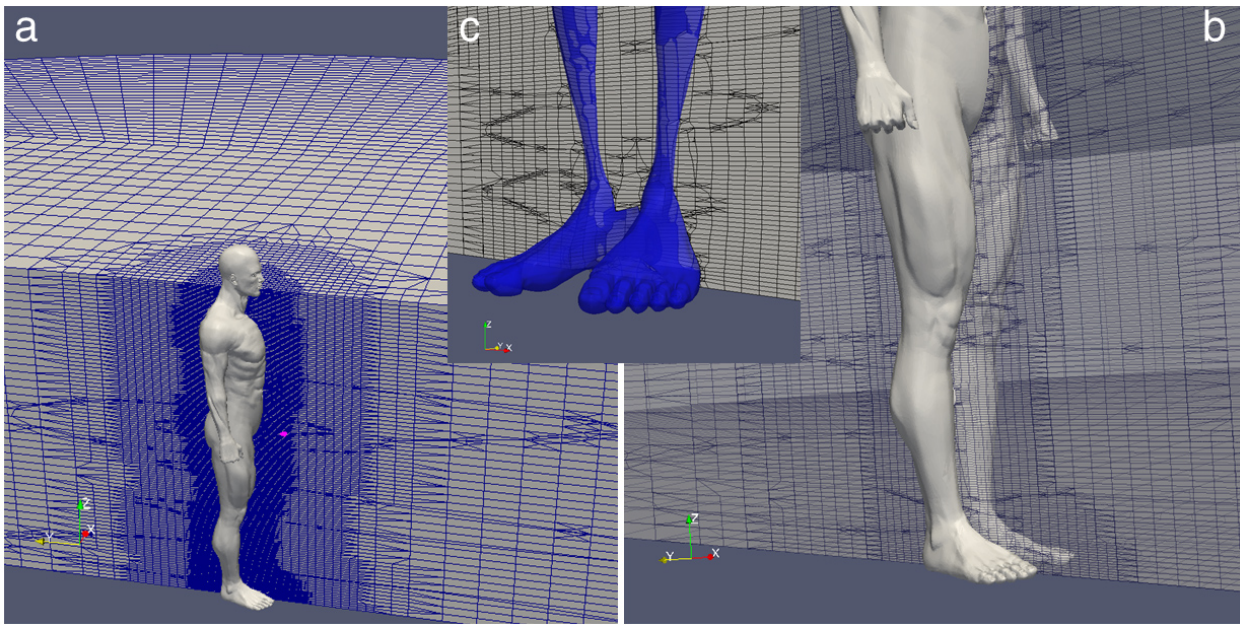
Figure 2. Computational mesh around the human body shown in a longitudinal cross section for the whole body (a), the legs (b) and a detail of the feet (c).
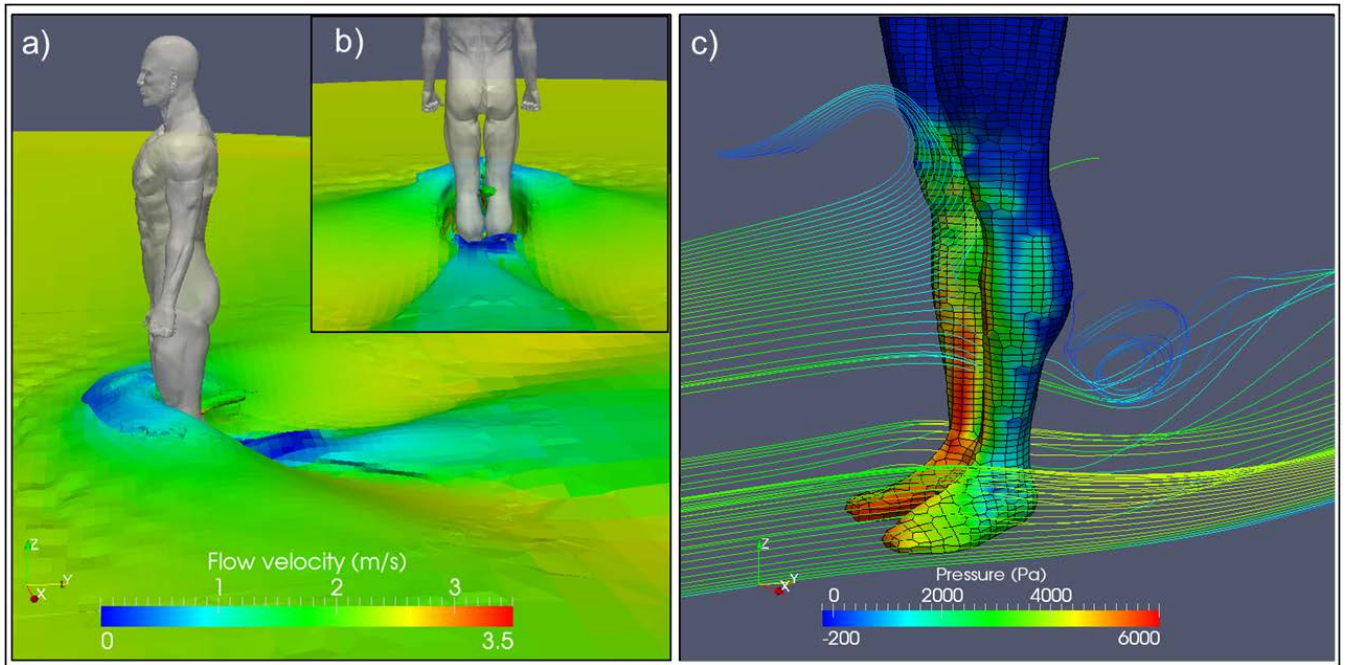
Figure 3. Splashing effect for super-critical flows shown as flow velocity (a), streamlines (c) and inset view parallel to flow direction upstream-oriented (b), for the subject tested by Jonkman and Penning-Rowsell (2008), H=0.35 m, U=2.40 m/s. Panel (c) also shows the pressure distribution on the feet and the legs of the subject.
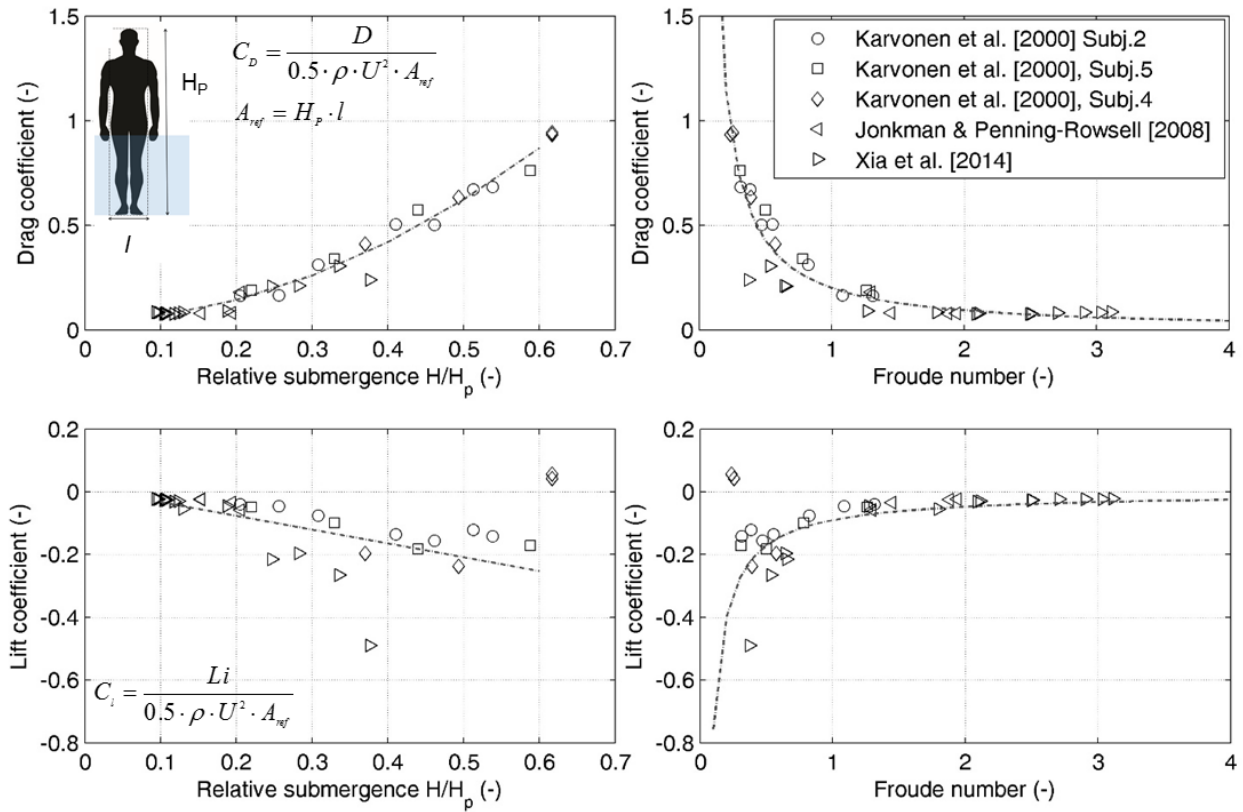
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Figure 4. Estimated drag and lift coefficients versus Froude number (top left and bottom left panels respectively) and versus the relative submergence (top right and bottom right panels respectively) for the four human subjects (Karvonen et al., 2000; Jonkman and Penning-Rowsell, 2008) and the human scale model (Xia et al., 2014). The inset in the first subplot shows the reference area used for the force coefficients calculation.
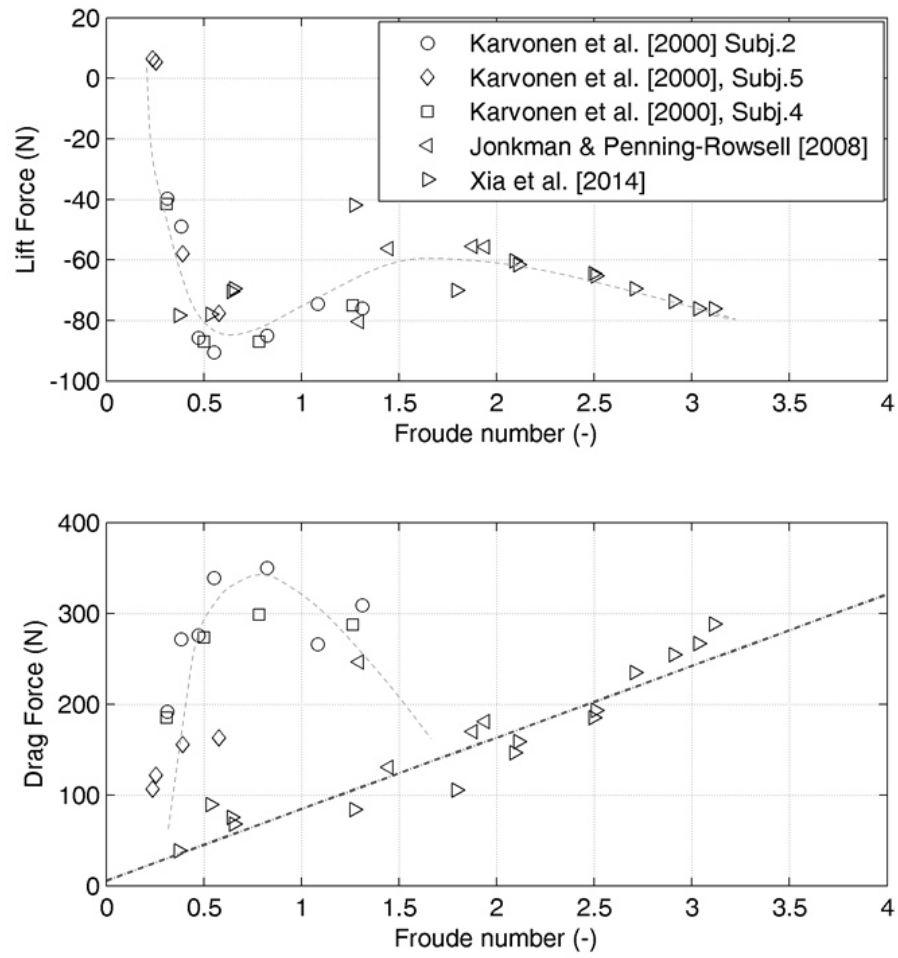
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Figure 5. Estimated lift (top panel) and drag (bottom panel) forces versus the relative submergence for the four human subjects (Karvonen et al., 2000; Jonkman and Penning-Rowsell, 2008) and the human scale model (Xia et al., 2014).
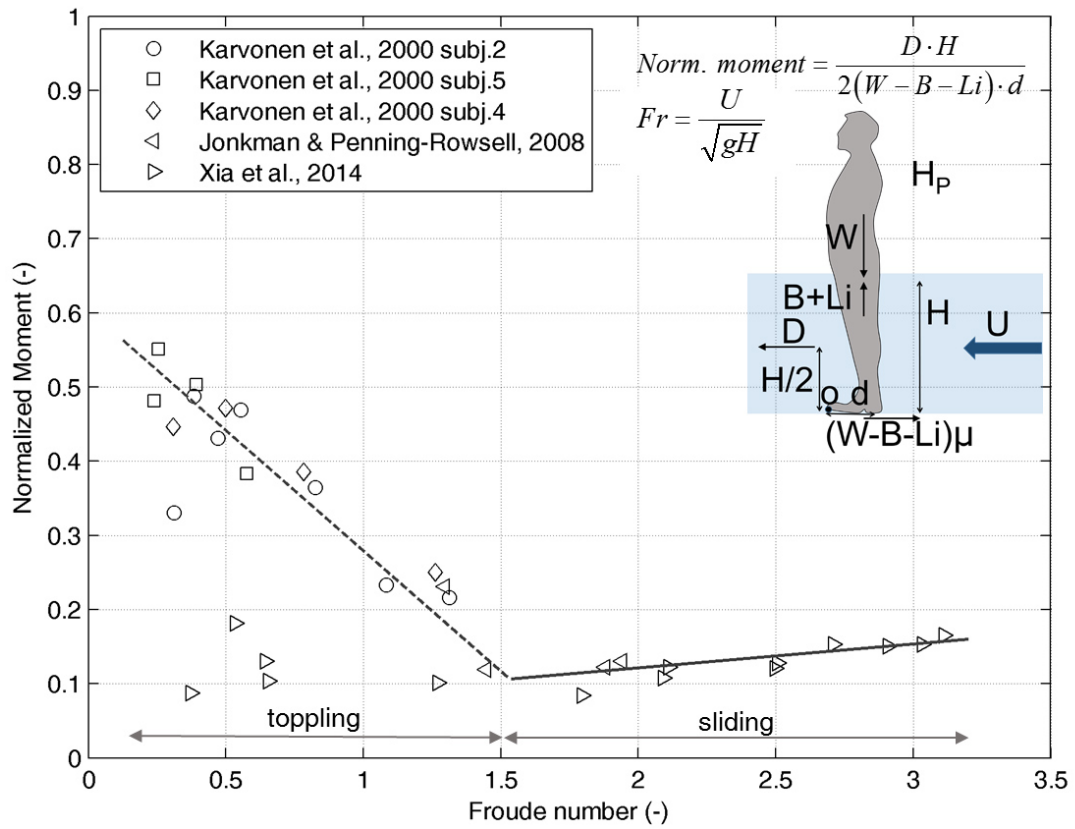
Figure 6. Normalized moment against Froude number for the four human subjects (Karvonen et al., 2000; Jonkman and Penning-Rowsell, 2008) and the human model (Xia et al., 2014).
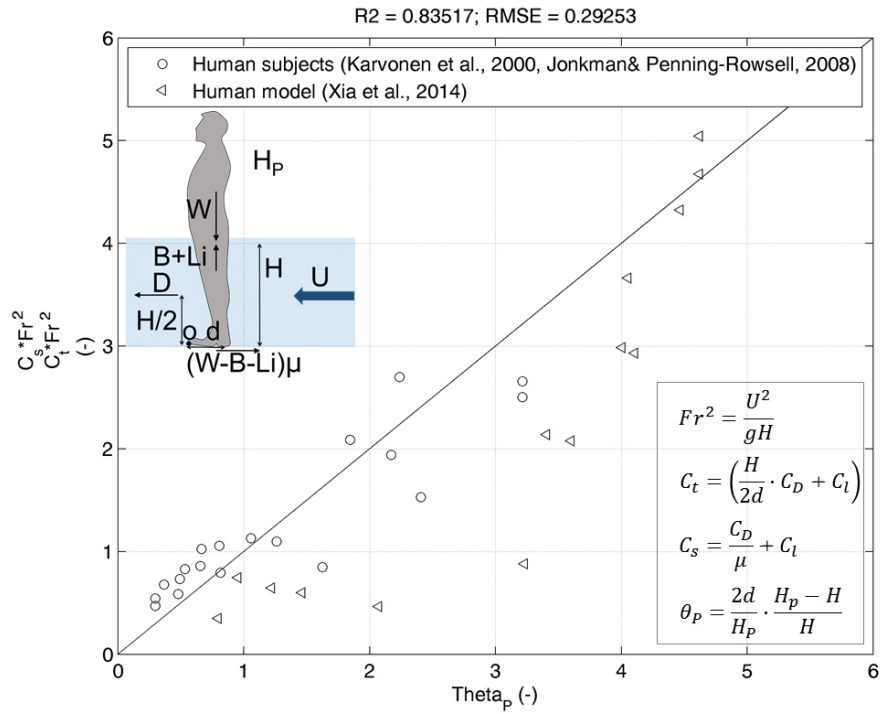
Figure 7. Comparison between experiments in terms of mobility parameter θ$_P$ and numerical results, with a distinction between the human subjects (circles) and human model (triangles). In the top of the Figure the determination coefficient R^2 and RMSE for the data on human scale model Xia et al. (2014) removed.

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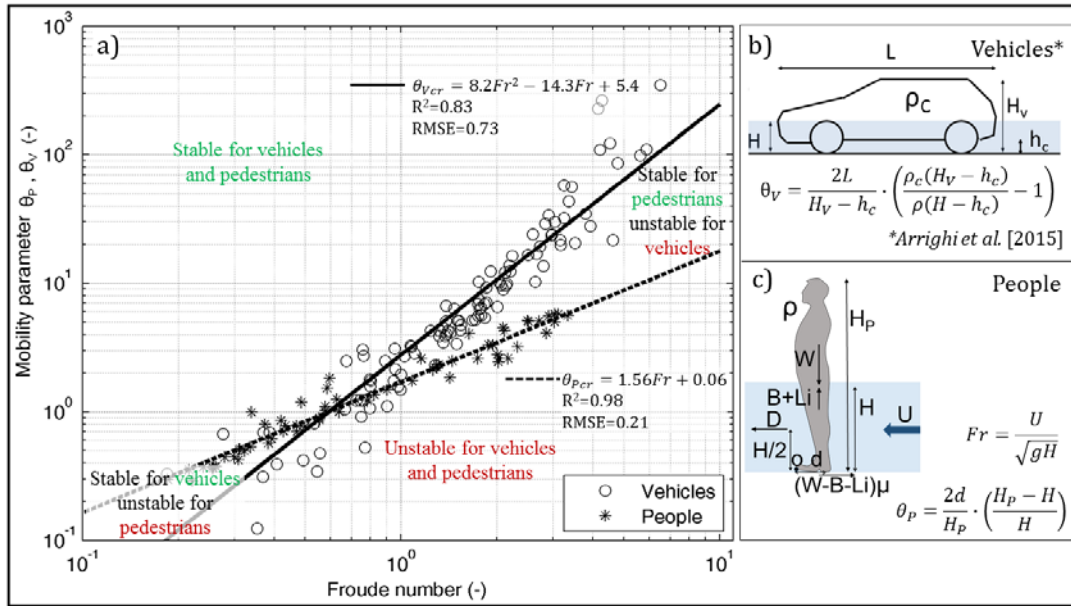
Figure 8. Comparison between dimensionless mobility parameter for people instability in flood flows θ_P and dimensionless mobility parameter for incipient motion of flooded vehicles (Arrighi et al. 2015) (a), definitions of the parameters and geometric sketches for vehicles (b) and people (c). The black continuous and dashed lines represent the critical dimensionless incipient motion curve for flooded vehicles and people respectively.

Table 1. Sensitivity of the general θ_P (Eq. 12) with respect to geometry and density parameters

	Parameter for the sensitivity X_j		
	$X_j=d$ *length of the foot*	$X_j=H_P$ *height of the subject*	$X_j=\rho_P$ *human body density*
Sensitivity function $\dfrac{\partial \theta_P}{\partial X_j}$	$\dfrac{2\rho_p}{\rho H}-\dfrac{2}{H_P}$	$\dfrac{2d}{H_P^{\,2}}$	$\dfrac{2d}{\rho H}$

Table 2. Simulated pairs of water depth H and flow velocity U for human subjects and scale model (Karvonen et al., 2000; Jonkman and Penning-Rowsell, 2008; Xia et al., 2014)

Water depth H (m)	Flow velocity U (m/s)	Froude number Fr (-)
Karvonen et al. (2000), subject 2		
0.40	2.60	1.31
0.50	2.40	1.08
0.60	2.00	0.82
0.80	1.55	0.55
0.90	1.40	0.47
1.00	1.20	0.38
1.05	1.00	0.31
Karvonen et al. (2000), subject 4		
0.6	1.4	0.58
0.8	1.1	0.39
1	0.75	0.24
1	0.8	0.26
Karvonen et al. (2000), subject 5		
0.40	2.50	1.26
0.60	1.90	0.78
0.80	1.40	0.50
1.07	1.00	0.31
Jonkman and Penning-Rowsell (2008), stuntman		
0.26	3.00	1.88
0.26	3.10	1.94
0.33	2.60	1.45
0.35	2.40	1.30
Xia et al. (2014), human model (Froude scaled H,U)		
0.64	0.85	0.34
0.57	1.15	0.49
0.48	1.27	0.59
0.42	1.21	0.60
0.32	2.05	1.16
0.22	2.40	1.63
0.21	3.03	2.11
0.20	2.93	2.09
0.18	3.35	2.51
0.18	3.30	2.50
0.18	3.60	2.71
0.17	3.70	2.91
0.16	3.80	3.03
0.16	3.90	3.11

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Table 3. Reference areas for force coefficients calculation and physical characteristics (height Hp, weght W and length of the foot d) of human subjects and human scale model.

Subject	N°2 Karvonen et al. (2000)	N°4 Karvonen et al. (2000)	N°5 Karvonen et al. (2000)	Jonkman and Penning-Rowsell, (2008)	Model scale 5.54, Xia et al. (2014)
A_{ref} (m^2)	0.49	0.42	0.46	0.43	0.014
H_p (m)	1.95	1.62	1.82	1.7	0.31
W (kg)	100	57	94	68.2	0.334
d (m)	0.30	0.25	0.28	0.26	0.048

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Table 4. Sensitivity of the goodness of fit to the parameters d and μ.

Exp.	Human subjects	All data	Human subjects	All data	Human subjects	All data	Human subjects	All data	Human subjects	All data
	Base case $d=0.15H_p$		d +10%		d -10%		d +30%		d -30%	
R^2	0.82	0.76	0.82	0.73	0.81	0.70	0.81	0.64	0.77	0.62
RMSE	0.28	0.67	0.29	0.67	0.31	0.69	0.31	0.97	0.32	1.26
	Base case $μ=0.3$		$μ$ +10%		$μ$ -10%		$μ$ +30%		$μ$ -30%	
R^2	0.82	0.76	0.82	0.72	0.82	0.74	0.78	0.69	0.80	0.71
RMSE	0.28	0.67	0.25	0.68	0.32	0.67	0.22	0.71	0.46	0.75