Experimental study of the stability of pedestrians exposed to urban pluvial flooding

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Abstract: Populations in urban environments are extremely mobile throughout the day and in various weather conditions; accounting for this pedestrian mobility and security becomes of high importance. Research into the security and stability of the pedestrian environment under exposure to critical water flows provides an essential knowledge base with which the associated hazard unto them can be critically evaluated. This research seeks to analyse degrees of hazard in relation to persons exposed to high volume rain events in urban areas. Several human trials of critical urban flows were conducted in order to determine the stability limits of pedestrians, crossing through a water flow in a real scale physic model. Additionally, the critical first step from a dry footpath into fast flowing water is considered and an assessment of the tested subjects' emotional responses when entering and crossing flooded roadways was carried out. Results from this study are compared with various proposed human stability criteria as well as alternatives proposed in other written works. The presented study offers a stability threshold focused on shallow depths and high velocity conditions, the most common urban flooding conditions.

Keywords: Urban flood risk; hazard; drainage system; pedestrian stability.

1. Introduction

Runoff studies of urban networks focus primarily on the rainfall-runoff transformation and subsequent evacuation of flows through drainage networks resulting in an excess overland flow. The removal of surface runoff is assumed as an automatic process based on rating curves and capture potential; once in the stormwater network the flows are no longer considered a risk to pedestrians. However, only a fraction of overland flow can be captured by storm water grates, the rest remains as overland flow, posing a potential hazard to urban constituents. With continued global urbanization, the volume of water and number of persons impacted by uncontrolled storm water is much higher than previously expected (Gómez and Russo 2011). Misunderstanding of the proper implementation of storm water grates has led to improper positioning and spacing of these critical elements. Spatial density criteria of inlets have been evaluated without consideration of inlets spacing's impact on potential flow interception.

When designing drainage systems, the dual drainage concept should be considered (Djordjevic et al. 1999; Nasello and Tucciarelli 2005; Concha and Gómez 2009; Nanía et al. 2015). This concept is includes the flow within the drainage pipe network as well as the circulation of runoff on the street level which is dependent on storm grate type and spacing. When optimizing and planning drainage networks, the flood hazard posed by this circulating flow requires careful consideration in order to minimize the total hazard to which the urban population are exposed.

A consensus has been reached within the field of urban drainage and storm water management that hazard can be assessed by accounting for the hydraulic variables resulting from storm events, namely, water depth and velocity. To determine the overall risk of an estimated storm event, this hazard is coupled with the vulnerability of exposed elements and the capacity of said element to withstand the hazard. (Sanyal and Lu 2006; Van Drie et al. 2013; Russo et al. 2013b). These hydraulic variables will prescribe a hazard level which can be used to evaluate potential impact on urban elements (i.e. pedestrians, vehicles, properties, etc).

The studies of Russo (2009), provide a solid basis for the research addressed in this paper. The study accounted for the hydraulic efficiency of grates to design the first iteration of an experimental campaign to evaluate the stability of pedestrians when attempting to cross a flooded street under various hydrodynamic conditions. These tests aimed to establish general hazard levels (low, medium or high) for pedestrians when attempting a street crossing under various combinations of water depth and velocity.

This hazard classification would allow for a threshold to be established. Hydrodynamic conditions which result in a low hazard posed to pedestrians should be allowed to occur in the urban environment while medium and high hazard conditions should be more carefully considered and mitigated if possible.

The present research work is a second iteration of the original experiment begun by Russo (2009). Similar trials were conducted as in the first trial but with varied classification of footwear, test subject age and weight, visibility conditions, and use of hands. This study is complemented with surveys completed by tests subjects after experiment participation to evaluate the emotional state and thoughts of the subjects during the test scenarios. Questions were related to the adequacy of the tests from the subject's perspective and to evaluate the perceived state of stability for each of the trials.

In order to give context to the research, a review of the state of the art in terms of stability criteria for people exposed to water flows is presented. Secondly, a description of the experimental set-up, including measurement techniques, experimental campaign and protocol adhered to, and variances in the investigated pedestrian characteristics. Finally this paper presents the obtained results and an extensive discussion of them by comparing with the results of other authors which lead to the proposed conclusions.

2. Outline of the state of the art

People's safety can be compromised when they are exposed to flows that impede their ability to remain standing or to securely traverse a street or a natural stream. This issue has been intently studied over the past decades in an attempt to identify the limits of human stability within different flow regimes. Several numerical and laboratory-based experimental studies have been carried out to achieve these aims. There is a broad agreement that the degree of flood hazard for pedestrians (defined as the conditions which cause persons to be swept away) is primarily influenced by hydrodynamic properties, primarily velocity (v) and depth (y). In order to express the hazard level in case of floods, several authors (Abt et al. 1989; Reiter 2000) have proposed different relationships between these two parameters, and generally the product of depth (m) times velocity ($m \cdot s^{-1}$) is in the range of 0.5-1.0. This can be clearly seen from the heavy reliance of pedestrian stability on the relationship between velocity and flow ($v \cdot y$) (Russo et al. 2013a) and ($v^2 \cdot y$) (Nanía 1999) products, so it is clear the relevance of the flow velocity parameter on the definition of hazard criteria. It seems that the velocity factor has a considerable influence on the determination of hazard and therefore accurate portrayal of both water depth and velocity is required in the production of meaningful hazard levels and interpretations.

However, many of the proposed and explored relationships between velocity and depth focus on scenarios in which the water depth is quite large and velocity of flow is low. This is contrary to the common occurrence in the urban paradigm where the depths are low and the velocities high. Therefore these relations do not prove very useful for critical evaluation of urban pluvial flooding scenarios.

Over the last four decades several studies, experimental and theoretical, on flood hazard in relation to the stability of persons have been conducted. The Australian Rainfall and Runoff Revision Project 10: Appropriate Safety Criteria for People report (Cox et al. 2010) reviews and discusses previous experimental investigations of human stability as well as theoretical formulations and safety guidelines. A significant scattering of the data is observed within individual experimental data sets. This scattering and lack of homogeneity in results is further compounded and exacerbated when results from various trials conducted are aggregated.

Sliding and toppling are the two primary mechanisms leading to pedestrian instability. Toppling is triggered by the moment induced by oncoming flow applying force to the pedestrian which exceeds the stabilizing moment generated by the weight of the body (Abt et al. 1989). Sliding instability occurs when the drag force induced by the horizontal flow is larger than the frictional resistance supplied by a person's shoe and the ground surface (Nanía 1999).

To date, there are only few references regarding flooding hazard in urban areas (Clark County Regional Flood Control District (CCRFCD) 1999; Nanía 1999; Agricultural and Resource Management Council of Australia and New Zealand (ARMC) 2000; Kelman 2002; Russo 2009; Chanson and Brown 2013; Russo et al. 2013a; Xia et al. 2014a; Chanson et al. 2014; Xia et al. 2014b; Xia et al. 2015; Chanson and Brown 2015). Generally, references deal only with floods in purely rural or coupled rural and urban basins, thus leaving them unresponsive to the singularities that occur in a purely urban pluvial flooding scenario. However, many of them are just as relevant to urban situations even if the word "urban" is not included

A summary of state of the art in regard to studies investigating stability of people exposed to water flows can be found in Tables 1 & 2. The first table is a collection of data from the early human stability testing for children by Foster and Cox (1973) expanding to the latest experimental test carried out by Russo (2009). The second table summarizes proposed stability criteria of some of the most relevant theoretical studies as well as several guidelines and recommendations. The earliest stability criteria presented is the Federal Emergency Management Agency (FEMA 1979) recommendation, maximum depth (y= 0.91 m), maximum velocity (v= 0.61 $m \cdot s^{-1}$), and a product (v·y) of less than 0.56 $m^2 \cdot s^{-1}$. The latest stability criteria is obtained from the Australian Rainfall & Runoff Guideline (Cox et al. 2010), differentiates the criteria according the characteristics of the population (e.g. for children a maximum water depth of 0.5 and a product (v·y) less than 0.4 $m^2 \cdot s^{-1}$).

3. Description of the laboratory and the experimental set-up

The outdoor hydraulic laboratory of Technical University of Catalonia contains the physical model implemented by Russo (2009) in the first investigative campaign into pedestrian stability during flood conditions in urban environments. The physical model is of sufficient dimensions so that the scale effects are avoided and test with human subjects can be easily conducted. The cross section of the model is representative of a typical urban street crossing. A typical urban street crossing is classified in this case as 1.6 meters in width and length of 5 meters. It is possible to vary the longitudinal slopes of the model from 0 to 10% incline and the cross section contains a fixed 2% transverse slope, typical characteristics of streets in most of cities. Aiming to carry out a realistic scenario, a sidewalk street interface was also introduced, allowing for the first step from the sidewalk to the flooded street to be evaluated as well. The inclusion of a curb allows greater realism in the tests and allows for an evaluation of the initial shock registered by subjects when experiencing the sudden introduction of force upon entering the flooded street from a dry sidewalk. Previous studies did not take into consideration this first steep which is often a critical stage in the evaluation of the stability of pedestrians in both the experimental tests and real situations. Figure 1 depicts the model cross section including dimensions; the higher curb is 15 cm depth as is typical of most urban codes.

In order to obtain and maintain a steady, uniform flow over the entire cross-section, an upstream regulation tank was constructed. The regulation tank's purpose also was to increase the accuracy of proper depth and velocity measurements as well as recreating an urban runoff environment with as much realism as possible. Figure 2 shows the physical model and a discharge of 300 $l \cdot s^{-1}$ flowing throughout the model road.

4. Discharges, velocities and water depths on the physical model

The discharges in the physical model are calculated by summing discharges registered at V-notch weirs via the Kindsvater-Shen method (U.S. Department of the Interior. Bureau of Reclamation (USBR) 1997), employing an effective discharge coefficient for partially contracted weirs (1),

$$Q = 1.366 \cdot h^{5/2} \qquad (1)$$

where Q ($m^3 \cdot s^{-1}$) is the discharge and h (m) is the hydraulic head over the weir crest.

Flows are generated by activation of a series of pumps. The capacity of each of three pumps ranges from 105.49 l/s up to 544.84 l/s reached when all three pumps were activated. Velocity measurement was accomplished via an ADV (Acoustic Doppler Velocimeter – Vectrino sidelooking) device. Detailed velocity measurements were completed in the testing section (where the subjects crossed the model) 74 cm upstream from the model outlet. Five velocity profiles were developed across the model the testing section in order to have a clear longitudinal velocity field along the model. Those five profiles were developed for 16 flow scenarios: result of the combination of 4, 6, 8 and 10% slopes and 300, 375, 450 and 550 l/s discharges. Each profile was the result of two minutes averages of instant velocities at points measured every centimetre from the road bottom. An average velocity in the testing section was related to each flow scenario, finally obtaining 16 average velocities. Figure 3 shows the ADV device set-up in the testing section. Water depths were measured with a ruler next to the higher curb of the testing section for each flow scenario. Before carrying out the experiments with the subjects all the measurements (i.e. water depths and velocities) were taken for all the flow scenarios, resulting on 16 pairs of velocities and water depths.

5. Tests & pedestrian profiles

The variables tested for in this experiment are not limited to only environmental parameters described in section 4. They also factor in situational variables such as type of footwear being worn, visibility conditions, and whether or not the pedestrian's hands are occupied. All pedestrian subjects were vested in Gore-Tex survival trousers and a simple T-shirt to provide uniformity in the attire-clothing type thus being excluded as a variable in this research. For every fixed discharge and model slope, each subject had to carry out a testing protocol wearing different kinds of shoes (Figure 4), with the hands busy (Figure 8) or free, and either good or bad visibility conditions (Figure 6c and 8).

An experiment was developed in order to determine the coefficient of friction provided by each of the different show types used in the test. The trials were executed on the test surface used in the stability experiment; both the shoe and the surface were wetted during the friction testing. Each type of shoe was weighed down on the test surface; subsequently lateral force was applied through the use of a spring weight measure until movement of the shoe was detected (Figure 5). The instant of movement denotes the reached force is the friction force (F_R); consequently it is possible to obtain the friction coefficient (μ) knowing previously the weight of the shoe. Thus the friction coefficient (μ) is obtained by dividing the friction force (F_R) by the gravitational force ($F_g= M_z g$), being M_z the weight of the shoe and g the acceleration of gravity. The results obtained are collected in Table 3.

Critical storm events do not occur in a regimented manner, they can occur at any time of day. Further complicating this fact is the high degree of variability with which persons conduct various activities within cities. Urban residents are not always prepared for storm events when they occur and can be conducting themselves in a myriad of way. The combinations represented in this experiment are aimed at representing a slice of the variety inherent in the collective demographic "pedestrian". Thusly, the differential in shoe types, whether carrying objects or not, and visibility attempts to include some elements of the dynamics into the experiment and allow for discussion on this variability. A positive correlation between the occurrence of unstable situations and the number of additional difficulties the participants is subjected to be expected. Difficulties are considered as low comfort level of footwear, low friction coefficient of footwear, poor visibility, and occupied hands during traversal.

In order to restrict the broad number of hydraulic combinations there were only taken into account for discharges above 300 l/s, as well as slopes more than 4%, thus neglecting hydraulic combinations with a low likelihood of instability according to the results of the experimental campaign of Russo (2009). Contemplating finally only four discharges, four longitudinal model slopes and the different wearing considerations (i.e. types of shoes, hands busy or free, and visibility conditions), there were a total of 192 possible combinations for each tested subject. Experimental sessions of 48 tests per each person were carried out, as a result of a fixed longitudinal model slope, four discharges and 12 wearing combinations per discharge.

The selection of pedestrian candidates focused on two main categories:

(1) People with physical characteristics (i.e. weight (P) and height (H)) which lead to a higher likelihood of instability situations, according to the results of the first experimental campaign (Russo 2009).

(2) Persons offering as broad and representative pedestrian sample as possible (i.e. variety of gender and ages) while focusing on the most susceptible to instability within each demographic delineation.

The final pedestrian test sample included 26 persons, constituted by 16 women, 5 men and 5 children (under 15 years of age). The ages were represented from 6 to 55 years, weights from 37 to 71 kg, and the heights from 1.32 to 1.73 m (Table 4).

6. Experimental campaign & test protocol

In this experimental campaign every test was carried out according to the test protocol proposed by Russo (2009). The tested subject attempted move through the flows in three directions, transverse, diagonal and longitudinal with respect to the main flow direction. Prior to attempting to walk in one of the three directions, the protocol dictates that the subject must enter the flow from the dry sidewalk (0*) to the flooded road (0) and then continuing wading in the three directions according the sketch shown in the Figure 7. The section 0-1, as Figure 7 shows, correspond to the testing section where the water depths and velocities were measured, located 0.74 cm upstream from the outlet of the model.

In accordance with Russo (2009), the hazard level classification of every experimental test was carried out adopting the following criteria:

- **High hazard**: The tested subject lost stability completely.
- **Medium hazard**: The tested subject showed a great difficulty in carrying out the complete protocol. The subject needed to make a great effort. Slowness, stumbles, slips and a loss of one or both shoes were other issues to consider a case as a medium hazard.
- **Low hazard**: Small or inestimable instabilities were observed. The tested subject was able to carry out the complete protocol without any inconvenience.

When classifying hazard level relative to each of the flow regimes, the subject’s personal feelings as to the hazard level were also assessed. The tests were carried out with certain degree of randomness. Not all the test subjects carried out the same number of sessions or the same sequence of discharges. In order to minimize the gaining of experience in manoeuvring through the flow (Abt et al. 1989), a reasonable period of time was allowed to elapse before the test subject was invited back for subsequent rounds of testing.

7. Results

In a total of 2345 assessed test cases, the number of high hazard scenarios, determined through a complete loss of stability, amounted to 38, 1.6% of the total cases. This may seem as a very low number of cases, however, the assessment of a high hazard situation was very rigorous and only account for instances where there was a complete loss of stability and fall (Figure 8). There were multiple instances where subjects lost balance but were able to recover their footing and continue without having fallen. These scenarios are classified as medium hazard as no fall occurred. Table 5 summarizes the assessed cases according the level of hazard.

A breakdown detailing the conditions under which the High Hazard events occurred can be found in Table 6. After scrutinizing the conditions present when a fall occurred, no clear correlation can be made due to visibility condition, therefore it is assumed this is not a causal factor. The same conclusion was achieved by Russo (Russo 2009). On the other hand, it is observed that most of the instability cases (71.1%) were produced wearing flip-flops, which indicates sliding instability according with the minimum friction coefficient determined experimentally for this kind of shoes (μ=0.44).

In turn, the assessment of the level of hazard for every test case was complemented by including surveys on the tested subject regarding their feelings during the tests. The aim was to evaluate the adequacy of the tests and more especially to evaluate the stability feelings of every person under different hydraulic conditions (water depths and velocities). The surveys were carried out immediately after every experimental session for each tested subject through an online questionnaire. The percentage of respondents to the survey was 59% (i.e. 34 answered surveys from a total number of 58 test sessions). The answers regarding the main points are summarized and listed below:

(1) **Discomfort caused by the safety equipment**: All the respondents agreed that the comfort of the safety equipment was good enough and it did not prevent to them from carrying out the tests naturally.

(2) **Duration of the tests**: The tests duration was adequate according to most of the respondents, thus the influence of fatigue is discarded.

(3) **Gaining experience**: All participants agree on the gaining of experience and increased ease of passage as the sense of insecurity wanes in comparison to the first undertaken tests with each subsequent passage.

(4) **Sense of security in respect of the different shoes, visibility conditions and hands busy or free**: There was a great agreement on the flip-flops as the most insecure shoes. Nobody noticed any substantial difference between wearing waterproof boots or flat-soled shoes/heeled shoes. Interestingly, the correspondents placed a higher level of insecurity resulting from low visibility over having their hands occupied holding item.

(5) **Protocol direction with most and less difficulties**: 100% respondents agree that the transverse direction (0-1 way according Figure 7) was the most difficult to carry out.

(6) **First impression after entering the first foot into the water**: Nobody expected such a water force even when the lowest of the discharges was flowing through the street model. Therefore, the first step further from the dry sidewalk (0* according Figure 7) to the flooded road (0 according Figure 7) is a critical stage when a pedestrian tries to cross a flooded street.

8. Discussion & comparison with other authors

In this section the obtained results are analysed from the point of view of the stability limit of pedestrians exposed to water flows according the hydraulic variables (i.e. water depth and velocity) of the street flow. Furthermore, in order to analyse the differences between the instability threshold obtained in this experimental campaign and the stability criteria proposed by others authors, both are represented together.

In order to be able to perform a higher quality analysis, the results from Russo's (2009) experiment are aggregated along with those obtained through this iteration of the experiment. In fact, one of the driving forces behind this second iteration was to obtain a greater number of instability points, focusing on subjects potentially more instable on the basis of acquired experience in the first campaign. Both sets of points (i.e. pairs of water depth and velocity for every case), represented in the graph of the Figure 9, define a lower limit function $(v \cdot y) = 0.22\ m^2 \cdot s^{-1}$. The most conventional stability criteria used in literature $(v \cdot y) = 0.5\ m^2 \cdot s^{-1}$ as shown in Figure 9 (based on thresholds defined by Abt et al. 1989; Témez 1992; Gómez 2008) is clearly not adequate. The security threshold obtained in this study $(v \cdot y) = 0.22\ m^2 \cdot s^{-1}$ is a more appropriate threshold to assess the stability for pedestrians exposed to water flows in urban areas. The presented study offers a revised limit to depth and velocity relationships for urban area flooding. This revised level is assumed to be a product of the higher frequency of shallow depth and high velocities found in urban zones as opposed to the high depth moderate velocity model which was used to develop the original stability threshold.

In order to more clearly see the critical data, Figure 10 depicts the points of high hazard from both the 2009 and current experiment for participants weighing less than 52 kg. The threshold functions proposed by Témez (1992), Nanía (1999) and Gómez (2008) are also represented in the same graph. The first stability criteria (Témez 1992) proposes a maximum velocity of 1 $m \cdot s^{-1}$, a maximum depth of 1 m·and a function limit given by the product $(v \cdot y) = 0.5\ m^2 \cdot s^{-1}$. The second one (Nanía 1999) is a slipping instability criteria which considers a pedestrian weight of 50 kg and a friction coefficient of μ=0.5, and its function is given by the product $(v^2 \cdot y) = 1\ m^3 \cdot s^{-2}$. The last criteria (Gómez 2008) was carried out through the toppling instability theoretical analysis proposing as a limit function the product $(v \cdot y) = 0.45\ m^2 \cdot s^{-1}$, and considering again a pedestrian weight of 50 kg.

The Témez (1992) criteria is excessively restrictive as all of the point of instability are found considerable distance away from the threshold according to Figure 10. This criterion was originally developed for floodplains where low velocities as 1 m/s, which is the maximum value proposed, are more reasonable. However, in the urban paradigm, this velocity threshold is regularly exceeded reaching greater velocity values. On the other hand, both the Nanía (1999) and Gómez (2008) criteria are not appropriate since instability points are found in their proposed "safety" area (i.e. below limit function).

Following Abt *et al.* (1989) and Russo (2009), a specific analysis concerning the relation between subject characteristics and the flow parameters was as well undertaken. Specifically, in the studies of Abt *et al.* (1989) a relationship was developed to approximate the product number at which a human subject would become unstable in flood flow conditions based upon the subject's height and weight. Twenty human subjects who ranged in weight (P) from approximately 40.9 to 91.4 kg and in height (H) from 152 to 183 cm were tested. Subjects were subjected to flow velocities ranging from 0.36 to 3.05 $m \cdot s^{-1}$and flow depths of 0.49 to 1.2 m. The stability tests were carried out over four types of surfaces, concrete, turf, gravel and steel and establishing two flume slopes, 0.5 and 1.5%. As Abt *et al.* (1989) proposed, in the Figure 11 is represented the square root of the product $(v \cdot y)$ versus the product $(H \cdot P)$ for each situation of instability, considering only the minimum $(v \cdot y)$ product for each tested subject. In the same graph the minimum stability point of the subjects tested over a concrete surface by Abt *et al.* (1989) are presented as well. It is possible to observe an evident similarity in both studies regarding the ascending tendency of the square root of the product $(v \cdot y)$ for greater values of the $(H \cdot P)$

product (Figure 11). However, the higher values of (v·y) in the study of Abt *et al.* (1989) focus on toppling instabilities (i.e. higher water depths and lower velocities) in contrast to the slipping instabilities of the present study (i.e. higher velocities and lower water depths).

Finally a comparison between the AR&R Guidelines stability criteria (Cox et al. 2010) and the set of instability points obtained in both herein and Russo (2009) is carried out. This criterion is the result of a review and discussion of previous experimental investigations of human stability (Foster and Cox 1973; Abt et al. 1989; Takahashi S. et al. 1992; Karvonen et al. 2000; Yee M. 2003; Jonkman and Vrijling 2008) which instability points obtained in every study are represented in the graph of the Figure 12 and 13. In order to define safety limits which are applicable for all persons, hazard regimes are defined for adults (H·P>50 m·kg) and children (H·P=25 to 50 m·kg), according the product height (H) x weight (P) of a person. The safety area for children is limited by the function (v·y)= 0.4 $m^2·s^{-1}$ and a maximum depth of 0.5 m whereas the adults safety area is limited by the function (v·y)= 0.6 $m^2·s^{-1}$ and a maximum depth of 1.2 m. For both the maximum velocity is 3.0 $m·s^{-1}$ at shallow depths.

All the instability points from this test program are found in the proposed safety area for adults, and even most of them below the limit function for children (v·y)= 0.4 $m^2·s^{-1}$. The criteria proposed by the AR&R Guidelines are not so appropriate to evaluate the hazard for pedestrians exposed to common urban pluvial flooding conditions included in this test program.

9. Conclusions

According to the brief review of the state of the present knowledge, a general consensus has been established on the hydraulic variables that define the hazard posed to humans exposed to urban storm flows. These variables are the flow depth and velocity as well as the relation between these two factors through which several thresholds can be formulated.

The most common flows, low depth with high velocities, found during urban storm conditions have been reproduced in a controlled laboratory setting through the use of a physical model. A sample of 26 subjects has been tested considering different conditions and exposure combinations (i.e. types of shoes, hands busy or free, and visibility conditions). The lower function threshold for all the assessed instability points is given by the product (v·y)= 0.22 $m^2·s^{-1}$, far below the conventional criterion of (v·y)= 0.5 $m^2·s^{-1}$. The representation of all the instability points together with some stability criteria proposed by other authors and guidelines indicates that these criteria are not appropriate to assess the stability of a pedestrian exposed to the typical urban pluvial flooding. The presented study offers a revised stability threshold, which concentrates on acceptable levels when operating under low depth and high velocity conditions, the most common conditions present when operating within the urban environment during storm events. Also, new aspects such as the critical first step from a dry footpath into fast flowing water and the assessment of subjects' emotional response and perceptions have been considered in the hazard analysis.

Accounting for these factors, a more restrictive stability criterion for pedestrians in urban paradigms is proposed. These results and recommendations should be taken into account by stakeholders' policy-maker in order to have improved flood risk management in urban areas. In order obtain said criterion, the results of this work will be an asset to urban drainage designers. If put into effects, these limits will be of great importance in the design and re-development of run-off management features within cities and highly developed areas in order to ensure the safety of inhabitants.

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References

Abt SR, Wittler R.J., Taylor A., Love D.J. (1989) Human stability in a high flood hazard zone. AWRA Water Resour Bull 25:881–890.

Agricultural and Resource Management Council of Australia and New Zealand (ARMC) (2000) Floodplain Management in Australia. Best Practice Principles and Guidelines. 120.

Belleudy P (2004) Risques Hydro-météorologiques, crues et inondations/risque, aléa et vulnérabilité/DDS-TUE364/4.

Chanson H, Brown R (2013) Turbulence in an inundated urban environment during a major flood: implications in terms of people evacuation and sediment deposition. Proc 21ème Congrès Français Mécanique CFM 2013. doi: 10.1051/meca/2014017

Chanson H, Brown R (2015) New criterion for the stability of a human body in floodwaters. J Hydraul Res 53:540–541. doi: 10.1080/00221686.2015.1054321

Chanson H, Brown R, McIntosh D (2014) Human body stability in floodwaters: the 2011 flood in Brisbane CBD. Hydraul. Struct. Soc. - Eng. challenges Extrem. The University of Queensland, pp 1–9

Clark County Regional Flood Control District (CCRFCD) (1999) Hydrological criteria and drainage design manual.

Clavegueram de Barcelona S.A. (CLABSA) (2006) PICBA06, Plan integral de Alcantarillado de Barcelona 2006.

Concha R, Gómez M (2009) Una aproximación a la modelización del Drenaje Dual Urbano mediante EPA SWMM 5.0. Jornadas Ing. del Agua 2009 (JIA 2009). pp 1–10. Madrid (Spain)

Cox RJ, Shand TD, Blacka MJ (2010) Australian Rainfall and Runoff (AR&R). Revision Project 10: Appropriate Safety Criteria For People. New South Wales (NSW), Australia

Department of Infraestructure Planning and Natural Resouces. New South Wales Goverment (2005) Floodplain Development Manual: the management of flood liable land. 31.

Djordjevic S, Prodnovic D, Maksimovic C (1999) An approach to simulation of dual drainage. Water Sci Technol 39:95–103. doi: 10.1016/S0273-1223(99)00221-8

Van Drie R, Simon M, Schymitzek I (2013) HAZARD :- Is there a better definition? & Impact of Not accounting for buildings! IPWEA Annu. Conf. NSW. Australia, p 13

Federal Emergency Management Agency (FEMA) (1979) The floodway: a guide for community permit officials (USA).

Foster DN, Cox R (1973) Stability of Children on Roads Used as Floodways, Technical Report No. 73/13. Manly Vale, NSW, Australia

Gómez M (2008) Curso de Hidrología Urbana (7^{a} Edición). Flumen Research Institute. Universitat Politècnica de Catalunya, Barcelona (Spain)

Gómez M, Russo B (2011) Methodology to estimate hydraulic efficiency of drain inlets. Proc ICE - Water Manag 164:81–90. doi: 10.1680/wama.900070

Jonkman SN, Vrijling JK (2008) Loss of life due to floods. J Flood Risk Manag 1:43–56. doi: 10.1111/j.1753-318X.2008.00006.x

Karvonen RA, Hepojoki HK, Huhta HK, Louhio A (2000) The Use Of Physical Models In Dam-Break Flood Analysis, Development of Rescue Actions Based on Dam-Break Flood Analysis (RESCDAM). Helsinki (Finland)

Kelman I (2002) Physical Flood Vulnerability of Residential Properties in Coastal Eastern England. PhD Thesis. University of Cambridge (U.K)

Ministerio de Medio Ambiente de España (1996) Guía Técnica para la Clasificación de Presas en Función del Riesgo Potencial, Madrid (Spain), p 64

Nanía LS (1999) Metodología numérico experimental para el análisis del riesgo asociado a la escorrentía pluvial en una red de calles. PhD Thesis. Technical University of Catalonia, Barcelona, Spain

Nanía LS, León AS, García MH (2015) Hydrologic-Hydraulic Model for Simulating Dual Drainage and Flooding in Urban Areas: Application to a Catchment in the Metropolitan Area of Chicago. J Hydrol Eng 20:04014071. doi: 10.1061/(ASCE)HE.1943-5584.0001080

Nasello C, Tucciarelli T (2005) Dual Multilevel Urban Drainage Model. J Hydraul Eng 131:748–754. doi: 10.1061/(ASCE)0733-9429(2005)131:9(748)

Ramsbottom D, Floyd P, Penning-Rowsell E (2006) Flood Risks to People; Phase 2: Project Record. FD 2321/PR. United Kingdom

Regione Liguria. Autoritá di Bacino Regionale. Ambito di Bacino No. 7 (1993) Piano di bacino stralcio per la difesa idraulica e idrogeologica. Italy

Reiter P (2000) International methods of Risk Analysis, Damage evaluation and social impact studies concerning Dam-Break accidents. EU-Project RESCDAM. Seinäjoki (Finland)

Russo B (2009) Design of surface drainage systems according to hazard criteria related to flooding of urban areas. PhD Thesis. Technical University of Catalonia, Barcelona (Spain)

Russo B, Gómez M, Macchione F (2013a) Pedestrian hazard criteria for flooded urban areas. Nat Hazards 69:251–265. doi: 10.1007/s11069-013-0702-2

Russo B, Velasco M, Suñer D (2013b) Flood hazard assessment considering climate change impacts-Application to Barcelona case study using a 1D/2D detailed coupled model. Int. Conf. Flood Resil. Exp. Asia Eur. Exeter (U.K), p 10

Sanyal J, Lu XX (2006) GIS-based flood hazard mapping at different administrative scales: A case study in Gangetic West Bengal, India. Singap J Trop Geogr 27:207–220. doi: 10.1111/j.1467-9493.2006.00254.x

Takahashi S., Endoh K., Muro Z-I. (1992) Experimental Study on People's Safety against Overtopping Waves on Breakwaters (in Japanese). Rep Port Harb Inst 34:4–31.

Témez JR (1992) Control del desarrollo urbano en las zonas inundables. Monogr. del Col. Ing. Caminos, Canales y Puertos n^{o} 10. Madrid (Spain), pp 105–115

U.S. Department of the Interior. Bureau of Reclamation (USBR) (1997) Water Measurement Manual. Chapter 7.

Xia J, Falconer R, Guo P, Gu A (2014a) Stability Criterion For A Flooded Human Body Under Various Ground Slopes. 11th Int. Conf. Hydroinformatics (HIC 2014). New York City (USA)

Xia J, Falconer RA, Wang Y, Xiao X (2014b) New criterion for the stability of a human body in floodwaters. J Hydraul Res 52:93–104. doi: 10.1080/00221686.2013.875073

Xia J, Chen Q, Falconer RA, Deng SS and Guo P. (2015). Stability criterion for people in floods for various slopes. Proceedings of the Institution of Civil Engineers-Water Management (http://dx.doi.org/10.1680/wama.14.00110). http://www.icevirtuallibrary.com/doi/full/10.1680/wama.14.00110

Yee M. (2003) Human Stability in Floodways. PhD Thesis. School of Civil and Environmental Engineering, University of New South Wales (Australia).

Table 1. Experimental studies (adapted from Cox *et al.* (2010))

	(Foster and Cox 1973)	(Abt et al. 1989)	(Takahashi S. et al. 1992)	(Karvonen et al. 2000)	(Yee M. 2003)	(Russo 2009)
Year	1973	1989	1992	2000	2003	2009
Setup	Flume	Flume	Funnelled basin	Moving platform through basin	Flume	Platform simulating street channel
Surface	Painted timber	Concrete turf. Gravel and steel	Metal load cell	Steel grating	Painted timber	Concrete
Slope	Horizontal	1(V): 115(H) and 1(V):38(H)	Horizontal	Horizontal	Horizontal	0, 2, 4, 6, 8, 10%
Subject Characteristics	Children (9-13 yrs)	Civilian adults with safety equipment	Adults	Rescue workers with safety equipment	Children	Civilian adults and children
Subject Action	Standing walking, turning and sitting	Standing, turning and walking	Standing	Standing, turning and walking	Standing, walking	Standing, walking, turning
Failure mechanism	Subject feels unsafe or loses footing	Subject loses footing	Subject loses footing	Subject loses footing	Subject feels unsafe or loses footing	Subject feels unsafe or loses footing
Number of subjects	6	20	3	7	4	23
Range of (y), (m)	0.09-0.41	0.43-1.2	0.44-0.93	0.4-1.1	0.18-0.53	0.11-0.16
Range of (v), (ms^{-1})	0.76-3.12	0.82-3.05	0.58-2.0	0.6-2.6	0.89-2.12	1.17-3.17
Range of (v·y), (m^2s^{-1})	0.16-0.52	0.71-2.13	0.64-1.26	0.6-1.3	0.33-0.55	0.09-0.44
Range of (P·H), (kg·m)	32-53.2	62.3-172.8	106.6-133.6	77-195	20.8-32.5	49-104

Table 2. Theoretical studies, recommendations and guidelines.

Source	Reference	y_{max} (m)	v_{max} (m/s)	Expression
Federal Emergency Management Agency (FEMA). The floodway: a guide for community permit officials. (USA)	(Federal Emergency Management Agency (FEMA) 1979)	0.91	0.61	$(v \cdot y) \leq 0.56$
Human Stability in a High Flood Hazard Zone. AWRA Water Resources Bulletin. (USA)	(Abt et al. 1989)	1.2	3.05	$0.71 \leq (v \cdot y) \leq 2.13$
Control del desarrollo urbano en las zonas inundables (España)	(Témez 1992)	1.00	1.00	$(v \cdot y) \leq 0.5$
Basin Plan for the hydraulic and hydro-geological protection of the land (Italia)	(Regione Liguria. Autoritá di Bacino Regionale. Ambito di Bacino No. 7 1993)	0.30-0.70	1.00 – 2.00	-
Clasificación de presas en función del riesgo potencial (España)	(Ministerio de Medio Ambiente de España 1996)	0.00 – 1.75	0.00 – 7.00	-
Clark County Regional Flood Control District (CCRFCD). Hydrological criteria and drainage design manual. Clark County (USA)	(Clark County Regional Flood Control District (CCRFCD) 1999)	0.30	-	$(v \cdot y) \leq 0.55$
Doctoral Thesis of Nanía, 1999. Technical University of Catalonia.	(Nanía 1999)	-	1.00	-
Agricultural and Resource Management Council of Australia and New Zealand (ARMC). Floodplain Management in Australia (Australia and New Zealand).	(Agricultural and Resource Management Council of Australia and New Zealand (ARMC) 2000)	1.20 – 1.50	1.5	-
EU-Project RESCDAM. Helsinki PR Water Consulting (Finland)	(Reiter 2000)	-	-	$0.25 \leq (v \cdot y) \leq 0.7$
Curso de Hidrología Urbana. Universitat Politècnica de Catalunya.	(Gómez 2008)	-	-	$(v \cdot y) \leq 0.45$
Doctoral Thesis of Kelman. University of Cambridge	(Kelman 2002)	1.25	5.00	-
Flood risks to people: Phase 1. R&D Technical Report FD 2317. Flood risks to people: Phase 2 R&D Technical Report FD 2321. Department of the Environment, Food and Rural Affairs and Environment Agency, London	(Ramsbottom et al. 2006)	-	-	$HR = y \cdot (v+0.5) + DF$
Risques Hydro-météorologiques, crues et inondations/ risqué, aléa et	(Belleudy 2004)	0.00 – 1.00	0.25 – 1.00	-

Source	Reference	y_{max} (m)	v_{max} (m/s)	Expression
vulnérabilité/ DDS-TUE364/9 (Switzerland)				
Floodplain Development Manual. The management of flood liable land	(Department of Infraestructure Planning and Natural Resouces. New South Wales Goverment 2005)	2.00	2.00	-
PICBA06: Pla Integral de Clavegueram de Barcelona 2006 (España)	(Clavegueram de Barcelona S.A. (CLABSA) 2006)	0.06	1.5	-
Australian Rainfall and Runoff. Project 10. Report for the Appropriate Safety Criteria for People.	(Cox et al. 2010)	1.2 (adults) 0.5 (children)	3.2	$(v \cdot y) \leq 0.40$ (children) $(v \cdot y) \leq 0.60$ (adults)

Table 3. Friction coefficients between shoes soles-terrain obtained experimentally.

Type of shoe	weight (g)	F_R (g)	μ
Heeled	208.0	110.0	0.53
Flip-flop	68.0	30.0	0.44
Flat	270.0	185.0	0.69
Waterproof boot	434.0	250.0	0.58

Table 4. Characteristics of the tested subjects.

Id.	Gender	Age	Mass [kg]*	Height [m]	Mass x Height [kg·m]
1	Female	21	52	1.57	81.64
2	Male	30	56	1.70	95.20
3	Female	33	56	1.59	89.04
4	Female	29	65	1.67	108.55
5	Female	37	61	1.65	100.65
6	Female	30	58	1.69	98.02
7	Female	20	58	1.70	98.60
8	Female	23	61	1.58	96.38
9	Female	21	51	1.61	82.11
10	Female	32	63	1.66	104.58
11	Female	55	65	1.70	110.50
12	Male	30	69	1.65	113.85
13	Male	37	67	1.69	113.23
14	Female	24	53	1.61	85.33
15	Male	15	48	1.69	81.12
16	Male	13	53	1.71	90.63
17	Male	11	68	1.71	116.28
18	Female	24	48	1.65	79.20
19	Male	22	71	1.57	111.47
20	Female	39	55	1.62	89.10
21	Male	9	42	1.49	62.58
22	Male	6	37	1.32	48.84
23	Female	33	61	1.73	105.53
24	Female	29	59	1.68	99.12
25	Male	29	66	1.66	109.56
26	Female	24	52	1.50	78.00

*3kg added to the subject’s weight because of the security equipment weight

Table 5. Experimental tests classification according to the level of hazard.

	TOTAL	
Low Hazard	1528	65.2%
Medium Hazard	779	33.2%
High Hazard	38	1.6%
Total	2345	100.0%

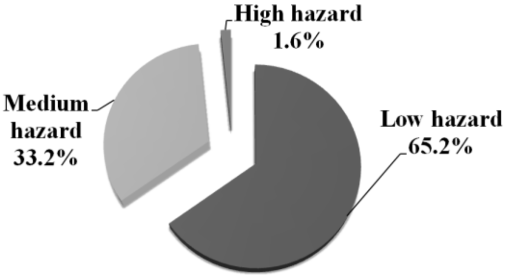
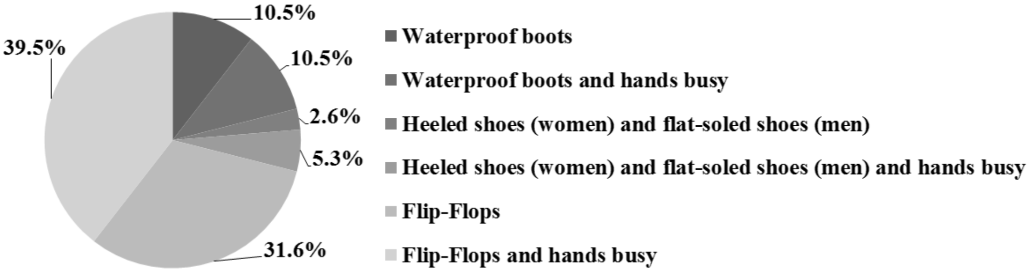


Table 6. High hazard evaluations divided according study cases.



nº	%	GV*	%	BV**	%	
4	10.5%	2	12.5%	2	9.1%	**Waterproof boots**
4	10.5%	2	12.5%	2	9.1%	**Waterproof boots and hands busy**
1	2.6%	0	0.0%	1	4.5%	**Heeled shoes (women) and flat-soled shoes (men)**
2	5.3%	0	0.0%	2	9.1%	**Heeled shoes (women) and flat-soled shoes (men) and hands busy**
12	31.6%	5	31.3%	7	31.8%	**Flip-flops**
15	39.5%	7	43.8%	8	36.4%	**Flip-flops and hands busy**
38		**16**		**22**		**TOTAL**

* Good Visibility / ** Bad Visibility

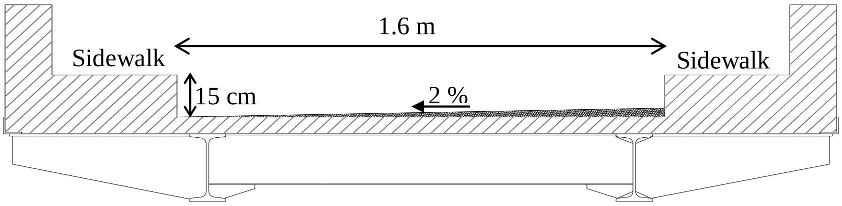


Figure 1. Cross section dimensions of the physical model

Figure 2. Physical model. Uniform flow entrance with a discharge of 300 l/s.

Figure 3. ADV set-up in the physical model

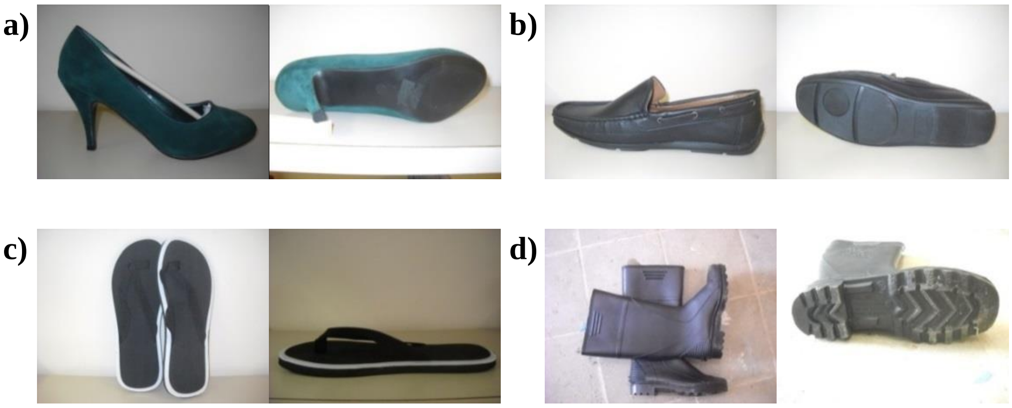


Figure 4. Types of shoes employed on the tests; a) heeled shoes (women), b) flat-soled shoes (man), c) flip-flops, d) waterproof boots

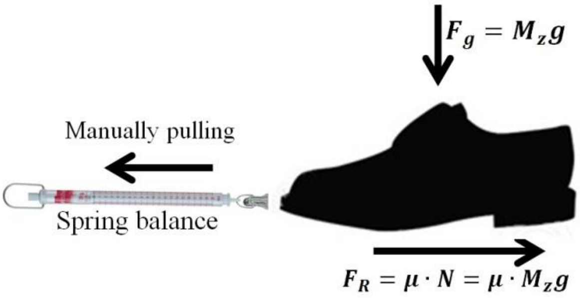


Figure 5. Obtaining the friction coefficient between shoe sole-terrain through a spring balance

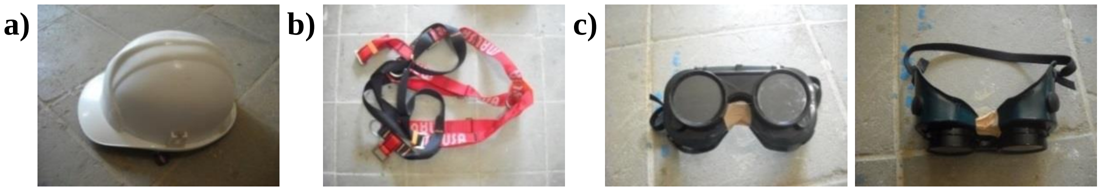


Figure 6. Elements wore for the tested people; a) safety helmet, b) safety harness and c) glasses to decrease visibility

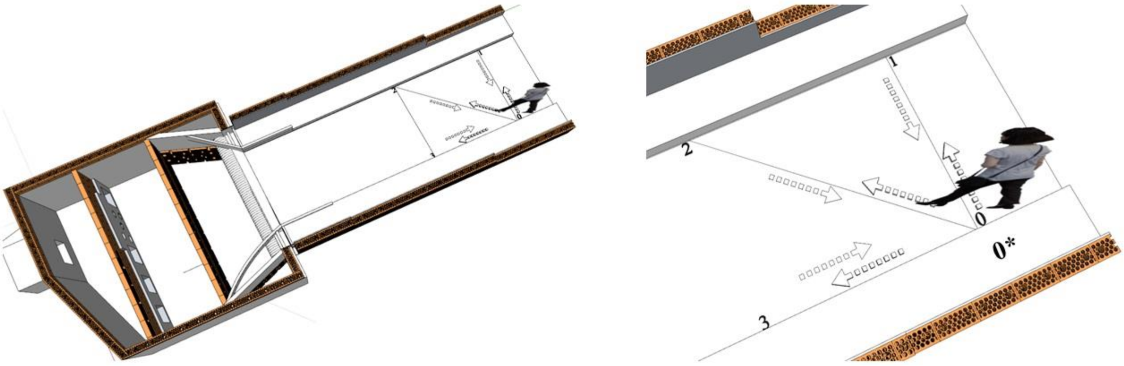


Figure 7. Test protocol sketch

Id:	**14**
P*H (kg·m):	85.33
Height H (m):	1.61
Mass P (kg):	53
Age (years):	24
Combination:	6
Visibility:	Good
$\bar{y}$ [m]:	0.069
y_{max} [m]:	0.085
v[m/s]:	3.50
Id:	**24**
P*H (kg·m):	99.12
Height H (m):	1.68
Mass P (kg):	59
Age (years):	29
Combination:	5
Visibility:	Bad
$\bar{y}$ [m]:	0.114
y_{max} [m]:	0.130
v[m/s]:	2.32

Figure 8. Examples of two instability situations. Good visibility, hands busy and wearing flip-flops for subject Id 14. Bad visibility, hands free and wearing flip-flops for subject Id 24

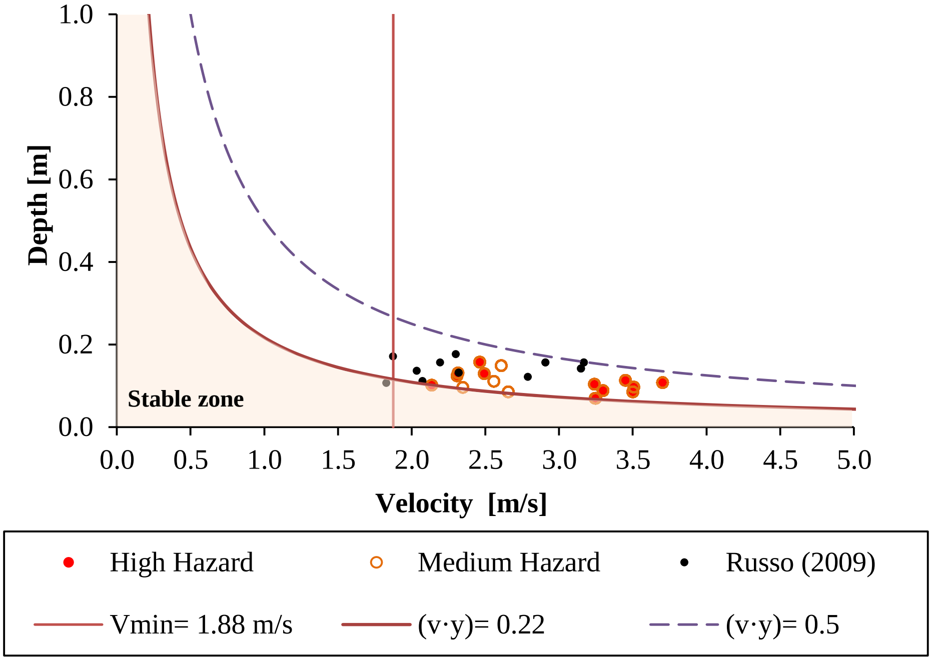


Figure 9. High and medium hazard points representation together with the limit (v·y)= 0.22 $m^2 \cdot s^{-1}$ obtained in the present research and the most habitual limit (v·y)= 0.5 $m^2 \cdot s^{-1}$

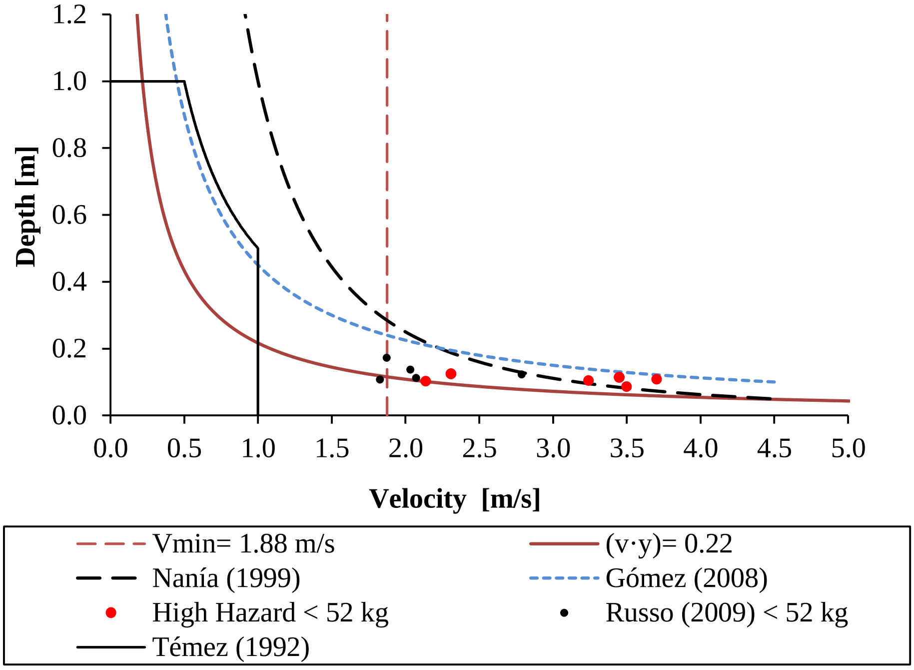


Figure 10. High and medium hazard points for weights lower than 52 kg representation together with the limit (v·y)= 0.22 $m^2 \cdot s^{-1}$ obtained in the present research and other limits proposed by other authors

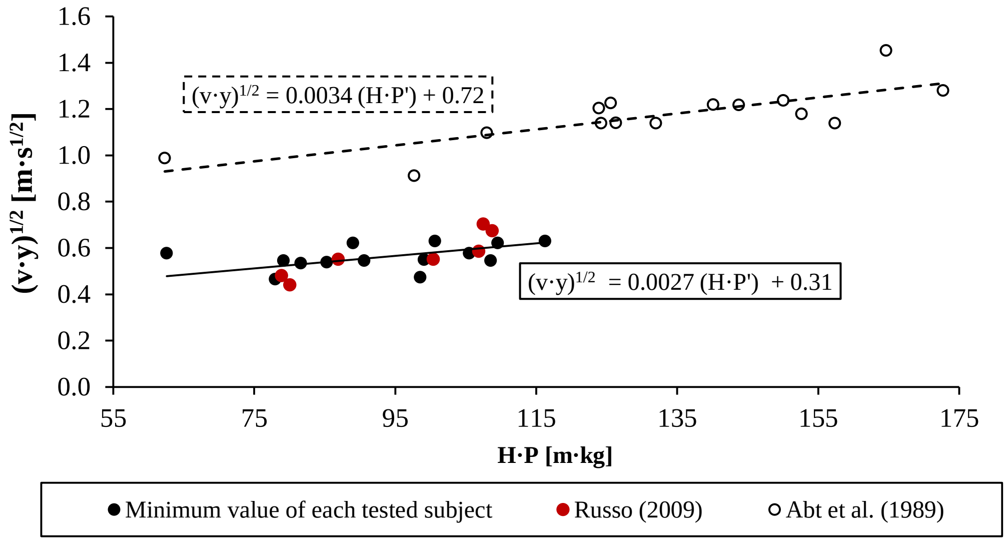


Figure 11. Representation of square root of the product (v·y) versus the product (H·P) of the minimum instability points for each tested subject herein and in Abt *et al.* (1989)

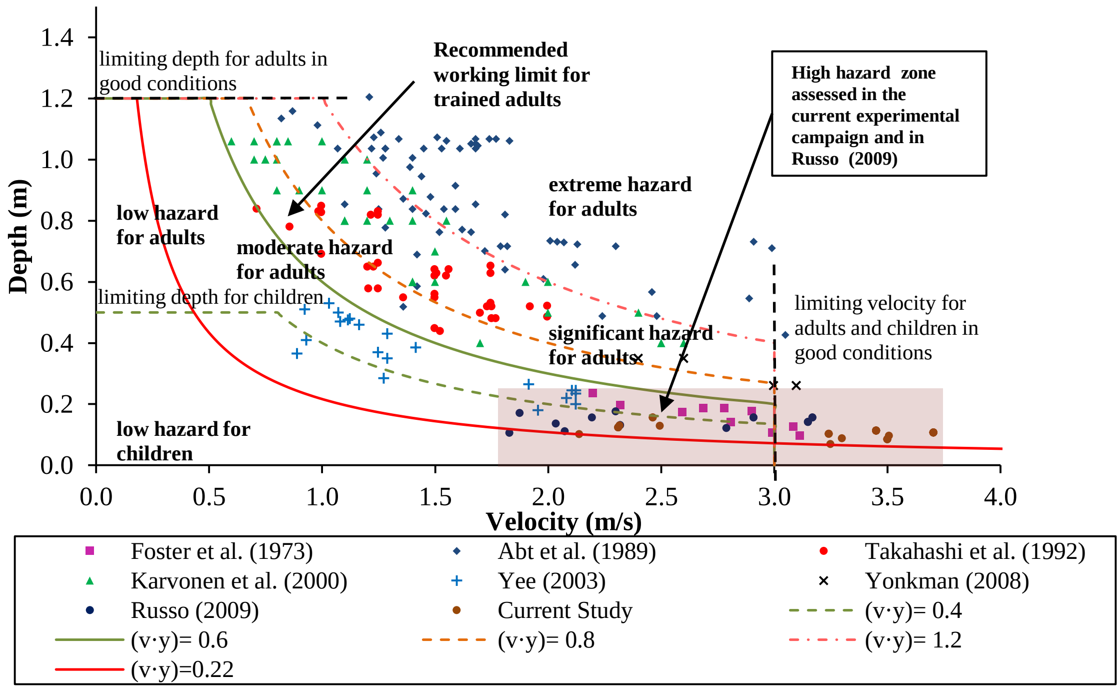


Figure 12. Representation of the AR&R Guidelines stability criteria (Cox et al. 2010) and the instability high hazard points obtained in this research and in Russo (2009) together with the limit function (v·y)= 0.22 $m^2·s^{-1}$ obtained in the present work

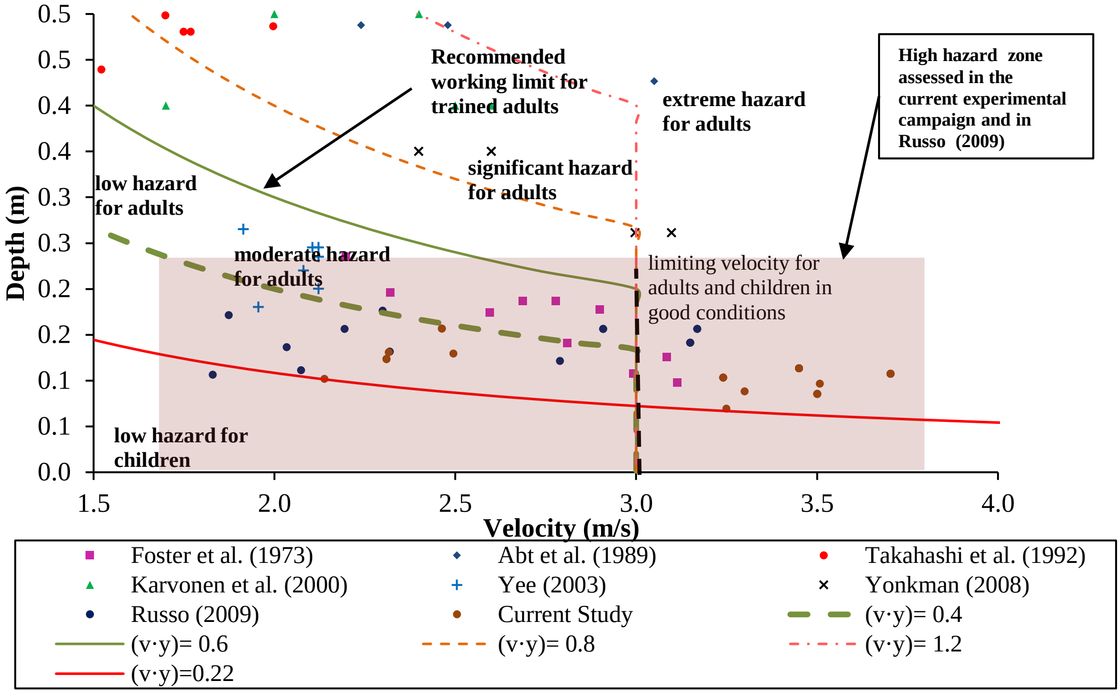


Figure 13. High hazard highlighted zone detail of Figure 12