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DOI

[10.9753/icce.v37.management.129](https://doi.org/10.9753/icce.v37.management.129)

Publication date

2022

Document Version

Final published version

Citation (APA)

Wüthrich, D., Rikkert, S. J. H., & Lanzafame, R. (2022). *Human Stability On Slopes Under Overtopping Waves*. Paper presented at ICCE 2022, Sydney, Australia.
<https://doi.org/10.9753/icce.v37.management.129>

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HUMAN STABILITY ON SLOPES UNDER OVERTOPPING WAVES

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INTRODUCTION

In a world affected by climate change and sea-level rise, intense storms are expected to become more frequent in the future. This implies that our coastal protections will be more often and more intensely affected by overtopping waves, potentially endangering the safety of our coastal communities. The objective of the present study is to investigate the hazard to people/pedestrians by post-wave overtopping flows over an inclined surface, simulating a coastal dike.

Literature agrees that human (in)stability is highly related to the flow depth h and flow velocity v . The first laboratory testing on human stability were conducted by Abt et al. (1989) and Karvonen et al. (2000), suggesting threshold values $0.64 < hv < 1.29 \text{ m}^2/\text{s}$. Jonkman and Penning-Rowsell (2008) showed that human instability can be triggered by two main physical mechanisms: (1) frictional instability; or (2) moment instability. The present study only focuses on frictional instability, which occur when the drag force ($F_{\text{drag}} = 0.5\rho C_D B h v^2$) is larger than the friction between person and soil ($F_{\text{friction}} = \mu mg$), where ρ the water density, C_D the drag coefficient, B the average body width exposed normal to the flow, μ the friction coefficient, m the mass of the person and g the gravitational constant. The critical value of hv^2 can be derived from the horizontal force equilibrium:

$$hv^2 = \frac{2\mu g}{C_D B \rho} \cdot m = C_F \cdot m \quad \text{Eq. 1}$$

where the critical value of hv^2 has a linear relationship with mass through a constant C_F . Based on laboratory studies on mannequins, Xia et al. (2014) developed more detailed expressions for human stability, taking into account body shape, height, weight and soil-foot friction values. Chanson & Brown (2015) tested and compared these results during a real flood in Brisbane (Australia). Sandoval and Bruce (2017) obtained stability data from videos during actual overtopping accidents and successfully compared them against a simple analytical model developed for a person's stability in a flow.

The majority of these studies are based on fluvial flooding (*i.e.* steady flow condition), with little attention to highly unsteady flows, with the exception of some preliminary results conducted in the DeltaFlume in 1992 (Smith 1994, Klein Breteler and Smith 1996). EurOtop (2018) suggests a value of 600 l/m, based on overtopping videos, but without direct tests on people.

Tests on human volunteers are scarce, with the exception of Jonkman and Penning-Rowsell (2008) and Van der Meer et al. (2022), who recently conducted prototype tests of human stability under overtopping waves, providing the following relationship for $3 < v < 8 \text{ m/s}$:

$$h = 0.34 - 0.036 \cdot v \quad \text{Eq. 2}$$

Nevertheless, data remains limited to one single (male) volunteer, preventing any consideration of variability in human stability in safety regulations. Thus, the objective of this ongoing research is to conduct more extensive tests, focusing on the human stability of people with different gender, height and weight, comparing the results with existing literature. A better knowledge on the human stability on coastal dikes under overtopping waves is critical for the development of effective emergency responses and evacuation plans.

EXPERIMENTAL SET-UP

Tests were conducted in the *Interreg Polder2C's* facility, the *Living Lab Hedwige-Prosperpolder*. Here, a wave overtopping simulator was installed on the dike crest, releasing overtopping volumes V from 200 to 2500 l/m over a section 4m wide (Fig 1). A number of 8 human test subjects participated in the tests, including 4 males and 4 females. As detailed in Table 1, their weights ranged from 63kg to 101kg (with equipment) and their heights from 1.55m to 1.83m, therefore providing an extensive and diverse dataset. All participants were located on a 1:3 sloping dike and were tested facing upstream. All participants were safely attached to a lifeline to prevent injuries and guarantee safety (Fig 1c). Participants were exposed to overtopping waves starting at $V = 200 \text{ l/m}$ and then increased by 100 l/m. Each wave was repeated 3 times and for each run a score of 1 (stable), 2 (simple movement), 3 (partial failure) or 4 (total failure) was given. A test was terminated after 3 total failures in a row. All tests were recorded using pictures and videos.

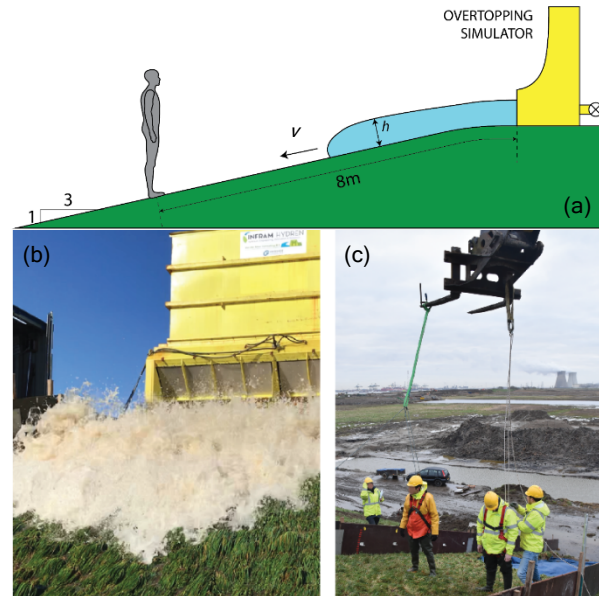


Figure 1 - (a) Sketch of the experimental set-up; (b) view of the overtopping simulator from downstream ($V = 200 \text{ l/m}$); (c) test preparation and safety attachment to lifeline.

Table 1 - Characteristics of test subjects in the present study

	Age	Gender	Height [m]	Weight [kg]
A	33	Male	1.80	82.7
B	36	Male	1.83	101.0
C	28	Female	1.60	64.1
D	27	Female	1.61	62.6
E	33	Male	1.70	81.3
F	27	Male	1.83	82.9
G	32	Female	1.55	70.6
H	25	Female	1.66	64.4

HYDRODYNAMIC WAVE CONDITIONS

Top and side-view video analysis was used to obtain the wave's hydrodynamic properties. These parameters are fundamental to link the human stability to the hydraulic properties of the unsteady flows. The **wave front velocity** was obtained through top view videos recorded with an acquisition frequency of 60 fps. Based on these images, the average wave front velocity at $x = 8\text{m}$ was computed as $v = \Delta x / \Delta t$, where Δx is the distance between the two measurement locations and Δt the corresponding wave travel time. Results led to wave front velocities in the range of 3.1-7.2 m/s (Fig 2a), with negligible differences between $\Delta x = 4$ and 6 m. The **water depth** h was obtained through side videos with a frequency of 30 fps, showing thicknesses up to $\sim 0.3\text{m}$ for largest volume (*i.e.* 2500 l/m). In the absence of more specific studies, the equivalent non-aerated flow depth h_0 was assumed $h_0 = (1 - c) \cdot h$, with c the aeration coefficient. Previous studies on similar flows showed that air entrainment may easily become 30-50% (Klein Breteler and Smith 1996, Van der Meer et al. 2022), and therefore herein assumed $c = 0.4$.

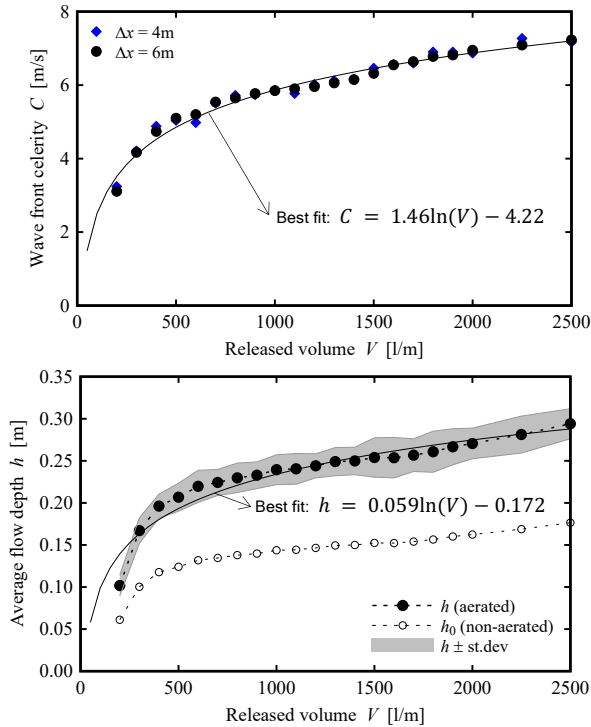


Figure 2 - Hydrodynamic properties of the generated waves: (a) wave front velocity; (b) flow depth.

VISUAL OBSERVATIONS

Eight human subjects with different characteristics were tested with increasing waves until a complete failure was observed. As expected, failure was dominated by friction instabilities, *i.e.* the drag force exerted by the flow became larger than the friction resistance between the feet and the ground. For all tested subjects, this resulted in a sliding of both feet in the downstream direction (Fig 3b). Despite differences associated with the participant's behaviour and body geometry, some common trends could be observed. Firstly, it was noted that all participants used their hands and body to balance the impact, which allowed to sustain larger waves, as shown in Fig b and c. Secondly, in line with Van der Meer et al. (2022), failure was not a sudden event, but some partial instabilities were observed prior to a complete instability, including some small localised movements and the failure of one single leg (Fig 3a,c,d). This shifted the complete weight on the one still-standing leg, increasing the normal force, and therefore the friction resistance, which allowed to withstand higher waves. Lastly, it was also noted that after the first failure, most people were able to withstand the second wave with the same intensity, showing some kind of 'learning process', already hypothesised in literature.

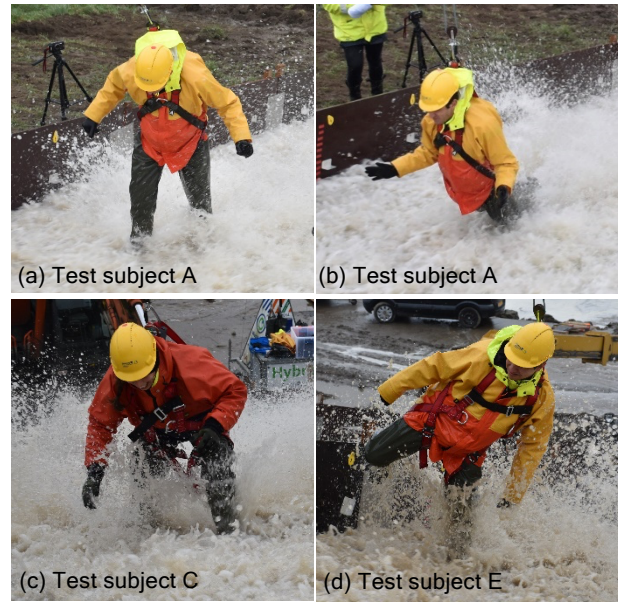


Figure 3 - Pictures of tests on human (in)stability.

RESULTS

Results obtained in the present study were compared to datasets and stability equations available in literature. The good agreement in Fig 4 for test subject A (Male, 33, $m = 82.7\text{kg}$) shows consistency with previous studies, in particular with the expressions by Sandoval and Bruce (2017) and Van der Meer et al. (2022). Present results also showed that each person became unstable for a different combination of velocity and flow depth $h_0 v^2$, suggesting a great variability of the hydrodynamic conditions that led to instability. A closer look revealed that weight was the most critical parameter when assessing the stability in overtopping waves, with heavier people (*e.g.* test subject B, $m = 101\text{kg}$) being able to withstand up to $h_0 \cdot v^2 = 5.49 \text{ m}^3/\text{s}^2$ (*i.e.* $V = 1200 \text{ l/m}$), while

lighter people (e.g. test subject C, $m = 64.1\text{kg}$) already became unstable for $h_0 \cdot v^2 = 4.13 \text{ m}^3/\text{s}^2$ (i.e. $V = 700 \text{ l/m}$). This showed that the limit suggested by EurOtop ($V = 600 \text{ l/m}$) is suitable for light-weighted people ($<70\text{kg}$), but conservative for heavier people. In Fig 5 current data were compared to previous datasets by Abt et al. (1989) on concrete and steel surfaces, confirming the relevance of weight (and therefore friction) on the stability. Present results showed more stable conditions compared to Abt et al. (1989), probably associated with the overall larger friction factor of the 1:3 sloping grass compared to steel or concrete. Analysis of present data yielded a value $C_F = 0.059$, which agrees well with data by van der Meer et al. (2022) on a similar sloping grass surface. Nevertheless, the model in Eq.1 does not consider the effect of slope, thus pointing out the need for future work.

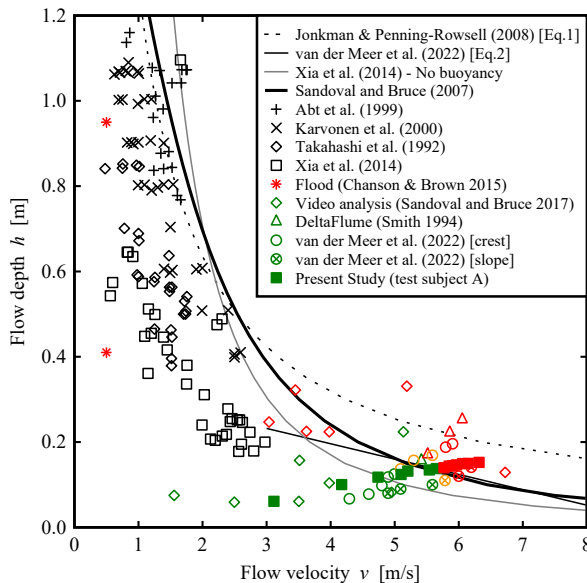


Figure 4 - Comparison of results for test subject A (Male, 33, 1.8m, 82.7kg) with previous studies. Colours: green = safe, orange = initially unstable, red = unstable.

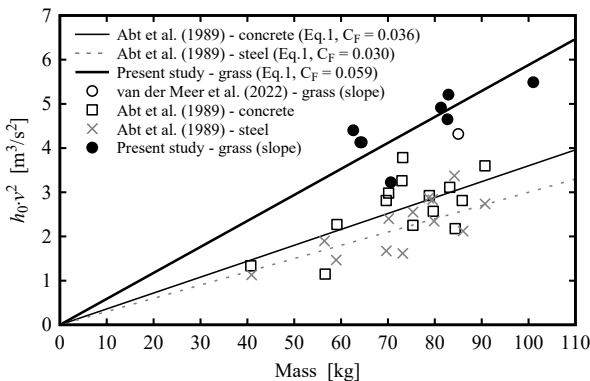


Figure 5 - Effect of body mass on frictional stability and comparison with previous studies.

CONCLUSION

The present study investigated experimentally the (in)stability of people during post-wave overtopping flows over an inclined surface, simulating a coastal dike. Test were conducted on a real dike with a slope 1:3 and

waves were generated using an overtopping simulator. Eight volunteers with different gender, age, weight and height participated to the study, providing a diversified dataset. Observations showed that frictional instability was not a sudden event and all participants used hands and body movements to counterbalance the action of the flow. Critical conditions for stability were shown to be in line with literature for steady and unsteady flows, confirming the importance of body weight. Compared to previous studies, present results showed more stable conditions, due to the larger friction of grass surfaces. Overall, this study provided new prototype and human-based data, contributing to a better understanding of the role of human variability and diversity. Nevertheless, more in depth analysis should be conducted on these issues, for a more comprehensive assessment of the stability of humans during extreme events.

ACKNOWLEDGEMENTS

The authors are grateful to the colleagues and volunteers who joined the project and would like to thank Prof. Van der Meer for his constructive comments. The financial support of the *Safety and Security Institute* (TU Delft) and of the *Interreg P2C* project are acknowledged.

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