Conference Paper, Published Version

Kerpen, Nils; Schoonees, Talia; Schlurmann, Torsten

A Review of a Model Scale Family Related to Wave-Induced Responses of Stepped Revetments

Verfügbar unter/Available at: https://hdl.handle.net/20.500.11970/106605

Vorgeschlagene Zitierweise/Suggested citation:
Kerpen, Nils; Schoonees, Talia; Schlurmann, Torsten (2019): A Review of a Model Scale Family Related to Wave-Induced Responses of Stepped Revetments. In: Goseberg, Nils; Schlurmann, Torsten (Hg.): Coastal Structures 2019. Karlsruhe: Bundesanstalt für Wasserbau. S. 1077-1085. https://doi.org/10.18451/978-3-939230-64-9_108.

Coastal Structures 2019 - Nils Goseberg, Torsten Schlurmann (eds) - © 2019 Bundesanstalt für Wasserbau
ISBN 978-3-939230-64-9 (Online) - DOI: 10.18451/978-3-939230-64-9_108

A Review of a Model Scale Family Related to Wave-Induced Responses of Stepped Revetments

N. B. Kerpen, T. Schoonees & T. Schlurmann
Ludwig-Franzius-Institute, Leibniz University Hannover, Hannover, Germany

Abstract: The responses of stepped revetments under waves were studied at the Ludwig-Franzius-Institute over the past seven years in a number of hydraulic model test campaigns at multiple geometrical scales. The research started off with small scale tests with regular waves to understand principle drivers in the hydraulics over a stepped revetment the investigations resulted in large scale tests with prototype conditions to quantify scale effects. The present paper provides (i) a summary of a number of hydraulic model tests focusing on stepped revetments in different scale and purpose, (ii) a discussion about the influence of the model scale and the wave characteristics on the significance of results and (iii) a comparison of findings from the different model tests. In small scale tests process-related knowledge about the interaction of waves with stepped revetments of different geometries was acquired. Observed phenomena and uncertainties in the discussion of results required additional tests with different objectives. Finally, scale effects could be studied by conducting and analyzing large scale model tests as reference.

Keywords: Coastal structures; Stepped revetment; Wave overtopping; Scale effects; Physical model test

1 Introduction

To estimate the performance of the wave overtopping reduction of a revetment with a stepped slope at a prototype site (Fig. 1) a laboratory model test of the coastal structure was conducted in a wave flume. The purpose of these model tests was to estimate the required freeboard height to derive a reliable protection regarding site-specific storm conditions by a cost-efficient realization. The beneficial aspect of a stepped revetment is a reduced required freeboard height compared to a smooth revetment due to the increased roughness. In parallel, the revetment is safely accessible for people

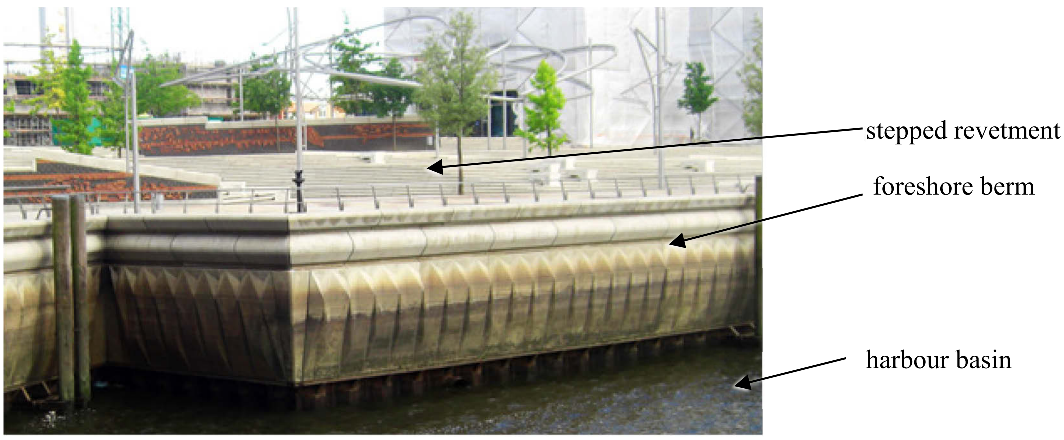


Fig. 1. Impression of the Marco Polo Terraces with dominant foreshore berm and adjacent stepped revetment located at a former harbor basin in Hamburg, Germany (view from offshore the harbor basin).

which is an advantage for coastal protection in urban locations. It turned out that the stepped revetment was feasible to reduce the wave overtopping volumes compared to a smooth slope. But due to the site-specific boundary conditions (e.g. the dominant foreshore berm) the individual reduction performance of the revetment was affected.

The gained results from these initial tests of the stepped revetment were promising as overtopping volumes could be reduced 2 to 5 times with respect to smooth slopes (Kerpen et al., 2014). An extensive literature review (Kerpen and Schlurmann, 2016) revealed general knowledge gaps regarding the principles and processes driving the overtopping reduction. A coherent process understanding was missing until now although there were more than 60 years of research and over 30 publications, scientific reports and manuals available focusing on wave interactions with stepped revetments.

The present paper describes the systematically procedure that was followed to enable uniform conclusions regarding wave-induced responses of stepped revetments based on findings from several additional model tests and before mentioned literature. In the section that follows, principles about the choice of a model scale and wave characteristics are shortly introduced. Section 2 provides an overview of conducted model tests and their individual purpose. The findings from the different tests are discussed in section 3 including a sub-section that addresses three lessons learned. Finally, the conclusions are given in section 4.

1.1 Model scale and wave characteristics

The purpose of a physical model is decisively defined by Hughes (1993) as follows: "A physical model is a physical system reproduced (usually at a reduced size) so that the major dominant force acting on the system are represented in the model in correct proportion to the actual physical system". Ideally, similitude between model and prototype is realized regarding the geometric shape, the kinematics of various motions and the dynamic forces acting in the model and prototype (Goda, 2010). But complete dynamic similarity is hardly ever possible to achieve. In general, the model design, the model scale and measuring effects affect each model result. It is the challenge for physical modelers to decide how far these effects can be neglected in the model design (Heller, 2011). Thus, depending on the target of a physical model, its complexity and scale may differ. Section 2 provides a brief description of the procedure and assumptions underlying the different sets of hydraulic model tests conducted in order to understand the interaction of waves with stepped revetments. It is indicated, that it is not always required to conduct full-scale model tests. Also small-scale tests can provide valuable insights to hydraulic phenomena. But, the significance of small-scale results is more valuable in terms of the general process understanding than in the quantification of individual terms.

The choice of the wave characteristics in a hydraulic model is always based on the objective of the tests. In context to the analysis of wave-induces responses with coastal structures studies with regular waves can contribute to understand general principles and processes of a system performance. Furthermore, specific aspects of a wave with an individual characteristic (e.g. a specific wave steepness) can be analyzed. The wave-by-wave repeated system behavior enables a more distinct detection and observation of hydraulic phenomena to the researcher. The requirement of a lower number of generated regular waves compared to tests with wave spectra enables short test durations and the possibility to conduct a larger number of tests in short time. By these tests, general trends can be defined in the system performance.

Nevertheless, tests with irregular wave trains are required to consider the effects of the deviating sequence of individual waves present in a natural wave spectrum (Goda, 2010). This inhomogeneity has a significant effect on the wave-induced responses (e.g. stability (Jensen et al., 1996) or wave overtopping (Tsuruta and Goda, 1968)) of a coastal structure. Furthermore, an adequate number of irregular waves in a wave train is required for a stochastically representative reproduction a wave spectrum (Daemrich et al., 2012). The use of irregular wave trains in hydraulic models enables a final quantification of processes for a reliable design (EurOtop, 2018). With this information in mind the following chapter provides an overview of the sequence of tests conducted related to wave-induced responses of stepped revetments.

2 Overview of conducted hydraulic model tests

Since 2012, a variety of approaches have been investigated at Ludwig-Franzius-Institute to understand the principles of the wave interaction with stepped revetments. Conducted hydraulic model tests were based on an ongoing literature review focused on this topic (Kerpen and Schlurmann, 2016).

Based on a request from an engineering company in 2012 a first model test on the wave overtopping at a stepped revetment (Froude scaling law, model scale 1:5) was conducted in 2013. Slopes gradients of 1:2 and 1:3 were analyzed. A sketch of the model set-up is given in Fig. 2. It turned out that a stepped revetment is feasible to reduce the wave overtopping volumes compared to a smooth slope. The milder slope was more effective than the steeper slope. But, due to site-specific boundary conditions a dominant foreshore berm had to be implemented to the model which affected the individual reduction performance of the revetment alone. Conclusions of general purpose for stepped revetments could therefore not be drawn. Results of tests with regular waves are documented in Kerpen et al. (2014).

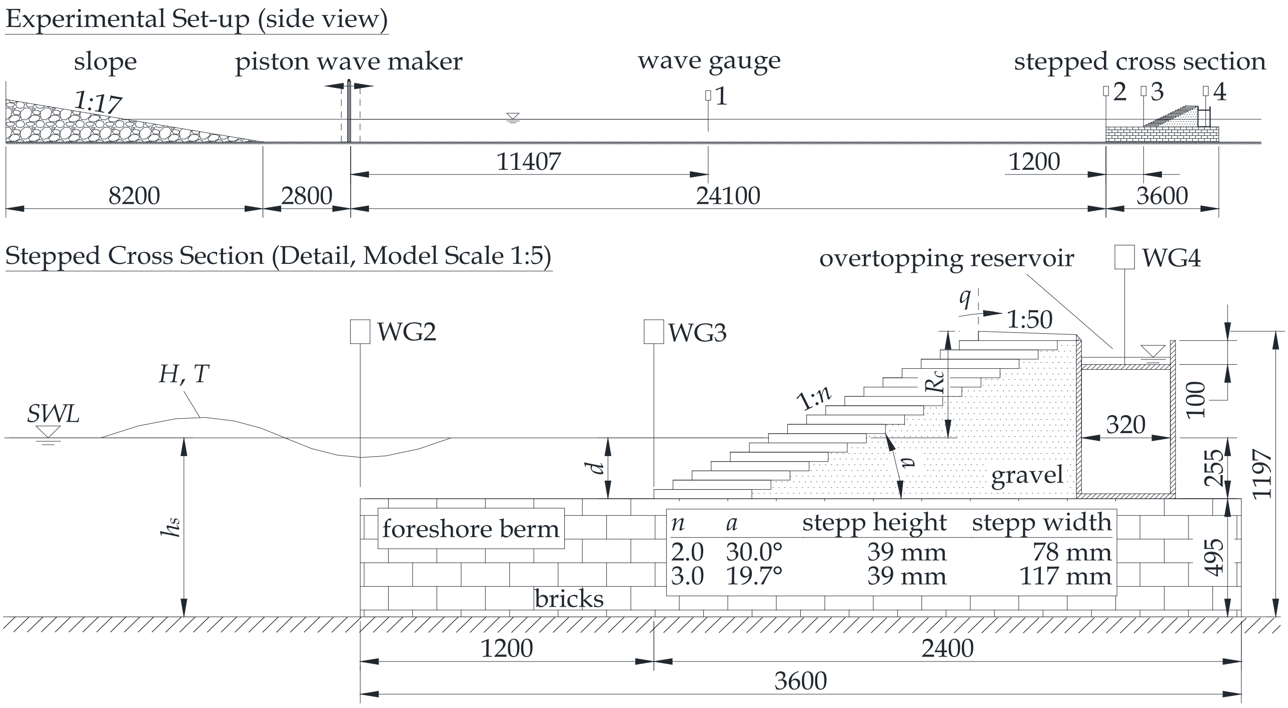


Fig. 2. Experimental set-up of the case study, detail of the stepped cross-section and position of data acquisition devices (measures in [mm]).

In a conceptual experimental realization in 2014 (Fig. 3) the authors studied the wave run-up induced by regular waves on a uniform stepped revetment in a scale of about 1:50 (step ratio: $0.08 < S_h/H < 0.33$, slope: $cot\alpha\{1; 2; 3\}$). Intention of the tests was a first impression of the run-up reduction performance related to the ratio of the step height and the wave height in alignment with the slope of the structure. These tests were unaffected by effects of foreshore berms. The set of tests should

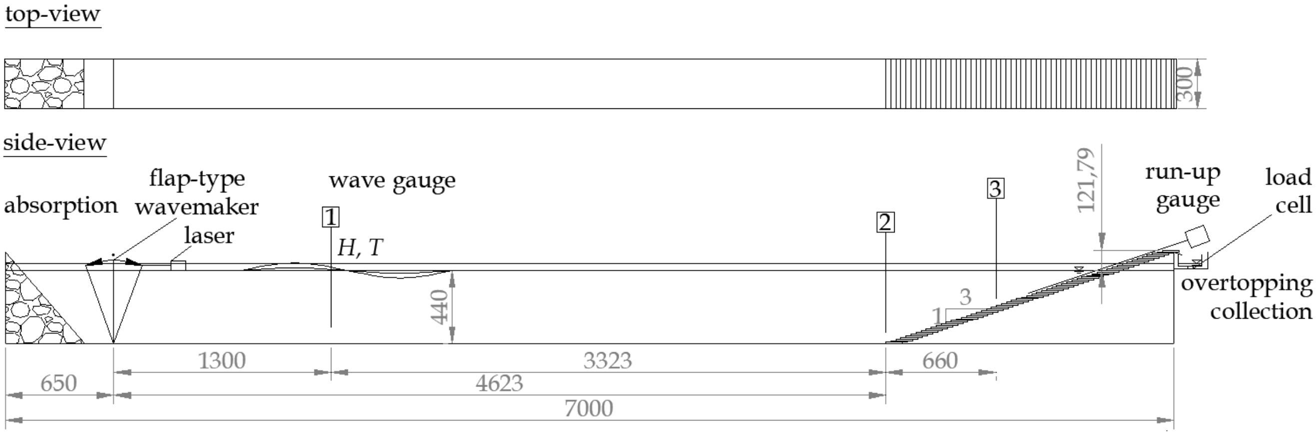


Fig. 3. Experimental set-up of the conception study in top- and side-view (measures in [mm]).

highlight driving parameters and exclude more negligible ones. The relatively small model scale enabled a quick and cost effective model construction. In addition, the general influences of shape adaptations of the steps (offshore inclined step faces, round step edges) were studied. The flap-type wave maker enabled a generation of first order regular waves without active reflection compensation. It was observed, that the wave run-up was reduced more effectively for milder slopes and for larger step heights. A modification of the step face (inclination towards offshore, round step edge) lead to negligible differences compared to vertical step faces. Despite a consideration of an applicable small model scale (Hughes, 1993; Heller, 2011) the overall turbulent wave run-up process appeared artificial and led to conclude that the results are obviously affected by scale effects.

Based on the findings from the conceptual tests and insights of an intensive literature study summarized in Kerpen and Schlurmann (2016) a new model set-up was derived (Fig. 4). The purpose of the new model set-up was addressing the influence of wave spectra regarding (i) wave reflection, (ii) wave run-up, (iii) wave overtopping and (iv) wave impact pressures on stepped revetments. Overall results are published in Kerpen (2017). Summarized it was found that for wave spectra the reflection coefficient of a stepped revetment is high ($0.6 < C_r < 0.95$) if the step height is larger than two times the wave height and moderate ($0.35 < C_r < 0.6$) for smaller step heights. Depended on the step ratio and the Iribarren number the wave run-up heights could be reduced by $10 - 60\ \%$ compared to plain slopes. It was found that the wave run-up and wave overtopping can be reduced with increasing step heights up to a step ratio of $H_{m0}/S_h = 2$. For larger values the reduction capability decreases again. Details of the findings from wave impact pressures on stepped revetments are published in Kerpen et al. (2018). It was found that horizontal and vertical impact loads increased with a decreasing step height. Furthermore, the impact duration decreased for increasing step heights. The overall impact properties for stepped revetments showed comparable rising times and process characteristic to vertical walls.

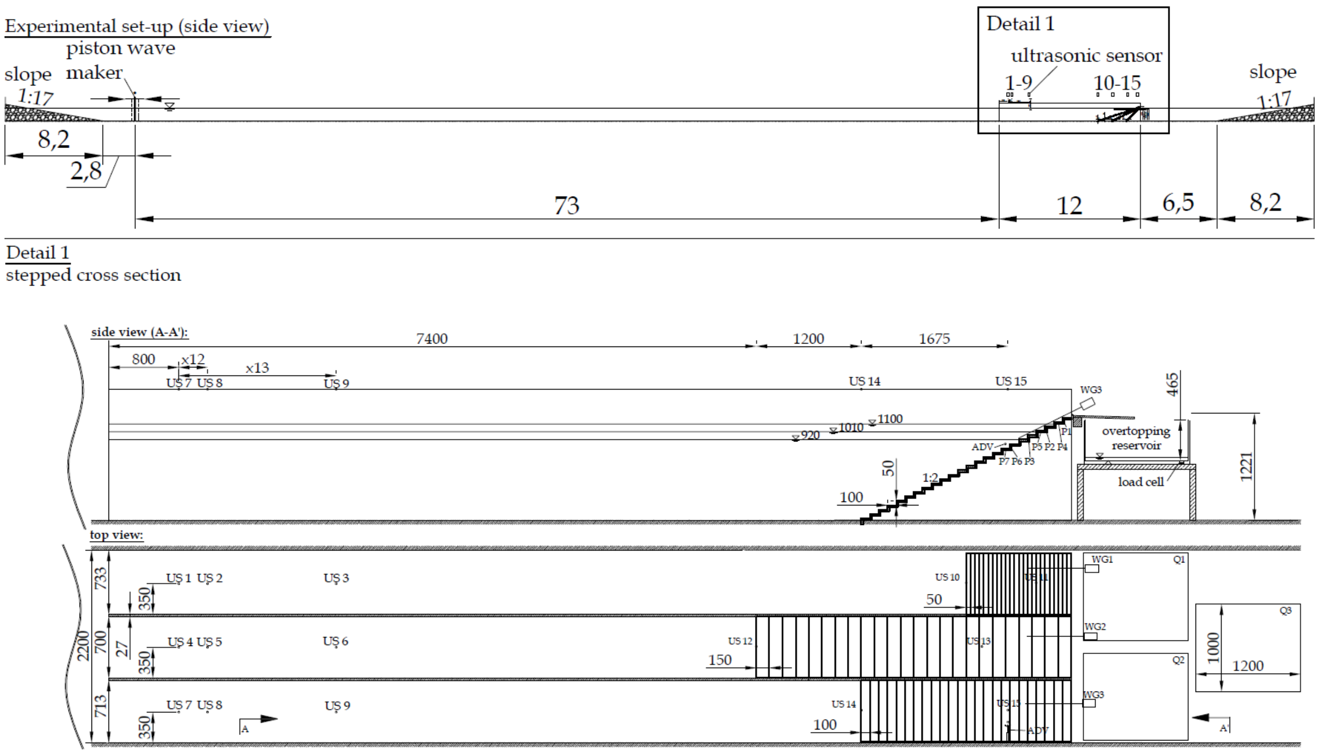


Fig. 4. Experimental set-up of the detailed study (measures of the side view [m], measures of the detail in [mm]).

As the former model tests showed the need of adequate boundary conditions for wave overtopping predictions a long wave propagation length was enabled in front of the model. Hence, the model was constructed far away from the wave maker and not close by, where the observation of the vorticity over the steps would have been possible through a glass window in the side of the flume. It turned out, that the wave-induced turbulence had a major influence on the energy dissipation within the run-up process of the waves. Accordingly, a deeper study of this phenomenon was required and an additional model test was conducted in front of the former mentioned glass window. A reduced set of tests was conducted with regular waves to study the aeration and vorticity over the step edges for waves with different steepness. Results are published in Kerpen et al. (2017). A decrease in the energy dissipation was found for a decreasing wave steepness.

One of the advantages of a stepped revetment is the effective wave run-up reduction also for steep gradients in correlation with a save access to humans. Hence, it is cost effective, to build the revetment as steep as possible and it was decided to test slopes from 1:1 up to 1:3. Comments from an allocated review group in the research project WaveSTEPS (BMBF, 03KIS118) claim the additional study of a 1:6 sloped stepped revetment for reference as many coastal protection sites in Germany are constructed with such a slope. So, an additional model test series was conducted with this relatively mild slope and the wave overtopping performance was studied (Fig. 5). Results were published by Schoonees et al. (2018). In comparison to a smooth slope a reduction in wave overtopping can be achieved. Compared to results from steeper slopes studied by Kerpen (2017) the reductive effect of the steps on wave overtopping for breaking waves became lower for the gentle sloped stepped revetment.

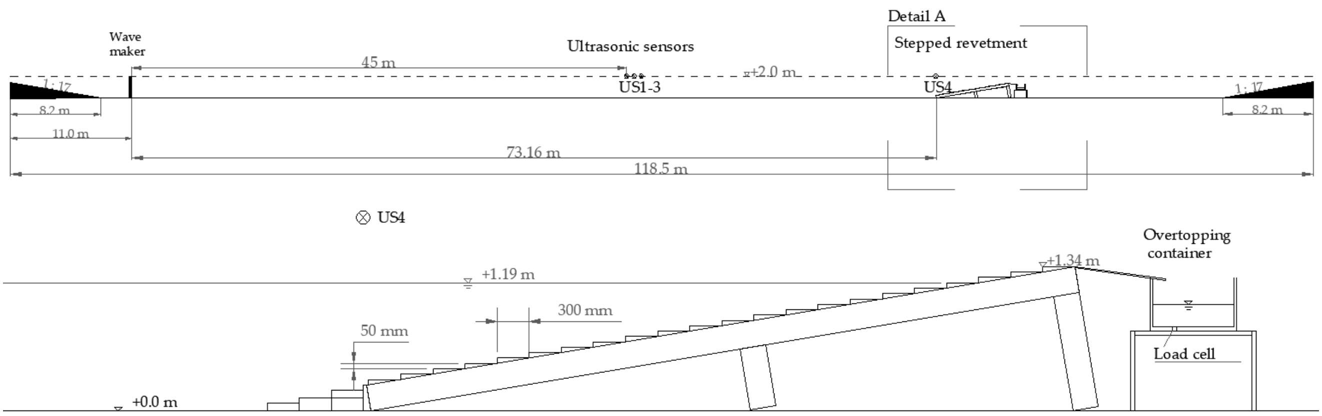


Fig. 5. Experimental set-up of the mild-slope study (measures as given).

It could be observed from all former studies that the aeration during the wave run-up process had a strong influence on the wave run-up itself. In parallel, also wave impact pressures and wave overtopping volumes at stepped revetments are affected and are therefore finally tested in a prototype scale in 2018 (Fig. 6). Geometrical and hydraulic related parameters of these tests were limited based on the findings from the numerous studies already conducted. The realization of these tests was funded by BMBF (03KIS118). The detailed analysis of the large scale data is ongoing. Preliminary overtopping results indicate that empirical predictions based on small scale tests (Van Steeg et al., 2018; Kerpen et al., 2019) underestimate the derived influence factor for roughness.

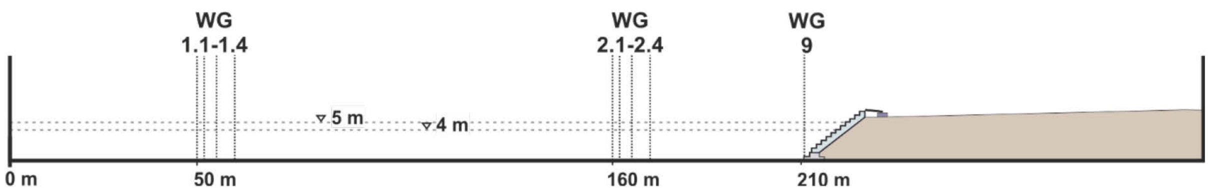


Fig. 6. Experimental set-up of the large-scale study (measures as given).

A general overview of the conducted hydraulic model tests at Ludwig-Franzius-Institute with respect to years of conduction, model scale, focus of the tests, publication reference and details of the boundary conditions is given in Tab. 1.

Tab. 1. Summary of conducted model tests according to the year of conduction, model scale, focus of the tests, publication reference and details to boundaries of the tests.

year	scale	focus of tests	published in	type of waves	step heights [m]	slope [$cot\alpha$]	range wave height [m]	number of tests
2014	1:50	concept study	-	Regular	0.005, 0.01	1; 2; 3	0.03 – 0.06	120
2013	1:5	overtopping	(Kerpen et al., 2014)	Regular	0.039	2; 3	0.11 – 0.16	29
2014	1:10	reflection, run-up, overtopping, impact pressures	(Kerpen, 2017; Kerpen et al., 2018, 2019)	Spectra	0.05; 0.3	1; 2; 3	0.07 – 0.20	102
2015	1:10	turbulence, energy dissipation	(Kerpen et al., 2017)	Regular	0.05	2	0.11 – 0.16	14
2016	1:5	milder slopes	(Schoonees et al., 2018)	Spectra	0.05	6	0.16 – 0.23	13
2018	1:1	scale effects	-	Regular, Spectra, Solitary	0.167; 0.5	3	0.33 – 1.70	80

3 Discussion

The aforementioned characteristics and differences of wave breaking, wave run-up and wave run-down between small-scale (1:6 slope) and large-scale tests (1:3 slope) are highlighted exemplarily in Tab. 2. It is clearly visible, that the aeration in the small-scale tests was much lower in all stages of the wave interaction. Especially the wave run-down showed a lower air entrainment in the small scale tests. Troch et al. (1998) observed a wave run-up height of about 50% higher at a prototype rubble mound breakwater compared to accepted calculation methods based on physical model tests. Besides the negligence of wind-driven effects in most laboratory tests, the influence of an inadequate reproduction of turbulence and aeration in the run-up process affects this finding. A correction method was derived by De Rouck et al. (2005). But, a validity of this approach for stepped revetments has not been proven yet.
The selection of the model scale and scientific focus depends on the one hand on the constraints in available funds, time, research infrastructure or individual scientific knowledge and on the other hand, the sensitivity of a phenomenon to be observed regarding scale. Fig. 7 illustrates conceptually the dependencies of the aforementioned boundary conditions on the model scale. Whereas small scale tests can be conducted relatively cost effective in short time with a large number of tests per day the admitted scale effects are comparatively high. With an increasing model scale the uncertainties of findings decrease. Also scale effects decrease, however a significant avoidance is only feasible for tests in prototype scale. The possible number of tests runs per day decreases accordingly to the increase of the model scale as the same number of waves requires more time (Froude scale).

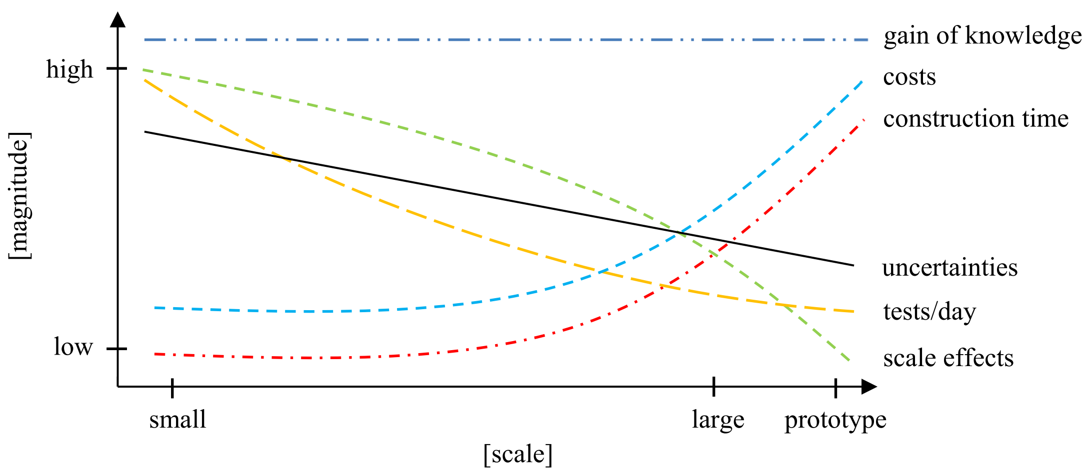
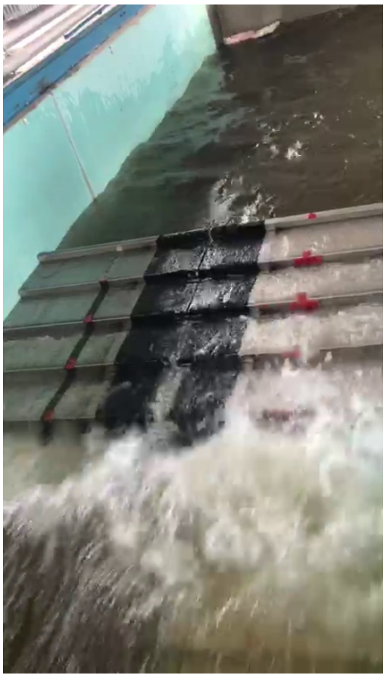
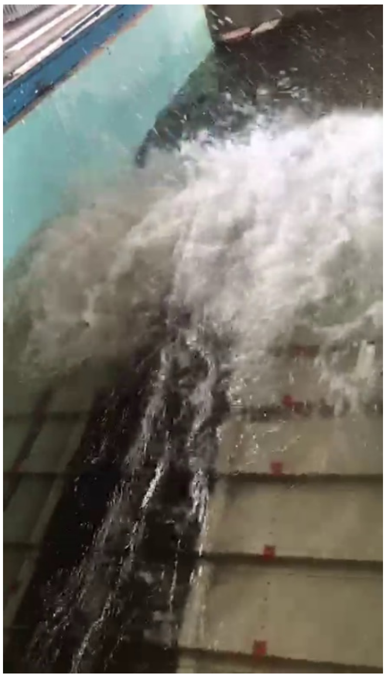


Fig. 7. Dependencies of costs, construction time, tests/day, scale effects and gain of knowledge on the model scale.

Tab. 2. Characteristics and differences of wave breaking, wave run-up and wave run-down in small-scale (1:6 slope) and large-scale tests (1:3 slope).

scale	wave breaking	wave run-up and overtopping	wave run-down
small-scale			
large-scale			

Costs and construction time of the model increase exponentially with the model scale due to

- the large amount of material – often heavy – needed for construction,
- comparatively large distances between sensors and data acquisition,
- a more complex fixation of instrumentation in the model due to higher wave-induced forces,
- higher amount of consumables and power consumption to run the infrastructure.

Despite the significant differences of the impact of the model scale on the diverse properties the gain of knowledge can be always high for results from each model scale, if the test addresses the right questions. To study general effects of a problem an extensive test series can be conducted in a relatively small scale with a comparable large number of tests. Although a quantitative conclusion is not advisable from these tests, a general understanding of processes and their interactions is possible.

A correction regarding scale effects and a quantification of the findings can be based on follow-up tests in larger scales with a reduced number of tests.

The gain of knowledge is a process for individuals, research groups or institutions and its time scale ranges from days to decades. The importance of a thorough and regular literature review is meaningful to consider and critically reflects findings from others.

4 Conclusions

In summary, it has been shown from this review that a number of laboratory model tests were required to improve the understanding of wave-induced responses of stepped revetments. The reduction capability of the wave run-up and wave overtopping compared to plain smooth slopes was derived for a wide range of hydraulic boundary conditions (wave height, wave steepness) and stepped revetments with varieties in geometry (slope, step height).

The key aspects of lessons learned can be listed as follows: (i) Importance of a thorough study of requirements regarding a model test from the perspective of different stakeholders, namely research, industry and government; (ii) a stepwise refinement of the complexity of a hydraulic model is useful; (iii) the constant analysis of literature and the exchange with other researches inspires new ways of thinking and improvements of the final results.

Regarding the first aspect it turned out that from an engineering point of view stepped revetments with a relatively steep slope seem beneficial. However, due to practical application reasons it was requested from the governmental side during the analysis of data to test the additional gentle slope of 1:6. An involvement of all relevant stakeholders in the very beginning would have saved efforts for at least one set of hydraulic model tests.

The stepwise refinement of the model complexity and the step-by-step increase of the model scale enabled the efficient exclusion of detailed studies of the shapes of individual step faces and edges. The eligible neglecting of the only minor influence of these parameters regarding wave run-up and overtopping could be proven in the very beginning by small-scale tests with regular waves. With further progress of the literature review this finding could be confirmed by others (Nussbaum and Colley, 1971; Van Steeg et al., 2012).

During the seven years of research on wave-induced responses of stepped revetment also other research groups investigated on this topic. University of Ghent focused on very steep slopes (Gallach-Sánchez, 2018) and provided a valuable extreme boundary condition. Deltares in the Netherlands provided data from another side-specific study that could be used continuously as reference and benchmark for the present findings (Van Steeg et al., 2012, 2018). The consideration of a required correction of the roughness reduction coefficient for revetments for non-breaking wave conditions, as formerly described in TAW (2002) and applied on the overtopping study of stepped revetments by Van Steeg et al. (2012) reduced the scatter of the present data set for an application to EurOtop (2018) formulae (Kerpen et al., 2019).

References

Daemrich, K.-F., Mai, S., Kerpen, N.B., 2012. On the reasons of scatter in data for design formula evolution, in: 6th CG Joint Symp. on Hydr. and Ocean Eng. Presented at the 6th Chinese-German Joint Symposium on Hydraulic and Ocean Engineering, Keelung, Taiwan, p. 6.

De Rouck, J., Geeraerts, J., Troch, P., Kortenhaus, A., Pullen, T., Franco, L., 2005. New results on scale effects for wave overtopping at coastal structures, in: Allsop, N (Ed.), ICE05 Costlines, Structures and Breakwaters 2005. Thomas Telford, pp. 29–43.

EurOtop, 2018. Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application, Second Edition 2018. ed. www.overtopping-manual.com.

Gallach-Sánchez, D., 2018. Experimental Study of Wave Overtopping Performance of Steep Low-Crested Structures (PhD Thesis). Ghent University, Zwijnaarde, Belgium.

Goda, Y., 2010. Random seas and design of maritime structures, 3. ed, Advanced series on ocean engineering. World Scientific Publ, Singapore.

Heller, V., 2011. Scale effects in physical hydraulic engineering models. Journal of Hydraulic Research 49, 293–306. https://doi.org/10.1080/00221686.2011.578914

Hughes, S.A., 1993. Physical Models and Laboratory Techniques in Coastal Engineering. World Scientific.

Jensen, T., Andersen, H., Gronbech, J., Mansard, E.P.D., Davies, M.H., 1996. Breakwater stability under regular and irregular wave attack. Coastal Engineering Proceedings 1. https://doi.org/10.9753/icce.v25.%p

Kerpen, N.B., 2017. Wave-induced responses of stepped revetments (PhD Thesis). Gottfried Wilhelm Leibniz University Hannover, Germany.

Kerpen, N.B., Bung, D.B., Valero, D., Schlurmann, T., 2017. Energy dissipation within the wave run-up at stepped revetments. Journal of Ocean University of China 16, 649–654. https://doi.org/10.1007/s11802-017-3355-z

Kerpen, N.B., Goseberg, N., Schlurmann, T., 2014. Experimental Investigation on Wave Overtopping on Stepped Embankments, in: Proceedings of the 5th International Conference on Application of Physical Modelling to Port and Coastal Protection. Presented at the Coastlab 14, Black Sea - Danube Coastal Research Association (BDCA), Varna, Bulgaria, pp. 262–269.

Kerpen, N.B., Schlurmann, T., 2016. Stepped revetments–Revisited, in: 6th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science (Coastlab16). p. 10.

Kerpen, N.B., Schoonees, T., Schlurmann, T., 2019. Wave Overtopping of Stepped Revetments. Water 11(5),1035, 17. https://doi.org/10.3390/w11051035

Kerpen, N.B., Schoonees, T., Schlurmann, T., 2018. Wave Impact Pressures on Stepped Revetments. Journal of Marine Science and Engineering 6, 156. https://doi.org/10.3390/jmse6040156

Nussbaum, P.J., Colley, B.E., 1971. Dam construction and facing with soil-cement, Research and Development Bulletin. Portland Cement Association, Chicago, Ill.

Schoonees, T., Kerpen, N.B., Liebisch, S., Schlurmann, T., 2018. Wave overtopping prediction of a gentle sloped stepped revetment. Coastal Engineering Proceedings 1, 99. https://doi.org/10.9753/icce.v36.papers.99

TAW, 2002. Technisch rapport golfoploop en golfoverslag bij dijken, Technical Report. Technische Adviescommissie voor de Waterkeringen (TAW), Delft, Netherlands.

Troch, P., De Rouck, J., Van Damme, L., 1998. Instrumentation and prototype measurements at the Zeebrugge rubble mound breakwater. Coastal Engineering 35, 141–166. https://doi.org/10.1016/S0378-3839(98)00026-X

Tsuruta S., Goda Y., 1968. Expected Discharge of Irregular Wave Overtopping. Coastal Engineering 1968, Proceedings 833–852. https://doi.org/10.1061/9780872620131.054

Van Steeg, P., Joosten, R.A., Steendam, G.J., 2018. Physical model tests to determine the roughness of stair shaped revetments, in: 3rd International Conference on Protection against Overtopping, UK, p. 8.

Van Steeg, P., Wolters, G., van Gent, M.R.A., 2012. Invloedsfactor voor ruwheid van een getrapt talud bij golfoverslag bij dijken: Verslag fysieke modeltesten en analyse, Project Report. Deltares, Delft, The Netherlands.