Flood Risk Management: Research and Practice – Samuels et al. (eds)
© 2009 Taylor & Francis Group, London, ISBN 978-0-415-48507-4

Coastal flooding: A view from a practical Dutchman on present and future strategies

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ABSTRACT: This key note paper intends to feed further discussion on safety against coastal flooding. It will mainly be based on the Dutch situation, where half of the population lives below sea level, but the paper will give enough discussion points for other situations. Observations, conclusions, etc., made in this paper and the presentation are on the personal account of the author, so do not represent any official view from the Netherlands.

The paper briefly describes the history of creating safety against flooding, which started after the large flooding in 1953 in the south west of the Netherlands with almost 2000 casualties. This led to the situation with high and strong dikes, which should withstand a storm with a certain return period between 2,500 and 10,000 years. A discussion started already 15 years ago on how to derive new rules, based on probability of flooding or even on flood risk. This discussion continues, but is now fed with many more calculations on failure of flood defence assets, breaching, inundation, damage, evacuation and last but not least: indestructible dikes.

1 INTRODUCTION

Coastal flooding has always been an important issue in the Netherlands, mainly because the whole country covers more or less the delta of the rivers Rhine and Meuse, and river delta's are by definition low compared to the sea. By protecting the low lying areas with dikes, the areas themselves settled by a metre or more and became even lower than the natural delta. Protection against flooding became more and more important.

The driving force for coastal flooding in the Netherlands will always be a very severe storm. In other countries also hurricanes or tsunamis may be driving forces. River flooding in the Netherlands, however, is closely linked to coastal flooding, mainly for two reasons. First there are estuarine areas where both a storm or a high river discharge may give flooding. The second reason is that the whole safety system in the Netherlands is not separated in coastal or river flooding, but is simply based on flooding in general. The paper will discuss some items where this may lead to wrong interpretations, basically due to not understanding fully the difference between the two driving forces, severe storm or high river discharge.

The word "dike" means any structure made out of soil (sand, clay), often protected by a kind of revetment on the sea or lake side to resist wave attack, and often with grass cover on crest and inner slope. Other countries may use terms like levees or embankments, but the structures are more or less similar.

The paper will cover past, present and future strategies. Interest in coastal flooding is increasing in the Netherlands and not only by coastal or civil engineers. Recently, this has widened the scope of feasibility studies to explore all kind of ideas, like insurance, evacuation, awareness, compartment (dividing a flood risk area in two parts, reducing the consequences of flooding) and also indestructible dikes. This last option would mean a flooding probability of (almost) zero and therefore a flood risk of almost zero.

As already noted, observations, conclusions, etc., made in this paper and the presentation are on the personal account of the author, so do not represent any official view from the Netherlands.

2 DECISIONS AFTER THE 1953 FLOOD

Early February, 1953, a severe storm hit the south west part of the Netherlands and also parts of Belgium and the UK, causing severe flooding with, in the Netherlands, almost 2000 casualties. Although people had warned before about the fairly low dikes and the real possibility of a major flood, the interest in those days after the world war was more directed to build up the country again, than on spending money for dike improvement.

After the flood the Delta Committee was formed with the main goal to present a safety policy against flooding for the future. In those days they performed a kind of flood risk analysis. They concluded that the probability of *flooding* for central Holland (Amsterdam, The Hague, Rotterdam) should be around 1/125,000 per year. But they wanted or had to be practical, and they understood that calculating probability of failure, including all failure mechanisms of dikes, was not yet possible.

The outcome was: design a *safe* dike for an *event* with a probability of 1/10,000 per year. This had two advantages. First it was clear for what kind of event the dikes should be designed and secondly, normal design procedures could be used (instead of describing failure mechanisms leading to flooding, which is necessary for flood risk design).

But the principal of flood risk was not forgotten. It was clear that some parts of the country had more inhabitants and more investments than other parts and consequences of flooding, therefore, would be different. Each part got his own "event" to design for: 1/10,000 per year for central Holland, 1/4,000 per year for most others and for smaller areas even 1/2,000 per year.

Later on, also the rivers were included in the safety policy. It was realized that evacuation would be possible for flooding from a high river discharge, as it would be predicted some days before. This would lead to less casualties and, therefore, most river dikes had to be designed for a water level which would have a probability to occur of 1/1,250 per year. Since then the safety against flooding always considers both, coastal flooding and river flooding. Figure 1 shows all primary flood defences.

It was Edelman (1954) who realized that if three weak points were present at a dike section under severe wave attack, it would fail:

1. If the crest was too low, this would lead to extensive overtopping;
2. If bad quality of material was present, infiltration of water in the dike would be fast;
3. If a steep inner slope was present, it would lead to a slip failure when wet.

Based on analysis of dike breaches in 1953, Edelman concluded that if one of these 3 items was not present, then very often there was no breach. His suggestion was to make inner slopes much more gentle, like 1:3, but allow overtopping. He was convinced that a dike could withstand wave overtopping, as long as the inner slope would be gentle enough.

The final decision for design, however, was different. It was indeed decided to make gentler inner slopes of 1:3, but moreover, not to allow (severe) wave overtopping. The crest height should be designed equal to the 2%-wave run-up level. It was expected that any dike crest and inner slope with grass cover would resist 2% of the incoming waves overtopping the crest.

Figure 1. The Netherlands as delta with all primary flood defences, both for coastal and river protection.

With this design principle all sea dikes have been improved since 1953 and actually, present designs still use these principles. In the nineties the 2%-wave run-up level changed to 1 l/s per m wave overtopping.

3 SAFETY ASSESSMENT

After improvement of most of the dikes in the Netherlands and construction of the storm surge barriers in the Eastern Scheldt and the entrance to the port of Rotterdam, it was realized that the flood protection system should not only be designed and constructed, but should also regularly be checked. The Flood Defence Act of 1996 ruled that every 5 years a safety assessment should be performed on all primary flood defence assets.

This safety assessment has been based on the same principle as for the design: the dike or flood protection asset should be safe for a certain event with a certain probability of occurrence. But there are certainly differences between safety assessment and design.

In a design the actual properties of the material of the dike are not known, but assumed. Safety factors are taken into account and a little more safety does not cost a lot more as it will all be part of a new or improved structure. In a safety assessment the structure is present and material properties can be measured. But including more safety means that the present structure will be disqualified too early and will directly lead to large costs for improvement. The main principle of a safety assessment should be, also indicated in the Dutch safety assessment manuals, that: "A lot may go wrong, but the dike may not breach".

Reality is different. Experience shows that where doubt is present, the dike section will be disqualified. There is probably another reason behind these decisions, not stated publicly. The water boards have to maintain the majority of the dikes. They have to pay the maintenance from local taxes they earn. But major improvements, as a consequence of the safety assessment, will be paid by the government. It is for this reason that water boards can not completely be objective in the safety assessment procedure. There is benefit in obtaining an improved protection.

The safety assessment is quite complex as it has to consider all parts of a dike or flood defence asset, for all kind of failure mechanisms. Certainly in the first assessments, parts were discovered which did not pass the assessment criteria or where assessment criteria were not yet available. In the latter case also design rules were not available and actual design had always been based on experience rather than design rules.

When the results of the first assessments were summarized, it appeared that in about one-third of all the dike sections, parts were disqualified (and had or have to be improved) or an assessment rule was not available (and therefore no assessment result was available). This has been interpreted from two sides. One side states that even with disqualification of parts, there is not a direct threat for flooding and there will be sufficient time to design and improve the part of the dike, such as a stronger revetment or a little higher crest. Lacking knowledge means that this knowledge has to be developed. The other side states that only two-third of all flood defence assets are safe and that the other one-third gives a serious threat. So politicians should release more money for improving dikes and developing knowledge.

A more general conclusion is that the Netherlands has never been more safe against flooding than in the present situation, but that still quite some work has to be done to be safe in agreement with the safety assessment rules.

4 FROM PROBABILITY OF EVENT TO FLOODRISK

The present design and safety assessment rule is that the flood defence asset should withstand an event with a certain return probability or probability per year. It does not explicitly state that the defence asset should also withstand a (much) more severe event, it should only be designed with some or enough safety.

Of course this has led to a discussion on other possible normative rules. Since 1990 a discussion started on better safety codes: from probability of event (present situation) to probability of flooding (breaching of dikes) to flood risk. All three have their pro's and contra's. The probability of flooding is easy to explain to the public: it gives the probability per year that it is expected to get wet feet. The difficulty is that one needs a full description of each failure mode from initial damage up to the initiation of a breach.

Work under Task 4 of FloodSite (Allsop et al., 2007) made a good step by describing most of the failure modes. But the result of a calculation is never better than the failure mode modeled. VNK 1 was the first attempt to calculate flooding probabilities for various areas in the Netherlands. (VNK stands for Safety of the Netherlands calculated and mapped). Real dike ring areas were considered and all possible failure mechanisms. It took a few years by a number of consortia to come up with results for some 10–15 dike ring areas (where we have more than 50).

One conclusion or result was that by this procedure it is easy to find the weakest locations in a dike ring and for what failure mechanism. Upgrading that section directly reduces the probability of flooding. It might be noted, however, that these "weak" sections can also be found by applying the regular safety assessment. The probabilistic method, however, gives how much the probability of flooding would improve, which is not possible with the safety assessment.

The calculations by VNK 1 also showed that some failure mechanisms were not well understood or not modeled well enough. And in such a case uncertainty is taken into account which sometimes led to unrealistically large flooding probabilities. In such a case more study is required to improve the modeling of the failure mechanisms.

Since VNK 1 the modeling has improved and production runs will be made in 2008/2009 to calculate flooding probabilities of all 53 dike ring areas in the Netherlands under VNK 2.

During (and after) VNK 1, a lot more information became available on the consequences of flooding. Numerical tools were developed to model realistically the water flow and inundation in time, assuming one or more initial breaches in the dike ring system. Damages were calculated as well as casualties. Extreme assumptions were made to find upper boundaries. Moreover, it gave insight in inundation depths and the most vulnerable locations in the Netherlands.

Flood risk is the product of probability of flooding and consequences, so probability multiplied by cost (money). There is similarity with an insurance premium. A flood risk could be for example 2 million euro per year. It is not an easy definition to explain to public. It is also not easy to regulate flood risks in a normative rule. Although 15 years ago the final goal seemed to be to come to regulations based on true flood risk, nowadays the insight has changed a little. Probability of flooding, as calculated by VNK 2, will probably be taken as the primary result. In future flood probability may become the normative rule. The *insight* in consequences (damage, casualties) will steer the normative rule, not the product of probability and damage.

5 SAFETY UP TO 2100

Many feasibility studies are going on in the Netherlands and safety against flooding now has interest from a wider professional audience than just civil engineers. On 19 June 2008 a one day conference/workshop (general presentation, workshop discussions, no papers available) was held with the title "The power of water". This conference released the policy for flood defence in the Netherlands and consisted of 3 layers:

1. Prevention is and stays number one. It is always better to prevent anything to happen than to minimize the consequences. More knowledge should be gained on the actual strength of flood defence assets, consequences should be studied and climate change should be taken into account. Innovative solutions should be studied, like indestructible dikes.
2. Spatial planning should include safety against flooding.
3. Reduce remaining consequences by evacuation and awareness.

All points will be elaborated a little more, starting with the new points 2 and 3. Policy makers believe that spatial planning can work if a safety assessment procedure will be part of it. It should lead to decisions not to built new houses or industry in some parts, where for example the area is many meters below sea level. Or it should lead to decisions to raise the level several meters before starting construction.

A large part of the conference did not believe that this second layer would work. The main reason is that spatial planning is in the hands of the local authorities who decide on it, not the government. Local authorities will always decide to improve their own area and will never say: go to the town 10 km further, because their level is higher than here! Another reason is that flooding by sea or river is not an issue in daily politics of a local area.

Evacuation belongs to the third layer. Due to the fact that discussion on flooding always includes both sea and river flooding, some interpretations of phenomena are considered true in both situations. For evacuation this is certainly not the case and only a few people are aware of it.

A high river discharge in the Netherlands, with consequently a high water level against the dikes, is not caused by flash floods, but by very heavy rain in Switzerland and the south of Germany, and probably the Netherlands. It takes days before this water comes to the border of the Netherlands and good computer models are available to predict where, when and how high the water level will come along the river dikes.

In case of an emergency, where predicted water levels may indicate an unsafe situation, there is time to evacuate thousands of people. In 1995, 100,000 people were evacuated in a situation where some dikes were not yet improved and where the safety could not be guaranteed during that high water. In those cases the weather is not too bad for evacuation and there is time enough.

Also for a hurricane, like in the US, there is time to evacuate. Evacuation in such a situation, however, is mainly based on the destructive wind along the coast, not entirely on a probability of flooding.

The possibility of evacuation is often transferred to coastal situations. And this is a complete mistake, certainly for Dutch situations! It may be possible in the UK in rural areas, where for example a small number of farmers live in a relatively small flood risk area, protected by dikes only able to protect against events smaller than 1/30 or 1/100 years (or even less). For each very severe storm warning they should evacuate. But here it will be a very small number of people who are aware of the situation.

Assuming that the dikes in the Netherlands can withstand an event with a return period of 10,000 years, evacuation would only be an option if a storm is expected which would even be worse. At present we are not able to predict whether a storm would be an event with a smaller or larger return period than 10,000 years. It depends also on the local conditions like tide where the worst condition with respect to maximum surge level and wave conditions will occur. This means that we should evacuate the whole north, west and south west of the Netherlands, say around 5–10 million people, for a storm warning with a return period in the order of 1,000 years or more.

But would that be possible? Such a severe storm will already have a wind force close to Beaufort 11 one day before the actual peak of the storm (with then certainly Beaufort 12 and more). Such a 1/10,000 years storm will have a devastating effect on the country. Many roofs will blow away, thousands of trees will break, tiles and everything which was not tied thoroughly, will fly through the air.

In 1999 a short but very strong storm hit the Atlantic coast north of Bordeaux in France. Large areas with trees were completely destroyed. Even after more than two years the trees were not yet all removed, see Figure 2. The storm led to flooding in the Gironde.

Figure 2. Two and a half years after a short but devastating storm, all fallen trees have not yet been removed. Gironde, France, June 2002.

It may be clear: nobody wants to evacuate in such a storm. It would be very dangerous. The only option is to wait in a safe place and, indeed, if a flooding occurs, go to the first or second floor and hope that the house will be strong enough to withstand the water.

So in planning any such evacuation, the division between coastal flooding and river flooding must be made, and it may be wiser not to assume that evacuation is always possible.

It is, however, always good to increase awareness for disasters, like a flooding, which is the second item of the third layer (evacuation and awareness). During such an event power may be shut down, as well as energy, water supply, etc. Awareness and preparations are good, not only for a disaster like flooding, but actually for all possible disasters.

6 SAFETY OF COASTAL DIKES

6.1 *Main failure mechanisms*

Coastal dikes are designed for high storm surges and related severe wave attack. Both the high water level and the waves give the loading to the dike. Two main failure modes exist for coastal dikes. One is the failure of the seaward protection by large waves. A many small and large scale model tests have been performed in wave flumes to find the relationship between wave attack and strength of a variety of revetments, from rock revetments to asphalt layers. We can conclude that we know a lot on strength of these kind of protection systems.

The other main failure mechanism is wave overtopping and failure of the inner slope of the dike. We know a lot about wave overtopping, or actually, the hydraulic behaviour of waves overtopping a dikes, see the Overtopping Manual, 2007. But we have only little experience about how strong dikes are against wave overtopping. This is simply because small scale model testing is not possible, due to the fact that clay and grass can not be scaled down. Until recently, only large scale testing in the Delta flume (the Netherlands) or GWK (Germany) have been options and indeed some tests have been performed in these facilities, in the past and recently.

The fact that the hydraulic behaviour of wave overtopping is known, has led to the idea of the Wave Overtopping Simulator. This new device has been used for erosion tests performed on several real dikes and insight in strength has gained tremendously. Results will be summarized here.

6.2 *Erosion by wave overtopping*

Two mechanisms may lead to failure due to wave overtopping. The first is infiltration of overtopping water into the dike and eventually sliding of the inner slope. The second is erosion of the cover layer of clay and grass by overtopping waves, followed by erosion of the inner slope (clay or clay layer on sand core).

The first mechanism, infiltration and sliding, can only occur if the inner slope is quite steep, see also the points mentioned by Edelman, 1954, in Chapter 2. For this reason most coastal dike designs in the Netherlands, after the flood of 1953, got a 1:3 inner slope. It is assumed that such a slope will not slide due to infiltration of water. But if a steeper slope is present, already 1 l/s per m overtopping would be enough to give sufficient infiltration of water.

This means that for steep inner slopes (steeper than 1:3 or may be 1:2.5) the critical overtopping discharge is already 1 l/s per m. For dikes with an inner slope of 1:3 or gentler we assume that infiltration and sliding is not a governing failure mechanism. Only erosion by overtopping remains.

Till a few years ago hardly anything was known about resistance of inner slopes of dikes with grass against wave overtopping. But in the beginning of 2007 and 2008 innovative erosion tests have been performed for various dike sections. In 2006 the Wave Overtopping Simulator was constructed, see Van der Meer et al., 2006. The basic idea is that a constant discharge is pumped into a box on top of a dike and then the pumped volume is released from time to time in such a way that it simulates overtopping waves in reality. Figure 3 gives an impression of the working of this wave overtopping simulator.

Tests have been performed for mean overtopping discharges starting at 0.1 l/s per m up to 75 l/s per m. In 2007 3 dike sections have been tested, which are reported by Van der Meer et al., 2007, Akkerman et al., 2007 and in the ComCoast reports (*www.comcoast.org*). In early 2008 another 9 dike sections were tested (see Figure 4) at three locations in the Netherlands.

Figure 3. The Wave Overtopping Simulator releases 22 m^3 of water over 4 m width in about 5 s. It simulates a large overtopping wave with a mean discharge of 75 l/s per m.

Figure 4. Damage to a dike section during a test with 75 l/s per m wave overtopping.

Part of the results has been given by Steendam et al., 2008, at this conference. They come to a few preliminary conclusions, mainly based on observation rather than thorough analysis, which still has to be performed. The most important one in relation to actual strength of dikes by wave overtopping is:

It seems unlikely that an inner slope with a clay cover topped with a grass cover (in Dutch situations) will fail due to erosion by overtopping waves with a mean discharge of 30 l/s per m or less. Future research may result in a final conclusion.

A large number of dike sections withstood 50 l/s per m and some of them even 75 l/s per m. No section failed for 30 l/s per m, which gives the basis for the preliminary conclusion.

7 INDESTRUCTIBLE DIKES

7.1 *Case study*

The 10^{-4} event is already very extreme. In stochastic terms a probability of zero does not exist, but "practically zero" can be defined as: two orders of magnitude more safe than now. If a dike can resist a 1/1,000,000 storm can we give it the title indestructible? What do we have to do to make such a dike?

A short feasibility study was made to explore this idea. Four cases (dike sections) were chosen, one in the north along the Waddensea, one directly on the North Sea coast, one in an estuary and one along the coast of the big lakes. All cases showed for the safety assessment situation (event around 1/10,000 per year) an overtopping discharge around 1 l/s per m.

Wave conditions and water levels were determined for the 10^{-4}, 10^{-5} and 10^{-6}-events and then PC-OVERTOPPING was used to calculate the overtopping discharges. These were respectively around 1, 5–10 and 20–30 l/s per m. The 20–30 l/s per m overtopping discharge is still equal to or smaller than the limit of 30 l/s perm.

A preliminary conclusion may be that a design with 1 l/s per m overtopping leads to a robust and "indestructible" dike section (with respect to erosion by overtopping). It should be noted that such a dike should have an inner slope of 1:3 or gentler.

A more extreme event does not only lead to higher water levels, but also to larger waves. Another failure mechanism is stability of the revetment. Most stability formulae are based on the stability number $H_s/\Delta D$, where H_s = the significant wave height (at the toe of the dike), Δ = relative mass density and D = a diameter or thickness.

A larger wave height leads then linearly to a larger diameter or thickness. The increase in wave height from a 10^{-4} to a 10^{-6}-event is more or less the same increase that is required to make the revetment "indestructible". In the case study the increase in wave height was 10–25%. The consequence to make an "indestructible" revetment would be to increase the thickness by at least 10–25% and also to apply the revetment protection to a higher level on the dike, as the 10^{-6} -event has a higher water level.

The conclusion might be that if coastal dikes can already resist a 10^{-4} storm, indestructible dikes are may be closer to become reality than we thought. Moreover, it is already tradition during the past 300 years that every one or two generations the dikes have been improved. There is no reason to believe that this tradition will stop. Improvements in the past few decades have always been designed for a life time of 50 years. It can be assumed that in the next 50 years almost all coastal dikes, or at least a majority, in the Netherlands will be improved again. That is a unique opportunity to investigate and go for indestructible dikes.

It is realized that this is perhaps a situation which is only present in the Netherlands. It is different in situations where the present safety is 1/100 per year or less. But even there, prevention is always better than facing a major flood.

7.2 *Fragility curves*

Safety assessments of flood defence assets are increasingly performed with the technique of structural reliability. All parameters, load parameters (hydraulic boundary conditions) and strength parameters (dike characteristics), are taken into account and expressed as stochastic variables. One of these structural reliability methods is to calculate the failure probability (P_f) of a flood defence, *given a certain water level*. Assembling the failure probabilities for several water levels constructs a fragility curve, see Van der Meer et al., 2008, presented at this conference.

This paper described the situation in the Netherlands, where design events have a return period in the order of 10^{-4} per year. The fragility curve gives the probability of failure given a certain water level, not a return period of that water level. But in an actual case there is a known relationship between the water level (storm surge), including wave conditions, and the return period of that event. Therefore, it is fairly easy to calculate a fragility curve where the probability of failure is give as a function of the return period of the water level or event. Figure 5 gives an example for a large sea dike (one of the case studies discussed before).

The graph shows actually three failure modes:

1. Infiltration of overtopping water and sliding of the inner slope (if the inner slope would be steep). This would occur for an overtopping discharge of 1 l/s per m;
2. Erosion of the inner slope by wave overtopping (the curves with overtopping discharges of 10–50 l/s per m);
3. Piping.

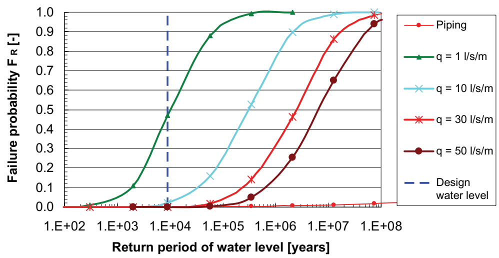

Figure 5. Fragility curves as a function of the return period of the water level.

Piping in this example does not give a serious probability of failure. The 1 l/s per m overtopping discharge gives more or less a probability of failure of 50% for the 10^{-4}-event. This is exactly the design condition.

But the graph gives also a similar impression as the calculations on indestructible dikes: the 50%-probability for 30 l/s per m in this graph gave a return period of 2.10^{-6}, which is more extreme than the 10^{-6}-event. One can say that the differences between the curves for 1 and 30 l/s per m in Figure 5 give the safety between design and failure and that the probabilities for the 30 l/s per m curve actually indicate that this dike section is "indestructible" with respect to erosion by wave overtopping.

8 CONCLUDING REMARKS

The major improvements of coastal dikes in the Netherlands, after the 1953 flood, was based on three principles. Design for an event with a return period around 10,000 years; make inner slopes of a dike at least 1:3; and design for the 2%-run-up level or 1 l/s per m wave overtopping. This has led to high and strong dikes.

A safety assessment procedure was introduced, which has to be performed every 5 years for all flood defence assets. The first assessments showed weak and inadequate parts, which are still being improved.

A new policy on flood defence was released recently, where three layers were introduced. The first still being prevention. The two added layers are to include safety against flooding in spatial planning and to make evacuation plans and to make people more aware of the possibility of a disaster. These two added layers still have to be explored.

The recent destructive tests with the Wave Overtopping Simulator showed that clay with a grass cover on the inner slope of a dike is well resistant to wave overtopping. More resistant than many people thought, including the author.

The fact that dikes in the Netherlands have already been constructed to withstand a very extreme event, with only minor overtopping, makes the step to indestructible dikes within reach. Only a feasibility study was made on a few case studies and more research is required to investigate all consequences, including costs. But it certainly is an opportunity if the next 50 years most coastal dikes will have to be improved once more.

ACKNOWLEDGEMENTS

The Directorate-General Water of the Rijkswater-staat and Deltares are acknowledged for the possibility to explore the idea of indestructible dikes. The Centre for Water Management of the Rijkswaterstaat and the project group on Erosion by Wave Overtopping, including Deltares, Infram, Royal Haskoning and Alterra are greatly acknowledged for recent overtopping tests at the Wadden Sea and the cooperation to come to early and preliminary conclusions on the test results. ComCoast is acknowledged for their support to develop the Wave Overtopping Simulator and to perform the first tests in Groningen. Finally, the Project Organization of Sea Defences (Projectbureau Zeeweringen) is acknowledged for their support to perform the overtopping tests in the south west of the Netherlands.

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