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CLIMATE ADAPTATION OF COASTAL STRUCTURES

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1. Introduction

Projections of sea level rise (SLR) vary in time and go together with large uncertainties (see also Figure 1 for variations in IPCC projections of SLR over time, for the year 2100). Not only best estimates of SLR vary in time, also the estimated uncertainties in SLR vary in time. Not all processes that cause the SLR are fully understood, which is illustrated by recent studies that discuss the rapid Antarctic ice sheet mass loss with a possibility of a much faster SLR than expected before. With rapid SLR significant changes in the hydraulic loading on coastal structures can occur within the lifetime of coastal structures. Since important changes, but with an unknown magnitude, can occur within the lifetime of coastal structures it is wise to anticipate for potential future adaptations, rather than ignoring potential future threats (leading to unsafe situations or high adaptation costs) or constructing coastal structures for the worst-case scenario (leading to un-economical designs). This paper illustrates a method to select adaptation measures for coastal structures for an uncertain future SLR. In addition, knowledge gaps that are relevant for the assessment of the optimal adaptation pathways are identified.

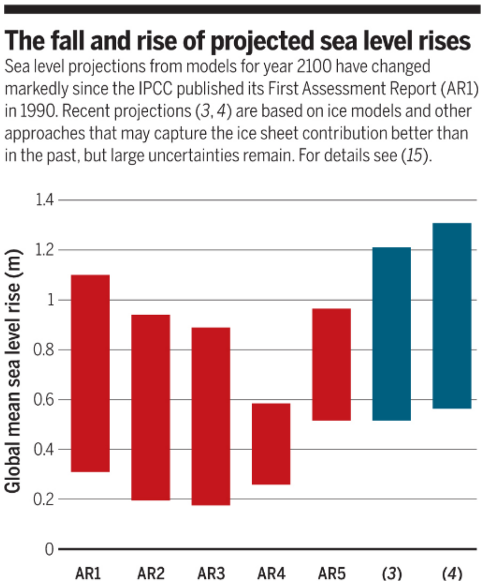

Figure 1. Variations in global sea level rise projections over time (from: Sciencemag.org, 2016).

2. Climate adaptation of coastal structures

SLR does not only lead to an increased water level that needs to be taken into account in the design of coastal structures, for structures exposed to wave loading in depth-limited conditions SLR is likely to increase the wave loading on structures as well. An increase of the water depth of

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1.0 m results in an increase of the wave height at the structure of about 0.5 m. An increase of the wave height by 0.5 m causes an increase of the wave run-up levels (estimated at roughly 3 times the wave height for relatively smooth impermeable slope protections such as placed-block revetments and/or grass), leading to a required crest level that needs to be increased by about 2.5 m per 1.0 m SLR (*i.e.* 1.0 m due to SLR and 1.5 m due to increased wave loading and wave run-up). Such a significant increase of the crest level of coastal structures such as dikes may be undesirable due to the additional space that is required for the structure (*e.g.* buildings may be present on the landward side while this space would be required if the crest needs to be raised and consequently the landward slope would have to be shifted inland), blocking the view to the sea, or an unacceptable additional load of the structure on a weak subsoil (*e.g.* clay subsoil underneath the structure). Here, a systematic method to take uncertainties in future SLR into account during the lifetime of a coastal structure is illustrated with an example of a dike for which raising the crest of the earthen part of the structure is not an option. The method to use adaptation pathways (see also Walker *et al*, 2001, and Haasnoot *et al*, 2013), including the so-called tipping points per adaptation measure, are applied here for coastal structures. See for details of this example Deltares (2019).

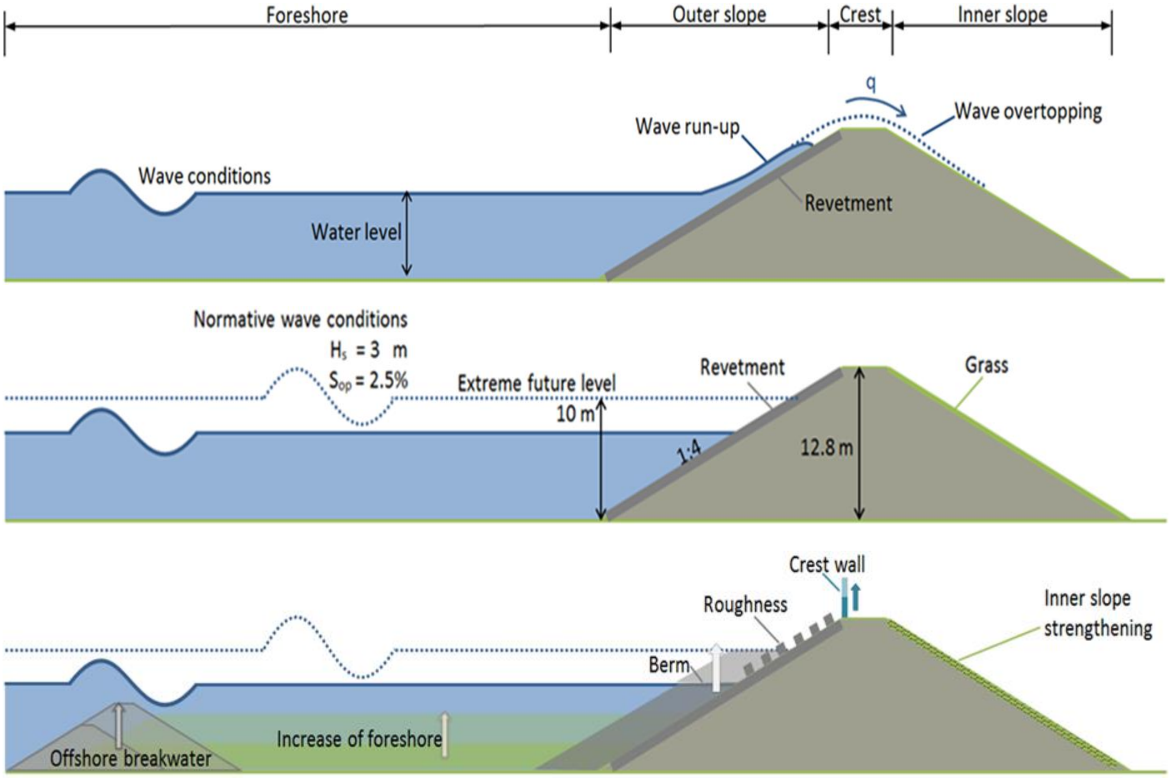

Figure 2. Adaptation measures for an existing dike.

The lower panel of Figure 2 shows a number of adaptation measures: *a)* Reducing wave loading on the dike by constructing a submerged offshore breakwater or increasing the level of the foreshore by adding sand to the existing foreshore, *b)* Dissipating energy on the seaward slope by adding a berm or adding roughness to the upper seaward slope, *c)* Adding a crest wall (here made of glass to facilitate the view to the sea), or *d)* Improving the strength of the inner slope to accommodate a larger overtopping discharge. The most cost-effective adaptation measure depends, amongst other aspects, on the climate change scenario used in the design. In this example a climate change scenario with an estimate of a SLR of 1.4 m is used with an option to adapt the structure for a larger SLR (to 2.5 m) if during the lifetime of the structure that appears to be realistic.

For each of the mentioned adaptation measures so-called tipping points are defined. These tipping points illustrate to which SLR the adaptation measure is a realistic solution. For instance, for a submerged offshore breakwater, a tipping point is introduced since the crest of the offshore breakwater should remain below the water level during normal conditions (including low-tide) in order not to block the view. This limits the height of the offshore breakwater and determines a limit of the SLR that can be accommodated for by this adaptation measure. Another example is adding roughness to the seaward (upper) slope of the dike. Revetments with blocks that protrude above the slope generally appear to be stable until the height of the protruding part is equal to the height (thickness) of the non-protruding blocks. This also limits the amount of roughness that can (relatively easily) be achieved with an increased roughness, and therefore limits the amount of SLR that can be accommodated for by increasing the roughness. After a tipping point for a specific measure is reached another adaptation measure needs to be taken.

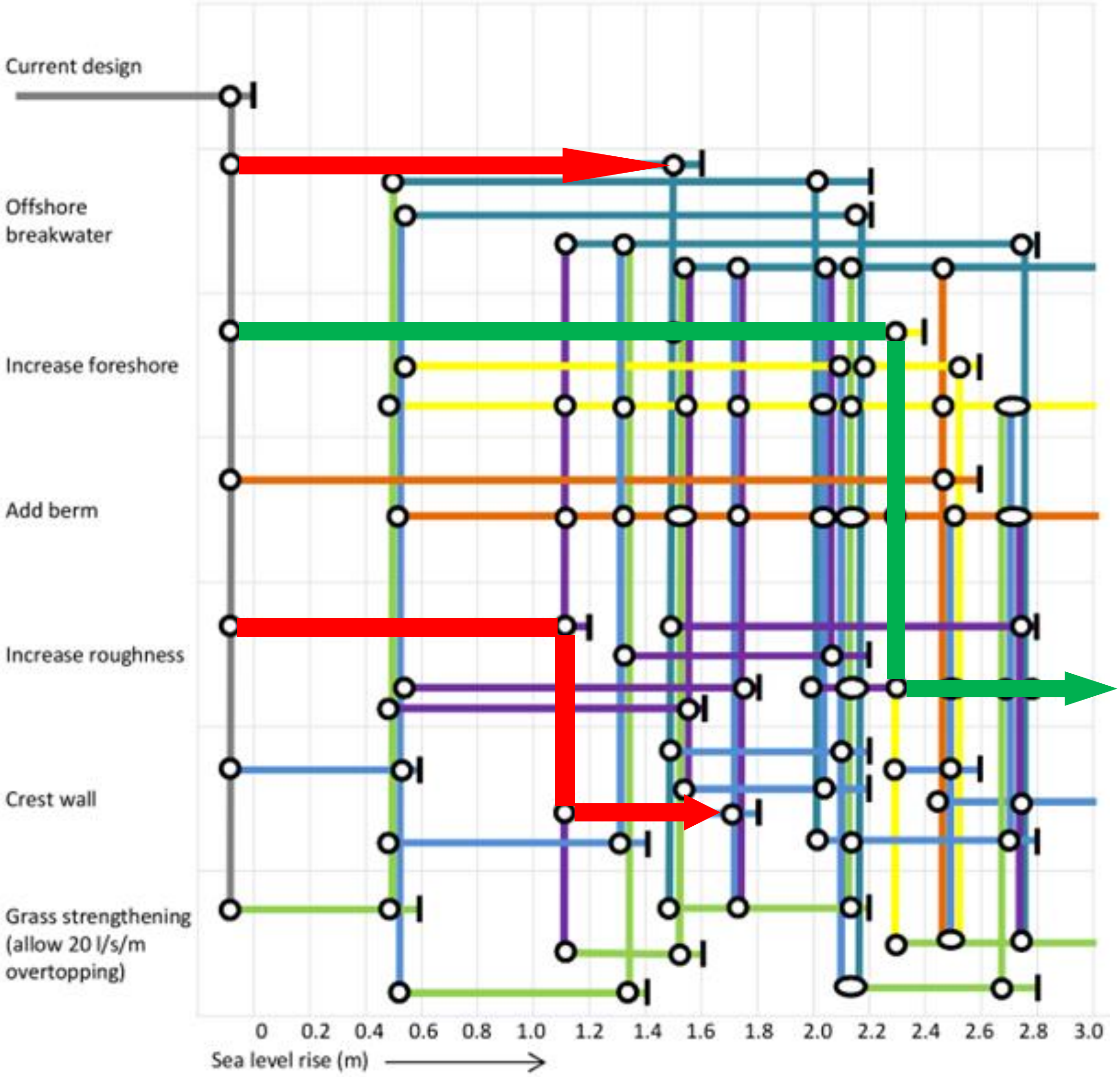

Figure 3. Illustration of adaptation pathways for dikes (with the magnitude of SLR on the horizontal axis).

Figure 3 illustrates adaptation pathways depending on the SLR (on the horizontal axis) for a given dike that is assumed to be suitable in the present situation but does not fulfill its function anymore after SLR (at the top of Figure 3 the current design reaches a tipping-point and an adaptation measure is required). The various potential measures are listed on the left side of Figure 3. Each measure is suitable for a specific range of SLR, illustrated by the horizontal lines. The circles denote points (in time, after a certain SLR denoted on the horizontal axis) where a decision can be taken for another adaptation measure (vertical transition lines to another measure). The short bold vertical lines at the end of horizontal lines denote tipping points that illustrate the (reasonable) limit of that particular measure.

In this example illustrated by Figure 3, the adaptation measures 'adding an offshore breakwater', 'increasing the foreshore by adding sand on top of the existing foreshore' and 'adding a berm to the seaward slope' are measures that can be applied to overcome a SLR of 1.4 m or more, without the need to increase the crest of the earthen part. The adaptation measures 'increasing the roughness of the existing seaward slope', 'adding a (glass) wall to the crest', and 'increase the strength of the landward slope' are measures that reach their limit at a lower amount of SLR. After each of the adaptation measures another measure (vertical transition lines to another measure) can be taken until again a limit is reached, and so on. Keeping all options open leads to a large amount of adaptation pathways that can deal with for instance a SLR of 1.4 m or a SLR of 2.5 m.

The selection of the most appropriate adaptation pathway is affected by various aspects, such as *a)* The climate change scenario (What is the best estimate of SLR? What is the assumed uncertainty? What is the worst-case SLR scenario that needs to be accounted for?), *b)* The space requirements (Is the space required for adaptation measures available? Can space be reserved for potential future adaptation measures?), *c)* The number of future adaptations (Is there a non-technical limit to the number of acceptable future adaptations to an existing structure?), and *d)* The costs of the present adaptation, potential future adaptations, and expected total lifecycle costs.

To select the most realistic adaptation pathway in the present example cost estimates of the various adaptation pathways are used. In this example, two adaptation pathways appear to be almost equally cost-effective if the structure would be designed for a SLR of 1.4 m. These pathways are *a)* adding a submerged offshore breakwater or *b)* increasing the roughness of the seaward slope and later adding a glass crest wall. These two potential adaptation pathways are illustrated in Figure 3 by the red pathways. However, if during the lifetime of the structure the SLR appears to be more significant than initially assumed (*e.g.* SLR=2.5 m) another adaptation pathway appears to be more cost-effective. This adaptation pathway starts with increasing the foreshore by adding sand on top of the existing foreshore and later increasing the roughness of the slope. This potential adaptation pathway is illustrated in Figure 3 in green. For a scenario of SLR of 1.4 m this adaptation pathway (in green) is slightly more expensive than the earlier mentioned adaptation pathways (in red), but this adaptation pathway (in green) is clearly less expensive if later the SLR appears to be more significant than the present best estimate of the SLR.

This illustrates that if SLR appears to be more than expected now, the initial adaptation measure may be different from those without taking the possibility of a more serious SLR into account. Postponing investments, including accounting for the possibility that SLR appear to be less than a worst-case scenario, is for many existing structures attractive. On the other hand, keeping the option open that a more serious SLR than expected now can occur, can reduce future costs and lead to a different initial adaptation measure.

This analysis with adaptation pathways (for details on this example see Deltares, 2019):

- provides insight into most realistic/feasible/economic adaptation measures.
- shows that a combination of more than 1 adaptation measure is required in case of high SLR.
- illustrates that postponing investments for adaptation to uncertain high SLR is attractive.
- shows that taking uncertainty in SLR into account may lead to another initial solution.

In the presented example use is made of existing guidelines for the evaluation of the structure performance. However, for a series of adaptation pathways the existing guidelines are not sufficiently validated. Adaptation measures are often validated for one adaptation measure but not for a combination of adaptation measures. There are clear indications that existing design guidelines are often not accurate for a combination of 2 or more adaptation measures. To accurately design coastal structures for climate adaptation, design guidelines that are also accurate for a combination of adaptation measures (and not only for a single adaptation measure) are required since the most realistic adaptation pathways require more than one adaptation measure.

3. Knowledge gaps

As illustrated in the previous section, significant SLR is likely to lead to adaptation of coastal structures where more than one adaptation measure is required. Existing design guidelines to determine the crest level and strength of coastal structures are often validated for one adaptation measure but often not for a combination of adaptation measures. Since a combination of adaptation measures is likely to become more relevant, here a few examples of relevant knowledge gaps are mentioned with respect to unknown or insufficient accuracy of existing design guidelines for the assessment of the required crest level based on estimates of wave overtopping:

- Structure with a revetment with increased roughness in combination with a shallow foreshore.

  The increased roughness at the seaward slope of structure can rather accurately be predicted using the method by Capel (2015). However, this method is developed based on conditions with relatively deep water at the toe of the structures. The presence of a shallow foreshore where severe wave breaking occurs, affects the wave loading and wave overtopping. Potential effects of broken waves reaching a slope with increased roughness may affect the performance of the roughness elements. The accuracy of the existing method for increased roughness in combination with a shallow foreshore is unknown.

- Structure with a crest wall in combination with a shallow foreshore.

  The influence of a crest wall on the wave overtopping at coastal structures has been studied and incorporated in design guidelines by EurOtop manual (2018) or Van Gent and Van der Werf (2019-a,b). The accuracy of these existing methods for wave overtopping over crest walls in combination with a shallow foreshore is unknown.

- Structure with a berm in the seaward slope in combination with a slope protection with increased roughness.

  The influence of a berm in the seaward slope on the wave overtopping discharge is incorporated in manuals such as TAW (2002) and EurOtop manual (2007, 2018). Also methods to account for roughness on the seaward slope are present in these manuals. Although these manuals provide methods that claim to be valid for a combination of roughness and berms, these methods have not been sufficiently validated. Chen *et al* (2019) showed that the mentioned manuals are inaccurate for a combination of a berm and roughness along the seaward slope (Figure 4 illustrates the significant inaccuracies), and that improved guidelines for this combination of adaptation measures are needed.

- Structures with a berm, with or without increased roughness in the seaward slope, in combination with oblique waves.

  Also, methods to account for the influence of oblique waves are present in manuals (*e.g.* TAW, 2002, EurOtop manual, 2007 and 2018). Although these manuals provide methods that claim to be valid for a combination of oblique waves and structures with a berm, these methods were not sufficiently validated at the time of writing of these manuals. Recent physical model tests have shown that these manuals are inaccurate for this combination of processes (Figure 5 illustrates the significant inaccuracies), and that improved guidelines for wave overtopping discharges are needed.

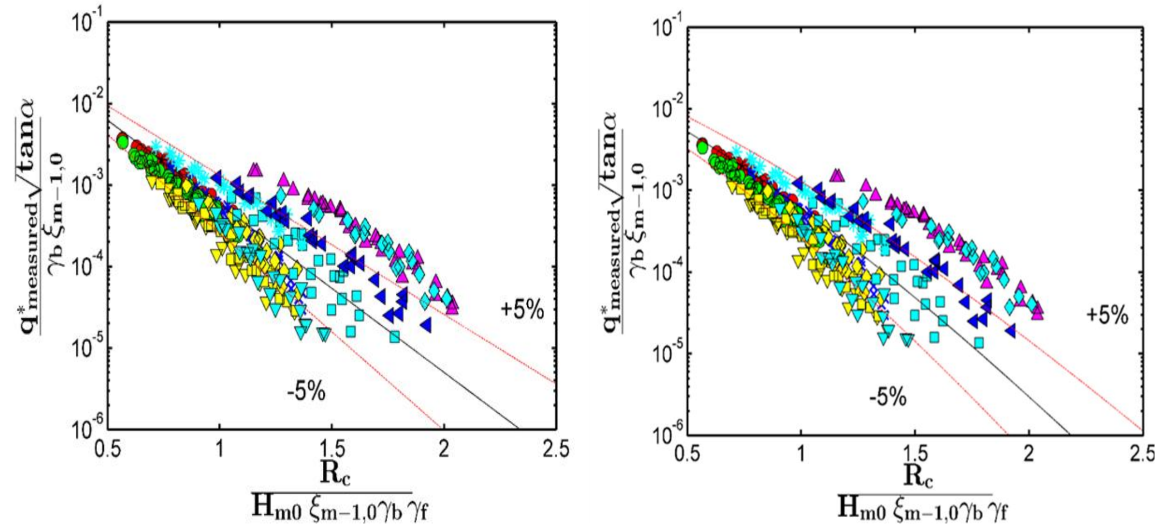

Figure 4. Measured wave overtopping discharges for dikes with a berm and increased roughness at the seaward slope (a non-dimensional overtopping discharge parameter at the vertical axis versus a non-dimensional freeboard parameter at the horizontal axis): Left panel: Data compared to TAW (2002); Right panel: Data compared to EurOtop manual (2018); data by Chen *et al* (2019).

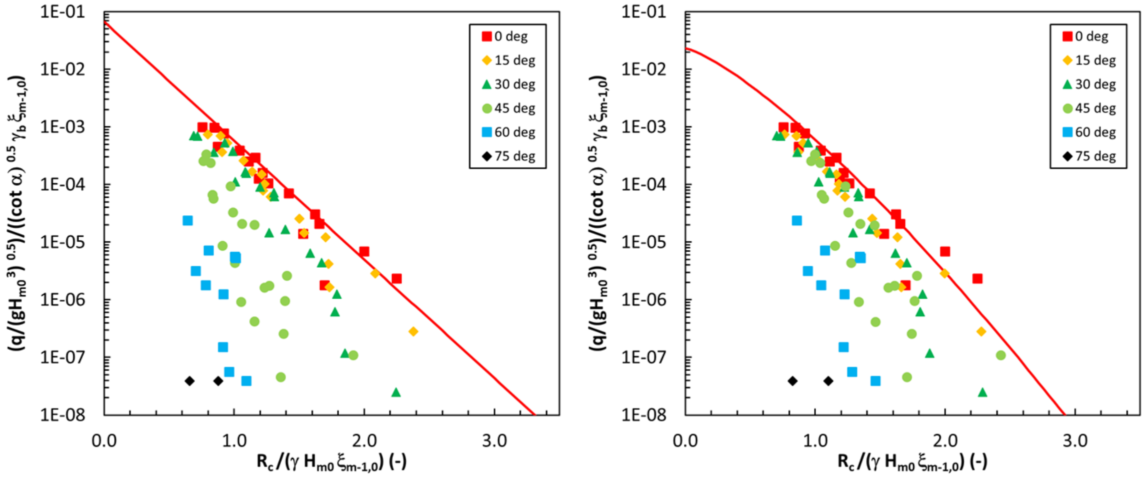

Figure 5. Measured wave overtopping discharges for dikes with a berm under oblique wave attack (a non-dimensional overtopping discharge parameter at the vertical axis versus a non-dimensional freeboard parameter at the horizontal axis): Left panel: Data compared to TAW (2002); Right panel: Data compared to EurOtop manual (2018); data by Deltares.

The assessment of potential climate adaptation measures as discussed in Section 2 illustrates that there is a clear need for design guidelines to assess the performance of coastal structures such as dikes for situations where more than one adaptation measure is required. For various combinations of adaptation measures existing design guidelines have not been validated or have shown to be inaccurate. The mentioned design guidelines can be used as first estimates for conditions for which they have not been validated or shown to be inaccurate, but the final design should not be based on those guidelines. Based on improved design guidelines, adaptation pathways as shown in Section 2 can be updated.

4. Conclusions and recommendations

Based on discussions in this paper the following conclusions can be drawn:

- Estimates of sea level rise (SLR) show large uncertainties.
- Estimates of uncertainties around best-estimates of SLR also vary in time and did not systematically reduce over the last decades.
- Relatively important consequences for coastal structures under sea level rise conditions exist for structures that are exposed to depth-limited waves during storms.
- For many coastal structures important changes are expected during their lifetime.
- Coastal structures designed for the worst-case scenario in terms of sea level rise projections are likely to be unnecessarily costly.
- If potential future adaptation measures are considered in the design, investments can be postponed or avoided if the actual SLR appears to be less significant than expected, while additional costs can be limited if the actual SLR appears to be more significant than expected.
- Pathway analysis provides insight into feasible and economic adaptation measures.
- The initial adaptation measure can be different if potential future adaptation measures are considered in the design.
- The combination of more than one adaptation measure is required in case significant SLR would occur and a significant increase of crest levels of coastal structures is impossible or undesirable.
- Taking climate adaptation measures into account reveals that there are important knowledge gaps. Knowledge gaps especially exist for a combination of adaptation measures:
  - *e.g.*: Coastal structures with an increased roughness on relatively smooth seaward slopes, and/or a crest wall at the crest, in combination with a shallow foreshore.
  - *e.g.*: Coastal structures with increased roughness on relatively smooth seaward slopes in combination with a berm and/or oblique wave attack.
- Present guidelines for wave overtopping that are used to determine required crest levels of dikes show large inaccuracies for important combinations of adaptation measures.
- Additional research in the field of knowledge gaps is necessary in order to accurately determine required crest levels of dikes and to determine realistic adaptation pathways for future sea level rise.

Accurate guidelines for a combination of adaptation measures appear to be very relevant to make coastal structures future-proof for an uncertain future sea level rise. It is recommended to improve the design guidelines to determine the required crest levels of dikes.

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