Impacts of climate change on the principles of dike design

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Introduction

Dike design is a very traditional craft. Since many generations dikes have been constructed in our part of Europe. After each disaster the dike was rebuilt, and improved. The improvement was always based on the experiences of the previous flood. For example, for many years the design height of a dike was determined as the height of the highest observed flood, plus a certain margin (usually a value in the order of 1 m). Of course, experience had shown that we also had to add some extra freeboard to take care of the wave run-up.

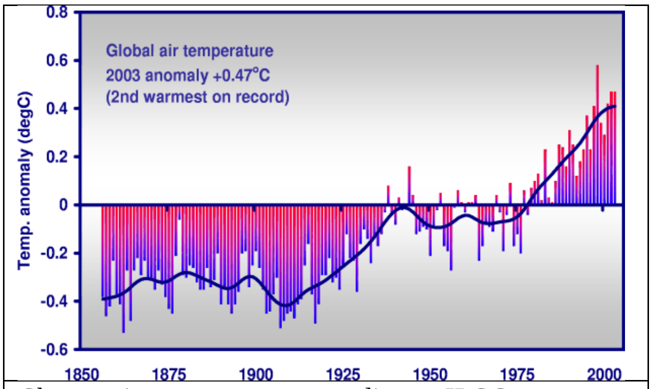
Johann Baptist Homann, *Vorstellung einer Bracke oder Durch-Bruch eines Dammes dadurch dass Landt vor jinnen überschwemmet wirdt*, 1718 (Staatsarchiv Oldenburg)

In the sixties and seventies, after the storm surges of 1953 in the Netherlands and 1962 in Germany, a more scientific approach to dike design was developed. It was realized that the old approach did not lead to a given (acceptable) probability, but leads to a undetermined probability of flooding. Therefore in present dike design the standard approach is:

- determine the acceptable probability of flooding (this is a political choice, partly based on economics, but also on social and cultural aspects);
- given this probability calculate the design storm which occurs with this probability;
- design a dike which is able to withstand this design storm.

Climate change

The climate is changing, and especially in politics there is quite some concern if we can cope with the effects of climate change on the long run. Should we abandon our land and move to "higher grounds"? Of course this is not a realistic option for the Netherlands, and probably also not for Northern Germany. So we have to do something. The question is if we may proceed as we have always done. This means, adapting the height of our sea defences to the new hydraulic boundary conditions. But in order to answer this question, we first will have to investigate the effects

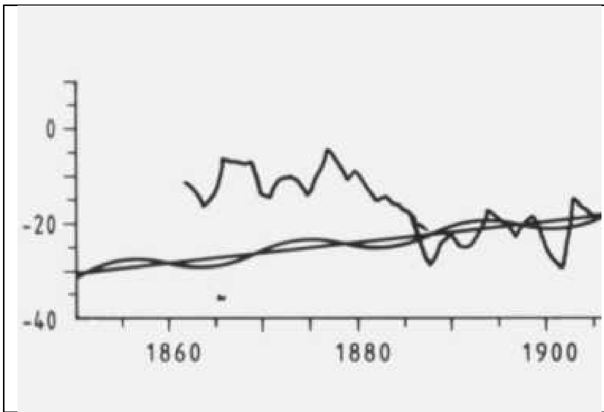


Changes in temperature according to IPCC

of climate change. Do we indeed see sudden changes? First of all we have to conclude that the climate is not only changed because of human involvement, but that there is a large natural variation. In dike design we have to cope with these variations.
Observations show that in the last decades the temperature is rising, not only in NW Europe, but anywhere in the world. There is a strong correlation with the increase of carbon dioxide in the atmosphere, which is for some people the proof that this is caused by the increased use of fossil fuels. This climate change causes a change in sea level, but also a change in storm patterns and a change in rainfall patterns.
But sea level rise is not only a matter of climate change. The heating of the atmosphere causes a melting of ice and a thermal expansion of the sea water. But the (relative) sea level may also rise by isostatic subsidence (which we have in NW Europe already for some millennia) and by pumping of oil, water and gas from the subsoil.

Some observations in our region

Detailed analysis of the water level records show that some changes are unexplainable. The sudden change of the tidal range in Harlingen around 1932 is obvious, but the change in the range in Vlissingen in the period between 1877 and 1896 is very strange, and until now no explanation has been given. The drop is some 25 cm in 10 years. In New York a similar drop was also observed around the turn of the century (but not exactly in the same years).
The long water level record of Amsterdam shows that the water level started to rise in 1860, well before the heavy industrialisation of the world.
Some researchers claim that there is more relation with sun-spot activity than with industrialisation.

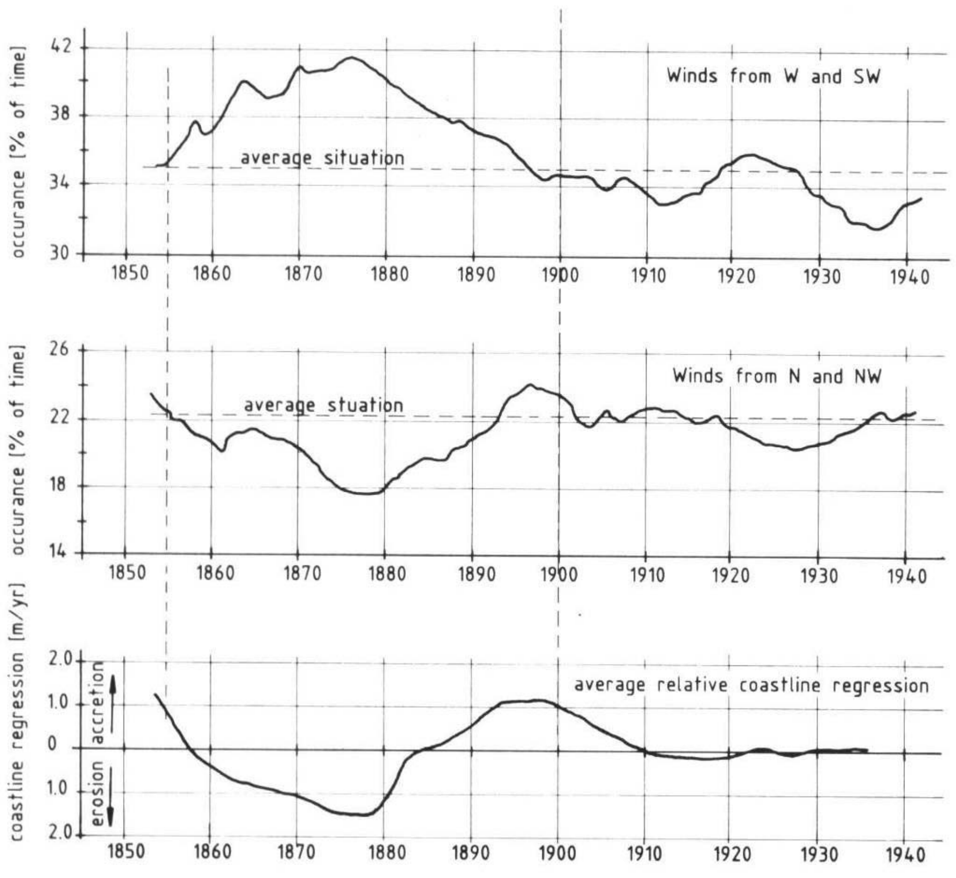


Mean sea level in Vlissingen

The pumping of gas is a very important aspect of relative sea level rise in the North East of the Netherlands. In the central part of the Slochteren gas field, a lowering of nearly 50 cm is expected. This has strong influence on the local water management, but fortunately not so much on the height of sea dikes. Pumping gas from the Wadden Sea might have more influence.

Not only the rise in sea level is relevant. Also the change in storm patterns is relevant. A different climate may cause more storms, or storms from a different direction. For dikes the change in wave direction is not that relevant, but for sandy coasts it might have a considerable effect. For example in the period between 1860 and 1900 there were significantly more westerly winds than normal. This resulted in a change in erosion/accretion rate along the coast. The net effect of this was that between 1860 and 1880 the average coastline of Holland accreted with 220 meters, and between 1880 and 1910 there was an erosion of 170 m. This enormous change in average position of the coastline was clearly due to the change in wind direction, but one cannot attribute this change to man-induced climate change.

The storm intensity also changes. In the Netherlands we have seen an increase of the number of storms in the period between 1900 and 1975, but during the last 25 years the number of storm per year is decreasing again.



Change in wind pattern and the relation with coastline regression (Verhagen, 1989)

In order to be prepared on the effect of climate change, in the Netherlands the Commission on Water policy for the 21st century (WB21) did determine a number of scenarios for climate change. Recently, the Royal Netherlands Meteorological Institute (KNMI) developed a new series of scenarios for the use in planning. The target year used in the table below is 2050.

target year 2050	Low	Middle	High
WB 21 scenarios (2002)			
Temperature raise (ºC)	+0.5	+1	+2
increase rainfall (%)	+1.5	+3	+6
sea level rise (cm)	+10	+25	+45
storm intensity (%)	-5 to +5	-5 to +5	-5 to +5
KNMI 2006 scenarios			
Temperature raise (ºC)	+1	+2	+2
increase rainfall (%)	+ 4	+7	+14
sea level rise (cm)	+15 to +25	+20 to +35	+20 to 35

Based on the scenarios of WB21, the Technical Advisory Committee on Water defences (TAW, now called ENW) developed a set of recommended values to be used in dike design. This set is published in the Guidelines for Sandy Coasts, but is also applicable to other sea defence structures.

Based on these values, the following guidelines have been developed for planning and design of dikes and other sea defences:

Year	2050	2100	2200
Minimum scenario			
Sea level	+0.10 m	+0.20 m	+0.40 m
Extra storm surge	-	-	-
Wave height	-	-	-
Raise cross section	+0.10 m	+0.20 m	+0.50 m
Middle scenario			
Sea level	+0.30 m	+0.60 m	+1.20 m
Extra storm surge	-	-	-
Wave height	-	-	-
Raise cross section	+0.30 m	+0.60 m	+1.20 m
Maximum scenario			
Sea level	+0.45 m	+0.85 m	+1.70 m
Extra storm surge	+0.40 m	+0.40 m	+0.40 m
Wave height	+ 5%	+ 5%	+ 5%
Raise cross section	+0.45 m	+0.85 m	+1.70 m

- Use minimum scenario for design of constructions which can be raised in a simple way (e.g. earthwork)
- Use middle scenario for design of structures which cannot be raised in a simple way (e.g. movable barriers)
- Use middle scenario and a time horizon of 200 years for areas with economic development (coastal resorts)
- Use maximum scenario and a time horizon of 200 years for areas with non-economic development (natural reserves, etc)

Reliability of the above figures

Of course all figures given above are very unreliable. Therefore the time horizon for construction is selected as short as possible, but especially for the reservation of space, long term planning and maximum scenarios are selected. It means in fact: The only thing we know for sure is that we don't know the exact values of the sea level and wave attack in future. Therefore we have to be aware (i.e. we have to follow the developments carefully by measurements) and we have to keep our system flexible. In the Law on Sea Defences in the Netherlands we have tried to develop a system that guarantees that sea dikes are assessed on a very regular basis. In this way we hope to prevent unwanted "surprises" as the 1953 storm.

The main policy in the Netherlands regarding climate change and sea level rise is:

- keep dunes in position with artificial beach nourishment;
- improve dunes if needed;
- strengthen dikes if needed.

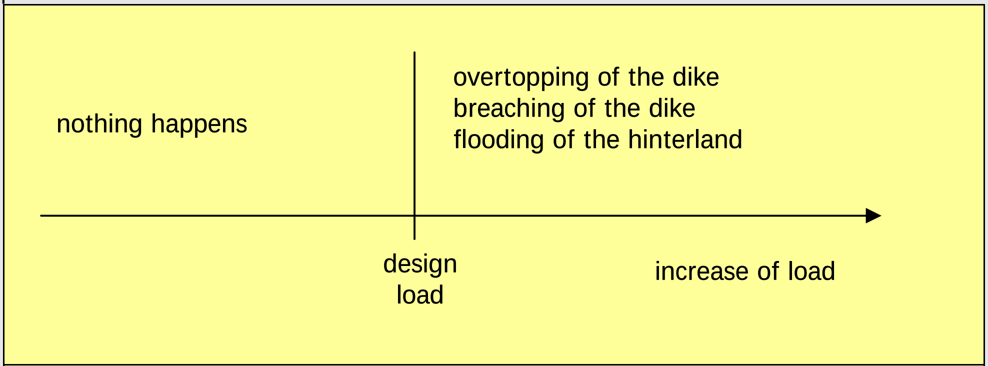
Of course there is an on-going discussion whether we are in a position to maintain this policy on the long run. Sand is ample available, so we certainly will continue with beach nourishment. We will reserve space for future improvement works, but also we have to look to more flexible systems. However, how we do we make our system more flexible ?

Intermezzo 1: Discussion on failure approach in the Netherlands

At this moment, especially in the Netherlands, there is an ongoing discussion on the fact if the choice to be made by politics is focused on the probability of occurrence of flooding or on the probability of the occurrence of the design flood. For example in the Netherlands we use for Central Holland at this moment a design frequency of 1:10000. This means that our dikes should be able to withstand a storm which occurs with a probability of 0.01 % per year. During such a design storm the dike will not fail, so there will be no flooding. Global computations have shown that the probability of failure of a dike during such design conditions is in the order of 10%, which means that the probability of flooding is in the order of 0.001 % per year. It might be that future politics will determine that for a given area the probability of flooding will be fixed to a certain value (for example 0.001 % per year). This means that we will have to include the residual strength of a dike into our design. However, for the discussion of the effects of climate change this aspect is not relevant. The choice between using the probability of a design load or the probability of dike failure remains the same.

Intermezzo 2: Unbreacheable Sea dikes

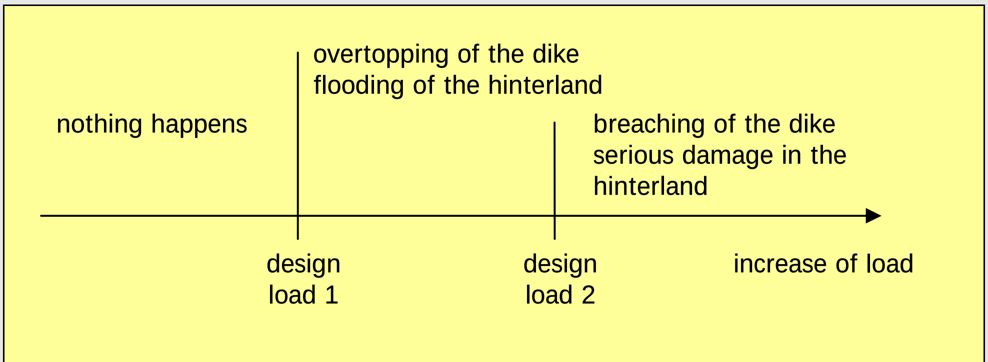
Basically the design philosophy of sea dikes in NW Europe is that dikes should be so high and so strong that they only fail when loads exceed the design storm. What happens after failure is not very well studied. So basically the idea is that until the design storm nothing happens, and after exceeding the design values we have a flood-disaster. In the past the extend of the disaster was controlled by the construction of compartmentalization dikes.



Schematic view of what happens in case of an increase of load on a sea dike

However, one may also design a dike as an "overtopping dike". This means that you design a dike in such a way that overtopping does harm the dike itself. This can be achieved by using gentle inner slopes and outer slopes, prevent scouring at both the inner and outer toe and make the revetment strong enough to withstand the forces of the overtopping water.

In fact, we design the dike in such a way that it is "unbreacheable". This idea was already presented in 1954 by Edelman. In December 1954 Edelman (an engineer of Rijkswaterstaat) wrote an internal memorandum on "unbreacheable sea dikes", where he advocated that dikes should not be constructed to such a height that overtopping becomes zero, but only to a height to prevent regular overflow. This will lower the costs, and gives a better benefit/cost ratio. He states that in order to achieve this, more attention has to be paid to the quality of the inner slope of the dike (slope 1:3, and good quality grass). In a reply his colleague Wemelsfelder argues that it is also necessary to make a threshold level to prevent overflow, in order to make clear to the public that they will not suffer from the inconveniences of overflowing water on a regular basis. However, in his examples Wemelsfelder stresses the problems which occur during the flooding of city centres, etc. Also because of this, the political attention for the memorandum of Edelman was very low, and the story disappeared into the archives.



Schematic view of what happens in case of an increase of load on a sea dike, using an "unbreacheable" dike

But when considering the effects of climate change on dikes, it might be worth to reconsider the thoughts of Edelman. The basis of his idea is that the probability of overtopping is low, but higher than a value in the order of 0.01% per year; however the dikes should be able to survive such an overtopping. This means that in case of flooding, the area behind the dike will be flooded, but that after the flood (and after pumping the water out of the polder) no serous repair works on the dikes are needed. So "only" the damage in the polder due to the inundation has to be accounted for. Of course this damage is considerable, but can be limited using smart compartmentalization.

Living with floods

Of course, the most simple option is simply allow the floods to flood the countryside. This is not new, we did this already many years ago in this region. To protect the inhabitants against wet feet, one can build Living Mounds (*Warften, Terpen*). However, this is rather cramped solution, and not very well fitted for urban development. Therefore this can only be applied in a few cases, but as a solution, it should certainly not being excluded. Especially in junction with a "unbreacheable dike" as described in intermezzo 2, it may play an important role in less densely populated areas.


Maasbommel, the Netherlands

But one can also build a completely floating city. At some places in the world there are examples, but these examples are still limited. In most cases, the reason of building a floating city is not for coping with floods, but usually it is the shortage of land. However, one sees at some places that this might be an interesting development.

Along some floodplains in the Netherlands (along the Maas river) some houses have been constructed on pontoons, able to float during high water in the river.

But in these projects the number of houses is still quite small. It seems not a very practical solution for coping with a rising sea level and a storm condition as we are faced with in NW Europe.

So, one option for the future might be to make a distinction between the probability of some flooding and the probability of a "full disaster".

The ComCoast approach

The European project ComCoast (Verhagen and Visser, 2007) is looking at how we use the coastal flood plain today and is seeking multifunctional solutions for its sustainable use in the future. The ComCoast concept is to create a more gradual transition from sea to land, instead of a traditional single line of water defence. The project is developing innovative flood risk management strategies to include wider social and environmental functions such as recreation, fishing, tourism and habitat creation. This approach aims at to highlight possibilities for developing the coastal area with respect to spatial planning, to benefit local and wider communities as well as maintaining the environment.

ComCoast focuses on sea dikes. The height of a sea dike is the sum of the design water level + freeboard. The required freeboard mainly depends on the acceptable amount of overtopping (traditionally in the order of 1 litre per second per meter dike). One may try do design dikes with lower freeboards. This may be achieved by:

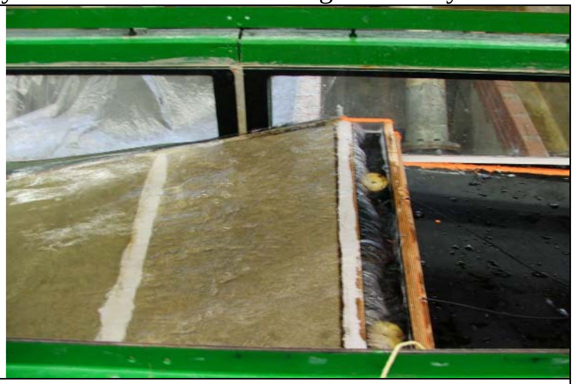
- decreasing the wave load on the dike;
- allowing more overtopping.

Lowering the dike below the design water level usually gives so much overflowing water, that this option is not realistic. This implies that ComCoast solutions are especially attractive in cases of dikes with considerable wave attack. Decreasing the wave load is possible by solutions in the foreshore; allowing more overtopping requires inshore solutions plus adaptation of the inner slope of the dike.

In this presentation I will only focus on the inshore solutions. Within ComCoast three landward solutions are investigated:

- overtopping defence;
- managed realignment;
- regulated tidal exchange.

In this paper the focus will be on the overtopping defence only, for the other solutions is referred to Verhagen and Visser (2007). Within the ComCoast project several technical methods were elaborated to make dikes overtopping resistant. A number of traditional ones are a hard protection (like placed blocks, riprap, asphalt or Elastocoast) or a strong vegetation (e.g. a grass cover in combination with gentle inner slopes). Also a number of new concepts are investigated, like the reinforced grass cover and the Crest Drainage Dike. For the first one, a prototype test facility has been developed and deployed this spring near Delfzijl, for the second one a number of laboratory tests have been performed both in Delft University as well as in Braunschweig University.

	
Overtopping tests in Delfzijl	Small scale tests of the crest drainage dike in Delft University

From the results follow that it is technically very well possible to design dikes in such a way that they are "unbreacheable". Of course, when opting for unbreacheable dikes, the storage area behind the dike should be sufficiently large and should not contain essential functions. This means that houses in such an area should be build on artificial elevations, and that no major infrastructure should be located in this area (e.g. no hospitals or telephone exchangers).
So this option means that, in view of an anticipated sea level rise, we should not heighten the dikes, but strengthen them and adapt the land use in the area behind the dikes.

Dealing with uncertainties

But the main lesson from the analysis of the climate change is: we can be sure that we are not sure about the real value of the sea level in 50 or 100 years. This means that we can opt for a very certain, but very costly approach. We can select a pessimistic scenario for sea level rise and design now all our dikes for such a design storm, including non-overtopping conditions. This is very costly, but also we run the risk to invest much money (and loose quite some natural values) unnecessarily. Therefore this is not a very wise approach.
It is much better to design sea defences on design conditions which are based on the present sea level rise (a present sea level rise of 20 cm/century with a low probability storm on top of it, for example a 1:4000 per year storm) and add some extra height to cover additional sea level rise during the coming 10 - 20 years. Normally we include a economic lifetime of a dike of 50 years. This means that we include 10 cm of sea level rise. Let's add 5 extra cm for anticipated increase of sea level rise, so the dike become 15 cm higher that needed for the conditions of today. When we have no additional sea level rise, the real lifetime of the dike will be not 50 years but 75 years. However, when the sea level rise is 45 cm in the next 50 years, the lifetime of our dike is only 28

years. So it means that we have to start improvement works much earlier. However, this does not cost anything extra. Financial theories show that it is normally most economic to invest as late as possible. So we have to realise that in fact the design height of our dike is not uncertain, but the design lifetime is uncertain.

Conclusions

The mean lesson from this analysis is that coping with the uncertain sea level rise in future means that we have to design our dikes for an uncertain lifetime, somewhere between 25 and 75 years. It means that we have to design dikes in such a way that they can be strengthened in an easy way. Thus we have to have sufficient space available, and we have to be very reluctant with allowing other permanent buildings on our dikes. Also new (permanent) nature development around the dike should be prohibited. "Temporary" nature may be an option.
And we may consider changing our safety policy from a "no-overtopping" design to an "unbreacheable" dike. However, this has the disadvantage that the land use behind the dike is quite limited. However, some people will consider this as an advantage (because it gives more possibilities for landscape and natural development)

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(the memoranda of Edelman and Wemelsfelder are available via www.hydraulicengineering.tudelft.nl ➔ research ➔ publications)