An introduction to flood defences

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Learning objectives;

After studying this part of the lecture notes and following the relevant modules of the online course, the student can indicate:

- What the different types of flood defences are;
- How the framework for safety of flood defences in the Netherlands is functioning;
- What the most important failure mechanisms and design aspects of dikes are;
- How the design elevation of a dike is determined.

Contents

1. Flood defences

1.1 Types of flood defences

Flood defences are of great importance to prevent flooding of low-lying areas. A flood defence is a hydraulic structure with the primary objective to provide protection against flooding along the coast, rivers, lakes and other waterways. Different types of flood defences exist. The most important ones are (see also Figure 1):

- A **dike** is a water retaining structure consisting of soil with a sufficient elevation and strength to be able to retain the water under extreme circumstances.
- A **dam**[1] is another type of water retaining structure The difference with a dike is that behind a dam water is located and behind a dike land. The Afsluitdijk (the closure dam) in the IJsselmeer (Lake IJssel) is in fact a dam. Other examples of dams along the Dutch coast are the Brouwersdam and the Haringvlietdam, which are a part of the Deltaworks.
- A **storm surge barrier** is a partly movable flood defence in a river or an estuary. A storm surge barrier can be temporarily closed by means of gates during high water levels to prevent high water level in the basin behind the barrier. Under normal circumstances the barrier is open to discharge water from the hinterland and/or to allow shipping. Well-known examples of storm surge barriers in the Netherlands are the Maeslantkering near Hoek van Holland and the Eastern Scheldt storm surge barrier (Oosterscheldekering).
- A **dune** is a ridge of sand along the coast, which is general formed by natural processes. Dunes provide protection against storm surges especially through their large sand volume and resistance against erosion. During high water levels and waves, a part of the dune will erode (dune erosion).
- A **flood wall** is a water retaining structure which generally consists of concrete, and sometimes also out of steel. Due to the high horizontal forces on the flood wall, a solid foundation is necessary.
- **Temporary flood defences** are used during high water levels to strengthen dikes or other vulnerable objects. Examples of temporarily flood defences are sandbags, synthetic-bellow barriers or box barriers that are filled with water for the purpose of stability, and various types of beams and stop logs.
- **Hydraulic structures**, such as sluices, siphons and pumping stations are structures that can be a part of a flood defence system. In this case they provide other functions, but also protection against flooding. Therefore they have to meet very strict safety requirements.

[1] In many places around the world dams are applied in river systems for the purposes of water management, navigation, energy generation or agriculture. These dams retain water but they have other primary functions.

Dike along the Waal near Ochten during high water in 1995 (image database: Rijkswaterstaat) 	Brouwersdam in Zeeland (image database: Rijkswaterstaat) 
Maeslant Barrier along the New Waterwa, near Rotterdam (Netherlands) 	Dune at Koksijde, Belgium (source: Wikimedia) 
Concrete floodwall during construction in New Orleans (LA, USA) 	Temporary flood defences: Box barriers consisting of synthetic boxes filled with water (Picture by Ilse van den Bosch, 2013) 

Figure 1: Overview of different types of flood defences

Apart from these interventions, other measures can be implemented to reduce the probability of flooding. Examples are interventions in the river bed to increase the discharge capacity of the river (Room for the River). Also measures can be taken to reduce the consequences of flooding, such as adaptation of buildings, evacuation and emergency plans.

The primary and most important function of a flood defence is of course retaining (high) water. Flood defences often have other functions, such as road transportation over a dike or dam, or as an element with landscape-, ecological- and sometime a cultural historical-value. For example in the city of Dordrecht, the flood defence is part of a street (the Voorstraat) in the historical city center.
In the remaining part of this chapter introduces the safety framework for flood defences in the Netherlands. Consequently the most important technical aspects of dikes and dike execution will be

discussed. Information on other types of flood defences can be found in other courses in the educational program of hydraulic engineering at TU Delft.

1.2 Framework for the safety of flood defences in the Netherlands

A large part of the Netherlands - about 60% - is prone to flooding and would be regularly flooded without the presence of the flood defences. Due to the location of the country in the deltas of the Rhine, the Muse and the Scheldt many floods have occurred in the past. The most recent catastrophic flood was the Storm surge disaster (Watersnoodramp) of 1953 and this event also resulted in the well-known Deltaworks.

In total, the flood defence system in the Netherlands consists of about 3800 kilometres of primary flood defences which prevent flooding from the sea, rivers and large lakes. In addition, the so-called regional flood defences exist along the waterways and the canals in polders and smaller lakes.

The primary flood defences and the high grounds in the Netherlands form so-called dike rings. A **dike ring** is a system of flood defences and sometimes high grounds that encloses an area in order to protect it against floods. Different types of flood defences can be a part of a dike ring. The dike ring that protects the province of South-Holland consists of dunes and river dikes and also the Maeslant barrier (a storm surge barrier) contributes to the protection of South-Holland.

In total the Netherlands there are about 100 dike rings that protect low-lying areas, also see Figure 2. The current safety standards for primary flood defences are expressed by mean probability of exceedance, ranging from 1/250 per year for the Meuse River, 1/1250 per year for other river areas to 1/10,000 per year for the provinces North-Holland and South-Holland. These safety standards indicate, for example, that the dikes around the province of South-Holland should be designed to safely withstand a hydraulic load (consisting of water levels and waves) which is exceeded on average once every 10,000 year. These standards strongly focus on overflow and overtopping of the flood defences. It is expected that in the autumn of 2014 the Dutch government will implement new safety standards for flood defences, which relate to the failure probability of flood defences. This will enable a more complete assessment of the different failure mechanisms of a flood defence. For example, in addition to overflow also the instability will be taken into account (see also section 1.3.2). The new safety standards will also take into account the contribution of various dike sections and structures in a dike ring to the failure probability of the system. The revision of the safety standards will be based on the concept of flood risk:

Risk= probability x consequence

To reduce the risk sufficiently, areas with large values get a relative high protection level.

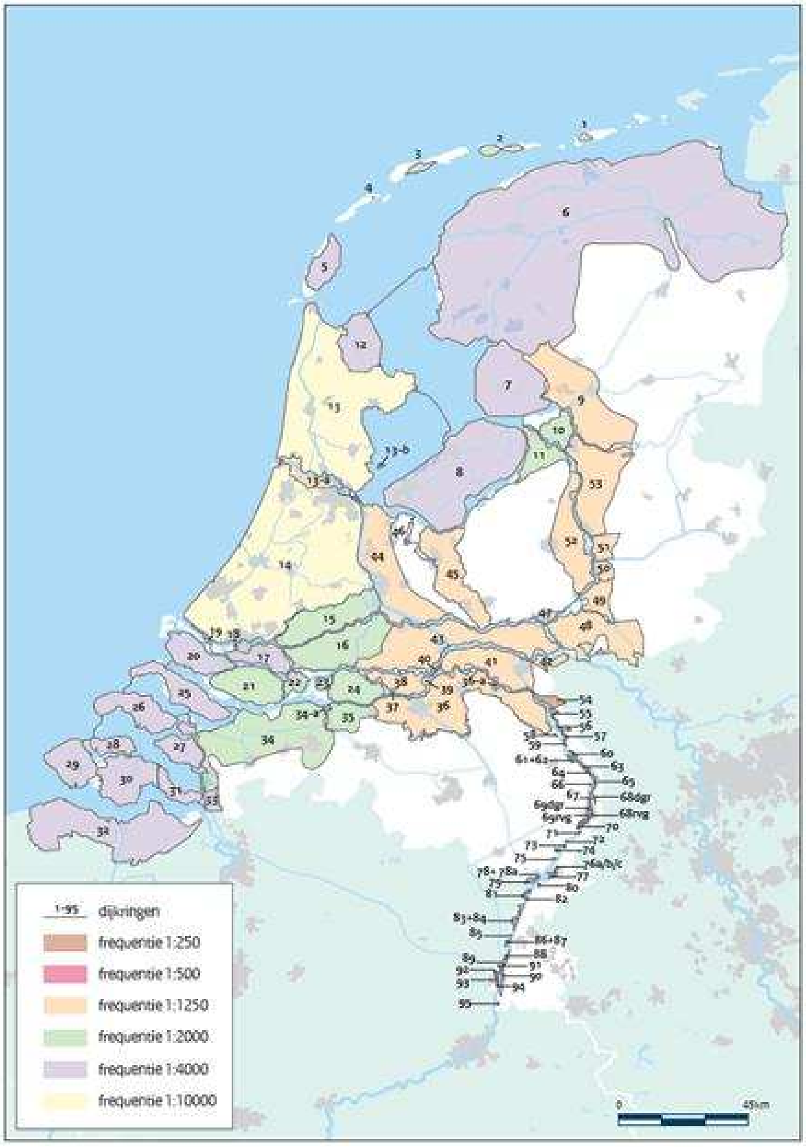


Figure 2: dike ring areas, primary flood defences and safety standards in the Netherlands. This figure also indicates the flood prone areas in the country.

In addition to the areas protected by flood defences, a small part of the country (about 3%) is located in so called **"unembanked areas"**. These areas are not protected by means of flood defences and do not have a legal safety standard. Examples of such areas are locations in the river system and coastal towns along the coast. A large part of the port of Rotterdam is located in an un-embanked area as well. The 2nd port extension (Maasvlakte) is constructed at 5 m above sea level to prevent flooding.

To maintain a safe system, a good management of flood defences is necessary. The management of the flood defences in the Netherlands includes several processes and organizations. The safety of the flood defences is assessed every 12 years according to legal requirements that also include the safety standards (see previous text). Flood defences that do not fulfil the legal requirements need to be strengthened in the years after the assessment. The federal government is responsible for defining the safety standards and the methods for the safety assessments and design of flood defences. Also, most of the storm surge barriers and dams are managed by the federal government (Rijkswaterstaat). Waterboards (waterschappen) are local water management organizations and are responsible for managing and maintaining the majority of the primary flood defences. The costs of dike reinforcements are shared by the waterboards and the federal government and citizens pay taxes to their water board. In the Netherlands the legal rules of maintaining the safety level are embedded in the Water Law (2009).

Although the Netherlands is one of the best protected countries in the world, there is still a lot of work to do. The most recent safety assessment in the year 2011 showed that about one third of the primary flood defences –about 1,225 km- did not meet the safety standards. In the future sea level rise and the change of the safety standards will lead to more reinforcements of the flood defences.

1.3 Dikes: technical aspects

1.3.1 General

The most important function of a dike is to retain the water. This means that a dike needs to be sufficiently high to withstand high water levels and wave run-up, be resistant against wave attack and overtopping and be stable and impermeable.

Figure 3 shows the most important elements of a dike. An important variable is the **crest level** of the dike. It should be sufficiently high to withstand extreme water levels (see also section 1.3.3). The dike revetment on the outside can consist of grass, concrete elements, stones or asphalt and should be able to withstand the expected wave attack. In some cases an outer berm can be implemented to break and slow down the waves. On the inside of the dyke, an inner berm can also be applied to prevent instability and piping. The slopes on the inside and outside have an effect on the wave run-up and the stability.

The **composition** of the dike core and base is related to the properties of the different types of soil. No single type of soil possesses all the characteristics that are desired for a dike structure; sand and gravel are stable but also very permeable. Peat is impermeable but is soft and easily compressed which makes it insufficiently stable for dike structures. In addition, peat shrinks when it becomes dry. Clay is maybe the most suitable. It is very impermeable but deforms easily when it gets wet. Many of the older dikes fully consist of clay. Nowadays a dike is constructed out of a combination of different types of materials, for example a dike core of sand with a cover layer of clay.

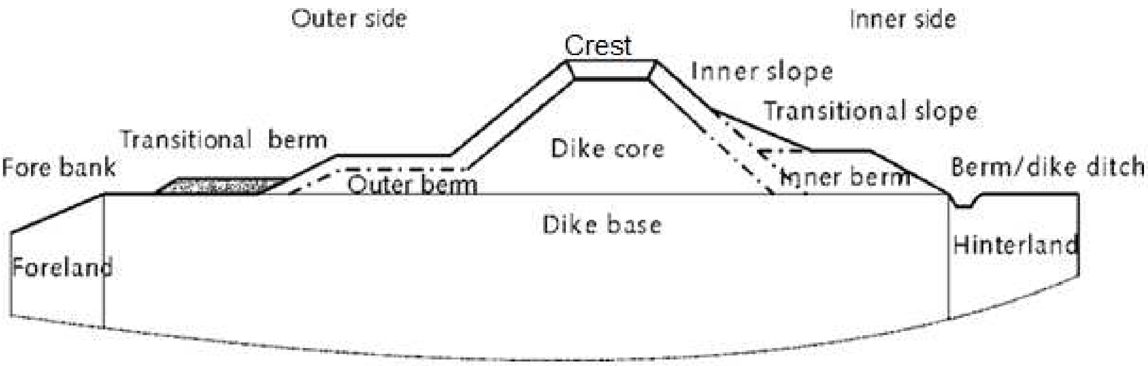


Figure 3: General dike profile sowing the most important elements of a dike.

The chosen dimensions of a dike will strongly depend on the design loads. For sea dikes due to the high waves formed during a storm at sea, a shallow outer slope, an outer berm and / or a dike revetment of stones or asphalt can be applied. Figure 4 shows an example of sea dike constructed out of a core of sand with a cover layer of clay, and asphalt and concrete revetments at locations where wave attack can be expected.

The waves along the rivers are generally smaller and outer berms are not applied. For river dikes an inner berm or a relatively flat inner slope is applied (usually smaller than 1 over 3) to provide sufficient stability during long periods of high water. Figure 5 shows an example of a river dike with an inner berm and a core of sand. When dimensioning a dike, the footprint and the land use in the surroundings should be taken into consideration (see also section 1.4).

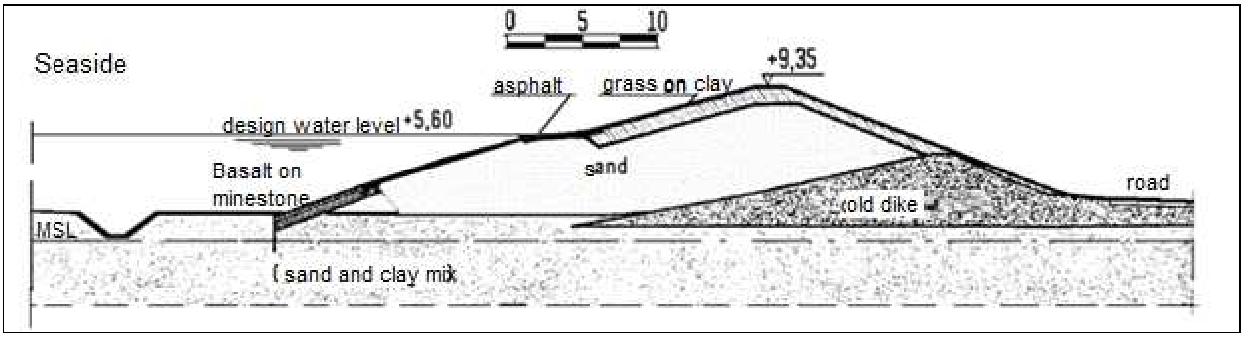


Figure 4: Example of a profile of a sea dike reinforcement.

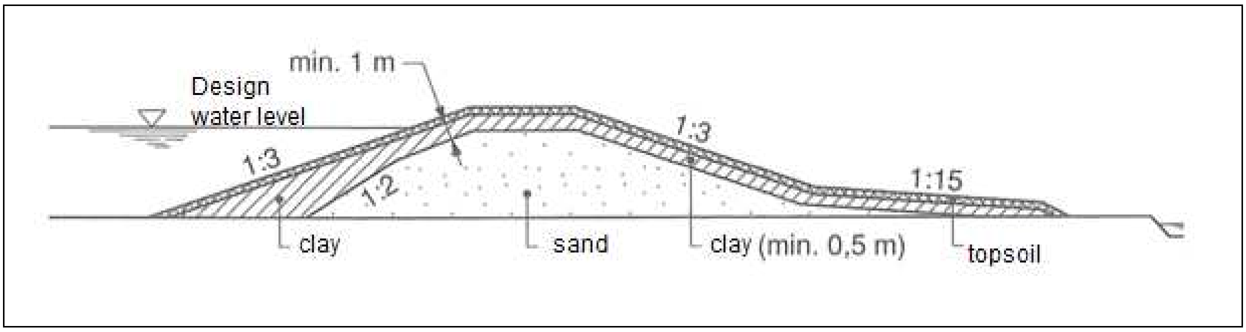


Figure 5: Example of a profile of a river dike (Source: Rivers and - B. van Leusden and J.W. van der Velden. Educatieve Partners Nederland. 1998).

1.3.2 Failure mechanisms

A dike can fail due to different causes, the so called **failure mechanisms**. Figure 6 shows the most important failure mechanisms for dikes.

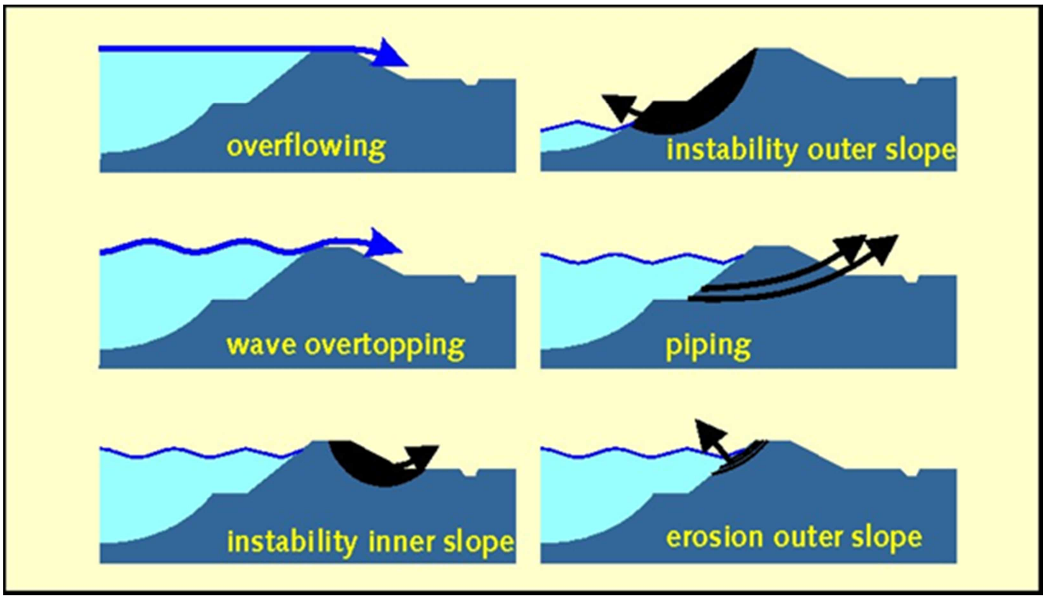


Figure 6: important failure mechanisms for dikes (Source: Rijkswaterstaat).

When a dike fails it will lose its retaining function. A dike can fail when too much water flows over the dike (**overflow**) or when too many waves overtop the dike (**overtopping**). In that case the inner slope can get saturated and eventually erode. Ultimately the dike can fail and a breach can occur.

The strength of the inner slope is expressed by means of a critical discharge for overflow or overtopping which depends on the type of revetment and the quality of the grass. Currently it is generally assumed that the critical discharge for dikes with grass layers of average quality ranges between 1 to 10 litres per second per meter.
Wave attack can lead to damage of the dike revetment on the outside, eventually resulting to erosion and potential failure. The revetment on the outside can consist of grass, stones or asphalt.

Instability concerns the sliding of a part of the dike body. This phenomenon can occur both on the in- and outside of a dike. During a high water, the water pressure in the dyke will further increase. The effective stress will be reduced, so that the soil structure of the dike will no longer have the strength to withstand the horizontal loads of the water. During a high water a part of the inner slope of the dike can slide. When the water level in the river has lowered, but the water pressures in the dike are still high, the outer slope on the river side can also slide.

A dike fails due to **piping** when a hydraulic head over the dike results in a flow of groundwater in the sand layers under the dike. This flow causes “pipes” through which sand can move. If this erosion process continues the dike can be undermined and fail. During a high water, dike managers try to control this process by raising the water level on the inside of the dike by means of sandbags. Permanent measures against piping include enlarging the berm on the inside of the dike or implementing vertical sheet piles to stop the groundwater flow.

For other types of flood defences other failure mechanisms are important as well. For example, for storm surge barriers or lock gates, also the structural failure and non-closure of the barrier are considered to be important failure mechanisms in addition to overflow.

1.3.3 Hydraulic loads on a dike and determination of the crest level

The hydraulic loads on a dike need to be taken into account in the safety assessment and design of a dike. The most important loads are the water levels and the waves. The safety standards for a dike are expressed by means of the probability of exceedance (see section 0), for example 1/10,000 per year for the dike ring around South-Holland. This corresponds to a design water level which is used for the safety assessment and design of dikes. The design water level is derived based on an extrapolation of observed water levels (see Figure 7), supplemented with model calculations. According to the current statistics the 1953 storm surge disaster has a probability of exceedance of about 1/400 per year.

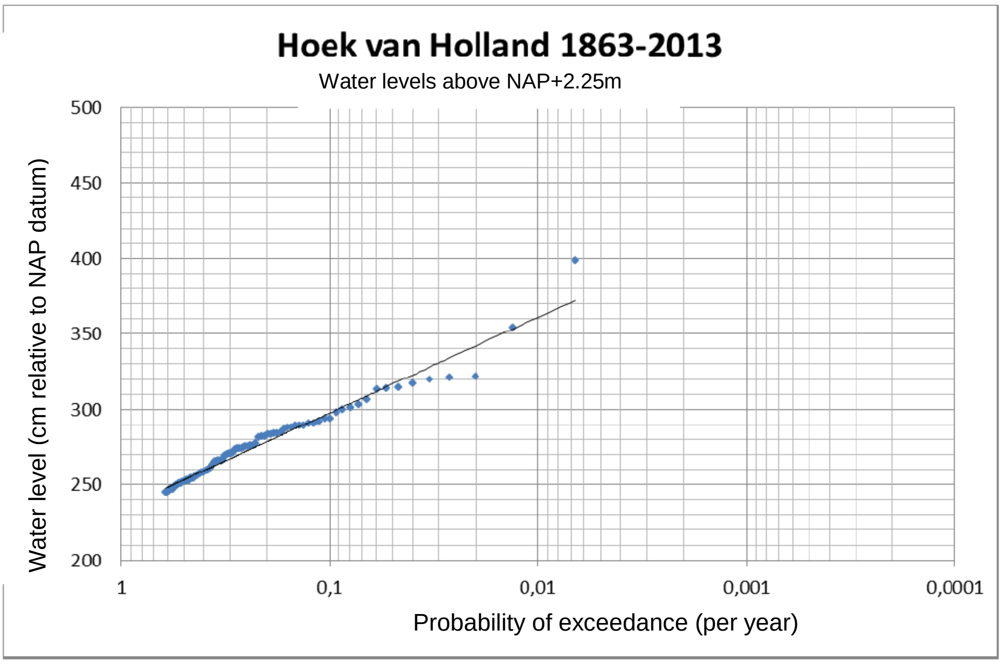


Figure 7: probability of exceedance of the water level near Hoek van Holland (Source: H.J. Verhagen).

The eventual height of the crest of a dike is determined by the following factors (also see Figure 8):

- The design water level at the end of the planning period, determined by a storm surge level with a certain probability of exceedance (see above).
- In addition a freeboard is determined, which include margins for:
  - **Wave run-up**: the height of the waves that will attack the dike is determined by factors such as the strength and the direction of the wind, the water depth and the so-called fetch length (over which the wind blows in the direction of the dike).
  - Margins for other factors like seiches and rainfall
  - A margin for sea level rise and subsidence
  - In the Netherlands a minimum of 0.5 m freeboard is applied for dikes that are not exposed to wave run-up.
- In addition to these margins above, an additional margin is applied to take into account the settlement and compaction of a dike.

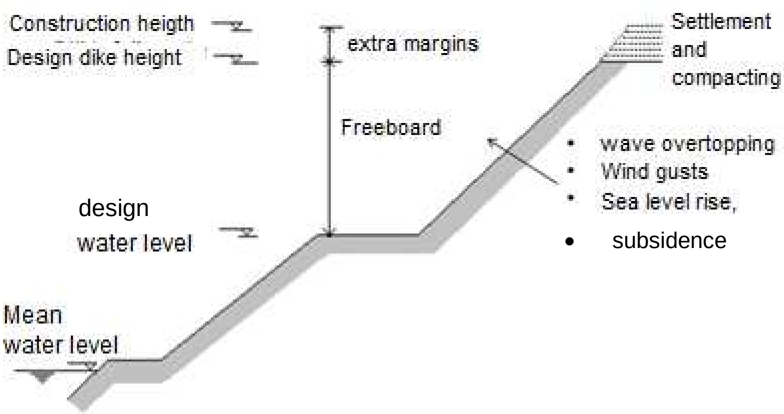


Figure 8: construction height of a dike

1.4 Dike reinforcements

The construction or reinforcement of a dike has many implications on the landscape in flood-prone and flat country like the Netherlands. This influence is not necessary negative. Dikes and the other flood defences determine the typical landscape of the Netherlands. New dikes are rarely constructed in the Netherlands, but dike reinforcements are often executed.
In many locations in the country populated areas exist are present nearby the flood defences and sometimes even buildings are constructed in the dike profile. When planning a dike reinforcement, the land use in the surrounding areas is therefore carefully taken into account and it is often even decisive for the chosen alternative for reinforcement. However in some cases buildings and houses have to be demolished and inhabitants have to be bought out as part of dike reinforcement program.

In the design of dike reinforcement several aspects need to be taken into account:

- The required heightening and widening of a dike to fulfil the safety standards;
- The effects on the surrounding areas, for example the existing buildings, land purchases and effects on nature values.
- The costs of these interventions depend on the construction method, the materials and equipment used and the need to take additional measures in the surroundings.

Dike reinforcement often comprises heightening and also widening of a dike. To maintain a similar dike slope (which is necessary for stability) when a dike is heightened, the width of the dike needs to increase as well. The measures and the interventions associated with failure mechanisms such as piping and instability, mainly take place on the inside (or land side) of the dike. The possibilities to find extra space are as follows:

- On the inside of the dike: however this can lead to conflict with existing buildings;
- On the outside of the dike: along the coast this is generally a good solution but in riverine areas this is often not desired because large-scale application would limit the discharge capacity;
- Other solutions with less use of space: for example structural solutions such as the placement of sheet piles or diaphragm walls in or just behind the dike. In general the costs of these interventions are higher than the reinforcements with soil on the inside or outside of a dike.

When choosing a location and a method for dike reinforcement, the bearing capacity of the subsoil should also be taken into consideration. Many locations in our country weak layers are present in the subsoil, such as peat, necessitating additional measures to provide sufficient stability

The eventual choice for a dike reinforcement strategy requires an integral and often complex consideration of solutions, costs and effects on the surroundings. For example, for the dike reinforcements along the river Lek between the towns of Kinderdijk and Schoonhovenseveer, different types of solutions have been implemented over a trajectory of several kilometres. These have been chosen based on the considerations such as safety, costs and effects on the surroundings (see also Figure 9). At several locations the dike reinforcements took place on the inside of the dike and sometimes the buildings that were present had to be removed. At locations with valuable (often historical) buildings more expensive but space saving measures were applied such as sheet piles. At several other places the dike has been reinforced on the outside.

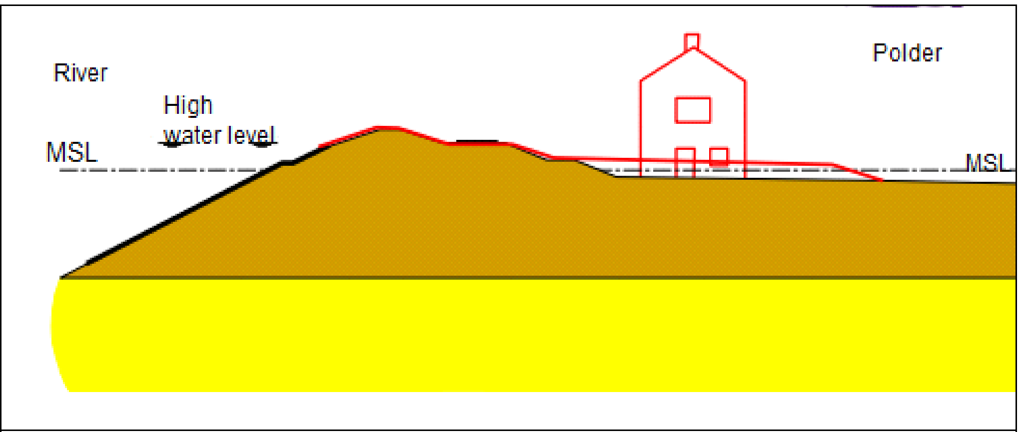
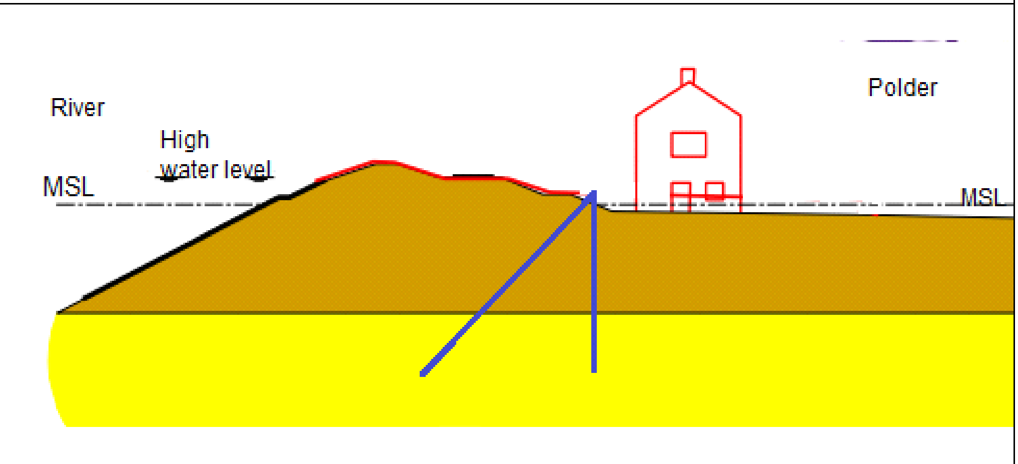
Dike reinforcement on the inside: applied at many locations, existing buildings are demolished	
Dike reinforcement on the inside with sheet piles for stability	
Dike reinforcement on the outside	

Figure 9: alternatives for dike reinforcements applied on several parts of the trajectories between the towns of Kinderdijk and Schoonhovenseveer (Source: Waterboard Rivierenland).

Also in the execution of the dike reinforcement the effects on the surroundings should be taken into account. Aspects that play a role are the accessibility of houses and companies and hindrance of traffic to the construction site and the execution. In some cases a different construction or execution method is chosen that causes less hindrance. For example, driving sheet piles causes a lot of noise, so an alternative construction method can be chosen in which they are pressed into the ground. In general it is not allowed to do construction work on or around flood defences during the autumn and winter periods, since this is the season in which high water levels generally occur in the Netherlands

More information / further reading:
http://www.enwinfo.nl/asp/uk.asp?documentID=110
http://www.helpdeskwater.nl/algemene-onderdelen/serviceblok/english/
http://en.wikipedia.org/wiki/Delta_Works
The international levee handbook: http://www.leveehandbook.net/
Rijkswaterstaat (Author R. Slomp) (2012) Flood Risk and Water Management in the Netherlands, a 2012 update. Report by Rijkswaterstaat July 9, 2012, download from:
http://www.helpdeskwater.nl/onderwerpen/wetgeving-beleid/nationaal/@34443/flood-risk-and-water/