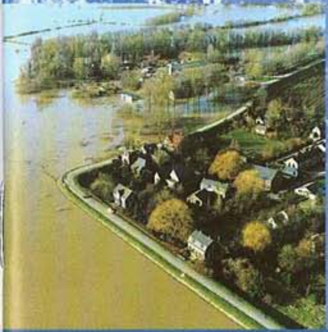
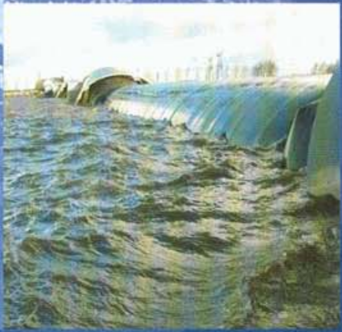
Hydraulic Boundary Conditions

Practical values for the safety assessment of primary flood defences in the Netherlands





Dictorate-General of Public Works and Water Management

Directoraat-Generaal Rijkswaterstaat

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Practical values for the safety assessment of primary flood defences in the Netherlands

Rijkswaterstaat

Dictorate-General of Public Works and Water Management

Colofon

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Introduction

The residents of the Netherlands live and work behind an extensive system of flood defences which protect the country from flooding during high water. The safety of millions of Dutch people and billions of euros of investments depend on the extent to which the dikes, dunes, dams, sluices and embankments in this system meet the required standards.

Obviously these flood defences are checked regularly. Until recently, however, inspections took place on a rather irregular basis. Furthermore, these inspections were sometimes impossible to compare because different methods of calculation and basic assumptions were used.
The Flood Protection Act (1996) altered all this. The Act designated 57 dike ring areas which are surrounded and protected by an unbroken series of primary flood defences. A standard was determined for each dike ring to indicate the required safety level. Every five years since the Act went into force, the primary flood defences are inspected to see whether they still meet the required standards.

The standard is translated into Hydraulic Boundary Conditions, that is, the water levels, waves and other loads to which the primary flood defences are subjected, for use during the inspections. These Hydraulic Boundary Conditions form the basis of the calculations used to check whether a flood defence still has the required strength and stability, or whether measures have to be taken to improve them. The Hydraulic Boundary Conditions therefore play a decisive role in assessing flood defences in the Netherlands. This pamphlet describes the hydraulic boundary conditions for each water system and explains how they are arrived at.

1 Background

Primary flood defence

Flood defences are constructions or natural, elevated areas with a water-control function, such as dikes, dams, dunes and sluices. If a flood defence makes up part of an unbroken series around a dike ring area, or is located in front of a dike ring area, it is known as a primary flood defence. Some primary flood defences connect dike rings to one another.

The Netherlands is, to a large extent, situated below sea level. Primary flood defences protect the country from flooding by the North Sea, the major rivers, the IJsselmeer and the Markermeer. But how high and strong does a flood defence have to be to provide this protection? And on what parameters are these criteria based? We cannot answer these questions without a brief review of the origin of the current water-control philosophy: the disastrous flooding of February 1953.

The Delta Committee

The Delta Committee, which was set up shortly after the flooding disaster in 1953, is mainly known for the Delta Plan it presented in 1960. However, it also made a number of other recommendations in the same year, one of which still forms the basis of the Dutch approach to flood defences today. The Delta Committee concluded that it would be impossible to build a dike high enough to totally rule out flooding, and suggested that a very low risk of flooding must be accepted.

The subsequent question was: what probability are we prepared to accept? All sorts of factors had to be taken into consideration when answering this question. Factors such as the cost of construction and maintenance of a flood defence and the financial damage if flooding does take place after all. For Central Holland (a region situated in the centre of the Netherlands and covering parts of the provinces Noord-Holland, Zuid-Holland and Utrecht), for example, it was determined that it must be possible to safely withstand a water level of five metres above Normal Amsterdam Level (NAP) at Hoek van Holland. The exceedance frequency of this water level is 1/10,000. This water level is 1.15 metres higher than the highest water level measured during the flood disaster of 1953.

Exceedance frequency

An exceedance frequency describes the average number of times in a specific period that a phenomenon reaches or exceeds a certain value. An exceedance frequency of 1/10,000 therefore indicates that a water level occurs on average once in 10,000 years, or that the annual probability that this will happen is 1 in 10,000. Incidentally, this probability is equally great every year. The probability that someone will witness a water level of 1/10,000 per year in his or her lifetime is approximately 1%. For other standards this probability is approximately 2.5% (1/4,000 per year), 5% (1/2,000 per year) and 8% (1/1,250 per year).

In other provinces, where less financial damage would result from flooding, flood defences had to safely retain a water level of 20 to 40 centimetre less, leading to a standard of 1/2,000 or 1/4,000 per year. After protests from the community against the intended large-scale dike improvements, the standard for the stretches along the upper rivers was determined later at 1/1,250 per year. The surprise effect of flooding in these areas is lower, and the damage resulting from 'fresh-water' flooding is more limited than that caused by flooding from the sea.

Dike ring area

A dike ring area is surrounded by a series of flood defences or elevated land which protects the area in question against flooding.

Flood Protection Act

In de Flood Protection Act of 1996 all areas which were vulnerable to flooding were divided into dike ring areas. A standard was laid down for each dike ring area which varied from 1/1,250 per year along the major rivers to 1/10,000 per year for dike ring area 14: Central Holland. The standard provides information about the protective level of the hinterland, but not directly about the required height or strength of the flood defences.

Connecting flood defence

No separate standards have been laid down for primary flood defences which connect dike ring areas to one another, such as the Afsluitdijk (IJsselmeer Dam). When this flood defence is inspected, the safety standards of the dike ring areas behind it are looked at.

In order to be able to assess the safety level of the flood defences, the standards must therefore be translated into the water levels and wave conditions the flood defences have to be able to withstand: that is, the Hydraulic Boundary Conditions.

The hydraulic boundary conditions are recalculated every five years. This takes place in accordance with methods and techniques which are broadly accepted in the field. The increase in sea level, the most recent insights regarding extreme river discharge, and the current bed level are also taken into account. The outcomes are subsequently laid down by the Dutch Minister of Transport, Public Works and Water Management in the Hydraulic Boundary Conditions for the Safety Assessment of Primary Flood Defences (Hydraulische Randvoorwaarden voor het Toetsen van Primaire Waterkeringen).

Hydraulic Boundary Conditions

'Hydraulic Boundary Conditions' is the collective term used to cover all the load factors on which primary flood defences are tested for safety. The most important of these is the water level. Other factors include wind-generated waves and time series of water levels.

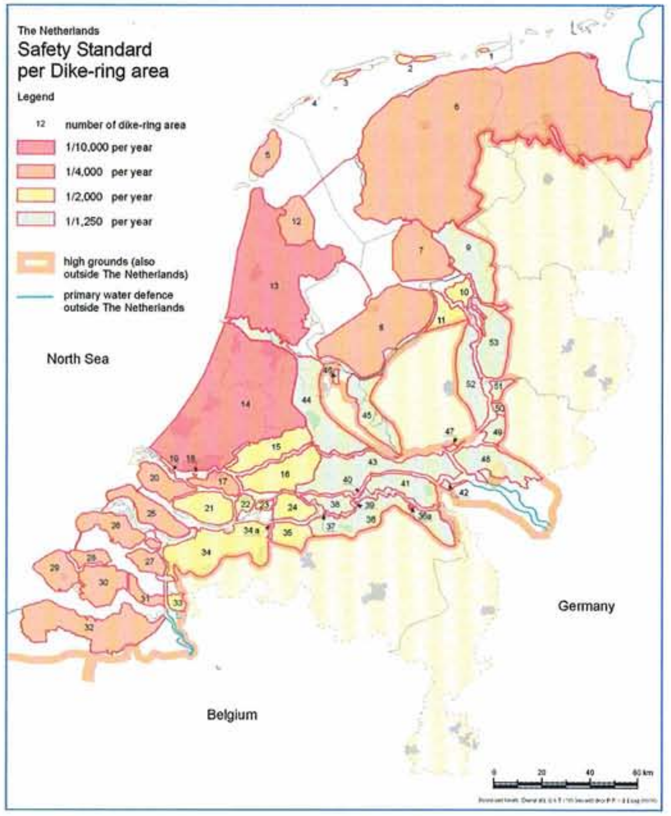
The hydraulic boundary conditions are published every five years by the Dutch Minister of Transport, Public Works and Water Management in conformity with the Flood Protection Act. The first edition appeared in 1996. All primary flood defences were checked against them between 1997 and 2001. The Hydraulic Boundary Conditions 2001 have since been published, which form the basis for the second inspection tour (2002-2006). The next series of boundary conditions will be laid down in 2006.

The hydraulic boundary conditions are intended for checking flood defences against the normative conditions in the actual situation. Therefore, they do not take future climate changes into account, although the latter are, of course, taken into account in dike improvements.

Safety Assessment

Every five years the flood defence managers (usually the water boards) check whether the flood defences can still withstand the Hydraulic Boundary Conditions. These safefty assessments are carried out in accordance with the process laid down in the Regulations for Safety

Assessments (*Voorschrift Toetsen op Veiligheid*). The Minister collects the results of the assessements and reports on them to the Upper and Lower Houses.



If a flood defence does not meet the standard, measures must be taken. The traditional approach is to raise the dike, but nowadays other alternatives are emphatically being sought. After all, the combination of increasingly higher dikes and a sinking ground level means that if, despite raising the dikes, flooding does take place at some point, the depth of water in the polder increases, with more damage and victims as a result. And instead of adjusting the dike to water level, the reverse is also possible: the Room for the River (*Ruimte voor de Rivier*) project, aims to lower high water levels by widening rivers or excavating flood plains for them. If these measures are not adequate, the flood defences will, of course, have to be raised after al.

Water systems

The way in which flood defences are subjected to loads varies depending on the water system involved: flood defences along the North Sea coast are primarily ravaged by waves, while flood defences along the rivers are mainly subjected to high water levels. The waves at sea are mainly caused by the wind, while the high water levels in the rivers result from the large amounts of water which are carried downstream. Flood defences along lakes, on the other hand, have more to fear from a combination of wind-generated waves and the mean water level of the lakes themselves.

The hydraulic boundary conditions distinguish three main water systems (rivers, lakes and the sea) and two transition areas (the tidal rivers and the deltas).

The following chapters describe the most significant sources of danger for each type of water system, how loads affect flood defences and how the hydraulic boundary conditions for these systems are calculated.

2 The upper river area

The upper river area includes the (Dutch) parts of the Rhine and the Meuse which are not influenced by the North Sea or the IJsselmeer. The most significant source of danger is a high river discharge (in short, discharge), that is, the volume of water which flows past a specific point in the river per second. If there is an enormous surge in this discharge, for example as a result of heavy rainfall and/or a great deal of melting snow in the areas upriver, the water levels may become so high that the flood defences are threatened.

Nominative discharge

The normative discharge is the discharge (in cubic metres per second) relating to the standard which has been laid down for the upper river area (1/1,250 per year).

The calculation

The standard for the upper river area is 1/1,250 per year. The flood defences must therefore be able to withstand a water level (the "reference level") with this probability. The most fundamental natural threat in the upper river area is, to put it briefly, the discharge with an annual exceedance frequency of 1/1,250 or the normative discharge.

Normative discharge

This normative discharge is calculated on the basis of discharge data at Lobith (for the Rhine) and Borgharen (for the Meuse). The large-scale river works which have been implemented in the past years are taken into account when these data are assessed. Subsequently, the discharge with an exceeding frequency of 1/1,250 per year is subsequently determined with the aid of statistical calculations. The Hydraulic Boundary Conditions 2001 lay down normative discharges of 16,000 m3/second for the Rhine at Lobith and 3,800 m3/second for the Meuse at Borgharen.

These figures are considerably higher than those stipulated in the previous hydraulic boundary conditions (from 1996), when the normative discharges were 15,000 m3/second and 3,650 m3/second respectively. In 2001, however, use was made of a longer series of measurements, which included the flooding of 1993 and 1995. These two periods of extreme flooding influenced the outcomes of the statistical calculations greatly.

Reference level

The reference level, which is used for the safety assessements, is the water level reached at the normative discharge. It differs according to

the location. It depends on the bed level, the width of the minor riverbed and the flood plains, whether there are obstacles in the river and the hydraulic resistance.
To calculate the reference level, the whole river has to be simulated in a computer model. This hydraulic model is adjusted as required, for example for bed level changes and for changes in the the flood plains.

After the normative discharge has been entered, the model calculates the variation in the water level for each location. The highest water levels calculated are laid down as reference levels.

Reference level

The reference level is the water level relating to the standard which has been laid down for the safety assessement of a specific flood defence. This is highly dependent on the location. The reference level is usually calculated at some distance from the dike although it may be calculated at the toe of the dike in future. When carrying out the safety assessments, the flood defence managers will then be able to calculate the water level at the toe of the dike, which corresponds with the reference level, while taking local conditions into account.

The Hydraulic Boundary Conditions 2001 deviate from the actual situation on one point. The calculations are, in fact, based on the discharge distribution of Rhine water over the rivers Waal, Nederrijn and IJssel, as included in the Hydraulic Boundary Conditions 1996. The actual discharge distribution is, however, currently different. If the hydraulic boundary conditions are to reflect the reality of the situation, river works will have to be carried out at the various splitting points to divide the water according to the agreements. The discharge distribution actually expected will probably be used in future editions of the hydraulic boundary conditions.

Bottom roughness

Of the factors which influence the water level in a river, the roughness of the bottom or hydraulic resistance is the most difficult to determine. In order to do so, a historic flood, such as that of 1995, is usually simulated in the computer model. The outcomes of the simulation are then compared with the water levels actually measured. The roughness of the river bottom can then be estimated on the basis of these differences.

3 The tidal river area

The tidal river area consists of the parts of the Meuse and Rhine which are influenced by the sea. Here, too, high water levels form the most significant loads on the flood defences. These water levels are, however, not only determined by river discharges, but also by the water levels along the coast. If there is a storm at sea, the water levels increase far inland, although these days the greater part of the tidal river area is protected by the Haringvliet sluices and the storm-surge barriers in the Nieuwe Waterweg and the Hartelkanaal. On the other hand, storms themselves often sweep over the tidal river area, resulting in extra water being pushed up and a considerable wave action.

The water level in the tidal river area is therefore determined by all sorts of factors: the Rhine discharge, the Meuse discharge, the water level at sea, the wind speed and wind direction and whether the storm-surge barriers are open or not. This means that a critical water level can be reached in many different ways. The combination of a violent storm and a large discharge can result in the same water level as an extreme discharge with no wind at all. In addition to the probability of, for example, an extreme storm or discharge occurring, the relationship between the various factors must also be looked at. If the water level at sea is high, it is likely to be very windy above the tidal river area. Similarly, if the Rhine discharge is extremely high, a substantial Maas discharge can be expected.

The calculation

With the aid of a computer model, the water level can be calculated for any required location for every random combination of river discharges, water level at sea and wind conditions.
Given that the same critical water level can be reached as a result of various combinations, this is not sufficient. A probabilistic computer model (Hydra-B) is therefore also used to examine which combinations yield the same water level. Subsequently, using a lot of statistics, the exceedance frequency is calculated for each critical water level. The water level relating to the standard then becomes the reference level.

Wind-generated waves, which can entail heavy loads for the flood defences, are of particular importance on the Haringvliet and the Hollandsch Diep. In order to be able to include the load caused by wind-generated waves in the check, a similar calculation is made to that for the reference level, but for water levels and waves together. The final result of the calculation is not the reference level, but the required dike height. This required dike height therefore incorporates the combined effect of water levels and waves.

4 The IJssel Delta

The IJssel Delta is the lowest part of the IJssel, between Hattem and the IJsselmeer. The most important load on the flood defence here is the water level. As is the case in the tidal river area, this water level is determined by various factors, the most obvious being the Rhine discharge and the level in the IJsselmeer. The wind also plays a significant role: wind set-up in IJsselmeer water can lead to increases in the water level of several decimetres in the IJssel Delta.

The calculation

A computer model similar to that used for the tidal river area is currently being developed for the IJssel Delta. Pending this model, the so-called 'surface profile method' was used for the Hydraulic Boundary Conditions 2001. In this method, the influence of the Rhine discharge and the combination of the IJsselmeer level and wind on the water levels in the IJssel Delta are first determined by two separate calculations. An estimate is subsequently made of the combined effect on the water level, after which the reference level is determined.

5 The Vecht Delta

The Overijsselse Vecht (insofar as there are any primary flood defences there), the Zwarte Water and the Zwarte Meer jointly form the Vecht Delta, which is a sort of miniature version of the Rhine and the tidal river area. The water level here is determined by the river discharge, the IJsselmeer level and the wind. The guard lock at Ramspol fulfils the same function in the Vecht Delta as the storm-surge barriers for the tidal river area.

The calculation

The calculations used in drawing up the Hydraulic Boundary Conditions 2001 were mainly made using two models (one hydraulic and the other probabilistic) developed in 1994 for the construction of the guard lock at Ramspol. However, these models are now out of date. A new model with a design similar to those used for the tidal river area and the IJssel Delta is currently under development.

6 The lakes

Two large water basins in the former Zuiderzee, the IJsselmeer and the Markermeer have primary flood defences. These structures are subjected to a combination of high water levels and waves. The factors determining the loads are the level of the lake and the wind.

Wind causes heightened water levels and waves. The higher the wind speed and the greater the distances over which the wind blows, the higher the water level and the greater the wave action.

The level of the lake is determined by the supply and discharge of water. Large amounts of water are carried from the IJssel, the Zwarte Meer and various polder pumping engines to the IJsselmeer. Most of this water is discharged, in turn, by the discharge sluices in the Afsluitdijk. In the event of sustained northerly winds, however, the water levels in the Wadden Sea become too high for discharge to take place and the level in the IJsselmeer can rise considerably. The volume of water flowing into the Markermeer is much lower and can be discharged, particularly via the North Sea Canal, without too much difficulty.

The calculation

The situation in the lakes is simulated in a hydraulic computer model which calculates the water levels and the waves for any required location for all sorts of combinations of lake level, wind speed and direction. The dike height required to safely retain the water level and waves concerned is examined for all these combinations. Given that various combinations result in the same required dike height, a subsequent step is also necessary. The exceedance frequency for every dike height is calculated in a probabilistic model (Hydra-M), using a lot of statistics. The dike height relating to the standard is then the required dike height for the safety assessment. The method of calculation corresponds with that for the tidal rivers, generally speaking.

7 Sea and estuary

Storm surge

A storm surge is a combination of storm and the high water phase of the tide. Extremely high water levels are, in practice, always a result of this combination.

The loads to which primary flood defences are subjected along the coast and estuaries are exclusively due to heavy storm surges. During the tidal cycle these storm surges cause extremely high water levels and violent waves which pound the flood defences. The wave load is greatest along the 'open coast', that is the west coast of the Zeeland Islands, the coast of North and South Holland and the North Sea side of the West Frisian Islands. Here the waves are not cushioned by shallow parts or broken by islands. In general, the waves in the Wadden Sea and Western Scheldt are not as high.

The most important cause of storm surges is the wind. The most violent storms do not, however, necessarily cause the heaviest storm surges. The type of storm and the course the depression takes also play an important role. Only when there is a protracted, extensive fetch (the distance of open water over which wind blows to generate a wave) above the whole of the North Sea with a north-westerly storm, does this lead to high water levels along the Dutch coast.

Wavereduction on the Eastern Scheldt

The Eastern Scheldt Barrier ensures that water levels are lower and waves less rough in the area behind it. But the storm surge barrier does not completely close off the sea arm, and wind-generated waves continue to batter the flood defences along the Eastern Scheldt. This is why these structures are rated among the primary flood defences and hydraulic boundary conditions are drawn up for them.

The calculation

Two types of hydraulic boundary conditions apply to the primary flood defences along seas and estuaries: reference and calculated levels are drawn up for the water levels, and the wave height, period and runup are calculated for the wave load.

Water levels: basic and reference levels

Since high water levels are determined by so many different factors, it is not simple to calculate the water levels relating to the standard purely from the wind data. In practice, therefore, series of measurements of water levels are used. Basic water levels were calculated from the series of measurements which, in 1985, had an exceedance frequency of 1/10,000 per year. After several corrections had been applied, these figures yielded a series of reference levels.

Correction of the basic water levels

Two sorts of corrections are applied to the basic levels with an exceedance frequency of 1/10,000 per year: one for economic reduction and one for increases in tide levels.

Economic reduction is the adjustment of the basic level to the lower safety level required in less densely populated and industrialized regions. In these areas, where the potential damage in the event of flooding is lower, standards of 1/4,000 or 1/2,000 per year suffice.

The increase in tide levels is the systematic rise in the water levels at high tide. Research has not only shown that the average sea level has risen during the last hundred years, but that tide levels have risen even more. It is assumed that this increase in tide levels has a roughly proportional effect on the hydraulic boundary conditions.

The hydraulic boundary conditions for dunes deviate slightly. Trial calculations with a calculation model for dune erosion show that the reference levels for dikes are insufficient for dunes and that possible combinations of wind speed, water level and wave height must be taken into account. A factor must therefore be added to the reference levels for dikes. The raised reference levels are applied in combination with the wave height on relatively deep water, that is at the Normal Amsterdam Level (NAP) - 20 m depth contour.

Wave load: height, period and runup

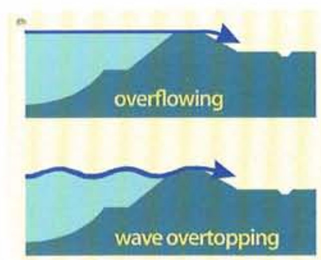
The wave load on a flood defence is determined by the height and period of the waves. The longer the period, the longer the time between the waves (and therefore the longer the waves) and consequently the higher the impulse. The combination with the length of the wave determines how high the water pressure is, and therefore the load. Wave growth models and statistical calculations are used to determine the wave height and period relating to the standard.

The calculations are carried out on the basis of wave measurements on fairly deep water (NAP - 20 m). Assuming extreme wind speeds (from 30 to 35 metre per second) and the water depth during a storm surge, the model calculates the average height of the waves at the point when they reach the flood defence. In reality, of course, the height of waves varies greatly during a storm. For this reason, the "significant wave height" is used. This is the height exceeded by 1 in 7 waves. In practice the significant wave height often corresponds with the estimate of the wave height made by an experienced observer.

Wave measurements are used for the wave growth model at most places along the Dutch coast. This information is not always available for the Western Scheldt, the Eastern Scheldt and Wadden Sea, where the wave data are often based on old reports. In fact, some reports are not based on wave measurements at all but on tide mark observations. These are height determinations based on observations made after a storm of how

far the water has risen on the dike slope. This can be seen from the grass, straw, wood and all sorts of rubbish left behind by the water. For places for which only tide mark observations are available, the models do not work with wave height but with wave runup. Wave runup is the difference in height between a specific water level and the tongue of water pushed up by the waves against a flood defence.

The term "peak period" is used for the wave period. Recently it became apparent that the peak periods used so far are too low for the standard. These peak periods have been reached several times, and sometimes even exceeded, during the last ten years, but the extent to which they should be raised is still unclear. Extensive research into this will be carried out during the next ten years.



8 The future

Ideally, the tools with which the hydraulic boundary conditions are calculated should be as uniform as possible in design and use generally accepted, up-to-date methods and technologies. They should also describe the actual situation and be suitable for direct use in checking the primary flood defences in accordance with the Regulations for Safety Assessments. These tools should be available for all primary flood defences, irrespective of whether the latter are subjected to loads by the major rivers, by the sea, or by the IJsselmeer or Markermeer.

Realization of the above visions is already underway. The bed level of the rivers and the layout of the flood plains in the various hydraulic models are being brought up to date. A new wave growth model (SWAN) and new probabilistic models for the different water systems are being developed. The Hydraulic Boundary Conditions 2006 will, for the first time, include hydraulic boundary conditions for the softening of river dikes and for the dike revetments in the different water systems.

In the future it will be possible to calculate hydraulic boundary conditions more and more accurately as a result of the development of the models and new insights based on measurements of waves, river discharges, etc. The continual improvement of the hydraulic boundary conditions will enable increasingly reliable checks on the safety of flood defences in the Netherlands.

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