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Abstract

In a historical perspective, flood protection in the past was not given high priority - plague and periods of famine and war took precedence. Poverty and a lack of knowledge made it difficult to create safer dikes. Dike engineering did improve in Napoleonic era due to the French Central Government, but many dikes still failed. A historical overview of the causes and mechanisms of dike failures in the Netherlands has been drawn up, and resulted in a list of 337 recorded events leading to an assumed total of 1735 dike failures in the Netherlands between 1134 and 2006. Storm surges were, generally speaking, the primary cause of dike failure, followed by high water and ice drift.

Two-thirds of all dikes failed as a result of the inner slope protection or the crest of the dike being eroded. The main causes for this were run-over and wave overflow, which could have been prevented, had the dikes been higher. The second cause of dike failure was ice drift. All other mechanisms were of minor importance, but were in the past either difficult to determine or even know about.

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1. Introduction

A high percentage of the world's population lives close to oceans, seas, lakes and rivers. In many cases the very lives of these people, together with their personal property and belongings, depend on flood defense systems. In order to optimize these systems, the relevant governments must be in a position to assess the total risk of flooding. In the Netherlands this kind of risk analysis must, by law, be carried out every five years on all the primary defense systems. There are two aspects to flood risk: the probability of occurrence, and the total damage. Damage is the sum of the number of deaths and injured, the number of houses destroyed, and extent of devastation to infrastructure, the costs of repairing the flood defense systems, and the loss of production in the flooded area. In a standard risk analysis of a flood defense system, the accuracy of the

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estimated total damage tends to be much higher than the accuracy of the probability of the flood defense system failing. One reason for this is that there are several different causes of failure i.e. many possible different failure mechanisms, and above all, there is no good understanding of the probability of occurrence of each individual cause and mechanism. It is sometimes the case that questions arise as to whether a certain assumed cause or mechanism actually ever occurred. To this end, an assessment was conducted to obtain an overview of the causes and mechanisms of historical dike failures in the Netherlands.

2. The History of Dutch Dikes

Prior to 1200 there were few dikes as we know them today - they were mostly small and low quays. Between 1200 and 1400 the main rivers were all enclosed by real dikes, but they often had serious shortcomings. They were often too steep, too low, contained too much peat and had insufficient slope protection. With at least 10 serious plagues raging between the 14th and 17th centuries, killing some 15-30% of the population each time, several periods of famine killing up to 16% of the population (City of Delft, 1556) and several wars (100 Year's Civil War, 80 Year Spanish War, Second World War), flood protection was not given high priority. Poverty and a lack of knowledge also diverted resources away from dike improvement. However, the Napoleonic era did see dike management starting to develop. In response to numerous disasters, the construction of the current extensive flood defense system started less than a century ago. Firstly, following serious dike breaching and flooding around the Southern Sea in 1912, it was decided that this inner sea be closed off, which was done by constructing the IJsselmeer Dam in 1933. Similarly, after the catastrophic flood disaster of 1953 in Zeeland it was decided to close off the islands in the southwest of the country from the sea. This was done by building 11 large dams and storm surge barriers, the construction of which was completed in 1997. Although the Dutch flood defense system has improved over the years, there were still serious dike problems with high water in the rivers in 1988, 1993 and 1995, leading, in 1993, to 250,000 people being evacuated. And in 2006, only 44% of the 2875 kms Dutch dikes, dams and dunes met the dike regulations set by the Ministry of Public Works and Water Management. The IJsselmeer dam is also one of the dams that does not meet the specified regulations.

3. Dike Failures and Flood Disasters

The oldest accurate recorded flooding in the Netherlands dates back to 26 December, 838, when a storm surge flooded most of the province of Friesland, in the northwest of the country. The overview presented in this article starts in 1134 when, according to Anselmus, abbot of the village of Gembloers near the city of Namen, "*...in the silence of the night a large seaquake occurred*". The result was considerable flooding in the southwest of the Netherlands where the land broke up into many islands. This archipelago is now the province of Zeeland. Many floods occurred over the years. The most severe ones, except one, all involved coastal flooding, see Table 1. In 1287, about 10 percent of the total population of the Netherlands drowned as a result of St. Lucia's flood.

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Table 1. Massive floods in the Netherlands

Flood	Location	Date	Casualties
St. Stephen's flood	Friesland, Groningen	26 December, 838	2437
St. Michael's flood	Zeeland and Flanders	29 September, 1014	thousands
Seaquake flood	Zeeland	October, 1134	unknown
St. Juliana's flood	North coast	17 February, 1164	thousands
St. Lucia's flood	Friesland, Groningen	14 December, 1287	50,000
2nd St. Elizabeth's flood	Zeeland, Holland and Flanders	18 November, 1421	2000
All Saints' flood	Zeeland	1 November, 1570	20,000
River Delta flood	Central + East Rivers	5 – 15 March, 1595	3000
St. Marten's flood	Northeast coast	12 November, 1686	(Dutch) 3000
Christmas flood	Northeast coast	25 December, 1717	(Dutch) 2500
1953 Flood	Zeeland and Flanders	1 February, 1953	(Dutch) 1836

Casualties were generally counted and recorded by priests, and details about the floods were recorded by the provincial administrations, municipalities and water boards. Without the help of historians it would be impossible to create a historical overview of all the dike failures and floods from these innumerable records. Buisman (1995, 1996, 1998, 2006a, 2006b) published a series of five books listing all known wind, weather and water disasters in the Netherlands from 763 to 1747. Gottschalk(1971, 1975, 1977) published three books listing all storm surges and river floods in the Netherlands between 755 and 1700. Rosema (2002) published a list of dike failures and storms between 1500 and 2000 based on 642 publications listed in the Dutch Central Catalogue. Their lists have been combined and updated to 2006 for this overview. In each case, the failure causes and mechanisms had to be determined. Often, the number of failed dikes or the cause of failure were not recorded and had to be conjectured from what is known, in order to obtain a general overview.

Fig. 1 St. Anthonis dike failure during St. Peter's flood, P. Nolpe, 4-5 March, 1651

4. Storm Surges and High Water

A total list has been put together that covers 338 recorded events that led to an estimated 1735 dike failures between 1134 and 2006. Table 2 sets out the six main causes of historical dike failures in the Netherlands. In addition to a total list, the floods are also divided up into three different eras. Storm surges were generally the major cause of dike failure, followed by high water and ice drift. A total of 136 storm surges were recorded on the North Sea between 900 and 2006. The percentage of failed dikes caused by storm surges after 1862 is even higher than before that date, but this can be attributed to the flooding of Zeeland in 1953, which led to 140 dike failures out of the 206 in this period.

Fig. 2. Overflow of dike along the river Maas after heavy rain, Nederasselt, 8 January, 1925

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Table 2. Causes and distribution of dike failures

Causes	1134 – 1783	1784 – 1861	1862 – 2006	Total
Storm surge	60%	8%	72%	55%
High water	23%	27%	14%	22%
Ice drift	5%	57%	0%	11%
External (human, animal)	5%	0%	5%	4%
Rainfall or drought	4%	8%	8%	5%
Miscellaneous	3%	0%	1%	2%
Number of failures	*1271*	*217*	*247*	*1735*

5. Ice Drift

The failure of sea dikes caused by ice is different from the failure of river dikes caused by ice. Ice piles up on the sea dikes as floating ice is blown in by the wind.

Fig. 3. Ice drift on the IJsselmeer Dam

Fig. 4. Ice drift on the IJsselmeer Dam

River dikes are affected in two ways by ice drift. Firstly, by ice pushed by the river current towards the dikes along the outside curves, and secondly by a higher water table (overflow) or a higher thrust of water (water pressures). The dikes that failed as the

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result of ice drift were, according to the records, almost all river dikes. Ice drift is the number three cause of failure, and at 57% it is the most prevalent cause of failure in the Little Ice Age between 1784 and 1861. About 140 river dikes failed due to excessive ice load and the thrusting water caused by ice drift in only 8 winters in this period.

Fig. 5. "The iceberg of Ochten (a village along the river Rhine) ... detonated on 24 January, 1789"

Fig. 6. Dike failure cause by ice in 1799

Fig. 7. Men trying to reduce the ice load on a dike

Ice drift was a major problem in the past. A text in old Dutch records depicts this well:

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> "*The government asked the preachers to change the common preaching service on Wednesday evening to a prayer service. Early on the morning of Thursday, February 3rd, 1729 at 3:30 AM, everybody was startled by a loud distant thump: the ice dam had broken loose. In minutes the water level had decreased by nine inches and the joy of the people was incredible.*"

Since 1861, less damage has been caused by ice drift, probably because the quality of the dikes improved, but also because the average river water temperature increased considerably over the years (See Figure 8. Source RIZA and KNMI). As a result, there were fewer days each year with ice drift (See Figure 9. Data recorded by Wemelsfelder and Wierenga but published by Wessels et al., 1999).

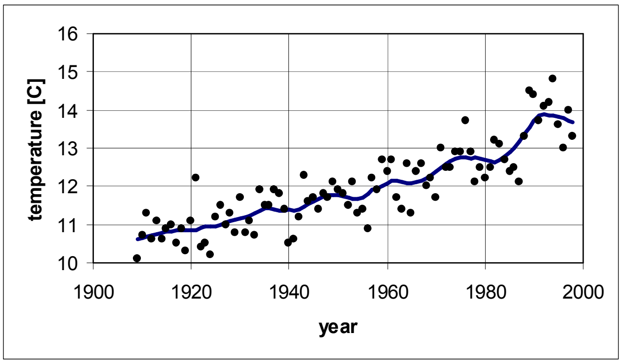

Fig. 8. Annual average temperature of the river Rhine near Lobith

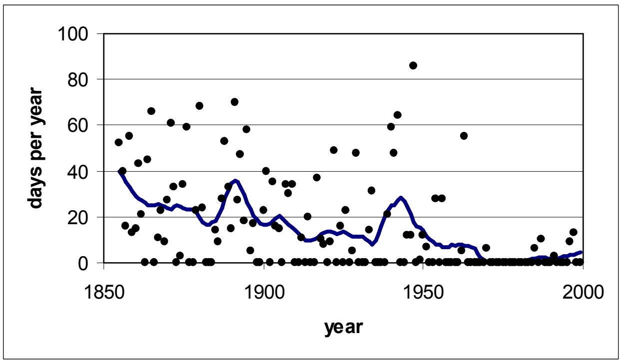

Fig. 9. Average number of days per year with ice drift on the river IJssel

6. External Forces, Rainfall and Drought

Only a small percentage of dikes have failed because of external forces. These failures can be attributed to either humans or animals. Human actions include, for example, dike piercing, bombing (war or terrorism), ship collision or leaking water pipelines. Many dikes were deliberately pierced for strategic reasons in particular during the 80 Years War (1568-1648) and the Second World War.

Animal activity includes, for example, rats or insects tunneling and burrowing. 1732 saw a devastating plague of pile worms throughout the country that destroyed the wooden piles, which in those days were used for outer slope protection and stability. There are many references to this plague, for example:

> "*... a Dutch complaint over God's coming judgments, clearly being recognized in the gnawing of the worms at the piles of the Dutch sea dikes - for the occasion of the thank, fast and prayer day - ...*"

Following this event, dikes were constructed without piles and with their flatter outer slopes protected by masonry pitching.

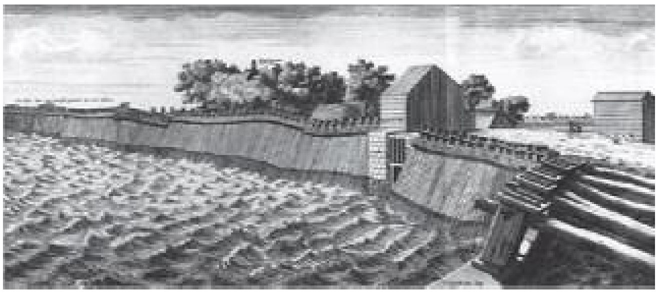

Fig. 10. Wooden piles protecting the Diemer sea dike near Amsterdam (N. Listingh, 1702)

Sometimes moles were given the blame for a dike failure when molehill shaped sand craters were found. These are generally caused due to the in those days unknown piping failure mechanism. The muskrat was brought to Europe by a Czech count about 100 years ago. These rats did not start to be a plague in The Netherlands until 1980, so no dike failure in the Netherlands can be ascribed to them.

Heavy rainfall or drought can also cause dikes to fail as a result of slope instability. Failure after heavy rainfall is mainly due to the clay in the dikes softening. Failure during drought is mainly due to a lack of weight of the dike (mostly peat dikes).

7. Failure Mechanisms

When designing and inspecting dikes, engineers must take into account all the mechanisms that cause dikes to fail. Dutch Dike engineering books list the following failing mechanisms:

A. Run-over (dike too low for water level);
B. Wave overflow (waves too high or too much run up);
C. Instability of outer slope protection or erosion (damage to masonry pitching or rock fill);
D. Erosion of inner slope protection (or dike crest, often by wave overflow infiltration);
E. Micro-instability (washing out of the dike core sediment, such as piping below the dike);

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F. Piping (local groundwater flow, sediment transport and erosion below/behind dike);
G. Heave (lifting of and liquefaction of inner sand layer by vertical groundwater up-flow);
H. Bursting (forcing up of polder top clay layer by high pore water pressure in sand layer below);
I. Liquefaction of shore line (loose sand layer in front of dike becomes unstable through wave action);
J. Sliding outer slope (macro instability of steep outer slope);
K. Sliding inner slope (macro instability of steep inner slope);
L. Horizontal sliding (complete dike pushed aside by water pressure);
M. Ice drift (both thrusting water load and direct ice load through current or wind);
N. External factors (Human: piercing, bombing, ship collision. Animal: worms, rats).

In 1998 the Dutch government proposed compiling a complete list of dike failure mechanisms to be used during dike inspections (TAW, 1998). Unfortunately this list is not complete. Mechanisms D, G, H and some of N are missing. The omission of mechanism “D. Erosion of inner slope by waves” is strange since it is the main mechanism behind the 1953 flood disaster in Zeeland. The other missing mechanisms: “G. Heave” and “H. Bursting of clay layers” are nowadays, in addition to mechanism “F. Piping”, of great concern because of the rising sea level, which leads to higher pore water pressures behind the dikes. Another weakness of the list is that when looking at mechanism: “N. External factors”, only the “Ship collision” option is mentioned, even though significant numbers of rats are still caught in the Netherlands every year (400,000 rats in 2003) and the latest canal dike failure (Stein in 2003), was caused by failing to examine an 80-year old water pipeline crossing this dike (Van Baars, 2004).

Fig. 11. Collapsed dike, Papendrecht 1953

In 2004 the government proposed compiling a new list (VTV, 2004). However, this list still omits mechanisms H and N (even ship collision), but this time also fails to include mechanisms L and M. Mechanism “L, Horizontal sliding” is, since 1999, believed by the Dutch government to be impossible, but the peat dike failures near Zoetermeer (1947, Oostzaan (1960), Wilnis (2003), Terbregge (2003) and the levee failures in New Orleans (2005) have proven this mechanism to be possible (Van Baars, 2003). The government considers that mechanism M “Ice drift” no longer poses a threat. This is not correct. Even though river water temperatures have increased over the years and the ice drift

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has decreased, a zero risk is not yet proven. Besides, unlike the temperature of river water, the temperatures of the North Sea and the IJssel Lake have not risen.

Fig. 12. Horizontally shifted peat dike, Wilnis 2003

A final comment is made about mechanisms "A. Run-over" and "B. Wave overflow". These mechanisms are to be found in all lists of failure mechanisms, although they are, in fact, not mechanisms but causes of dike failure. Both causes lead to failure mechanism "D. Erosion of the inner slope protection and crest". In order to conduct satisfactory flood risk analyses, the distributions of occurrence of the failure mechanisms should be known. However, they are difficult to determine. As a first indication, the percentages of failure per mechanism of past recorded dike failures are listed in Table 3.

Table 3. Failure mechanisms in the Netherlands between 1134 and 2006

Mechanism	Distribution
Erosion of inner slope protection + crest	67%
Ice drift	11%
Erosion or instability of outer slope protection	6%
Sliding inner slope	5%
External (human and animal)	4%
Sliding outer slope	3%
Liquefaction of shore line	2%
Piping	1%
Micro instability	0.5%
Horizontal shear	0.5%
Bursting of inner clay layer	0.0%
Heave	0.0%
Total	*1735*

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The table shows that two-thirds of all dikes failed due to erosion of the inner slope protection or crest. The main causes for this are run-over and wave overflow, which could easily have been prevented by higher dikes. A stronger crest and slope protection might also have prevented many breaches. The number two mechanism was ice drift. This creates a higher water level and crest damage. This can lead to overflow and then erosion of the inner slope protection and crest.

All the other mechanisms seem to be of minor importance, but it should be realized that, in the past, it was difficult to recognize or even be aware of the other mechanisms. For example, slope instability is often triggered by softening of the clay layers during a storm or high water and will often not be seen as an independent dike failure mechanism. The same applies to the mechanisms liquefaction, piping and heave. Dike failures due to unstable, loosely compacted sand layers near the dike (liquefaction), the transport of sand particles in the permeable sand layers below the dike (piping), or uplift behind a dike of a clay layer on top of a sand layer by high pore pressures (bursting) are all triggered during a storm or high water. Nowadays, the mechanisms piping, bursting and liquefaction are regarded as being the most dangerous mechanisms. Firstly, because the dikes are much higher than in the past, which diminishes the probability of run-over and wave overflow happening before other mechanisms can occur. Secondly, because the sea water level rises and the land subsides thereby increasing the probability of piping, bursting or liquefaction by higher pore pressures near the dike.

One other point can be concluded from the data, but is not apparent in the table. Most dike failures are not solitary events. In 58% of the recorded events, the disaster was caused by a series of failures. Major disasters in particular, such as the flood in Zeeland of 1953 and the disaster caused by Hurricane Katrina in New Orleans in 2005, are a combination of a large number of failures. This means that evacuation, flooding and dike repair analyses, based on a single dike failure, are far from reality.

8. Conclusions

The causes and mechanisms of some 1735 dike failures in the Netherlands since the creation in 1134 of the Dutch province and archipelago Zeeland were examined. The records of these dike failures show that storm surges were, in the past, the biggest overall cause of dike failure, followed by high water and ice drift. Over the years the risk of ice drift has diminished since river water temperatures have risen. The records also show that two-thirds of all dikes failed due to erosion of the inner slope protection or crest. The main causes for this are run-over and wave overflow. The number two mechanism was dike damage caused by ice drift. All other mechanisms were of minor importance. In the past, the more complex mechanisms were difficult to recognize or even be aware of and were therefore rarely recorded. In 58% of the (recorded) events, the disaster was caused by a series of failures. Over the past thousand years about 100,000 people drowned in one of the ten large flood disasters. Although the last one, in 1953, was relatively small, the 140 dike breaches and the resulting 1836 casualties necessitated the Dutch to create a much safer flood defense system. Unfortunately, in 2006, only 44% of the sea, lake and river dikes and dams met the Dutch dike regulations.

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