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Post-flood investigation in the Lower Chao Phraya River Basin

Post-flood field investigation in the Lower Chao Phraya River Basin 23 - 27 January 2012

Findings of the Thai - Dutch Reconnaissance Team

Organized by ENW: the Dutch Expertise Network for Flood Protection

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Voorwoord

Nederland staat graag bekend als de best beschermde Delta van de wereld. Mensen uit de hele wereld komen naar ons land om te zien hoe we dit hebben bereikt en hoe we er voor zorgen dat het zo blijft. Het Expertise Netwerk Waterveiligheid (ENW) heeft hierin de belangrijke taak om, zoals staat in het instellingsbesluit *'[..] de kennis over de beveiliging van Nederland tegen overstroming samen te brengen, te ontwikkelen, vast te leggen en te verspreiden ten behoeve van de wettelijke taakuitoefening van het Rijk, de provincies en de waterschappen.'*

Om kennis te ontwikkelen en te toetsen zijn we aangewezen op proefopstellingen, computersimulaties en calamiteiten in het buitenland. Immers, we leven in een veilige Delta en passen de waterkeringen regelmatig aan de nieuwste inzichten aan, waardoor na de ramp van 1953 de opgetreden calamiteiten van beperkte omvang waren. De belangrijkste les die we moeten leren van de dijkdoorbraken en overstromingen in New Orleans 2005, Frankrijk 2010 en Thailand 2011 is dat er geen absolute veiligheid bestaat. De bescherming tegen overstromingen verdient dan ook onze voortdurende aandacht. Dit vraagt veel kennis en inzicht die de Nederlandse specialisten als geen ander hebben. Het blijft echter leerzaam en daarom nodig om onze inzichten te toetsen bij omvangrijke calamiteiten zoals nu in Thailand. Het initiatief van een aantal ENW-leden om naar Thailand te gaan heb ik dan ook van harte ondersteund.

Het succes van een expeditie zoals deze hangt af van de openheid van de betrokkenen. Ik vernam dat de openhartigheid van onze Thaise gastheren en dames over de overstromingen groot was. Overstromingen waarbij honderden doden zijn gevallen en die tientallen miljarden dollars schade hebben veroorzaakt. In dit rapport is te lezen wat we kunnen leren over het snel dichten van bressen. Het laat het belang van het deskundig ontwerpen van aansluitconstructies zien. Iets waar ENW al geruime tijd aandacht voor vraagt in zijn onderzoeksagenda. Ik raad iedereen aan dit verslag te lezen en de lessen tot zich te nemen.

Als voorzitter ben ik trots dat het ENW deze missie mogelijk heeft kunnen maken. Ik hoop dat de samenwerking met Thailand maar ook andere landen doorgaat en dat we van elkaar blijven leren.

Ir. Gert Verwolf, voorzitter

Preface

The Dutch proud themselves for their country to be known as the best defended delta in the world. People from far and wide come to The Netherlands to see how we have achieved this and how we make sure that we maintain this high standard. The government gave the Expertise Network for Flood Protection (ENW) the important task to collect, develop and disseminate the knowledge needed to uphold our high level of flood protection.

To develop and test our knowledge we have to use experiments, computer simulations and insights from calamities abroad, since after the disastrous flooding of 1953 only floods of limited size and impact have occurred in our country. However, the most important lesson we should learn from events in New Orleans 2005, France 2010 and Thailand 2011 is that there is no such thing as absolute safety. Our flood protection requires our constant attention. Dutch specialists have demonstrated that they possess the much-needed technical know-how. However, it is necessary to continuously update our knowledge based on events that occur in other parts of the world. I therefore heartily supported the initiative to go to Thailand to do just that.

The success of an expedition like this relies to a large degree on the willingness of the local participants and experts to share information. I was impressed and grateful for the openness about the flooding events that was demonstrated by our hosts in Thailand. The events in their country caused the death of hundreds of people and led to billions dollars worth of damage, and we sympathize with their losses. In this report you can read what we can learn about the techniques to close breaches and about the causes of the failure of the levees. It shows the importance of a thorough design of the transitions between earthen dikes and concrete structures. This is something that the ENW has pointed at in the past in his research agenda.

As chairman I am proud that the ENW could make this research mission happen. I hope that we can continue the cooperation with Thailand and other countries so that we can continue to learn from each other.

Ir. Gert Verwolf, chairman

Samenvatting

Grote delen van centraal Thailand zijn in het jaar 2011 overstroomd. Tijdens deze overstroming zijn verschillende dijken en kunstwerken bezweken in de benedenloop van de Chao Phraya rivier en in de ringdijken rond industriegebieden nabij de stad Bangkok. Door het Expertise Netwerk Waterveiligheid (ENW) is samen met Thaise partijen tussen 23 en 27 januari 2012 een verkenningsmissie georganiseerd om meer inzicht te krijgen in de faalgevallen. Op diverse plekken in de benedenloop van de Chao Phraya rivier zijn dijken bezweken door overloop en de daarop volgende erosie van het dijklichaam. De meeste geconstateerde bressen vonden plaats bij zwakke plekken, zoals lokale verlagingen en aansluitingen met kunstwerken.

De drie kunstwerken die zijn bezocht zijn alleen gefaald ter plekke van de aansluiting tussen het kunstwerk en het dijklichaam. Dit toont het belang van een robuust ontwerp van aansluitconstructies aan. In Rojana industrial estate zijn zeven bressen opgetreden in het 70km lange dijksysteem rond het industriegebied.

Daarnaast zijn de oorzaken en effecten van overstroming van twee historische in Ayutthaya geanalyseerd, en is de ringdijk rond Bangkok (the King’s dyke) bezocht. In het rapport zijn de belangrijkste bevindingen beschreven en zijn technische aanbevelingen en kansen voor verdere samenwerking tussen Thaise en Nederlandse onderzoekers benoemd.

Summary

Large parts of central Thailand were severely flooded during the year 2011. This event has been characterized by a number of failures of dykes and structures in the Lower Chao Phraya river basin and the flood defence systems of industrial estates around Bangkok. The Dutch Expertise Network for Flood Protection (ENW) has organized a post-flood field investigation in cooperation with Thai partners to investigate the failures and damages due to the floods.
The investigation took place between January 23 and 27, 2012. Several large breaches occurred in the canal dykes in the Lower Chao Phraya river basin mainly due to overflow and consequent erosion of the dyke body that consisted of clay. Most breaches occurred at weak spots in the system (lower parts of the dyke, connections with structures and at obstructions).

Three hydraulic structures were visited that all failed at the connection between the structure and the earthen dyke. This illustrates the importance of a robust design of these transitions. At Rojana Industrial Estate seven breaches caused by overflow of floodwaters were reported in the 70km long dyke system around the estate.

In addition, the team investigated the causes and effects of flooding of two historical sites in Ayutthaya and visited sections of the King’s dyke around Bangkok. The report documents the main findings of the Thai-Dutch investigation in more detail, as well as lessons learned, technical recommendations and opportunities for further research and cooperation between Thai and Dutch parties in the field of flood risk management.

Table of contents

Keywords:
2011 floods, Thailand, flood defences, dykes, hydraulic structures, breaches, failures, water management.

1
Introduction and background

Large parts of central Thailand have experienced severe flooding during the second half of the year 2011. The economic and societal damage is enormous: more than 800 fatalities and more than US $ 45 billion (Sources: Wikipedia, Worldbank), making it one of the most costly disasters at a global scale ever.

In order to be able to design and maintain safe flood defences, it is essential to understand why and how flood defence systems fail and / or perform during extreme conditions. Especially for a country such as the Netherlands, with high safety standards (1250 year return periods or safer), loads near or over the design capacities hardly ever occur. It is therefore important to learn the lessons from other events that occur in other regions. During previous floods, such as the flooding of New Orleans after hurricane Katrina (2005) and the coastal flooding in France after storm Xynthia (2010), valuable lessons have been learned and documented by Dutch experts on the consequences of flooding and the causes of flooding (e.g. dyke failures and failure mechanisms).

Scope and objectives
The flooding in Thailand has been characterized by a number of failures of dykes and structures around the large industrial estate areas, the Chao Phraya river dykes and adjacent irrigation canal dykes[1].

An investigation has been organized to investigate the dyke failures and performance of various systems. There are three primary areas of interest:
1 dykes around industrial estates near Bangkok;
2 The system in the Lower Chao Phraya river Basin (north of Bangkok, see annex);
3 King's dyke, i.e. the ring dyke for the protection of Bangkok.

In addition, some historical sites at Ayutthaya (north of Bangkok) have been visited (see section 2 for an overview of the system and the site visits).

The objectives of the investigation were as follows:

- To collect data on the flood events for representative sites in the above areas (e.g. flood conditions and heights, field observations, collect and interpret existing geotechnical data)
- To determine the mechanisms of dyke failure from field observations
- Formulate lessons learnt in the field of flood defence for the Netherlands and other countries.

Although this was outside of the scope of this mission with a duration of 1 week, it is envisioned that as a follow-up after the mission that some of the failure cases could be analysed in greater detail. In these efforts the failures could be reconstructed by means of available (soil and hydraulic) data and models for failure mechanisms. Insights will be important for our knowledge of failure mechanisms of dykes and the formulation of design guidelines. Such analyses could also contribute to a further improvement and refinement of models for the analysis of the safety of flood defences.

The scope of the mission is mainly technical and it is outside of the scope to formulate an integrated and comprehensive set of recommendations for flood management in Thailand.

[1] In Thailand the spelling "dyke" is used for dike levee, flood defence or dyke.

Organization of the field investigation
This investigation has been organized by the Dutch Expertise Network for Flood Protection (ENW). The team consisted of Thai and Dutch experts that represented several organizations:

- Thailand: Kasetsart University, Chuchawal Royal Haskoning, Royal Irrigation Department (RID)

- The Netherlands: ENW, TU Delft, Rijkswaterstaat, Royal Haskoning, Fugro, Deltares

An overview of the team members is given in Appendix I.

The findings of the investigation will be publicly available and this report will be published on the ENW website.

Structure of this report
Section 2 will present an overview of the system and the site visits.
Section 3 presents the findings for the different areas of interest.
Section 4 summarizes the main lessons learned and recommendations.

2
System characterization and overview of field visits

2.1 System overview

The total basin covers the central part of Thailand and during the 2011 floods large parts of the basin were flooded. The length of the Chao Phraya river is about 370km and it runs through Bangkok. The investigation focused on the Lower part of the Chao Phraya River Basin (see map in Figure 2.2 and schematic picture in Figure 2.3). The maximum discharge capacity in the lower part of the basin ranges from 2750 m^3/s to 3500 m^3/s.

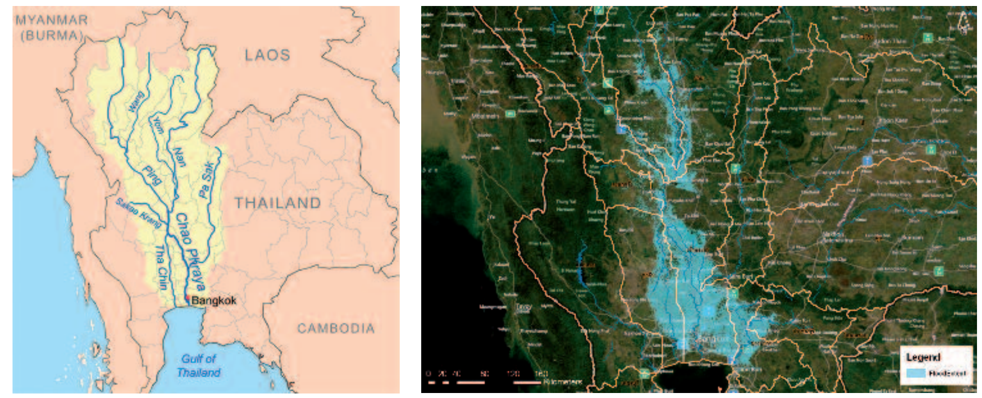


Figure 2.1
Overview of the Chao Phraya River Basin (left, source Wikipedia) and flooded area during the 2011 floods (right)

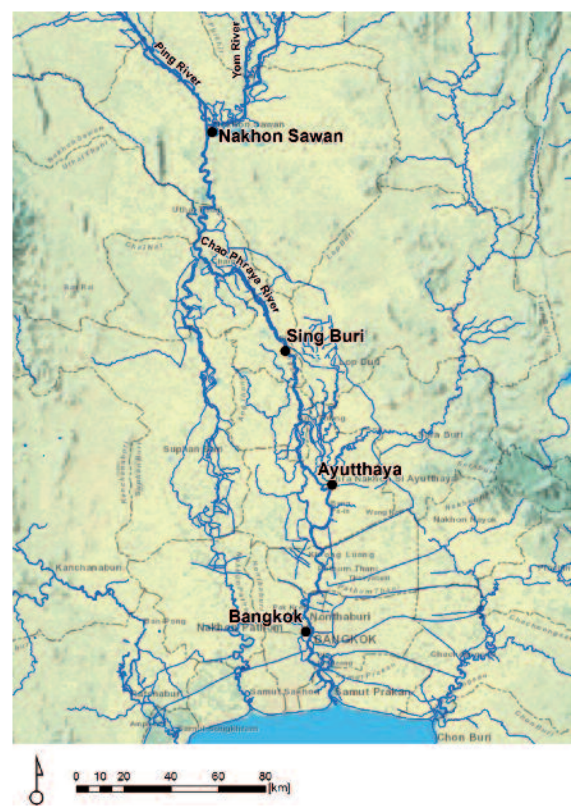


Figure 2.2
Overview of the Lower Chao Phraya River Basin

The Lower Chao Phraya river basin is a complex network of rivers, canals and streams. A schematic characterization of the system of the part that the team visited between Sing Buri and Chainat is shown in (Figure 2.3 - plan view) and (Figure 2.4 - cross section). These figures show a typical situation east of the river. During the floods the floodwater overflowed the river banks and then impacted the canal dykes, which breached at some locations. Several canals connect the river and the parallel canal system, and hydraulic structures are present to regulate the flow between both systems.

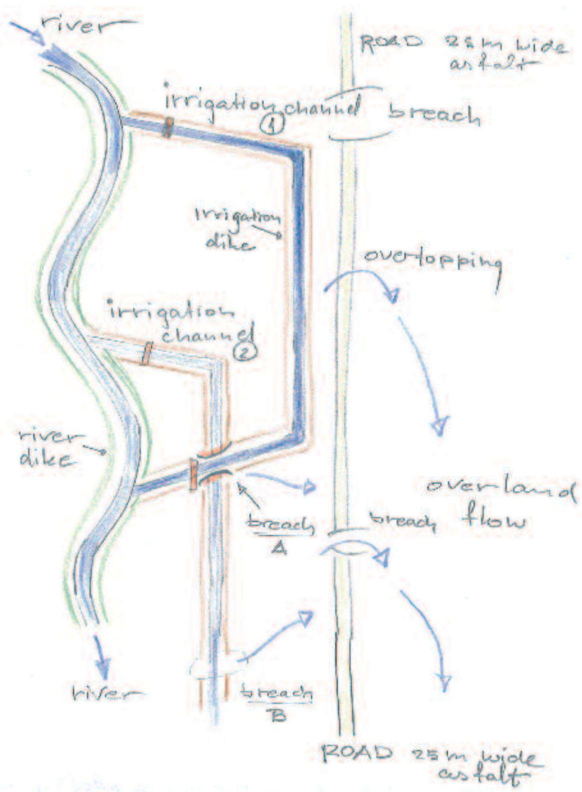


Figure 2.3
Schematic plan view of a typical situation in the Lower Chao Phraya River Basin

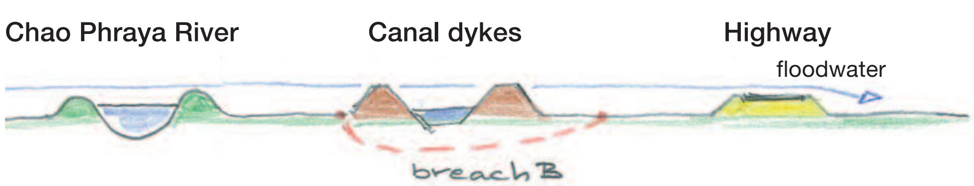


Figure 2.4
Schematic cross section of a typical situation in the Lower Chao Phraya River Basin

Situation in the greater Bangkok area
Bangkok and the surrounding area are also located in the deltaic floodplain of the Chao Phraya River. Historically, people in Bangkok lived in floating houses or elevated houses, but over the last decades a densely populated city with a population of over 10 million people has developed. Some form of protection is achieved by a the King's dyke that forms a ring around Bangkok. An extensive system of irrigation canals, hydraulic structures, such as drainage sluices and floodgates, and pumps has been developed to drain the city.

Over the last decades several industrial estates have been developed around Bangkok and these are home to very large production and manufacturing facilities. As these are located in floodplains and / or flood prone areas, dykes were constructed around many of the estates. During the 2011 floods seven industrial estates were flooded, leading to enormous economic damages. During the field investigation Rojana Industrial Estate, north of Bangkok, near Ayutthaya was visited.

North of Bangkok at the Chao Phraya river, the historical city of Ayutthaya is located (Figure 2.2). Several old temples and historical sites (incl. Baan Hollanda) are within the Ayutthaya historical park that is located at the river banks.

2.2 Overview of field visits

From January 23 to January 27 several sites where visited in the Lower CP River Basin, see Table 2.1. As a reference in scheduling the field visit an overview map was used (Figure 2.5) and these numbers are also included in the table.

Date	Location visited	Nr. on map
Monday Jan 23	Meeting at Kasetsart University	
	Rojana Industrial Estate	1
	Pra Ngam floodgate	2
Tuesday Jan 24	Meeting at RID district	
	Breaches in Manorom dykes	3
	Breach in Maharaj dyke	4
	Bang Chom Sri floodgate	5
	Participation in festivities for the new director of the RID Singburi district	
Wednesday Jan 25	Meeting at RID District Yangmanee	
	Pra Ngam floodgate	2
	Klong Ta Nueng floodgate, additional dyke breaches in that area	6
	Chao Phraya barrage	7
Thursday Jan 26	Ayutthaya: Baan Hollanda (Holland House)	8
	Ayutthaya: Wai Chai Wattanaram temple	9
	King's dyke Bangkok	10
Friday Jan 27	Reporting and internal in the hotel and Chuchawal Royal Haskoning office	
	Meeting at the Dutch embassy	

Table 2.1
Overview of the schedule of field investigations

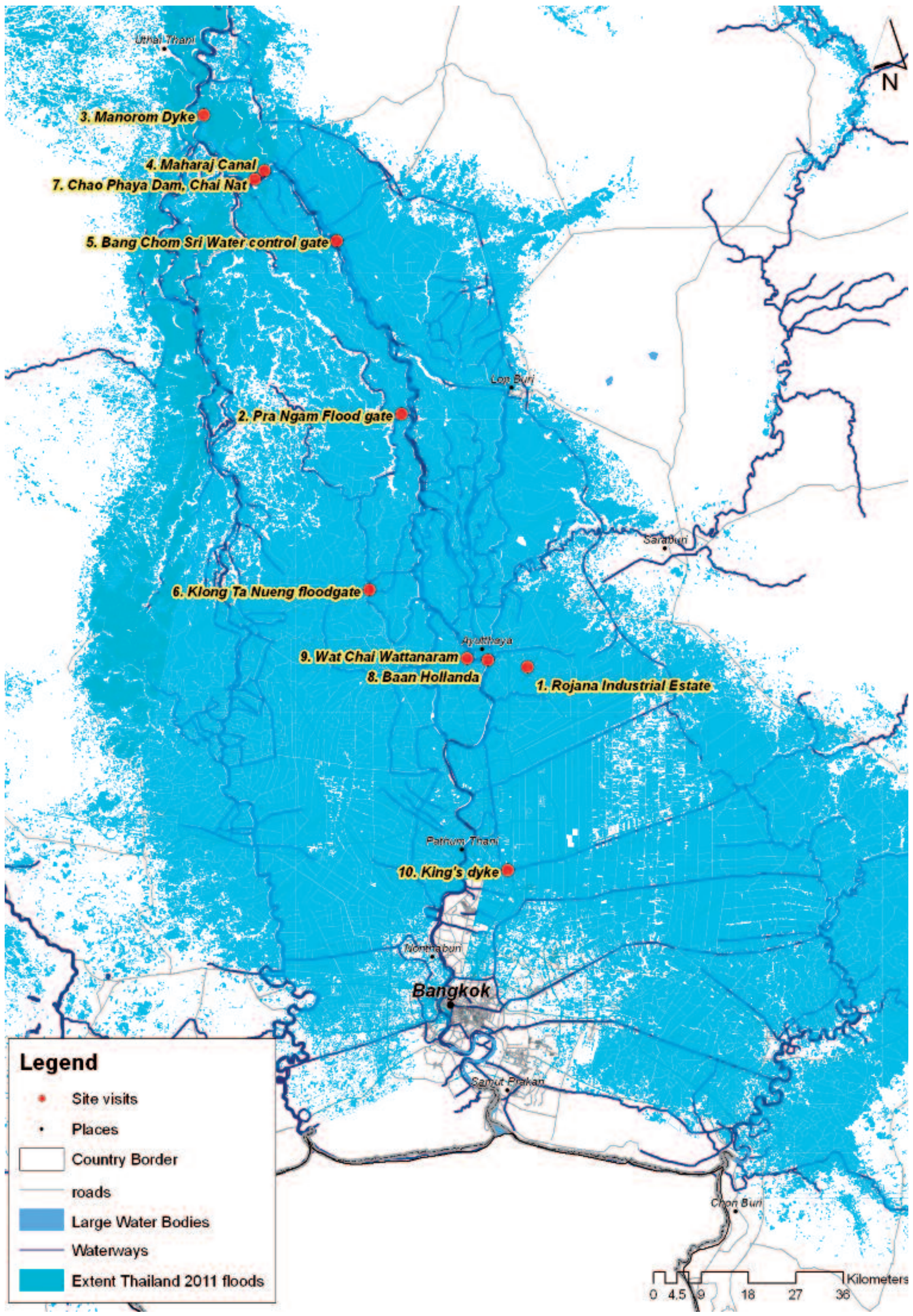


Figure 2.5
Overview of the 2011 flood extent and the locations that were visited during the field investigation

3
Findings

The findings are grouped according to the various types of situations and systems that the team has encountered. The findings are preliminary as these are mainly based on observations in the field and information given by local experts and managers during the investigation mission (Jan 23 – 27, 2012).

3.1 River and canal dykes in the Lower Chao Phraya Basin

During the visit several dyke breaches were visited. The dykes were mainly designed for irrigation purposed and typically consisted of local clay and soils, had relatively steep slopes (1:1.5). The dykes had a wide crest (5m) and typical heights were 3m to 4m. A revetment was not applied and the dykes had various covers, such as bushes and trees and no cover at some location. The field visits and the information obtained from RID gave insight in the causes of failures, breach characteristics and the emergency closures. The main findings can be summarized as follows.

Failure mechanisms
Overflow of dykes was reported in large parts of the Lower Chao Phraya river Basin. The reported water depths on top of the dyke ranged from 0.3m to 1m. Most failure cases were due to overflow of water, consequent erosion of the dyke at the inner slope and formation of a breach (Figure 3.1). One of the largest breaches that was visited is described more in detail in Textbox 1.

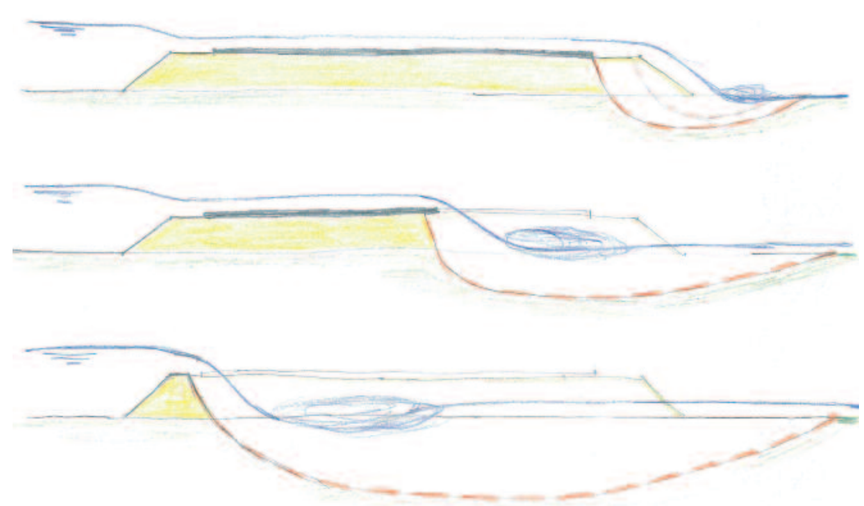


Figure 3.1
Erosion of dykes dye to overflow

At several locations the erosion and breaching process was not fully developed. Here severe erosion of the earthen dyke and asphalt road on top of the dyke was observed at the inner slope, see Figure 3.2.

Figure 3.2
Erosion on the inner slope of the dyke and the asphalt road of a dyke near the Klong Ta Nueng floodgate

Textbox I
Breach in the Manorom dyke near Chainat (at location km 2 +650) okt 5

Several breaches occurred in the Manorom dyke near the city of Chainat. The largest breach occurred at the location km 2 +650. This failure was caused by overflow and this resulted in a breach of about 100m wide.

A four lane asphalt road was located behind the dyke. This four lane road was fully eroded in about two days. At the time of the visit a new two lane road was constructed at this site. The figures below show a picture of the situation during the time of the visit, and sketches of the plan view and cross section of the location. It is remarkable that such a wide structure, consisting of the dyke and road body, could be fully breached due to overflow. This is a relevant finding for the discussion in the Netherlands on wide / unbreachable dykes, sometimes also referred to as deltadykes. Especially since the road body consisted of clay, which in the Netherlands would be characterized as an erosion resistant material.

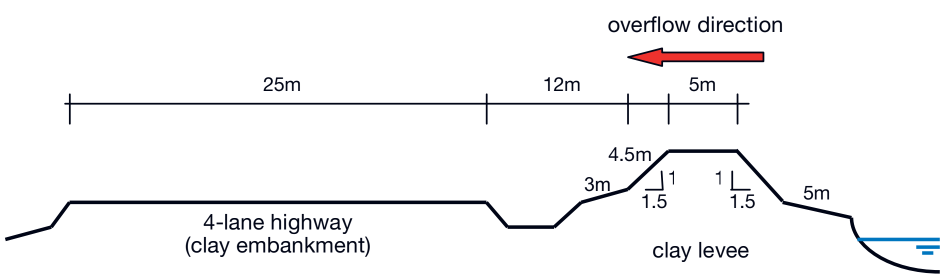
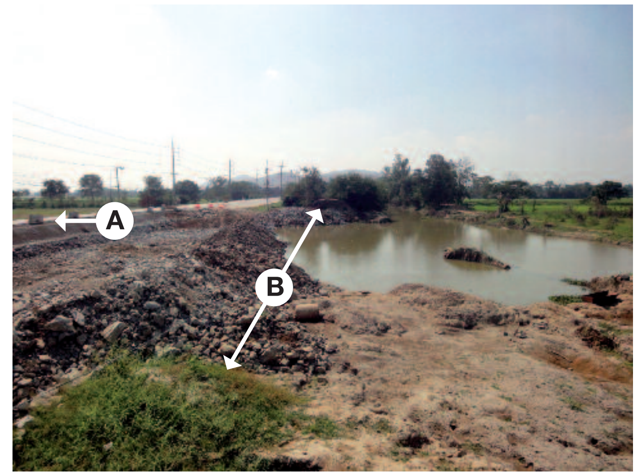


Figure 3.3
Schematic cross section of the Manorom dyke near chainat (location km 2 +650) in the pre-flood situation.



A *breach through dyke and 4-lane road*
B *breach width 95~100m*

Figure 3.4
Breach in the Manorom dyke near Chainat (location km 2 +650)

Figure 3.5
Measuring the breach in the Manorom dyke near Chainat (location km 2 +650)

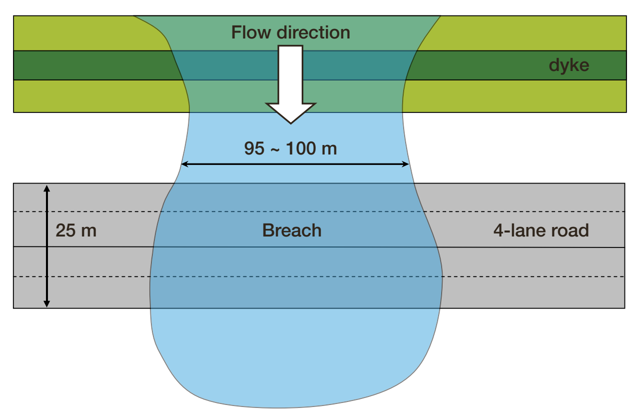


Figure 3.6
Schematic plan view of the breach in the Manorom dyke near Chainat (location km 2 +650)

In many situations two parallel dykes were breached. They formed the boundaries of the irrigation canal (see Figure 2.5). Overflow, and consequent erosion and breaching of the outer dykes led to an increased hydraulic impact on the second dyke. In many cases it was observed that both canal dykes breaches at the same location.

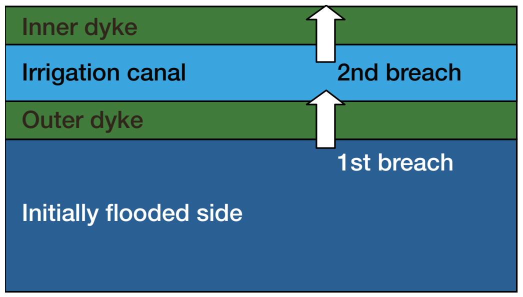


Figure 3.7
Schematic plan view of double breaches in the dykes of the irrigation canal

There was one occasion of a breach in a dyke near Bang Chrom Sri floodgate, where the local RID officers that breaching may have been caused by seepage through the dyke. At the time of the visit some flow of water and sand through the dyke was observed. One of the reasons could be that a road had been constructed on the old dyke. Sand layers that were used as part of the road foundation thereby became part of the dyke body, thus creating a potential weak spot for seepage.

Breach characteristics
The event was characterized by multiple breaches. Sometimes multiple breaches occurred within a few kilometers of dykes. Other historical events in which the system was overloaded (e.g. New Orleans in 2005, the Netherlands in 1953) were also characterized by multiple breaches.

Most breaches that were visited occurred at some weak spots in the system. These could be:

- Lower parts in the dyke system (e.g. due to road crossing)
- Connections with hydraulic structures (see section 3.2)
- Obstructions in front of the dyke such as perpendicular dykes that could increase the loads by concentration of flowing water at the intersection of the dykes.

The field observations also gave insight in the development of breaches in space in time. The breaches that were visited occurred in dykes that mostly consisted of clay. Breach widths ranged from 30 to 100m. From eyewitness accounts it can be derived that the development of breaches took several hours (for smaller breaches) up to two days (for larger breaches – see also Textbox 1). It is recommended to further analyze these breach cases and compare observations with existing models to analyze breach growth.

Emergency operations and breach closures
The information obtained during the field visit gave insight in the challenges associated with breach closures. Various materials were used to close breaches: rock fill, gabions and sheet piles. In multiple occasions the local authorities reported difficulties to close the final part of the breach due to high flow velocities.

Innovative solutions (multiple gabions tied together) were used in these situations. The use of rock fill and gabions or stacked gabions was necessary to close the breach in a short time in fast flowing water. Next the rock fill was covered with locally obtained clay and on some locations the slopes were finished with concrete plates as a protection from erosion.

Logistical challenges occurred because access roads (often located on top of or behind the breached dyke) where flooded or not present anymore. In these cases boats were used to transport materials to the site.

Location	Situation	Breach closure operations
Manoram dyke km 2 +650	■ dyke failure including breach ■ including a 4 lane asphalt road ■ moderate water velocities	■ 3 weeks needed for reparation ■ sheet piles, gabions, sand bags ■ access by road (4 lane highway)
Kali mountain dyke km 12 +500	■ dyke failure ■ moderate water velocities	■ 1 week preparation and 4 weeks closure operations ■ side 1: sheet pile walls (access by road) ■ side 2: rock/gabion closure (access with barges)
Pra Ngam floodgate	■ transition zone failure ■ approx 11 m deep erosion pit ■ approx 2 m/s high water velocities	■ 1 week preparation and 1 week closure operations ■ rock/gabion closure (8 gabion packages needed) ■ rock/gabion closure (8 gabion packages needed) ■ access by road

Table 3.1
Overview of some dyke failure locations and breach closure operations

The main findings are that next to the hydraulic and geotechnical circumstances (depth, velocities, erosion rate) also the accessibility of the site and the availability of materials and equipment are very important.

3.2 Hydraulic structures in the Lower Chao Phraya Basin

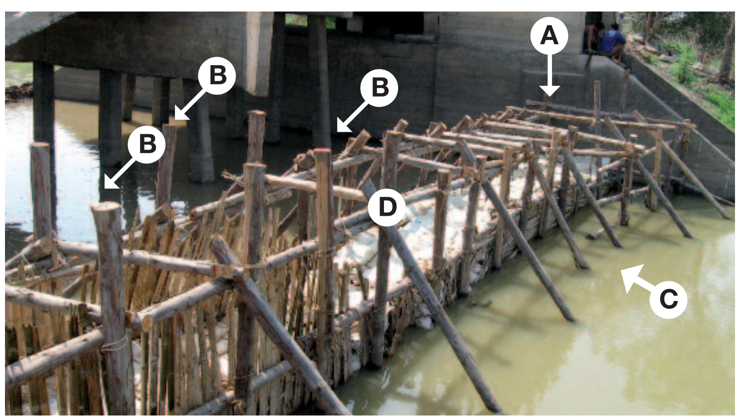
The team has visited three hydraulic structures that failed during the 2011 floods:
- Bang Chom Sri floodgate & siphon (nr. 5)
- Klong Ta Nueng floodgate (nr. 6)
- Pra Ngam floodgate (nr. 2)

Numbers refer to the location in figure 2.5.

The findings can be summarized as follows:
- The structures were mainly designed for irrigation and not so much for flood control. During the 2011 events the structures experienced higher loads and sometimes loads from a different direction than during normal irrigation conditions. During the floods sandbags were placed on top of the structure to prevent or reduce overflow.
- All the structures that were visited failed at the connection of the structure and the earthen dyke. This indicated how vulnerable these connections are [2].

- Because the structures are mainly designed for irrigation purposes with small water heads, provisions to prevent seepage / piping during floods seem to be limited, especially on the connection with the adjoining dykes or dam. Thereby scouring and breaching could occur besides the structures. This is illustrated in Figure 3.8 (Klong Ta Nueng floodgate) and Figure 3.9 (Pra Ngam floodgate), which show a photo of the situation and a sketch of the failure.
- A separate rock-fill closure dam was constructed behind the Pra Ngam floodgate to close the canal. For the initial closing of the gaps gabions and loose rock fill were used. In the last stages of the closure single gabions were washed away due to high flow velocities. In that case up to 8 gabions were tied together. Later the rock fill is covered with compacted clay and revetments. These are temporary measures.
- It was indicated by employees from RID that seepage screens / front walls will be placed in permanently repairing the floodgates. The use of rock fill and gabions introduces a new problem. It is very difficult, if not impossible, to drive sheet piles through the rock fill or to excavate trenches to construct seepage walls next to the structure. A point of attention is the size of the screen. The screens should be wide an deep enough to prevent seepage and erosion of materials under and besides the structure. A last point of attention is the connection of the front wall / seepage wall to the structure. At the field visits no reinforcing steel rods were seen sticking out of the structure. Therefore it is expected that there was no connection between the structure and the original front wall that could transfer loads.

[2] Similar observations were made in New Orleans after hurricane Katrina.



Klong Ta Nueng floodgate

(A) connection of front wall
(B) soil washed away
(C) flow during flooding
(D) temporary coffer dam

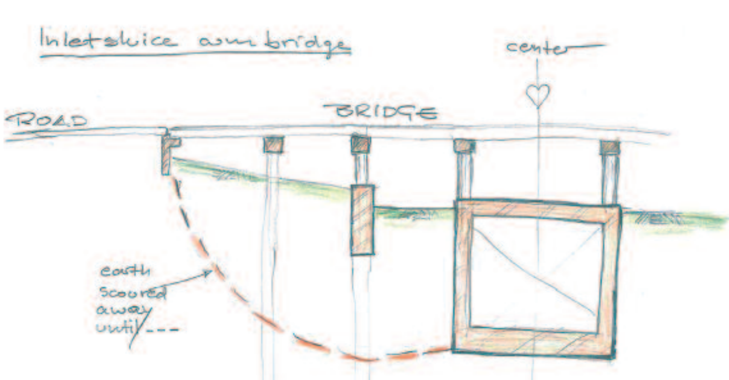


Figure 3.8
Failure of the Klong Ta Nueng floodgate

Pra Ngam floodgate

(A) sand fill at the original breach
(B) regular flow
(C) flow during flooding

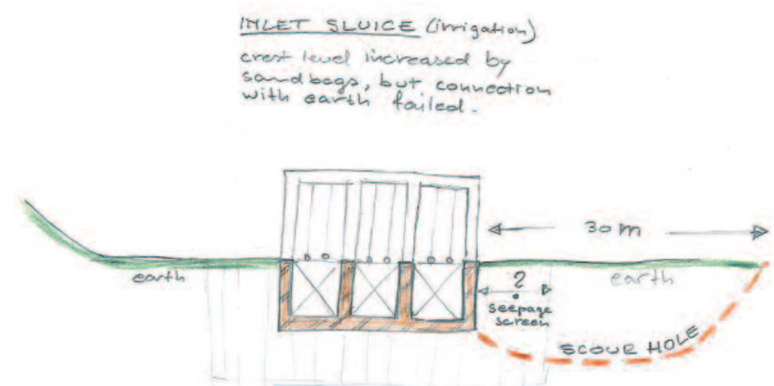


Figure 3.9
Failure of the Pra Ngam floodgate

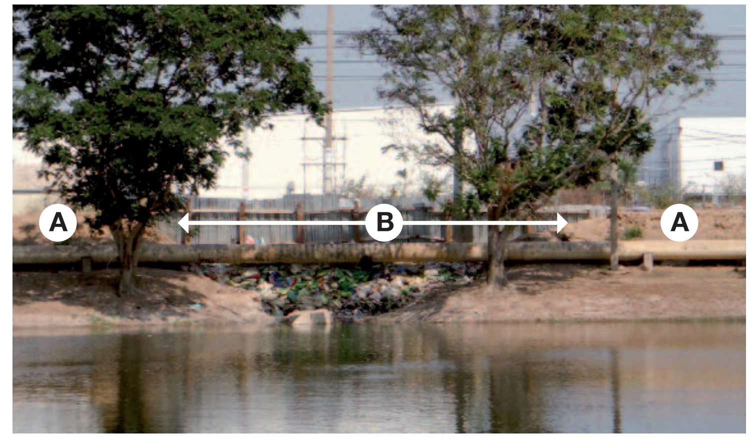
3.3 Rojana Industrial estate

The team has visited the Rojana industrial estate which was developed 23 years ago (in 1989). It is located north of Bangkok near the city of Ayutthaya. It is protected by about 70km of dykes and the estate in fact consists of multiple “dyke rings”. The area is protected by dykes with a height of about 4.5m. Floods occur regularly in this area. In 1999 a flood event occurred, which led to some overtopping of the dykes but not to breaching.

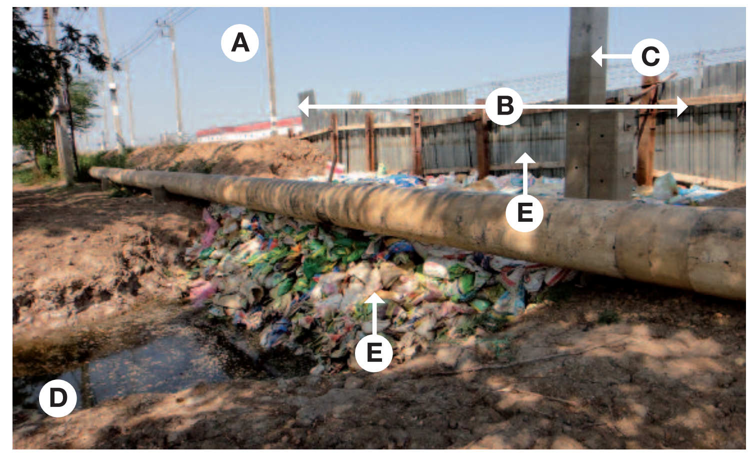
2011 floods: general information and breaches
The flood levels were higher than the flood defences and led to overtopping and consequent breaching of the dykes. In total seven breaches occurred, most of those due to severe overtopping. Flood depths up to 3 meters occurred within the estate (Figure 3.10).

Figure 3.10
Left: Dyke section at Rojana Industrial Estate during the 2011 floods (Oct. 8th, 2011);
Right: Water marks indicating the flood levels within the estate

Two breaches were visited. The first breach was caused by overtopping and it had a width of about 20m. The canal levee had been raised as flood fighting measure by 0.5m with a backhoe. Still, the final flood levels exceeded the crest level by far (0.8 ~ 1.0m). The pipe along the slope and the columns on the protected area side may be speculated to have contributed to the erosion failure. The failure had occurred after no more than 6 hours after the levee started being overtopped.



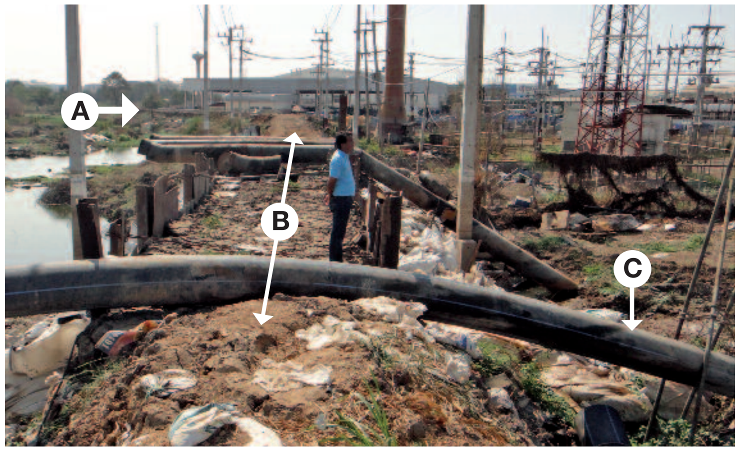
A *earthen dyke*
B *breach and emergency repair*



A *canal side*
B *breach width ~20m*
C *water mark*
D *protected area*
E *temporary repairs*

Figure 3.11
First breach visited in Rojana Industrial estate

The second breach that was visited occurred at a pipe in the dyke, which was not protected by seepage screens. At this location the failure started with seepage along a pipe through the levee (no seepage screen) and failure progression accelerated when it was also overtopped. According to eye witnesses it took about 2 hours to form the 30 wide breach. The levee was rather new and built after floods in 1999.



A overflow direction
B breach width ~30m
C relocated pipe (through levee without seepage screen before)

Figure 3.12
Breach at Rojana Industrial Estate (location 2) from canal side

Damages
The damage is substantial within the industrial estate.

- About 3000 out of the total of 50,000 jobs were lost.
- The production has been down for about 4 months, but has been picking up slowly since early 2012.
- At the time of the visit (End of January 2012), the use of power was about 5% of the pre-flood use of power, indicating that most industries were not back in business. Mostly clean up activity was observed during the visit to the estate.

The team expects that this impact situation is similar in other industrial areas, illustrating the severe economic impact of the floods on the industry. More in general, it was observed by the team that a few months after the floods recovery was much faster in agricultural than in industrial areas. While agricultural areas were fully “back in business”, the industrial areas were still at very low production levels (5-20%) with many facilities still starting up at all.

Original and New Dyke Designs Rojana Industrial Estate
At the time of the visit the industrial estate already had plans to reinforce levees around the area before the next flood season. The figures below show the original as well as the new designs. In the new design, the earthen dyke is strengthened and heightened by 1.5m by means of floodwall. About 10m long sheetpiles are used to prevent instability and seepage.

Although it is outside of the scope of the field investigation it was striking to the team that several canals went through industrial estate, thereby increasing the exposed dyke length. It might be relevant to consider closing some of these canals by means of gates and thus shortening the exposed dyke length. It would also be relevant to investigate the level of protection (and resulting design height of the dykes) for Rojana and other industrial estates in a risk-based analysis. In such an analysis the potential damage and increasing costs for better protection are taken into account to determine an optimal level of protection from an economic perspective. Indicative calculations for hypothetical industrial areas indicated that protection levels of 100 to 1000 years return period could be defensible. A risk-based flood management policy can also take into account different damage potential between various areas, e.g. by varying the level of protection between agricultural and industrial areas.

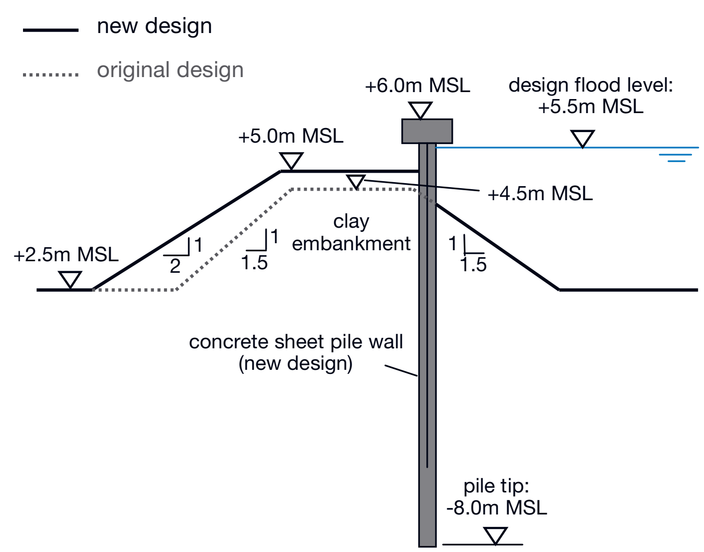


Figure 3.13
Original and new design of the dykes around Rojana estate

3.4 Ayutthaya historical sites

The team has visited two historical sites in Ayutthaya: Baan Hollanda and the Wai Chai Wattanaram – Buddhist temple. Both sites were damaged, illustrating the effects that floods can have on cultural sites as well.

Baan Hollanda (Holland House) is a reconstructed historical Dutch settlement that is located on the banks of the Ayutthaya river. It was flooded by about 1m of water during the events in 2011 (Figure 3.14). It took a team of about 20 people a week to clean-up this site. The representative from the embassy made a request to the Dutch experts to develop solutions to prevent flooding of Baan Hollanda in the future.

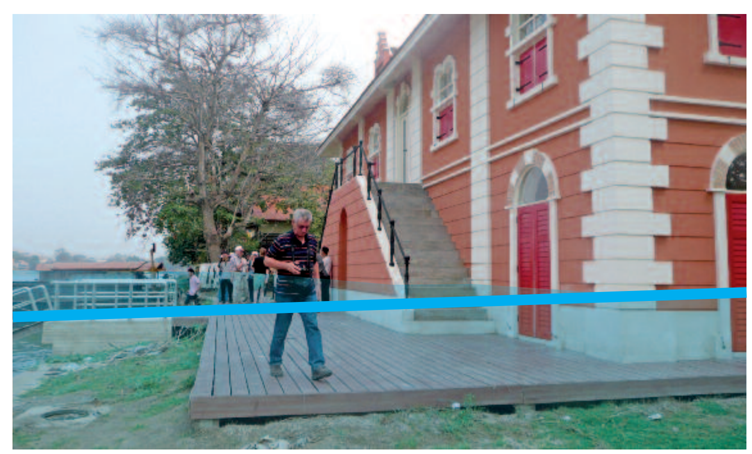


Figure 3.14
View on Baan Hollanda from the riverside, and indication of the flood level during the 2011 floods

The Wai Chai Wattanaram temple is also located at the river banks. It is protected by movable flapgates on the river site and masonry walls on the other sites of the area. Flooding occurred at the southern corner at the connection of the movable gates and the wall, illustrating the vulnerability of such connections. The exact cause of flooding (overflow due to local waterlevel rise and/or breaching of walls) could not be determined on-site. The flooding has had a severe impact and most of the site is still closed for the public. Both cultural sites could be used as very visible 'beacons' to monitor flood risk resilience during future floods.

Figure 3.15
Movable floodgates at The Wai Chai Wattanaram temple (left) and location of connection at southern end of the terrain where flooding occurred (right)

3.5 King's dyke Bangkok

The team has made a short visit to parts of the King's dyke around Bangkok. At most of the locations the dyke is integrated in the road system and has a limited elevation ranging from +1.0 to 2.9m (MSL). At some locations the dyke is not present. The team visited one of these sections. The flooding that occurred due to missing sections of the dyke resulted in flooding of parts of Bangkok, including the Don Muang airport.

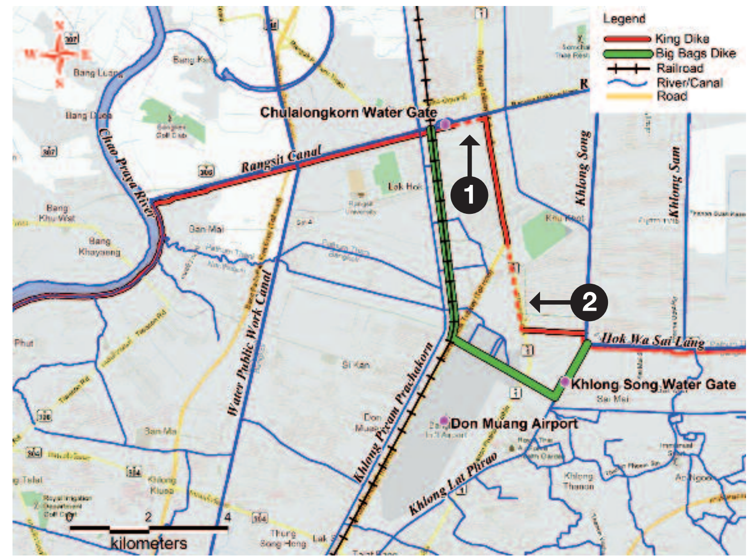


Figure 3.16
Openings (1 and 2) in the King's dyke on the Northern side of Bangkok and the temporary dyke of big bags

During the floods a dyke of bigbags of several kilometers was constructed to protection Bangkok. The railway line and existing objects (concrete walls etc.) were used as part of this flood defence.

The team was also informed about the discussion that arose when such emergency measures were (proposed to be) implemented. The protection of one area by means of sandbags would increase the flood levels for the neighborhood at the other side of the sandbags. This illustrates how such social issues could (negatively) affect the implementation and performance of such emergency measures.

4
Lessons Learned and Recommendations

4.1 Lessons learned and Technical recommendations

Based on the findings presented in the previous sections a number of lessons learned and some (technical) recommendations have been formulated for the Dutch and international community involved in the design and management of flood defence systems.

- **Dykes** appeared to be vulnerable for overtopping and subsequent erosion. This was not only the case for dykes with steep slopes and a mixed cover (bushes, trees, no cover), but also for larger clay dykes with roads on top of the dyke or behind it. It is recommended to further test our current assumptions and models for overflow erosion based on failure cases from Thailand and other regions.
- **Transitions** between hydraulic structures and (earthen) dykes again proved to be weak spots, but these transitions receive limited attention in current methods for design and safety assessment in the Netherlands and other countries. Design guidance is needed to ensure the safety of these connections. As part of the safety assessment or periodic inspections a number of principles, checks and simple design rules should be developed to be able to assess the safety of these connections. As a general rule, transitions should be designed to be more reliable than the adjacent "standard" elements (e.g. dike reaches).
- **Breach closures**: the failure cases in Thailand gave insight in both technical and logistic challenges associated with closure of breaches. It is recommended to develop a set of principles and best practices for the closure of breaches. In closing the breaches the Thai showed great improvisation skills and decisiveness.
- The situation in Thailand has shown how conditions change over years and decades. **Changing conditions** include: the loads on the system (water levels), the strength (subsidence), the values protected by the system and the demands on the system (from irrigation to flood management). At the time of the visit repair works of failed structures and dykes were ongoing. A **systems approach** for design and management is required to ensure safe flood defences in the future. It is important to take into account the lessons from the previous technical failures (see above) and the fact that conditions change in the reparation and upgrading of the system. In addition to the physical system, a strong organizational & management system for flood and water management is needed.
- **Flood and emergency management**: This topic was outside of the direct scope of this investigation, but from the field visits it became clear that this was a major issue during the 2011 floods. Various discussions are ongoing about the operation and management of reservoirs, dams and barrages, the flood warning and communication and the implementation and effectiveness of emergency measures, such as temporary sandbag [3]. It would be interesting to investigate the events during the 2011 floods in Thailand and formulate some (general) lessons learned in this area.

[3] These discussions about the effects of temporary bigbag dykes included social aspects as well. The protection of one part of Bangkok by means of these temporary defences implied that the flood level and duration increased on the other side of the temporary defence.

4.2 Recommendations for cooperation and research

- It is important to document and share information on the performance and failure of flood management systems. This is necessary to improve the understanding of the failure modes of such systems. This knowledge can be used to improve the design guidance to improve flood protection and mitigation in the future. It is suggested to develop an international database to store, document and share these failure cases.
- Not only should the knowledge be documented, but relevant knowledge should also be disseminated to the professional community and to students.
- This report is mainly based on field observations obtained in the course of a single week. It is recommended to further analyze the failure cases and to attempt to reconstruct these cases by means of existing models (i.e. back-analysis).
- The current system in Thailand has mainly been designed for irrigation. It could be useful to promote research training on integrated flood management. These efforts could be undertaken by Dutch and Thai partners. Possible activities include short courses for professionals, exchange of students and researchers at various levels. Technical aspects should be an important part of these programs.
- It is recommended to strengthen the design basis for design of flood management infrastructure in Thailand. Using international experience (e.g. Dutch experience and information from the international levee handbook), guidelines for the design of flood defences in Thailand could be developed. Special attention should be given to the issue of how the flood defence and irrigation systems can be integrated. The parties that participated in this field investigation could be involved in such a cooperation. These parties include Kasetsart University, the Royal Irrigation Department, ENW, TU Delft, Deltares, Rijkswaterstaat, representatives from the private sector and the Dutch embassy.

4.3 Acknowledgements

The team members acknowledge those organizations that have provided information during the investigation: the Royal Irrigation Department, the management of Rojana Industrial estate and the Dutch embassy in Bangkok. The organizations that we have met were very open and shared the information that they had. This is very much appreciated by the team. The Dutch Expertise Network for Flood Protection (ENW) is acknowledged for organizing and funding this investigation.

Appendix
Overview of team members

Bas Jonkman is a researcher, advisor and expert in the field of flood risk management. He holds a PhD in civil engineering from Delft University and is currently working part-time as an associate professor for that university. Since 2007 he has also worked for Royal Haskoning on projects in the Netherlands and other regions (New Orleans, Vietnam, Cambodia, Romania and Qatar).

Barames Vardhanabhuti is an assistant professor in Department of Civil Engineering, Kasetsart University, Bangkok, Thailand. He obtained a PhD in Civil Engineering from University of Illinois at Urbana-Champaign, USA, specialized in geotechnical engineering. During the 2011 flood disaster in Thailand, he assisted the Royal Thai Government with a Dutch flood expert and worked at Flood Relief Operation Center. Now he continues to give technical supports for the flood prevention in Thailand.

Peter Blommaart is a senior adviser on flood protection. He holds a MSc in civil engineering from Delft University of Technology and is currently working at the Rijkswaterstaat Centre for Water Management, which is part of the Dutch Government. As an adviser he is involved in major flood protection programs, policy making, safety assessment of flood defenses and geotechnical research.

Bas de Bruijn is a retired advisor and expert in the field of flood protection. He worked nearly 40 years for several Waterboards. After 1995 het had the management task to reïnforce the dikes (170 km) in his Waterboard Rivierenland. During the last 15 years he represented the Waterboards (and the Union of Waterboards) on the National and International level. After his retirement he is still advisor for ENW and the Rijkswaterstaat Program Direction Room for the Rivers.

Bianca Hardeman is an advisor in the field of flood protection for Rijkswaterstaat Centre of Watermanagement. She holds a MSc from Amsterdam University. She is a project manager for several long-term research projects on the strengths and loading of flood defense structures. This program provides insights to improve the assessment of the defenses. She also manages in situ-failure tests in order to better understand the failure behavior of flood defenses on peat soil.

Kemika Kaensap is a civil engineer and an expert in the field of civil engineering, water resource engineering. She obtained master degree in Water Resource Engineering and bachelor's degree in Irrigation Engineering from Kasetsart University, Thailand. Since 2010 she has worked for Chuchawal Royal Haskoning in Thailand. Her experiences range from flood protection, road and drainage design in projects in Thailand, Africa and India.

Martin van der Meer is Technical Director of Fugro Water Services. Since 2008 he is busy with flood defence and dike safety worldwide (Netherlands, France, Hungary, USA, Singapore, Hong Kong). After his study Civil Engineering at the Delft University, he started work for Fugro Netherlands in 1988. He set up Fugro's Hydraulic Engineering Department, specialised in state-of-the-art dike safety assessments. Since 2006, he is also part-time lecturer Geo Risk Management at the Delft University.

Timo Schweckendiek is a researcher/consultant in geotechnical engineering and risk analysis at Deltares, a Dutch institute for applied research in the field of water, subsurface and infrastructure. His primary fields of expertise are reliability of flood defenses and flood risk. He is a member of TC304 (Risk Management in Engineering Practice) of the ISSMGE (Int. Soc. of Soil Mechanics and Geotechnical Engineering) and of the Dutch Expertise Network for Flood Protection (ENW).

Han Vrijling is a professor in hydraulic structures and probabilistic design at Delft University. The first part of his carreer he has worked for Rijkswaterstaat where he has developed the probabilistic approach for the design of the Easter Scheldt storm surge barrier. He is a well-known expert in (probabilistic) design of civil engineering systems and flood protection.

Kitipong Rakjanya is an irrigation engineer at the Royal Irrigation Department, Thailand. He is a chief engineer at PakHai Irrigation Project located at the lower Chao Pharaya River Basin.

Yuttikorn Sinsukwilai is a researcher in Department of Civil Engineering, Kasetsart University, Bangkok, Thailand. He completed a master degree in Civil Engineering at Kasetsart University, and he speciallizes in geotechnical engineering.

The following staff from Kasetsart University participated in specific parts of the investigation mission and their contribution is gratefully acknowledged: Korchoke Chantawarankul, Apiniti Jotisanaka, Bart Lambregts.

Group photo at the Chao Phraya barrage

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