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Lessons from New Orleans for the design and maintenance of flood defence systems

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ABSTRACT: The flood disaster of New Orleans due to hurricane Katrina in August 2005 can provide valuable lessons for the design and maintenance of European flood defence systems. The system partially failed because the design conditions (water levels, waves) were exceeded by the hurricane. The other part of the system failed at water levels below design level due to geotechnical failure of the floodwalls' foundations. The disaster showed the importance of a careful determination of design conditions, the significance of transitions and objects on the slopes and it showed that geotechnical failure is of major importance for the reliability of flood defence systems.

1 INTRODUCTION

The flood disaster in New Orleans in August and September 2005 due to Hurricane Katrina showed once again the vulnerability of low lying areas to floods. Hurricane Katrina closely passed New Orleans, causing the flood defence system to breach on many locations. The severe effects shocked the world, with over 700 direct casualties, more than 100 billion US$ damage and an enormous social disruption.

1.1 *New Orleans*

New Orleans is situated in the southern state Louisiana in the United States of America. The city is bordered by marshes on the south that gradually transition into the Gulf of Mexico. The east of the city is not bordered by marshes, but by Lake Borgne ('1' in Figure 1), which is actually connected to the Gulf of Mexico. The city is bordered on the north side by Lake Pontchartrain ('2'), a brackish lake with a narrow connection with Lake Borgne, while the Mississippi river ('3') is flowing through the city. The Mississippi river, Lake Pontchartrain and Lake Borgne are connected to each other by shipping canals. However, the Mississippi is separated form the other parts of the water system by a lock.

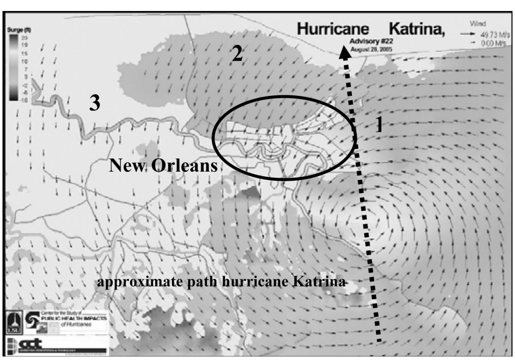

Figure 1. Approximate path of hurricane Katrina and simulation of wind directions (modified after LSU 2005).

1.2 *Vulnerable flood defence systems in Europe*

The situation of New Orleans is comparable to European areas that are threatened by floods. Especially the Rhine and Elbe river deltas are similar since these are also situated in low-lying deltas composed of organic soils, being threatened by both river and sea. The difference between European systems and New Orleans is that floodwalls are used in many locations in New Orleans, while the European systems merely are composed of earthen embankments. Figure 2 shows the European areas that have to deal with flood risk.

The disaster in New Orleans can provide valuable lessons for the design and maintenance of European flood defence systems since the city is also situated in a low-lying delta composed of soft soils. This paper focuses on the technical aspects of the failure and on the lessons that can be drawn for the European situation.

1.3 *Outline*

In Section 2, the influence of hurricane Katrina on the water systems will be discussed. In section 3, the response of the whole system will be considered. The different dike ring area's are elaborated in sections 4

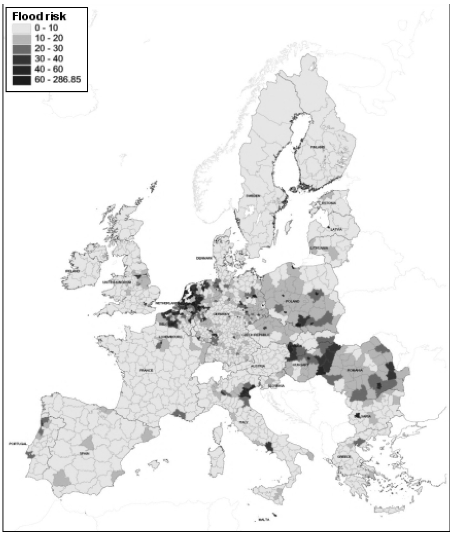

Figure 2. Flood risk in Europe (WDNH 2005).

to 6, summarizing all failure mechanisms in section 7 and finishing with conclusions in section 8.

2 HURRICANE KATRINA

Hurricane Katrina approached New Orleans from the south on August 28th, 2005, passing the city on the eastern side, see Figure 1. The hurricane gained full force above the Gulf of Mexico. It caused the water levels on the coast to rise due to wind set up. The counter clockwise rotation of the hurricane magnified the wind set up near New Orleans (arrow in Figure 3). Besides, the high wind speeds (over 250 km/hour) resulted in a severe wave attack on the coast. The high water levels in Lake Borgne progressed into the city through shipping canals that connect the Mississippi River with the Gulf of Mexico and Lake Pontchartrain. As the hurricane passes the city, the winds on Lake Pontchartrain start to blow from the north, resulting in high water levels due to wind set-up on the north side of New Orleans. The water levels of the Mississippi River are not considered in this paper since no damage to the Mississippi dikes has been reported to cause flooding in New Orleans.

3 RESPONSE OF THE SYSTEM

The flood defence system of New Orleans was not able to withstand the load induced by hurricane Katrina. When considering the response of the flood defence system, we can define dike ring areas (areas surrounded by a closed system of flood defences and/or high ground) to describe the failure. The following

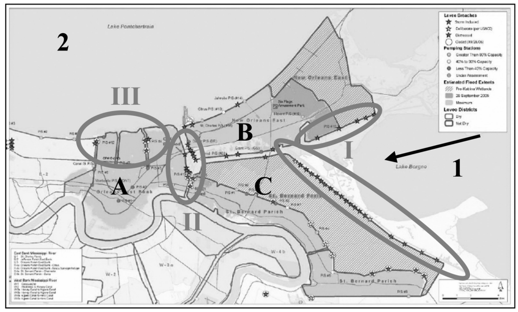

Figure 3. Flood defence system in New Orleans (modified after ILIT 2006).

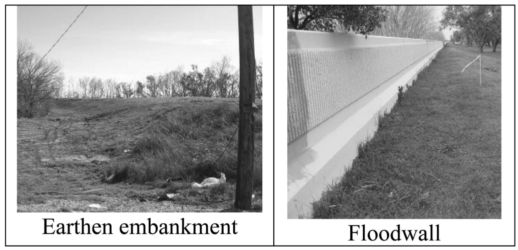

Figure 4. Two types of flood defences in New Orleans.

dike ring areas are considered: Orleans East Bank ('A' in Figure 3), Orleans East ('B') and St. Bernard ('C'). Furthermore, a distinction has to be made between two types of flood defences: earthen embankments and floodwalls, see Figure 4. Other words for flood defences are levees (in the USA) or dikes (in the EU). Failure is defined as: a flood defence that looses its water retaining function.

In general, three types of failure could be observed:

1. Erosion of the flood defences along Lake Borgne ('I' in Figure 3). These flood defences mainly consisted of earthen embankments and were destroyed for many kilometres because the flood defences were not high and strong enough to withstand the water levels and waves.
2. Failure of flood walls and scour around transitions. The high water levels in Lake Borgne progressed into the shipping canals that connect the Mississippi with Lake Pontchartrain and the Gulf of Mexico. The floodwalls were not high enough or the transitions between soils and solid structures were not strong enough and erosion due to overtopping caused several failures. ('II' in Figure 3).
3. Geotechnical failure of floodwalls along dewatering canals ('III' in Figure 3). The wind induced high water levels along the south shore of Lake Pontchartrain progressed into the dewatering canals that enter the city. The floodwalls along these canals

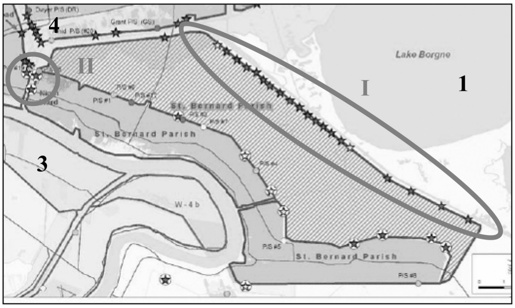

Figure 5. St. Bernard dike ring (modified after ILIT 2006).

failed at three locations although the water levels did not reach the design level.

The above-mentioned observation is only general, on several locations (not classified in Figure 3) other failures or near-failures can be observed. An important observation was that most failures or near-failures were concentrated around transitions and objects which were starting points for erosion. The failure of the three dike ring areas are elaborated in the next sections, considering the failure of the systems and the lessons learned. The failure mechanisms of New Orleans' flood defences are summarized in section 7.

4 ST. BERNARD DIKE RING

The St. Bernard dike ring is situated on the eastern part of the city, with Lake Borgne on its east side('1' in Figure 5), the Mississippi on its southwest ('3') and shipping canals on it north and west side('4'). The dike ring is mainly inundated due to two causes:

1 Failure of many kilometres of earthen embankment due to overflow and wave overtopping ('I' in Figure 5)
2 Failure of two floodwalls after wave overtopping ('II')

4.1 *Failure earthen embankments St. Bernard dike ring*

A significant part of the 20 kilometre long earthen embankment along Lake Borgne failed. The wind set-up caused a storm surge in combination with high waves. This completely overloaded the defence, resulting in multiple breaches. The water levels exceeded the design levels by many decimetres, causing the embankment to scour away on many locations (see Figure 6). Although the system was designed on a design storm with an estimated return period of 200–300 years (in the 1960's, based on GAO 2005), the design level was exceeded. There is no consensus yet what the actual return period of hurricane Katrina was, but it seems less than the estimate. Besides the exceeding water levels, there was no protection of the outer slope of the embankment to prevent the waves from eroding the slope. In Dutch codes and recommendations, the erosion resistance of the revetment is of major importance and stone layers or other protection systems are usually applied to protect the slope (TAW 1998).

Figure 6. Breached embankment in St. Bernard dike ring (ILIT 2006).

Figure 7. Failed floodwall in St. Bernard dike ring on the Lower Ninth Ward site (IPET, 2006).

4.2 *Failure flood walls in St. Bernard Parish*

The second major group of failures that caused inundation of the St. Bernard dike ring, was the failure of two floodwalls near the Lower Ninth Ward. The high water levels in Lake Borgne progressed into the shipping canals, causing a severe load on the floodwalls surrounding these canals. The scour holes behind neighbouring floodwalls indicate that considerable quantities of water flowed over the walls. Most probably the earth behind the floodwall was scoured away, after which the floodwall lost its strength and was pushed away by the water, see Figure 7. The effects of these two failures were more severe than the overflowing of the embankment, since the floodwalls collapsed suddenly. Many casualties were found in the areas behind these two breaches.

5 ORLEANS EAST DIKE RING

The Orleans East dike ring is the situated in the north-eastern part of New Orleans. It is bordered by Lake

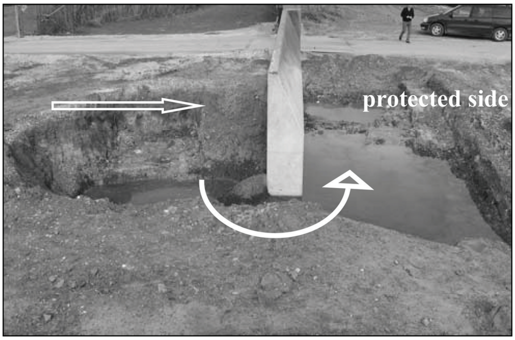

Figure 8. Scour around a transition from floodwall to earthen embankment.

Pontchartrain on the north and east, by Lake Borgne on the south and by shipping canals on the south and west. Besides the erosion of earthen embankment along Lake Borgne, similar to the failure described in section section 4.1, we can observe many failures around transitions between solid structures (floodwalls, doors, sheet piles) and the earthen embankment. A few floodwalls failed as well, similar as described in section 4.2. The flow around such a transition is contracted, resulting in increased flow velocities and turbulence, causing scour around the structure.

The scour effect along the shipping canals was more severe than at the lakefront. The water levels in the canals were relatively high, causing a higher loading on the transitions, often resulting in failure of the flood defence, see Figure 8. These transitions are mentioned as a failure mechanism in Dutch codes (TAW 1998), but the disaster in New Orleans showed these are of major importance.

Scour around structures was also observed along the Lake Pontchartrain defences. However, the scour caused hardly any breaches on the system. The major part of the lakefront defences performed well, indicating that the conditions were relatively less severe that the Lake Borgne and shipping canal conditions. The only points of attention were scour spots around objects in de earthen embankment (fences, staircases) and other local different circumstances (below a bridge). This problem is merely a maintenance problem; maintenance should be aimed at assessing and improving these points.

6 ORLEANS EAST BANK DIKE RING

The Orleans East Bank is bordered by Lake Pontchartrain on the north ('2' in Figure 9), shipping canals on the east ('4'), the Mississippi River on the South ('3') and high grounds on the west ('5'). Several failures were observed along the shipping canals; failure

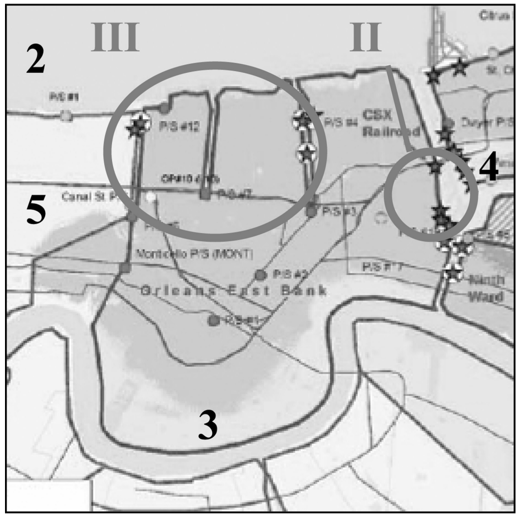

Figure 9. Orleans East Bank dike ring (modified after ILIT 2006).

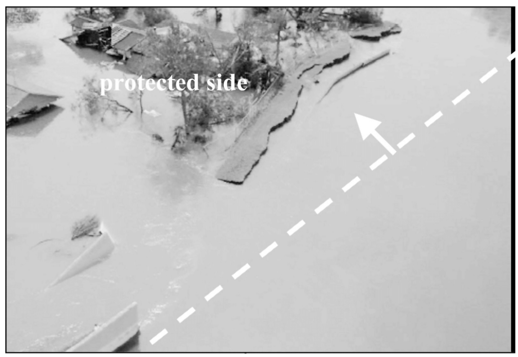

Figure 10. Failure of 17th Street Canal (modified after ILIT 2006).

of floodwalls and the failure of a sand-bag wall that replaced a broken gate ('II' in Figure 9). However the major part of inundation was caused by geotechnical failure of floodwalls along dewatering canals ('III').

As hurricane Katrina passed the city, the wind started to blow from the north, causing the water levels of Lake Pontchartrain to rise on the northern part of the dike ring. This high water levels progressed into the dewatering canals that were constructed to connect the city's pumping stations with Lake Pontchartrain. Three floodwalls breached along two of the dewatering canals, one along the 17th Street Canal and two along London Avenue Canal. The failure of the 17th Street Canal floodwall got a lot of attention. Pictures show that the dike body was pushed inland horizontally, see Figure 10, most probably due to a combination of weak soils and high water pressures (ILIT 2006). It must be noted that no evidence has been recovered that the water level exceeded the crest of the floodwall or even the design level.

Although the mechanism of horizontal instability is mentioned in the codes (TAW 1998), and although it has happened before in the Netherlands (Van Baars 2005), there are no design codes available in the Netherlands to deal with this mechanism properly.

The original designs (in the 1960's) did consider the instability, however not all possible failure planes were taken into account. Besides, the highly variable subsoil, in combination with design calculations based on expected values (instead of quantiles) played an important role. The sub-soils at the failure location were 20% weaker than adjacent sections (IPET 2006).

The two failures at the London Avenue Canal were most probably caused by a combination of the water pressures against the floodwall, the water pressures inside a permeable sand layers below the floodwall and weak soils behind the floodwall. The water levels at these locations most probably did not exceed the design levels either. The most important factor in the two failures were the permeable sand layers below the floodwall that were not taken into account adequately, causing seepage erosion and reduced stability.

The three geotechnical failures might have caused up to 80% of the flooding of the Orleans East Bank dike ring (ILIT 2006), showing that the probability of geotechnical failure can be of major importance. This is in contrast with the starting design points in Dutch regulations. The codes and regulations assume that overflow and overtopping of a dike (caused by water level and waves) have the highest contribution to the probability of failure, while the probability of other mechanisms than overflow/overtopping should be minimal (TAW 1989). The remaining part of the flooding of this dike ring is caused by floodwalls and roads along the shipping canals that eroded due to overtopping water.

7 FAILURE MECHANISMS IN NEW ORLEANS

There are many failure mechanisms that can cause the failure of a flood defence. In the previous section, it was discussed how the different dike rings of New Orleans failed. In this section, the different failures are categorised to show the relevance of the different failure mechanisms.

7.1 *Failure mechanisms of flood defences*

A list of commonly known failure mechanisms is presented in Table 1. The most important failure mechanisms are summarized in a failure tree (TAW 1998), see Figure 11.

Table 1. Failure mechanisms of flood defences (TAW 1998).

Dikes	Hydraulic structures	Dunes
– Overflow	– Strength/stability of structure	– Erosion
– Overtopping	– Strength/stability of foundation	– Erosion foreshore
– Sliding inner slope	– Strength/stability of transmission	– Sliding inner slope
– Horizontal sliding	– Non closure of structure	
– Sliding outer slope		
– Micro-instability		
– Piping		
– Erosion outer slope		
– Erosion foreshore		
– Settlement		
– Drifting ice		
– Ship Collision		

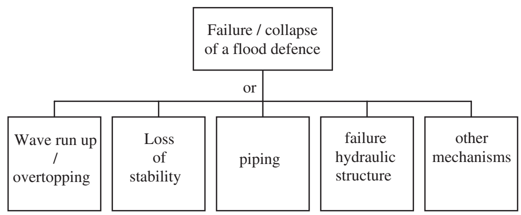

Figure 11. Failure tree of a flood defence with most important failure mechanisms (based on TAW 1998).

Wave run up/overtopping is caused by high water levels and/or waves, resulting in erosion of the inner slope and finally a breach. In Dutch flood defence regulations, the mechanisms of wave run-up and overtopping is assumed to contribute most to the total probability of failure of a flood defence system. Loss of stability occurs when the structure undergoes large deformations due to a load that is higher than the resistance; this can be micro or macro stability. Failure due to piping occurs when soil particles are washed out below the structure due to seepage. Failure of a hydraulic structure occurs when the strength/stability is insufficient (structure, foundation or transition) or when the moveable parts of the structure fail due to not closing or due to a water level that is higher than the top of the structure. Piping, loss of stability and failure of a structure due to insufficient strength or stability is usually referred to as geotechnical failure.

In the FLORIS project in the Netherlands (FLORIS 2005), a project in which the safety of the Netherlands is assessed, a slightly different failure tree is considered: Loss of stability is reduced to sliding of the inner slope; A ship collision and piping are explicitly assessed for hydraulic structures and erosion of the dike's revetment is taken into account as a major failure mechanism.

7.2 *Failure mechanisms in New Orleans categorized*

The following mechanisms occurred in New Orleans:
St. Bernard dike ring: This dike ring mainly flooded due to:

- Overflow/overtopping (root 1 in Figure 11)
- Failure hydraulic structures (root 4 in Figure 11; a combination of overflow and insufficient stability of the structure and its foundation)

Orleans East dike ring: This dike ring mainly flooded due to:

- Transitions around structures, not in Figure 11, but identified in Table 1.
- Overflow/overtopping (root 1 in Figure 11)
- Failure hydraulic structures (root 4 in Figure 11; a combination of overflow and insufficient strength/stability of the structure and its foundation)

Orleans East Bank dike ring: This dike ring mainly flooded due to:

- Horizontal sliding (See Table 1 and root 2 in Figure 11)
- Failure of hydraulic structures due to a combination of piping and reduced stability (boxes 3 and 4 in Figure 11).
- Failure hydraulic structures (root 4 in Figure 11; a combination of overflow and insufficient strength/stability of the structure and its foundation and the non-closure of a structure)

8 CONCLUSIONS

The flood disaster in New Orleans due to hurricane Katrina was a clear, yet tragic example of how a flood defence system can fail. Some important lessons can be learned for the European situation:

Careful determination system load. Firstly, the disaster showed the importance of a careful determination of the design conditions, the chosen water levels and waves criteria were severely exceeded by hurricane Katrina.

Transitions. Transitions between a structure and an earthen embankment are essential for the functioning of the system. Although transitions are not explicitly mentioned in design codes and regulations, these are of major importance for the functioning of a flood defence system.

Objects. Object like staircases and fences are also a starting point for erosion and should be avoided as much as possible (in the design and maintenance of the system).

Geotechnical failure. The disaster also showed that the probability of geotechnical failure is far from negligible (as desired in codes and regulations). All mechanisms should be taken seriously in the design of flood defences since geotechnical collapse is a brittle mechanism giving hardly any warning, potentially resulting in many casualties.

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