Briefing: Lessons learned from failures of flood defences

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Failure of flood defences during extreme events can lead to enormous damage and loss of life. This paper presents
lessons learned from investigations of flood events over recent years, including the 2005 flooding in New Orleans,
USA, caused by hurricane Katrina. Based on these findings, new developments in the field of research, design and
engineering of flood defences are discussed, such as the introduction of risk-based approaches and better
utilisation of failure data, field observations and monitoring. Such approaches are crucial to allow extrapolation
for more extreme load conditions due to climate change, with anticipated sea level rise and increasing
precipitation.

1.   Introduction

The majority of the global population is located in flood-prone coastal deltas, coastal areas and along rivers. Failure of flood defences (also termed levees, dykes or embankments) during extreme events can lead to enormous damage and loss of life (e.g. Jonkman, 2005). Therefore, an adequate understanding of the safety and vulnerability of flood defences is essential for design and assessment purposes. In this paper a few of the lessons learned from investigations of recent flood events are highlighted. Based on these findings, new developments are discussed, such as the introduction of risk-based design approaches and better utilisation of failure data, field observations and monitoring.

2.   Lessons from historical failures of flood defences

In order to illustrate some lessons learned from large-scale flood events in the last decade, the authors have synthesised a number of general observations and lessons learned. Table 1 provides an overview of the considered events, some of which the authors have been involved with through post-flood field investigations. Note that this is just a very small sample of the total number of significant flood events in this period of time.

Although all events are characterised by unique conditions and patterns, a number of general observations can be derived from the post-flood investigation reports.

2.1   The importance of geotechnical failures

During the flood events along the Elbe, the dyke failure in Wilnis and the flooding of the central parts of New Orleans, geotechnical failure mechanisms such as instability and internal erosion (piping) were the main causes of flooding (see Figure 1 for an example of a geotechnical failure). These mechanisms occur while the outside water level is below the crest or top of the flood defence structure. Uncertainty in ground conditions and the presence of unidentified adverse geological details are common causes of failures (Danka and Zhang 2015). This highlights the need for proper site investigation and the use of all the information that can be obtained on the (sub)soil conditions.

2.2   Vulnerability of transitions

In Thailand and New Orleans the transitions between hard structures and earthen dykes proved to be vulnerable weak links. In many cases erosion started at these locations. Design and safety assessment of flood defences often focuses on representative cross-sections, for which appropriate computational models are available. It seems that engineers are doing

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Event and location	Date/period	Type of event	Main failures and failure mechanisms	References
Wilnis, Netherlands	26 August 2003	Drought	Single canal dyke failure due to horizontal sliding. Peat dyke had decreased in weight significantly owing to a long drought period	Van Baars (2005)
Hurricane Katrina, New Orleans (2005)	29 August 2005	Hurricane surge	About 25 breaches; in the eastern part of the city these were due to overflow and overtopping, in the central part due to sliding and piping	IPET (2008), Seed et al. (2008a, 2008b)
Storm Xynthia, Girone and Loir estuaries, France	28 February 2010	Storm surge	Overflow and failure of dykes and dunes owing to erosion at several places	Kolen et al. (2013)
Chao Phraya river basin, Thailand	October–November 2011	Large-scale river floods	More than ten failures owing to overflow of the system	ENW (2012)
Elbe floods (in 2013), Germany	June 2013	River floods	50–500-year return period event. Several dyke failures due to geotechnical failure mechanisms	ENW (2013)

Table 1. Summary of events and some main observations

a sound job on these standard profiles, but the transitions between them are often engineered unsatisfactorily.

2.3 Multiple breaches
The floods in New Orleans (in 2005), Thailand (in 2011) and Germany (in 2013) were characterised by a large number of breaches in the flood protection system. However, other historical events, such as the 1953 storm surge in the Netherlands (more than 100 failures) or the Elbe floods (in Germany, during 2002) with more than 70 failures (Heyer and Horlacher, 2007), show similar patterns. In all these cases

Figure 1. Breach of about 100 m width at Fischbeck along the Elbe (Germany, June 2013) induced by a geotechnical failure. The photograph shows the breach with the emergency repair works, consisting of a sheet pile in a soil embankment

overloading of the system led to multiple failures, exacerbating the extent of the flooding and the damage.

2.4 Human and organisational factors
Evaluations after the floods highlighted that the flood defence systems were not properly designed for the events they faced. The canal dykes in Thailand were mainly built for water management purposes, but not for that level of flooding. The pre-Katrina hurricane protection system of New Orleans was 'a system in name only' (IPET, 2008), as it had varying elevations and insufficient strength for resistance against geotechnical failures. Also, there were striking differences in elevations of levee sections exposed to similar hydraulic conditions (i.e. water levels). Human and organisational factors, as well as poor management and maintenance, played a key role in the New Orleans failures (Bea, 2008) as well as in many other cases worldwide.

2.5 Damage and loss of life
The last general lesson concerns the large damages caused by failures of flood defences. The failures of flood defences of New Orleans caused hundreds of fatalities and billions of US dollars' worth of damage. The economy of Thailand was disrupted for several months owing to the flooding, and the flood caused a significant drop in economic growth. Almost 50 people were killed – a lot of them trapped in vacation homes – during the coastal floods in France (Lumbroso and Vinet, 2011). During the events in France and New Orleans, elderly people appeared to be most vulnerable. The (material and immaterial) costs of large-scale flooding are many times higher when compared to the costs of building and maintaining proper protection.

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3. New developments and directions

Based on these observations and lessons, a number of challenges and new promising developments are addressed in the field of research and design of flood defences, which should contribute to better understanding, improved performance and higher reliability.

3.1 Probabilistic design and risk analysis

Flood defence failures teach us that some failure modes are usually more critical in design than others, among other aspects, this can be attributed to the uncertainties faced in different conditions (e.g. loads or ground conditions). Probabilistic design allows the provision of tailor-made solutions, by taking all failure modes and all elements of the protection system into account, as well as their dependence in terms of reliability. This in turn allows targeted and cost-effective investment at weak spots. The Dutch VNK2 project (Jongejan and Maaskant, 2015) is a recent example of a rigorous nationwide flood risk analysis. It has led to major insights in, for example, the relative importance of failure modes, such as backward erosion piping or geotechnical stability. Furthermore, the insights of this project have been heavily relied on in the decisions on new safety standards for flood defences in the Netherlands (Delta Program, 2014). These standards are formulated in terms of acceptable probabilities of flooding, which have been derived from assessments of both economic risk and risk to life. Also, in other countries, the use of risk-based protection standards is investigated. For example, in the USA, the National Research Council has recommended the use of risk assessment to derive standards for coastal flood protection (NRC, 2014).

3.2 Learning from actual failures

Despite extensive theoretical and experimental research on failure modes of flood defences such as instability, internal erosion or overflow-induced breaching, considerable uncertainties in failure modelling and prediction remain. The understanding of geotechnical failure mechanisms can be significantly improved by hind-casting historical levee failures (see e.g. Kanning et al., 2008; Rajabalinejad et al., 2010). The learning aspects are essentially three-fold.

- The models can be improved by better calibration.
- It is possible to learn which failure modes or types of structures are the most critical, and in which conditions.
- 'New' failure modes are discovered that are not yet commonly considered in designs.

One example of the latter is the canal dyke at Wilnis, which failed in 2002 owing to a combination of circumstances hitherto unknown to practitioners. The peat in the dyke body had dried out, leading to a considerable decrease in its weight, plus drying cracks in the subsoil led to changes in the water pressures under the levee. In the aftermath, this failure mode was incorporated in the relevant Dutch guidelines.

Furthermore, individual efforts have been undertaken to document failures of flood defences after disasters (e.g. Heyer and Horlacher, 2007; Seed et al., 2008a, 2008b), yet no systematically gathered large-scale datasets are available for thorough scientific research in the way that they exist for other civil engineering domains (Breysse, 2012). Recently, the present authors launched an initiative to set up an international levee performance database, in order systematically to collect and analyse levee performance data; this should allow the research community to improve understanding of the performance of flood defences, on a systems level as well as for individual structures and failure modes.

3.3 Learning from observations

Near-failures or performance observations at heavily loaded flood defences can provide valuable information for safety assessments and reinforcement designs. Schweckendiek et al. (2014) demonstrate how observations of good performance (e.g. survival or no damage), as well as of bad performance (e.g. seepage or sand boils) without failure can significantly change the probability of backward internal erosion failure for future events, by reducing the uncertainty in geotechnical conditions. Monitoring the pore pressure response to external loading by increased water levels provides similar insights (Schweckendiek et al., 2013).

As geotechnical uncertainties play a key role, better site characterisation is needed. Probabilistic and risk-based approaches can also help to optimise investments by balancing the investigation cost with the risk reduction achieved, or by minimising the cost to achieve a pre-defined reliability target.

4. Conclusion

Given the large economic damage potential in most flood-prone areas, the available means to reduce uncertainty should be employed to reduce flood risk and to target investments in flood protection at the most effective spots.

A better understanding and more robust design of flood defences systems will become even more important in the future, when hydraulic loads are expected to increase due to the effects of sea-level rise and increasing precipitation. This will lead to more frequent events that are beyond the domain of our experience with the defences' performance. Proper understanding of flood defence failure then becomes crucial in extrapolating to more extreme load conditions.

Information from actual failures is particularly valuable. Important lessons have been learned from them in the past and this line of work must be continued. Preferably, this should

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be done in a more systematic manner, such that the insights are shared more effectively among researchers and with practitioners. Also near-misses and performance observations from non-failed flood defences contribute to overall understanding.

Moreover, the demand for safety will increase, owing to the economic and population growth in urbanised flood-prone regions (Hallegatte *et al.*, 2013). A better understanding of the reliability and failure mechanisms of flood defences will contribute to safer and more cost-effective designs, and ultimately to reducing damages and loss of life.

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