CHAPTER 11

Novel Emergency Response Interventions for Flood Resilience

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Abstract

Worldwide, climate change is expected to lead to increased probability of severe weather conditions and therefore an increased probability of flood events. Therefore, within the Netherlands, authorities have adopted several long-term programmes to secure flood resilience of the densely urbanised Dutch delta areas. Here, we focus on one of the strategies to mitigate the effects of flooding: emergency response interventions. The latter constitute an important aspect of the strategic approach towards flood resilience. Emergency response is also the adaptive measure in which civil authorities collaborate with the military. They bring in personnel, logistic capacities and are also at the frontline when such measures are deployed. Therefore, we focus on the role of the military in emergency response and present the results of large-scale experiments under artificial high-water conditions. These experiments, a joint effort of military, academic and flood risk professionals, are aimed at developing novel methods that can be employed by the military during future flood crises.

Keywords: climate resilience, critical infrastructures, emergency response, flooding, explosive breach initiation, waterborne emergency interventions, civil-military interaction

11.1 Introduction

It is now commonly believed that climate change is leading to an increased likelihood of unpredicted and severe weather conditions. Think of the extreme precipitation events as experienced in Western Europe in the summer of 2021. A major consequence is an increased probability of floods, threatening human lives, disrupting economic activities and the environment. In climate change research, the concept of such risk is usually defined as the combination of hazard, exposure, and vulnerability (Parry, 2007). This definition is currently universally accepted by policy makers and the public at large. Interestingly, some natural disaster historians argue that this perception of risk is for a large part a “physical construct, with the degree of environmental exposure and the nature of hazard often overshadowing social vulnerability" (van Bavel, et al., 2020). In short, these authors show how in the past, communities had developed resilient lifestyles: hazard and vulnerability were part of daily life. And preparedness consisted of "… 'traditional' coping mechanisms: strongly localized 'indigenous' knowledge on disaster prevention and mitigation, which was often passed from generation to generation, and might be 'reactivated' to complement 'modern' disaster prevention or relief mechanisms." With respect to flood resilience, Soens mentioned these resilient practices as 'amphibious communities' (Soens, 2023). Widespread public engagement, when dealing with risks associated with climate change, has been neglected for a long time. Risk mitigation and disaster relief became primarily the responsibility of authorities and dedicated government agencies. Although the focus of this work is merely on centralised response strategies to flooding, it should be emphasised that when dealing with the unexpected, improvisation and public engagement are to be incorporated as important aspects of societal resilience to effects of climate change.

Traditionally, flood risk has been anticipated by flood prevention strategies e.g. by reinforcing and raising existing flood defences such as levees. The history of the Dutch Delta program offers a good example of how the Dutch approach to water security has changed throughout the years (Expertise Network for Flood Protection, 2017). The first initiatives and efforts, after the North Sea flood of 1953, were based on calculated flood risks. After river floods in 1993 and 1995, a risk-based approach was introduced. Instead of merely focusing on reinforcement of the levee-system, a more integral approach, "room for the river", was adopted, in which a widening of the floodplain of rivers was promoted (Slomp, 2015). In the Netherlands, the flood mitigation approach has recently shifted from flood prevention to the more integral approach of flood risk management. This so-called multi-layer safety model (STOWA, 2017) intends to reduce flood risk by integrating defensive measures against floods (layer 1), resilient spatial planning (layer 2), and effective crisis management measures (layer 3). Within layer 3, effective emergency response methods are an important means of managing and preventing the consequences of flooding.

A recent example of the layer of spatial adaptation is the transformation of the Dutch Hedwigepolder and the Belgian Prosperpolder into new tidal nature. This has offered the opportunity of using an existing levee for strength and emergency response tests: the Living Lab Hedwige-Prosperpolder. For this, a multinational consortium from the 2 Seas Region was founded to join efforts in the European Union funded programme Polder2C's. The Dutch Ministry of Defence (MoD) was a leading member of this consortium. Within this project the MoD's main tasks were the development and testing of novel and effective emergency response methods for flood resilience. Two means of emergency response have been considered more closely. Firstly, interventions that preserve the water-retaining function of a levee exposed to extreme high-water conditions. Secondly, means to reduce the water-load on segments of the levee-system. This can be achieved by dedicated breach-initiation upstream from the endangered levee segment, followed by peak water storage in temporary inundation areas. In this chapter, we present the results of large-scale experiments on the feasibility of these emergency response methods. Eventually, this may lead to a new set of effective response concepts, to be utilised and employed by the military in case of imminent flooding disasters.

Finally, it should be emphasized that current (summer 2023) geopolitical developments, especially the war of the Russian Federation against Ukraine, have led to a drastic shift of scope of the Dutch military. A shift is being made towards the first of its three main tasks i.e., defending its own territory and that of its allies. From a water resilience perspective, the war in Ukraine has emphasized the importance of hydraulic warfare. In a way, this is the mirror image of the research presented here. Breach initiation and inundation were tactically employed by the Ukrainians during the Battle of Kyiv, recalling the traditional Dutch approach to water as a means of defence (Bruijstens, 2023). Another infamous example is the destruction of the Kakhovka dam by the Russians. While the need for improvised reinforcement of damaged infrastructure, e.g. the Antonivka road bridge (Persson & Verwiel, 2022), echoes the damage mitigation approach presented in the next paragraphs of this chapter. Specifically, application of a floating pontoon, the BresDefender, in the case of stability criticality of levees under high-water conditions.

11.2 Emergency Response Interventions in Flood Disasters

As the Netherlands is a delta area where more than half of the land and population and two-thirds of the economic activity are flood-prone, flood resilience is really an issue of national security. Given the prospects of climate change and the related increase of frequency and severity of high-water events, solutions from a singular perspective i.e., the strengthening of the levee-system by merely technical-engineering solutions, is not sustainable. Integral methods, such as the multi-level safety approach, are required to meet challenges that cannot be addressed by other means.

When water defences happen to not function as expected, appropriate measures should be taken to prevent flooding of valuable areas. These are the emergency response interventions – as mentioned before – that constitute the third layer in the multi-level water safety philosophy. Here, emergency response is defined as “the systematic response to an unexpected or dangerous occurrence, which goal it is to mitigate the impact of the event on people and the environment” (“Safeopedia”, 2023). Contingency measures and emergency interventions must be called by the responsible authorities within the water chain: water boards, regional safety authorities and dedicated crisis task forces. At this stage also the military – here the Dutch Ministry of Defence (MoD) – become involved, through invoking its third main task: support the government with law enforcement, disaster relief and humanitarian aid, nationally and internationally. Then, other contingency options have been exhausted, and the military is called to provide personnel, logistics, robust command and control structures, perseverance, and equipment. To guarantee optimal performance of the military operations during actual crises ("the warm phase"), it is necessary that the military is already involved in planning and preparation with respect to future flood events ("the cold phase"). In the cold phase, water safety professionals and military personnel collaborate in emergency exercises and jointly develop tools and strategies to assure optimal joint disaster prevention or mitigation operations during actual crises.

11.2.1 Means of physical emergency intervention

It is the cold phase in flood risk management that justifies the involvement of the Ministry of Defence in the Polder2C's project. The Ministry of Defence was involved through various internal stakeholders, including operational units (e.g. 105th Hydraulic Engineers Company) and Knowledge Centres and institutes (Knowledge Centre Military Engineering and Netherlands Defence Academy). The MoD's role within Polder2C's was in the areas of emergency response and disaster relief, both at the level of scientific research and practical training. The collaboration with external stakeholders, as well as training and knowledge exchange, are considered key enablers to the final layer of climate adaptation i.e., through emergency response.

When it comes to physical emergency response interventions, one may distinguish two fundamentally distinct strategies:

i. Prevent structural failure of the levee or the levee system. This can be achieved through reinforcement of levee segments, emergency repairs or temporary increase of the levee's crest height.
ii. Reduce the hydraulic loading on the levee.

These approaches will be detailed in the forthcoming paragraphs.

11.2.2 Interventions to prevent structural failure of levees

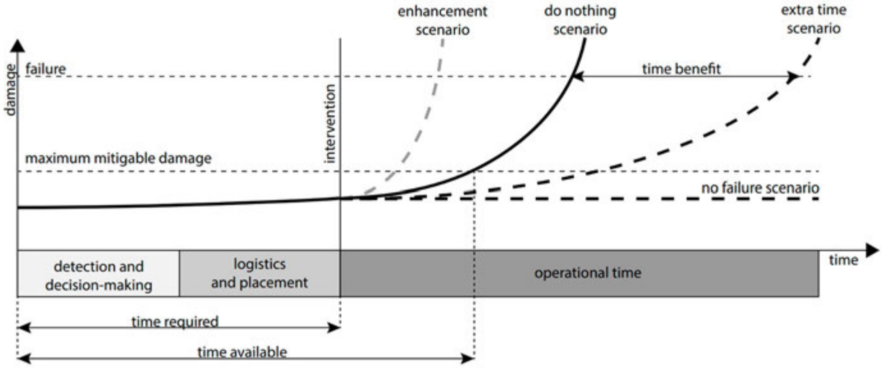
Interventions to prevent structural failure of levees aim to preserve the water-retaining function of a levee. This has for long been the traditional means of flood-crisis support by the military (Leger verhoogt dijk in Roermond met zandzakken, 2021; Vossers, 2013). These relief operations can be deployed from the land (land-borne) such as the placement of sandbags or other mobile barrier systems. However, during a water crisis it can be undesirable – and difficult – to approach a saturated levee from the landside. In that case water-borne interventions are to be preferred.

Land-borne emergency response measures have been evaluated to study the performance of novel mobile barrier solutions (van Duinkerken, 2022). An important benefit of these mobile barrier systems is that they use the water, which is always abundantly available at a potential flood-endangered location, as the substance that provides weight and stability to the temporary protective structure. Of course, such novel solutions should at least provide the same amount of protection and performance as the traditional sandbag. Also, the ease of placement and logistical issues should be addressed, before implementing these systems in real crisis circumstances.

Another concept is the deployment of preventive measures from the riverside: waterborne emergency response measures. One possibility is the use of military pontoons, which are commonly used to construct temporal floating bridges. Initially this concept was successfully tested (proof of concept) by military engineers in collaboration with water authorities during the exercise Alert 2015. This waterborne intervention method is referred to as BresDefender. The BresDefender concept can be considered as an example of an adaptive military (Dutch: *adaptieve krijgsmacht*), as it utilises existing military equipment in an alternative manner.

To describe the deployment of the BresDefender intervention method – and actually any means of levee reinforcement – with respect to decision processes, logistics and its actual performance as an emergency intervention method, a conceptual framework (Janssen, Schmets, Hofland, Dado, & Jonkman, 2020) has been developed, see Figure 11.1.

Figure 11.1. Effect of emergency response intervention scenarios on time to failure (Janssen, Schmets, Hofland, Dado, & Jonkman, 2020).

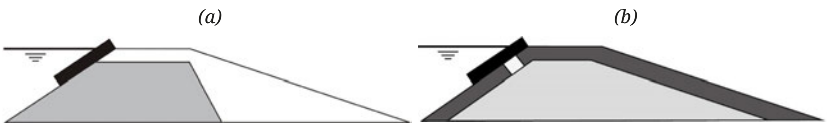


Within this framework time is displayed at the horizontal axis against a parameter that represents the level of structural damage of a levee section. Two special damage levels are to be considered with respect to eventual intervention actions. Firstly, the damage level that represents complete functional failure, i.e., the water retaining function of the levee cannot be maintained; neither autonomously nor by any sort of external intervention. This damage level is represented in Figure 11.1 by the upper, horizontal dotted line labelled 'failure'. Secondly, the maximum damage level that would still allow for successful emergency intervention; the maximum mitigatable damage, represented by the lower, horizontal dotted line in Figure 11.1. Then, the solid line in Figure 11.1 represents a possible trajectory of structural damage development over time. During periods of high-water in a river, the weaker sections of a levee will be most susceptible to dynamic damage processes. At these locations, damage could initiate and start developing. Initially, damage will increase slowly with time, and eventually accelerate to reach structural failure. Failure of large-scale structures such as levees are often found to follow this type of 'power law' pattern (Bažant & Chen, 1997). Thus, the solid line identifies the time to failure in case no emergency intervention is to be employed: the do-nothing-scenario. Then, the various dashed lines in Figure 11.1 correspond to the possible effect of various intervention scenarios on the damage growth process. Obviously, the ideal case of a perfect intervention is represented by the no-failure-scenario. The enhancement-scenario illustrates a situation where it would be unwise to intervene at all. The most desirable effect of an intervention is illustrated by the extra-time-scenario in Figure 11.1. In the latter scenario, the time to failure increases the time benefit. This time benefit serves as a measure for the effectiveness of an emergency intervention.

Any intervention is triggered by the detection of damage at its early stages. Detection is usually achieved by intensified levee inspections or by remote methods using drones. Drones equipped with Lidar (Light Detection and Ranging) sensors allow for the detection of tiny movements of landmasses, pinpointing regions where structural damage of a levee may develop. After initial damage detection, crisis managers decide which response actions are to be launched, and whether military assistance should be called in. In the latter case, the military chain of command must be activated, and the deployment process starts (Kalkman, 2021). In case of employment of the BresDefender, a pontoon is to be shipped to the desired location, followed by the onsite placement (van Veelen, 2021) of the system. The complete intervention process, from detection through decision-making and up to physical placement of a structure, requires optimisation. Such optimisation will shorten the time required and hence increase the probability that the levee will hold during a high-water event (van de Velde, 2022).

Of course, interventions only add value when they perform according to an intended effect. This requires a priori knowledge about the physical damage processes that are to be mitigated by an emergency measure (Elsing, 2018). In the case of the BresDefender, two primary damage mechanisms have been identified which can be slowed down or stopped. Firstly, it can arrest the breach initiation process (Figure 11.2a). This is achieved either by a temporary increase of crest height, to prevent the erosive forces associated with wave overtopping, or by blocking the water flow into an already existing breach (Janssen, Hofland, Schmets, Dado, & Jonkman, 2023), inhibiting imminent breach growth.

Figure 11.2. Scenarios for deployment of BresDefender: (a) stop overflow and arrest breach growth, and (b) reduce stability reduction by blocking infiltration of water at damaged levee sections (Janssen, Schmets, Hofland, Dado, & Jonkman, 2020).



Secondly, the method can provide a water-impermeable seal covering the outer slope of the levee. In this way the development of the phreatic surface (water level) in the levee is expected to increase slower and to lower equilibrium levels (van de Wilt, 2020). Controlling the phreatic surface in a levee is a particularly important addition to traditional methods, as it interacts with an invisible damage pathway, that usually ends in sudden slip failure of the complete structure. Lab-scale and real-scale experiments, supported by numerical calculations, hint that application of an impermeable seal does extend the time to failure at least by one hour (Janssen, et al., 2023; Hommes, 2022). The overall effectiveness and operational reliability of the BresDefender methodology for some river flooding scenarios are presented elsewhere (Janssen, Jonkman, Schmets, Hofland, & Dado, 2023).

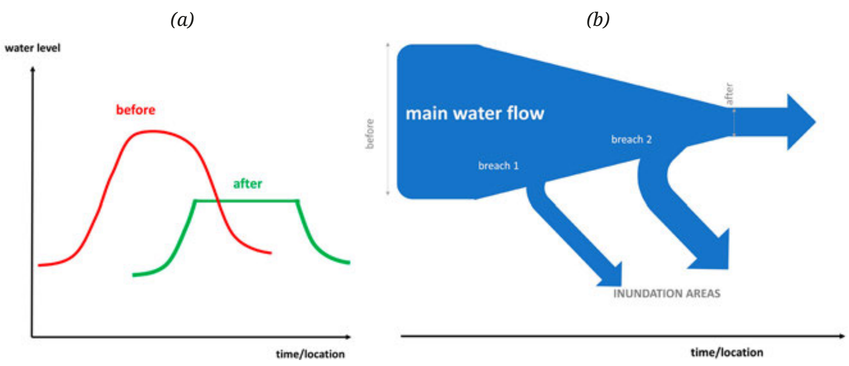
11.2.3 Interventions to reduce hydraulic loading on levees

In contrast to levee reinforcement as a method of emergency intervention, one can also consider reducing the hydraulic load at a designated levee segment during a high-water crisis. This would require decreasing the water level in a river at the site of a vulnerable levee segment. This can be achieved by topping off the high-water peak (Figure 11.3a), through deviating excess water to areas where temporary flooding would have lesser impact on human life, infrastructure, and economic development (Figure 11.3b). In case constructions that allow for inundation, such as inlets, are absent, the method of choice would be to intentionally initiate a levee breach by pyrotechnic means. It is anticipated that after initiating a breach, the water flow into the inundation area will start eroding the breach, i.e., a breach growth process will develop.

In the past, large scale breach growth experiments have been conducted on a large scale, homogeneous sand dike at Het Zwin (Bakker, et al., 1996). Here, two successive tests were conducted with artificially created, 2.5-metre-wide initial breaches, while the outer water level was about +0.25–0.50 metres relative to the bottom of the artificial gully. Within an hour, equilibrium breach widths of 13 and 41 metres were measured, respectively. Moreover, model calculations have demonstrated that breach widening rates at constant flow velocities through the breach, are most sensitive to soil erodibility and the shear strength of the soil mass (Robbins, 2022).

Certainly, the total available volumetric capacity of the inundation area should be sufficient to achieve the desired reduction of peak discharge. Another critical factor is the precise timing of the (explosive) breach initiation. Too early breach initiation will cause the inundation area to be filled up before the peak discharge has passed the breaching location, which will leave the peak discharge, and consequently the water level, of the river largely unaltered at the levee section to be protected.

Figure 11.3. (a) The concept of reduction of river discharge (water levels), by (b) deviating part of the flow by intentional levee breaches and inundation of designated areas. The width of the arrow represents the flow rate. Figure source: the authors.



To achieve a desired decrease of water level in a specific river, details of the discharge characteristics of such a river are required. For instance, based on data from the department of waterways and public works in the Netherlands, it is known that rivers Waal and IJssel may accommodate peak discharges of 10.500 m^3/s and 2400 m^3/s respectively. As a rule of thumb, to achieve a 1 cm decrease in water level at peak discharge conditions, one should deviate 25 m^3/s for the river Waal and 10 m^3/s for the river IJssel (van der Nat, 2023). The data allows for estimating the minimum discharge a breach – or multiple breaches – should be able to deviate eventually.

A helpful method to estimate the discharge through a breach of known geometry is due to Visser (Visser, 1998). The method derives from the theory of open channel flow through a breach, with the assumption of critical water flow conditions, i.e., that the Froude number $Fr = 1$. For the specific condition of critical flow, the discharge through a breach happens to be a function of just a few geometric parameters, such as the wet cross-sectional area, the water depth in the breach and the average flow velocity. Then, the discharge through a levee breach is given by,

$$Q = m \left(\frac{2}{3}\right)^{\frac{3}{2}} \sqrt{g}\, B \left(H_w - Z_{br}\right)^{\frac{3}{2}}, \tag{1}$$

with Q [m^3/s] the flow rate through the breach, m [-] a breach-inflow factor, g [m^2/s] the acceleration of gravity, B [m] the average width of the wet cross-section of the breach, H_w [m] the riverside water level, and Z_{br} $[m]$ the height of the bottom of the breach relative to an arbitrary reference level. Moreover, equation (1) can also be used to calculate the leakage discharges, and reduction thereof, when employing intervention measures like BresDefender.

In preparation for the real scale explosive breach initiation experiments, the parameters that govern the breach initiation and subsequent breach growth processes needed to be established. First, details of craters due to subsoil detonations were studied for dry and saturated sand bodies (Zoomers, 2019). Next the same was studied, but now the sand was covered by a layer of clay, mimicking the typical layout of a Dutch river levee (Mekenkamp, 2022). Next, the breach growth process after pyrotechnic breach initiation was studied (Steneker, 2022), and at last the concept was tested through real scale experiments (Mossinkoff, 2023).

Finally, the method of explosive breach initiation is by no means an unexplored topic. It was used to liberate the Dutch town of Alkmaar in 1583 from Spanish troops by flooding the enemy positions. In the Second World War the Royal Airforce had to spend significant effort to breach the sea dike at Westkapelle (Zeeland, the Netherlands) from the air. In the USA, embankments of the Mississippi river were breached in 2011 to achieve the same effect as mentioned earlier: decrease the river's water level to safeguard levee systems protecting densely populated areas.

11.3 Large, Real-Scale Emergency Response Experiments

The Living Lab Hedwige-Prosperpolder offered an excellent environment to study real scale flood defences and emergency response actions under controlled, but realistic conditions. By a treaty between Belgium and Netherlands, the Belgian Prosperpolder and the adjacent Dutch Hedwigepolder was to be depoldered to create natural qualities, such as tidal marshes. The depoldering was also part of a Belgian flood protection plan, for which it is to serve as a natural flood control area. In late 2022 the sea water finally flooded the polders at high tide. Interestingly, an adjacent former polder known as the Drowned Land of Saeftinghe, was inundated by breaching the sea dikes in 1584 during the Eighty Years' War by Dutch troops, drowning the small town of Saeftinghe.

After a new dike was built inland, and the hinterland was protected, the sea dike at the Western Scheldt, and the polders behind it, became available for the living lab. The consortium undertook many separate tests, ranging from nightly civil-military levee-guard exercises with up-to-date tools (damage-locator app with GPS and handheld IR-cameras) to extensive destructive overflow tests (Polder2C's, 2020–2023). Other activities within the programme were extensive wave-overtopping and wave-impact tests, emergency response exercises, breach initiation tests, etc.

In the following, the focus will be on the design and construction of experiments within the living lab environment, to assess water-borne interventions (BresDefender) for reinforcing a levee at emergency, high-water conditions.

11.3.1 Real scale experiments for reinforcing the water retaining function of a levee

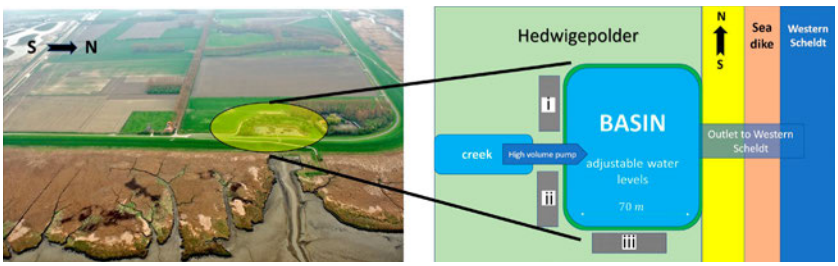
11.3.1.1 Design of a real-scale test setup for levee stabilisation experiments

To test emergency interventions, the minimal requirement is the availability of a levee with the outer water at very high levels, i.e., the outer water level should be at least 0.5 *m* below the crest, preferably even closer (artificially created emergency conditions). Even at spring tide this condition would never be reached at the sea dike of the Western Scheldt. Hence, designing tests to be deployed at the sea dike proved to be impossible. Then, it was decided to use an existing retention basin, and redesign the levee surrounding it to purpose (Schmets, Dado, Leertouwer, de Rijke, & Postma, 2021), see Figure 11.4. The basin had dimensions of 100 by 50 metres and was specifically designed to simulate high water conditions in a river. When filled with water to 0.1 m beneath crest level, the basin held about 20000 m 3 water, almost 10 Olympic swimming pools. High-capacity pumps (up to 10.000 m 3/hour) were installed to fill the basin to emergency water levels. An existing unidirectional (because of PFAS) outlet was used to flush water from the basin to the Western Scheldt at the end of an experimental session.

The levee was designed to resemble an average Dutch river levee (Technische Adviescommissie voor de Waterkeringen, 2001). The levee consisted of a permeable, sandy core, covered with a 0.5 m clay layer. The outer slope of the levee was according to standard practice 1:3. Three test areas were assigned to separate locations on the 5m-wide crest, Figure 11.4(b). At location (i), where the BresDefender was to be deployed, the outer slope was covered with sods, to closely mimic a typical Dutch grass covered levee.

Figure 11.4. (a) Overview of the (once) existing retention pool in the former Hedwigepolder. (b) Sketch of the design of the basin, with new levees, water supply from an existing creek, and water outlet to Western Scheldt. The sites i, ii, and iii indicate the dedicated test areas for BresDefender, mobile barriers and (intended) breach initiation, respectively. Figure source: the authors.

(a) *(b)*



11.3.1.2 Results of levee stabilisation experiments using the BresDefender

In the period November 2021 to January 2022 the basin was built, and pumps and measurement equipment were installed. A section of military engineers from 105 Geniecompagnie Waterbouw moored a pusher boat and floating pontoons in the basin, Figure 11.5(a). For the experimental scenario which intended to reduce the water flow through a breach, see Figure 11.2(a), an artificial breach was purposely created. Within the artificial breach a hatch was installed, Figure 11.5(b), and a flow rate measurement box was placed at the landside of the artificial breach.

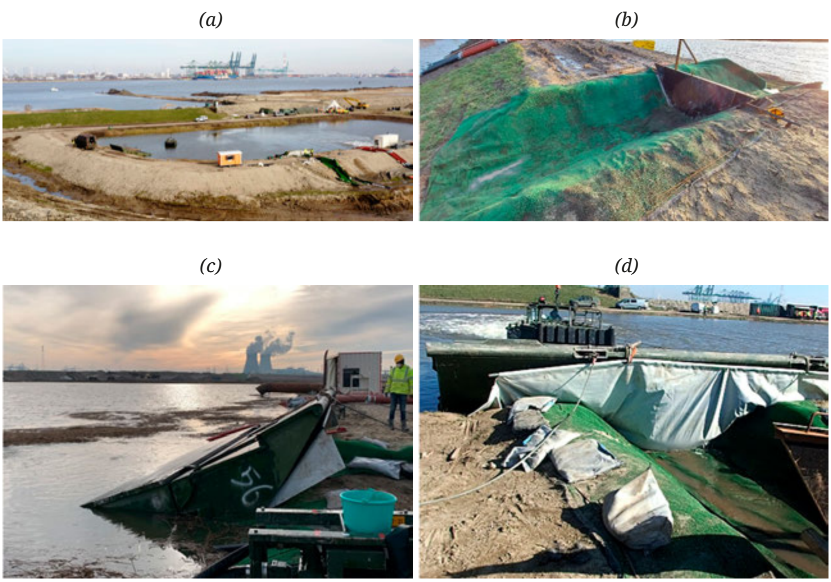
Actual experiments were performed during February-March 2022 (Rozendaal, 2022). Two different scenarios were assessed. The first test scenario involved an unmodified pontoon, while the second scenario used a pontoon with a flexible plastic sheet (tarpaulin) attached to the bottom, Figure 11.5(c,d). After minor adjustments to the original pontoon, it could be sunk in front of the weakened levee section, i.e., the artificial breach, to reduce the discharge over or through the levee. The discharge reduction for the first scenario was found to be insignificant.

However, for the second scenario, with the tarpaulin applied, the discharge through the breach was measured to decrease more than 99% compared to the situation without an intervention installed (Janssen, Hofland, Schmets, Dado, & Jonkman, 2023). Also in this scenario, the measured discharges might still lead to erosion of dike core material. But now at erosion rates which are a few orders of magnitude lower compared to the situation without an emergency measure installed.

Altogether, application of the BresDefender can achieve a time benefit as sketched in Figure 11.1. Also, a substantiated estimate of this benefit can be found from physical models (Janssen, Hofland, Schmets, Dado, & Jonkman, 2023). Breach growth happens to be arrested, which allows time for evacuation of people and livestock from the hinterland.

Parameters related to the other anticipated effect of BresDefender, reduction of the water flow into the levee leading to a decrease of phreatic surface level, could not be obtained from these large-scale experiments. But dedicated lab-scale and intermediate-scale experiments elsewhere have demonstrated that also this effect offers a time benefit, i.e., a prolonged time to failure (van de Wilt, 2020; Janssen, et al., 2023).

Figure 11.5. (a) The purposely build test facility in the former Hedwigepolder. (b) Artificial breach with hatch for BresDefender experiments. (c) Pontoon covered with flexible sheet placed in front of breach. (d) Flow reduction through breach after application of pontoon. All images from February/March 2022. Figure source: Bureau Multimedia, Den Helder.



11.3.2 Real-scale breach initiation experiments

11.3.2.1 Design of a real-scale test setup for breach initiation experiments

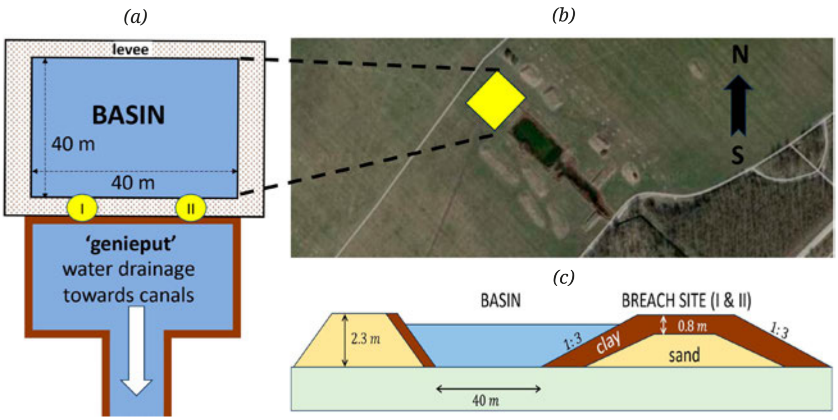
Initially, the basin in the Hedwigepolder was also intended for explosive breach initiation experiments. These experiments would involve the use of explosive charges applied to the levee. However, the Hedwigepolder is located close to a very busy waterway and high-pressure pipelines transporting chemicals to and from the nearby chemical industry. Also, the nuclear powerplant of Doel (Belgium) is at less than 2 kilometres from the basin. Therefore, first an assessment of the seismic consequences of levee breaching by detonation had to be made. Large impact tests were performed at the levee, creating, after appropriate scaling, seismic effects like those expected from a detonation (de Graaf, 2022). In this way, it could be predicted that the seismic effect of explosive breach initiation would stay well below the norm value of 3 mm/s (peak particle velocity) for nuclear installations. The predicted soil velocity at the location of the nuclear powerplant caused by detonation was found to be less than 0.1 mm/s. However, by the time this result was established, the decommissioning of the basin had already been planned. The time it would have taken to convince the stakeholders in the Antwerp-harbour area was unfortunately not favourable for timely execution of the breach initiation experiments at the dedicated site in the Hedwige-Prosperpolder Living Lab.

Therefore, breach initiation experiments had to be conducted elsewhere. At the military training grounds in Marnewaard a facility resembling the basin in the Hedwigepolder, though smaller, was built in the autumn of 2022, Figure 11.6a. Also, this basin was surrounded by levees, which were designed according to the specifications of an average Dutch river dike, Figure 11.6c. Once more, large pumps were installed to raise the water in the basin to emergency levels. Here, emergency level refers to almost-flooding conditions, with river levels close to the crest of the levee. After creation of a breach, water could flow through the breach into an already existing pond (*genieput*).

Breach initiation tests, operation name Breaching Beaver, were conducted at two different days in 2023, at two different breaching sites at the levee, indicated as I and II in Figure 11.6(b,c). Apart from the water retaining levee of the basin, a purposely built levee section not retaining water, indicated as dry levee, was built near the basin. It served as a physical twin structure of the basin's levee. For every breach experiment, the dry levee was subjected to the same breaching procedure as the basin's levee. The explosive breaching experiment of the physical twin levee was meant to obtain data on the size and velocity distribution of ejected soil fragments, which is important for the determination of safety distances for personnel involved in the breaching procedure. Moreover, the breach in the dry levee will have an almost similar breach geometry as the breach in the basin's levee. This guarantees a precise definition of the breach geometry at the start of the dynamic breach growth process.

The first experiment, Breaching Beaver I, was conducted for a water-filled basin, to study the effect of breaching on a hydraulically loaded levee. However, the subsequent breach growth process, caused by the outflow of water, was not representative for a river breach due to the decreasing basin water level over time. Therefore, in the follow-up experiment (Breaching Beaver II), water was continuously pumped back into the basin, maintaining the basin water at emergency levels for a period as long as was achievable.

Figure 11.6. (a) The existing site at Marnewaard with the projected (yellow) location of the basin. (b) Sketch of the design of the basin, the new levee, and breach sites I (January 24th, 2023) and II (February 28th, 2023). (c) Cross section and dimensions of the basin, and design details of the levee. Figure source: the authors.



11.3.2.2 Results of breach initiation experiments

Using explosives to initiate a breach has advantages over traditional methods, i.e., using heavy equipment such as excavators. Apart from not having heavy equipment on a potentially unstable levee, explosive breach initiation is also a flexible and fast method: a group of combat engineers can be deployed by boat, over land and even through the air. All necessary tools and the explosives can be easily brought to the detonation site by backpack. However, it is especially important to precisely time the moment of breach initiation in relation to the passing of the discharge peak in a river, see Figure 11.3. Only then can the intended reduction of hydraulic loads on levee segments downstream be achieved.

The pyrotechnic breaching experiments were conducted on two days, in January and February 2023 (Dekker, 2023). The principle of the explosive breach initiation procedure is as follows. By precise positioning of explosive charges at the levee, and their subsequent simultaneous detonation, the erosion resistant clay layer is removed. This starts off the discharge of basin water through the breach, accompanied by erosion of the levee's sandy core. In this way, a breach growth process is triggered, leading to breach widening and increased water discharge rates.

Figure 11.7. (a) The purposely built test basin facility at Marnewaard, with the test levee prepared for detonation at location II, visible in the foreground. (b) Explosive breaching of the test levee. (c) Initial breach and water outflow immediately after detonation. (d) Final equilibrium state of the breach. Figure source: the authors, February 28th, 2023.

(a)

(b)

(c)

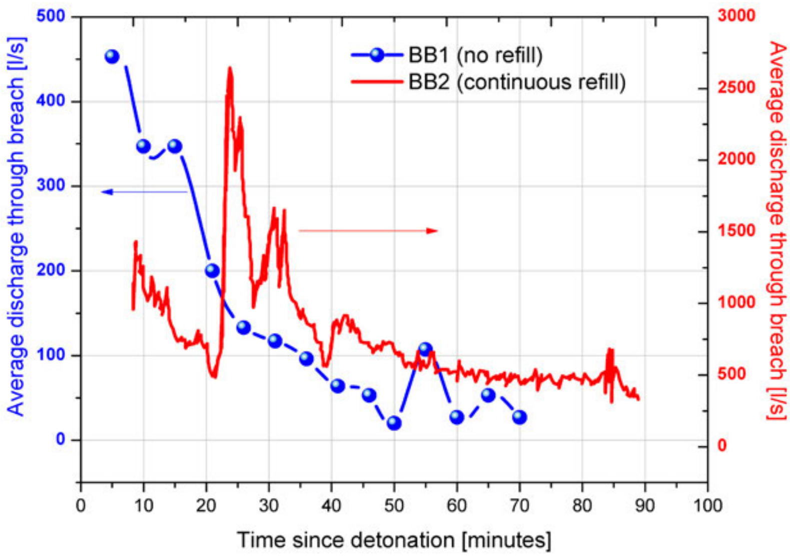
(d)

At the time of detonation, the basin water level was at approximately 20 cm below the crest. Multiple, standard military grade, plastic explosive charges were buried inside the levee, using a soil auger. The charges were placed in a string-like fashion across the levee. The tests allowed for evaluating and improving on earlier established estimates of breach parameters (Zoomers, 2019; Mekenkamp, 2022). These parameters included the depth of burial of the charges, the number of charges required, the amount of explosive to be used for each charge location and the precise position of each charge on the levee, Figure 11.7(a). The order of events during Breaching Beaver II is presented in Figure 11.7.

To monitor details of the explosive effects in general, and the breaching process in particular, various measurement systems were put in place. From the air, sensor-equipped drones collected multispectral and lidar data over time. In this way the geometry changes of the levee, the initial breach as well as the soil and water surfaces were recorded over time. A series of electronic pressure sensors installed in the basin allowed for measuring the discharge through the breach. High-definition photography and high-speed cameras imaged the various stages of the process, including the size and velocity distribution of soil fragments ejected from the breach site. The latter has provided unique data for estimating safety distances for this type of operation.

In Figure 11.8 the experimentally obtained discharge through the breach as a function of time is presented for both experiments. The measured peak discharges are found to differ significantly between both experiments. Peak discharges of almost 500 l/s and 2500 l/s were measured for Breaching Beaver I (BB1) and Breaching Beaver II (BB2) respectively. The observed difference originates from variations in experimental setup between the two tests. In BB1 the basin level decreased over time, while for BB2 a constant water level could be maintained for a longer time after detonation by synchronous refilling the basin with large pumps. Another reason for the observed discharge differences was an improved explosive charge geometry. The improved geometry was inspired by the result of the earlier experiment, BB1.

Figure 11.8. Measured discharges through breach as function of time after breach initiation event for Breaching Beaver I (BB1, constant volume basin) and II (BB2, constant backflow into basin). Figure source: the authors.



Remarkably though, the final breach width was found to be four metres in both experiments. This is small compared to the final breach dimensions of the Zwin experiments (Bakker, et al., 1996), possibly due to a higher value of the driving potential of the water flow, i.e., the factor $(H_w - Z_{br})$ in equation 1. Another remarkable finding is that the time for the breach growth process to stop is found to be between 40–50 minutes, for both Marnewaard experiments as well as for the Zwin experiments. Whether this is only a coincidence is to be subject of further research.

These initial results suggest that the method can be used in smaller, almost stagnant water systems, such as lakes, basins, and canals, with relative ease. This is because the effect of the breach is easily predicted, given the desired water volume to be deviated and the size of the retention area. However, application of this method in the case of rivers will be more involved. For rivers proper timing of the breach creation – relative to the passage of the discharge peak – as well as the size of the breach are essential for the method to be effective. Further analysis of the results (Mossinkoff, 2023), extrapolating to the boundary conditions set by river levees, indicates that implementation of the same method will lead to deviation discharges up to 20 m^3/s. This estimation assumes that real rivers allow for complete development of the breach growth process, because of abundant availability of water. Overall, the method has been proven to work, but waits for testing on real river systems. Also, development of computational models could guide the future selection of the various parameters involved.

Finally, the experiments presented here demonstrate that military engineering service men are already sufficiently trained to successfully execute a breach initiation as an operational task under emergency conditions. However, it is particularly important that they receive accurate instructions, in which also the aims of the breach and the importance of accurate timing of the action are explained. The desired technical information required involves the coordinates of the desired breach site, accurate predictions of the moment of breach initiation, and details about the cross-sectional properties of the levee, i.e., layer thicknesses, crest cover material (grass or asphalt), etc. The latter information should be supplied by the water authorities, otherwise it should be gathered by a separate intelligence harvesting mission prior to deployment of the breachers team.

11.4 Conclusions

Here we have presented novel methods for military led emergency response interventions during river flood crises. River flooding is expected to occur more often, and with more severe consequences, due to climate change. Two principally different emergency intervention strategies were presented. Firstly, the temporary strengthening of the levee's water retaining function by waterborne deployment of a seal: the BresDefender. Secondly, the local reduction of the hydraulic loading on a selected levee section by partly deviating the river's discharge to an inundation area upstream. This inundation is achieved by localised, explosively initiated breaching of upstream levees.

These techniques were developed and evaluated using large scale facilities (basins) in Hedwigepolder and Marnewaard. These facilities were designed to resemble Dutch river settings and to allow for emergency-like water levels by application of large pumps.

BresDefender's effectiveness as a waterborne, levee reinforcement technique, and its potential for use in real emergency response situations, was studied under realistic environmental conditions. The primary aim of the experiments was to evaluate the applicability and effectiveness of a stiff structure positioned in front of a locally reduced crest, in minimising the total discharge through the breach. In addition, the placement procedure of the pontoon was assessed. The application of a flexible sheet or tarpaulin between the stiff structure and the levee proved to be crucial for the effectiveness of this method. It was demonstrated that deployment of the BresDefender emergency response measure has several advantages over the application of traditional measures to stop a breach in its early stages:

- It makes up the only theoretical underpinned solution to avoid or arrest the breach initiation process in its early stages.
- The method leads to a significant reduction of water flow to the hinterland. It also arrests the growth of the breach because reduced flow rates lead to decrease of soil erosion rates.
- Altogether, the method delivers with respect to the aspect of creating a time benefit (Figure 11.1). This time benefit can be required for evacuation, but it could ideally make the levee survive the flood.
- The method has been demonstrated to work when applied to overflow in case failure of a levee has led to local decrease of crest height.
- The method can also be applied when the outer slope, or its protective cover layer, is damaged. The method is found to significantly slow down the ingress of water into the levee and prevents shear failure due to increased loading by the increased outer water level.

Explosive breach initiation and subsequent breach growth were studied experimentally, aiming at developing best practices for future use during high water events. This emergency intervention method intends to reduce hydraulic loads on critical levee segments. The method has been proven to work and may also be applicable in a military context for counter mobility or other defensive purposes.

The main findings of the breach initiation and growth experiments can be summarised as:

- Levee dimensions, soil stratification and composition are required to properly design a charge geometry for effective breach initiation.
- Breach growth has been observed, and final breach widths up to 4 metres were obtained. Experiments at real rivers should be conducted to assess the extrapolation-based assumption of achievable deviation volumes.
- Small military teams equipped only with backpacks, deployed by either land, water or air, can achieve deviation discharges of 20 m^3/s per breach, for a typical Dutch river levee.
- Further research should lead to charge configurations that allow for optimal breach growth and breach growth velocities. This would make the method more useful for practical application, as precise timing with respect to the approaching discharge peak becomes possible.
- More studies are advised to make the method more versatile. The procedure should be evaluated for diverse types of levees (clay, sand, peat, roads on top, stone, or asphalt revetment, etc.). Also, the decision-making process by water managers and civil administrators, during an actual crisis, leading up to a breach creation by the military, should be examined.

Overall, novel emergency response intervention techniques have been presented. Both, the BresDefender technology and the explosive breach initiation technologies are, or will be, added to the International Handbook of Emergency Response, a document with similar aims as the International Levee Handbook (Sharp, et al., 2013). The next step would be for the water-safety authorities to weigh its usefulness, and then request the military and/or civil authorities to develop the proposed techniques for tools which could be embedded in the regular military training programs. As disaster events and circumstances are always unpredictable, emergency measures should lean on proper preparation by training. Here, training means not only following procedures, but also using the trained skills to improvise successfully in all sorts of environments under extreme circumstantial conditions.

Finally, the project and its deliverables result from a collaboration between military, national partners in the water safety chain and international partners. It was a learning environment for all, and a fruitful experience in international civil-military interaction. Such longer term, cold phase collaborations have proven to deliver a lot, not least mutual understanding, a critical requirement for effective emergency response. Finally, 'playgrounds' like Hedwige-Prosperpolder prove to be important triggers for collaboration and testing desktop ideas in the field.

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