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EFFECTIVENESS AND RELIABILITY ANALYSIS OF EMERGENCY MEASURES FOR FLOOD PREVENTION

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ABSTRACT: During flood events emergency measures are used to prevent breaches in flood defences. However, there is still limited insight in their reliability and effectiveness. The objective of this paper is to develop a method to determine the reliability and effectiveness of emergency measures for flood defences. The investigation is focused on measures that prevent breaching of a flood defence in a river system; measures to limit and/or close breaches are beyond the scope.

To determine the failure probability of flood defences with emergency measures two assessments are made: 1) the reliability of implantation of emergency measures is determined and 2) the effect of the implemented emergency measures on the reliability of the flood defence. For an emergency measure to function correctly three phases need to be passed successfully: ‘Detection’, where weak spots in the flood defence are detected, ‘Placement’, where emergency measures are built on time, and ‘Construction’, which is the successful functioning of the emergency measures.

The reliability of ‘Detection’ and ‘Placement’ depends on human and organizational reliability and the feasibility of complete placement of the measures within the available time. The reliability of the ‘Construction’ concerns the structural performance of the emergency measure. For a case study along a part of a river in the Netherlands a failure probability of emergency measures for the piping failure mechanism is estimated to be 1/3 per event. The human / organizational reliability during ‘Detection’ and ‘Placement’ proved to be dominant. When translated to dike ring level the failure probability is reduced with about a factor 2. This is largely explained by the length effect: with increasing amounts of weak spots in a flood defence the contribution of emergency measures will decrease.

Keywords: Emergency measures; Flood Reliability analysis; Risk

1 INTRODUCTION

1.1 Background

Recent river floods in Central Europe and Great Britain demonstrated once again that floods account for a large part of damage and loss of life caused by natural disasters. In the summer of 2013 large rainfalls occurred in Central Europe resulting in high water levels on the Elbe and Donau rivers in Germany, the Czech Republic and Austria. Local authorities, civilians and the army worked together to place tens of thousands of sand bags attempting to prevent large breaches in the flood defences. In spite of these attempts several dike breaches occurred which flooded large parts of Central Europe (Ellenrieder & Maier 2014). Also, in the Sacramento – San Joaquin river delta in California, emergency measures and “flood fighting” are used on regular basis (Corn & Inkabi 2013).

These events demonstrate that emergency measures, such as sand bags and big bags, are often used during threatening floods to prevent breaches and/or protect critical infrastructure. Emergency measures are defined as measures applied to protect, or repair, weak spots in flood defences which develop flooding. The location and type of measure depend on the specific situation, which is unknown beforehand.

1.2 Objective

The objective of this paper is to develop a framework and/or method to determine the reliability and effectiveness of emergency measures for flood defences. The reliability of emergency measures is quantified through an extensive reliability analysis.

Previous studies have focussed on specific aspects of emergency measures. These concluded that organizational and logistic aspects of emergency measures require more investigation (Leeuw et al. 2012; Boon 2007), as their reliability determines to a large extent the reliability of a system of emergency measures. A similar conclusion is drawn in (Corn & Inkabi 2013) which describes the effect of human intervention on the reliability of flood defences. This paper complements to the previous studies by further elaborating human reliability aspects and determining the influence of time and technical reliability of emergency measures. The investigation is focussed on emergency measures for overtopping and piping at river dikes which prevent breaching of flood defences. Measures to prevent breach growth and/or close breaches are beyond the scope of this paper, these are investigated in (van Gerven 2004; Joore 2004).

This paper is structured as follows: section 2 describes the framework developed to determine the effect of successful implementation of emergency measures on the reliability of dike sections. The length effect is explained in section 3, which describes how the reliability of all dike sections together determines the reliability of the dike ring. The framework is applied to a case study at Groot Salland in section 4 after which the results are discussed in section 5. Concluding remarks are given in section 6.

2 FRAMEWORK FOR THE RELIABILITY ANALYSIS OF EMERGENCY MEASURES

In this section a framework is developed to determine the reliability and effectiveness of emergency measures. It is based on the Dutch situation, but can be used in any other flood prone area. In the Netherlands the flood prone area is divided in dike rings; rings of flood defences which protect the surrounded area. Specific government organizations called 'water boards' are responsible for maintenance of these dike rings. The framework contains four steps:

- Determine reliability of flood defences without emergency measures;
- Determine reliability of a system of emergency measures given flooding;
- Determine effectiveness of the emergency measures applied;
- Determine the combined reliability of flood defenses and emergency measures.

For a complete assessment of the reliability of a system of flood defences insight is required in the (prior) failure probabilities of the system without emergency measures. This can be obtained by dividing the dike ring in several sections with similar strength properties; for each section the failure probability is determined after which the failure probability of the dike ring is calculated by combining the individual sections while taking into account dependencies. This method is explained in more detail in (VNK 2005).

When including emergency measures in the reliability analysis of flood defences failure can occur when the flood defence fails in spite of a correct functioning emergency measure or when the emergency measure fails and the flood defence fails, see Figure 1. So even when emergency measures are successfully applied the flood defence can still fail. To determine the failure probability of flood defences with emergency measures two assessments are made:

1) The reliability of emergency measures needs to be determined;
2) The effect of the emergency measures on the failure probability of the flood defence needs to be determined.

The effectiveness of the emergency measure (ad 2) determines the maximum increase in reliability with an emergency measure. The combined reliability of a dike ring with emergency measures is determined by combining the reliability without emergency measures with the reliability and effectiveness of the emergency measures at section level, after which these are combined to obtain the reliability of the dike ring.

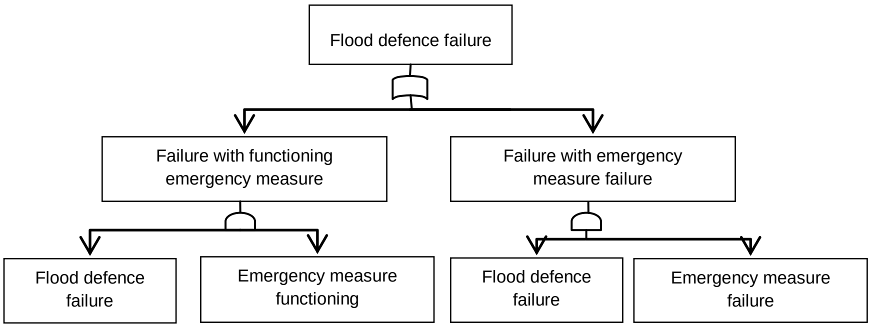

Figure 1: Fault tree of flood defence including emergency measures

2.1 Reliability of emergency measures given flooding

During flood threats the authorities responsible for the flood defences perform inspections in search of possible weak spots, which can lead to breaching. Weak spots are defined as damages in the flood defence (visual or non-visual) where a breach can occur during the expected river flood if no measures are taken. If weak spots are found an assessment is made whether or not emergency measures are required which are then placed attempting to prevent breaching of the flood defence.

The probability of a correct functioning control and/or emergency measure depends on the completion of three phases: Detection – Placement – Construction (Dupuits 2011). The failure events are therefore labelled 'Detection failure', 'Placement failure', and 'Construction failure'. The system is modelled in an event tree forming a series system (Figure 2):

1) Detection failure: in the 'Detection' phase the upcoming high water is monitored and inspections of the flood defences are performed to find possible weak spots. Failure occurs when the organization fails to detect all weak spots.
2) Placement failure: in the 'Placement' phase a diagnosis is made whether or not measures are required taking the expected water levels and severity of the weak spot in to account, after which water board contractors build the emergency measures. Failure occurs when the organization fails to build the required emergency measures.
3) Structural failure: during the 'Construction' phase the emergency measure needs to function correctly to effectively prevent further damage to the flood defence. Failure occurs when the measure fails for example due to instability or overflow.

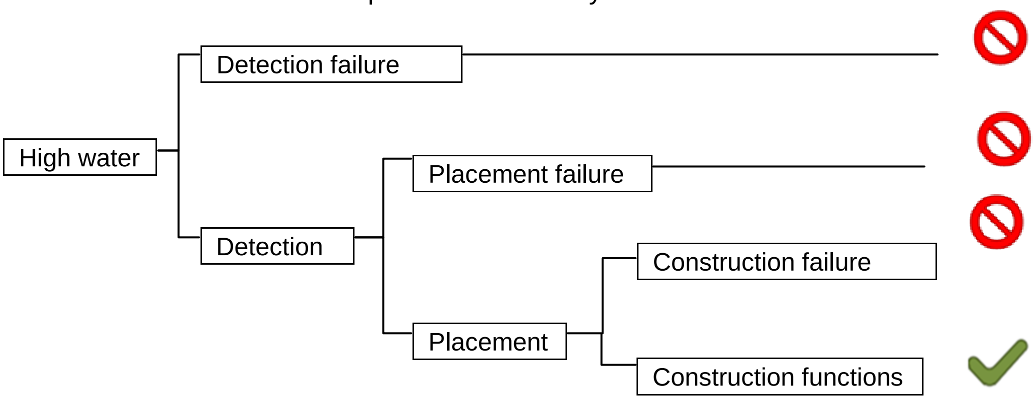

Figure 2: Event tree control and/or emergency measures

There are two failure modes for the 'Detection' and 'Placement' phases:

- Failure to detect weak spots or correctly apply the emergency measure;
- Failure to complete the placement of emergency measures within the available time.

Failure to detect weak spots or correctly place an emergency measure is dependent on the reliability of the organization. The probability of complete placement of the emergency measures within the available time depends on the time required for placement of all emergency measures. The ‘Construction’ phase can fail due to structural failure of the emergency measure. This will be further elaborated in the following sections.

2.1.1 Organizational / human reliability

Failure to detect weak spots or place an emergency measure is dependent on the reliability of the organization. Although human and organizational factors have been incorporated in the reliability evaluation of a variety of engineering fields they continue to be commonly omitted in flood protection models and reliability valuations (Corn & Inkabi 2013). Human reliability practitioners have to rely on expert judgment in combination with limited numerical data, due to lack of a successful database of human error probabilities. This database is then used by the assessor to find probabilities of errors for the specific tasks to be performed within the system. The analysis of human reliability in engineering systems typically seek only orders of magnitude of errors rather than exact descriptions (Bea 2010). As a result the most important aspect is the qualitative analysis of the system (Rasmussen 1982).

To estimate typical error rates of the ‘Detection’ and ‘Placement’ phase for emergency measures the methods of Rasmussen are used. Rasmussen uses a generic psychological classification of human errors which can be applied to specific task performances (Rasmussen 1982). In his model distinction is made between three levels of behaviour: Knowledge based, Rule based and Skill based (Rasmussen 1983).

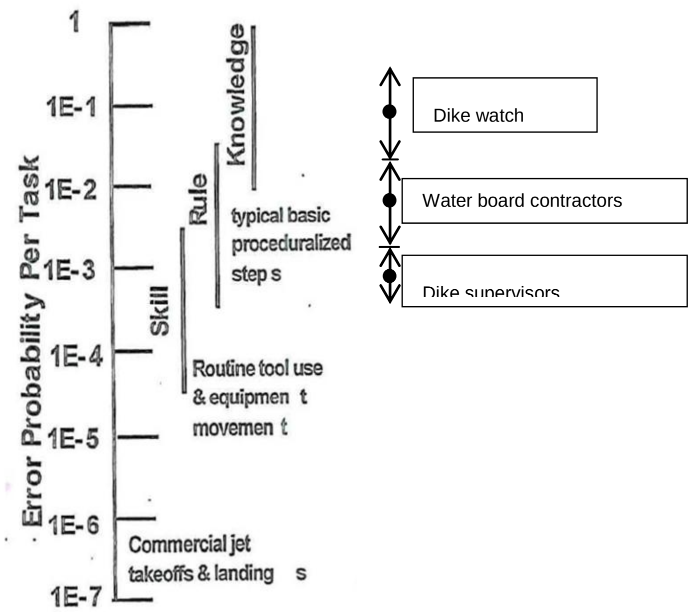

Figure 3: Human error probabilities and performance levels by Watson and Collins (Bea 2010)

Knowledge based behaviour is the least reliable behaviour with error rates between 5 e-1 and 5 e-3 per task. This corresponds with little knowledge and experience with the system (unfamiliarity) (Rasmussen 1983). Rule based behaviour is the next level, with error rates between 5 e-2 and 5 e-4 per task. This class involves responding to a familiar problem according to standardized rules (Rasmussen 1983). Skill based performance is the most reliable behaviour level with error rates between 5 e-3 and 5 e-5 per task. At this level the conditions occur so often that the response is almost automatic (Rasmussen 1983).

The relation between common error probabilities and the three performance levels is show in Figure 3. The main stakeholders involved in the system of emergency measures are the dike watch, for inspection of the emergency measures, water board contractors, for placement of the emergency measures and dike supervisors which are responsible for day to day maintenance of flood defences. A classification according to the performance levels of Rasmussen is made based on examination of tasks, interviews, observations and expert judgment, see Figure 3.

2.1.2 Probability of complete placement within the available time

The reliability of emergency measures also depends on the feasibility of complete ‘Detection’ and ‘Placement’ before the peak of the water levels. The expected water levels in the system can be predicted hours in advance (e.g. storm surge / rain) to days in advance (e.g. river floods). This implies that there is always a certain ‘available time’ to prepare for the hazard (Leeuw et al. 2012): the available time is defined as the time between the moment the hazard is predicted until it arrives. This window is available to detect and place emergency measures.

The accuracy of the predicted water levels increases with decreasing time to the arrival of the peak of the river flood. Overtopping will only occur when the water levels exceed the dike height (during the peak of the river flood), which can be predicted fairly accurately. Piping can however occur at lower water levels, before the peak of the river flood arrives. Combined with the fact that Dutch river systems are more vulnerable for piping failure it is expected that in the early stages after prediction of the river flood more attention is paid to finding weak spots for piping than overtopping. At a later stage, when the predictions of expected water levels are more accurate and overtopping threatens to occur, attention will be paid to overtopping measures.

The required time is the time needed for detection and placement of the emergency measure. Whether or not the emergency measure is built in time depends on, among others, the capacity of the organization (personnel, equipment and material), travel distances, weather conditions and detection- and/or placement speed. The time line is illustrated in Figure 4.

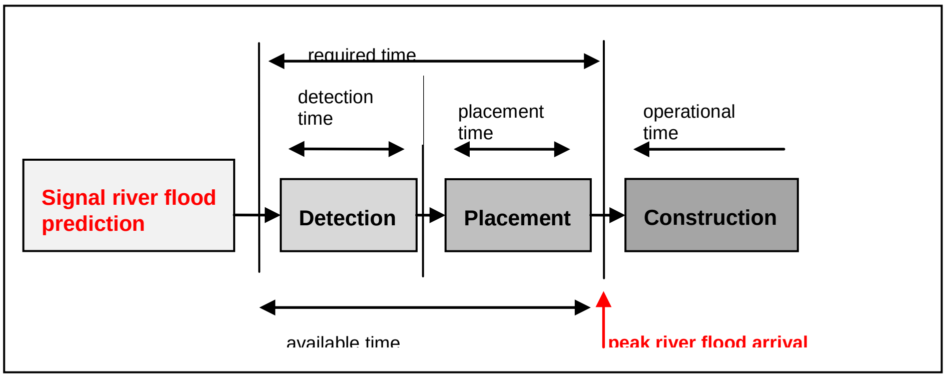

Figure 4: Time line control / emergency measures

For each dike section the probability of no (incomplete) placement is determined probabilistically. Distributions are assumed for the available ($T_{available}$) and required time ($T_{required}$) in hours; the latter consists of the summation of detection ($T_{detection}$) and placement time ($T_{placement}$), see equation 3. Through Monte Carlo simulation an estimate is made of the failure probability in time, see Figure 5.

$$Z = T_{available} - T_{required} \quad [1]$$

$$T_{required} = T_{detection} + T_{placement} \quad [2]$$

$$Z = T_{available} - T_{detection} - T_{placement} \quad [3]$$

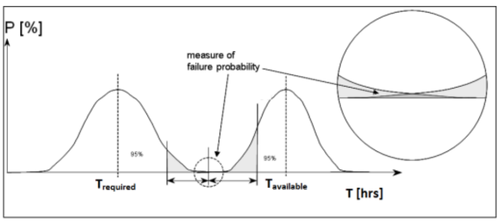

Figure 5: Required versus available time

2.1.3 Technical reliability of the emergency measure ('Construction')

The main failure mechanisms of river dikes are overtopping, piping, inner slope instability and outer slope erosion, according to (VNK 2005). This paper focusses on the application of emergency measures for overtopping and piping, as these are dominant along Dutch rivers.

When a dike section is subject to overtopping two types of emergency measures can be used to prevent breaching: either the retaining height is increased locally with a temporary water retaining structure or the inner slope is protected against erosion. Regarding the latter it is assumed once placed correctly these measures (e.g. geo textiles stabilized with sand bags) will have negligible technical failure probabilities; similar measures are used to protect the outer layer of the flood defense.

The first signs of piping failure are the development of boils and/or sand boils on the inner side of the dike, see (Schweckendiek et al. 2014). To prevent sand boils from growing containments are built around the boils with temporary water retaining structures. These containments fill with seepage water providing counter pressure and thus reducing the flow velocity and further erosion of sand particles. When high density of sand boils is found along a certain dike section more 'drastic' measures are taken. Examples are piping berms which reduce the water head and provide extra stability at the toe of the dike (these measures are also applied to prevent inner slope sliding of the flood defense).

For both overtopping and piping measures temporary water retaining structures are used to increase the retaining height locally or construct sand boil containments. Even though new products are available, authorities still largely rely on the 'traditional' sand bag. The cross section of a structure of sand bags can be built in single stacks, pyramids or other any form in between. Dutch water boards recommend a pyramid shape; each subsequent layer consisting of one sand bag more than the latter. These structures can be seen as small gravity structures, which obtain stability through their own weight, see Figure 6.

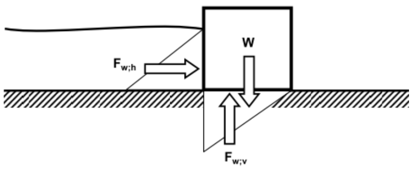

Figure 6: Pressure and acting forces on a gravity structure [2]

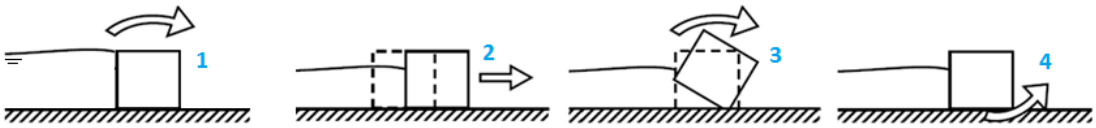

Figure 7: Failure mechanisms: Overtopping (1), Sliding (2), Rotation (3) and Piping (4) (Boon 2007)

Failure can occur due to overtopping, horizontal sliding, rotation and seepage (Figure 7). The stability is largely influenced by the development of upward water pressure under the structure, which depends on the subsoil, loading time, and connection between the structure and the subsoil. On permeable subsoil the upward pressure is assumed maximum, as the water will infiltrate the subsoil quickly. On impermeable subsoil the infiltration is much slower, resulting in little upward water pressure to be taken in to account due to the temporary nature of loading on the structure. Infiltration of water inside the sand bags will partly reduce the self-weight of the structure. Depending on the subsoil one of the failure mechanisms mentioned before will be dominant: on impermeable subsoil sliding is dominant; piping is dominant on permeable subsoil. Assuming these structures are built on impermeable subsoil, present on the outer layer of flood defences, sliding instability will be governing (Boon 2007).

Sliding occurs when the horizontal force on the structure exceeds the friction force between the structure and the subsoil due to self-weight. For a temporary structure of sand bags sliding can occur between each subsequent layer of sand bags or between the bottom layer of sand bags and the subsoil. The interface where sliding failure occurs depends on the friction force between two layers of sandbags and between sand bags and subsoil, see (Krahn et al. 2007). Through tests with single stacks of sand bags, and probabilistic calculation it is concluded that sand bags on peat will slide on the interface between sand bags; on clay the structure will fail at the interface between the bottom layer and the subsoil. The failure probabilities of a pyramid structure of sand bags are negligible (order of 10^{-5} per event) when compared to human/organizational failure and/or the feasibility in time (order of 10^{-1} per event).

2.2 Effectiveness of emergency measures given successful implementation

During the ‘Construction’ phase, a correctly placed emergency measure is expected to reduce the failure probability of the dike section. The extent of this reduction depends on the type of measure and the failure mechanism. The fragility curves in Figure 8 illustrate the potential increase in safety due to emergency measures for overtopping, which locally increase the retaining height, and piping, which locally reduce the hydraulic head over the flood defence. Overtopping measures only effectively reduce the failure probability of the dike section for water levels close to the crest; piping measures however can potentially reduce the failure probability at lower levels.

Note that emergency measures meant to increase the reliability for one failure mechanism, can have a negative effect on the reliability of another failure mechanism. For example: when placing sand bags on the flood defence to increase the retaining height the weight increases, which can increase macro instability. Therefore before emergency measures are placed an assessment is required to determine the increase in reliability of all failure mechanisms, not only the corresponding failure mechanism.

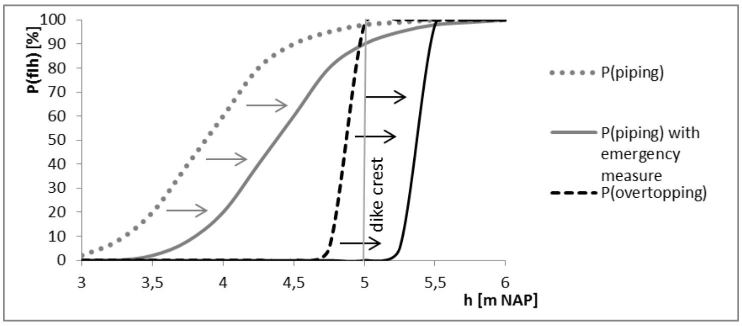

Figure 8: Potential effectiveness of overtopping (blue) and piping (green) measures

3 COMBINING THE RELIABILITY OF FLOOD DEFENCES AND EMERGENCY MEASURES

Event tree analysis is used to combine the reliability of the flood defenses with the reliability of emergency measures. The event tree in Figure 9 is used to determine the failure probability of one dike section with emergency measures. When the ‘Detection’, ‘Placement’ or ‘Construction’ phase fails the reliability is described by the reliability without emergency measures; when every phase is completed successfully the reliability is described by the reliability with emergency measures.

To determine the failure probability of the dike ring all sections are modelled as a serial system. The failure probability of the dike ring can be determined when insight is obtained about the dependencies of the different sections. Dike sections subject to overtopping are modelled dependent, as it can be assumed that if one dike section is overtopped it is most probable that the next section will also overtop. Sections subject to piping are modelled independent, because of large uncertainties and high variability in the subsoil. Piping has a large ‘length effect’ (VNK 2005), which is the result of modelling dike sections independently: longer dike rings will have higher failure probabilities for piping than shorter dike rings.

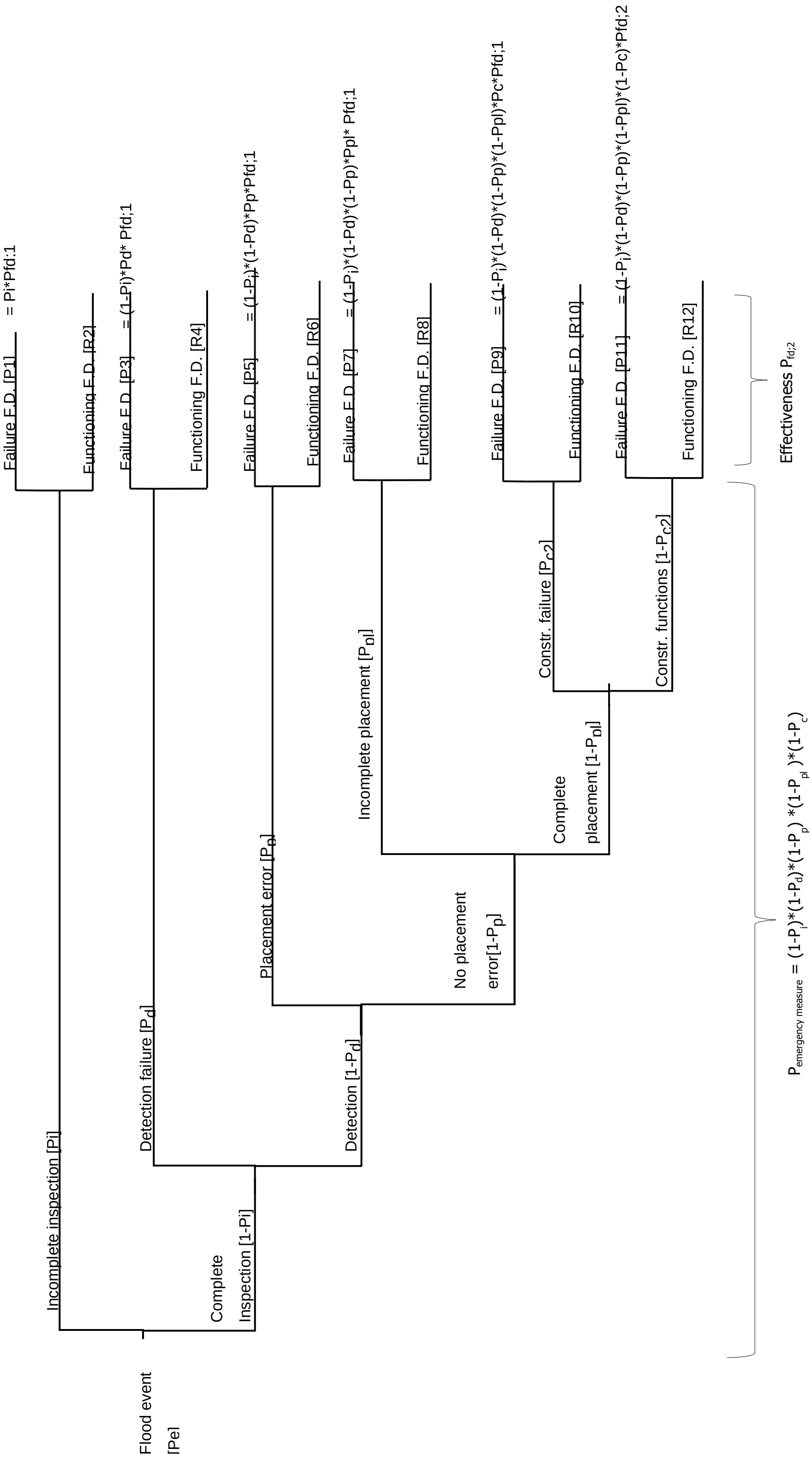

Figure 9: Total model event tree, note that the probabilities are conditional

Emergency measures have a similar ‘length effect’ which depends on the amount (or length) of emergency measures required. With increasing amounts of weak spots along a flood defence the contribution of a system of emergency measures will decrease. The length effect determines to a large extent the feasibility and type of emergency measure. It can be assumed that a dike watch who detects an overtopped dike section will also find other dike sections subject to overtopping, because this is clearly visible. However, sand boils are much more difficult to detect; the detection of one sand boil is no guarantee for finding the next. Therefor, overtopping is assumed dependent and piping independent, resulting in length effect for piping.

4 CASE STUDY ‘SALLAND’ IN THE NETHERLANDS

The framework developed is applied to a case study for dike ring 53 at Dutch water board ‘Groot Salland’. The probability of flooding of the dike ring, determined by VNK, is larger than 1/100 per year, as a result of high probability of piping (Dijk & Plicht 2013). The water board acknowledges the problems with piping as it is known that along several parts of the dike numerous sand boils often occur during river floods. In (Dijk & Plicht 2013) sensitivity analyses were made to determine the effectiveness of emergency measures for both piping and overtopping along the weakest parts of the flood defence. The results are explained shortly in the following section.

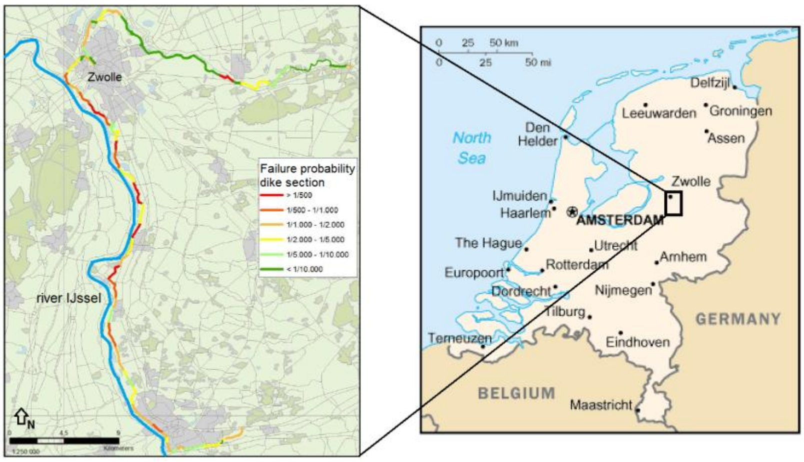

Figure 10: Case study area with failure probabilities of flood defences (left)

For piping the effect of reducing the water head over the full length of the dike was determined. Without head reductions the failure probability is 1/63 per year, with a head reduction of 0.5 meter the failure probability is reduced to 1/150 per year. This illustrates the maximum reduction of failure probability with emergency measures for piping. For overtopping the effect of increasing the retaining height of local ‘dents’ in the dike was determined, with a maximum length of 250 meter. Without emergency measures the failure probability is 1/610 per year, when all ‘dents’ are filled the failure probability is reduced to 1/3,600 per year. Note that this is the potential reduction of flood risk with emergency measures, not taking the probability of successful implementation of emergency measures in to account.

The reliability of emergency measures depends on both the reliability of the organization and the feasibility of complete placement within the available time. During river floods the dike watch performs inspections of the flood defences and reports weak spots directly to supervisors of the water board. The supervisors decide upon the application of emergency measures, which are placed by the water board contractor. Through interviews and observations during a river flood exercise estimates were made of the performance levels of the personnel involved during both the ‘Detection’ and ‘Placement’ phases, which are shown in Figure 3. The reliability of complete placement within the available time was determined based on data of the water board (WGS 2012).

The failure probability for piping emergency measures is estimated at 1/3 per event. Taking the effectiveness of the measures in to account this resulted in a decrease of the failure probability of dike sections with a factor 1.5 to 3. At dike ring level the failure probability is reduced to 1/120 per year, which is about a factor 2. This validates the statement made that with increasing length (number of weak spots) the contribution of a system of emergency measures to the reliability of the flood defence decreases. Due to the length effect the reduction at dike ring level is lower than at dike section level.

The failure probability for overtopping emergency measures is estimated at 1/9 per event. This resulted in a reduction of the failure probabilities of dike sections with a factor 2 to 6. At dike ring level the failure probability is reduced to 1/3000 per year, which is a factor 3.6.

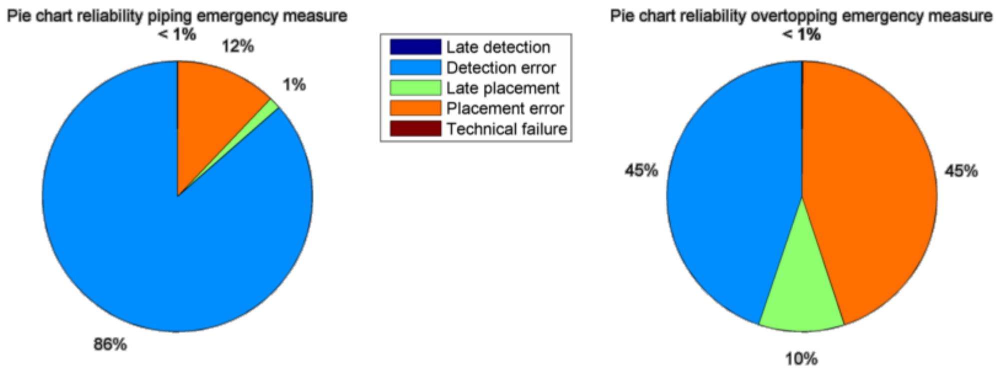

Figure 11: Distribution of reliability of overtopping and piping emergency measures

Overtopping measures are more reliable than piping measures, which is explained by the fact that it is easier to detect overtopping than piping. The distribution of aspects which determine the reliability of both piping and overtopping emergency measures is shown in the pie charts in Figure 11. The charts show that errors during the 'Detection' and 'Placement' phase account for over 90% of the failure probability of emergency measures. The organizational / human failure probabilities determine to a very large extent the reliability of the emergency measures. Especially errors during 'Detection' prove to be dominant for piping emergency measures.

5 DISCUSSION

Reducing the probability of errors during 'Detection' and 'Placement' will have a large effect on the reliability of emergency measures. The effect of reducing the failure probability of the dike watch and contractors on the total failure probability of emergency measures is shown in Figure 12. The figure shows that reductions up to a failure probability of 1/100 per event are effective, after which reductions of the failure probabilities during 'Detection' and 'Placement' have little effect on the failure probability of the emergency measure.

This is explained by the fact that the reliability of emergency measures is also determined by the feasibility in time, which has failure probabilities of one order lower than the probabilities of errors. However, when these probabilities are reduced to around 1/100 per event the feasibility in time becomes dominant. This can also occur when the framework is applied to a coastal system. In this paper river systems are treated, with prediction times of 2 to 4 days. In a coastal system the prediction time is much shorter, about 12 hours; as a result the feasibility in time will be more dominant.

Methods to reduce the probabilities of errors during 'Detection' and 'Placement' consist of increasing the performance levels of the people involved (dike watch). To increase human performance levels training with the specific repertoire of (unexpected) possible behaviour of the system proved to be highly effective (Rasmussen 1983), other methods often consist of documenting procedures and rules for the application of emergency measures. Furthermore innovative detection methods, such as remote sensing and the use of drones, could increase the reliability of the 'Detection'.

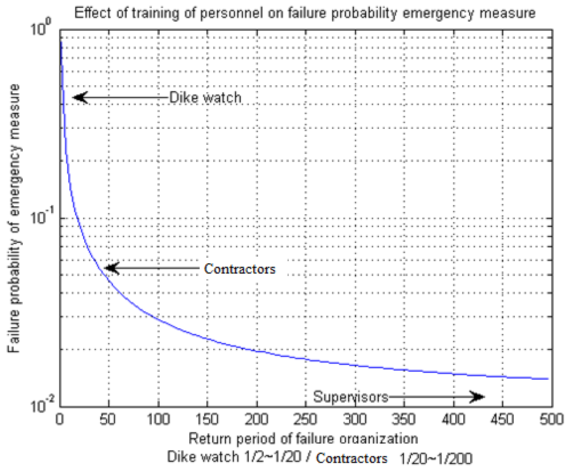

Figure 12: Influence of human reliability on total failure probability of the emergency measures

The assignment of error rates to the different employees of the water boards is based on expert judgement of the author. During an exercise with emergency measures these estimates where not refuted. The approach relies very much on the cooperation of the organization involved. Further investigation of human tasks in flood prone areas is recommended, which can provide more insight in error rates.

The analysis is based on an event tree, which allows for an analysis in binary sense. An analysis using Bayesian networks may give more accurate reliabilities and insight in the correlations and common factors between aspects. This method is also used in (Schweckendiek et al. 2014), which shows that the presents a method to update piping reliability after detection of sand boils.

6 CONCLUDING REMARKS

This paper presents a framework which can be used to estimate the reliability and effectiveness of emergency measures for flood prevention. The framework is applied to a case study at water board Groot Salland, where the reliability of overtopping measures is estimated at 1/9 per event. Piping measures have higher failure probabilities due to the length effect: 1/3 per event. Note that these estimates are case dependent and strongly influenced by the amount of weak spots in the flood defence. Errors during ‘Detection’ and ‘Placement’ prove to be dominant in the reliability of the emergency measures, specifically for piping where errors in ‘Detection’ account for almost 90% of the total failure probability.

Taking the limitations discussed in the previous section in to account, this paper provides insight in the important factors which determine the reliability of emergency measures for flood prevention. Furthermore, this paper demonstrates that the reliability of flood defences can be increased with emergency measures. The increase in safety depends on the failure mechanism of the flood defence, the organization responsible for emergency measures and feasibility of complete detection and placement within the available time.

The method presented can be used to compare various strategies for flood risk reduction in flood prone areas. The effectiveness of dike reinforcements can be compared with the effectiveness of emergency measures to obtain insight in the most cost effective strategy for flood risk reduction.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Bea, R., 2010. *Human & Organizational Factors : Risk Assessment & Management of Engineered Systems Proactive*, California: University of Berkeley.

Boon, M.J.J., 2007. *Water Controlling Water: Emergency flood protections*. TU Delft.

Corn, H. De & Inkabi, K., 2013. Method to Account for Human Intervention in Calculating the Probability of Failure. *Journal of Management in Engineering*, (July), pp.259–268. Available at: http://ascelibrary.org/doi/abs/10.1061/(ASCE)ME.1943-5479.0000143 [Accessed November 20, 2013].

Dijk, M. Van & Plicht, N. Van Der, 2013. *Veiligheid Nederland in Kaart 2: Dijkring gebied 53*, Utrecht.

Dupuits, E.J.C., 2011. *Opkisten van wellen Een onderzoek naar de invloed van noodmaatregelen op*, Delft.

Ellenrieder, T. & Maier, A., 2014. Floods in central Europe. *Topics Geo: Natural catastrophes 2013*, pp.17–23.

Van Gerven, K.A.J., 2004. *Dijkdoorbraken in Nederland: ontstaan, oorzaak en voorkomen*. TU Delft.

Joore, I.A.M., 2004. *Noodsluiting van een dijkdoorbraak bij hoogwater Noodsluiting van een dijkdoorbraak bij hoogwater*. TU Delft.

Krahn, T. et al., 2007. Large-scale interface shear testing of sandbag dyke materials. *Geosynthetics International*, 14(2), pp.119–126. Available at: http://www.icevirtuallibrary.com/content/article/10.1680/gein.2007.14.2.119 [Accessed October 9, 2013].

Leeuw, S., Vis, I. & Jonkman, S., 2012. Exploring Logistics Aspects of Flood Emergency Measures. *Journal of Contingencies and …*, 20(3). Available at: http://onlinelibrary.wiley.com/doi/10.1111/j.1468-5973.2012.00667.x/full [Accessed November 20, 2013].

Rasmussen, J., 1982. Human errors. A taxonomy for describing human malfunction in industrial installations. *Journal of occupational accidents*, 4, pp.311–333. Available at: http://www.sciencedirect.com/science/article/pii/0376634982900414 [Accessed November 20, 2013].

Rasmussen, J., 1983. Skills, Rules, and Knowledge; Signals, Signs and Symbols, and Other Distinctions in Human Performance Models. In IEEE, pp. 257–266.

Schweckendiek, T., Vrouwenvelder, a. C.W.M. & Calle, E.O.F., 2014. Updating piping reliability with field performance observations. *Structural Safety*, 47, pp.13–23. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0167473013000799 [Accessed January 10, 2014].

VNK, 2005. *Veiligheid Nederland in Kaart Hoofdrapport onderzoek overstromingsrisico ' s*, The Hague.

WGS, 2012. Hoogwaterklapper noodmaatregelen WGS, Zwolle.