Geotechnical Safety and Risk V
T. Schweckendiek et al. (Eds.)

doi:10.3233/978-1-61499-580-7-528

Application of Fragility Curves in Operational Flood Risk Assessment

K. WOJCIECHOWSKA, G. PLEIJTER, M. ZETHOF, F.J. HAVINGA, D.H. VAN HAAREN, W.L.A. TER HORST
HKV Consultants, the Netherlands

Abstract. The aim of this article is to present and discuss fragility curves that were derived for numerous dikes in the Netherlands within the Dike Data Service Centre (DDSC) initiative. A fragility curve of a dike is a mapping from the set of loads, acting on the dike, to the set of conditional dike failure probabilities. The DDSC is a platform around a database for measurements related to water defences in the Netherlands. The measurements include real-time and historical data such as height measurements, pore water pressures, temperature etc. Besides the database functionality, the DDSC can be applied to interpret the information and issue warnings. The fragility curves were derived for failure mechanisms overtopping, piping and macro-stability as well as for combination of these mechanisms. Also, application of the fragility curves is addressed. The application includes: (i) insight into the effect of reducing uncertainties in subsoil-related parameters on the dike's reliability, (ii) derivation of the actual flooding probability and the actual local mortality risk, and (iii) prioritization of emergency flood measures. The derived fragility curves are conform findings of past studies: for water levels lower than the dike height, piping and macro-stability play an important role. Furthermore, the fragility curves prove to have an added value in operational flood risk assessment.

Keywords. fragility curves, dikes, reliability assessment, flood risk

1. Introduction

In the Netherlands, the Dike Data Service Centre (DDSC) is a platform for storage and use of real-time and historical data/measurements related to dikes (www.ddsc.nl/en/). The measurements include e.g. height measurements, pore water pressures, temperature and are obtained with electronic dike sensors embedded in several dikes across the country. The DDSC facilitates interpretation of the data/measurements and can be used to issue warnings when measurements exceed predefined values. For the purpose of the DDSC, fragility curves were derived for more than 400 dike sections in 2014.

A fragility curve of a dike is a mapping from the set of loads, acting on the dike, to the set of conditional dike failure probabilities. The concept is well known in the literature (van der Meer et al., 2008; Vorogushyn et al., 2009; Bachmann et al., 2013).

In this article, the derived fragility curves are presented and discussed. Also, application examples of the curves in operational flood risk assessment are given, such as: (i) insight into the effect of reducing uncertainties in subsoil-related parameters on the dike's reliability, (ii) derivation of the actual flooding probability and the actual local mortality risk, and (iii) prioritization of emergency flood measures.

2. Fragility curves of dikes

2.1. Definition

A dike fails due to one or more dike failure mechanisms occurring (Vrijling, 2001). Examples of such mechanisms are overflow, overtopping, piping and macro-stability. Overflow occurs when the water level at the dike exceeds the dike's height. In case of overtopping, additionally waves contribute to the failure. If this persists sufficiently long, both mechanisms can lead to erosion of the inner dike slope and successive dike breach. Piping is a creation of open pipes under a dike resulting from erosion induced by seepage flow through the dike's foundation. The pipes can undermine the dike leading to its collapse. Occurring of mechanisms uplift and heave is a precondition for piping when the dike is founded on a low-permeable blanket layer. Macro-stability occurs when a massive part of a dike slides as a consequence of insufficient shear strength of the soil.

A dike failure mechanism is usually described by a limit state function Z, in which the load at the dike (S) and the dike's strength (R) are compared, typically $Z = R\text{-}S$ (Steenbergen et al., 2004). A dike fails due to a failure mechanism, when the load exceeds the strength and hence when the corresponding limit state function is less than 0. Since R and S are often functions of many variables, we write Z as $Z(X_1,\ldots,X_n)$.

Note that the vector $(X_1,\ldots,X_n)$ contains random load and strength variables, and that the failure probability of a dike is:

$$P\{Z(X_1,\ldots,X_n) < 0\} \quad (1)$$

Using the law of total probability, Eq. (1) can be written as:

$$\int P\{Z(X_1,\ldots,X_n) < 0 \mid X_i = x_i\} \cdot f(x_i)dx_i \quad (2)$$

where $f(x_i)$ is the probability density function of variable X_i. Note that the inner probability in Eq. (2) is the conditional dike failure probability. We denote this probability as $P_f(x_i)$.

A fragility curve of a dike is a mapping from the set of loads, acting on the dike, to the set of conditional dike failure probabilities. In this study, assuming X_i is a load variable, a fragility curve of a dike is:

$$x_i \rightarrow P_f(x_i) \quad (3)$$

In applications, X_i is often a water level at the dike or a river discharge (that determines the water level).

A fragility curve of a dike is characterized by the following properties:

- Values of the function are bounded by 0 and 1.
- The function is non-decreasing, because increase in the conditioning load (X_i) leads at most to decrease in the dike's reliability.
- Gradient of the function informs about the degree of uncertainty imposed by variables other than the conditioning load.

The fragility curve in Eq. (3) is a function of one variable. In theory, a fragility curve can be a function of all present load variables. Derivation of such fragility curve/plane is however difficult in practice as an analyst is often limited by the available tools (software). Moreover, in Eq. (3) one limit state function (one failure mechanism) is considered. A fragility curve, in which different failure mechanisms are combined can be as follows:

$$x_i \rightarrow P\{Z_o < 0 \cup Z_p < 0 \mid X_i = x_i\} \quad (4)$$

In this case, Z_o and Z_p are limit state functions corresponding respectively to overtopping and piping.

2.2. Derivation approach

In this study, fragility curves of numerous dikes in the Netherlands are derived with PC-Ring, which is a computer program that computes annual dike failure probabilities for different failure mechanisms and for combination of the mechanisms, see (Steenbergen et al., 2004) for more information. In PC-Ring, the spatial variability of dikes (i.e. correlations) in the longitudinal direction is taken into account. The implemented computational techniques comprise level II (e.g. FORM) and level III (e.g. Numerical Integration). PC-Ring was applied in the national flood risk analysis accomplished in 2014 (Jongejan et al., 2012).

Adjustment of input files/parameters in PC-Ring allows for derivation of fragility curves of dikes, because the program 'as it is' cannot compute the curves. In relation to this, the following lessons learned emerge:

- It is necessary to choose the time interval for the probabilities $P_f(x_i)$. The interval of 12 hours is suitable for operational flood risk assessment.
- Since a workaround is applied to compute the fragility curves, it is necessary to check whether the annual failure probabilities derived directly with PC-Ring agree with the annual

failure probabilities derived using the fragility curves (as given by Eq. (2)).

- Adjustment of the code of PC-Ring is required, if fragility curves of dikes in complicated water systems (e.g. the sea) need to be derived.

2.3. Examples

In the Netherlands, a dike-ring is a closed system of primary water defences and high grounds. Dikes, dunes and hydraulic structures constitute primary water defences when they protect the hinterland from large rivers/lakes and the sea. An area protected by a dike-ring is called a dike-ring area.

In this study, fragility curves are derived for dikes in dike-rings 6, 10, 43 and 48. These dike-rings are chosen due to the past and ongoing projects such as Flood Control 2015, LiveDijk, HWBP-2, and due to availability of data. Figure 1 and Table 1 give information about these dike-rings.

Figure 1. Selected dike-rings in the Netherlands.

Table 1. Information about the selected dike-rings (* dikes must withstand loads related to the standards, ** a dike segment coherent with respect to load and strength)

Dike-ring	Length of dikes [km]	Safety standard* [1/year]	Dike sections** [#]
6	230.6	1/4,000	185
10	47.7	1/2,000	55
43	169.9	1/1,250	156
48	51.1	1/1,250	52

Except for dikes in dike-ring 6, the fragility curves are computed with PC-Ring (assuming the time interval of 12 hours). The curves are derived for overtopping, piping (the Sellmeijer model) and macro-stability (the Bishop or the Lift Van model), and for combination of these mechanisms. For dikes in dike-ring 6, which is situated in a complicated water system, a separate computer program has been developed. The program computes the fragility curves for piping using Monte Carlo simulation. The spatial variability of dikes is however not included.

Information about the dikes (e.g. geometry, soil profiles and parameters) comes from the national flood risk analysis (Jongejan et al., 2012) and the water level is the conditioning load.

As an example, Figures 2 and 3 present fragility curves of two dikes in dike-ring 10. In Figure 3, when the water level at the dike is NAP+3 m (NAP is a reference level in the Netherlands), then the failure probability due to piping is 0.51. By definition, the combined failure probability is higher and equals to 0.82 in this case.

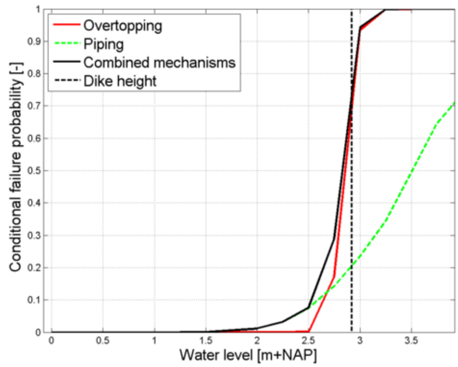

Figure 2. Fragility curves of a dike section in dike-ring 10 (macro-stability is not relevant for this dike section).

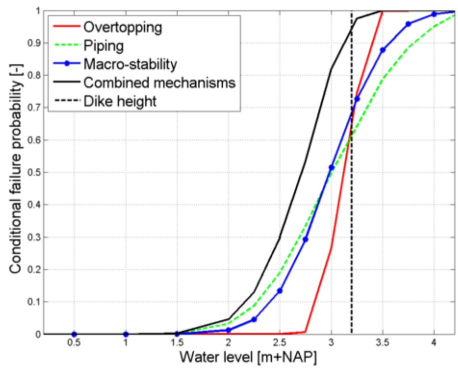

Figure 3. Fragility curves of a dike section in dike-ring 10.

Based on the results, it can be concluded that piping and macro-stability can be dominant for water levels (much) lower than the dike's height. For these mechanisms, the dike's safety strongly depends on variables such as seepage length, polder water level (piping), cohesion and internal friction of the soil, pore water pressures (macro-stability). For water levels in the vicinity of the dike's height, overtopping plays an important role. The related probabilities, however, are not necessary equal to 1 when the water levels exceed the dike. This is caused by uncertainty introduced by variables other than the conditioning load. The presented findings are consistent with results of previous studies (van der Meer et al., 2008).

3. Application of fragility curves

3.1. Effect of reducing uncertainties

Fragility curves can be used to analyse the effect of reducing uncertainties in subsoil-related parameters on the dike's reliability. Within the DDSC, this can be done using measurements instead of model estimates/results.

In this study, this application is presented for dike-ring 6 and piping mechanism. It is assumed that uncertainties in the permeability of the sand layer under the dike (k) and the damping factor (λ) (both important in the Sellmeijer model) are reduced due to measurements. The reduction is expressed as decrease in standard deviations of both random variables.

Figure 4 gives fragility curves of a dike section in dike-ring 6 for two cases: reference (no measurements) and 50% reduced standard deviations of k and λ. Note that the gradient of the fragility curve with the reduced uncertainty is higher than the gradient of the reference fragility curve. This is conform expectations. As a remark, in practice, measurements may lead to decrease in the mean values of variables (and not only to decrease in the standard deviations).

3.2. Actual flooding probability and flood risk

As an extension of the flood risk approach, fragility curves of dikes can be used to determine the actual flooding probability of an area and the actual local mortality risk. In this study, both indicators are derived for dike-ring area 43.

The flooding probability is defined as the failure probability of at least one of dike sections

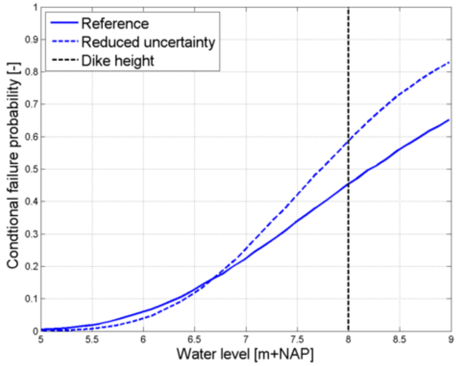

Figure 4. Fragility curves of a dike cross-section in dike-ring 6 with and without measurements (one subsoil scenario).

in a dike system. For a system consisting of two dike sections, the flooding probability in a simple form is:

$$P_{flood} = P(Z_1 < 0 \cup Z_2 < 0) = \\ P(Z_1 < 0) + P(Z_2 < 0) - P(Z_1 < 0 \cap Z_2 < 0) \quad (5)$$

where Z_1 and Z_2 are limit state functions corresponding to the two dike sections.

In this study, the flooding probability of dike-ring area 43 is determined for different values of the Rhine discharge measured at the upstream location Lobith. Relations between the discharge at Lobith and water levels at dikes in dike-ring 43 are known (the so-called *QH*-relations). Given discharge at Lobith, the corresponding water levels are found with the *QH*-relations and next the conditional failure probabilities of the dikes (all mechanisms) are derived with the fragility curves. Assuming the individual dike sections fail independently (which is a simplification), these dike failure probabilities are combined into the conditional flooding probability of the area.

The local mortality risk (LMR) is the risk of dying at a particular location as a consequence of flooding and it is generally defined as:

$$LMR = P_{flood} \cdot P_M \quad (6)$$

where P_{flood} is the (actual) flooding probability and P_M is the mortality [%] without possible evacuation. The mortality depends on a flood pattern (water depth, flow velocity and rise rate of water). Jonkman (2007) and Maaskant et al. (2009) give the flood mortality function used in Dutch applications. In this study, the local mortality risk is derived based on the national flood risk analysis (Jongejan et al., 2012).

Figure 5 presents the conditional flooding probabilities of dike-ring area 43 (the discharge at Lobith is translated into the corresponding water level). Given the water level of NAP+17.5 m, the actual flooding probability is 0.27. Figure 6 presents the corresponding LMR-map. Due to the flooding probability and local geography, the risk is higher in the downstream part of the area.

Both indicators can support operational flood risk management (e.g. evacuation process). Furthermore, the indicators can be used for planning and training purposes.

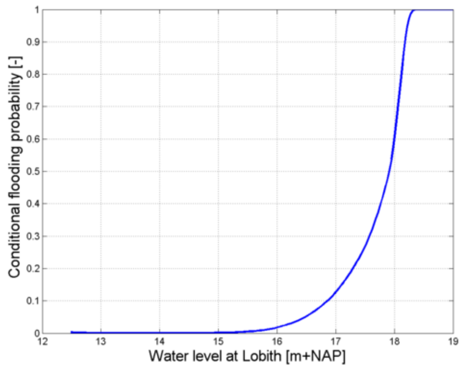

Figure 5. Flooding probability of dike-ring area 43.

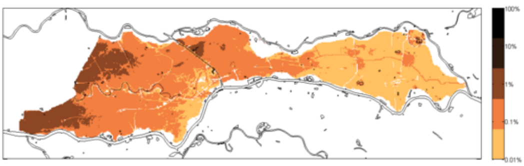

Figure 6. Actual local mortality risk map, dike-ring area 43 (water level at Lobith is NAP+17.5 m).

3.3. Prioritization of emergency measures

Fragility curves of dikes, derived per failure mechanism, can be used to prioritize emergency flood measures such as:

- Placing of sandbags at the crest of the dike: this measure aims to increase the dike's height (influence on overtopping).
- Increase of the polder water level: this measure aims to decrease the seepage flow through the dike (influence on piping).
- Placing of a support berm on the landward side of the dike: this measure aims to increase the shear strength of the soil (influence on macro-stability).

In this study, effect of these measures on the dike failure probability (fragility curves) is assessed for dikes in dike-ring 10. Placing of sandbags has been modelled as an increase of the dike's height (+ 0.5 m). The second measure has been modelled straightforward, because the polder water level is a variable in the limit state function of piping (the increase is also + 0.5 m). To model the placing of a support berm, analysis with the D-Geo Stability has been performed.

Note that this modelling approach entails dike failure probabilities with *successfully* applied measures. In practice, however, factors such as time, experience of the crew, availability of the material or constructive reliability of the measure influence its performance (Jonkman et al., 2012). In other words, there exists a probability > 0 that the measure fails. To take this into account, the following formula is used:

$$P_{f|M}(x_i) = \alpha\left(P_{f|M,0}(x_i)\right) + \beta\left(P_{f|M,1}(x_i)\right) \quad (7)$$

where $P_{f|M}(x_i)$ is the conditional dike failure probability with an emergency measure, $P_{f|M,0}(x_i)$ is the probability without the measure and $P_{f|M,1}(x_i)$ is the probability with successful emergency measure. In addition, functions α and β depend on: probability that the weak spot is not detected (P_D), probability that the measure is not correctly placed (P_P), probability that the measure is not placed in time (P_T) and probability of constructive failure of the measure (P_C). This approach is based on the study of Lendering et al. (2014).

Consider Figure 2 with fragility curves of a dike section in dike-ring 10. Based on this figure, piping is more dominant than overtopping for water levels lower than NAP+2.5 m and hence measures aiming to decrease the piping probability should be taken (e.g. increase of the polder water level is preferable if decision makers perceive the dike failure probability as high). This is an opposite when the water level is higher than NAP+2.5 m and e.g. placing of sandbags is advisable then. Figure 7 presents the dike failure probabilities combined over the mechanisms for three situations: no emergency measures (reference), with sandbags, with increase in the polder water level. To derive these probabilities, Eq. (7) is applied with information from Table 2.

Table 2. Failure probabilities related to emergency flood measures (* average values concluded from (Lendering et al., 2014), ** first-guess estimates)

	Overtopping*	Piping*	Macro-stability**
P_D	0.05	0.29	0.05
P_P	0.05	0.07	0.5
P_T	0.007	0.01	0.5
P_C	0.0	0.0	0.0

Figure 8 presents the combined probabilities corresponding to Figure 3. Notice that the influence of individual measures is small due to the fact that all failure mechanisms are relevant. For this dike, a combination of emergency flood measures can be an interesting option.

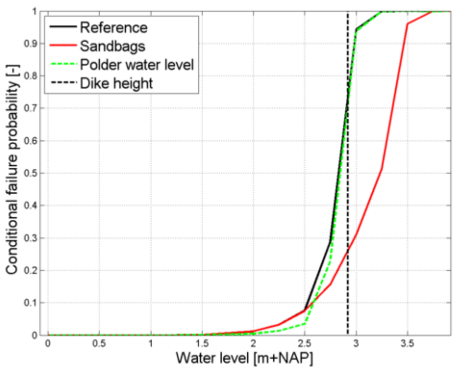

Figure 7. Fragility curves of a dike section in dike-ring 10, effect of measures (combined over failure mechanisms).

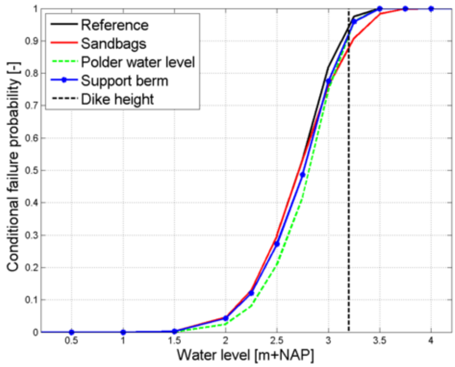

Figure 8. Fragility curves of a dike section in dike-ring 10, effect of measures (combined over failure mechanisms).

4. Conclusions and recommendations

Fragility curves of dikes offer a quick and extensive insight into the dike's reliability, and can be applied in general types of studies.

This article shows that fragility curves have an added value in operational flood risk assessment as the curves can be used to e.g. derive the actual flood risk indicators and to prioritize emergency flood measures.

It is recommended to ease applications of fragility curves by development of corresponding visualisation tools. A graphical presentation will contribute to better understanding of the concept among a wide range of professionals.

References

Bachmann, D., Huber, N.P., Johann, G., Schüttrumpf, H. (2013). Fragility curves in operational dike reliability assessment, *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards* **7** (2013), 49-60.

Jongejan, R., Maaskant, B., ter Horst, W., Havinga, F., Roode, N., Stefess, H. (2012). The VNK2-project: a fully probabilistic risk analysis for all major levee systems in the Netherlands, *IAHS Publ.* 357, 5-85.

Jonkman S.N. (2007). *Loss of life estimation in flood risk assessment. Theory and applications*. Phd thesis, Delft University of Technology.

Jonkman, S.N., Dupuits, E.J.C., Havinga, F. (2012). The effects of flood fighting and emergency measures on the reliability of flood defences, *In Proceedings of Comprehensive Flood Risk Management FLOODrisk 2012*, Klijn & Schweckendiek (eds), Rotterdam, the Netherlands, 19-23 November 2012.

Maaskant B., Jonkman S.N., Kok M. (2009). *Analyse slachtofferaantallen VNK2 en voorstellen voor aanpassingen van slachtofferfuncties*. HKV, technical report in Dutch, January 2009.

Lendering, K.T., Jonkman, S.N., Kok, M. (2014). *Effectiveness and reliability of emergency measures for flood prevention*, TU Delft/STOWA, 2014-02-21.

Steenbergen, H.M.G.M. Lassing, B.L. Vrouwenvelder A.C.W.M. & Waarts P.H. (2004). Reliability analysis of flood defence systems, *Heron,* **49** (2004) 51–73.

van der Meer, J.W., ter Horst, W.L.A., van Velzen, E.H. (2008). Calculation of fragility curves for flood defence assets, *In Flood Risk Management: Research and Practice*, Samuels et al. (eds), 567–573, CRC Press 2008.

Vorogushyn, S., Merz, B., Apel, H. (2009). Development of dike fragility curves for piping and micro-instability breach mechanisms, *Natural Hazards and Earth System Sciences* **9** (2009), 1383-1401.

Vrijling, J.K. (2001). Probabilistic design of water defence systems in the Netherlands, *Reliability Engineering and System Safety*, **74** (2001) 337-344.