# Do all dike instabilities cause flooding?

Van Der Krogt, Mark G.; Schweckendiek, Timo; Kok, Matthijs

**DOI**
10.22725/ICASP13.461

**Publication date**
2019

**Document Version**
Final published version

**Published in**
13th International Conference on Applications of Statistics and Probability in Civil Engineering (ICASP13)

# Do all dike instabilities cause flooding?

Mark G. van der Krogt
*PhD Candidate, Dept. of Hydraulic Engineering, Delft Univ. of Technology, Netherlands*
*Researcher/consultant, unit Geo-Engineering, Deltares, Delft, Netherlands*

Timo Schweckendiek
*Researcher, Dept. of Hydraulic Engineering, Delft Univ. of Technology, Netherlands*
*Researcher/consultant, unit Geo-Engineering, Deltares, Delft, Netherlands*

Matthijs Kok
*Professor of Flood Risk, Dept. of Hydraulic Engineering, Delft Univ. of Technology, Netherlands*

ABSTRACT: One of the failure mechanisms of dikes is slope instability at the landward side. Often, one instability does not lead to flooding, and several successive instabilities are needed before the dike overtops, and erosion and breaching can occur, especially at lower water levels. In this paper we propose a method to estimate the probability of flooding, taking into account the residual resistance against flooding after the first instability. We base ourselves on basic probabilistic techniques and common slope stability analyses and estimate the probability of flooding by calculating the probability of several successive (conditional) instabilities. Because the geotechnical failure and dike failure is not the same for each water level, we evaluate the probability for different water levels. The case example shows that there is a considerable margin between the probability of geotechnical failure and the probability of flooding, especially at relatively low water levels. It also shows that the current practice of assuming that the probability of flooding is equal to the probability of instability is very conservative.

The protection of low-lying land against flooding often relies on the presence and resistance of earthen dikes. One of the failure mechanisms of dikes is slope instability, where a soil mass slides along a slip plane, see Figure 1. However, not all slip planes will remove such a large part of the dike section that this will lead to flooding. Almost certainly not when instability coincides with low water levels, see Figure 2.

The safety standards for dikes in The Netherlands are among others based on an optimization of economic and societal risk of flooding (ENW, 2017). The consequences of flooding include both the cost of damage to the flood defence itself and the cost due to damage (and casualties) in the protected area. Therefore, the safety standards, defined as maximum probability of failure, should be interpreted as probability of flooding.

*Figure 1: Slope instability without flooding.*

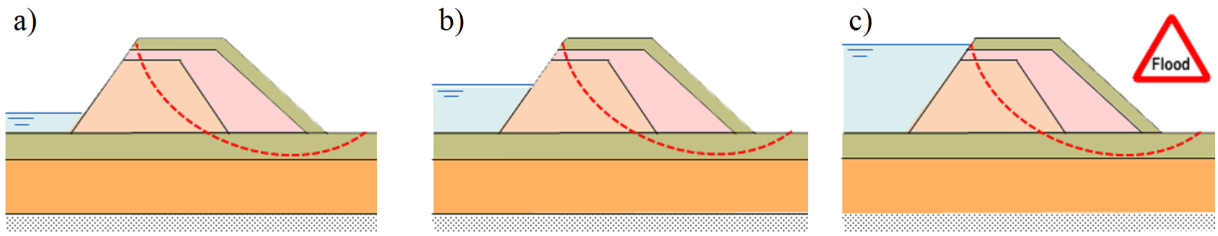


*Figure 2: The first slope instability does not cause flooding at each water level, especially at low water levels (a and b).*

In the current Dutch safety assessments it is, however, common practice to assume that a single slope instability always leads to flooding. Assuming that the probability of flooding is equal to the probability of geotechnical failure is certainly conservative and does not take into account that there can be significant resistance left to protect the hinterland from flooding. For example, the dike height can be sufficient to withstand the high water level and the residual profile can have enough resistance to prevent successive instabilities. At present, we do not consider that significant damage to the dike body (e.g. by retrogressive slope failure) is necessary before a breach occurs which leads to extensive erosion and flooding that eventually lead to the damage as referred to in the safety standards.

Models that describe the full process of flooding due to slope instability require the integration of geotechnical (stability) models with erosion and breach growth models. Such models are complex, because those have to deal with large deformations and complex soil-water interactions. Currently, geotechnical models are being developed to describe this process numerically, using the Material Point Method. Although the Material Point Methods has been demonstrated successfully for slope failure in dikes (e.g. Zabala and Alonso (2011); Wang et al. (2016); Coelho et al. (2018)), the use of such models is not common practice. And, unfortunately, such models are also computationally demanding (Remmerswaal et al., 2018) and hence not very suitable for probabilistic analyses with low probabilities. Therefore, we propose a practical method to incorporate the residual resistance of the dike after slope instability of the landward slope. The method is based on basic probabilistic techniques and common slope stability analyses and can be used to judge about the level of conservatism of the current practice. First we define the correct limit state for flooding. Then we propose a method to incorporate the probability of successive slip planes in the probability of flooding, demonstrate the method with a case study and finally show the impact of this method, compared to the current practice.

## 1. FLOODING IS FAILURE

In this article failure is defined as the state in which the primary function is no longer fulfilled. For dikes, the primary function is to protect the hinterland against flooding. Therefore the probability of failure is defined as the probability of flooding and not as the probability of geotechnical failure. In addition, dikes can have also other important functions such as traffic or recreation, for which geotechnical failure often directly leads to loss of function. These secondary functions, however, do not have to meet such strict safety standards as statutory for flooding, which are in the order of 1/1000 to 1/1 000 000 per year in The Netherlands. We only speak of flooding when the water leads to loss of life and significant economic damage (ENW, 2017). Such damage can only be caused when significant volumes of water flow into the protected area, for example when extreme overtopping occurs or when a breach is formed.

### *1.1. Flooding by retrogressive slope failure*

There are many failure modes for flooding due to instability. In general we can speak of flooding when significant volumes of water can flow into the polder e.g. by a breach in the dike. This is typically the case when instability causes reduction of

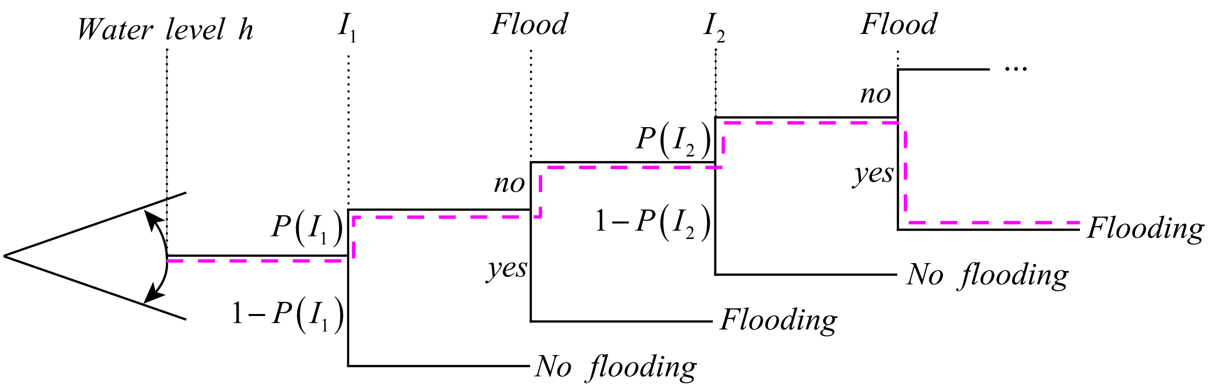


*Figure 3: Event tree for flooding caused by several successive slope instabilities.*

the dike height and hence overtopping, erosion and breaching can occur. A reduction of the crest height can happen by one instability, but also by several successive instabilities. This is shown in the event tree in Figure 3. From the event tree, it follows that the probability of flooding by retrogressive failure is a parallel system (all events must occur), whereas the different failure modes act like a series system.

Figure 4 shows one example of how successive instabilities eventually can lead to flooding. In the example, a breach is only likely to occur after the second instability. So, only when both the first ($I_1$) and the second instability ($I_2$) occur, we can speak of flooding. Notice that the event of the second instability is conditional to the damaged geometry profile after the first instability: $I_2|I_1$. The events that must occur for this specific failure mode are depicted with a pink dashed line in the event tree. Because all event must happen, we can can write the probability of the failure mode in this example as follows:

$$P(F) = P(I_2|I_1 \cap I_1) \qquad (1)$$

More generally, we can write the probability of flooding due to successive instabilities (retrogressive failure) as follows:

$$P(F) = P\left(\bigcap_{i=1}^{n} I_i\right) = P\left(\bigcap_{i=2}^{n} I_i|I_{i-1}\right) \cdot P(I_1) \qquad (2)$$

Where $I_i$ is the event of instability $i$ and $n$ the total number of successive instabilities necessary for flooding. Note that each instability $I_i$ is always conditional to the preceding instability: $I_i|I_{i-1}$.

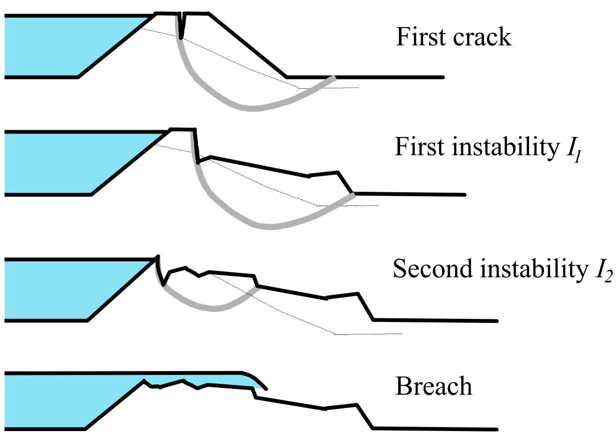


*Figure 4: Process of several successive slope instabilities that lead to flooding.*

### 1.2. *Implementation with slope stability analyses*

In the previous paragraph, we propose to incorporate the probability of retrogressive slope failure in the probability of flooding by approaching it as a chain of conditional events of successive instabilities that all have to happen to cause a flood. In this subsection we demonstrate a practical implementation with common slope stability analysis, such as Limit Equilibrium models Bishop and Spencer. To that end we follow the next step wise plan:

1. Determine the critical slip plane in the original geometry profile. The critical slip plane is the most likely slip plane, i.e. the slip plane with the highest probability of failure. The probability of the first instability is denoted by $P(I_1)$.

2. Assess the damaged geometry profile (based on simple assumptions or rules-of-thumb) af-

ter the first instability. Evaluate if the instability causes a flooding. In order to avoid conservatism, we propose a pragmatic definition for flooding: if the remaining crest level is lower than the outside water level.

3. If the instability causes flooding, then $P(F) = P(I_1)$. Else, take the damaged geometry profile as starting point for a next slope stability calculation and compute the probability of instability of the next critical slip plane, which is conditional to the first instability: $P(I_2|I_1)$.

4. Again, assess the damaged geometry profile after the preceding instability and evaluate if flooding occurs. If this instability causes a flooding, then we calculate the probability of flooding as probability that the first and the next instabilities have occurred: $P(F) = P(I_1 \cap I_2) = P(I_2|I_1) \cdot P(I_1)$. Else, repeat step 4 until the failure criterion is met.

Because failure in this example is dependent on the water level, we need to consider the probability of flooding conditional to the water level. Therefore we write Equation 2 conditional to the water level as:

$$P(F|h) = P\left(\bigcap_{i=1}^{n} I_i|h\right) = P\left(\bigcap_{i=2}^{n} I_i|I_{i-1},h\right) \cdot P(I_1|h) \quad (3)$$

By numerical integration of the conditional failure probability with the probability density of the outside water level, we obtain the probability of flooding:

$$P(F) = \int P(F|h) f(h) dh \quad (4)$$

Note that, although the water level (and therefore the reaction to the phreatic level) is in reality time-dependent, this analysis assumes that the probability density function of the water level refers to steady state conditions at the peak water level of the high water wave. We discuss this further in section 4.

### *1.3. Correlation between slip planes*

The probability of failure of a parallel system (AND-gate) depends on the correlation between the considered events. When all instabilities are mutually dependent, then the probability of the system is determined by the lowest probability of the individual components $P(F) = \min(P(I_i|I_{i-1}))$. In case all instabilities are mutually independent, then the probability of the system is the multiplication: $P(F) = \prod P(I_i|I_{i-1})$.

For successive slope instabilities it is neither expected that two slip planes are fully independent, nor fully dependent. It is a conservative approach to assume that two sliding planes are fully dependent (like in e.g. van Montfoort (2018)). Therefore it is more accurate to base the system probability on the actual correlation between the events, e.g. using the equivalent planes method (see Hohenbichler and Rackwitz (1982); Roscoe et al. (2015)). According to Vrouwenvelder (2006), we can approximate the (linear) correlation coefficient between two sliding planes ($i$ and $j$) based on the FORM influence coefficients $\alpha$ and the auto-correlation $\rho$ for variable $k$, see Equation 5.

$$\rho(I_i, I_j) \approx \sum_{k=1}^{m} \alpha_{i,k} \cdot \alpha_{j,k} \cdot \rho_{ij,k} \quad (5)$$

## 2. CASE STUDY

### *2.1. Case description*

We apply the proposed method to estimate the probability of failure to a simple cross-section of a clay dike on a clay layer. The strength of the dike core above the phreatic level is modelled by a critical state friction angle and the dike core below the phreatic level and the other clay layer with undrained shear strength parameters. The phreatic line is modelled as steady-state response to the water level. The geometry is illustrated in Figure 5 and the material properties in Table 1.

### *2.2. Probabilistic analysis*

In this example we select the critical slip plane based on a deterministic analysis with 5%-characteristic values for the material parameters. The probability of failure (reliability) for this slip plane is calculated using the First Order Reliablity

*Table 1: Probability distributions of the random variables*

| Name | Unit | Description | Distribution | Parameters |
|---|---|---|---|---|
| DikeCore, $S$ | - | Undrained shear strength ratio | Lognormal | $\mu = 0.35$ $\sigma = 0.05$ |
| DikeCore, $m$ | - | Strength increase exponent | Lognormal | $\mu = 0.85$ $\sigma = 0.05$ |
| DikeCore, $\varphi_{cs}$ | $^\circ$ | Critical state friction angle | Lognormal | $\mu = 32.0$ $\sigma = 2.5$ |
| DikeCore, $POP^*$ | kPa | Pre-overburden pressure | Lognormal | $\mu = 15.0$ $\sigma = 4.0$ |
| Clay, $S$ | - | Undrained shear strength ratio | Lognormal | $\mu = 0.30$ $\sigma = 0.02$ |
| Clay, $m$ | - | Strength increase exponent | Lognormal | $\mu = 0.85$ $\sigma = 0.05$ |
| Clay, $POP^*$ | kPa | Pre-overburden pressure | Lognormal | $\mu = 10.0$ $\sigma = 4.0$ |
| Sand, $\varphi_{cs}$ | $^\circ$ | Critical state friction angle | Lognormal | $\mu = 35.0$ $\sigma = 1.5$ |
| $h$ | m+REF | Outside water level | Gumbel | $\mu = 1.6$ $\beta = 0.17$ |
| $m_d$ | - | Model uncertainty | Lognormal | $\mu = 1.005$ $\sigma = 0.033$ |

$^*$) *The POP values are defined at 'daily' conditions, i.e. a phreatic water level of* 0.75m+*REF.*

Method (FORM), conditional to four water levels. By linear interpolation (in $\beta$-space) of these calculated points, we obtain a fragility curve, see Figure 8. The probability of failure is calculated by integrating the conditional probability with the probability density of the water level, according to Equation 4, using a linear interpolation in $\beta$-space between calculated points, see Figure 8. For further reading about the use of fragility curves as approximation method we refer to Schweckendiek et al. (2017). For the first critical slip plane, $P(I_1) = 4.6 \times 10^{-2}$ (reliability index $\beta = 1.7$).

*Table 2: Calculated reliability indices of stability at different water levels for successive instabilities.*

| | Reliability index $\beta$ | | | |
|---|---|---|---|---|
| Water level $h$ | $I_1$ | $I_2^*$ | $I_3^*$ | $I_3 \cap I_2 \cap I_1^*$ |
| 1.0 m+REF | 1.68 | 5.71 | 9.60 | 11.06 |
| 2.0 m+REF | 1.67 | 5.42 | 9.17 | 9.94 |
| 3.0 m+REF | 1.57 | 4.63 | 8.35 | 8.65 |
| 4.0 m+REF | 1.43 | 3.77 | N/A | 3.77 |
| Integrated | 1.69 | | | 5.34 |

$^*$) *Note: the second and third instability is conditional to the preceeding instability, i.e.* $I_2 = I_2|I_1$ *and* $I_3 = I_3|(I_2 \cap I_1)$.

## 2.3. *Retrogressive failure*

Figure 6 shows the critical slip plane in the initial situation. The sliding plane enters in the crest of the dike, but does not lead to a reduction in crest height. Therefore, the failure definition (flooding) is not met for any of the water levels. We schematize the dike geometry after the instability, based on the assumption that the soil wedge subsides half the dike height, see Figure 6. Although this assumption is certainly not perfect, it is a realistic assumption and suits the goal of demonstrating the probabilistic method.

We use the damaged geometry profile after the first instability (Figure 6) as starting point for the next probabilistic slope stability analysis. In reality, it is possible that the soil properties at the slip surface or in the disturbed part will change to certain degree, however for the purpose of illustration of the probabilistic method we assume that the critical state strength is not altered.

The next critical slip plane enters the dike body at a level around 3.5m+REF and causes a reduction in dike height, see Figure 7. This slip plane will therefore lead to flooding for water levels higher than the remaining dike height. However, for water levels lower than approximately 3.5m+REF, flooding will not yet occur and successive slidings are required before flooding occurs.

The damaged geometry profile after the second instability (see Figure 7) is used for the next slope stability calculations. Only analyses are made for water levels lower than the remaining crest height. The third of the successive instabilities also leads to a crest height reduction and therefore flooding for water levels above 3.0m+REF. The results of the probabilistic stability analyses $I_1$, $I_2|I_1$ and $I_3|I_2$ are shown in Table 2.

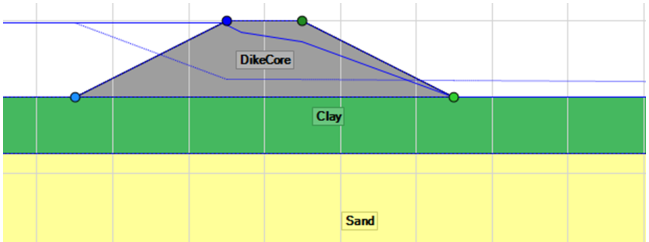


*Figure 5: Slope geometry with clay dike ('DikeCore') on a clay blanket ('Clay') on top of an aquifer ('Sand'). The head in the aquifer is different from the phreatic level and indicated with the dotted blue line.*

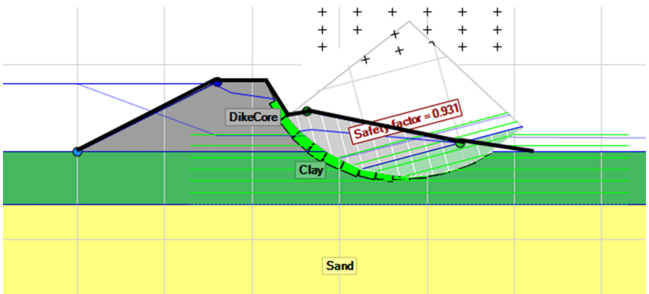


*Figure 6: Critical slip plane in the initial situation. The damaged geometry profile after $I_1$ (black line) is schematized based on rough assumptions.*

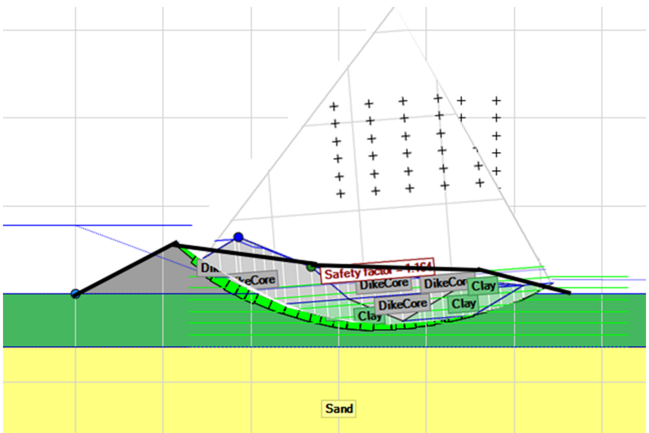


*Figure 7: Critical slip plane after the first instability ($I_2|I_1$). The damaged geometry profile after $I_2$ (black line) is schematized based on rough assumptions.*

## 2.4. *Combination of successive instabilities*

The probability of flooding conditional to the water level $P(F|h)$ is calculated by combining the probabilities of the individual instabilities per water level $P(I_i|h)$, as in Equation 2, accounting for the actual correlation between the slip planes, using the Equivalent Planes method. The result is shown in Figure 8 with markers. The dashed lines indicate the upper and lower bounds for the system failure probability; fully dependent or fully independent successive instabilities, respectively.

We combine the probability of flooding conditional to the water level with the probability density of the water level, according to Equation 4 and obtain the probability of flooding by retrogressive failure: $P(F) = 4.6 \times 10^{-8}$ ($\beta = 5.3$).

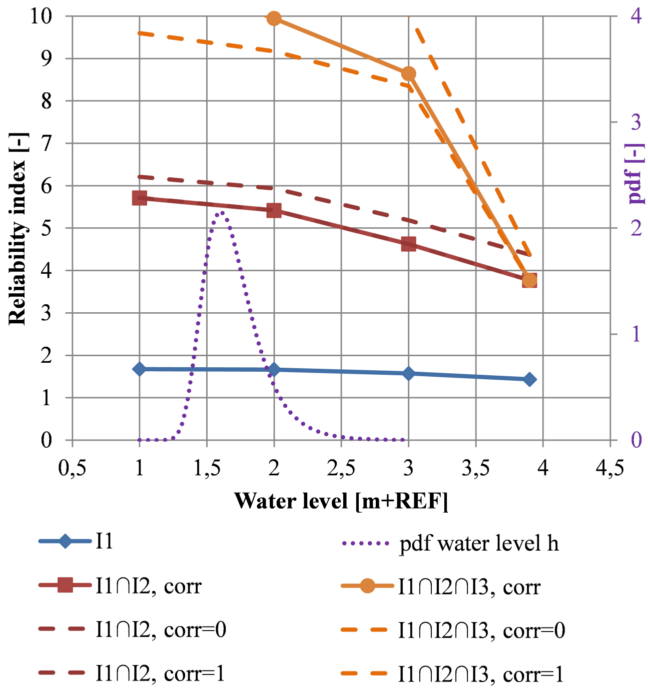


*Figure 8: Reliability indices, conditional to the water level. Results for the initial instability $I_1$ and combined probability for successive instabilities $I_2$ and $I_3$.*

## 2.5. *Instability that directly leads to flooding*

As indicated in the event tree (Figure 3), we must also look at a failure mode where the first instability directly leads to flooding. For the example considered, this is calculated by setting a constraint to the location where the slip plane enters the dike. The reliability against instability is respectively 8.8, 4.3 and 2.0 for slip circles that would lead to overflow at respectively 2.0, 3.0 and 4.0 m+REF. Weighted with the probability density of the outside water level, results $P(F) = 2.4 \times 10^{-7}$ ($\beta = 5.03$).

For the considered example, a large slip plane that leads directly to failure of the flood defence, has a larger probability of failure than retrogressive slope failure. An explanation can be that the slide mass has a positive effect on the successive instabilities, see Figures 6 and 7. Obviously, this is not always the case and dependent on the shape of the slide mass. Both failure modes (flooding by one instability or retrogressive failure) are largely correlated, so the failure probability of the 'series system' is close to the maximum of the two: $P(F) = 2.4 \times 10^{-7}$.

## 3. PRACTICAL IMPLICATIONS

It is clear that the probability of multiple successive instabilities is much lower than the probability of instability of the first critical slip plane. Especially for low water levels, there is significant difference between the probability of flooding and the probability of geotechnical failure. The impact on the total probability of flooding (integrated over the water level) is also significant, because (1) the probability is dominated by geotechnical uncertainty and not the water level and (2) most of the probability density of the water levels is at relatively low water levels. In the example considered, the probability of flooding by the first instability governs the failure probability. However, it is not to be expected that this will be always the case, so assessing the 'large instability' only is not always safe.

## 4. DISCUSSION

In the current example we did not consider extraneous effects that can influence the residual resistance after an instability. An example is that the first instability can lead to damage to pipelines, which are often located in the dike. This damage can result in gas explosions or leakage of water pipes, which can cause additional damage to the dike or increase the phreatic levels. We also disregarded the effect that more water can infiltrate when an impermeable cover layer slides off after an instability. If such 'second-order' effects are important, these can be implemented in the conditions for the subsequent stability analysis.

In the current method, we only looked at one combination of successive slip planes, however other combinations of slip planes can result in different failure probabilities. It is recommended to investigate how relevant these limitations are for practical use of the method, for instance by probabilistic modelling of retrogressive slope failure using the Material Point Method.

In the analyses we assumed steady state conditions at the peak water level for the water level. However, the peak water level is not necessarily the most critical situation for slope stability. For instance if a slope instability occurs before or after the peak of the water level, a flooding can be more, or less likely. In addition, including the time that is necessary for the successive instabilities to occur, may reduce the probability of flooding conditional to the instability. This could be implemented in the proposed method by replacing 'no' and 'yes' in the event tree (Figure 3) by a probability/likelihood of flooding, conditional to the preceding instability. We expect this to be particularly impact when the load is a relatively short flood wave.

## 5. CONCLUSION

The statutory safety standards for primary flood defences in the Netherlands are defined as maximum probability of flooding. Not every instability of the landward slope leads to flooding at every water level, which is why we need to look to instabilities that lead to flooding. In addition to large instabilities which lead to flooding directly, a flood can also result from multiple successive instabilities.

This article proposes a practical method to assess the probability of flooding by this retrogressive slope failure, based on basic probabilistic techniques and common slope stability analyses. The case study shows that there is a considerable margin between the probability of instability (geotechnical failure) and the probability of flooding, especially at relatively low water levels.

In the example, the probability of a single instability that directly leads to flooding governs the probability of flooding, although the probability is very close to the probability that retrogressive failure leads to a flood. The reliability indices $\beta$ are respectively 5.0 and 5.3. Since the failure probabilities are so close to each other, it is not to be expected that assessing the 'large instability only' is a conservative approach, since there are likely cases where retrogressive slope failure is the governing failure mode. The advanced method proposed in this paper can be used when as tailored safety assessment of dikes.

## 6. ACKNOWLEDGEMENTS

This work is part of the research programme All-Risk with project number P15-21, which is (partly) financed by NWO Domain Applied and Engineering Sciences. Deltares is also gratefully acknowledged for supporting this research.

## 7. REFERENCES

Coelho, B., Rohe, A., Aboufirass, A., Nuttall, J. D., and Bolognin, M. (2018). "Assessment of dike safety within the framework of large deformation analysis with the material point method." *Prooceedings of NUMGE2018*.

ENW (2017). *Fundamentals of flood protection*. Ministerie van Infrastructuur en Milieu.

Hohenbichler, M. and Rackwitz, R. (1982). "First-order concepts in system reliability." *Structural Safety*, 1(3), 177–188.

Remmerswaal, G., Hicks, M. A., and Vardon, P. J. (2018). "Ultimate limit state assessment of dyke reliability using the random material point method.." *Book of extended abstracts 4th international symposium on computational geomechanics*, Assisi, 89–90.

Roscoe, K., Diermanse, F., and Vrouwenvelder, T. (2015). "System reliability with correlated components: Accuracy of the Equivalent Planes method." *Structural Safety*, 57, 53–64.

Schweckendiek, T., van der Krogt, M., Teixeira, A., Kanning, W., Brinkman, R., and Rippi, K. (2017). "Reliability updating with survival information for dike slope stability using fragility curves." *Geo-Risk 2017*, American Society of Civil Engineers (June).

van Montfoort, M. (2018). "Safety assessment method for macro-stability of dikes with high foreshores." MS thesis, Delft University of Technology, Delft University of Technology (January).

Vrouwenvelder, A. C. M. W. (2006). "Spatial effects in reliability analysis of flood protection systems." *Second IFED Forum*, Lake Louise, Canada.

Wang, B., Hicks, M. A., and Vardon, P. J. (2016). "Slope failure analysis using the random material point method." *Géotechnique Letters*, 6(2), 113–118.

Zabala, F. and Alonso, E. E. (2011). "Progressive failure of Aznalcóllar dam using the material point method." *Géotechnique*, 61(9), 795–808.