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Integral Failure Analysis of Pipelines in Flood Defenses

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Abstract: The presence of pipelines in flood defenses presents a challenge for assessing the probability of flooding. To prevent costly structural measures compensating for the possible negative effects of pipeline failure, we developed a framework for an integral failure analysis of pipeline and dike failure. The assessment framework is based on an event tree with several scenarios or paths resulting in failure of the flood defense and subsequent flooding of the hinterland. The event tree allows us to combine the probability and consequences of pipeline failure with the failure mechanisms of the flood defense and the possibility of detecting and repairing the damage before a flood or other hydraulic loading. The framework has proven to be effective in preventing costly structural measures for a pipeline in the crest of a dike in Amsterdam.

Keywords: Dikes; flood protection; pipelines; failure analysis; slope stability.

1 Introduction

In the Netherlands, the legally established safety requirements for dikes and other flood defenses are defined as acceptable probabilities of failure per dike segment (i.e. reaches with lengths of typically tens of kilometers). Accounting for the length-effect and the presence of several potential failure modes, such as overtopping, internal erosion or slope instability, we can define target probabilities of failure for specific locations and specific failure modes in order to assess these individually (Schweckendiek et al. 2012). The presence of pipelines, either parallel to or crossing dikes, is not uncommon and presents a particular challenge for assessing the reliability of existing flood defenses. In the Dutch situation the relevant codes of practice (NEN 2012a; NEN 2012b) require costly structural measures such as erosion and stability screens (e.g. sheet pile walls or cofferdams) for newly constructed flood defenses with pipelines in their zone of influence. For existing structures, the codes allow for dedicated risk or reliability assessments in order to determine if additional measures are necessary. This paper describes a framework to carry out such assessments, taking into account the failure modes and effects of pipeline and dike failure at the same time. Subsequent to describing the framework, we provide an example of a recently assessed pipeline in the crest of a dike in Amsterdam, see Figure 1.

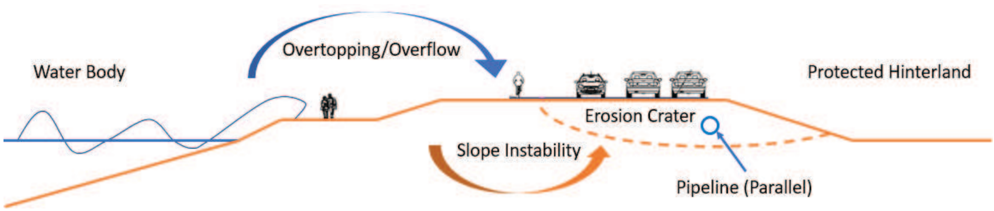

Figure 1. Schematic cross-section of the dike protecting an island in Amsterdam. The dike contains a parallel pipeline in the crest. The main failure modes are overtopping/overflow and slope instability. Also erosion craters as a consequence of pipeline failure can lead directly to failure in flood situations.

2 Assessment Framework

The assessment framework is based on an event tree with several scenarios or paths resulting in the failure of the flood defense and subsequent flooding of the hinterland. In a general sense, the event tree as depicted in generic form in Figure 2 allows us to combine the probability and consequences of pipeline failure with the failure mechanisms of the flood defense, taking into account the possibility of detecting and repairing the damage before a flood or other hydraulic loading. Separate event trees are constructed for the different failure mechanisms of the dike, while the results are compared with the corresponding target probabilities of failure. In this article the assessment for the failure mechanism *slope stability on the water side* is presented to showcase our framework, since this is the governing failure mechanism in the considered case study.

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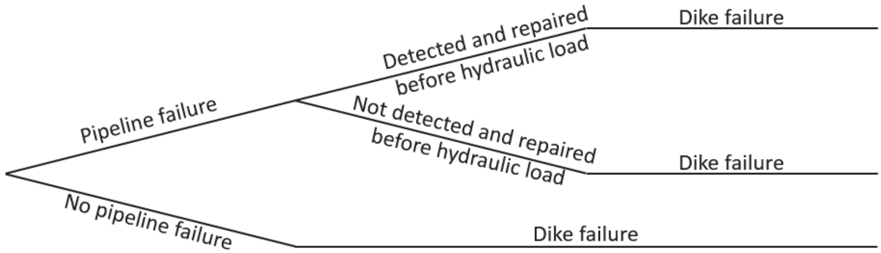

Figure 2. Generic event tree showing consecutive events leading to flooding.

2.1 Pipeline failure

At the first bifurcation in the event tree the probability of failure of the pipeline is required. Furthermore, we distinguish between the different consequences of pipeline failure. The different consequences distinguished are an increase of the pore water pressures in the soil in case of minor leaks and erosion craters in case of major leaks with high leak discharges and subsequent erosion of the surrounding soil. The probability of failure of the pipeline for our example was based on literature (NEN 2003) providing the yearly probability of failure per meter pipeline. A subdivision between large holes (*major leak*) and small holes (*minor leak*) is adopted from (RIVM 2017), where 75% of the pipeline failures are minor leaks and 25% major leaks. The failure probabilities per meter length are subsequently multiplied with the present length of the pipeline, 270 meters, with the assumption that at each location pipeline failure will influence the reliability of the dike. The resulting annual probabilities of failure are presented in Table 1.

Table 1. Annual failure probability for the considered pipeline.

Failure mode	Per meter	Entire pipeline (270 m)
Total pipeline failure	2.6E-04	7.0E-02
Major pipeline failure	6.5E-05	1.7E-02
Minor pipeline failure	1.9E-04	5.2E-02

Note that where more data is available, the probability of pipeline failure in general, and more specifically for different types of leaks, can be obtained by incident statistics in large databases (e.g. databases of the *European Gas Pipeline Incident Data Group* and *The Oil Companies International Study Group for Conservation of Clean Air and Water in Europe*), conditioning on the type of pipeline and the environmental conditions. An example of such an approach is reported in the follow-up study Deltares (2019) considering a fluid pipeline crossing a river dike.

2.2 Probability of hydraulic load during non-repaired damage

Pipeline failure itself does not lead to a decrease of the reliability of the dike if it does not coincide with hydraulic loading. The statistics of the hydraulic loads are expressed as yearly exceedance probabilities of a certain water level, water level drop or overtopping rate. The probability of co-occurrence depends on the repair time and the duration of the hydraulic load. The probability of co-occurrence of the yearly hydraulic load and the pipeline damage is calculated with Eq. (1).

$$\mathrm{P_{co-occurence}} = \frac{\text{duration of hydraulic load in days} + \text{detect and repair time pipeline damage in days}}{\text{365 days}} \tag{1}$$

The representative hydraulic loading situation for *slope stability on the water side* is an extreme water level drop, as explained in paragraph 2.4. The yearly maximum water level drop has a typical duration of 3 days. Three days after the outside water level drop, the water pressures in the dike are released as well. The detect and repair time is assumed to be 15 days for a major leak (expert estimate by the relevant water authority). The probability of co-occurrence is included in Table 2.

Table 2. Probability of an extreme water level drop during non-repaired damage for a major leak.

Duration of hydraulic load (days)	Repair time pipeline damage (days)	Probability of hydraulic load during non-repaired damage (/leak)
3	15	0.05

As a conservative assumption, a minor leak is assumed to not be detected within a year. The probability of hydraulic load during non-repaired damage is thus 1.0.

2.3 Erosion crater

Major leaks result in erosion craters. The size of erosion craters is calculated according to the empirical models from relevant codes of practice (NEN 2012a; NEN 2012b). The empirical coefficient in the equation is regarded as a stochastic variable to reflect the model uncertainty.

The larger the erosion crater, the lower the conditional reliability of the dike. Beyond a certain size the crater is so large that no additional dike failure mechanism is necessary to lead to flooding (*direct dike failure*). We define the dike as failed if the minimum required dike profile is damaged. Any residual strength is not taken into account. In Figure 3 the probability density function of the erosion crater is given, including the dimensions of the minimum required dike profile.

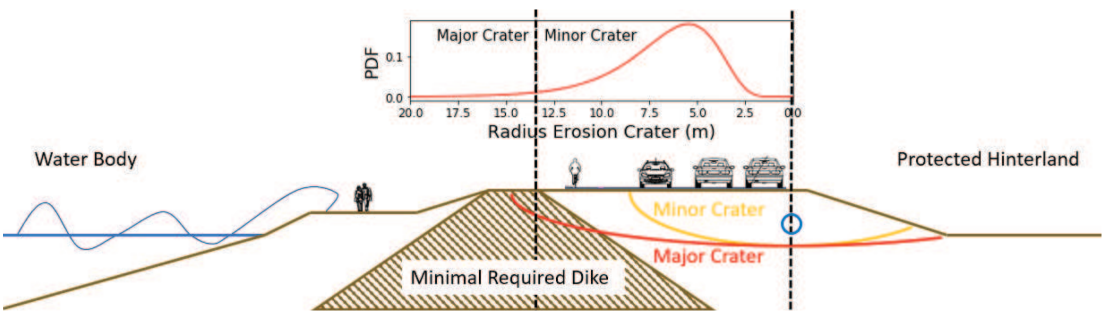

Figure 3. The probability density of the erosion crater size. Given a major erosion crater the dike is defined as failed since the minimum required dike profile is damaged.

The contribution of *direct dike failure* has to be accounted for in only one of the event trees. As a pragmatic choice this contribution is accounted for in event tree of overtopping/overflow. In the event tree for slope stability on the water side only major leaks with minor craters and minor leaks with increased pore water pressures are relevant.

2.3 Dike failure

The dominant failure mode in case of the Amsterdam flood defense is *slope stability on the water side*. The assessment and results of this failure mode are included in this article. For the other failure modes, we refer to Deltares (2018b). Slope stability on the waterside occurs when high water pressures in the dike are combined with a low counter-pressure from the outside water level. In the water body bordering Amsterdam this is especially the case when strong southwesterly storms cause a sudden drop of the outside water level. This failure mode is shown schematically in Figure 4a. Both a minor leak with increasing pore water pressures and an erosion crater resulting from a major leak can negatively influence the reliability of the dike, as illustrated schematically in Figure 4b and 4c.

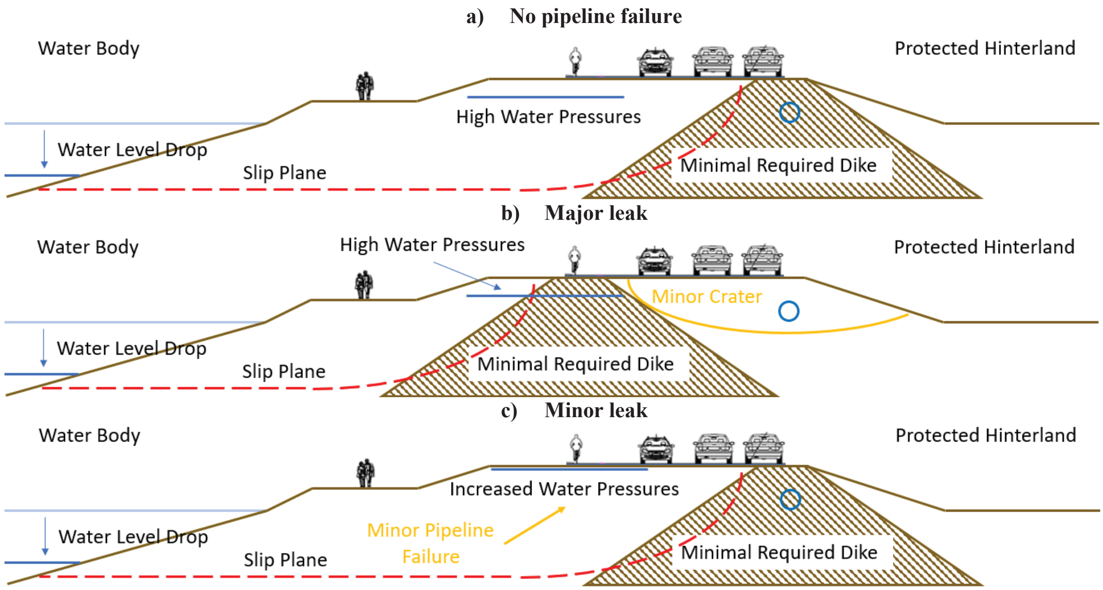

Figure 4. Slope instability on the water side occurs when high water pressures in the dike are combined with a low outside water level (a). If co-occurring with a major leak, smaller slip planes will now cause dike failure because of the presence of the erosion crater (b). If co-occurring with a minor leak, the water pressures in the dike increase even further (c).

3 Results

The conditional probability of failure of the dike was calculated for different combinations of erosion craters sizes and water level drops. An example of a slip plane is given in Figure 5. We assemble these conditional probabilities in a fragility curve, presented in Figure 6. The reliability decreases for increasing crater dimensions and for decreasing water level (i.e. increasing water level drops).

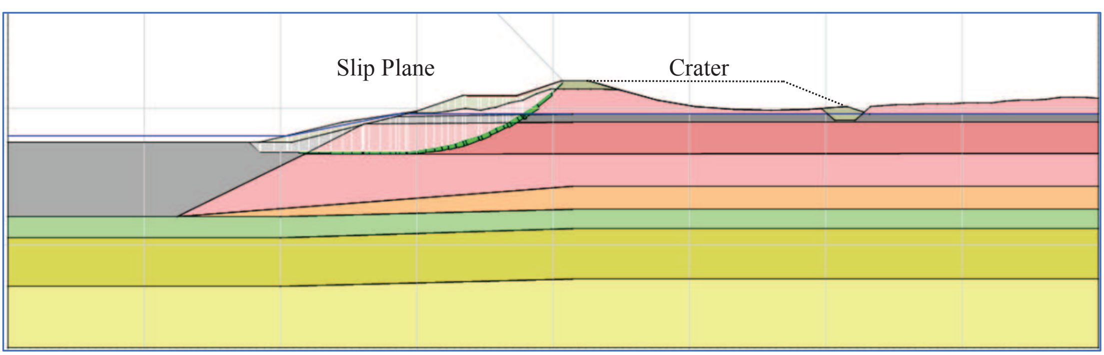

Figure 5. Example of a sliding plane for water-side slope failure.

Integrating the product of the fragility curve and the joint probability density function of the conditioning hydraulic loads and erosion crater dimensions provides the probability of failure for the scenarios with major pipeline failure.

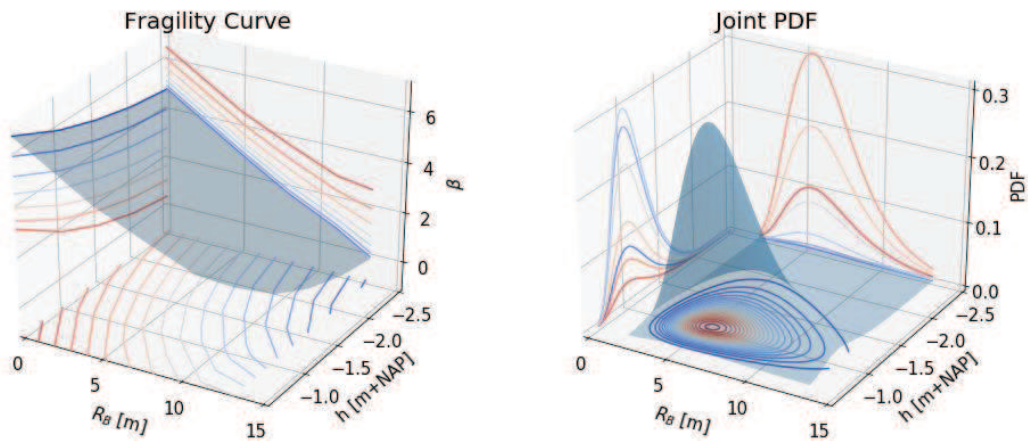

Figure 6. Left the fragility curve showing the conditional reliability (β) of the dike given the water level (h) relative to the datum (NAP) and the erosion crater dimension (R_B). Right the joint probability density function of the erosion crater size and water level. Integration of the two provides the overall probability of failure given a major leak.

We repeat this procedure for all the other scenarios presented in Figure 4 and combined with the probability of failure of the pipeline and the probability of a hydraulic load during non-repaired damage of the pipeline in order to calculate the probability of failure per failure mode. They are presented in the event tree in Figure 7. The event tree also shows the contribution of the different failure paths to the overall dike failure probability due to slope instability on the water side. This distribution is uneven and dominated by the failure due to minor leaks and major leaks.

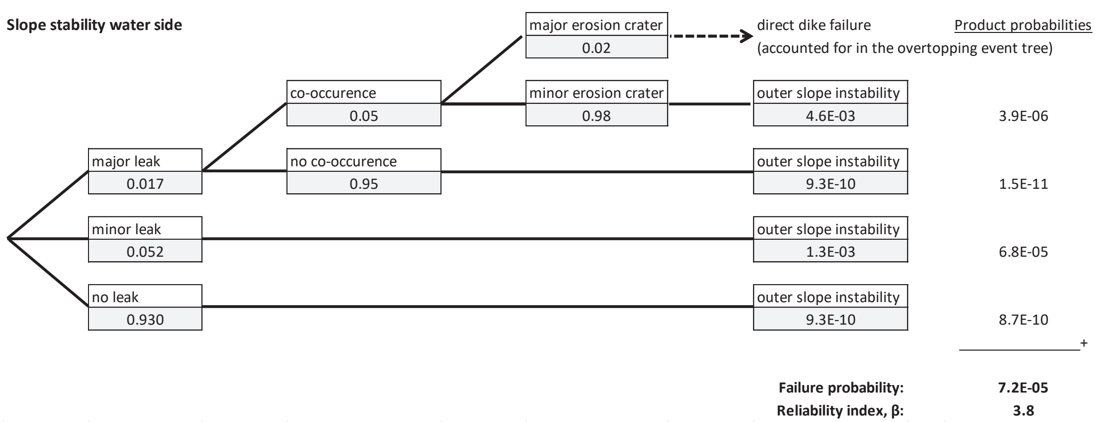

Figure 7. Event tree, for the failure mechanism outer slope instability, showing the different consecutive events leading to failure of the dike, based on the entire 270 m long dike section with parallel pipeline.

Similarly, we used our framework to calculate the reliability of the other failure modes and compare them with the target reliability values in Table 3. For all failure mechanisms the reliability complies with the target values. The fact that the conditions including potential pipeline failure could be shown to comply with the safety requirements resulted in a cost saving of roughly 3 million Euros which would otherwise have been necessary to implement structural measures to mitigate the consequences of pipeline failure.

Table 3. Overall results per failure mode and the corresponding targets.

Failure mode	Reliability	Target reliability
Overtopping/overflow	4.0	3.0
Slope instability land side	6.3	4.1
Slope instability water side	3.8	3.5

4 Discussion and Further Research

We have shown that potential pipeline failure can be incorporated in the reliability analysis of flood defenses by integrating the effects of pipeline failure with the failure modes of the flood defense, particularly for the example of dike slope stability. The example also showed that we can handle the uncertainty in water levels and in erosion crater dimensions by using fragility surfaces.

The approach followed in the example project was a reliability verification 'from coarse to fine' in the sense that we started with conservative assumptions on many aspects and refined where necessary and feasible. The reason for that is that in reliability verification, as opposed to risk analysis, we do not worry about bias in the reliability estimates and conservative assumptions are usually obtained with much less effort than best estimates. When expert judgement- based, conservative assumptions are typically also much less controversial, as experts can often easily agree on worst-credible conditions. New challenges will arise in other examples, where the probability of failure estimate needs to be based on more detailed analysis to meet the regulatory reliability requirements.

At the time of writing, the authors were also involved in a follow-up study on a pipeline crossing, which contains additional challenging elements, mainly related to the unknown location of potential pipeline failure. In such cases, it seems sensible to define discrete zones for the analysis of both pipeline and dike failure.

We expect the presented analysis framework of integrated reliability analysis to lead to much more realistic safety assessments and designs of situations with pipelines in the vicinity of flood defenses, compared to the classical assessment approaches based on the combination of worst-case assumptions.

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