Semi-Probabilistic Safety Assessment of Pipelines near Levees

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Abstract. Traditionally Dutch design codes require a minimum distance between a pipeline and the toe of the levee: the ‘safety zone’. The codes provide additional design and maintenance requirements for pipeline sections located within this ‘safety zone’. For existing pipelines, designed before the establishment of the codes, the sections located in the vicinity of the levee often do not pass the deterministic criteria of the flood risk assessment guidelines. Relocating the pipeline or the levee at those sections will dramatically impact on social and economic aspects and is therefore only recommended if absolutely necessary.

Dutch flood risk assessment guideline and pipeline code do allow for a more advanced assessment of the safety of these sections. One of the options is a probabilistic assessment; however the code does not provide clear guidance on how to perform such an assessment.

Royal HaskoningDHV has developed a semi-probabilistic design approach to assess the probability of levee failure due to pipeline rupture. The approach has been successfully applied to the levees along the River Meuse in the south of the Netherlands. The semi-probabilistic approach that has been developed compares the expected likelihood of a dike failure caused by a pipeline rupture with the allowable probability of failure. The method has been presented to both the Dutch Pipeline Design Community and the Water Board and has been positively received.

Keywords. Semi-Probabilistic assessment, pipelines, levees, safety zones, Dutch design codes

1. Introduction

After the floods of the River Meuse in 1993 and 1995 in the South of the Netherlands (Limburg Province) the Dutch Ministry of Transport & Public Works asked the Commission of Immediate Flood Protection (named Boertien II) to advise what measures should be taken to reduce floodings in Limburg. As part of the flood defence scheme, Boertien II advised the building of emergency levees to provide a return period of fifty years for flood events as soon as practicable. The Dutch government gave the Water Boards the mandate to construct these levees in 1995 and 1996.

The alignment of the emergency levees was mainly based on the location of the villages and structures, landscape contours, location of the infrastructure above ground and land ownership. At that time the emergency levees were classified as regional levees which do not form part of the ‘Wet op de Waterkering’ (Dutch law for water management which was later changed into ‘Waterwet’). No mandatory standards in the Dutch water law were applicable for the emergency levees and all existing pipelines were maintained despite their location within the ‘safety zone’ of the levees.

In 2005 the Dutch government decided that the emergency levees along the Meuse in Limburg shall be considered as primary levees and thus became part of the ‘Wet op de Waterkering’. In addition the government increased the allowable design return period for flood events to 250 years. The Water Boards in Limburg and Maaswerken-Rijkswaterstaat (part of Dutch Ministry of Public Works and Water Management in Limburg) have carried out improvement works since 2007 and plan to complete the work in 2020.

One of the main issues in the dike improvement works are the presence of the pipelines in and around the levees. Most pipelines are designed and constructed before the establishment of the levee and often the sections in the vicinity of the levee do not pass the deterministic criteria of the flood risk assessment guidelines. Relocating a pipeline or the levee at those critical sections will dramatically impact on social and economic aspects and is therefore only recommended if absolutely necessary.
2. Use of Dutch Guidelines for Dike Assessment

2.1. Existing Dutch Practice

The current Dutch Flood Risk regulation, *Voorschrift Toetsen op Veiligheid* (Ministerie van Verkeer en Waterstaat, 2007) and the pipeline requirements for pipelines in or nearby important public works, *NEN3651:2012 Aanvullende eisen voor buisleidingen in of nabij belangrijke waterstaatswerken* (NNI, 2012) dictate how to deal with pipelines in the vicinity of the levees.

Basically the assessment process contains three steps:

1. The assessment of the impact of a pipeline rupture on the safety of the levee.
2. The structural assessment of the pipeline section located within the safety zone.
3. An advanced assessment.

The flood risk guideline and pipeline code provide detailed procedures for step 1 and 2 but very little information on how to perform an advanced assessment.

Figure 1 presents the most basic check of the impact of a pipeline rupture on the safety of the levee. The pipeline code includes empirical formulas to estimate the dimensions of a disturbance zone that could result from pipeline rupture. The code also specifies a ‘safety zone’ between the disturbed zone and the levee itself. This ‘safety zone’ can be determined based on stability and piping calculations and in some cases, on pragmatic ‘rules-of-thumb’ relations.

Figure 1. ‘Safety zone’ and disturbed zone according to existing deterministic safety assessment

If the first step concludes that the impact of a pipeline rupture is not acceptable, the pipeline can be subjected to a structural strength assessment. The collection of structural pipeline data and information on the actual state and maintenance of the pipeline often requires substantial effort from the engineer who performs the assessment and from the company that operates and maintains the pipeline. In some cases the required information is even not available in databases or in other forms.

An advanced assessment can be considered when the first two steps do not provide satisfactory results or when the execution of one of the first steps is expected to be very comprehensive and time consuming. This advanced assessment could comprise of either a probabilistic assessment or an assessment of “proven strength” when the pipeline and levee have been subjected to similar loads in similar condition.

A probabilistic assessment is an attractive alternative compared to a structural strength assessment as it can be carried out with less detailed structural pipeline data. The performance of the probabilistic assessment can therefore be quicker and more effective. Another advantage of a probabilistic assessment is that it automatically prioritises critical pipeline sections: pipeline sections can be ranked based on calculated probability of failure.

Despite of the promising advantages this probabilistic approach it has not been widely implemented at present. The flood risk regulation and the pipeline requirements do not give clear guidance on how to perform such a probabilistic assessment. A probabilistic assessment can be performed at different levels, ranging from comparing the expected probability of failure with an allowable probability of failure to a full probabilistic risk analysis inclusive the assessment of likelihood and consequences of failure.

Since the probabilistic approach is not prescribed in the codes, most Water Boards have been reluctant to adopt this approach.

2.2. Semi-Probabilistic Assessment

Since 2011, Royal HaskoningDHV (RHDHV) has been involved in the assessment and design of levee improvement works in Limburg.
As existing pipelines are one of the main elements, RHDHV has investigated and developed a semi probabilistic method that can be used to assess the effect of the pipelines on the levee’s safety. The objective was to reduce the economic impact of relocation of pipelines. The method was developed under the condition that it complies with the current Dutch flood risk regulation and corresponding guidelines. In 2013 the method was presented to the Dutch pipeline design community and the water board and has been positively received.

3. The Method and Procedure

The approach followed by RHDHV combines a probabilistic top-down approach with defining the actual strength of the embankment that remains after a pipeline rupture. The combination of those two principles results in a pragmatic, easy-to-handle method.

The semi-probabilistic approach that has been developed compares the expected likelihood of a dike failure caused by a pipeline rupture with the allowable probability of failure.

3.1. The Principles of the Semi-Probabilistic Approach

The principle of the semi-probabilistic approach is based on the following formula:

\[ P_{\text{fail.due to rupture}} \leq P_{\text{all.prob.failure}} \]  

(1)

where \( P_{\text{fail.due to rupture}} \) is the calculated probability of failure of the levee (per year) due to rupture of the pipeline during flood level in the river. \( P_{\text{all.prob.failure}} \) is the allowable probability of the failure of the levee due to rupture of the pipeline during flood level in the river. The allowable probability of failure is based on fault tree analysis.

The calculated probability of failure of the levee is formulated by the following:

\[ P_{\text{fail.due to rupture}} = P_{HW} \cdot P_{\text{rupture}} \cdot P_{\text{instab|rupture|HW}} \cdot P_{\text{repair}} \]  

(2)

In which:

- \( P_{HW} \) is the probability of exceedance of the maximum flood level that can be retained by the levee after a pipeline rupture (expressed by a probability per year).
- \( P_{\text{rupture}} \) is the probability of failure (or rupture) of the pipeline (expressed by a probability per year).
- \( P_{\text{instab|rupture|HW}} \) is the probability of failure of the levee in the situation of two simultaneous events: rupture of the pipeline and high water (expressed by absolute probability). In case of a residual profile that cuts into the levee (figure 4) this term could be set to 1.
- \( P_{\text{repair}} \) is the probability that the period of high flood levels will overlap with the period that is needed for repair the levee and the pipeline after a rupture within the year that the flood happens.

Figure 2. Determination of HW for \( P_{HW} \) due to assessment failure4 modes taking into account pipeline rupture

All items of formula 1 and 2 will be elaborated in this section.

3.2. Allowable Probability of Failure

The allowable probability of failure for a specific failure mode such as ‘dike breach as a result of pipeline rupture’ is derived from a prescribed allowable probability of failure of the top-event ‘dike breach’ via a fault tree analysis (Figure 3). The allowable probability of failure of the top-event is laid down by law, the ‘Waterwet’, and is equal a return period of 250 years for the dike perimeters along the River Meuse in Limburg. In 1989 the Dutch flood defence design guideline *Leidraad voor het ontwerpen van rivierdijken, deel 2 – benedenrivierengebied* (TAW, 1989) presented a breakdown of failure modes in a fault tree. More recent flood risk guidelines are
developed further to certain basic choices that were established in (TAW, 1989), such as: 90% probability of exceedance for ‘overtopping and overflow’ and 10% for the other failure mechanisms. The distribution of top-event over the subsequent failure modes is based on balancing dike improvement costs against benefits in terms of safety. Currently this distribution is being re-evaluated in the Netherlands and new flood risk regulations are being developed. It is expected that these new developments will take effect by 2018.

Figure 1 presents the fault tree for a specific dike perimeter in Limburg. The breakdown of failure modes and the applied probability of failure have been set up in consultation with the water board authority that is responsible for the safety of the dike perimeter. The resulting allowable probability of failure for the failure mode ‘dike failure due to pipelines’ is set to 1.5% of the top-event. In other words, the probability that rupture of the pipelines causes dike failure should be less than one in 16,667 years.

Figure 3. Probability of exceedance determined for specific levee improvement Limburg

The presented probability of exceedance holds for all pipelines that affect the dike perimeter. The allowable probability of failure for each pipeline is simply calculated by dividing the amount of pipelines in or along the levee of the polder. For example, if 8 pipelines are present the allowable probability of failure per pipeline is 1/133,333. The allowable probability of failure per pipeline becomes smaller when the number of pipeline sections in the vicinity of the levee increases. This approach assumes that the pipeline rupture events for each particular pipeline section could be considered statistically independent and that the probability of failure of all individual events should therefore be added together. This is a conservative assumption. For instance, in reality some pipeline sections are part of the same pipeline system and individual rupture events might then be correlated to a certain extent. This kind of consideration should be further elaborated when applying the method to large number of pipelines in a dike perimeter.

3.3. Probability of Exceedance of Flood Level

The probability of exceedance of the flood level \( \left( P_{3H} \right) \) is determined in three steps.

First step is to determine a so-called ‘residual profile’. This is the cross-section of the levee that remains after pipeline rupture and subsequent failure of the levee embankment. The second step is to determine the maximum flood level that could be retained by this ‘residual profile’. The third step is to determine the corresponding probability of exceedance.

The ‘residual profile’ is created by the disturbance of the ground near the failing pipeline. The disturbance might be in the form of a crater that cuts into the actual embankment (Figure 4) or might be an indirect impact, for instance an increased ground water table. Defining the dimensions of the residual profile could require comprehensive detailed analysis.

Figure 4. Residual profile

A pragmatic alternative approach is to define a robust residual profile that is resistant against all possible failure modes. RHDHV advocates using this simplified method as a first estimate. The dimensions of this simplified profile could
be defined based on conservative stability and piping calculations that follow the design rules of flood protection design guidelines. A typical stable residual profile has a 3m crest width and shallow slopes, such as 1V:4H for clay and loam dike fill material and 1V:6H for sandy fill material (to cope with superficial instability due to ground water gradients near the slope). Besides stable slopes, the residual profile should be safe against piping and should have sufficient freeboard to avoid erosion of the (unprotected) inner slope of the residual profile.

The probability of exceedance curve for the river level can be used to determine $P_{HW}$, Figure 5. 

In case of a pipeline crossing there is hardly any residual profile left and the maximum water level that can be retained is equal to the ground level behind the levee.

### 3.4. Probability of Failure of Pipeline

The statistics from the industry can be used to estimate the probability of failure of pipeline rupture $P_{rup}$. In the Netherlands this information has been collected in publications such as NPR3659 (NNI, 1996+2003) and in Risicoanalyse van hoge drukleidingen (Provincie Zuid-Holland, 1978). These publications are currently being re-evaluated.

Typical values do not explicitly include factors such as:
- Age of the pipeline
- Transitions of alignment, diameter and material
- Characteristics of casing
- Effects of dike raising or excavations close to pipeline

Therefore it is recommended to modify published values to account for the above factors.

### 3.5. Probability of Repair During Flood

$P_{repair}$ is the probability that the pipeline rupture happens during the period of flooding within the year of the design flooding event. Two periods should overlap: the period of high flood levels (approximately 2 weeks for River Muese) and the period in which the levee will be affected by the pipeline rupture. The latter starts from the moment of occurrence of a rupture and lasts until the completion of the levee repair works.

$P_{repair}$ is estimated by the following formula:

$$P_{repair} = 1 - \left( 1 - P_{rup\text{-per}} \cdot P_{HW\text{-per}} \right)^{Time} \quad (3)$$

Where $P_{rup\text{-per}}$ is probability of period of repair after a rupture in a random time unit in the year, $P_{HW\text{-per}}$ is probability of period of flooding in a random time unit in the year and $Time$ is the number of time units in the year when flooding could occur.

The flood season for the Rivers in the Netherlands lasts 6 months starting in October and ending on the first of April. The duration of a flood is normally about two weeks. Because of this, $P_{HW\text{-per}}$ is 2/26 (2 weeks in 26 weeks) and Time is 26 (weeks). It is assumed that the presence of a disturbed zone occurs for a maximum of three weeks. This is inclusive of the time required to perceive the rupture and repair the pipeline and surface. $P_{rup\text{-per}}$ is therefore 3/52 (3 weeks in 52 weeks; as the rupture can occur the whole year).

For all assessed levees the probability of repair during flood is the same. The above results for the assessment in $P_{repair}$ is approximately 0.1.

### 4. Results of the Assessment

The result of the semi- probabilistic approach for the assessed levees in Limburg is that most pipelines, in small perimeter dikes pass the safety assessment when located in the vicinity of the levees and no expensive measures are required. Only pipelines that are in poor condition like old asbestos cement pipes need to be replaced. In larger perimeters, where the number of pipelines is relatively high (>20), the allowable probability of failure will reduce and less pipeline will pass the probabilistic safety assessment.
In this section the results of one of the dike perimeters is presented. The perimeter is located in the middle of the province. The total length of the levee is only 1,250 m and the design water level is +23.3 m NAP. There are 8 pipelines located in the vicinity of the levee. 7 pipelines have successfully passed the assessment. 1 pipe, an asbestos cement pipe, has to be replaced and/or relocated.

For the presentation in this section one parallel pipeline and one intersecting pipeline is highlighted. Table 1 shows the highlighted pipelines in the vicinity of the assessed levee. Both pipelines are made of steel and approved.

<table>
<thead>
<tr>
<th></th>
<th>Position</th>
<th>Type</th>
<th>Diameter</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cross</td>
<td>Gas</td>
<td>914 mm</td>
<td>66 bar</td>
</tr>
<tr>
<td>2</td>
<td>Parallel</td>
<td>Brine</td>
<td>457 mm</td>
<td>40 bar</td>
</tr>
</tbody>
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Based on the traditional deterministic approach both highlighted pipelines require mitigation measures. The mitigation measures are relocation of the pipelines or construction of a replacement retaining wall in the core of the levee which is a back-up water retaining structure in case of rupture of the pipeline and collapse of the soil structure.

Based on the semi-probabilistic approach both pipelines are approved and no mitigating measures are required. Table 2 shows the results of the assessment. The allowable probability of failure (P_{all.prob.failure}) is $1/133,333$ per year per pipeline ($7.5 \times 10^{-6}$ per year).

<table>
<thead>
<tr>
<th></th>
<th>Pipe No.</th>
<th>HW</th>
<th>NAP+/m</th>
<th>P_{mv}</th>
<th>Prupture</th>
<th>P_{all.prob.failure}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NA</td>
<td>1</td>
<td>2.16 $\times 10^5$</td>
<td>2.36 $\times 10^5$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>22.9</td>
<td>0.11</td>
<td>5.84 $\times 10^5$</td>
<td>7.09 $\times 10^5$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Because pipeline number 1 intersects the levee, there is no residual profile and it should be assumed that rupture of the pipeline results in failure of the levee down to surface level of the hinterland. Still in this case, the required probability of failure is higher than the calculated probability of failure, because of the low probability of failure of the gas pipeline and the relatively high allowable failure (top-event of 1/250).

5. Conclusions

The application of a semi-probabilistic assessment of levee safety can result in major cost savings in case of pipelines in the vicinity of the levee. Current guidelines allow for probabilistic design but do not prescribe how to apply a probabilistic approach. Royal HaskoningDHV has developed a semi-probabilistic approach which is a pragmatic approach in line with the design philosophy of the Dutch guidelines. The semi-probabilistic approach is based on a fault tree analysis and a prescribed allowable probability of failure.

In all cases the semi-probabilistic approach is an excellent tool to prioritize critical pipelines that impact the levee. In case the pipeline does not pass the semi probabilistic check, a detailed strength assessment of the particular pipeline section could be carried out. In this case the semi-probabilistic approach is used as a first scan.

Acknowledgement

The development of this methodology could not have been possible without the co-operation and help of engaged employees of the Water Board authorities and the pipeline operating companies in Limburg and representatives of the pipeline design community.

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