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Backward Erosion Piping For Situations With A Riverside Blanket

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ABSTRACT

The failure mechanism of backward erosion piping (BEP) contributes to high calculated failure probabilities of many river embankments in countries such as the Netherlands and the United States. In the risk analysis for BEP in the Netherlands, commonly used calculations models do not take the full hydraulic impedance of the floodplain into account, due to the risk that the pipe encounters a defect, such as a crack, in the floodplain which would lead to failure. Knowledge of the pipe length as a function of the head drop would aid in assessing the risk of the pipe progressing below the floodplain. This paper presents a conceptual model explaining how different factors affect the pipe length, which is supported by results of 2D numerical computations using the Sellmeijer model. Based on these insights and additional field scale computations two curves were derived which assist a practitioner in making a first estimate of the pipe length for a given case.

INTRODUCTION

The failure mechanism of backward erosion piping (BEP) poses a threat to embankments that are founded on a granular aquifer which is covered by a cohesive blanket layer. Such situations are common for many river embankments in the Netherlands. The physical process of pipe formation has been studied in experiments and numerically by e.g. Hanses (1985), Sellmeijer (1988), Van Beek (2015) and others. Based on these insights, the expected process of BEP during a highwater event can be described. First, the pore water pressure in the aquifer rises inducing seepage flow in the aquifer from the river to the landward side of the embankment. If an unfiltered exit is present, such as a ditch or a crack which cuts through the blanket, the seepage flow may erode sand grains from the aquifer. This can result in the formation of small hollow ‘pipes’ at the top of the aquifer, with the blanket acting as a roof preventing the pipes from collapsing. The pipes initially lengthen in the upstream direction as the water level increases. If a critical water level is exceeded, the pipe can proceed to lengthen upstream without a further increase in the water level eventually reaching the river. At this critical water level, which is denoted by the critical head H_c, the pipe has the critical pipe length L_c. When the pipe reaches the river, or in cases with a floodplain that makes contact with the river through a defect in the river side blanket layer, erosion increases significantly, potentially leading to collapse of the embankment and flooding.

The Sellmeijer model (Sellmeijer 1988, 2011) is used in the Netherlands to assess the risk of flooding due to BEP. This model describes the erosion of sand grains in a pipe as the result of groundwater flow. The Sellmeijer model has been implemented in the numerical finite element groundwater model D-Geo Flow (van Esch et al., 2013 and van Beek et al., 2022) which computes the head drop at which a pipe can grow upstream and lead to flooding. In this 2D model the pipe is simulated by line elements with hydraulic conductivity based on equations for pipe flow and particle equilibrium in the pipe. The tip element is evaluated for potential particle equilibrium to determine whether the pipe will lengthen. By gradual increase of head in the model, the critical head and critical pipe length are obtained. However, to efficiently compute H_c, without numerical simulations, a 2D calculation rule (the Sellmeijer calculation rule) was derived (Sellmeijer et al., 2011).

The Sellmeijer calculation rule is most often used by practitioners to assess the risk of BEP in the Netherlands. The model assumes that the blanket is impermeable. For situations with a floodplain, the hydraulic impedance of the blanket layer in the floodplain can be estimated based on the leakage length. The leakage length can be used to compute an ‘effective’ seepage length (L_s) with impermeable blanket. However, due to the risk of defects in the blanket only a limited length of floodplain is taken into account and modelled, because of the risk that the pipe will form under the flood plain and causes a short-cut with the outer water body. Properties of the flood plain blanket are often unknown. Therefore, typically, the seepage length is limited to twice the width of the embankment because, in the design approach, it is assumed that the pipe is no longer than half of the total seepage length when the critical head is reached. This would prevent the presence of a pipe below the floodplain as illustrated in Figure 1. However, this results in an underestimation of the critical head for situations where the effective seepage length is longer than twice the embankment width. This effect can lead to an overestimation of the probability of failure due to BEP by a factor of 100-1000. A better estimation of the pipe length would aid users to make full use of the resistance of the flood plain in BEP calculations, without the risk of short-cut of pipes through defects in the blanket.

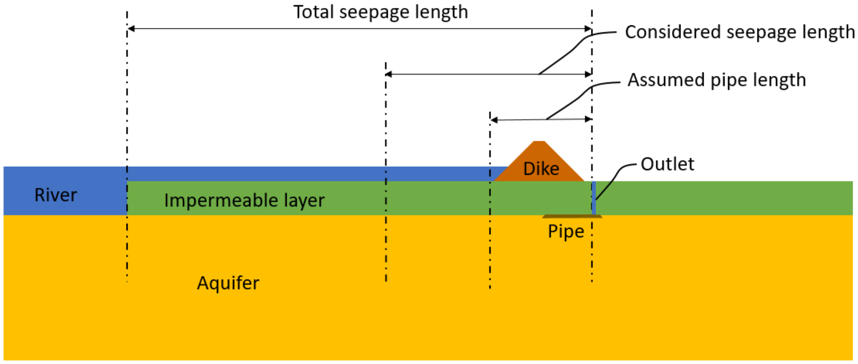

Figure 1. Illustration of the current assumption that the pipe length is half of the seepage length and therefore only a reduced seepage length is used equal to twice the embankment width.

Using D-Geo Flow, the pipe length can be computed as a function of water level. This gives the pipe length (L_{pipe}) for a given water level, as well as the critical pipe length (L_c) and critical head drop (H_c). Computations using D-Geo Flow often result in L_c significantly less than half the seepage length, clearly indicating that the restriction of the effective seepage length is often too strict.

However, D-Geo Flow computations are time intensive, the computational model has not been validated for computation of L_{pipe} and L_C, and there is a desire for easier methods to assess the pipe length. A better understanding of the length of the pipe at the critical head drop, as well as the growth of the pipe at lower head drop levels, is needed to support considering the full floodplain.

This paper first presents a conceptual model explaining the influence of factors on L_c. Subsequently, a method by which practitioners can easily make a first estimate the pipe length for a given situation is presented.

CONCEPTUAL MODEL

The conceptual model presented here is based on a 2D situation with an isotropic and homogeneous aquifer, and the physical mechanisms of pipe growth as described by the Sellmeijer (1988) model. For ease of explanation, we first consider situations where the blanket in the protected area is relatively impermeable such that groundwater flow concentrates towards the pipe.

When a high water level occurs, flow concentrates to the defect in the blanket. Initially, the outlet hole is small. However, at a given water level, seepage forces can become large enough to erode grains through the outlet leading to pipe forming. This pipe then lengthens by erosion of grains from the pipe tip. This lengthening can be seen as having two simultaneous effects on the groundwater flow

- Effect 1: pipe growth increases the total outflow area, leading to a reduction of the concentration of flow at the pipe tip.
- Effect 2: the pipe tip gets closer to the river which increases the average gradient upstream of the pipe.

These two effects counteract one another and form the basis of the conceptual model. When the pipe is short, the relative influence of pipe lengthening is typically larger on effect 1 than on effect 2, making effect 1 dominant. This causes the pipe to stop growing due to the reduction of concentration of flow at the pipe tip. For further pipe progression the head drop needs to be increased. As the pipe lengthens the relative change in effect 1 decreases and effect 2 increases, until a tipping point is reached where effect 2 becomes dominant and the pipe lengthens until it reaches upstream. This tipping point is the critical head drop, and the pipe length is the critical pipe length. This stepwise growth is often observed in BEP experiments in the laboratory (e.g. Van Beek, 2015).

Considering the effects of parameters on the critical pipe length, we would expect that factors which increase the relative importance of effect 1 over effect 2 would lead to longer L_c, because effect 1 stays dominant for a longer time. Effect 1 is mainly dependent on the groundwater contours. This would imply that factors which influence the groundwater contours affect L_c, whereas factors that only influence the critical head drop (such as permeability) do not. Thus, aquifer thickness is an important factor that affects L_c. With a thicker aquifer, effect 1 remains dominant for a longer time due to the greater depth which leads to higher discharge volumes that the pipes need to drain.

In situations where the blanket in the protected area is semi-permeable, L_c is expected to be shorter than with an impermeable blanket. The semi-permeable blanket means that water can flow towards the protected area, which reduces the influence of pipe growth on the concentration of flow to the pipe. The most extreme example of this would be a situation with no blanket at all; the outflow area is effectively infinitely long so that growth of the pipe would have a negligibly small influence on the groundwater contours and effect 1 would be negligible.

Numerical computations in D-Geo Flow support the following hypotheses that follow from the described conceptual model:

- Increasing depth increases L_c
- Increasing the permeability of the blanket in the protected area reduces L_c
- Grain size, and permeability of the aquifer have no influence on L_c.

As D-Geo Flow was not initially intended to compute pipe lengths, a validation of the model is desirable. However, most experiments in which the pipe length was recorded have a 3D configuration with a hole outlet, making them unsuitable to validate a 2D model (Van Beek 2015). Experiments by Silvis (1991) with a ditch outlet and the formation of a network of pipes come close to a 2D situation. These three experiments were modelled in D-Geo Flow (Wopereis et al., 2023). Figure 2 shows the results of pipe growth during two of the Silvis experiments called T2 and T4 in comparison with pipe growth found in D-Geo Flow. During the Silvis experiments multiple pipes were formed (6 pipes in T2 and 7 in T4), each colored line represents the growth of one of these pipes. This figure shows that L_c is reasonably well estimated, however, the pipe length at lower head drops appears to be consistently underestimated.

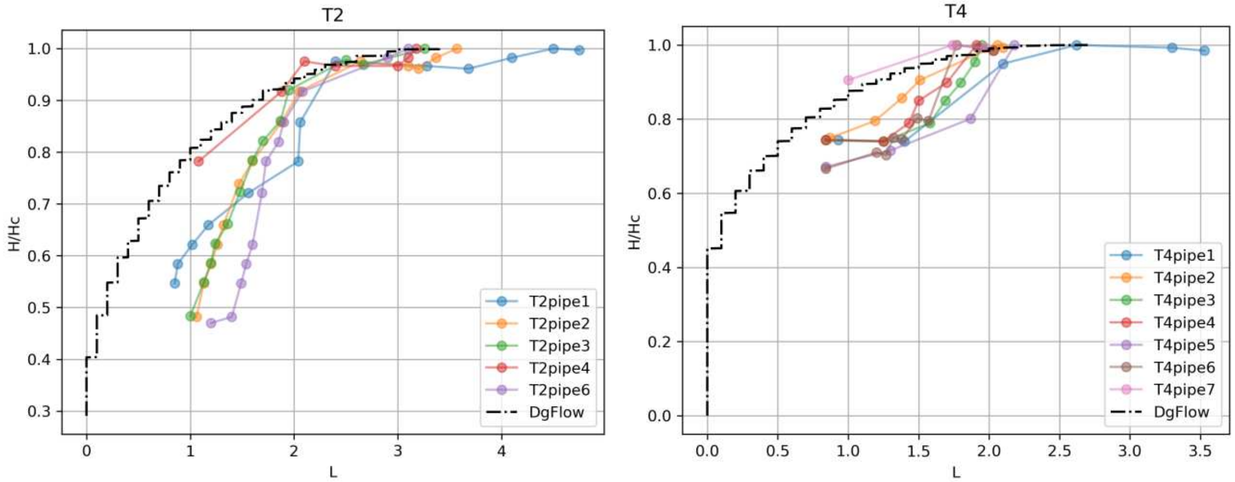

Figure 2. Comparison between modelled and experimental pipe growth. Modelled pipe growth is found with D-Geo Flow and experimental pipe growth is based on the Silvis (1991) experiments. Left in experiment called T2 of Silvis and right of experiment T4. The pipe length on the x-axis is in meters.

METHOD TO ESTIMATE PIPELENGTH

Over 60 D-Geo Flow computations for different configurations were used to compute critical pipe lengths both for experiments and for plausible situations that can be expected to occur in the field. Based on these computations a clear relation between the critical pipe length normalized by the seepage length (L_c/L_s) and the aquifer depth normalized by the seepage length can be observed in Figure 3 for impermeable blankets (red symbols). Figure 3 also shows how a semi-permeable blanket in the protected area reduces the pipe length (purple and blue symbols). However, the degree to which this occurs depends on a combination of geometrical factors, depth, seepage length, and on the permeability of the aquifer and blanket, therefore no clear trend is observed. Figure 3 also shows that for most cases the critical pipe length is way below half of the seepage length. The y-axis ($\frac{L_c}{L_s}$) is maximized by 0.48 but is often much lower.

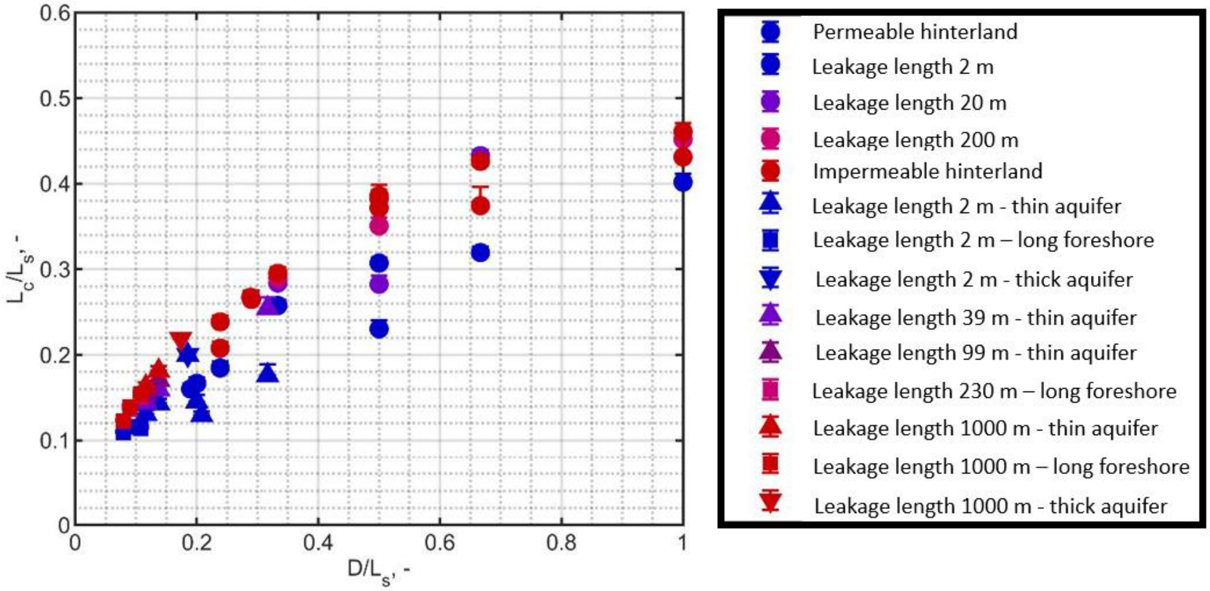

Figure 3. Normalized critical pipe length (L_c/L_s) versus normalized thickness of the aquifer (D/L_s). Both are normalized with the seepage length, L_s. The red symbols show cases with an impermeable blanket in the protected area. Purple and blue symbols show a semi-permeable blanket and cases with no blanket respectively.

For heads below the critical head, we also see that the relation between the computed pipe length normalized by the critical pipe length (L_{pipe}/L_c) and the head drop normalized by the critical head drop (H/H_c) is very similar for situations with impermeable blanket in the protected area, regardless of the D/L_s (Figure 4).

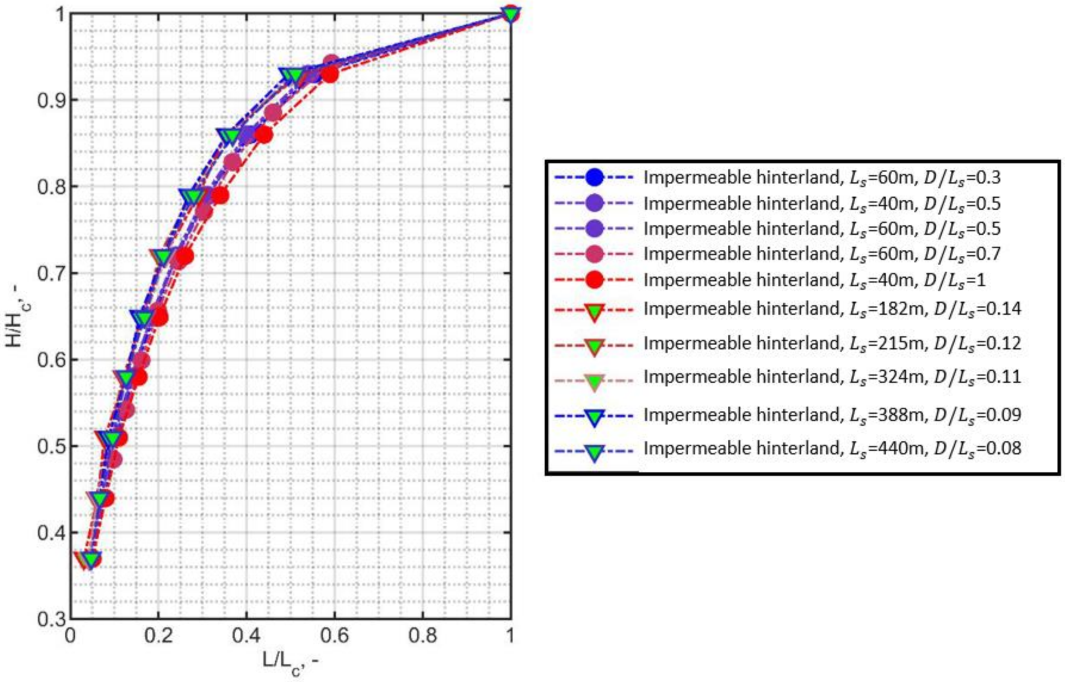

Figure 4. Normalized hydraulic head versus normalized pipe length for different geometrical configurations.

Application

Figures 3 and 4 can be used to make a first estimation of the pipe length at the critical head drop, or of the pipe length at the design water level. This estimate can be used to identify whether there is a risk of the pipe growing below the floodplain blanket.

The water authorities in the Netherlands increasingly make use of GIS applications in which many assessments or design computations are made automatically using the Sellmeijer calculation rule and features of the subsurface and embankment. Such assessments can be done using semi-probabilistic or probabilistic methods, the latter making use of the Probabilistic Toolkit (PTK) (de Wit, 2021). The parameterization of the curves in Figures 3 and 4 can easily be implemented in this workflow, which was done to investigate the applicability for Water Authority Rivierenland (WSRL) (Methorst et al., 2021).

In Wopereis et al., 2023, data of a levee reinforcement project Neder Betuwe from the Water Authority Rivierenland, used these curves to investigate the contribution of pipe growth to the overall failure probability of BEP. Failure for BEP is currently defined as the design head drop exceeding H_C, however as this paper has explained, failure can also be defined as L_C exceeding the embankment width (i.e. pipe growth below the floodplain blanket) when the influence of the whole floodplain is taken into account.

For this dataset, a fully probabilistic analysis was made considering failure due to exceedance of H_c and failure due to L_c exceeding the levee width. Furthermore, the system failure probability was computed by considering the previous two failures as a series-system. These computations assumed a model factor on the pipe length to account for uncertainty. The model factor has a mean of 1 and a standard deviation of 0.3.

This study shows that the risk of the pipe being long enough to grow under the floodplain blanket is negligible. The dominant failure mechanism is exceedance of the critical head. When the critical head was not exceeded, the head drop was considerably lower than the critical head meaning that the pipe length was negligeable. These findings can have important implications, as there are significant lengths of embankments in the Netherlands that appear to need reinforcement when the floodplain is not entirely considered.

However, the same approach needs to be followed using additional case studies to ensure that the whole range of possible underground scenarios are covered before conclusions can be drawn. For example, the dataset considered relatively thin aquifers which often leads to shorter pipe lengths. Furthermore, the pipe length uncertainty was based on the L_c of a few experiments and should be revised as it was found that the model appears to consistently underestimate the pipe length at lower head drops. The underestimation at lower head drop could be accounted for by using a model factor that is dependent on the ratio of head drop to critical head (H/H_c). The first results from this study are however promising.

DISCUSSION AND RECOMMENDATIONS

This paper addresses an important conservative assumption that is often made in the assessment of the risk of BEP in the Netherlands, the extent to which the influence of the floodplain blanket is considered in the analysis. Floodplains provide resistance to BEP due to the hydraulic impedance of its blanket layer. However, current practice is to neglect a large extent of this resistance due to uncertainty in de length of the pipe in design conditions. This paper presents insights that allow the user to take the full influence of the floodplain into account by estimating the pipe length using the curves in Figure 3 and 4, and consequently accounting for the risk of a shortcut. First investigations for realistic cases indicate that this risk will often be negligible.

The curves shown in this paper are derived for situations with a homogeneous aquifer with isotropic permeability and 2D groundwater flow. The curves are derived based on experiments and D-Geo Flow computations for which the validation of the pipe length has now been conducted with only three experiments. The model factor applied in practice should account for the uncertainty in validation of the D-Geo Flow pipe length. Therefore, a wider availability of experiments with a 2D pipe pattern could improve the estimation of the model factor for pipe length. In the field we may also encounter 3D situations, such as a sand boil with one or few pipes forming. A 2D model can be expected to lead to a degree of under estimation of H_c (e.g. Van Beek et al. 2022) and L_c is expected to be longer in 3D situations. For 3D piping calculations more research is recommended.

With situations that do not fall within the scope of the curves, such as anisotropy and/or an aquifer consisting of multiple layers, users can make a D-Geo Flow computation to better assess the pipe length instead of using the curves. These situations often lead to longer pipe lengths. The curves can be used to identify at which locations the length of the pipe is of most concern and therefore to minimize the required number of D-Geo Flow computations.

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