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Pol, Joost

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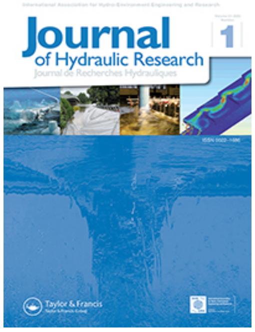

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Discussion

Influence of erosion on piping in terms of field conditions

By G. HOFFMANS, *J. Hydraulic Res.* 59(3), 512–522. 2020. https://doi.org/10.1080/00221686.2020.1786741

Discusser:
JOOST POL, Researcher, *Department of Hydraulic Engineering, Delft University of Technology, Delft, the Netherlands; Flood Risk Advisor, HKV, Lelystad, the Netherlands.*
Email: j.c.pol@tudelft.nl

Introduction

The Shields–Darcy (SD) model by Hoffmans and Van Rijn (2018) describes the resistance of hydraulic structures to backward erosion piping, which is a form of internal erosion. In the article being discussed, Hoffmans compares the SD model to the model by Sellmeijer et al. (2011), focusing on field scales. This Discussion presents finite element simulations that deviate from Hoffmans' conclusions that the model by Sellmeijer et al. (2011) results in an unrealistically low critical gradient. As both the SD and Sellmeijer models fit reasonably well to laboratory experiments (Hoffmans & Van Rijn, 2018), extrapolation to field scales (say aquifer thickness $D > 5$ m, seepage length $L > 10$ m) is important, particularly since these models are used for the design of flood defences. Hoffmans addresses this issue by analysing the resistance as function of aquifer depth D. Hoffmans recommends checking the outcomes of the SD model with a mathematical piping model like that of Van Esch et al. (2013).

Methods

As part of a broader analysis (Pol, 2020), this paper analyses the effects of scale (D and L) on the critical gradient using the DgFlow model (Van Esch et al., 2013). This finite element model solves the Laplace equations of 2D groundwater flow, which are coupled to Poiseuille pipe flow and a particle equilibrium according to Sellmeijer et al. (2011). For given head boundary conditions, it computes pipe dimensions for which the particles in the entire pipe are just in equilibrium. The highest head difference for which equilibrium is obtained is defined as the critical head H_c, and correspondingly the critical horizontal gradient $S_{dike,c}$ equals H_c/L. This Discussion compares the critical horizontal gradient $S_{dike,c}$ predicted by Sellmeijer et al. (2011), the SD model and DgFlow.

Multiple scenarios are assessed in DgFlow to compare Sellmeijer et al. (2011) and the SD model. As the (polder) boundary conditions are expected to affect the seepage to the polder, and thus the groundwater flow to the pipe, we applied three scenarios (D1). Scenario A is a fully impermeable polder blanket with constant head at the exit, like the configuration assumed by Sellmeijer et al. (2011). Scenario B is a fully permeable polder blanket with constant head along the polder surface. Scenario C is a constant head over the entire aquifer depth below the exit, as assumed by Hoffmans and Van Rijn (2018). The simulated seepage lengths L are 0.3, 3, 30 and 100 m, and $D = L/3$. Results are presented for fine uniform sand with particle diameters $d_{15} = 0.113$ mm, $d_{50} = 0.180$ mm, $d_{70} = 0.214$ mm, and hydraulic conductivity $k = 1.32{\cdot}10^{-4}$ m s^{-1}.

Results

Figure D2 shows the resulting critical dike gradient $S_{dike,c}$ as function of L (and implicitly D due to the fixed D / L ratio). Differences between models are small for $L = 0.3$ m but increase with larger scale. The scaling of $S_{dike,c}$ with L is very similar for Sellmeijer's formula and the DgFlow simulations A and B. The lack of scale effects in the SD model on field scale (say $L > 10$ m) is not reflected in the simulations, even in case of boundary condition C. Although Hoffmans concludes that Sellmeijer et al. (2011) results in a H_c which is likely a factor 2 too small, we find a very good correspondence between the scale effects in Sellmeijer et al. (2011) and DgFlow. Furthermore, D3 shows the relation between simulated pipe gradient $S_{pipe,c}$ and upstream gradient $S_{sand,c}$. In contrast to the SD model, both the pipe gradient and upstream gradient calculated with DgFlow decrease with increasing L, while the ratio $S_{sand,c}$ / $S_{pipe,c}$ remains relatively constant. This deviates from Hoffmans' finding that "the Shields term (but not the Darcy term) governs both

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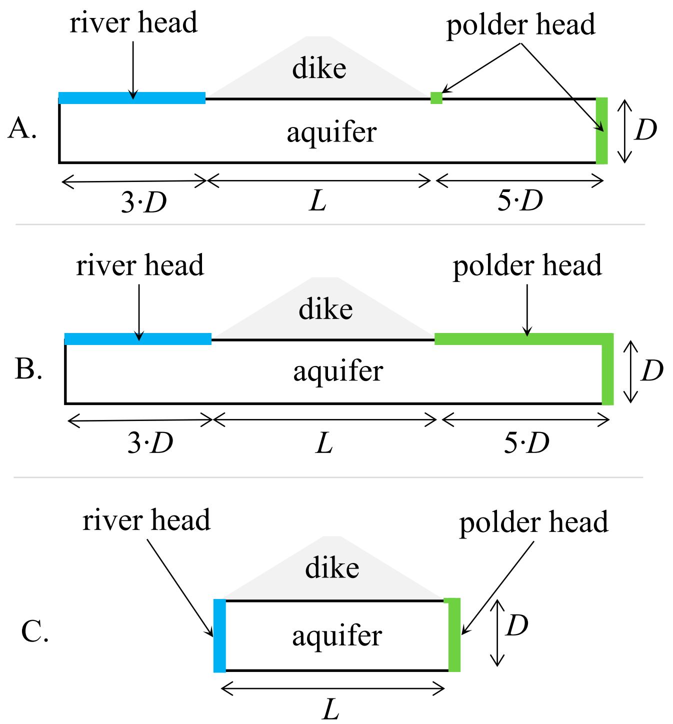

Figure D1 Illustration of boundary condition A, B and C in the DgFlow model set-up. No-flow boundaries are indicated in thin black, upstream (river) head boundary in blue and downstream (polder) head boundary in green

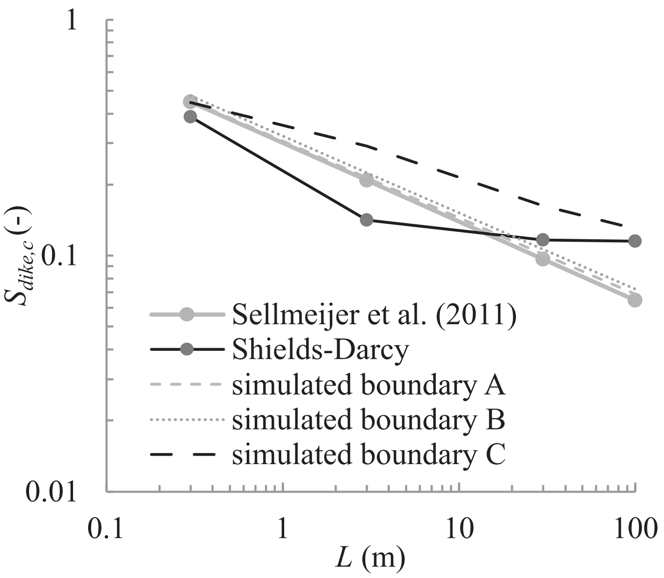

Figure D2 Critical overall gradient as function of scale

erosion and piping". Figure D3 also shows the simulated equilibrium pipe flow conditions. The increasing aquifer dimensions yield higher pipe discharges, resulting in deeper pipes and lower pipe gradients.

The increase of discharge (and resulting decrease of pipe gradient) with aquifer depth is expected for the impermeable boundary (A), as most flow passes through the pipe. However, similar scale effects are obtained with the fully permeable

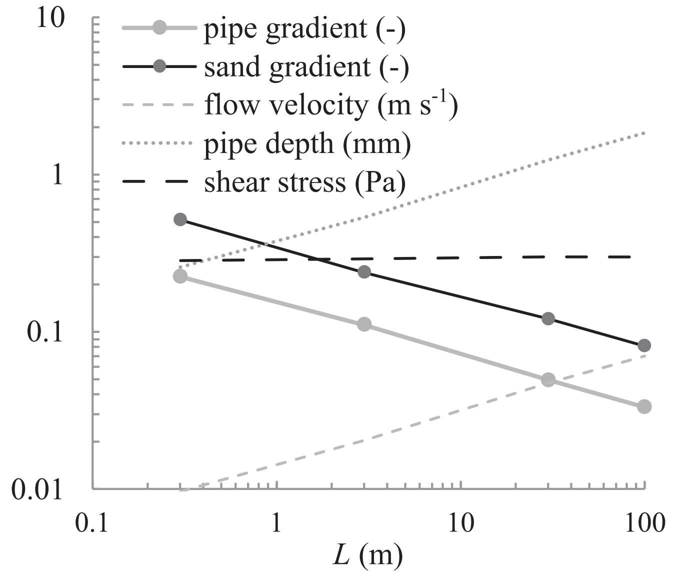

Figure D3 Critical gradients and pipe flow conditions halfway along the pipe (boundary condition A)

boundary condition B (Fig. D2), for which still about 60% of the discharge flows through the pipe. Hence, the presence of scale effects is not due to the impermeable boundary condition (A) used by Sellmeijer et al. (2011). Note that the discharge distribution may change in specific cases such as 3D seepage or layered aquifers, but these aspects are not modelled by either Sellmeijer and SD.

Discussion

An explanation for these different scale effects between SD model and DgFlow simulations is that the SD model assumes that the critical pipe discharge $q_{p,c}$ depends only on d_{50}, not on scale (Eq. 22). However, from experiments on fine Baskarp-sand (Van Beek et al., 2015) it can be estimated that the critical discharge is approximately a factor 9 larger for medium scale (L = 1.39 m) compared to small scale (L = 0.34 m). Similarly, the SD model assumes the critical Reynolds number halfway along the pipes (in the form of Reynolds coefficient α_{Re}) to be constant (Eq. 18). However, the DgFlow simulations suggest that both α_{Re} and $q_{p,c}$ depend on scale. Finally, the SD model assumption of hydrostatic pressure at the exit (boundary C) is too favourable as it forces most water to flow to the boundary instead of the pipe. For the simulated case, this results in a 50% higher H_c compared to case B.

As Hoffmans notes, the critical gradient by Sellmeijer et al. (2011) and DgFlow can decrease to lower values than found by Bligh (1910). However, we consider this not unrealistic for the situations analysed in this Discussion. This is mainly because the DgFlow model is physics-based: it fulfils the fundamental groundwater flow and pipe flow equations and the shear stress in the entire pipe equals its critical value. No assumptions are required on the distribution of flow to the pipe and polder or the magnitude of pipe discharges. Second, Bligh's cases include a significant vertical seepage path, which makes it questionable to compare Bligh's design rule directly to a model based on horizontal pipes.

For many field conditions, the SD model predicts a higher strength (H_c) than Sellmeijer et al. (2011). The introduction of the Shields diagram by Hoffmans and Van Rijn (2018) to model the pipe resistance is considered as a step forward. On the other hand, the analyses show that the SD model assumptions regarding the distribution of groundwater flow to the pipe and the polder determine the scaling effects and hence the higher H_c for field conditions. The DgFlow simulations presented here do not support those assumptions. This Discussion also reveals the need for systematic experimental research into scale effects of backward erosion piping, not only effects on the average gradient but also on pipe geometry and pipe flow conditions.

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Disclosure statement

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Notation

d_n = particle diameter, nth percentile of distribution (m)
D = aquifer thickness (m)
H_c = critical head difference (m)
k = hydraulic conductivity (m s^{-1})
L = seepage length (m)
$S_{dike,c}$ = H_c / L = critical global hydraulic gradient (–)
$S_{pipe,c}$ = critical hydraulic gradient in the pipe (–)
$S_{sand,c}$ = critical hydraulic gradient upstream of pipe (–)
$q_{p,c}$ = critical pipe discharge (m^2 s^{-1})
α_{Re} = calibrated Reynolds coefficient (–)

ORCID

JOOST POL http://orcid.org/0000-0001-6895-8256

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GIJS HOFFMANS (IAHR Member), Hydraulic Specialist, *Hoffmans Advice, The Hague, the Netherlands.*

Email: hoffmans.advice@outlook.com

1 Introduction

This Closure is focused on an issue that the Rijkswaterstaat and many Dutch water boards face. Based on Dutch legislation, the probability of failure in piping is so unrealistically high that experts doubt the computed seepage length, which is required to fulfil primary flood defences as agreed in Dutch law. Therefore, for prototype conditions, we discuss the unrealistic or realistic low critical dike gradients obtained from DgFlow (Van Esch & Sellmeijer, 2012), Sellmeijer II (Sellmeijer et al., 2011) and Shields–Darcy (SD).

DgFlow computes the groundwater flow with a finite element method. Herein, Laplace's equation, a differential equation based on Darcy's law and mass balance (the continuity equation), is numerically calculated. The pipe flow and particle