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V. M. van Beek
Deltares / Delft University of Technology, The Netherlands

Q. L. Yao
China Institute of Water Resources, China

M. A. Van
Deltares, The Netherlands

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V.M. van Beek
Deltares / Delft University of Technology
Delft – The Netherlands

Q.L. Yao
China Institute of Water Resources and Hydropower Research
Beijing – China

M.A. Van
Deltares
Delft – The Netherlands

ABSTRACT

Backward erosion piping, the process of shallow pipe development in the sandy foundation of levees, is a threat to the safety of levees in countries like China and the Netherlands. Several models are available to predict the required critical head for this phenomenon, i.e. Bligh's model and Sellmeijer's model. Well-documented breach cases, which unfortunately are rare, give the opportunity to verify the applicability of prediction models. In this paper two piping cases in China and one piping case in the Netherlands have been described and analyzed in order to compare the outcome of prediction models with this actual data. It is concluded that Bligh's model is easy to apply due to a small number of input parameters. The use of this model as a first step in safety assessment is limited due to the fact that it can give lower critical head predictions than the more accurate Sellmeijer model. On the other hand, the Sellmeijer model is more difficult to apply due to its sensitivity to permeability and grain size parameters. This sensitively results in a wide range for the critical head due to large uncertainties in the parameters. A probabilistic approach for parameter estimation combined with a more detailed soil investigation where necessary is recommended for a more accurate piping prediction.

INTRODUCTION

Backward erosion piping is a failure mechanism for levees and dams with permeable granular layers in the subsurface. The water flow through these layers during a flood can cause transport of particles, thereby initiating the development of shallow pipes at the interface of the sand layer and the overlying cohesive layer.
In China during the 1998 flood, several dike breaches occurred along the Yangtze River and Nenjiang River of which several were caused by piping (Yao et al., 2009). In history, levee failures caused by piping accounted for 90% of the total number of failures (Cao, 1994).
In the Netherlands, during the floods of 1993 and 1995, the water in the river reached a level of 0.50-1.50 m below design level. During these floods, respectively around 120 and 180 sand transporting sand boils were observed along the rivers Rhine, Waal, IJssel and Maas, indicating the susceptibility of Dutch levees to this mechanism. Although failure of the levees did not occur during these floods, several failures in the past are attributed to piping, like the failure near Zalk, Nieuwkuijk and Tholen (ENW, 2010). More recently, the flood in 2011 caused a large amount of sand transport along the Waal dike in Vuren.

The comparisons of breach case and predictions are interesting for the verification of applicability of the prediction models. Several prediction models are available to calculate the critical head, at which breach will occur, such as the empirical model of Bligh (1915) and the Sellmeijer model (Sellmeijer, 1988, Weijers et al., 1993, Sellmeijer et al., 2011). The presence of a sand boil does not directly result in a critical situation Sand boils can occur at a level lower than the critical head. For that reason real breach cases are very interesting for model verification. In this article, cases in China and the Netherlands are described and compared to the results of the Bligh and Sellmeijer model.

DESCRIPTION OF CASES

Three cases will be described for the verification of applicability of prediction models. These piping cases occurred during the floods in 1998 in China and 2011 in the Netherlands.

China

The 1998 flood in China resulted in many sand boils, but also in several dike breaches. Two of these breaches are attributed to piping and are well-documented.

The breach in the first case occurred on August 7th, 1998, in the Yanjiatai reach of the Mengxi dike ring at the right bank of the Hudu River, which is a tributary of Yangtze River. The Mengxi dike ring protected an area of 340.4 km2 of which 131 km2 was farmland. In the dike ring were 3 towns, 72 villages, and 156500 residents.

The piping process started with small sand boils in the pond behind the levee which became more critical in time. Despite of countermeasures (filter wells), the sand boiling and sand deposition continued, resulting in muddy flow from the wells and slope instability at the river side of the levee. The landside slope slipped down in the scope of 20m long with settlements of 0.5~1m, some longitudinal and transversal cracks of about 6 cm wide appeared on the surface of the dike. The final breach had grown to 185 m width (Yao et al., 2009). The time from the initial sand boil to complete failure was about one month, although the time span from muddy water to failure was only 25 minutes. Figure 1 shows the water level nearby the breach. The maximum head difference between river and pond was 6.7 m.

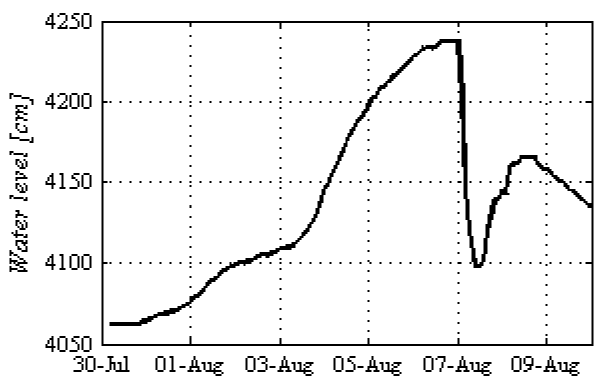

Figure 1: Water level at the Zhakou station from July 30 to August 10th(Yao et al. 2009)

The dike consisted of clay, with sandy loam, sand and clay layers in the subsurface (figure 2). Piping occured in the sand layer. The total seepage length in this layer is 63 m.

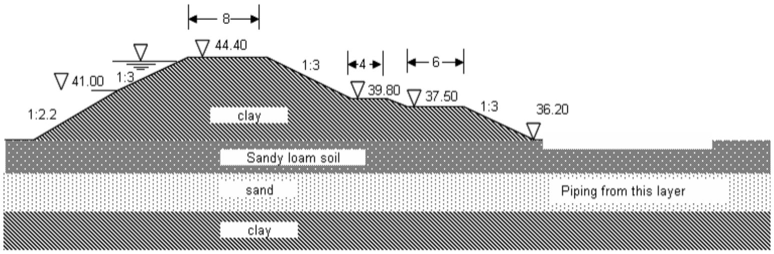

Figure 2: Cross section of the Mengxi dike (Yao et al., 2009)

The main properties of the subsoil layers are given in table 1.

Table 1. Mengxi dike subsoil characteristics

	Thickness D [m]	Permeability [m/s]	Grain size [mm]
(Fine) sand	2.0	1.6E-4 – 6.8E-3	0.25-0.05
Sandy loam	2.1 – 2.7	1.10E-04-9.30E-04	n.a.
Clay	unknown	8.20E-06 - 3.00E-05	n.a.

The breach in the second case occurred on August 1st, 1998, in the Paizhou dike (or named Hezheng dike ring), which was a farm dike situated at the right bank of the Yangtze River in Jiayu County, Hubei Province. The Paizhou dike was located at the largest meandering reach of the middle reach of the Yangtze River, and was 45 km away from Jiayu County and Wuhan City (Yao et al., 2009). The protected area of the Paizhou dike was the main economic development zone of Jiayu County. In addition, it was important to the flood control of the nearby area of Wuhan City. The Paizhou dike protected 32 villages, a population of 57048 people, 1039 km^2 farmland and 165 enterprises.

Despite of filter measures, small sand boils (with a ring of 0.15-0.20 m) turned into large sand boils (within 25 minutes) and breach (after 100 minutes) within short time. The total time from observation of the first sand boil to breaching was two days.

The water level was recorded at Paizhou Town station and Yongyi Gate, both located upstream of the breach position. The water level curves are presented in figure 3. Due to the breach no water level records were available at Paizhou Town station from August 2nd till August 12th. The water level of the breach location was 0.8 m lower than the recordings at Paizhou Town station and 1.9-2.0 m lower than the recordings at Yongyi gate station.

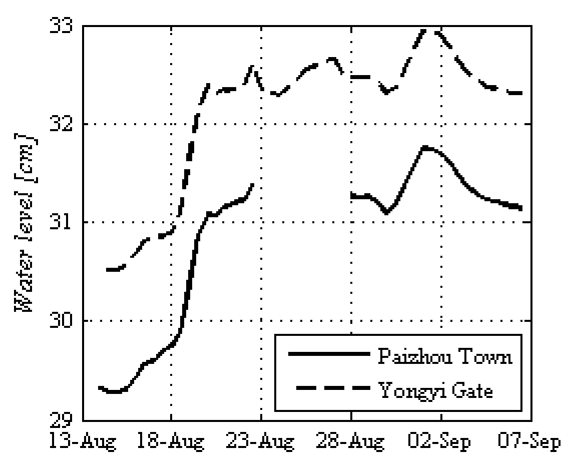

Figure 3: Water level at Paizhou Town station and Yongyi Gate (Yao et al., 2009)

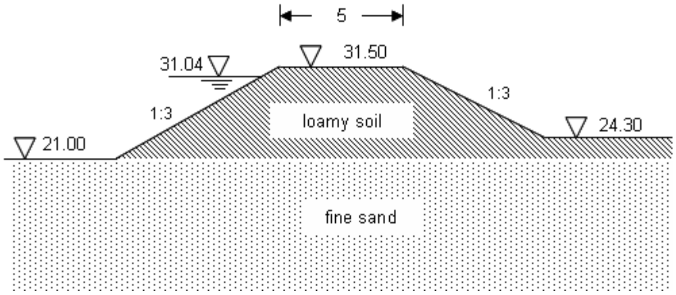

Figure 4: Cross section of Paizhou dike (Yao et al., 2009)

The cross section of the dike is shown in figure 4. The dike body and the top ground layer consisted of loamy soil. The dike foundation consisted of a fine sand layer with thickness of over 30 m. Below this sand layer a gravel layer was present. The main properties of the subsoil layers are displayed in table 2. The total seepage length, measured from upstream to downstream toe was 58 m.

Table 2. Paizhou dike subsoil characteristics

	Thickness D [m]	Permeability [m/s]	Grain size [mm]
Loamy soil	3.3 - 5	5E – 8	n.a.
Fine sand	> 30	0.6 – 2.4 E-4	0.25-0.05
Gravel	unknown	1.8E-3	n.a.

The Netherlands

Although sand boils are observed regularly in the Netherlands, registered breach cases due to piping are rare and date from early previous century. The limited documentation of these breaches does not allow for verification of prediction models. However, a recent flood (January 2011) caused a large sand boil at a section of the Waaldijk (hm403). Due to the large amount of sand transported, it is believed that the actual head drop has exceeded the critical head drop required for piping to progress to breaching in time. Therefore, this case is also used for model verification.

The dike is part of dike ring 43 (Betuwe, Tieler- en Culemborgerwaarden) and located at the north-side of the river Waal, near the village Vuren. The dike ring protects an area of 66.000 ha with an estimated population of around 250.000 people (Provincie Gelderland en Ministerie van Verkeer en Waterstaat, 2010).

The sand boil (shown in figure 5)was first observed at the 14th of January in a ditch (0.65 m-NAP, water level estimated to be 0.40 m-NAP), at this day the head difference between river and ditch was estimated to be 3.8 m. The water level during the flood period is shown in figure 6. As a counter measure sand bags have been placed around the well, which reduced but did not stop the sand transport. The total volume of transported sand is estimated to be 10 m^3.

Figure 5: Sand boil surround by sand bags (Picture by Laurens Pompe, Waterschap Rivierenland)

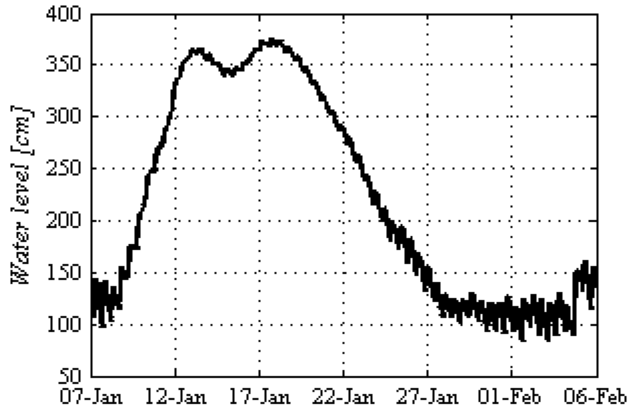

Figure 6: Water level during flood in 2011 in Vuren (www.waternormalen.nl)

The location of the sand boil is shown in figure 7 (black dot). Near the considered section the levee has been reinforced in 1995, for which sheet piles have been placed. The sheet piles near the sand boil location were placed to a depth of 11.5 m-NAP.

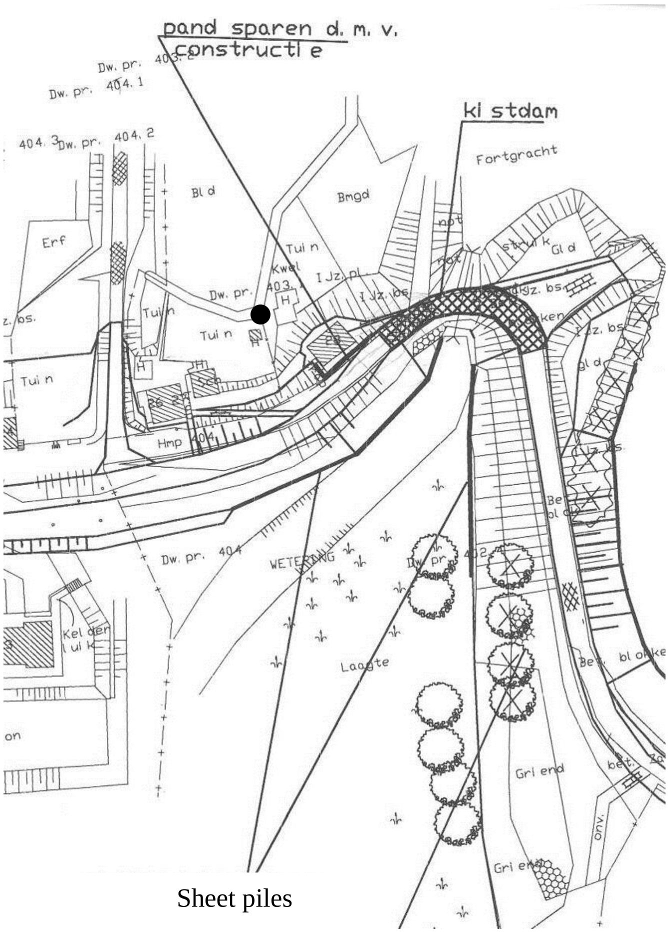

Figure 7: Schematized map of the Waaldijk near hm403

The subsurface geology is characterized by a soft soil layer of clay and peat, reaching to a depth of 8 m-NAP, locally intersected by sand channels (fine sand to silty sand). Below the soft soil layer the Pleistocene sand layer can be found (Kreftenheye Formation) with a thickness of 35 m.
Near location 'hm 404' the soft soil layer is intersected by a small sand channel at a depth of 5 m-NAP. Near 'hm 402' a larger sand channel is present from a depth of 1 m+NAP. This larger sand channel is presumably intersected by the sheet pile, which is considered to be impermeable. The two situations are schematized in figure 8 and 9.

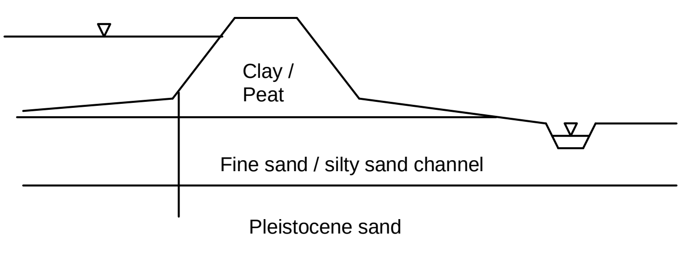

Figure 8: Scenario 1 - Dike cross section with large channel

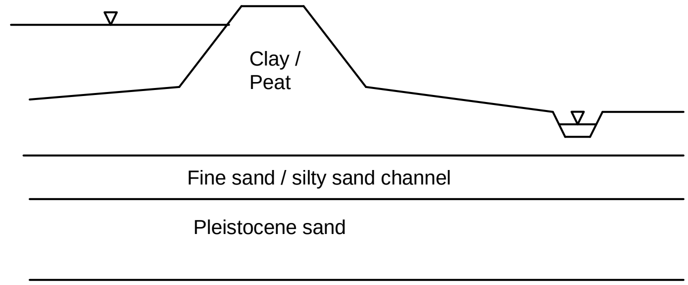

Figure 9: Scenario 2 - Dike cross section with small channel

As the subsurface is unknown at the exact location of the sand boil and the larger sand channel may extend slightly beyond the reach of the sheet piles, both configurations have been used in the model verification, thereby neglecting the influence of the sheet piles. Excluding the foreland, the total seepage length is estimated to be 58 m.
The grain size distribution of the sand found near the sand boil is determined in the laboratory for two sand samples. These two samples show a large variation (Table 3). Presumably, the coarsest sample is more representative, as this sample was found further from the sand boil and is therefore likely to reflect the characteristics of the sand transported during the highest water level.

Table 3. Grain size characteristics transported sand Waaldijk

	d50 [mm]	d70 [mm]	U [-]
Center of sand boil	0.092	0.113	2.7
At distance from center	0.259	0.367	3.2

The subsoil characteristics are summarized in table 4.

Table 4. Subsoil characteristics Waaldijk

	Thickness D [m] – 1*	Thickness D [m] – 2*	Permeability [m/s]	Grain size [mm]
Clay / Peat	0	4.4	n.a.	n.a.
Sand	42	38	8E-4	0.367

*1: scenario 1 – large channel, 2: scenario 2 – small channel

MODEL VERIFICATION

The models used in the verification are Bligh's empirical model and Sellmeijer's model. With these models a critical head drop H_c can be calculated to be compared with the actual head drop across the levee. In Dutch practice, it is common to correct the actual head drop for the presence of a top soil layer at the seepage exit point. The head loss as a result of the vertical seepage path through the top soil layer allows for a reduction of actual head drop equal to 1/3 of the total vertical seepage path (TAW, 1999), resulting in:

$$\left(H-0.3\cdot d\right)\leq H_c$$

In which *d* represents the thickness of the soft soil layer and *H* the actual head drop and *Hc* is the critical head drop.
Bligh's model assumes a linear relationship between head drop and seepage length, characterized by the percolation coefficient *c* (Bligh, 1915).

$$L=c\cdot H_c$$

For the considered sand types the percolation coefficient can be taken as 18.
Sellmeijer's model is a semi-theoretical model which considers the equilibrium of grains at the bottom of the pipe. This criterium depends on the flow through and towards the pipe. Using this model the critical head is calculated as the head drop at which the grains are in equilibrium. The model has been calibrated and adapted by large-scale and small-scale experiments (Sellmeijer et al., 2011).
The critical head drop has been calculated for the two Chinese cases and the Dutch case using the two models. No safety factors or conservative estimates have been applied, as the goal is to calculate the critical head as precise as possible.

Calculation of Critical Head for Mengxi Dike

As can be noted from table 1 the input parameters required for the calculation of critical head are not exact numbers, but give a range of values. The thickness of the soft soil top layer ranges from 2.1-2.7 m. For the calculation an average of 2.4 m is used. For permeability and grain size the entire range of estimated input values is used to estimate a range of critical head drops.
Table 5 shows the results of the calculation using the Bligh model, compared to the actual head drop, corrected for the soft soil top layer. Figure 10 shows the range of critical head drops, as calculated by Sellmeijer's model.

Table 5. Critical head drop Bligh and actual head drop

	Hc_Bligh [m]	H-0.3d [m]
Mengxi dike	3.5	6.0

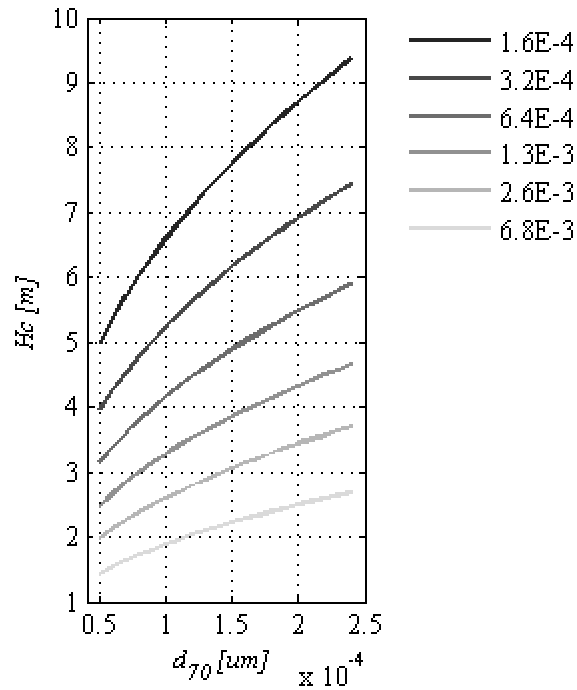

Figure 10: Critical head drop Sellmeijer model for Mengxi Dike ring as function of d_{70} for different permeability values (m/s)

Calculation of Critical Head for Paizhou Dike

Just as for the Mengxi dike, uncertainty exists for input parameters of Paizhou dike. The thickness of the soft soil layer near the exit point is 3.3 – 5 m. For the calculation, an average of 4.2 m is used. Insufficient data is available with respect to the soil conditions at greater depth. The fine sand layer is estimated to be at least 30 m thick, and underlain by gravel of unknown thickness. As the thickness of the fine sand layer is considerable, the river does presumably not cut through this layer and the gravel layer is assumed to have little influence on the flow towards the pipe. It is assumed that the fine sand layer will be between 30 and 50 m in thickness. The Sellmeijer rule shows that for this case the influence of thickness of the sand layer is limited and that for an increase of 30 m to 50 m the critical head decreases with less than 10%. The thickness is therefore assumed to be 30 m.
For permeability and grain size the entire range of estimated input values is used to estimate a range of critical head drops. Table 6 shows the results of the calculation using Bligh's model and the actual head drop, corrected for the soft soil top layer. Figure 11 shows the range of critical head drops, as calculated by Sellmeijer's rule.

Table 6. Critical head drop Bligh and actual head drop

	Hc_Bligh [m]	H-0.3d [m]
Paizhou dike	3.2	5.5

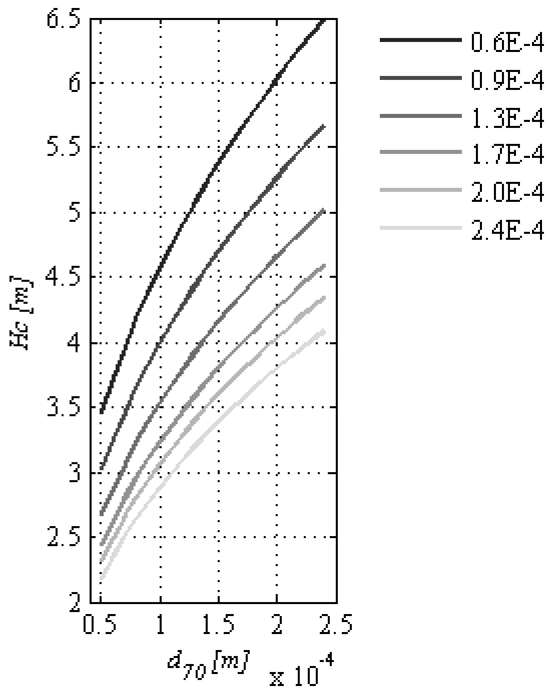

Figure 11:Critical head drop Sellmeijer model for Paizhou Dike ring as function of d_{70} for different permeability values (m/s)

Calculation of Critical Head for the Waal Dike (nearby Vuren)

For the Waal dike the input parameters do not show a large range. There is some uncertainty with respect to the subsurface conditions though, due to which two scenarios have been set up. The first scenario (figure 8) is based on the presence of a large sand channel intersecting the soft soil layer. Though it is expected that the sheet piles will form an impermeable barrier, it is unknown whether the large channel extends beyond the sheet piles in lateral direction. For critical head prediction, the sheet piles are therefore neglected in this scenario. The second scenario, shown in figure 9, is based on subsurface data west of the sand boil location, showing a smaller sand channel intersecting the top soft soil layer.

Table 7 shows the results of the calculation using Bligh's and Sellmeijer's model and the actual head drop, corrected for the soft soil top layer, for the two scenarios.

Table 7. Critical head drop Bligh, Sellmeijer and actual head drop for scenario 1 and 2

	Hc_Bligh [m]	Hc_Sellmeijer	H-0.3d [m]
Waal dike – 1	3.2	3.1	3.8
Waal dike – 2	3.2	3.1	2.5

DISCUSSION AND CONCLUSIONS

Two breach cases from China and one piping case from the Netherlands have been analysed to compare the outcome of prediction models with actual data. The two considered models are the empirical model of Bligh and Sellmeijer's model.

For the Chinese cases Bligh's model appears to be conservative, whereas for the Dutch case the actual head difference is more or less equal to the predicted critical head using Bligh's model.

Due to the wide range of input parameters, a wide range of critical head drops is obtained for the Chinese cases using Sellmeijer's model. Using average input parameters the model predictions are very similar to the actual head drops, with calculated critical heads being more close to the actual heads than the Bligh model. Using conservative input data, however, the Sellmeijer model results in very conservative critical heads.

For the Dutch case the predictions using Sellmeijer's model are similar to, and slightly lower than, the predictions using Bligh's model. Both prediction models are close to the actual head drops.

It is clear that Bligh's model is easier to apply than Sellmeijer's model, as it requires less input data. In Dutch practice, the model has therefore been used as a first step in safety assessment for many years. However, it appears that in some cases the critical head as estimated by Bligh's model exceeds the critical head as estimated by the Sellmeijer model, which is expected to be more accurate as influence of scale and sand characteristics can be taken into account.

On the other hand, the cases show that the use of the Sellmeijer model can result in larger uncertainties. The model is sensitive to input parameters like permeability and grain size, resulting in a wide range of possible critical heads. The use of conservative assumptions for the input parameters may lead to unrealistic high failure probabilities. A probabilistic approach for parameter estimation combined with more detailed soil investigation where necessary would therefore be a step forward in piping prediction.

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