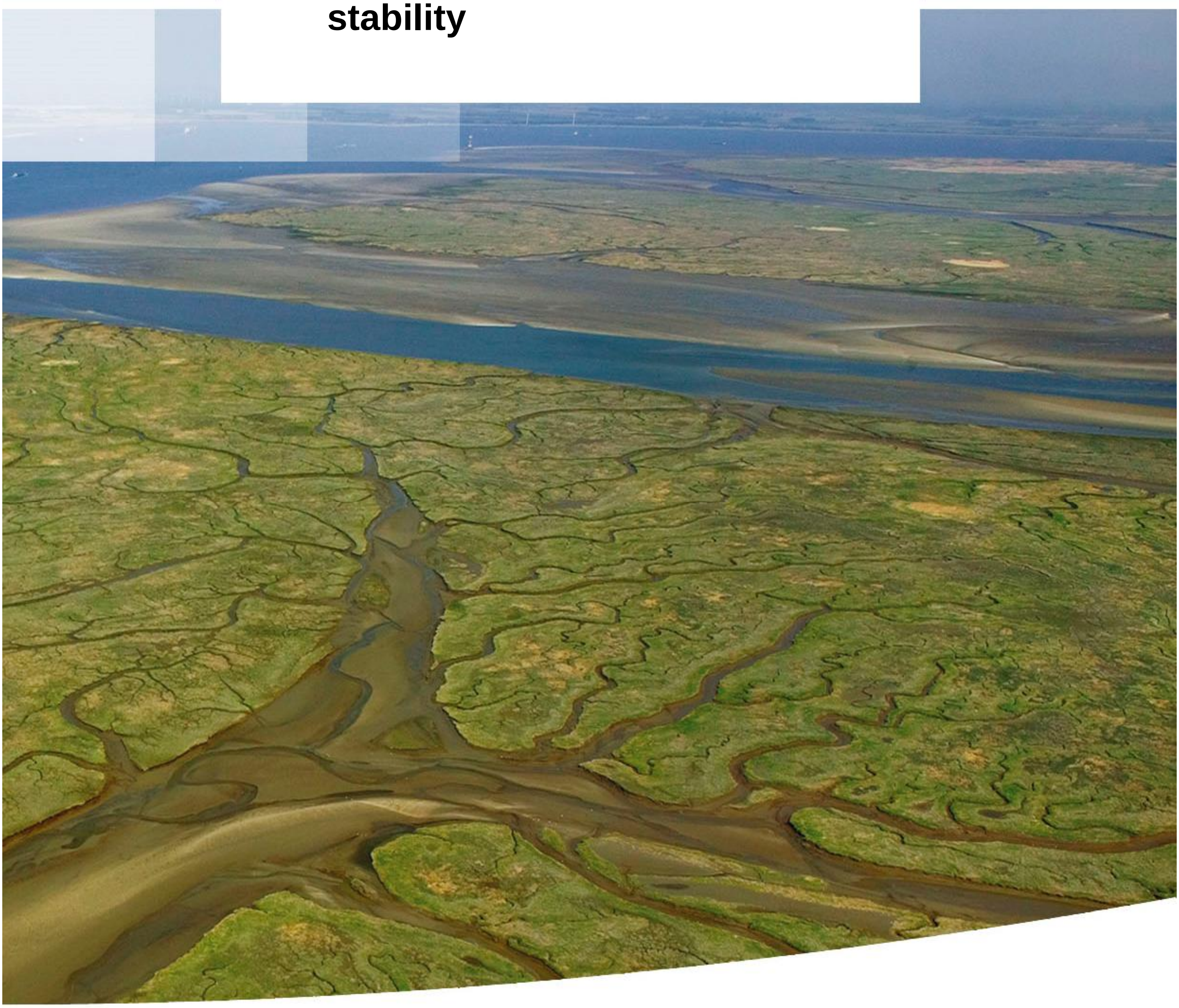
# Memo: Pore water pressure uncertainties for slope stability



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# Memo: Pore water pressure uncertainties for slope stability

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**Title**
Memo: Pore water pressure uncertainties for slope stability

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**Trefwoorden**
Pore water pressure uncertainties, slope stability inner slope, dikes

**Samenvatting**
Pore water pressures (pwp) can have a significant impact on the inner slope stability of dikes (STBI). Ignoring uncertainties in pore water pressures can thus lead to a serious over or under estimation of slope stability. There are two projects for which the pwp uncertainties currently are of major importance: Reliability Updating using Past Performance (RUPP) and calibration of safety factors for slope stability. The goal of this memo is to describe the general implementation of pore water pressure uncertainties and the specific implications for RUPP and Calibration.

General pore pressure uncertainties are described in Rozing (2015). This memo describes how these uncertainties can be implemented in slope stability computations. The following uncertainties are considered: leakage length, intrusion length and phreatic line. Furthermore, a new uplift strength reduction model is proposed for probabilistic computations. The implementation of pwp uncertainties is tested for various possible dikes that are representative for the upper and lower river area in the Netherlands.

In general it is concluded that pwp uncertainties can have a significant impact on the failure probability of STBI; although the impact is very case specific. Furthermore it can be implemented for slope stability analysis and no major implementation issues are expected in terms of convergence problems beyond what is regularly encountered in probabilistic slope stability analyses in general. It is recommended to apply the implementation of pwp uncertainties for calibration and RUPP. Uncertainties in the phreatic line are recommended to be implemented as scenarios in RUPP and as stochastic variables in the calibration. Leakage length and intrusion length are recommended to be implemented as stochastic variables in both projects.

**Referenties**
Please refer to Chapter 7.

| Versie | Datum | Auteur | Paraaf | Review | Paraaf | Goedkeuring | Paraaf |
|---|---|---|---|---|---|---|---|
| 1 | april 2016 | dr.ir. W. Kanning | | dr.ir. T. Schweckendiek | | dr.ir. M.S. Sule | b/a |
| | | | | ing. A.P.C. Rozing | | | |

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# Contents

# 1 Introduction

## 1.1 Rationale and goal

Pore water pressures (pwp) can have a significant impact on the inner slope stability of dikes (STBI). Ignoring uncertainties in pore water pressures can thus lead to a serious over- or under estimation of slope stability. General pore pressure uncertainties are described in Rozing (2015). There are two projects for which the pwp uncertainties currently are of major importance: Reliability Updating using Past Performance (RUPP; Schweckendiek and van der Krogt, 2015) and calibration of safety factors for slope stability (Kanning et al, 2015).

The goal of this memo is to describe the general implementation of pore water pressure uncertainties and the specific implications for Reliability Updating and Calibration.

The words blanket and aquitard are used throughout this paper to describe the relatively weak, low permeable layer between aquifer and ground surface or dike body. Furthermore, some variables, such as the outside water level, have various names in the used software. The variable names as used in the software are presented in the result tables, which sometimes leads to multiple variable names for the same variable.

## 1.2 Scope

The modeling of pore water pressure (pwp) in the semi-probabilistic approach is typically either done based on measurements or on conservative defaults. The semi-probabilistic defaults are described in TAW (2004) and are implemented in the WBI WaternetCreator (WNC). The WNC is the starting point for this memo, based on which pwp uncertainties are implemented.

## 1.3 Approach

The approach is as follows:

- First, the current assumptions on pwp implementation in the WNC are described (CH2).
- Next, uncertainties pwp uncertainties are discussed (CH3).
- The implementation of pwp uncertainties is presented in CH4.
- The implications for the projects reliability updating and calibration are finally discussed in CH5.

The subsequent cases are used to illustrate pwp uncertainty effects and its implementation:

1. Bovenrivierengebied case: a fictitious example with a relatively thin blanket, typical for the Dutch upper river area.
2. Benedenrivierengebied case: a fictitious example with a relatively thick blanket, typical for the Dutch lower river area.

# 2 Pore water pressure description and modeling

## 2.1 Dike types

The WNC distinguishes four types of dike, based on the dike's core and subsoil, see *Table 2.1*.

| | Dike core | |
|---|---|---|
| | | 1 Clay/peat | 2 Sand |
| **subsoil** | A Clay/peat | 1A | 2A |
| | B Sand | 1B | 2B |

*Table 2.1 Dike types in the Waternet Creator*

## 2.2 Overview pore water pressure parameters

### 2.2.1 General

Within the WNC, there are three aspects in pore water pressures:

1. Phreatic line: hydraulic head in the dike body (PL1)
   a. During daily conditions: a minimum level, calculated with the Dupuit-formula.
   b. During high water: use of offsets of the level relative to the outside water level.
2. Leakage length: how far do excess water pressures propagate in the sand layer (PL3).
3. Intrusion length: how far do pore water pressures from the sand layer intrude in the clay/peat subsoil layer until they reach the daily pressures (PL2).

These three aspects are parameterized in the WNC.

### 2.2.2 Implementation

These 3 aspects are modelled in the Waternet Creator for the 4 dike types and can be manipulated for probabilistic computations. For case 1A, the effects WNC modeling of phreatic line (Figure 2.1), heads in sand layer (Figure 2.2) and intrusion (Figure 2.3) are presented. For the other dike types, please refer to TAW (2004).

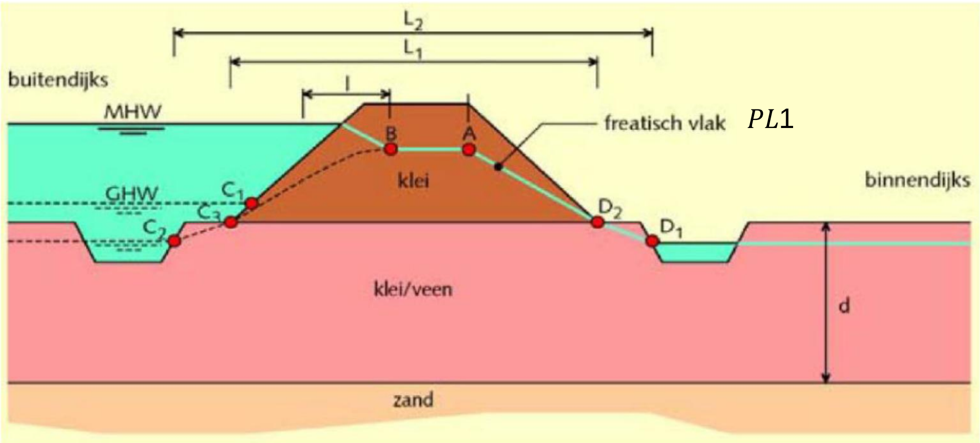



*Figure 2.1 Modeling of the phreatic line (PL1), dike type 1A (based on TAW, 2004)*

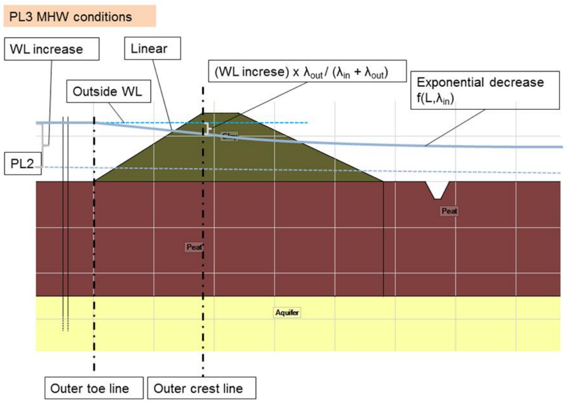



*Figure 2.2 Modeling of the pressures in sand layer as function of outer water level (PL3), (based on TAW, 2004)*

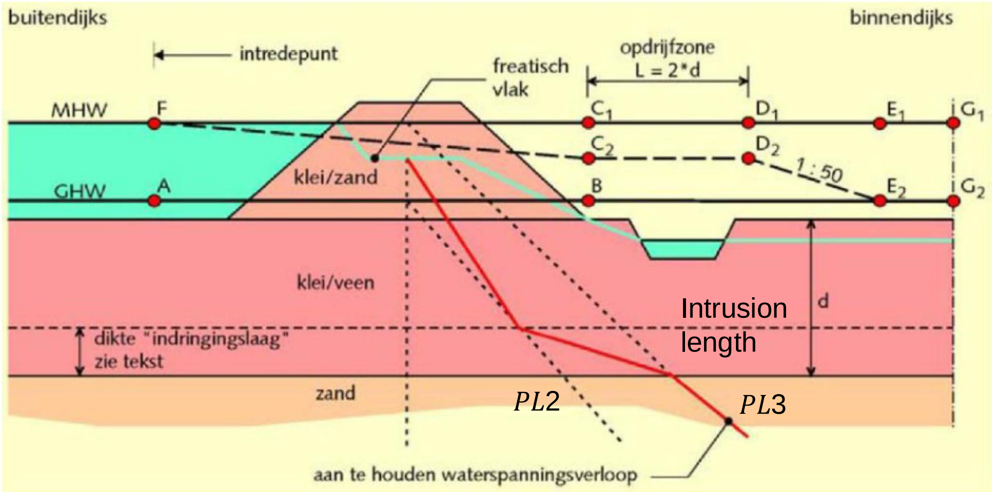



*Figure 2.3 Modeling of the intrusion length that shows transition between PL2 and PL3, dike type 1A, (based on TAW, 2004)*

These three effects and their implementation in the WNC are further elaborated in the subsequent sections.

## 2.3 Phreatic line

The phreatic line describes the pore pressure in the dike body. During daily conditions, the phreatic line is typically higher in the lower river area than the outside water level (WL) due to precipitation and evaporation (Figure 2.4). For the upper river area the offset of the phreatic line may be 0. This is modeled in the WN with a point below the outer crest and a point below the inner crest. As the outside WL increases, generally the phreatic line also increases (Figure 2.5), except for dikes with a relatively impermeable core and high initial phreatic level. The phreatic line is modeled in the WNC by offsets: one offset at the outer crest, one offset at the inner crest and small offsets at the toe and berm (if present). The default offsets of Figure 2.5 are based on a Clay on Clay dike and are 1 m (outer crest) and 1.5m (inner crest); see Table 2.2. These are considered conservative values. The uncertainties provided in Rozing (2015) can be used for a stochastic incorporation of the phreatic line. For low water levels, the level of the phreatic line is limited by a minimum level (calculated by e.g. the Dupuit formula; see e.g. Appendix of Rozing, 2015). There is linear interpolation between the points.

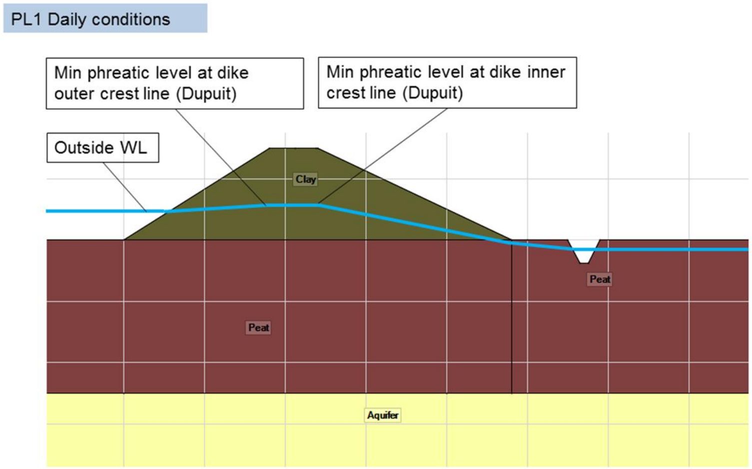



*Figure 2.4 Phreatic line in daily conditions*

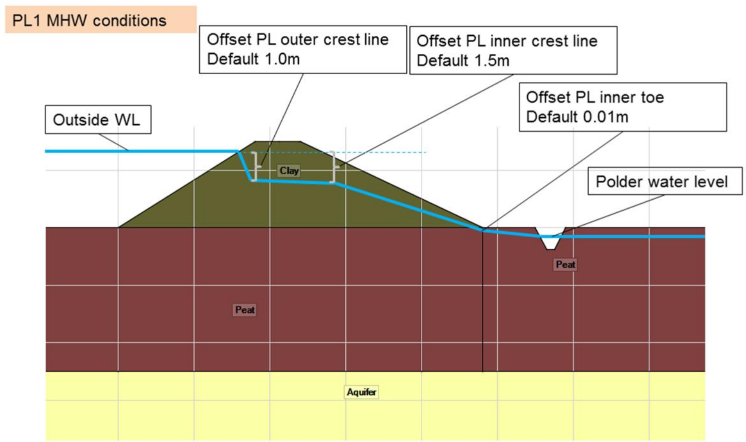



*Figure 2.5 Phreatic line during extreme (MHW) conditions*

## 2.4 Pore pressures in the aquifer

The modelling of pwp in the WNC is further elaborated in van der Meij et al (2014). The pore water pressure in dikes are modelled in the WNC using Piezometric Lines (PL), which show the piezometric head at various lines and typically use interpolation between these lines to determine the pwp in the each point. The pore water pressures in the aquifer during extreme events are determined by two effects:

1. The pressure in the aquifer during daily conditions (PL2), Figure 2.6.
2. The pressure increase during extreme conditions (PL3), Figure 2.7.

PL2 is determined in the WNC by the minimum of water level during daily conditions (GHW) and a user input of the PL2 (see eqn. 2.1). For an open connection at the outside water level and long duration of GHW, these values will be similar on the outer side of the dike:

$$PL2_{outer,calc} = \min(GHW, PL2_{outer,input}) \quad (2.1)$$

where $PL2_{outer,input}$ is input in Waternet Creator and $PL2_{outer,calc}$ is the result of eqn. 2.1. The PL2 line is constructed by linearly interpolating the PL2 at the outer side of the dike ($PL2_{outer,calc}$) to PL2 at the land side.

The PL3 describes the piezometric head for an increased outside water level (MHW). The PL3 line is determined in two steps:

1. The PL3 at the outer crest is determined by the leakage length (resistances) of the peat/clay aquitard on the inside ($\lambda_{in}$) and outside ($\lambda_{out}$):
$$PL3_{outer,crest} = \frac{MHW - GHW}{1 + \frac{\lambda_{out}}{\lambda_{in}}} + PL2_{outer,crest} \quad (2.2)$$
The PL3 line from the outside to this point is a linear interpolation
2. The PL3 line from $PL3_{outer,crest}$ to the landside (*PL3(x)*) is an exponential decrease according to eqn 2.3.
$$PL3(x) = (PL3_{outer,crest} - PL2_{outer,crest}) \cdot e^{-\frac{x}{\lambda_{in}}} + PL2(x) \quad (2.3)$$
Where *x* is the distance from the outer crest and *PL2(x)* is the value of the PL2 at *x.*

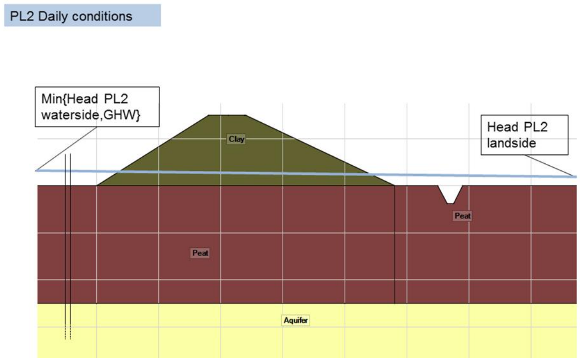



*Figure 2.6 Pore pressure aquifer during daily conditions*

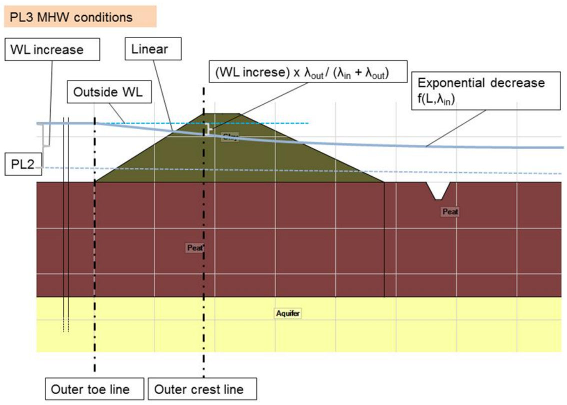



*Figure 2.7 Pore pressure aquifer during extreme conditions*

## 2.5 Intrusion aquifer pressures into clay/peat layer and total pwp

The increased pwp in the aquifer due to a higher outer WL (PL3) vertically intrudes in the peat/clay aquitard. How far this excess pwp intrudes is modeled with the intrusion length (IL). The effect of IL is shown in Figure 2.8 and Figure 2.9. During daily conditions, Figure 2.8, the pwp is obtained by a linear interpolation between the phreatic line (PL1) and head in the aquifer (PL2). During extreme water levels, the higher pwp in the aquifer (PL3), intrude into the clay/peat aquitard according to the IL. Above the zone that is influenced by intrusion (modeled by the intrusion length), there is a linear interpolation between PL1 and PL2. In the

intrusion zone, there is a linear interpolation between the PL2 head and the PL3 head, see Figure 2.9.
With new versions of the WNC, it is possible to model hydrostatic pressure in the dike body. In this case, from the end of the hydrostatic pressure (typically transition dike core to subsoil layer), there is linear interpolation to the intrusion zone.

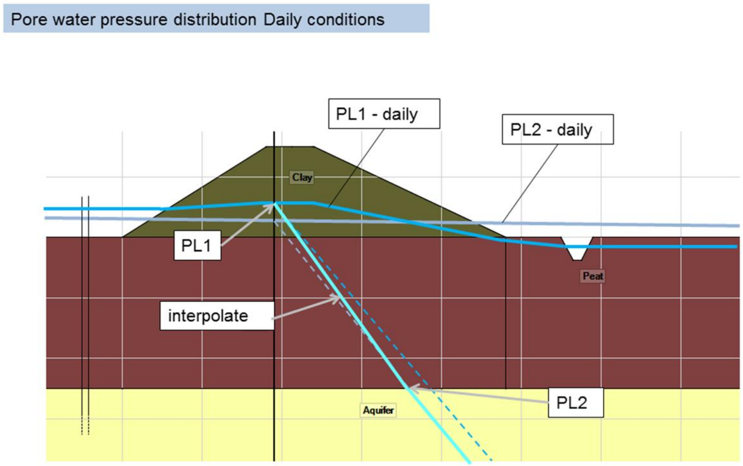



*Figure 2.8 Pore water pressure during daily conditions*

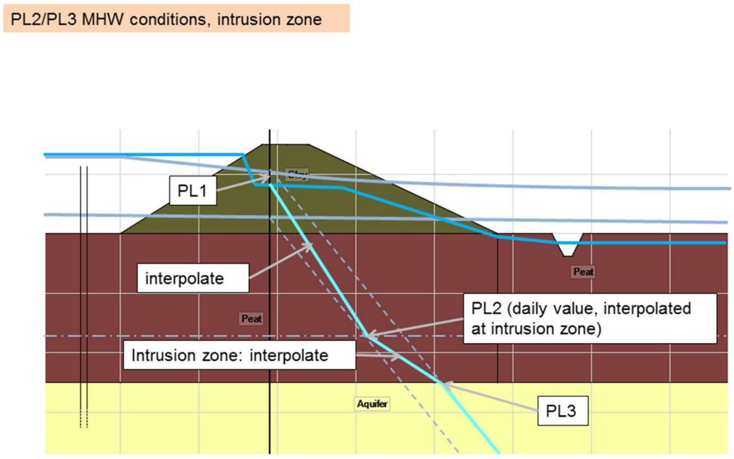
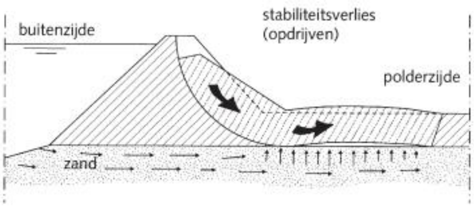



*Figure 2.9 Pore water pressure during extreme conditions*

There is a special condition in the WNC: in case the IL is larger than approximately half the aquitard thickness, the IL approach is not deemed conservative enough and IL should be (manually) set to 0. If the IL is set to 0, this implies that the pwp are interpolated between PL1 and PL3 along the vertical which would be the more conservative choice.

## 2.6 Uplift/rupture strength reduction

The pwps influence the occurrence of uplift (in Dutch: “opdrijven”) or rupture of the blanket due to local zero effective stresses. In case of uplift, a local reduction of effective stresses (at the interface of blanket and aquifer) reduces the local shear strengths to 0 at the mentioned interface. In case of rupture, the whole blanket ruptures and no shear strength can be mobilized along the part of the slip circle that is within the uplift zone.




*Figuur 5.3.3 Opdrijven*

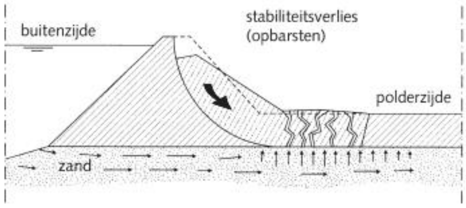



*Figure 2.10 Uplift (opdrijven) vs rupture (opbarsten), source: TAW (2001).*

In the current assessment guidelines VTV (Ministerie Verkeer en Waterstaat, 2007), it is stated that in case of a safety factor for uplift ($N_{uplift}$ based on total heads/weights) lower than 1.2, there is rupture and no shear strength ($s_{u,reduced}$) may be used in the computation of the safety factor, see Figure 2.11. In D-Geo Stability this is implemented as:

$$s_{u,reduced} = 1 \cdot s_{u,calc} \text{ for } N_{uplift} > 1.2 \quad (2.4)$$
$$s_{u,reduced} = 0 \cdot s_{u,calc} \text{ for } N_{uplift} \leq 1.2 \quad (2.5)$$

The safe default of 1.2 is likely not appropriate for probabilistic computations, see Section 3.4. The boundary of $N_{uplift}$ = 1.2 is chosen in according with TRWG to connect between Bishop and Uplift Van (see TAW, 2001); this topic is currently re-evaluated within the “POVM – Opbarsten”. Furthermore, PL3 is adjusted for uplift to avoid negative pore pressures (such that $N_{uplift}$ = 1).

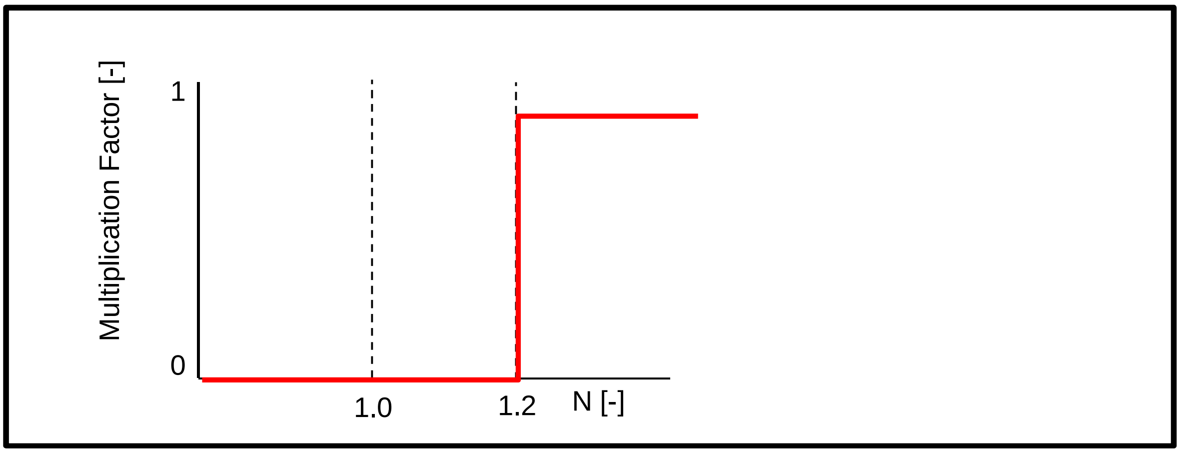



*Figure 2.11 Multiplication factor N for blanket rupture in current implementation based on VTV (Ministerie Verkeer en Waterstaat, 2007)*

## 2.7 Overview parameters and modeling Waternet Creator for various dike types

### 2.7.1 Overview default values WNC for various dike types

An overview if the default WNC values for the 4 dike types of Section 2.1 is presented in *Table 2.2*. The values of parameters 2-5 are conservative estimates according TAW (2004), other values are used input ('Local var.'). For the phreatic line, mainly the dike body is of interested and hence the phreatic line in 1A is equal to the phreatic line in 1B and 2A's line is equal to 2B's line since these have the same dike body.

| # | Parameter | Description | Default values WNC [m] | | | |
|---|---|---|---|---|---|---|
| | | Dike type | 1A | 1B | 2A | 2B |
| | *PL1 Phreatic line* | | | | | |
| 1 | WL | Outside water level | Local var. | Local var. | Local var. | Local var. |
| 2 | B | PL1 offset outer slope | 1.0 | 1.0 | $0.5h_w$ | 0 |
| 3 | A | PL1 offset landside crest | 1.5 | 1.5 | Interp. | Interp. |
| 4 | D2 | PL1 offset shoulder berm - optional | 0.01 | 0.01 | | |
| 5 | D1 | PL1 offset toe | 0.01 | 0.01 | $–0.25h_w$ | $–0.25h_w$ |
| 6 | PWL | Polder water level | Local var. | Local var. | Local var. | Local var. |
| 7 | | Minimum level phreatic line at dike top outside (daily phreatic line) | Local var. | Local var. | Local var. | Local var. |
| 8 | | Minimum level phreatic line at dike top inside (daily phreatic line) | Local var. | Local var. | Local var. | Local var. |
| | *PL2 Intrusion* | | | | | |
| 9 | | Head PL2 during daily conditions outside | Local var. | Local var. | Local var. | Local var. |
| 10 | | Head PL2 during daily conditions inside | Local var. | Local var. | Local var. | Local var. |
| 11 | | Intrusion length | Local var. | Local var. | Local var. | Local var. |
| 14 | GHW | Outside water level daily conditions | Local var. | Local var. | Local var. | Local var. |
| | *PL 3 Leakage length* | | | | | |
| 12 | $\lambda_{out}$ | Leakage length outside | Local var. | Local var. | Local var. | Local var. |
| 13 | $\lambda_{in}$ | Leakage length inside | Local var. | Local var. | Local var. | Local var. |
| 14 | GHW | Outside water level daily conditions | Local var. | Local var. | Local var. | Local var. |
| 15 | HeadPL3 | Needed for the WNC to run with new WL; is equal to WL | WL | WL | WL | WL |

*Table 2.2 Default deterministic values WNC*

### 2.7.2 Various options WNC

Next to the above described modeling of pwp in the WNC, the following options are present, e.g. :

- Drainage construction for 2A and 2B.
- PL4: $\lambda_{out}$ and $\lambda_{in}$ in case of second inbetween aquifer (tussenzandlaag).

However, these are not further discussed in this memo.

# 3 Uncertainties in pore water pressures

This chapter describes estimates of uncertainties in the various parameters that determine the pwp as well as the implementation of these using probabilistic software.

## 3.1 Default uncertainty estimates

Default uncertainty estimates based on Rozing (2015) are provided in Table 3.1. These will be used in the remainder of this memo to investigate the influence of pwp uncertainties. For the location of the mentioned points, please refer to Figure 2.1 and Figure 2.3.

| | | Measurements or computations available? | Uncertainties pore water pressures 1) | | | |
|---|---|---|---|---|---|---|
| | | | case 1A<br>Clay on clay | case 1B<br>Clay on sand | case 2A<br>Sand on Clay | case 2B<br>Sand on sand |
| Phreatic level | PL-1 | yes | point B and C: std 0.3m | point B and C: std 0.3m | point C2: std 0.1*h<br>point D1: std 0.05*h | point C2: std 0.15*h<br>point D1: std 0.05*h |
| | | no | point B and C: mean with Dupuit 2) and std 0.9m | point B and C: mean with Dupuit 2) and std 0.9m 6) | point C2: mean 0.33*h and std 0.1*h<br>point D1: mean 0.16*h and std 0.05*h | point C2: mean 0.75*h and std 0.15*h<br>point D1: mean 0.16*h and std 0.05*h |
| Heads in aquifer | PL-2 | yes | std 0.10m | std 0.2m | std 0.10m | Not applicable; Hydrostatic pwp with respect to PL1 |
| | | no | when mean from ground water maps: std 0.3m<br>or<br>mean with eqn 3 and 4 3) and CoV 0.2 for leakage length | std 0.2m | when mean from ground water maps: std 0.3m<br>or<br>mean with eqn 3 and 4 3) and CoV 0.2 for leakage length | Not applicable; Hydrostatic pwp with respect to PL1 |
| | PL-3 | yes | std 0.2m<br>or<br>mean with eqn 1 and 2 4) and CoV 0.1 for leakage length | std 0.2m | std 0.2m<br>or<br>mean with eqn 1 and 2 4) and CoV 0.1 for leakage length | Not applicable; Hydrostatic pwp with respect to PL1 |
| | | no | std 0.4m<br>or<br>mean with eqn. 1 and 2 4) and CoV 0.2 for leakage length | std 0.2m | std 0.4m<br>or<br>mean with eqn. 1 and 2 4) and CoV 0.2 for leakage | Not applicable; Hydrostatic pwp with respect to PL1 |
| Intrusion length | | yes | CoV 0.5 for Cv 7)<br>or<br>CoV 0.2 on the mean of intrusion length L' | CoV 0.5 for Cv 7)<br>or<br>CoV 0.2 on the mean of intrusion length L' | CoV 0.5 for Cv 7)<br>or<br>CoV 0.2 on the mean of intrusion length L' | Not applicable |
| | | no | lower river area and coast: mean based on 9) and CoV 0.3 on L'<br>other areas: no intrusion lenght 5) | lower river area and coast: mean based on 9) and CoV 0.3 on L'<br>other areas: no intrusion lenght 5) | lower river area and coast: mean based on 9) and CoV 0.3 on L'<br>other areas: no intrusion lenght 5) | Not applicable |
| Remarks: | | | | | | |
| 1) mean; std = standard deviation; CoV = Coefficient of Variation; h is outside water level; | | | | | | |
| 2) Equation of Dupuit, see Section 4.3.1 in Rozing (2015) | | | | | | |
| 3) Equation 3 and 4 to compute PL-2 with leakage lengths (see Section 4.3.2 from Rozing, 2015) | | | | | | |
| 4) Equation 1 and 2 for computation PL-3 with leakage lenghts (see Section 4.3.2 from Rozing, 2015) | | | | | | |
| 5) No intrustion length means pwp are assumed linear from PL-1 to the bottom of the blanket | | | | | | |
| 6) Computation of mean of the level of the phreatic line with the equation of Dupuit will result in a value that is too high since the draining capacity of the | | | | | | |
| 7) Cv is consolidation coefficient. A lower value of CoV can be used if this can be substantiated | | | | | | |
| 8) Eqn. 5 for the computation of intrusion length L' (see section 4.3.3 of Rozing, 2015) | | | | | | |
| 9) Table 2 based on 'Indrining van waterspanning in samendrukbare gelaagde grondpakketten', dr. S. Schoofs and ing. T.A. van Duinen. Geotechniek Januarai 2006 (see Section 4.3.3 of Rozing 2015) | | | | | | |

*Table 3.1 Summary table default uncertainties translated from Rozing (2015).*

## 3.2 Implementation uncertainties in probabilistic software

With the version of D-Geo Stability of December 2015 that uses the WNC, it is not possible to define PL-lines manually, though it is possible to manipulate leakage length, intrusion length and phreatic line using parameters as defined in *Table 2.2*. This option is used to make probabilistic computations in both the Probabilistic Toolkit for Reliability Updating and the

Prototype (for calibration purposes); see also Chapter 5. This means that uncertainty in PL1, PL2 and PL3 are incorporated by manipulating these parameters that are considered as stochastic variables.

## 3.3 Design values of main pwp variables

There is no established, documented relation between mean, standard deviation and design values for pwp uncertainties; opposite to e.g. shear strength uncertainties where typically 5% lower quantiles are chosen as design values. For pwp variables, typically, conservative estimates of parameters are used in case no measurements are available. This strongly depends on the experience of the engineer in charge.

For studies where a lot of variations should be modeled (e.g. calibration), the following is recommended to be used as design values in order to reflect sufficient conservative estimates and follow TAW (2004) as much as possible:

- Phreatic line PL1: defaults from TAW (2004). These are conservative estimates.
- Intrusion length mean values since it cannot be determined unambiguously beforehand if a low value is conservative or not.
- Leakage length outside ($\lambda_{out}$): 5% lower bound since this is the conservative choice.
- Leakage length inside ($\lambda_{in}$): 5% upper bound since this is the conservative choice.

## 3.4 Leakage length uncertainty

### 3.4.1 General values leakage length

In order to obtain an insight in the range of leakage lengths that are found in the Netherlands, the overview of Teixeira et al (2015) is used, see Figure 3.1. In this figure, the inside leakage length is based on the thickness and permeability of the layers. The outside leakage length is based on an assumed response factor (ratio of piezometric level at inner toe and head difference over dike) of 0.75 and thus less well founded. This outer leakage length it is often determined by the length of the foreshore, in case the river or channel is so deep that the bottom of the channel has direct contact with the aquifer. Hence, the figures below should be treated with care. Also, cases in the east typically do not have high leakage lengths.

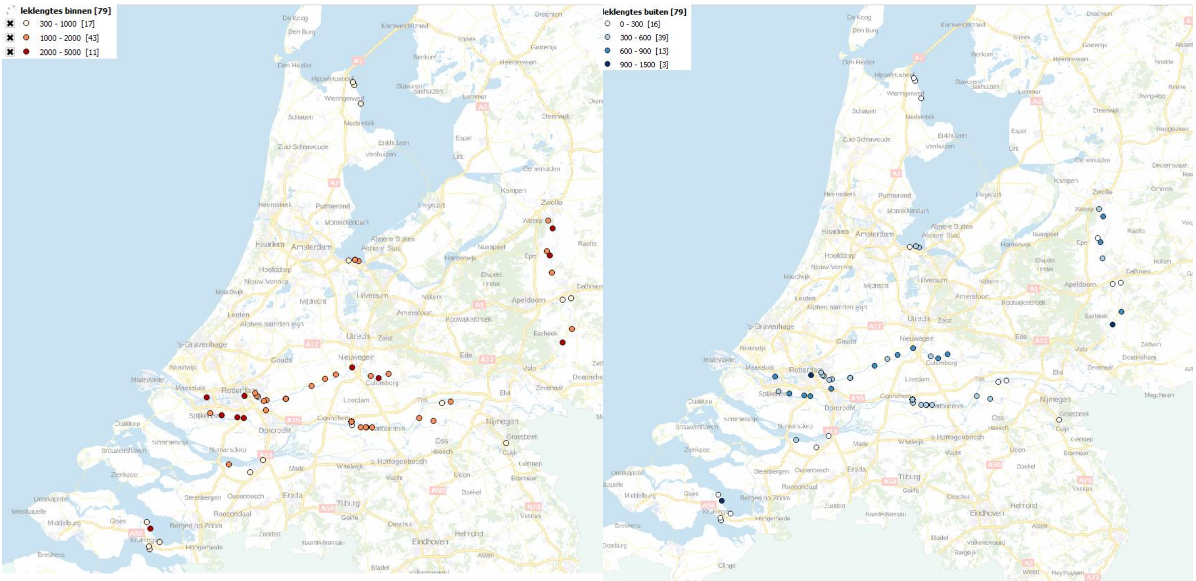



*Figure 3.1 Leakage lengths inside (left) and outside (right), based on (Teixeira et al, 2015)*

### 3.4.2 Effects uncertainties leakage length on uncertainty in pore water pressure

The effects of uncertainties in the leakage length on uncertainties in pwp in PL3 at the outer crest (Figure 2.7) and at the inner toe is investigated in this section. This is done for varying leakage length ($\lambda_{out}$ and $\lambda_{in}$) and Coefficient of Variation (CoV) in these. $\Delta H$ is calculated at below the outer crest using eqn. 2.2; the response is calculated at the inner toe, which is assumed 20 m from the outer crest. The resulting mean value of the pwp ($\mu(\Delta H)$) and standard deviation ($\sigma(\Delta H)$), as well as mean value and standard deviation of the response is computed using Monte Carlo sampling. PL2 is assumed 0 in this computation. The base case is a dike with a head difference of 5 m, leakage lengths of 1000 m and CoV's of 0.2 that represent a situation without measurement (see Section 3.1). The resulting $\sigma(\Delta H)$ is shown in *Table 3.2* as case 1. Varying the leakage length in cases 2 to 4 show some effect on $\sigma(\Delta H)$. This is mainly determined by the ratio of leakage lengths. The absolute values of $\sigma(\Delta H)$ correspond to the standard deviation of 0.4 based on Rozing (2015) as presented in Section 3.1. Also the cases with lower CoV, 0.1 corresponding to a situation with measurement, show good accordance with the value provided by Rozing of 0.2. A histogram of the response factor for case 4 is shown in Figure 3.2. In general the response is mainly sensitive for a combination of low leakage lengths. Furthermore, there is relatively limited uncertainty in the response.

| case | H [m] | $\boldsymbol{\lambda_{out}}$ [m] | CoV $\boldsymbol{\lambda_{out}}$ [-] | $\boldsymbol{\lambda_{in}}$ [m] | CoV $\boldsymbol{\lambda_{in}}$ [-] | $\boldsymbol{\mu(\Delta H)}$ [m] | $\boldsymbol{\sigma(\Delta H)}$ [m] | $\boldsymbol{\mu(\text{Response})}$ [-] | $\boldsymbol{\sigma(\text{Response})}$ [-] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 5 | 1000 | 0.2 | 1000 | 0.2 | 2.5 | 0.37 | 0.49 | 0.002 |
| 2 | 5 | 1000 | 0.2 | 100 | 0.2 | 4.53 | 0.13 | 0.74 | 0.035 |
| 3 | 5 | 100 | 0.2 | 1000 | 0.2 | 0.47 | 0.13 | 0.09 | 0.0005 |
| 4 | 5 | 100 | 0.2 | 100 | 0.2 | 2.5 | 0.37 | 0.41 | 0.019 |
| 5 | 5 | 1000 | 0.1 | 1000 | 0.1 | 2.5 | 0.18 | 0.49 | 0.001 |
| 6 | 5 | 1000 | 0.1 | 100 | 0.1 | 4.54 | 0.06 | 0.74 | 0.015 |

*Table 3.2 Uncertainty in pwp based on uncertainty in leakage length*

It should be noted the this table only deals with pwp uncertainty in PL3 at the outer crest, the uncertainties will be different (likely lower) at locations away from this point as they come close to the boundaries. Also $\sigma(\Delta H)$ will change with different head difference H. Based on this analysis, it can be concluded that implementing CoV's for the leakage length is expected to give outcomes for pwp uncertainty that match expectations based on Rozing (2015).

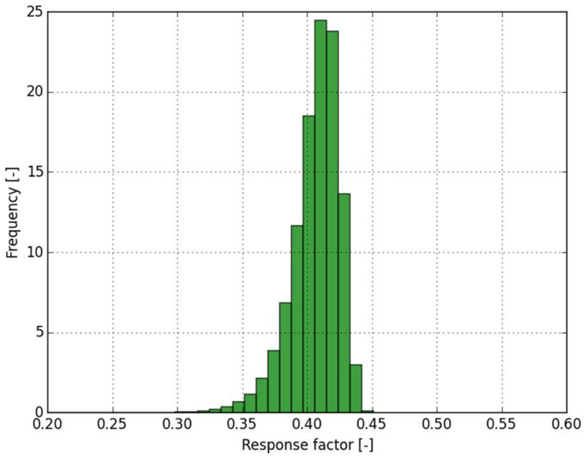



*Figure 3.2 Response factor histogram case 4*

## 3.5 Probabilistic implementation strength reduction due to rupture

### 3.5.1 Results of deterministic sensitivity

Before implementing a new strength reduction model, first the sensitivity of uplift on the SF is evaluated. The results of a deterministic sensitivity study based on design values for the Bovenrivierengebied case are shown in Table 3.3. In this sensitivity study, the lower point (l) of $N_{Uplift}$ is varied (see Figure 3.3) and the effect on the SF is computed. As can be seen, the SF is very sensitivity for the rupture reduction model for this case that experiences uplift between $N_{Uplift}$ = 1 and 0.8.

| Variable | Example 1 | Example 2 | Example 3 |
|---|---|---|---|
| $N_{Uplif\_u}$ | 1.2 | 1.2 | 1.2 |
| $N_{Uplift\_l}$ | 1 | 1.199 | 0.8 |
| $MF_u$ | 1 | 1 | 1 |
| $MF_l$ | 0 | 0 | 0 |
| *SF* | *1.033* | *1.015* | *1.348* |

*Table 3.3 Effects uplift potential on SF for bovenrivierengebied case*

### 3.5.2 Options rupture reduction

The current method for strength reduction due to rupture (Section 2.6) is not suitable for probabilistic implementation since it is a deterministic, conservative approach. The current design and assessment approach is the red line in Figure 3.3 in which $N_{uplift}$ is the uplift safety factor as defined in the VTV (Ministerie Verkeer en Waterstaat, 2007) and the Multiplication Factor (MF) that shows how much of the mobilized strength is used in the computation (see Section 2.6).

A probabilistic incorporation should:

- Connect to current practice as good as possible.
- Allow for uncertainty in strength reduction due to rupture.
- Allow for reductions that will be less than the MF=0 assumption for low $N_{uplift}$ to account for the 3D and valve effects that result in some shear strength in the soil body after uplift.
- Connect to the deterministic implementation for safety factors higher than 1.2.
- Should be a gradual function to allow for FORM analysis.

Three options for implementation are shown in Figure 3.3. Option 1 and 2 are full probabilistic options where MF at $N_{uplift\_l}$ (N=1.0) is modeled as a (truncated) normal distribution or uniform distribution. Between $N_{uplift}$ = 1 to 1.2 ($N_{Uplif\_l}$ to $N_{Uplif\_u}$), MF goes from the random variable to 1. Option three is a more gradual decrease of the MF between $N_{Uplif\_l}$ and $N_{Uplif\_u}$.

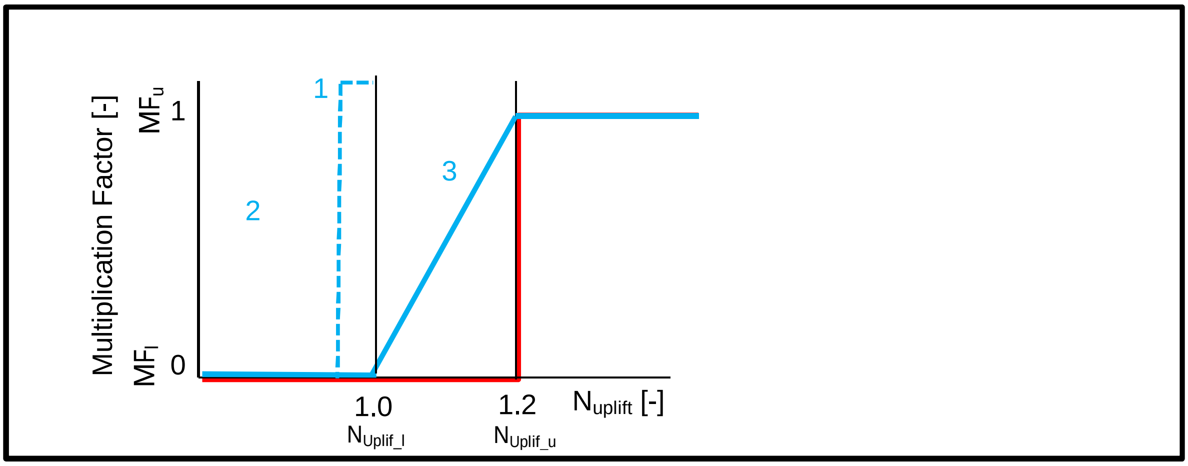



*Figure 3.3 Multiplication factor blanket rupture options for (probabilistic) implementation*

### 3.5.3 Probabilistic implementation for fixed water level

The probabilistic implementation as proposed in Section 3.5.2 is applied to the same Bovenrivierengebied case for a water level difference of 5m where uplift is likely to occur.
The reliability index (beta) and FORM sensitivity coefficients ($\alpha$) are computed using the Probabilistic Toolkit. The result for probabilistic implementation with a truncated normal distribution (mean 0.5, std 0.2; limits 0 and 1) is shown in *Table 3.4*, probabilistic implementation with uniform distribution in *Table 3.5* and option 3 of Figure 3.3 is shown in *Table 3.6*. It can be seen that there is a very significant effect on the beta and alfa's. The difference between uniform and normal distribution mainly shows in the beta, and less in the alfa values.

| | | $\alpha^2$ |
|---|---|---|
| Beta | 2.33 | |
| S ratio | | 0.257 |
| m strength increase coefficient | | 0.006 |
| Friction angle | | 0.000 |
| Yield stress | | 0.148 |
| Model | | 0.056 |
| MF | | 0.533 |
| Design point MF | 0.17 | |

*Table 3.4 Probabilistic computation case Bovenrivierengebied with probabilistic strength reduction due to rupture using a truncated normal distribution*

| | | $\alpha^2$ |
|---|---|---|
| Beta | 1.73 | |
| S ratio | | 0.239 |
| m strength increase coefficient | | 0.005 |
| Friction angle | | 0.000 |
| Yield stress | | 0.135 |
| Model | | 0.052 |
| MF | | 0.569 |
| Design point MF | 0.05 | |

*Table 3.5 Probabilistic computation case Bovenrivierengebied with probabilistic strength reduction due to rupture using a uniform distribution*

| | | $\alpha^2$ |
|---|---|---|
| Beta | 0.529 | |
| S ratio | | 0.559 |
| m strength increase coefficient | | 0.010 |
| Friction angle | | 0 |
| Yield stress | | 0.311 |
| Model | | 0.120 |

*Table 3.6 Probabilistic computation case Bovenrivierengebied with probabilistic strength reduction due to rupture using option 3 in Figure 3.3*

### 3.5.4 Probabilistic implementation for stochastic water level

Finally, the computation is repeated for a stochastic outside water level, the results are presented in *Table 3.7* and *Table 3.8* for a truncated normal and uniform distribution respectively.

| | | $\alpha^2$ |
|---|---|---|
| Beta | 2.27 | |
| WL | | 0.404 |
| CuPc | | 0.164 |
| m | | 0.002 |
| fric | | 0.000 |
| Yield | | 0.138 |
| Model | | 0.036 |
| Multiplication Factor MF | | 0.256 |
| Design value WL | 2.52 | |
| Design value MF | 0.27 | |

*Table 3.7 Probabilistic computation case Bovenrivierengebied with probabilistic strength reduction due to rupture using a truncated normal distribution, for a stochastic water level*

| | | $\alpha^2$ |
|---|---|---|
| Beta | 1.97 | |
| WL | | 0.600 |
| CuPc | | 0.080 |
| m | | 0.001 |
| fric | | 0.000 |
| Yield | | 0.066 |
| Model | | 0.018 |
| Multiplication Factor MF | | 0.235 |
| Design value WL | 2.59 | |
| Design value MF | 0.17 | |

*Table 3.8 Probabilistic computation case Bovenrivierengebied with probabilistic strength reduction due to rupture using a uniform distribution, for a stochastic water level*

| | | $\alpha^2$ |
|---|---|---|
| Beta | 1.41 | |
| WL | | 0.851 |
| CuPc | | 0.073 |
| m | | 0.000 |
| fric | | 0.000 |
| Yield | | 0.059 |
| Model | | 0.016 |
| Design value WL | 2.41 | |

*Table 3.9 Probabilistic computation case Bovenrivierengebied with probabilistic strength reduction due to rupture using option 3 in Figure 3.3, for a stochastic water level*

### 3.5.5 Recommendations

Since there is no knowledge on strength reduction due to uplift, it is recommended to use the model that linearly decreases the strength from 1 to 0 for $N_{uplift}$ = 1.2 to 1 (see Figure 3.3). This model should reflect physics better (gradual decrease) and builds upon the current implementation. Additionally, the more gradual decreases in strength reduction is expected to result in less FORM stability issues than the current binary implementation. A full probabilistic implementation would reflect the mechanism even better, but given the absence of any information on the mechanism, this option is not yet recommended.

Furthermore, it is recommended to evaluate the outcomes of the POV-M study on rupture, which may allow for a more accurate and/or probabilistic modeling of rupture.

# 4 Probabilistic incorporation of pore water pressures

This Chapter focusses on the probabilistic incorporation of pore water pressures with several examples to show the impact of pwp uncertainties. For more examples, please refer to the appendices.

## 4.1 Lower River case for implementation of intrusion and leakage length.

The lower river (benedenrivieren) area is characterized by thick blankets and pwp's that are influenced by the leakage length and intrusion length. This in contrast to cases with thinner blankets where intrusion is very large. The default (deterministic) phreatic offsets as presented in *Table 2.2* are used in this section.

The following cases are analyzed:

A. Low water level (conditional reliability, sensitivity indices and sensitivity study of Appendix A).
B. High water level (conditional reliability, sensitivity indices).
C. Stochastic water level (conditional reliability, sensitivity indices).
D. Stochastic water level with doubled uncertainty in the pwp parameters.

Furthermore, various leakage lengths are considered.

### 4.1.1 Inputs

The benedenrivieren case is presented in Figure 4.1. The relevant default parameters are shown in *Table 4.1*.

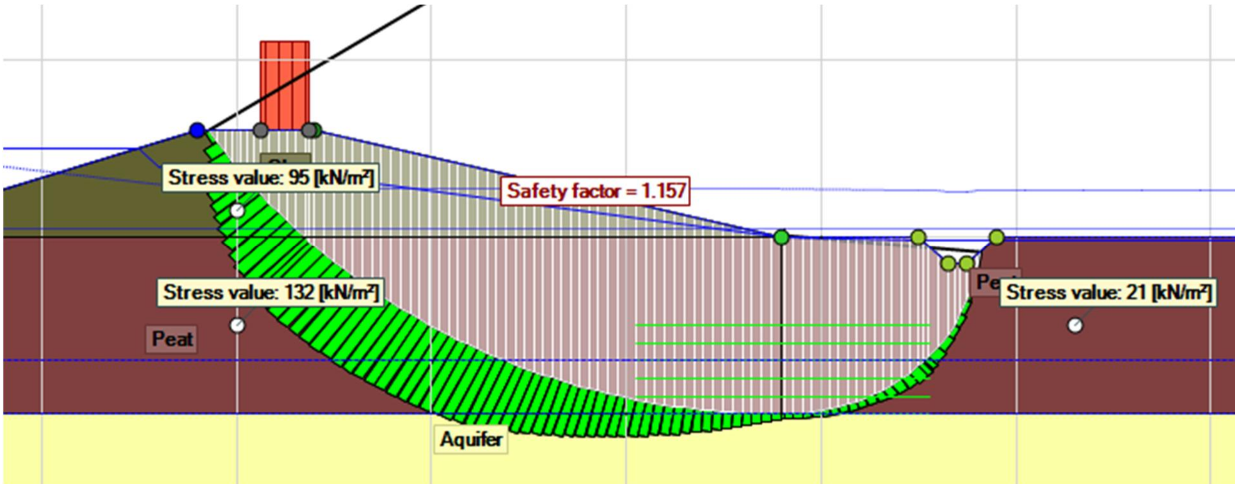



*Figure 4.1 Benedenrivieren case at design water level (thickness peat layer – 10 m; height dike – 6 m; width dike: 48 m)*

| Variables | Description | model | mean | standard deviation |
|---|---|---|---|---|
| WL.Value | Outside water level | Deterministic | 5 | |
| PL2_out | Outside head during daily conditions | Normal | 0.5 | 0.3 |
| PL2_in | Inside head during daily conditions | Normal | 0.5 | 0.3 |
| PL2_IL | Intrusion length | Normal | 3 | 0.9 |
| PL3_LL_out | Leakage length outside | Normal | 1000 | 200 |
| PL3_LL_inn | Leakage length inside | Normal | 1000 | 200 |
| PL3_GHW | Mean high water, see Section 2.4 | Normal | 0.5 | 0.3 |
| Model.Factor | Model uncertainty | Normal | 0.995 | 0.033 |

*Table 4.1Water pressure inputs benedenrivieren case: base case*

### 4.1.2 Output without WNC uncertainties

The output of a probabilistic computation without WNC uncertainties is presented in *Table 4.6*. The reliability index of this case is 4.34 and the main sensitivity coefficients ($\alpha$) are the shear strength ratio and the yield stresses. The yield stresses in the table correspond to the three points shown in Figure 4.1.

| Variable | Description | $\alpha$ | $\alpha^2$ | Design point |
|---|---|---|---|---|
| CreateWaternet.WL | Outside water level | -0.194 | 0.038 | 2.101 |
| Clay.CuPc | Undrained shear strength ratio clay | 0.180 | 0.032 | 0.368 |
| Peat.CuPc | Undrained shear strength ratio peat | 0.732 | 0.536 | 0.338 |
| Aquifer.Fric | Friction angle aquifer | 0.000 | 0.000 | 34.826 |
| Clay.m | Strength increase exponent m clay | 0.005 | 0.000 | 0.899 |
| Peat.m | Strength increase exponent m clay | 0.023 | 0.001 | 0.898 |
| 149.Yield | Yield stress at location 149 | 0.195 | 0.038 | 127.786 |
| 151.Yield | Yield stress at location 151 | 0.164 | 0.027 | 89.903 |
| 153.Yield | Yield stress at location 153 | 0.467 | 0.218 | 10.330 |
| Model.Factor | Model uncertainty | 0.332 | 0.110 | 0.948 |

*Table 4.2 Probabilistic output bovenrivierengebied case without WNC uncertainty*

### 4.1.3 Output with WNC uncertainties

The output for the benedenrivierengebied case is presented in *Table 4.4*. A couple of observations may be made:

Table 4.3 Probabilistic output bovenrivierengebied case without WNC uncertainty

- The influence of the WNC uncertainties increases between A and B, likely because at A the water level is that low, that no effect of changes in WL result in changes in effective stresses and thus in safety factor.
- When considering C and D, it shows that a doubling of WNC uncertainty also results in an increase in the $\alpha$ of the WL.
- The changes in LL mainly influence the $\alpha$ values for the cases with stochastic WL (C and D).

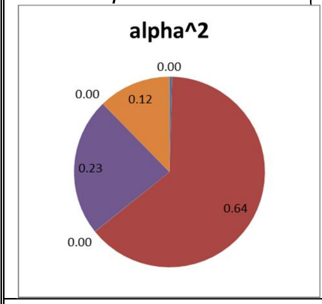
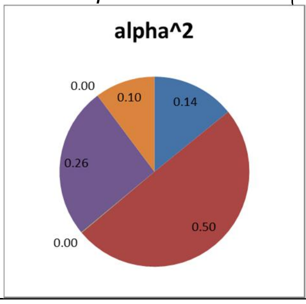
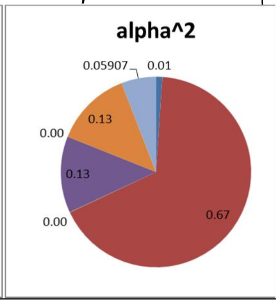
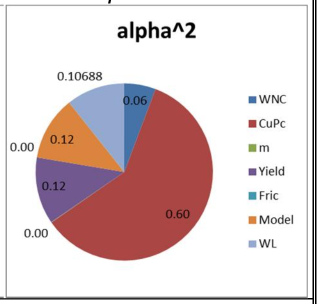
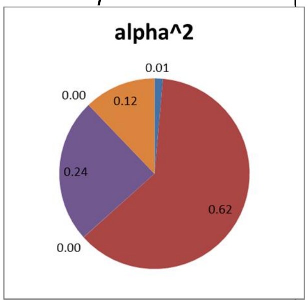
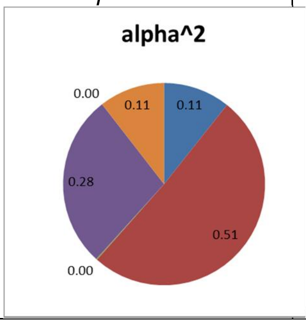
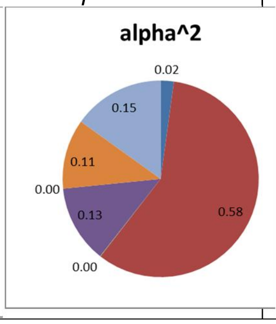
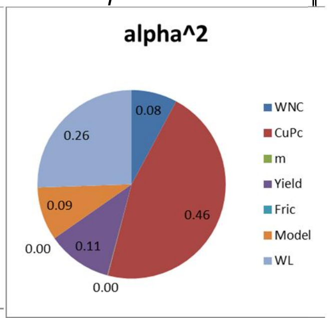
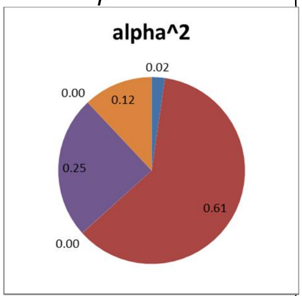
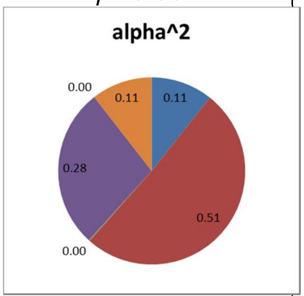
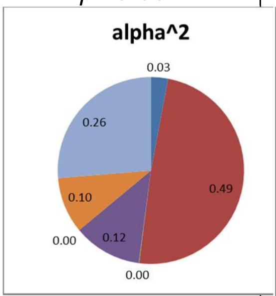
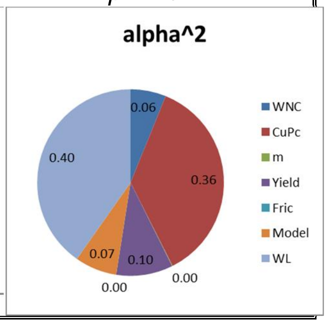
<table>
<tr><th>A: Fixed WL = 1.5m</th><th>B: Fixed WL = 5m</th><th>C: Stochast WL</th><th>D: Double WNC uncertainy</th></tr>
<tr><td colspan="4">Base case: leakage length inside = 1000m; leakage length outside = 1000m</td></tr>
<tr><td>$\beta$=4.74</td><td>$\beta$=3.48</td><td>$\beta$=4.83</td><td>$\beta$=4.71</td></tr>
<tr><td>
</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td colspan="4">Leakage length inside = 1000m; leakage length outside = 300m</td></tr>
<tr><td>$\beta$=4.55</td><td>$\beta$=3.03</td><td>$\beta$=4.46</td><td>$\beta$=4.29</td></tr>
<tr><td>
</td><td>
</td><td>
</td><td>
</td></tr>
<tr><td colspan="4">Leakage length inside = 1000m; leakage length outside = 100m</td></tr>
<tr><td>$\beta$=4.44</td><td>$\beta$=3.03</td><td>$\beta$=3.89</td><td>$\beta$=4.01</td></tr>
<tr><td>
</td><td>
</td><td>
</td><td>
</td></tr>
</table>

*Table 4.4 Output benedenrivierengebied case*

### 4.1.4 Conclusions

There are several conclusions from the computations and results:

- GHW influences PL2 and PL3 (See Section 2.4), however, there is no conclusive relation between GHW and SF, as it depends on PL2. This leads to convergence problems with FORM. Hence, GHW not implemented as random variable.
- PL2 only affects SF when smaller than GHW, this reduces the effects of variations in GHW on SF.
- For high leakage lengths, the outer leakage length has a higher influence than the inner leakage length (for this case, to be confirmed with other cases). In general, the inner leakage length will be higher than the outer leakage lengths.

## 4.2 Upper River Area case for implementation of intrusion and leakage length

The upper river (bovenrivierengebied) case is mainly of importance for leakage length effects since intrusion is less important due to the thin blanket. Hence, uplift/rupture conditions are of major importance. The deterministic strength reduction due to rupture is applied, see Section 2.6. The default (deterministic) phreatic offsets as presented in *Table 2.2* are used in this section.

### 4.2.1 Input

The cross-section and inputs for the pwp generation are presented in Figure 4.2 and *Table 4.5*.

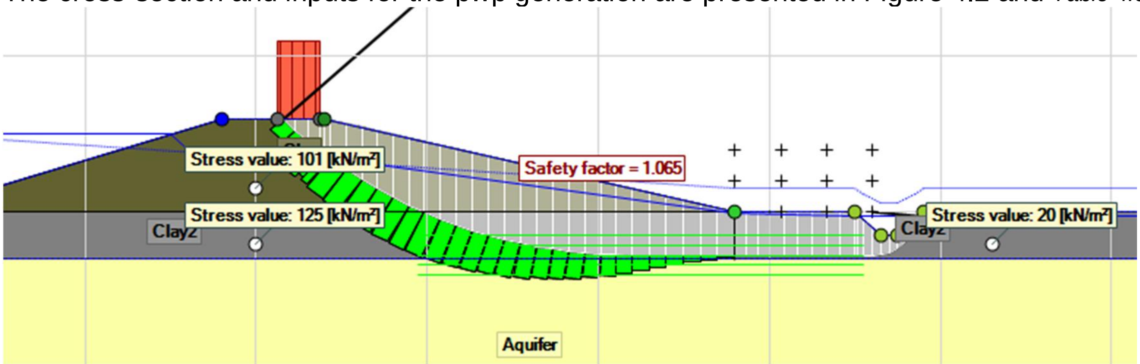



*Figure 4.2 Cross-section bovenrivierengebied case at design water level (thickness clay layer – 3 m; height dike – 6 m; width dike: 48 m)*

| Variables | Description | model | mean | standard deviation |
|---|---|---|---|---|
| WL.Value | Outside water level | Deterministic | 5 | |
| PL3_Head | Head in aquifer during high water, assumed equal to outside water level | Deterministic | 5 | |
| PL2_out | Outside head during daily conditions | Normal | 0.5 | 0.3 |
| PL2_in | Inside head during daily conditions | Normal | 0.5 | 0.3 |
| PL2_IL | Intrusion length | Deterministic | 0 | |
| PL3_LL_out | Leakage length outside | Normal | 1000 | 200 |
| PL3_LL_inn | Leakage length inside | Normal | 1000 | 200 |
| PL3_GHW | Mean high water, see Section 2.4 | Normal | 0.5 | 0.3 |
| 1.2.upliftreduction.Value | Uplift reduction value upper bound | Deterministic | 1 | |
| 1.upliftreduction.Value | Uplift reduction value lower bound | Deterministic | 0 | |
| Model.Factor | Model uncertainty | Normal | 0.995 | 0.033 |

*Table 4.5 Input variables for pwp generation bovenrivierengebied case*

### 4.2.2 Output without WNC uncertainties

The output of a probabilistic computation without WNC uncertainties is presented in *Table 4.6*. The reliability index of this cases is 1.41.

| | $\alpha$ | $\alpha^2$ | **Design point** |
|---|---|---|---|
| CreateWaternet.WL | -0.92 | 0.85 | 2.4 |
| Clay.CuPc | 0.19 | 0.037 | 0.34 |
| Clay2.CuPc | 0.19 | 0.036 | 0.34 |
| Aquifer.Fric | 0.00 | 0.000 | 35 |
| Clay.m | 0.012 | 0.000 | 0.90 |
| Clay2.m | 0.016 | 0.000 | 0.90 |
| 149.Yield | 0.17 | 0.030 | 123 |
| 151.Yield | 0.17 | 0.029 | 99 |
| 153.Yield | 0.017 | 0.000 | 19 |
| Model.Factor | 0.13 | 0.016 | 0.99 |

*Table 4.6 Probabilistic output bovenrivierengebied case without WNC uncertainty*

### 4.2.3 Output with WNC uncertainties

The output for the bovenrivierengebied case is presented in *Table 4.7*. The case is dominated by uplift, leading to e.g. the same output at fixed water level, independent of leakage lengths (due to the adjust for uplift of PL3), as well as very low reliability indices.

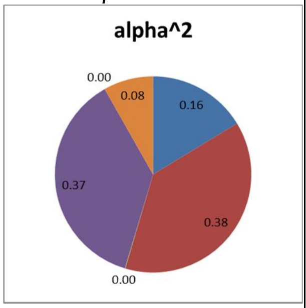
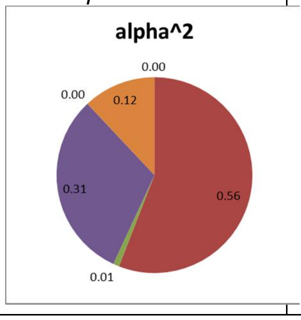
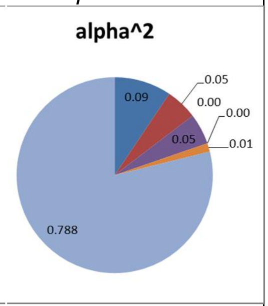
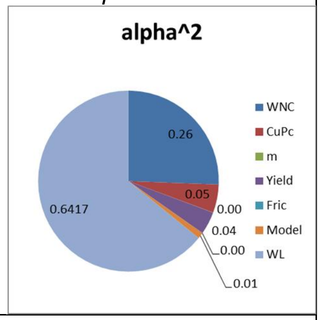
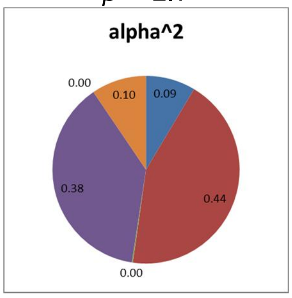
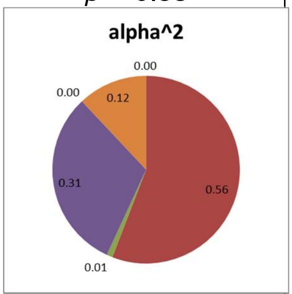
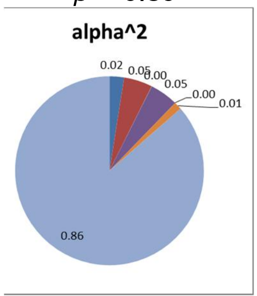
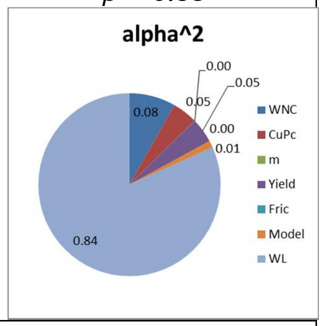
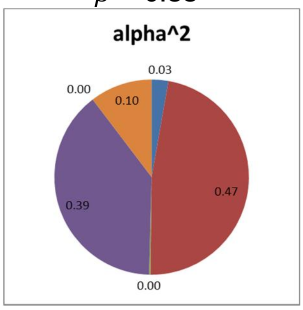
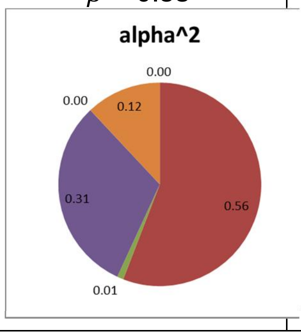
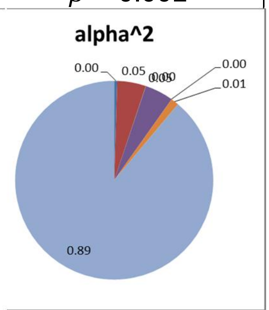
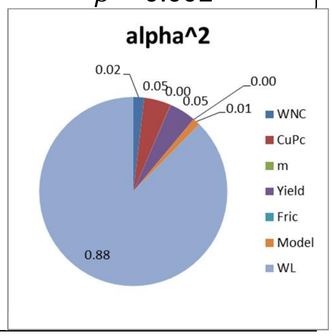
| A: Fixed WL = 1.5m | B: Fixed WL = 5m | C: Stochast WL | D: Double WNC uncertainy |
|---|---|---|---|
| Base case leakage length inside = 1000m; leakage length outside = 1000m | | | |
| $\beta$ = 3.1   | $\beta$ = 0.53   | $\beta$ = 1.35   | $\beta$ = 1.18   |
| Leakage length inside = 1000m; leakage length outside = 300m | | | |
| $\beta$ = 1.7   | $\beta$ = 0.53   | $\beta$ = 0.39   | $\beta$ = 0.38   |
| Leakage length inside = 1000m; leakage length outside = 100m | | | |
| $\beta$ = 0.83   | $\beta$ = 0.53   | $\beta$ = 0.001   | $\beta$ = 0.001   |

*Table 4.7 Output bovenrivierengebied case*

Furthermore, the fragility is constructed for the base case, see Figure 2.1. The increasing reliability after WL = 3 is likely due to a yield stress point that is changing from above the water table to under the water table. This is solved by choosing yield stress points in such a way they won't experience this effect.

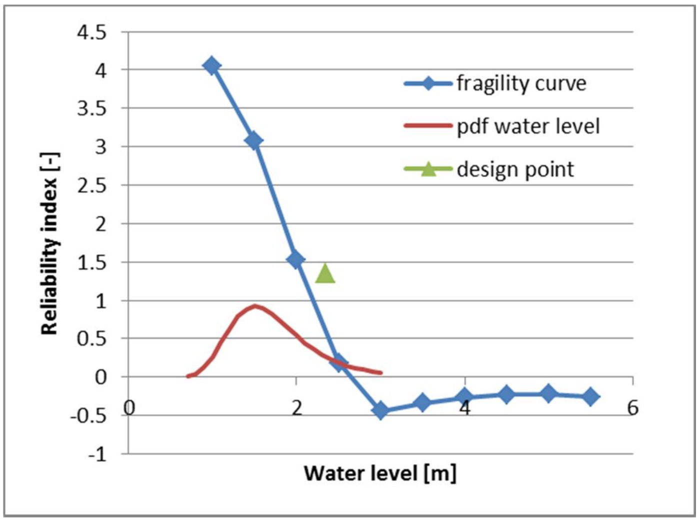



*Figure 4.3 Fragility curve bovenrivierengebied case*

### 4.2.4 Conclusions

The following conclusions are drawn based on the bovenrivierengebied analysis:

- There is a relatively high influence ($\alpha$) of the WNC for low water levels.
- There is a relatively low influence ($\alpha$) of the WNC for high water levels due to PL line reduction after uplift
  – The “AdjustPLVoorUplift” in combination with uplift results in PL3 being corrected for uplift, in which case leakage lengths typically have very limited influence on the safety factor.
  – If there is no uplift, leakage lengths do influence the results.

## 4.3 Phreatic line (PL1) uncertainties

This section describes the implementation of phreatic line uncertainties. Since the presented analysis are done with a version of D-Geo Stability without full implementation of hydrostatic pore water pressures, results will need further verification once the final D-Geo Stability is available. Only the Clay on Clay case is considered.

### 4.3.1 Inputs and modeling

The WTI defaults to model a clay on clay dike are (see Chapter 2):

- PL1 offset at outer slope = 1.0.
- PL1 offset at crest polder side = 1.5.

The probabilistic implementation of the phreatic line is shown in Figure 4.4. According to Rozing (2015), the standard deviation of the PL1 line is about 0.9m. Assuming the WTI defaults are conservative values, the mean values for the offsets are assumed respectively: 1.0 + 0.9 = 1.9 m and 1.5 + 0.9 = 2.4m. This is shown in Figure 4.4 with the red line. The uncertainty around the mean values is plotted in green. The mean and standard deviation are summarized in *Table 4.8*.

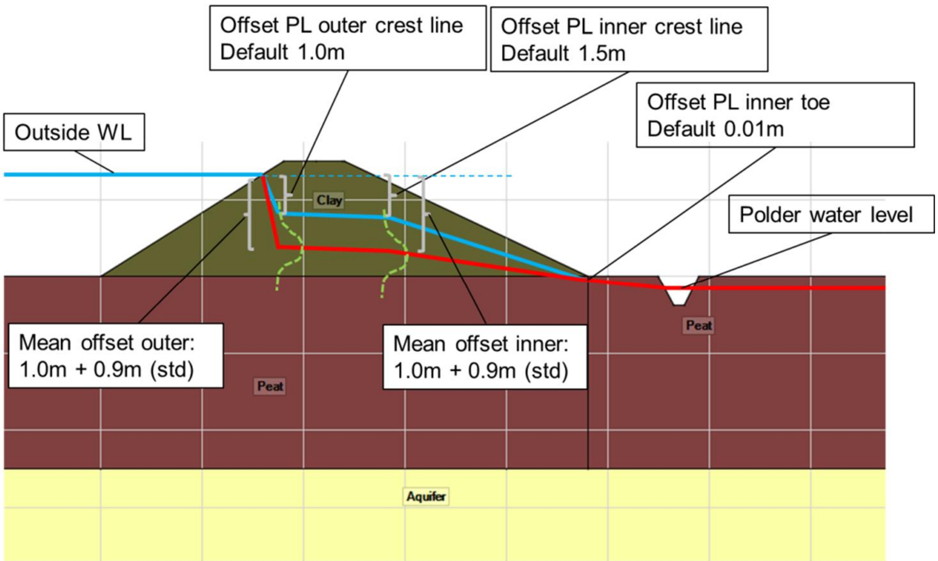



*Figure 4.4 Implementation uncertainty in phreatic line*

| **Water level** | **Mean** | **Std** |
|---|---|---|
| PL1 offset at outer slope | 1.9 | 0.9 |
| PL1 offset at crest polder side | 2.4 | 0.9 |

*Table 4.8 Uncertainties phreatic line*

Because it is very likely that the phreatic level is correlated in space, full correlation between offsets 1 and 2 is applied. The minimum water level in the dike body (Dupuit level) is not taken into account yet as stochastic variable, since this introduces undesired interdependencies.

Two calculations have been made: one for the benedenrivieren area and one for the bovenrivieren area. The first represents a large slip plane, the second a small slip plane. For both cases, only a high water situation is regarded, since for lower water levels, the minimum PL1 water level (Dupuit) is always higher than the PL1 line.

### 4.3.2 Benedenrivierengebied impact

To compare the influence of the stochastic implementation of the phreatic level in the dike body, the following situations are analysed:

1. PL1 Conservative: offset 1 and 1.5. This case uses conservative yet deterministic value for the offsets. These are the default offsets for assessments in the WNC.
2. PL1 Mean Deterministic: offset 1.9 and 2.4. This deterministic case uses offsets in order to reflect the mean location of the phreatic line.
3. PL1 Mean + std: This case uses random variables according to *Table 4.8* to model uncertainties in phreatic line, conditional to a water level.
4. Full probabilistic: same as 3., but with stochastic WL

The results are presented below. *Table 4.9* shows the SF hardly depends on the PL1 line, which could be explained by the large slip circle (large portion of slip circle not influenced by PL1) and the low dependency of the shear strength on the vertical effective stress. *Table 4.10* shows the FORM $\alpha$ for case 4. The PL1 offset has a very low $\alpha$, emphasizing the limit influence of PL1.

| computation | WL* | 1. PL1 Conservative | 2. PL1 Mean Deterministic | 3. PL1 prob\|H | 4. Full probabilistic* |
|---|---|---|---|---|---|
| Safety factor | 5.0m | 1.4244 | 1.4240 | N/A | N/A |
| Reliability index | 5.0m | 3.32 | 3.33 | 3.32 | 4.24 |

*Table 4.9 Safety factor and reliability index benedenrivieren case*

| Variable | $\alpha$ | $\alpha^2$ | Design point |
|---|---|---|---|
| Water Level | -0.20 | 0.04 | 2.09 |
| PL1 Offset | 0.00 | 0.00 | 1.90 |
| Clay. CuPc | 0.18 | 0.03 | 0.37 |
| Peat.CuPc | 0.70 | 0.49 | 0.34 |
| Aquifer Friction Angle | 0.00 | 0.00 | 34.83 |
| Clay.m | 0.01 | 0.00 | 0.90 |
| Peat.m | 0.01 | 0.00 | 0.90 |
| Yield Stress location 149 | 0.38 | 0.15 | 120.96 |
| Yield Stress location 151 | 0.17 | 0.03 | 89.92 |
| Yield Stress location 153 | 0.40 | 0.16 | 11.51 |
| Model.Factor | 0.32 | 0.10 | 0.95 |

*Table 4.10 Design point and $\alpha$ values benedenrivieren case for 4. full probabilistic analysis*

### 4.3.3 Bovenrivierengebied impact

The same analysis as in the previous section was repeated for the bovenrivieren case. The same 4 cases are used. The sensitivity for PL1 and the effects of PL1 uncertainties are shown in *Table 4.11*.The SF and reliability index depend on PL1 (difference between case 1 and 2), but not much. Also the $\alpha$ of PL1 is very small, see *Table 4.12*. This might be due to the occurrence of uplift in this case.

| computation | WL* | 1. PL1 Conservative | 2. PL1 Mean Deterministic | 3. PL1 prob\|H | 4. Full probabilistic* |
|---|---|---|---|---|---|
| Safety factor | 5.0m | 1.058 | 1.050 | N/A | N/A |
| Reliability index | 5.0m | 0.529 | 0.452 | 0.446 | 1.41 |

* Full probabilistic case has stochastic WL

*Table 4.11 Safety factor and reliability index bovenrivieren case*

| Variable | $\alpha$ | $\alpha^2$ | Design point |
|---|---|---|---|
| Water Level | -0.92 | 0.85 | 2.41 |
| PL1 Offset | 0.00 | 0.00 | 1.90 |
| Clay. CuPc | 0.19 | 0.04 | 0.34 |
| Peat.CuPc | 0.19 | 0.04 | 0.34 |
| Aquifer Friction Angle | 0.00 | 0.00 | 34.83 |
| Clay.m | 0.01 | 0.00 | 0.90 |
| Peat.m | 0.02 | 0.00 | 0.90 |
| Yield Stress location 149 | 0.17 | 0.03 | 123.12 |
| Yield Stress location 151 | 0.17 | 0.03 | 99.12 |
| Yield Stress location 153 | 0.02 | 0.00 | 18.72 |
| Model.Factor | 0.13 | 0.02 | 0.99 |

*Table 4.12 Design point and $\alpha$ values bovenrivieren case*

### 4.3.4 Conclusion

There seems very limited effect of PL1 uncertainty based on the 2 examined cases. This may have partly to do with the CSSM method that was used since with the method, the mobilized shear strength is less dependent on the vertical effective stress as is the case with a drained analysis. Furthermore, the benedenrivieren case has a large slip plane, of which only a part is affect by PL1, which limits PL1 effect. Also, the bovenrivieren case experience uplift, which limits the effect of PL1. The limited sensitivity may change in case:

- Hydrostatic pore pressures are implemented.
- Cases with smaller slip circles are analyzed..

Finally, there are no issues with convergence found for the considered cases.

# 5 Implementation pwp uncertainties

Based on the previous chapter, recommendations for pwp uncertainty incorporation are presented for the following project:

- Reliability Updating using Past Performance (RUPP).
- Calibration of safety factors (CSF).

The choices are made taking into account the following considerations:

- Uncertainties in pwp should be well reflected by the parameters that are chosen as random variables.
- Keep the implementation as simple as possible.
- Use the values of Rozing (2015) where applicable.
- Use local data if available (e.g. RUPP) and generic rules if local data is not available (e.g. CSF).

## 5.1 Reliability Updating

For reliability updating, the following choices are proposed regarding the incorporation of pwp uncertainties:

- Implement uncertainty in intrusion length by making IL a stochastic variable. Take the values of Rozing (2015) with or without measurements.
- Implement inside and outside leakage length as stochastic variables depending on whether measurements are present or not. Values according to Rozing (2015).
- Implement uncertainties in the phreatic line by scenarios, and not by continuous random variables, due to the specific nature of the Markermeer dikes.
- All other pwp related variables are kept as deterministic (e.g. PL2, GHW).
- Do not include uplift rupture strength reduction according to Section 3.4 since it's not relevant for the Markermeer dikes.
- Assume full correlation of leakage length between observation and assessment, and no correlation for the intrusion length, since intrusion length is more sensitive to e.g. loading duration.
- Design values of IL and LL should be conservative choice based on the MMD uitgangspunten; the mean of IL should well reflect the conservative IL and LL choice.

## 5.2 Calibration of safety factors

For the calibration of safety factors (CSF), a relation between the calculated reliability index (probabilistic) and the deterministic (semi-probabilistic) factor of safety is calibrated: a so-called beta-gamma relation. For this calibration, a safety format should be defined. In the WTI2017 calibration for slope stability elaborated in 2015, pore water pressures were not included, however in the follow up in 2016 this will be. For the CSF project, the same choices as for PURR are proposed, except:

- Implement uncertainties in phreatic line as proposed in Section 4.3; with the current defaults of 1 and 1.5 m (for Clay on Clay) as conservative design values and uncertainties of *Table 4.8*.
- Use the uplift strength reduction model of Section 3.5.
- Use 5%/95% conservative quantiles to determine design values of intrusion length and leakage length.

In the 2015 study, no explicit uncertainties in pore water pressures were included. Only deterministic values (both mean and arbitrary conservative values) for leakage length, intrusion length and offsets of PL1 relative to the outer water level.

Since, some of the parameters regarding pore water pressures are implemented probabilistically, the safety format of the semi-probabilistic assessment needs to be changed. It needs to be defined if mean, characteristic or general conservative values need to be used for the calculation of the factor of safety. The proposed changes in safety format (compared to the 2015 calibration in grey, is presented in *Table 5.1*.

| Parameter | Probabilistic | Semi-probabilistic | 2015 calibration |
|---|---|---|---|
| PL1 offsets | Stochastic parameter | Conservative WNC Defaults | Conservative WNC Defaults |
| PL1 level polder | Expected value | Expected value | Expected value |
| | | | |
| Leakage length outer side | Stochastic parameter | Characteristic | Expected value |
| Leakage length inner side | Stochastic parameter | Characteristic | Expected value |
| Intrusion length | Stochastic parameter | Characteristic | Expected value |

*Table 5.1 Overview semi-probabilistic and probabilistic slope stability assessment*

# 6 Conclusions, lessons and recommendations

## 6.1 Conclusions

The following is concluded from the implementation of pwp uncertainties, based on the considered cases in this report:

- The parameterized implementation of pwp uncertainties using the WNC runs stable for the considered cases using FORM.
- The effect of uncertainties in pore water pressure is strongly location dependent and depends on e.g. the size of the slip plane and uplift conditions.
- Most contribution of pwp uncertainties on reliability and sensitivity coefficients are generally expected of uncertainty in leakage length and intrusion length. Modeling uncertainty in leakage length and intrusion length results in uncertainty in pwp that is very similar to values proposed by Rozing (2015).
- The proposed implementation of pwp uncertainties has not been fully tested for all dike configurations (mainly tested on Clay on Clay, as most relevant), neither for all possible sub-soil schematisations and geometries. Although the results provide confidence for the implementation of pwp uncertainty, specific conditions may still pose unidentified challenges. For example for the intrusion length, convergence issues may be encountered for configuration where intrusion is just/just not touching the slip circle. Choosing robust FORM settings or a suitable probability distribution will probably remedy the issue in most cases.
- A new model for the soil strength in the uplift zone is proposed that is better suitable for probabilistic computations and should reflect the physics better, though the theoretical foundation of the modeling remains limited and will be further investigated in the POV-M project.
- The phreatic line uncertainty had limited effect on reliability and sensitivity factors. This could both have to do with the considered uplift case and case with large slip circle, but also with the CSSM shear strength model.

In general it is concluded that pwp uncertainties can be implemented for slope stability analysis and no major implementation issues are expected in terms of convergence problems beyond what is regularly encountered in probabilistic slope stability analyses in general.

## 6.2 Recommendations

The following recommendations are made based on this study:

- It is recommended to apply the implementation of pwp uncertainties for calibration and reliability updating using past performance as described in Chapter 5. In this proposal, uncertainties in the phreatic line are implemented as scenario in RUPP and as stochastic variables in the calibration. Leakage length and intrusion length are recommended to be implemented as stochastic variables in both projects.
- Since not many subsurface compositions have been tested, it is recommended to implemented pwp in the mentioned projects and solve possible problems while making the computations.
- The WNC and D-Geo Stability kernel are still evolving. It is recommended to re-evaluate phreatic line effects with the final implementation of pore pressure distribution in a vertical (e.g. partly hydrostatic pore pressure) in the WNC.
- For phreatic line uncertainties, it is recommended to evaluate calibration cases with small slip circles and no uplift, to investigate effect of the phreatic line and the initial

(Dupuit) water level. This might lead to higher sensitivity for uncertainty in the phreatic line.

- For uplift, it is recommended to follow the developments in the POV-M study on uplift, which may lead to reconsidering the proposed strength reduction model in the uplift zone.

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