Forensic Analysis of Levee Failures: The Breitenhagen Case

Job J. Kool, *Researcher, Hydraulic engineering, Delft University of Technology (Delft, the Netherlands); email: j.j.kool@tudelft.nl*
Willem Kanning, *Researcher, Hydraulic engineering, Delft University of Technology (Delft, the Netherlands) and Deltares (Delft, the Netherlands); email: w.kanning@tudelft.nl*
Torsten Heyer, *Researcher, Wasserbau, Dresden University of Technology (Dresden, Germany); email: torsten.heyer@tu-dresden.de*
Cristina Jommi, *Professor, Geoscience and Engineering, Delft University of Technology (Delft, the Netherlands); email: c.jommi@tudelft.nl*
Sebastiaan N. Jonkman, *Professor, Hydraulic engineering, Delft University of Technology (Delft, the Netherlands); email: s.n.jonkman@tudelft.nl*

ABSTRACT: *Forensic analysis of past failures is valuable to improve our understanding of levee behavior. In this article a new systematic approach of forensic analysis for levee failures is proposed and applied to the Breitenhagen levee breach that occurred along the river Saale in Germany in 2013. The purpose of this study is to identify the cause of the breach based on the proposed approach, even though limited data is available. Based on the information prior, during and after the breach of the levee, a slope stability model is developed for the entire event. First, results from this model are obtained based on the expected values of the uncertain parameters and the best estimates of the situation. Uncertainty of the model is included in the calculation subsequently by defining possible failure scenarios. The most likely failure scenarios are derived from the data and included into the model so that it is possible to eliminate or validate all possible causes by means of a sensitivity calculation. It is concluded that the levee breach is likely caused by locally weak soil conditions, unexpected high water pressures due to a connection between a pond and the aquifer and unexpected saturation of the levee. These conditions are associated with the occurrence of a previous breach at this location.*

KEYWORDS: forensic analysis, slope instability, hindcasting, river levee, levee breach

SITE LOCATION: Geo-Database

INTRODUCTION

It is of the utmost importance that the understanding of levee failures is increased since the consequences of flood defense failures during extreme events are very significant, including damages and possibly loss of lives (Jonkman, 2005). Hindcasting of levee failures can provide valuable information about general levee performance, the quality of the strength models and the dominant factors that contribute to levee failure. New insights that are gained from the hindcasting of breaches can be used to support and to introduce developments in the field of research, design and engineering of flood defenses. Examples are the utilisation of failure data (Schweckendiek & Vrouwenvelder, 2014), field observations and monitoring (Kanning, Van Baars, & Vrijling, 2008; Seed & & All., 2006; Seed et al., 2008; Zang, Xu, & Peng, 2013), or even new design criteria (Bligh, 1915; Lane, 1935; Van Baars, 2005). Over the years, much research has been done on the subject of forensic analysis (strategies) of historical (near-) failures in order to increase the understanding of levee performance behavior under extreme circumstances and to develop calculation models to predict performance of the levees and to make their uncertainties explicit (Jonkman & Schweckendiek, 2015; Rao & Sivakumar Babu, 2016; Vorogushyn et al., 2009). Nevertheless, the rivers in Germany experienced a large discharge in the years 2003 and 2013. This resulted in flooding in 12 of the 16 federal states in Germany causing enormous damage (Thieken, et al. 2016). The levee in Breitenhagen, Germany, failed in 2013 during a high river level and is considered to be a failure due to the instability of the landside slope of the levee (Grubert, 2013). The

Submitted: 30 January 2018; Published: 25 November 2019
Reference: Kool, J.J., Kanning, W., Heyer, T., Jommi, C. and Jonkman, S.N. (2019). Forensic Analysis of Levee Failures: The Breitenhagen Case. International Journal of Geoengineering Case Histories, Vol.5, Issue 2, p. 70 - 92.
doi: 10.4417/IJGCH-05-02-02

first explorative calculations of the strength and performance are based on best estimates of the situation and do not indicate that this particular levee should have failed. This indicated a further need for a systematic investigation of the failure.

The discipline of forensic analysis roughly distinguishes three activities (Bell, 2001): collecting and reviewing data, executing a hindcast analysis with computational models to determine and report the cause in order to learn from the findings. Literature shows that forensic engineering and hindcasting can be used on different professional levels (Terwel et al., 2012). Current applications of forensic engineering to levee failure are dominated by large parameter and model uncertainties leading to seemingly arbitrary decisions that do not account for the uncertainties, and leave the outcome of the analysis open for discussion (Grubert, 2013; Kanning, Van Baars, & Vrijling , 2008; Vorogushyn, Merz, & Apel, 2009).

This article aims to identify the most likely causes of the Breitenhagen levee failure with the help of a generic systematic approach of forensic analysis. The original elements in this paper are the analysis of the Breitenhagen levee failure and the development of a generic approach for identifying the most likely causes of geotechnical failures. Attention is paid to a well-argued deduction, how to account for all considerations and modelling choices that were made during forensic analysis. The analysis considers the uncertainties introduced by commonly geotechnical analytical simple models in combination with the lack of typical vital information, which is common when a levee accidentally fails. At the same time the developed approach of forensic analysis is expected to contribute to the overall quality, repeatability, transferability, transparency and recognisability of the analysis of levee failures. It can thereby contribute to insights in the strength and performance of levees.

First the relevant data are presented for the case. The method of the analysis is then explained followed by the assumptions regarding the sensitivity calculations. Subsequently, the results are presented. Finally, the approach of the analysis in relation to the results is discussed, followed by conclusions and the recommendations.

THE BREITENHAGEN LEVEE FAILURE

During the floods of the Saale River in June 2013, the east embankment breached near Breitenhagen (Saxony-Anhalt, Germany) (Figure 1 and Figure 2) (Grubert, 2013). The breach of the levee caused a lot of economic damage that was financially covered by the state of Saxony-Anhalt (Drews, 2017). The failure appears to be the result of slope instability due to the long lasting high water level in both the Elbe and the Saale (Drews, 2017; Grubert, 2013). Historical documents indicate that the levee was built in the second half of the 19th century (Sixdorf, 2016). The overview photo shows a grassy levee with a paved road on top of the levee which can be used by heavyweight traffic (Figure 2). Trees grow along the length of the levee in the floodplain of the Saale. The overview photo also shows a pond near the location of the breach at the river side of the levee (Figure 2).

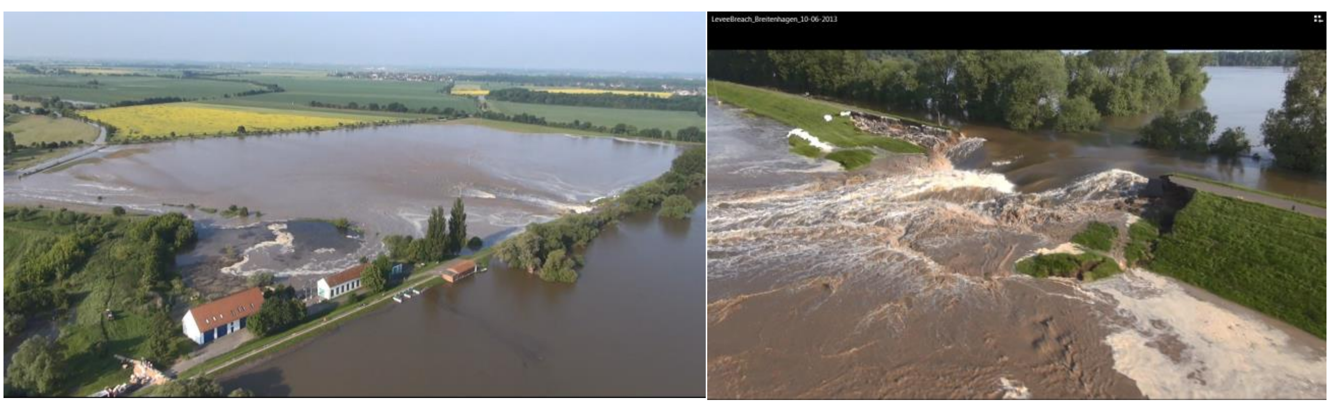

Figure 1 Left: Overview photo of the landside while the flooding evolves, Right: Overview photo of the breach on June 10th 2013 (Weichel, 2013).

Figure 2. Overview of the location of the breach (GeoBasis-DE/BKG, 2009).

An analysis of the case is carried out by using the provided and relevant information (Table 1). The collected information is analysed considering the factors that influence the performance behavior that include input parameters (possible causes of failure e.g. pore water pressures and shear strength of the soil) and model choices (e.g. LEM and (un)drained soil behavior). These factors are used as bases of the computational models that are used to execute the hindcasting in order to determine the most likely cause of failure. This section presents an overview of relevant information that is available. This includes an introduction of the history of the construction, failure and repairs, the water levels, an analysis of the local conditions, the external features, the known geotechnical aspects and the findings from a previous analysis.

Table 1. Overview of collected documentation (Grubert, 2013; Sixdorf, 2016; Weichel, 2013).

Document	Information
Design of the upgrade 1846 (Sixdorf, 2016)	Design drawings of the cross sections. The design was not actually realized.
Photo reportage 2003 (Sixdorf, 2016)	Photos of the installation of sheet piles to prevent seepage near the pumping station
Photo reportage 2004 (Sixdorf, 2016)	Photos of the construction of the road on top of the crest
Video footage, 2013 (Weichel, 2013)	Video footage during the breach by drone flight
Saaledeich bei Breitenhagen, geotechniscche untersuchungen der Bruchstelle Empfehlungen zut Sanierung, dr.-Ing. P. Grubert, 2013 (Grubert, 2013)	Photo reportage (during and after the breach) Analysis based on calculations Location overview Levee profile (measurements) Levee profile km 0+590 (incl. borings) Soil mechanic laboratory tests Water content determination Sieve curves Geotechnical stability calculations (Bishop and Janbu) variety of scenarios Underground hydraulic analysis (stationary and transient pressures) Earth stance, assessment of uplift
Photo reportage and paper clippings of the repair 2013 (Sixdorf, 2016)	Photo footage of the repair of the levee Clippings of the plans of construction in the area Photo footage right after the repair

Water Levels During Elbe and Saale Flood of 2013

In the summer of 2013 both the Elbe and the Saale river experienced high water levels due to heavy rainfall upstream. The peaks of the high water levels met each other at the intersection of the Saale and the Elbe near Breitenhagen. The actual water height was not measured at the location of the breach, but the water levels were measured at the nearest upstream and downstream measurement station and the levels at Breitenhagen were interpolated (Figure 3) (Drews, 2017). The elevation of the (water) level is expressed as a standard reference level called the NormalHohenNull (NHN) which is approximately equal to mean sea level. The breach occurred just at the moment that the water levels in both rivers reached their peak on June 8th, 2013. It appeared that the water levels of 2013 were the highest water levels ever measured in both the Saale and the Elbe (Drews, 2017). Both water levels have a return period of 100 to 200 years (Drews, 2017; Elbe, 2014).

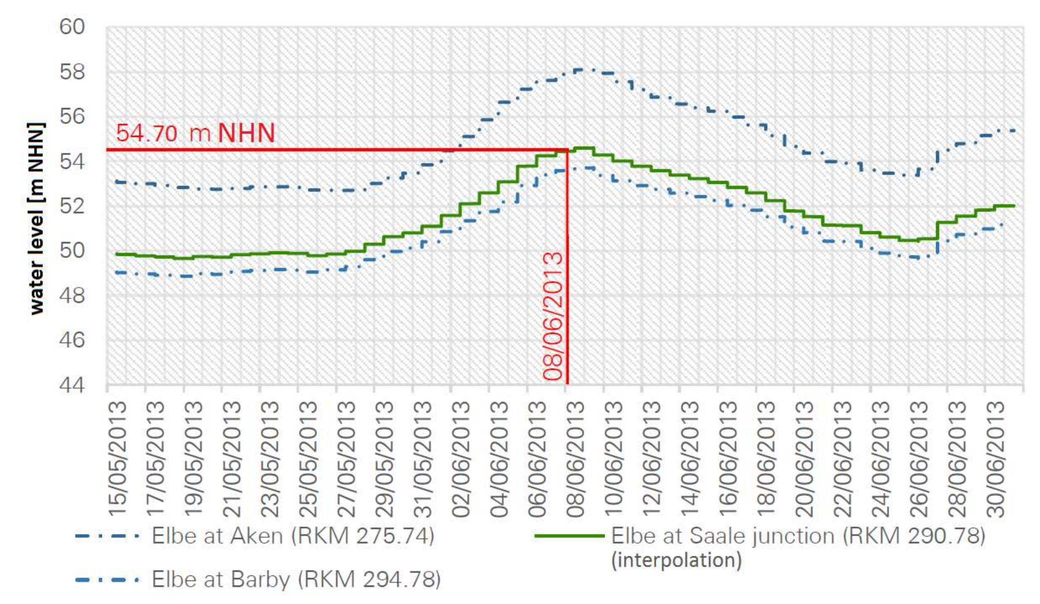

Figure 3. Graphs with water levels over time of the Elbe and Saale near Aken and Barby. Water level at Elbe and Saale junction, RKM 290.8, is NHN+54.7 m (Drews, 2017; Grubert, 2013)

Cross-Section and Stratigraphy

The stratigraphy is reconstructed using the borings that were completed over five cross-sections, including samples at the toe and the crest of the levee (Grubert, 2013). The borings were positioned near the location of the breach (length marker +600 m). In total twelve borings were completed to a depth of approximately 3 m to 4 m. The borings show little variation in width over the cross-section (Figure 4).

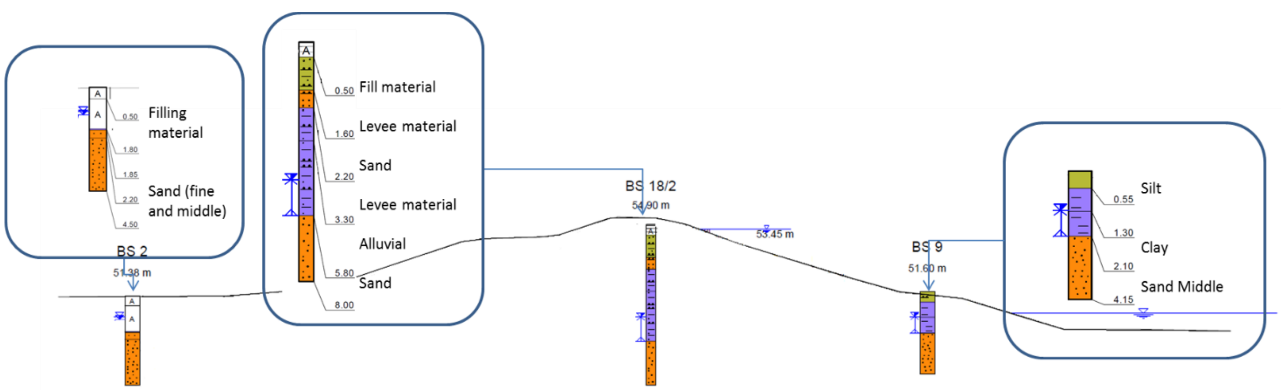

Figure 4 Cross-section of the levee (right is riverside) near the location of the breach (length marker +590 m), with the water levels, groundwater levels and the results of the borings (titled BS2, BS18/2, BS9 taken about 10 m in distance of the start of the breach (Grubert, 2013). The borings were taken both before and after the breach of 2013.

The cross-section generally consists of two layers (Figure 4 and Table 2) (Grubert, 2013). The top layer of the levee consists of largely homogeneous cohesive material (clay-like). A few inclusions of locally mixed-grained soils are identified. The bottom layer consists of a sand layer that can be found throughout the cross-section at an approximate elevation of NHN+49.5 m about 5.5 m deep from the surface (Table 2). This layer likely functions as an aquifer. The identified soil types are characterised by the typical characteristic parameters listed in Table 3 (Grubert, 2013; Schneider & Albert, 2014).

Table 2. Stratigraphy at the location of the breach (Grubert, 2013). The description of each layer per boring is presented. The position of each soil layer is related to the NHN, with matching soil layer number in the calculative models used in Grubert (2013), see Figure 5.

Toe (landside) code: BS2			**Crest code: BS18/2***			**Toe (waterside) code: BS9**		
Soil description	Layer Nr.	[m NHN]	Soil description	Layer Nr.	[m NHN]	Soil description	Layer Nr.	[m NHN]
fill up material	Nr.1 and Nr.3	51.4-49.6	fill up material	Nr.1	54.9-54.4	Silt	Nr.1	51.6-51.0
Sand (fine and middle)	Nr.4	49.6-46.9	Levee material	Nr.2	54.4-53.3	Clay (fine)	Nr.2	51.0-50.3
-		-	Sand	Nr.2	53.3-52.7	Clay	Nr.2 and Nr.3	50.3-49.5
-		-	Levee material	Nr.2	52.7-51.6	Sand (middle)	Nr.4	49.5-47.5
-		-	Alluvial	Nr.3	51.6-49.1	-		-
-		-	Sand	Nr.4	49.1-46.9	-		-

*this boring was conducted in 2007

The dimensions of the cross-section of the levee are mapped at the location of the breach (Figure 5). The measurements show that the levee is about 3.50 m high with a crest width of 3.00 m. The landside slope is 1:2.1 and the waterside slope is 1:3.1. The distance between the waterside toe and the pond is about 3.00 m.

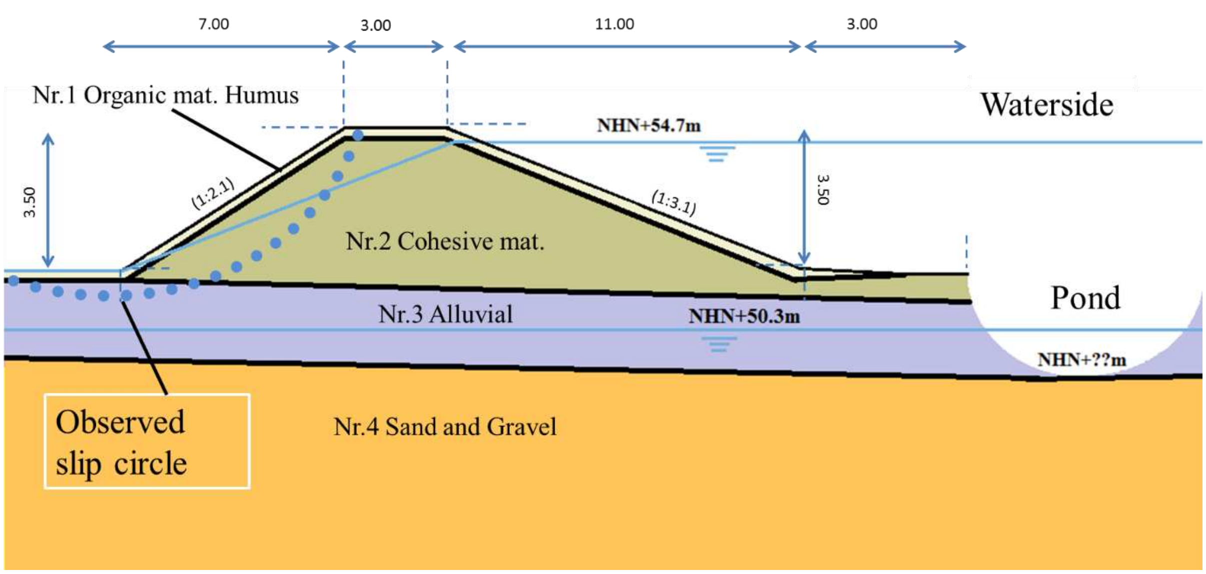

Figure 5. Dimensions of the Breitenhagen levee including simplified soil layering flood level and assumed aquifer level (pre-failure, left side is landside, right is the waterside). The 2013 high water level is NHN+54.7 m, the measured groundwater level is NHN+50.3 m. The soil modelling is based on the forensic engineering report (Grubert, 2013), incorporated with maximum occurred flood level, and soil types (Grubert, 2013).

The findings from the borings were translated in a 2D-geotechnical model to simulate the resistance of the levee (Figure 4) (Grubert, 2013). The cross-section in this model consist of mostly cohesive material in the top layers and levee itself, with a subsoil of sandy material (Table 3 and Figure 5) which is considered to be very conductive.

Geotechnical Parameters

The results of the borings as shown in Table 2 and are related with the values of parameters with similar soil descriptions (shown in Table 3). Best estimates for relevant soil parameters from the standard best estimate values provided by the Deutsches Institut fur Normung (DIN) or Table 2.7 from “Bautabellen für Ingenieure” (Grubert, 2013; Schneider & Albert , 2014).

Table 3 Best estimate of relevant parameters used for the different soil type (bulk unit soil weight :γ, friction angle: φ ', cohesion: c') (Grubert, 2013; Schneider & Albert , 2014).

Layer Nr.	Name soil layer (Grubert, 2013)	Description of the layers of soil (Schneider & Albert , 2014)	γ [kN/m³]	φ ' [degr]	c' [kN/m²]
Nr.1.	S 0a-Mutterboden	Organic mat. Humus	18.0	26.0	7.0
Nr.2.	S1a-Deichkorper, bindig	Cohesive material	20.0	25.0	10.0
Nr.3.	S 2-Aueablagerungen	Alluvial	20.0	25.0	10.0
Nr.4.	S 3-Sand und Kiese	Sand and gravel	18.0	33.0	0.0

History of The Breitenhagen Levee: Construction, Failure and Repair

In this section, the past performances of the levee are summarized in terms of construction, upgrades, repairs and breaching thus providing insight in the past performance of the levee (Sixdorf, 2016):

- 1845: first documentation of the levee protection with a crest height of 0.50 m;
- 1862: the levee is breached on purpose in order to drain the polder, which was flooded, followed by a repair of the levee;
- 1955: Installation of an electric pump near the levee. For this purpose, a cable was installed from Breitenhagen to the pumping station inside the levee cross-section;
- 2003: a high water level took place;
- 2003: installation of sheet piles into the levee body, just up to the location of the pumping station as a measure against seepage;
- 2004: the construction of the crest road;
- 2013: levee breach;
- After the flood, installation of more sheet piles as prevention of seepage and installation of stability berm to prevent instability of the slope at landside.

Findings Based on Previous Analysis of The Breitenhagen Failure

The Breitenhagen levee failure was studied by Grubert (2013). The purpose of this study was to investigate the cause of the breach and the measures required for permanent repairs. At some distance from the breach, cracks were found in the dyke body. The investigations were therefore extended to the adjacent area. The analysis in this study on the Breitenhagen case notes that the roots of the trees at the riverside of the levee grow inside the levee (Grubert, 2013). The contribution of the tree roots inside the levee is considerable and is indicated as a probable cause of the breach. The analysis is based on geotechnical investigations and stability analyses that are included in the report. The results show that a part of the cause is probably uplift of the top layer. This is considered a secondary cause, since the observed sliding mode does not meet the typical dimensions of such a mechanism. The most important causes of the failure and adjacent cracks are a combination of (Grubert, 2013):

- The relatively steep angle of the slope at the landside;
- An unusual vertical crack that occurred in the body of the levee due to drying out of the clay;

- Horizontal conductive layer due to tree root growth on the riverside in a horizontal plane;
- Levee made out of plastic clay which is low in water content.

Two different scenarios of water pressure development in the cross-sections were analysed in the stability models (i.e. with tree roots and without tree roots growing in the cross-section). The results are expressed as a ratio between the resistance (R) and the loads (S) which is called factor of safety (FoS=R/S). The scenario with tree roots (FoS =0.92) and without tree roots (FoS=2.04) were both analysed with the help of the Janbu stability model. The Bishop model of the levee show that the levee without the trees is stable (FoS= 1.45). Both analyses use the characteristic values of soil of Table 3 as a conservative estimate. The findings of Grubert (2013) are incorporated in this study.

Observations Before, During and After The Breach in 2013

With the help of the collected data (mostly photographs), an exploration of visual indicators is performed. The analysis of the data also provides possible input of the model (factors of influence) such as geometry of the levee and the geometry of the sliding mode, stratigraphy, phreatic lines and transient groundwater flow in possible highly conductive layers. The data indexed as prior, during and after the breach.

Observations Before The Breach

The data collected prior to the breach provide an indication of the condition of the levee prior to the breach. The overview photo shows a pond in front of the levee possibly caused by an earlier breach (Figure 2). This indicates the possibility of a direct connection between the outside water level and the aquifer below the levee. The photos show a row of trees at the riverside toe of the levee which might influence the conductivity of the levee due to the intrusion of the roots inside the levee, or might indicate the presence of a more conductive layer inside the levee (Figure 2). The slope of the levee is very steep (about 1:2.1 vertical to horizontal) with a gradient that exceeds the friction angle of most soil types. The slope at the landside is prone to instability (Figure 5).

Observations During The Breach

Photo data were collected during the breaching process as well, showing recognizable indications of the levee failure. The indicators were used to identify the deformations and the geometry of the slip circle (Figure 6). Also, ponding due to possible seepage of water at the landside is shown. Possible high water pressures in the aquifer may cause seepage and saturation of the soil at the landside of the levee.

Figure 6. Photo series over time (upper left: 08.06.2013-10:37, initial break at the edge of the slope, upper right: 08.06.2013–14:10, horizontal shifts, bulge of the toe, lower left: 08.06.2013–20:51 continuing failure, lower right, 08.06.2013–20:55, continuing failure with the visual predictors (Grubert, 2013). Riverside of the levee is on the right for all photos.

On the left side of the picture an electricity pole is recognized which seems to tilt over time, until it is almost completely horizontal (Figure 6). Also the slip circle is expanding until the road is completed damaged indicating an increasing deformation over time. The initial failure is considered to have weakened the levee to such a level that the levee lost all its retaining capacity.

Observations After The Breach

The photos taken after the breach show the presence of roots in the cross-section even after the breach as shown in Figure 7. The roots are numerous and the length of the roots indicate that they have grown deep into the levee. The presence of the tree roots might indicate a highly conductive layer which could have a direct effect on the local pore pressures inside the levee. The soil surface that is exposed by the breach, seems to consist of a cohesive material.

Figure 7. Photo of the cross-section of the breached levee (Grubert, 2013).

FRAMEWORK FOR FORENSIC ENGINEERING ANALYSIS AND ITS APPLICATION TO THE BREITENHAGEN LEVEE FAILURE

In this section, a framework for forensic analysis of levee failures is developed which is based on a generic approach of forensic engineering originally developed by the Dutch Organization for Applied Scientific Research (TNO) to analyze structural failures (Borsje, Renier, & Bruggraaf, 2014). However, the TNO forensic engineering approach is not sufficiently applicable to analyze levee failures that are associated with different and larger uncertainties and different failure modes. In the following paragraph the proposed "generic" approach for general forensic engineering by TNO will be discussed first. In the second paragraph a specific approach for forensic engineering of levee failures is introduced. The third and fourth paragraph describe in more detail the approach and considered scenarios for the Breitenhagen failure respectively.

Forensic Engineering

TNO has developed a generic approach for a systematic investigation of structural incidents that provides clear insight into the use of all information during analysis (Borsje, Renier, & Bruggraaf, 2014). The approach accounts for all decisions as some typical and vital information might be uncertain. This approach is designed to make the input and modelling uncertainties explicit in order to simulate the actual event as realistically as possible without the usage of probabilistic techniques. The generic approach of forensic engineering analysis of TNO uses the collected data in two steps (Borsje, Renier, & Bruggraaf, 2014). The first part results in an overview of all possible scenarios, based on the situation before the failure. The history of loading and performance of a structure is investigated up to the failure. The first sign of failure is located. Then all possible scenarios are verified or eliminated, leaving the most likely causes for further consideration. Detailed structural calculations are conducted to examine the most likely scenario of combined causes of the failure, in order to reproduce what happened (hindcasting). The final conclusion is based on rational deductions and every decision related to uncertainties is rationally argued during the process.

Compared to steel structures, which were the object of TNO's investigation, geotechnical failures introduce an additional complexity regarding the input and modelling uncertainties. Documentation of the complete history and performance of a geotechnical structure (in this case a levee) is often limited or incomplete. Even when the data of relevant parameters are available from local site investigations, they do not necessarily represent the site specific data in great detail (Schweckendiek & Vrouwenvelder, 2014; van Baars, 2005). In the analysis of the levee using geotechnical models, multiple model choices can be used to determine the strength behavior of the levee. No matter how advanced these models are, they will always suffer and reflect uncertainties in the model outcome. Typical input parameters from standard laboratory data are used, which in general do not account for time dependent behavior and, thus cannot be representative of the natural heterogeneity of the soil on site. Validation of the geotechnical models is complex as during the failure, all detailed processes within the cross-section are withdrawn from observation, and after the failure usually all evidence is washed away. Also different failure mechanisms may overlap or influence each other (Kanning, Van Baars, & Vrijling, 2008). The sum of uncertainties results in many combinations and possibilities that could lead to failure. The suggested approach of forensic engineering for the case of levee failure focuses on several individual factors that are typically points of special attention when performing a simulation of levee strength. The approach analyses their influence one by one.

Proposed Approach for Forensic Analysis of Levee Failures

To identify the most likely cause of a levee failure, a systematic approach for forensic analysis of levee failures is suggested. In order to make the generic forensic analysis approach more applicable to levee failures, the standard three steps of forensic engineering as proposed by TNO (see section 3.1) are adapted into three more specific steps for levees (A, B and C, see Figure 8).

In step A, the collected data that are typically relevant for levee breaches, are sorted in three ways, i.e. data collected prior, during and after the failure as shown in Figure 8. This provides a clear overview of which data are relevant in terms of factors that are of influence on the performance behavior and a first impression on the performance behavior of the levee during extreme circumstances. A distinction is made between input parameters (which are considered as possible causes e.g. pore water pressures and shear strength of the soil) and model choices (e.g. LEM and (un)drained soil behavior). With the data during and after the failure, possible failure scenarios are determined and the behavior of a levee is studied.

In step B, a sensitivity analysis is used to validate or eliminate possible causes contributing to the levee failure (hindcasting) (Figure 8). Using the data and additional literature, the best estimate scenario and expected values for the input parameters are modelled (further referred to as "base model"). During the process of developing a "base model", all the individual uncertainties are identified and introduced as scenarios (in terms of input parameter and modelling choices). During the sensitivity analysis, the expected values of the still uncertain input parameters are replaced one by one by realistic upper and lower limit boundary values.

Exploration of all possible combinations of individual scenarios can be a very time consuming exercise. The focus of the scenarios and sensitivity analysis is mainly on the influence of the different individual uncertain factors of influence, except for a number of combinations of causes which are suspected to cause failure. The results of the sensitivity analysis validates or eliminates the different scenarios of individual possible causes of the failure and is itended to identify the most likely causes in step C. The most likely causes can be further validated by performing additional field tests, research or more detailed calculations resulting in the final conclusion assuming the most likely individual cause of the levee failure.

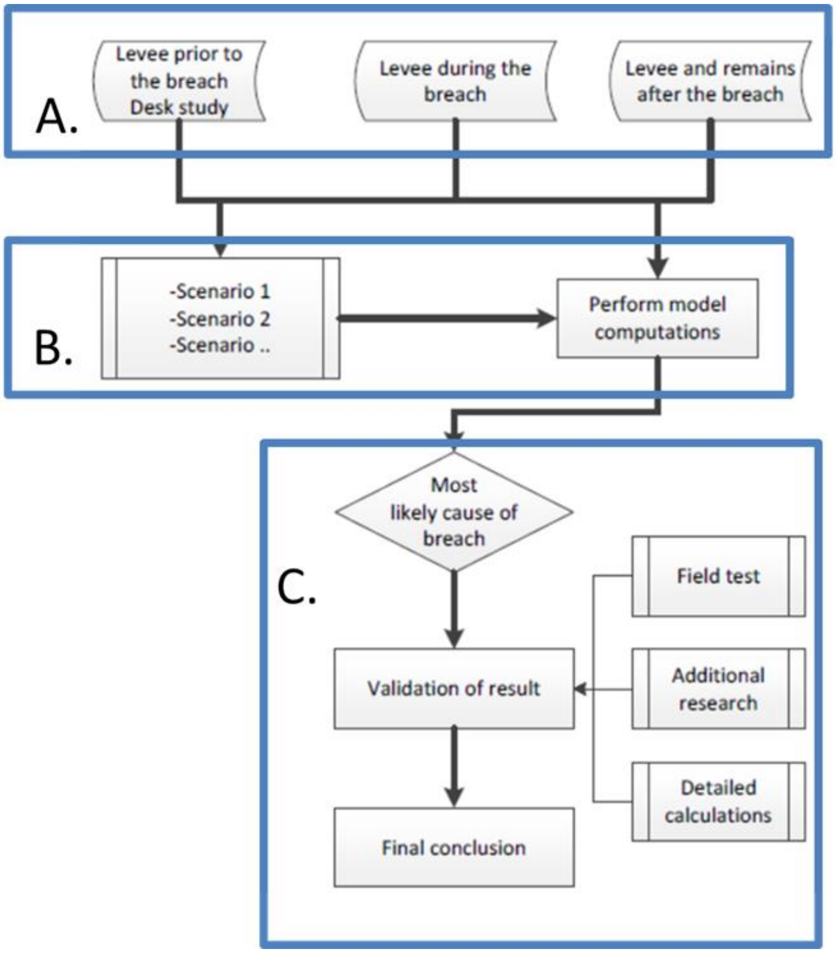

Figure 8. Generic approach for levee forensic analysis based on Borsje, et al. (2014) Step A.: Collecting information for exploring possible scenarios; Step B.: Evaluate with a computational model; Step C.: When results do not identify the cause, additional information can be gathered.

Forensic Analysis of The Breitenhagen Failure

The generic approach of forensic analysis for levee failure, as presented in the previous section, is applied to the Breitenhagen levee failure. This paragraph elaborates on the identification of all possible scenarios and causes of failure that are distilled from the collected data (step A) which are used for the sensitivity analysis in step B as proposed in the previous section.

Based on the available evidence, the Breitenhagen case is considered to be a failure due to instability of the slope at the landside. When performing a levee stability analysis, the following factors influence the levee performance and are categorized in terms of input parameters and model choices (CIRIA, 2013; van Deen & van Duinen, 2016):

- The geometry of the levee;
- Stratigraphy of the soil;
- Water levels (inside and outside);
- The water pressure (development) inside the levee and hydraulic head in the subsoil;
- The values of the geotechnical parameters of the soil;

- The drainage rate of the soil;
- The specific Limit Equilibrium Method (LEM).

In step A, the collected data are analyzed to identify all uncertainties. The geometry, stratigraphy of the soil, water level could be identified using the collected evidence. The water pressures and hydraulic head in the subsoil, and the soil strength in terms of geotechnical parameters of the soil are still uncertain and are considered as possible causes of the levee failure. Also the model choices in terms of drainage rate of the soil for the LEM are still uncertain.

To determine the possibe contribution to failure of the uncertain input parameters and model choices, all possible scenarios and causes of failure are identified. The collected data are used to construct a stability model in order to simulate the best estimate scenario together with the expected values of input parameters (representing the best estimate conditions). This model is called the "base model" and is shown in Figure 10. In case of the Breitenhagen levee failure, the focus is on the uncertainties in water pressure development (level 1), the drainage rate of the soil (level 2) (whether the reponse of the soil is better represented by drained or undrained schemes) and the related values of shear strength parameters (level 3). Moreover different LEM schemes (Bishop, Uplift Van, and Spencer) are used to analyze the model uncertainty (level 4).

The next step is to identify the individual influence of the uncertain factors (level 1 to level 4) and verify whether the calculated slip circle naturally matches the actual observed slip circle (Figure 11) and doesn't intersect with the sand layer. For the input parameters, the lower and upper limit boundary values are introduced, one by one, into the "base model" (Figure 10, Table 4 and Table 5). The actual input values and factors are introduced and discussed in the next section. The results that are expressed as factor of safety (FoS) show a range of possible outcomes, related to each individual factor of influence. Additional analyses on combinations of possible causes are executed. Thus, an overview of stability with one or more dominant contributors is developed. When the related FoS is below a value of one, the situation is considered to be unstable and the scenario is identified as a possible cause of failure.

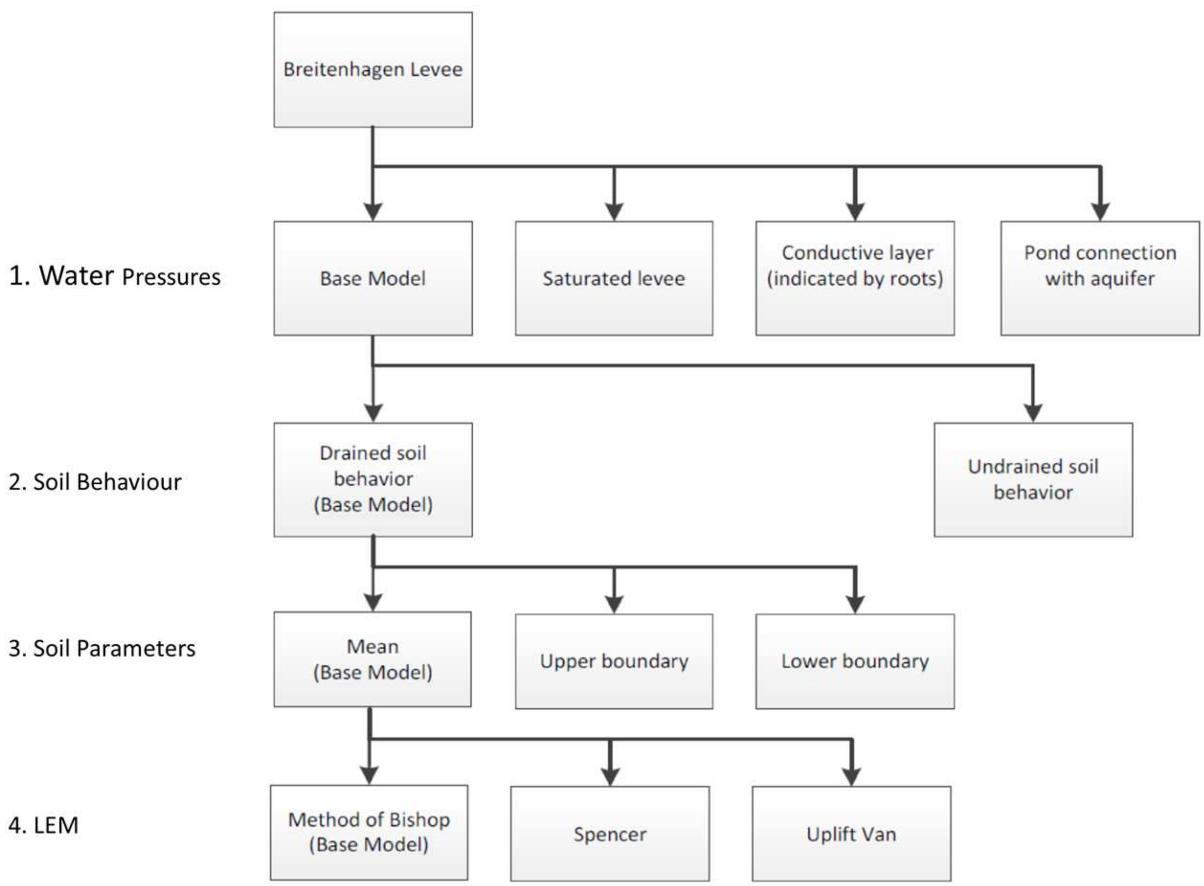

Figure 9. Overview of all factors of influence to vary in the sensitvity analysis one by one. Level 1.: Water pressure scenarios. Level 2.: Soil reaction behavior scenarios. Level 3.: Soil parameter scenarios. Level 4.: LEM scenarios.

Scenarios For Analysing The Performance Behavior of The Breitenhagen Levee

In this section, the scenarios of water pressure and hydraulic head in the subsoil, soil strength in terms of soil parameter, soil reaction behavior scenarios, or LEM as shown in Figure 9, are further elaborated and quantified.

Pore Water Pressures

The intrusion of water at high water levels inside the levee causes the strength of the levee to decrease. The process is best described by the two sub-processes i.e. infiltration and groundwater flow, which initiate local high water pressures inside the levee. High water pressures lead to low effective stresses and result in local shear strength reduction. The water pressure in the base model (A) is modeled with a phreatic line in the levee body and water pressures in the aquifer (Figure 10). The analysis of the collected data shows that there are three possible scenarios in addition to the base model (A): increased rise of the phreatic line (scenario B:"Saturated levee", modeled as 'high' phreatic line), a conductive layer as a result of tree roots growth (scenario C:"Conductive layer, indicated by roots"), and high water pressure under the levee due to a connection of the outside water level and the aquifer (scenario D:"Pond connection with the aquifer") (Figure 10). In the sensitivity analysis, the input uncertainty is taken into account for scenario B and D by introducing the extreme upper, best estimate and extreme lower boundary value of water pressure development (Figure 10). The four water pressure scenarios are further elaborated below the figure.

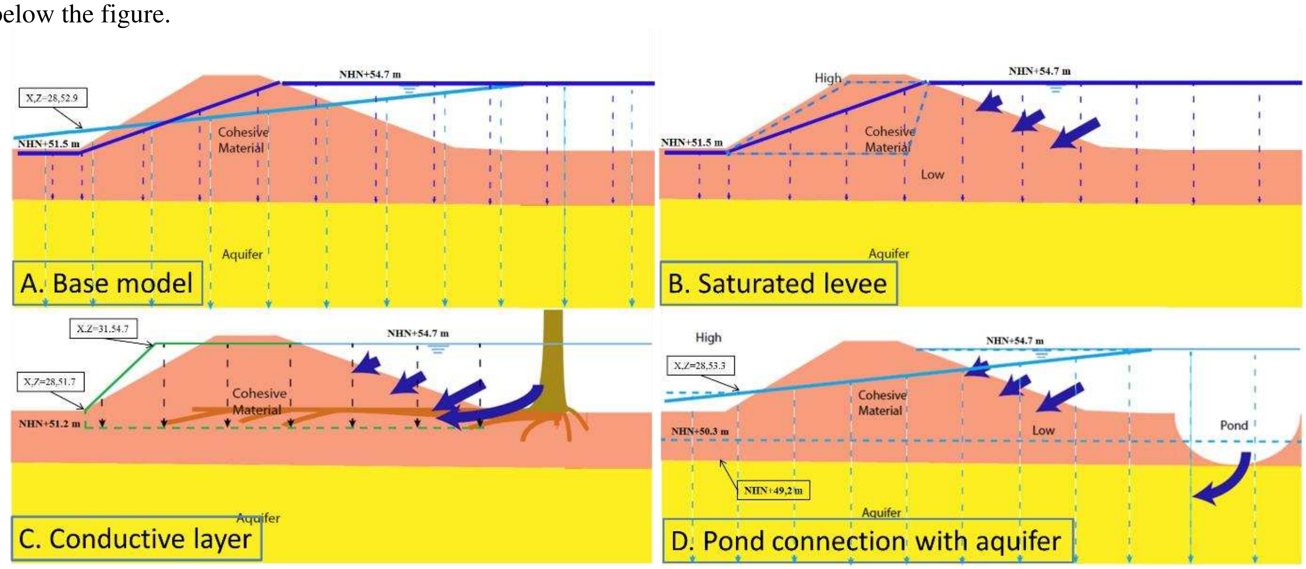

Figure 10. View of the four possible scenarios derived from the data analysis. ScenarioA: Best estimate of phreatic line inside the levee (solid dark blue) and best estimate hydraulic head in the aquifer (solid light blue), called "Base model". The river head (NHN+54.7m) and localy heightened polder head (NHN+51.5m). Scenario B: Infiltration of water through the levee slope which is called "Saturated levee" (dashed light blue lines); Scenario C: Infiltration through a conductive layer related to the tree roots which is called "Conductive layer, indicated by the tree roots" (situated at NHN+51.2m)(the hydraulic head in green is the head at the location of the roots, the phreatic line is the same as the Base model. Inside the levee, water pressures in the levee are interpolated between the phreatic line and the green line); and Scenario D: Infiltration through the connection between the outside water level and the aquifer which is called "Pond connection with aquifer" (polder head of NHN+51.5m) with an upper and lower head (dashed light blue lines);.

The analyses and the assumptions of the Grubert report (2013) are used to model the expected phreatic line and the hydraulic head inside the aquifer. Observations indicate that the phreatic line equals the surface level at the landside at the time of failure. The phreatic line is interpolated linearly between the river level and the polder head. At the same time, the hydraulic head in the aquifer beneath the layer might increase due to a connection between the river level and the aquifer. This causes a local increase in water pressure in the aquifer compared to the water pressure corresponding to a hydrostatic phreatic line.

The water potential inside the aquifer is limited by the weight of the blanket layer, which might otherwise cause uplift. The hydraulic head of scenario A, i.e. the "Base model" (best estimate) is fitted to the weight of the covering soil, at the toe of the levee. The water pressure inside the levee is interpolated between the phreatic line and the hydraulic head at the interface between sand and clay.

In the scenario of the "Saturated levee" (scenario B), the only phenomenon that is taken into account is the development of the phreatic line in the levee body (Figure 10). The development of the phreatic line in the levee itself is caused by the infiltration of the high water wave from the river in the levee body. Due to the low permeability of the cohesive material, the infiltration of the water in the levee is a relatively slow process. The intrusion length of the high water wave is limited by the width of the levee. The extreme low and high boundary of the phreatic line are based on standard phreatic models to represent infiltration (upper extreme boundary) and transient (lower extreme boundary) flow are suggested by literature (TAW, 2004). The models incorporate the influence of the dominant factors that influence the phreatic lines, i.e. infiltration and groundwater flow in order to simulate the transient flow and the different possiblities of steady state flow.

In the scenario of the "Conductive soil" (scenario C.), the roots inside the levee indicate a more conductive layer due to a relatively large permeability (Figure 10). Therefore, the intrusion length of the water wave is increased in this layer. This causes a local increase in water pressure. Moreover, the velocity of the high water pressure wave in the conductive layer is relatively fast compared to the levee body. In this area, the water potential equals the outside water level. At the inside toe of the levee, the potential inside the rooted area is limited by the covering soil. The analysis of Scenario C. is executed as a direct relation to Scenario B. to show its influence on the upper, mean and lower bound of the phreatic line. The water pressure inside the levee is interpolated between the phreatic line and the hydraulic head inside the conductive soil layer.

In the scenario of the "Pond connection with aquifer" (scenario D), the pond in front of the levee might introduce a connection between the aquifer layer and the outside water level (Figure 10). This causes a local increase in water pressure in the aquifer compared to the water pressure corresponding to the phreatic line. Because of a relatively large leakage length of the outside water level, the water pressures inside the aquifer might cause a shear strength reduction at the landside. The weight of the blanket layer limits the hydraulic head in the aquifer. The water pressure inside the levee and the blanket layer is interpolated between the phreatic line and the (limited) hydraulic head at the interface between sand and clay.

Geotechnical Shear Strength

The shear strength of the soil is introduced for both drained and undrained response behavior to determine the amount of shear stress that the soil can resist. Besides the drainage rate of the soil, the shear strength of the soil depends on the values of the geotechnical input parameter.

The drained soil response behavior is introduced by the Mohr-Coulomb model and depends on three parameters, i.e. cohesion (c' [kPa]), soil friction angle (φ [deg]) and the effective vertical stress (σ' [kPa]). The undrained soil response behavior for low permeability materials is introduced with help of the SHANSEP implementation (Ladd, 1991) of the Critical State Soil Mechanics (Schofield & Wroth, 1968) (Equation 1):

$$s_u = \sigma'_{v,i} \; S \; OCR^m \text{ with } OCR = \sigma'_{vy}/\sigma'_{v,i} \text{ and } \sigma'_{vy} = \sigma'_{v,i} \; POP \qquad (1)$$

Where s_u [kPa] is the undrained shear strength ratio, $\sigma'_{v,i}$ [kPa] is the in-situ vertical effective stress, S [-] the undrained shear strength ratio, OCR [-] the Overconsolidation Ratio, m [-] the strength increase exponent, σ'_{vy} [kPa] the vertical yield stress, and POP [kPa] the pre-overburden pressure.

The shear strength of the soil is influenced not only by the pore water pressure, but also by the values of the geotechnical input parameters. The parameters are uncertain (Figure 5 and Table 2). Therefore values of the parameters are based on values coming from Dutch literature (Normcommissie, 2011; RWS, 2016; van Deen & van Duinen, 2016). In this sensitivity analysis, the input uncertainty is taken into account by applying the extreme upper, mean and extreme lower boundary value for the soil parameters related to the identified soil type, for both drained and undrained soil behavior (Table 4 and Table 5). The coarse-grained soil (sand and gravel) are expected to behave drained and are implemented as such, also in the undrained analyses. Since the behavior of the fine grained soils is unknown, these are modelled as both drained and undrained. The sensitivity analysis does not consider individual layers of soil. The introduction of the upper, mean or low boundary values affects all soil layers at the same time.

Table 4. Assumed lower and upper bound of soil properties. Mohr-Coulomb parameters are used for the sensitivity analyses (extreme value for the soil weight: $\gamma_{up/low}$, expected values: γ_{mean}, extreme value soil friction angle: $\varphi_{up/low}$, expected values: φ_{mean}, extreme value cohesion: $c'_{up/low}$, expected values: c'_{mean}) (Grubert, 2013; Normcommissie, 2011).

Layer Nr. and Soil type (Grubert, 2013)	Description of soil layer (Normcommissie, 2011)	γ_{mean} [kN/m^3]	$\gamma_{up/low}$ [kN/m^3]	φ_{mean} [deg]	$\varphi_{up/low}$ [deg]	c'_{mean} [kPa]	$c'_{up/low}$ [kPa]
Nr. 1. Organic mat Humus	Clay, clean and moderately stiff	17	20/14	21.25	25/17.5	7.5	15/0
Nr.2. Cohesive mat.	Clay, little bit of sand, stiff	18	21/15	25	27.5/22.5	7.5	15/0
Nr. 3. Alluvial	Clay, little bit of sand, stiff	18	21/15	25	27.5/22.5	7.5	15/0
Nr.4. Sand and gravel	Gravel, bit silty, clean	18.5	22/19	36.25	40/32.5	0	0/0

Table 5. Typical parameter values of undrained soil behavior (Critical State Soil Mechanics) that are used for the sensitivity analysis and are very common in the Netherlands with similar soil description (where $S_{low/up}$ are the extreme boundary values of undrained shear strength ratio, S_{mean}, are the expected values, $m_{low/up}$ are the extreme boundary values of strength increase exponent, m_{mean} are expected values, $POP_{low/up}$ are extreme boundary values of pre-overburden pressure, POP_{mean} are expected values) (Ladd, 1991; RWS, 2016; Van Deen & Van Duinen, 2016).

Layer Nr. And Soil type (Grubert, 2013)	Description of soil layer	$S_{low/up}$ [-]	S_{mean} [-]	$m_{low/up}$ [-]	m_{mean} [-]	$POP_{low/up}$ [kPa]	POP_{mean} [kPa]
Nr. 1. Organic mat Humus	Sandy and Silty Clay	0.22/0.50	0.30	0.5/1.00	0.9	0/75	22
Nr.2. Cohesive mat.	Levee material	0.23/0.50	0.31	0.5/1.00	0.9	0/150	30
Nr. 3. Alluvial	Levee material	0.23/0.50	0.31	0.5/1.00	0.9	0/150	30

BREITENHAGEN LEVEE FAILURE: SENSITIVITY CALCULATIONS

With the selected scenarios introduced in the previous section, a sensitivity analysis was conducted in order to find the most likely causes of the failure (Figure 9). In the following paragraphs, the results related to the scenarios of water pressures are presented, followed by the influence of the soil response behavior (drained and undrained), the influence of the different shear strength parameters and the influence of the different LEM. In order to highlight the potential of further research, the results of the more prominent combinations of possible causes are presented as well. In total 32 scenarios and different combinations are taken into account. The model of the best-estimate situation represents the base of the sensitivity analysis (referred to as "base model") and is presented in the first paragraph. In the last paragraph an overview of all results is given.

Base Model

The "base model" (scenario A) represents the best estimate scenario with the expected values of input parameters. The "base model" functions as the basis of the sensitivity analyses (Figure 9). The LEM calculation is executed using the Bishop method and drained soil behavior. The Bishop method is used as best-estimate since this method reflects the circular observed slip circle relatively well. The results of the simulation of the best estimated situation show a FoS=1.61 [-], which is considered stable (FoS>1.0). The shape of the slip circle shows realistic similarities with the actual slip circle (Figure 11). However the slip circle starts at the riverside of the top of the levee, instead of the landside. Also the slip circle intersects the sand layer, which is not considered realistic.

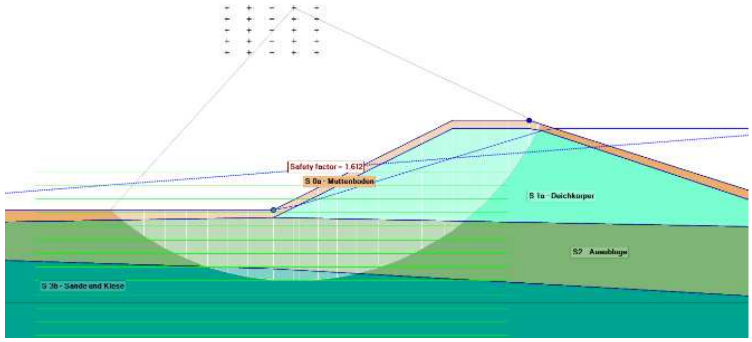

Figure 11 View of the LEM calculation using Bishop stability model with drained soil behavior (FoS=1.61).

Water Pressure Scenarios

The development of water pressure inside the levee is hard to determine, but has a significant influence on the strength of the levee (Figure 9 at "level 1"). There are three different scenarios of pore pressure development incorporated into the sensitivity analysis, i.e., scenario B: "Saturated levee", scenario C: "Conductive layer (related to the roots)" and scenario D: "Pond connection with aquifer" (Figure 10). The different scenarios are introduced to simulate the transient flow and the different possibilities of steady state flow at level 1 of the flow chart (Figure 9 "level 1"). All scenarios are assessed with the help of LEM using Bishop's method and a drained analysis.

Scenario B.:"Saturated Levee" and Scenario C.:"Conductive Layer"

The analysis of the "Saturated levee" uses 3 different scenarios of water pressures to incorporate the uncertainty in transient flow and the contributors in the phreatic line (rain, groundwater, high water wave, etc.) e.g. convex, straight and concave (Figure 10). The analyses with the straight phreatic line is similar to the base model that is introduced as the base case (Figure 9). The analysis of the "Conductive layer (indicated by roots)" is executed as a direct relation to the saturation of the levee as described earlier.

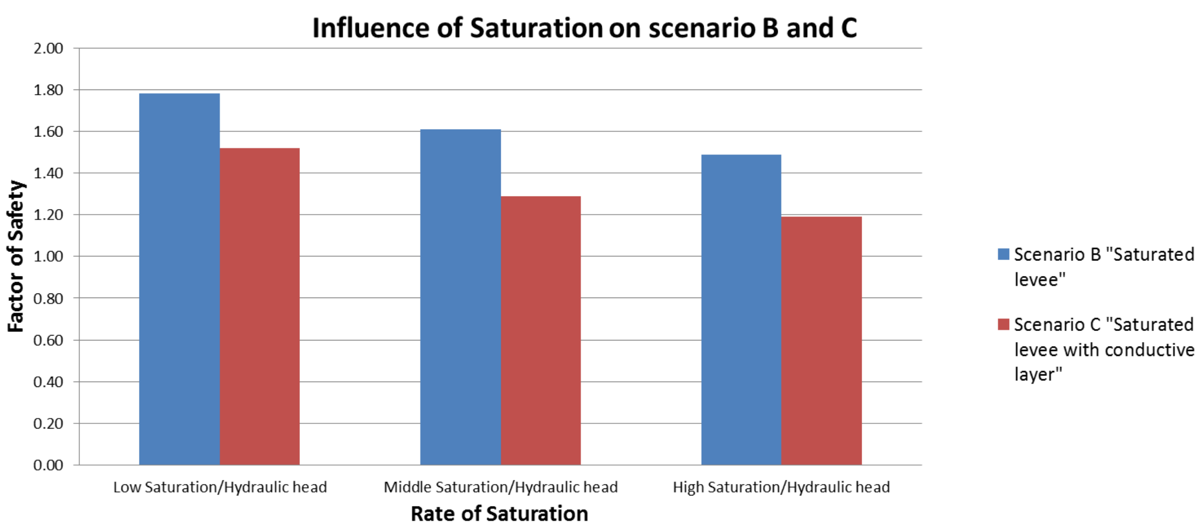

Figure 12. Blue: Influence of the saturation of the levee on the FoS. Red: Influence of the saturation when the local high water pressures in the conductive layer are introduced.

The FoS is negatively correlated with increase in water pressures, because the effective stresses are reduced, which in turn causes the shear strength to decrease. Due to the rising phreatic line, the range of FoS is in between 1.78 and 1.49 (Figure 12). The analysis of the increased potential head in the conductive layer around the tree roots results in FoS of 1.52, 1.29 and

1.19. The lowest factor of safety is found for the highly saturated cross-section in combination with the conductive layer. All models, yield safe values for the FoS.

Scenario D: “Pond Connection with Aquifer”

The stratigraphy shows an aquifer below the levee which might be in direct contact with the water level at the riverside by means of a pond in front of the levee (Figure 10). Similar to the phreatic line, the different water pressures in the aquifer influence the shear strength as well. For the analysis of the contribution of the aquifer to the cause of failure, the model uses three scenarios for the water pressure. The results are shown in Figure 13.

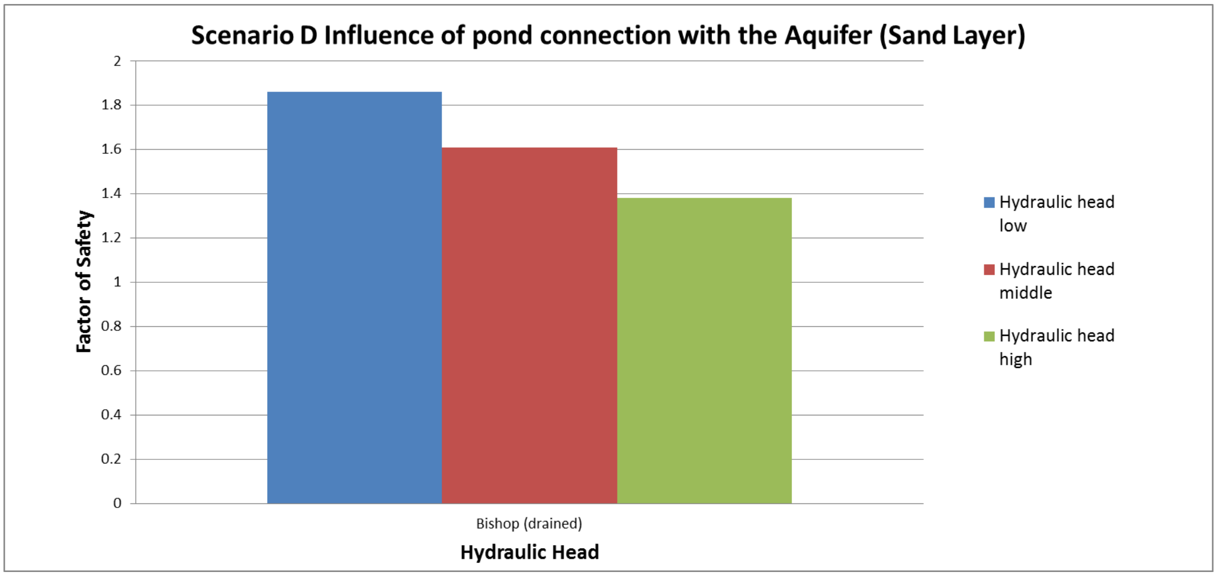

Figure 13. Influence of the rise of the hydraulic head in the aquifer with three different levels in hydraulic head in scenarios D.

Due to the rise of the hydraulic head in the aquifer, the range of the FoS overall is between 1.86 and 1.38. The shape of the slip circle shows realistic similarities with the actual slip circle. However the slip circle still intersects the levee crest instead of starting from the landside of the levee.

Introducing undrained soil behavior for the clay, scenario D, results in FoS between 1.66 and 1.28. The slip circle of the actual failure (Figure 6) and the calculated slip circle (for example with the use of Bishop with undrained soil behavior and Spencer with drained soil behavior) differ in geometry. The slip circle of the Spencer method seems to show more realistic geometry of slip circle than the Uplift Van method and Bishop’s method in case of low effective soil pressures at the interface between sand and clay (Figure 14).

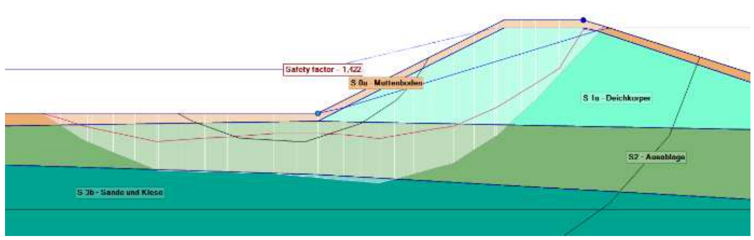

Figure 14 View of scenario D: ”Pond connection with aquifer” output. The high hydraulic head is included and the Spencer model is used (with drained soil behavior) which results in FoS=1.42.

The joint occurence of a saturated cross-section (high phreatic line) and a high water pressure in the aquifer are considered with help of Bishop's method and both drained and undrained soil response. Assuming drained soil behavior results in a FoS of 1.28 and assuming undrained soil behavior results in a FoS of 1.20 with both realistic and similar slip circle shapes in comparison with the actual slip circle (except for intersection of the sand layer with the slip circle). In addition, a combination of scenario 1, 2 and 3 is taken as extreme and combined into one scenario (with Bishops's method). Assuming drained soil behavior results in a FoS of 1.23 and assuming undrained soil behavior results in a FoS of 1.21. Both calculations show realistic slip circles (except for intersection of the sand layer with the slip circle).

Influence of The Soil Model

Since the cross-section of the levee mostly consists of clay, the influence of undrained soil reponse of the cohesive soils (Verruijt, 2010) is assessed relative to the "base model". The calculations are executed using the Bishop method and incorporates the undrained shear strength with the expected values of the input parameters. The result of the simulation shows FoS of 1.50, whereas a FoS=1.61 is found when the "base model" incorporates drained soil behavior. The shape of the slip circle shows realistic similarities with the actual slip circle similar to the "base model" (Figure 11). However the slip circle starts at the riverside of the top of the levee, instead of the landside of the levee and shows an intersection of the sand layer with the slip circle.

Influence of Soil Parameters

The analysis of the extremes of the soil parameters to establish the influence of each individual input parameter and the influence on the performance is compared to the "base model" (Figure 9 at level 3). The contribution of the weight (for both drained and undrained soil model) and the internal friction angle (for drained soil model) are very limited, implying that they do not have a dominant contribution in the failure and therefore are excluded from further analysis. The sensitivity analysis is performed using Bishop's LEM.

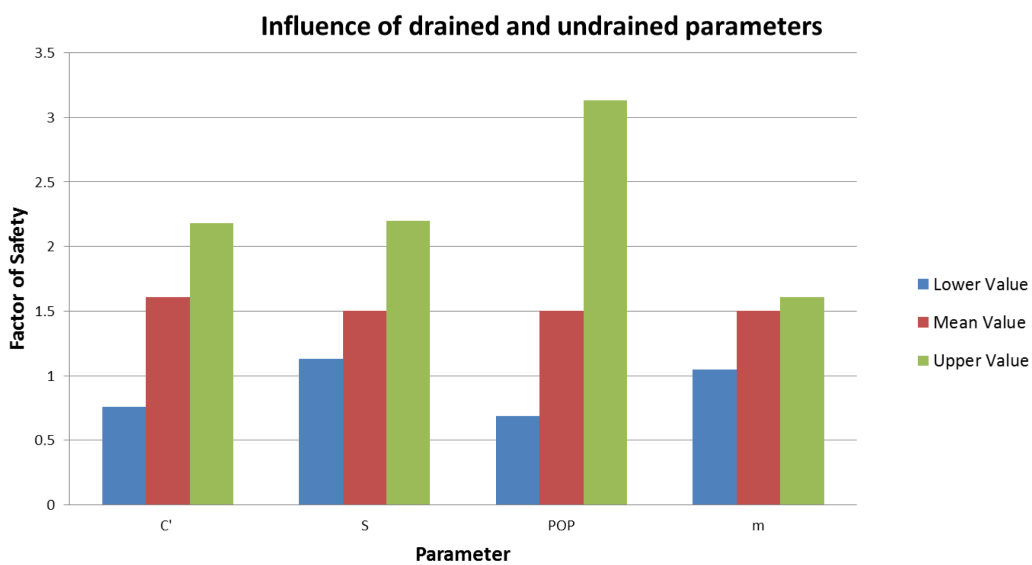

Figure 15. Results of the sensitivity analysis of drained parameter cohesion and undrained parameters.

Varying the cohesion, which is the dominant parameter of the drained soil model, the FoS covers a range between 0.76 and 2.18 (Figure 15). The undrained shear strength has a high variability, due to the uncertainty of the previous stress history and related overconsolidation state (the POP, pre-overburden presure, was used to describe this uncertainty). The results of the calculations greatly reflect this uncertainty in the calculated FoS ranging from 3.13 and 0.69. The parameters S and m, used to model undrained shear strength, result in large variation in FoS, but do not result in values below 1, which would represent failure of the levee. The calculation using the low cohesion values and the Bishop model show similarities with the actual slip circle and do not reach the sand layer underneath the cohesive layers (Figure 16).

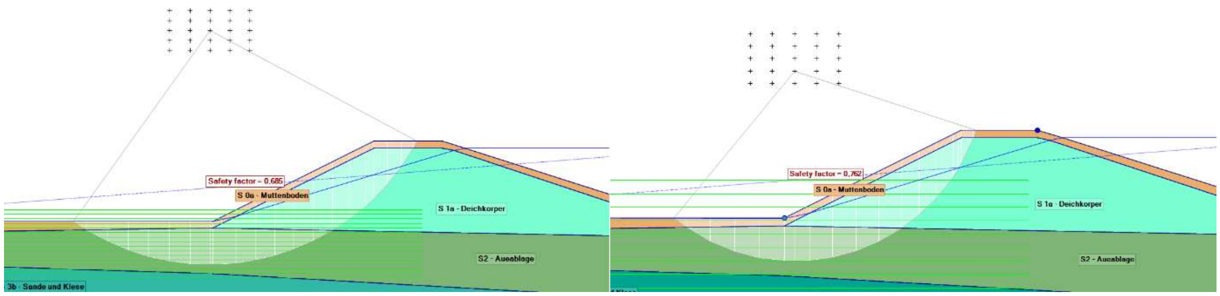

Figure 16 Left: View of scenario A. "Base model" using the Bishop slip circle and low values of POP resulting in FoS=0.69 (undrained soil behavior). Right: Scenario A. "Base model" using the Bishop model and low values of cohesion resulting in FoS= 0.76 (drained soil behavior).

The additional calculation run with a combination of low values of cohesion with high water pressures in the aquifer results in a FoS of 0.55, using Bishop's LEM. The resulting slip circle seems shallow compared to the actual observed failure surface.

Limit Equilibrium Method

Three different LEM are used in the assessment on the levee strength, i.e., Bishop, Uplift Van and Spencer (Figure 9 level 4) in the D-Geo Stability software (Deltares, 2016). All three LEMs are applied to the "base model". The sensitivity analysis is used to establish the influence of different LEM. The FoS determined with the help of the Bishop, Uplift Van and Spencer model covers a range between 1.55 and 1.61. All models result in approximately the same slip circle (Figure 11, Figure 17). The Spencer method shows the most realistic geometry of the slip cirlce (i.e., the slip circle doesn't intersect the sand layer).

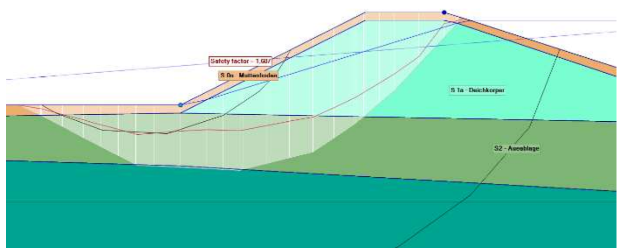

Figure 17 View of scenario A. "Base model" using the Spencer method presenting the calculated critical slip circle (FoS=1.61).

Results of The Sensitivity Calculations

The FoS of the individual causes and additional analyses with combinations of scenarios on the stability of the levee are presented in Table 6. The results are presented in terms of upper, best-estimate and lower boundary values of FoS (Table 6). Four types of uncertainties are considered i.e., water pressures, soil reaction behavior, soil parameters and LEM (Figure 9).

As expected, the upper bounds of the water pressures in the scenarios of "saturated levee" and "pond connection with the aquifer" are related to lower values in FoS. All water pressure related scenarios of failure seems unable to create an unstable situation as an individual cause but do have a significant influence.

Lower values of cohesion and POP lead to FoS values that are significantly lower than 1. The calculations suggest that the individual cause of low shear strength can result in calculative slope instability. Moreover, the shape of the slip circle (Bishop) associated with the low value of cohesion shows large similarities with the shape of the actual slip circle. For the scenario with the low value of POP a slip circle with less resemblence to the actual is obtained.

The use of difference LEMs does not lead to significantly different results. Although the critical failure plane of the LiftVan model intersects the interface of the sand and clay layer and therefore shows unrealistic results. This is probably due to the skewed interface between the sand and clay layer and high values of hydraulic head.

The analyses focus on combinations of individual possible causes that show low results of FoS and result in instability (FoS<1). The results of the combinations of causes show that the combination where low values of POP or cohesion are included can result in instability. Especially when the low values of cohesion are combined with the presence of the conductive layer associated with the tree roots and the pond connection with the aquifer, predicts an instability situation. When the dominant individual factors are combined, the FoS drops to a value of 0.16. However, the shape of the slip circle, associated with the low cohesion and the high water pressure values in the aquifer is very shallow and does not show similarities with the actual slip surface.

*Table 6. Summary of results over the upper limit and the lower limit boundary in FoS per factor (uncertainty). The best-estimate scenario is calculated with the Bishop method and drained soil behavior (Figure 9). *Calculated slip circle matches the shape of the actual slip surface.**shows a slip circle that intersects the sand layer*

	Uncertainty	Upper FoS	Best estimate situation	Lower FoS
Base model	Scenario A.: Best estimate situation (drained model, Bishop)	-	1.61**	-
Water pressures (Level 1)	Scenario B.: Saturated levee (drained model, Bishop)	1.78**	1.61**	1.49**
	Scenario C.: Increased pore by conductive layer (drained model, Bishop)	1.52	1.29	1.19
	Scenario D.: Aquifer connection with pond (drained model, Bishop)	1.86	1.61**	1.38**
Soil behavior (Level 2)	Soil model Undrained (Bishop)	-	1.50**	-
Soil parameters (Level 3)	Cohesion (c’) (Bishop)	2.18**	1.61**	**0.76***
	Undrained Shear strength ratio (S) (Bishop)	2.20**	1.50**	1.13
	Strength increase exponent (m) (Bishop)	1.61**	1.50**	1.05
	Pre-overburden pressure (POP) (Bishop)	3.13**	1.50**	**0.69**
LEM (Level 4)	Spencer	-	1.61	-
	Uplift Van	-	1.55**	-
Combinations	High phreatic line and high aquifer connection (drained, Bishop)	-	-	**1.28****
	High phreatic line and high aquifer connection (undrained, Bishop)	-	-	**1.20****
	Increased pore pressure by conductive layer (undrained, Bishop)	-	-	1.33
	High phreatic line, conductive layer and aquifer connection (drained, Bishop)	-	-	**1.23****
	High phreatic line, conductive layer and aquifer connection (undrained, Bishop)	-	-	**1.21****
	Aquifer connection (drained model, Spencer)	-	-	**1.42**
	Aquifer connection (drained model, Uplift Van)	1.85	1.55**	**1.34****
	Aquifer connection (undrained model, Bishop)	1.66	1.50**	**1.28****
	Low value in cohesion and high aquifer connection (drained, Bishop)	-	-	**0.55**
	Low value in cohesion, high phreatic line, conductive layer and aquifer connection (Bishop)	-	-	**0.16**

DISCUSSION

In the next sections the newly developed generic approach of forensic analysis of levee failures and the results of the Breitenhagen case are separately discussed.

Proposed generic framework for forensic analysis of levee failures

The proposed framework provides a generic approach to forensic analysis of failed levees, to explicitly and transparently account for the most relevant uncertainties and modelling decisions. The systematic approach enhances the process of logical deduction in forensic analysis of levee failures dealing with significant uncertainties since the information prior to the breach is typically limited. In addition, obtaining more information after the breach is also limited since part of the information is washed away. Part of the forensic analysis is the simulation of the event, called hindcasting. The models that are used to simulate the event introduce input parameter- and model uncertainties. The proposed approach is successfully applied to the Breitenhagen levee failure; however, it might need adaptations for future use, once multiple breaches have been assessed using this approach.

The arrangement of the information in a chronological order (prior, during and after the failure) provides a start for a structured overview of the evidence. Moreover it gives good insights into the levee history and, the behavior during the failure event. By isolating and indicating the typical relevant data, an assessment of available and missing data is achieved. The approach achieves consistency between the identified most likely possible causes, the earlier collected evidence and the remaining uncertainties of input parameters and model uncertainties that are involved.

Hindcasting of geotechnical structures is typically dominated by several input and model uncertainties. The introduction of all possible scenarios of individual causes and combinations of possible causes, enables hindcasting that simulates the actual situation, and identifies the most likely causes. The proposed approach makes all uncertainties explicit, but doesn't quantify the likelihood of occurrence. The likelihood of occurrence has to be estimated by the forensic engineer to come to a final answer. Therefore the actual situation is not necessarily objectively reflected in the outcome, since it is possible to have multiple outcomes in terms of likely causes.

Analysing all possible combinations of lower and upper bound of parameters results in many scenarios and is very time consuming. Limiting the analysis to the individual possible causes and suspected combination of causes as possible scenarios gives important insights in the individual contribution on field performance and is less time consuming.

As suggested in the approach itself (step C, Figure 8), the next step is to weigh the outcome based on the likelihood. However, as no probabilities of scenarios are estimated, this is not possible within this approach. To consider probability, more advanced probabilistic approaches are recommended. This would make it possible to introduce the visual observations into the analysis as well, further limiting the input parameter uncertainties and model uncertainties.

Application to The Breitenhagen Levee Failure

The forensic analysis approach was developed in conjunction with the Breitenhagen analysis. Hence, challenges encountered during the approach such as the sensitivity of the results to shear strength parameters are incorporated in the results. That said, the approach might need small adaptations in case of different available datasets, while the general framework is expected to be sufficiently robust.

The chosen limits of soil parameters are used to incorporate the uncertainty in the soil parameters. However, the chosen extremes values of soil parameters dominate the outcome, especially since all layers (dike body and blanket) are assumed weak simultaneously. This can put too much emphasis on locally weak soils and individual weak soil layer should be considered as well. Since most shear resistance is generated by the dike body, considering individual layers is not expected to influence the outcome of the analysis much. The values of parameters of the drained soil behavior are based on Dutch literature, the chosen values might be very conservative and justify further research. German literature suggests larger values of cohesion (Schneider & Albert, 2014) and therefore shear strength is expected to be less dominant for the Breitenhagen case. However, very low values of cohesion (c'~0 kPa) result in low values of FoS and indicate instability. These results seem obvious since the applied slope is steeper than the applied friction angle of the soil. The angle of the slope of the levee was also mentioned in the earlier forensic engineering report of Grubert (2013) as a point of attention. More data of local soil characteristics would reduce the uncertainty of the input parameters.

Which soil model is most appriopriate to use in a stability analysis depends on many different factors. Whether the response of the soil was undrained or drained cannot be observed, since it is hidden inside the levee. However, the observed relatively slow process (more likely for drained behavior) in combination with low permeability materials (more likely for undrained analysis), indicates a partially drained behavior. Partially undrained soil behavior is not taken into account in the type of computational models that are used in this paper.

The hydraulic head in the conductive layer around the tree roots and the influence of these on the surrounding soil are assumed conservatively. The measurement of the actual development of the hydraulic head and the range of the influence of the conductive layer could limit the influence of pore water pressures resulting in a more accurate simulation of the influence on the levee behavior.

The models that are used to predict field performance are developed under controlled conditions and are not well validated to predict the performance of a levee under extreme conditions or when confronted with variability and heterogeneity of the soil. Using the scenarios approach gives insights in which model simulates most accurately and limits the uncertainties as much as possible. More advanced Finite Element Method (FEM) based models would possibly be able to describe the behavior better and reduce the uncertainty, but advanced models are very time consuming and introduce other uncertainties. Furthermore, the used LEM models reflect the failure mode sufficiently well.

The proposed approach worked well for the Breitenhagen levee failure partly because it concerns an unexpected instability (FoS>1.0 for the best estimate conditions). This implies that possible failure cases can be found by searching for combinations of parameters that result in a FoS<1.0, which results in a limited number of combinations for this case study. In situations where the best estimate situation results in a FoS closer to, or below 1.0, differentiating between the possible causes (using the criteria of FoS<1.0) becomes more complex since many possible causes will result in FoS<1.0. Moreover, the cause resulting into the lowest FoS is not necessarily the most likely cause. In this case, probabilistic methods would be a useful addition.

Likely Causes of The Breitenhagen Levee Failure

The sensitivity analysis identifies two most likely causes of instability of the slope of the levee, which are low values of POP and cohesion, both related to weak soil. Low values of POP and cohesion result in low values of FoS (FoS<1). The high resemblance between the calculated shape of the slip circle when analysing the influence of the cohesion and the actual slip circle reinforces these findings. The influence of the hydraulic head in the aquifer especially in combination with high saturation of the levee (tree roots) is significant. The collected data shows that at this particular location, the levee has most likely been breached before (Sixdorf, 2016). As a result of the repairs of the breach, the soil conditions might deviate from the other soil conditions of the levee and are suggested to be weak. It seems that the pond in front of the levee is a leftover of this former breach. The relation between the breach, repairs, weak soil and the high hydraulic head in the aquifer would explain the occurrence of the breach at this location in 2013. Although the breach and the repairs do not support the contribution of conductive layer around the tree roots, they do not exclude the conductive layer around the roots as a possible contributor to failure.

Earlier forensic engineering analysis by Grubert (2013) identified a combination of causes of failure which are similar to the findings of this analysis. The conclusion of the earlier forensic engineering analysis suggests that the cause of the breach relates to the high saturation of the levee, the relative steep angle of the levee and the highly conductive soil layer that is associated with the tree roots. The conclusion does not explicity address the pond connection with the aquifer or weak soil conditions, although the calculations by Grubert seem to acknowledge the connection of the outside water level and the aquifer and assume a direct connection with the outside water. Here, special attention is paid to the possibility of uplift, but this is indicated to be secondary to the influence of the tree roots. The present study supports the findings of Grubert (2013) and adds additional insights in different scenarios of possible causes of failure and in how these relate to the history and the collected evidence. Which findings are more likely, cannot be concluded from this analysis.

CONCLUSIONS AND RECOMMENDATIONS

The developed approach of forensic analysis in this paper has been applied to the levee failure near Breitenhagen in order to identify the most likely cause of failure. The collected evidence is assessed, and the results of the sensitivity analysis are discussed. Conclusions and recommendations are presented below.

Conclusions

This article suggests a newly developed generic approach of forensic analysis of levee failures. The approach includes the most relevant uncertainties and modelling decisions explicitly and transparently. The approach allows to systematically generate possible realizations of reality. Also, the approach provides insight in the uncertainty of input parameters and model uncertainties explicitly by introducing all possible causes as scenarios and by validating or eliminating each scenario. The forensic analysis approach requires to analyse all possible scenarios including all combinations of possible causes, thus making this approach very time consuming. The forensic analysis approach does not quantify the uncertainties in a probabilistic manner, and does not prioritize the most likely causes based on the probability of occurrence.

In this case study, the results indicate that locally low strength associated with low values of POP or cohesion justify the failure. Other scenarios analyzed resulted in either a FoS that does not justify failure or, show a slip surface that differs from the observed failure surface. High hydraulic head in the aquifer and unexpected saturation of the dyke body are considered to have contributed significantly in bringing the levee to instability. Both the presence of a pond and locally weaker soil may be justified by an old levee breach that previously occurred at this location in 2013 (Sixdorf, 2016). Historical data cannot confirm or rule out the contribution of unexpected high saturation, thus reducing the resistance of the levee, that is related to the presence of tree roots.

Recommendations

The generic approach is developed for the purpose of forensic analysis on levee failures in general. It is advised to apply the approach on another type of levee failure mechanism for the purpose of further development of the forensic engineering approach of geotechnical failure cases.

In future forensic engineering analyses of levee failures it is recommended to use a probabilistic analysis which is capable to quantify the input parameter and model uncertainties and make them more explicit by incorporating the likelihood of each scenario. This approach takes the correlation of all contributors into account and explores all possible combinations of probable causes. This increases insight in the collection and the actual weight of every contributor and supports an unambiguous outcome.

Furthermore, there are several refinements possible for the Breitenhagen analysis. The uncertainty regarding shear strength parameters, and the resulting high variations in input, may be reduced by performing local field tests (e.g. CPTs) or collecting samples for lab tests. This cannot be done on the failed soil, since that has washed away, but local soils should give a better approximation and lower range of parameters than the currently used default values for Germany and the Netherlands.

Discerning drained from undrained response seems not feasible in most breach cases. Investigating the influence of a time dependent, partly drained/undrained, response could give better insight into the “true” failure conditions.

Applying parameters that are more representative for the actual location would limit the influence of the input parameter uncertainty on the result. This can be done by doing more field tests. But also consultation with local authorities and companies would lead to better assumptions for inputs, such as the possible values of cohesion and POP and values of the potential head in the aquifer and the phreatic line. However, this is not expected to change the overall conclusions of this case significantly.

ACKNOWLEDGEMENTS

We thank Dr.-Ing. Thilo Weichel of the Landesbetrieb fur Hochwasserschutz und Wasserwirtschaft Sachsen-Anhalt for providing us with his drone movie of the breach of the levee near Breitenhagen and other relevant data.

This research was performed as part of the NWO TTW project SAFElevee (project number 13861)

REFERENCES

Bell, G. R. (2001). *“Civil Engineering Investigation.” Forensic Engineering,* K. L. Carper, CRC Press, Florida.
Bligh, W. (1915). Submerged weirs founded on sand. *Dams and weirs*.

Borsje, H., Renier, B., and Bruggraaf, H. (2014). "Collapse of the roof of a football stadium." *Int. Symp. On Engineering for Progress, Nature and People*, 37th IABSE, Madrid.
CIRIA. (2013). *The International Levee Handbook.*
Deltares (2016). *D-Geo Stability.*
Drews, N. (2017). *Investigation of the dike failure near Breitenhagen (Saale River) during the flood in June 2013*, TU Dresden, Dresden
IKSE & MKOL (2014). *Hydrologische Auswertung des Hochwassers vom Juni 2013 im Einzugsgebiet der Elbe,* IKSE-MKOL, Magedburg
GeoBasis-DE/BKG (2009). https://www.google.nl/maps/@51.9430762,11.9041776,14.3z (May 5, 2017).
Grubert, P. (2013). *Saaledeich bei Breitenhagen, Geotechnische Untersuchungen der Bruchstelle Empfehlungen zur Sanierung,* Gesellschaft für Grundbau und Umwelttechnik mbH, Magdeburg
Jonkman, S. (2005). "Global perspectives of loss of human life caused by floods." *J. Natural Hazards*, 34, 151-175.
Jonkman, S., and Schweckendiek, T. (2015). "Briefing: Lessons learned from failure of flood defences." *J. Forensic Engineering*, 168, 85-88.
Jupner, R., Brauneck , J., and Pohl , R. (2015). "Einsatz von Drohnen im Hochwasserfall-Erfahrungen und Ideen." *J. WasserWirtschaft*, 9, 49-54.
Kanning, W., Van Baars, S., and Vrijling , J. (2008). "The Stability of Flood Defenses on Permeable Soils: The London Avenue Canal Failures in New Orleans." *International Conference on Case Histories in Geotechnical Engineering.* Missouri.
Ladd, C.C. (1991). "Stability evaluation during staged construction (22nd Terzaghi Lecture)." *J. of Geotech. Eng.*, 117(4), 540-615.
Lane, E. (1935). "Security from under-seepage masonry dams on earth foundations." *J. Transactions American Society of Civil Engineers*, 100, 1235-1351.
Normcommissie, 351 006 "Geotechniek" (2011). *NEN9997-1 Geotechnisch ontwerp van constructies - deel 1: Algemene regels,* Nederlands Normalisatie-instituut, Delft
RWS. (2016). Schematiseringshandleiding macrostabiliteit version 1.0, WBI2017. Ministerie van Infrastructuur en Milieu.
Rao, V., and Sivakumar Babu, G. (2016). *Forensic Geotechnical Engineering,* Springer, Bangalore
Schneider, K.-J., and Albert , A. (2014). *Bautabellen für Ingenieure,* Werner Verlag.
Schofield, A.N. and Wroth, C.P. (1968), *Critical state Soil Mechanics,* McGraw-Hill.
Schweckendiek, T., and Vrouwenvelder, A. (2014). "Updating piping reliability with field performance observations." *J. Structural Safety*, 47, 13-23.
Seed, R. B., Bea, R. G., Athanasopoulos-Zekkos, A., and Boutwell, G. P. (2008). "New Orleans and Hurricane Katrina. III: The 17th Street Drainage Canal." *Journal of Geotechnical and Geoenvironmental Engineering*, 134.
Seed, R., et al. (2006). *Investigation of the Performance of the New Orleans Flood Protection System in Hurricane Katrina on August 29, 2005*, University of California, Berkeley
Sixdorf, H. (2016). "SAVElevee, Notes on the Dike chronic by Heinz Armin Sixdorf." *Interview N. Drews*
Terwel, K., Ratay, R., Bruhwiler, E., Wood, J., Godart, B., and Dalmy, D. (2012). "An Initial Survey of Forensic Engineering Practices in Some European Countries and the USA." *Int. Symp ASCE 6th Congress of Forensic Engineering*, San Francisco.
Thieken, A. H., Bessel, T., Kienzler, S., Kreibich, H., Muller , M., Pisi, S., et al. (2016). "The flood of June 2013 in Germany: how much do we know about its impacts?" *J. Natural Hazards and Earth System Sciences*, 16, 1519-1540.
Van Baars, S. (2005). "The horizontal failure mechanism of the Wilnis peat dyke." *J. Geotechnique*, 55, 319-323.
Van Deen, J., and Van Duinen, A. (2016). *Schematiseringshandleiding macrostabiliteit,* Deltares, Delft
Verruijt, A. (2010). *Grondmechanica,* Technische Universiteit Delft, Delft
Vorogushyn, S., Merz, B., and Apel, H. (2009). "Development of dike fragility curves for piping and micro-instability breach mechanisms." *J. Natural Hazards and Earth System Sciences*, 9, 1883-1401.
Weichel, T. (2013). "Failure of the Breitenhagen levee (2013)."*Drone Film* Breitenhagen: Landesbetrieb für Hochwasserschutz und Wasserwirtschaft Sachsen-Anhalt. <http://leveefailures.tudelft.nl/media.html#showmedia/121/222>
Zang, L. M., Xu, Y., and Peng, M. (2013). "Assessment of flood risks in Pearl River Delta due to levee breaching." *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, 7(2), 122-133.