Case Study: Zutphen

Estimates of levee system reliability

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Figure 1. Levee system considered in the case study; three levee segments, 13a, 13b, and 14, which protect agricultural land and the western part of Zutphen from the IJssel River.

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CASE STUDY: ZUTPHEN

ESTIMATES OF LEVEE SYSTEM RELIABILITY

Estimates of levee system reliability can conflict with experience and intuition. For example, a very high failure probability may be computed while no evidence of failure has been observed, or a very low failure probability when signs of failure have been detected. This conflict results in skepticism about the computed failure probabilities and an (understandable) unwillingness to make important management decisions based upon them. Bayesian networks (BNs) are useful in these circumstances because they allow us to use observations to improve our reliability estimates quantitatively.

Here we describe the application of a BN to calculate the system failure probability due to the failure mechanism piping, for a set of primary levees protecting the city of Zutphen from the IJssel River (see Figure 1), both with and without a survival observation (i.e. an observed high water level in which the levee survived). We additionally calculate the system failure probability with algorithms from the Hydra-Ring software, to compare system reliability estimates. The structure of the BN in this case study is dictated by the formulaic representation of piping, which is provided in the associated dissertation (Roscoe, 2017). The variables that play a role in the piping mechanism, which are described in Table 1 (tables see next page), are the input random variable nodes in the BN. Table 1 also indicates whether a variable is constant over the length of the segment. If so, it will be represented by one node per segment in the system BN. The variables that are not constant are spatially variable and will be represented by *n* nodes, where *n* is the number of cross sections representing the segment. Figures 2 and 3 show the BNs for a cross section and a segment (represented by three cross sections), respectively. The number of cross sections is dependent on what is necessary to adequately represent the spatial variability, and generally ranges from 20 to 80. Arcs in the network that lead into functional nodes (nodes with black edges) are described by formulas. Arcs between input random variables (such as D^1 and D^2) are specified by a product moment correlation coefficient.

Tables 2 and 3 show the results for two (hypothetical) observed water levels, one that has a return period of 40 years, and another of 400 years, to see how the reduction in system failure probability depends on the extremity of the observed water level. The prior and posterior system failure probability (the latter is after including the survival observation) were computed with the BN and with the Hydra Ring algorithms. The latter are denoted in the table as MO/EP for modified outcrossing (MO) and equivalent planes (EP), the two algorithms that calculate the segment and system failure probability in Hydra Ring, respectively.

For a 1/400 year water level observation in which the levee survived, the ratio of prior to posterior system failure probability is 7.5, which means that the posterior system failure probability is 7.5 times lower due to the survival observation. The impact is substantially less with the 1/40 year water level observation, with a ratio of 2.1. An observation with a return period of 40 years is relatively high given the length of the record, but is not high enough to greatly impact a system with such a low prior failure probability. This prompted us to consider when survival observations are useful. In general, they are most useful when the resistance (soil) variables have a large influence on the failure probability, or when the prior failure probability estimate is high. This is discussed in detail in (Roscoe, 2017).
The comparison between the Hydra-Ring algorithms and the BN are quite good. In terms of reliability index, which is an alternative and quite common way of communicating failure probabilities, the differences were limited to a few percentage points. Given that the BN is a more exact method with fewer assumptions than the Hydra-Ring algorithms, this serves as a verification of those algorithms.

Table 1.

Variables used in piping analysis

Variable	Description	Constant over segment
D_0	Thickness of aquifer	No
D	Thickness of blanket layer	No
L	Distance, waterside levee toe to landside water	No
θ	Bedding angle of sand	No
d_{70}	70th-percentile of sand grain diameter	No
η	Drag coefficient	Yes
γ_{wc}	Volumetric weight of blanket layer	No
γ_k	Volumetric weight of sand	No
m_u	Error in critical pressure difference, for uplift	Yes
m_h	Damping factor	No
m_s	Error in piping model	Yes
h_{ls}	Water level on landside of levee	Yes

Table 2.

For an observed 1/400 year water level: Prior and posterior segment fallure prohabilities for Segments 13a, 13b, and 14 computed with the BN and tehe MO method, and the system failure probabillity computed by BN, and a combination of the MO and EP methods. The ratio of prior to posterior failure probability is als given.

Return period of observed water level: 400 years

Segment	BN Prior	BN post.	BN ratio	MO/EP prior	MO/EP post.	MO/EP ratiow
13a	6.8E-5	4.4E-5	1.6	9.0E-5	4.7E-5	1.9
13b	1.4E-3	1.2E-4	11.8	1.6E-3	1.4E-4	11.3
14	5.7E-4	1.5E-4	3.7	8.4E-4	1.8E-4	4.8
System	**1.9E-3**	**2.8E-4**	**7.0**	**2.5E-3**	**3.3E-4**	**7.5**

Table 3.

For an observed 1/40 years water level: Prior and posterior segment failure probabilities for Segments 13a, 13b, and 14 computed with the BN and the MO method, and the system failure probabillity computed by the BN, and a combination of the MO and EP methods. The ratio of prior to posterior failure probability is also given.

Return period of observed water level: 40 years

Segment	BN Prior	BN post.	BN ratio	MO/EP prior	MO/EP post.	MO/EP ratio
13a	6.8E-5	6.6E-5	1.0	9.0E-5	6.9E5	1.3
13b	1.4E-3	5.2E-4	2.7	1.6E-3	6.1E-4	2.6
14	5.7E-4	4.6E-4	1.2	8.4E-4	5.3E-4	1.6
System	**1.9E-3**	**9.7E-4**	**2.0**	**2.5E-3**	**1.2E-4**	**2.1**

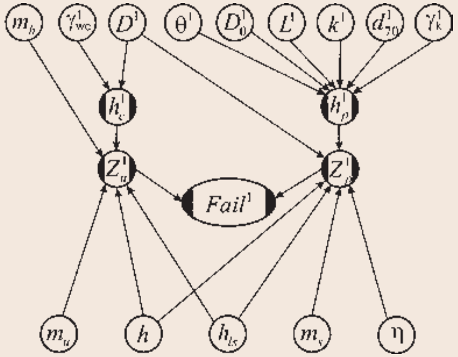

Figure 3. Bayesian network to calculate failure probability of a single cross section, due to the piping mechanism. The superscript indicates these variables are for the first cross section in the segment.

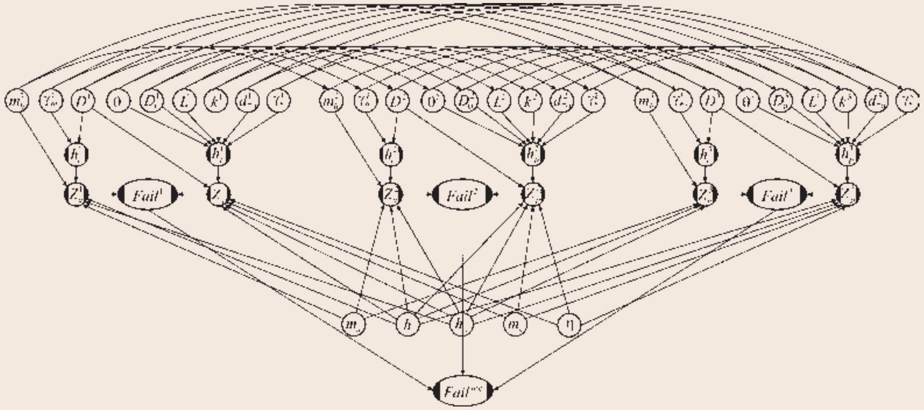

Figure 4. Bayesian network to calculate failure probability due to the piping mechanism for a levee segment represented by three cross sections. Spatially variable input random variables are shown repeated for each cross section (variable superscripts indicate cross section). Variables which are constant over the segment are shown near the bottom of the network (once for the whole segment).