RISK ASSESSMENT METHODOLOGY FOR QUANTIFYING THE IMPACT OF SCOUR

A SERIOUS THREAT TO RIVER CROSSINGS

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BACHELOR THESIS

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PREFACE

This report contains the risk assessment methodology for the quantification of the impact of scour on river crossings. For me, as a civil engineer, this topic was very interesting and broadened my knowledge concerning risk assessment and the phenomenon scour.

The report has been written for my Bachelor thesis. The information given in the report provides information for risk management and risk mitigation strategies. The realization of this report has been done at GDG Geo Solutions at Dublin, in the course of three months. Because of this short period, no calculations were made concerning the impact on scour. The report only provides the general methodology to explain how these calculations can be done.

For the realization of this report, I want to thank GDG Geo Solutions, especially Dr. K. Gavin and K. Martinovic, who provided me a place to work on the project and provided me information and help when needed. Furthermore I want to thank the University of Twente, especially Dr. Irina Stipanovic, for giving me the opportunity to do my research in Dublin and for providing the research topic.

With best regards,

Ramon ter Huurne
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ABSTRACT

Transport systems are exposed to many risks. Damages done to transport systems may cause a lot of problems, not only in economic matters, but even in the form of casualties and fatalities. Therefore, risk assessment of these risks is very important. One of these risks is scour which can cause damage to river crossings. In this report, the main question is how the impact of scour on river crossings can be quantified. In other words, how vulnerable is a river crossing to scour.

Scour is the removal of streambed or bank material from the river crossings foundation due to the flowing water. The removal of this material may lead to unstable foundations, which can eventually result in the collapse of a river crossing. How serious the problem is, illustrates the fact that in the United states, scour is the most common cause of highway bridge failure (Kattel & Eriksson, 1998). Because of the serious threat of the scour to river crossings, risk assessment is a very important part of the risk management process. In the risk assessment procedure, we can identify three phases: risk identification, risk analysis and risk evaluation.

In this thesis the identified risk for river crossings is scour. Scour can occur in many different ways. This all depends on the circumstances that are present on a certain location. To get a clear insight which variables contribute to scour, scour quantification models were analysed. The most important parameters from these models are flow, soil and structure characteristics. Besides, it showed that river crossings are vulnerable to scour because of the decrease of the bearing capacity of the soil and the exceedence of the ductility limit of the structure.

With the information gathered during the risk identification process, risk analysis is possible. For the determination of the impact of scour to river crossings, fragility curves and a risk model using Bayesian Belief Network (BBN) are considered as a good methodology. A fragility curve shows the probability of failure, a form of vulnerability, given a certain loading or intensity measure. In the case of scour, scour depth has been chosen as an intensity measure. BBN risk models provide a network with all the variables and relations between the variables, combined with the so called Bayesian probabilities. These probabilities show the probability of occurrence of each variable based on expert knowledge and 'belief'. Besides Bayesian probabilities, classical probabilities, which are based on historical data about events or simulations models, may be blend with Bayesian probabilities to try to get the model as accurate as possible.

The fragility curve and BBN risk models are developed concerning the risk of scour to river crossings. For fragility curves, different damage states are possible. These damage states shows how vulnerable a structure is depending on a certain degree of the intensity measure. These damage states are often slight, moderate, severe and complete damage. Damage states also represent a degree of serviceability. For the damage states these are respectively fully serviceable, serviceable but impaired, not serviceable and collapsed. For example, a certain amount of scour may cause an exceedence of the slight damage state, this means the river crossing is no longer fully serviceable. The information that should be gathered to develop

the fragility curve for scour is the information needed to calculate the scour depth, the probability of failure and the limit states of each damage state.

For the development of the BBN risk model, it is very important to analyse the process of how scour occurs. The scour quantification models provide very useful information about the process of scour. They show the variables that are contributing to scour and the relationship between them. With this information, it is possible to set up a network with all the variables and the relations between them. However, as the quantification of the impact of scour is the main question, the network itself is not enough. Therefore, BBN risk models show the probabilities of each variable, and in the end, what the impact of scour is. This impact is regulated the same as with the fragility curves, who's damage states are integrated into the BBN risk model. This means that as an output for the BBN risk model, the damage states are given.

The calculations of the probabilities for each variable can be done by using historic data or simulation models. However, each river crossing has a different set of variables and parameters, why it is impossible to set up a general BBN risk model what can be applied to all the scour events and river crossings. Therefore, only the probabilities of heavy rainfall that cause floods are determined though these only can be applied on river crossings in the Netherlands, as the data is obtained from a Dutch institute.

The risk analysis of scour shows how scour may occur and how this can be quantified in such a way, that it is clear whether or not the river crossing is still serviceable or not. Therefore, fragility curves and BBN risk models provide an excellent insight in the impact that scour may have on river crossings. They quantify how vulnerable a river crossing is, and based on this information, measures can be taken or not. Although the report does not provide calculated examples of a fragility curve of BBN model for scour, they are widely adopted in other risk assessment projects. For this reason, as a risk evaluation and the last step of the risk assessment process, the methodologies shown in this report considering fragility curves and BBN risk models are a perfect way to quantify the impact of scour on river crossings.

The outcomes of a fragility curve and BBN risk model can be used for further research in the areas of risk management models and risk mitigation strategies. It is clear that scour is a big problem and measures has to be taken and scour management and scour mitigation is needed.

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1 INTRODUCTION

Transport substructure systems such as bridges, roads and tunnels, are part of a bigger transport network, which provide the required traffic flows. Problems with a substructure could cause problems for the bigger network. If for example a bridge is damaged, traffic won't be able to use that part of the network anymore, which could mean that some destinations can't be reached anymore. This causes a lot of problems, not only for travelers, but also in economic matters and not to forget fatalities and injuries. The costs of making river crossings less vulnerable to scour is small when compared to the total cost of failure which can even be two or three times the original cost of the bridge itself (Landers, 1992).

To reduce these problems, we should maintain the different substructures in such a way, that these problems don't happen. To do this, it's necessary to investigate the risks and causes that are apparent for each substructure. Mitigation and managing of these risks would decrease the overall problems for the bigger system. In this research though, only one of these substructures will be analysed, which are river crossings.

River crossings are obviously exposed to water, which can cause erosion or removal of the streambed or bank material from the river crossings foundation due to flowing water. This phenomenon is called 'scour'. Scour is the main topic of this research and is the most common cause of highway bridge failures in the United States (Kattel & Eriksson, 1998), which indicates that it's a serious threat.

This research will focus on the risk assessment of scour to river crossings. Risk assessment is part of the risk management procedure, which can be seen in the flow chart presented in Figure 1.

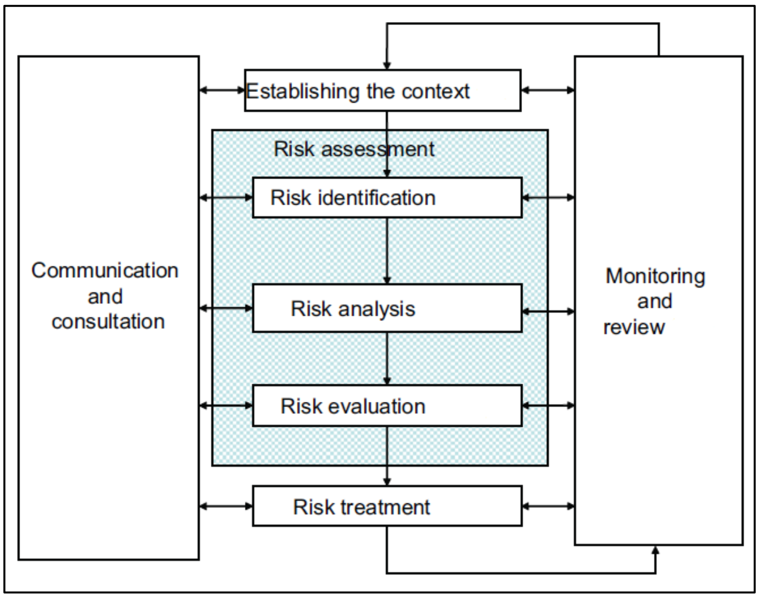


Figure 1 - Risk management process (ISO/TC TMB, 2009)

Risk assessment contains the risk identification, risk analysis and risk evaluation phases. For this research this will mean that first we have to identify the scour as a risk. This contains the explanation and investigation of the process of scour. Risk analysis of scour contains the impact that scour may have on river crossings and how to quantify this. At last, the outcomes of the risk analysis and risk identification will be evaluated.

In this research, the focus will lie on the methodology of how to analyse scour on river crossings and how to quantify this and how the findings from these analyses should be interpreted. The methodology of how to quantify the vulnerability of river crossings to scour is the main goal of this research.

The outcomes of the research (risk assessment) can be used for risk treatment. Treatment will eventually be part of risk management models or risk mitigation strategies. These models and strategies will be used to prevent river crossings from damage due to the scour, which will increase the safety and durability of river crossings and the transport network as a whole. As it can be seen in the flow chart in Figure 1, these models and strategies will be monitored and reviewed and if turns out that they are not working properly, further research is needed.

1.1 Scope

In this research, the outcome will be a risk assessment methodology of how to quantify the vulnerability of scour to river crossing. As seen in the flow chart in Figure 1, risk assessment contains the risk identification, risk analysis and risk evaluation. For the analysis of scour different techniques and methods will be shown. At first, scour will be quantified by using existing models. With the information of these models, it will be possible to determine the vulnerability of scour on river crossings.

The vulnerability of river crossings to scour can be expressed in different ways. For this research, a fragility curve and a Bayesian Belief Network (BBN) risk model will be used. A fragility curve is a graph that shows, as the name indicates, the fragility (in other words, vulnerability) of an object exposed to a certain intensity measure (loading). For this research, this means the fragility curve will show the vulnerability of a river crossing given a certain intensity measure, which could be the amount of scour.

A BBN is a network that shows all the variables and relations between them that contribute to a certain topic. In this case, this model will show all the variables that contribute to the vulnerability of river crossings exposed to scour. The variables can have different values or may occur only given a certain output of another variable. A BBN risk model shows therefore the probabilities of occurrence of each variable. These probabilities are called Bayesian probabilities and are based on 'belief' what means that they are based on people knowledge and expertise. In short, BBN are graphical models that use Bayesian probabilities to model the dependencies within the knowledge domain (Jensen, 1996). More information about the fragility curve and BBN can be found in respectively chapters 5 and 6.

A fragility curve therefore can be seen as a part of the BBN risk model. The BBN is the whole network and a fragility curve is one way of representing the probabilities of failure given in the BBN risk model. To get to the fragility curve and BBN, first of all a study to scour itself has to be done, including historic events, which can tell what happened wrong in the past. The next step is to determine how we can calculate the vulnerability of river crossings against scour. With this information, the methodology for the fragility curve will be developed. With the information from the models and fragility curves, the BBN will be developed. This means that the final outcome of the research will be the methodology of how to develop a BBN risk model for scour. Below, these steps are summarized.

- Background study to scour;
- Analyse historic events;
- Evaluate vulnerability of river crossings to scour;
- Develop methodology for fragility curve for scour;
- Develop methodology for BBN risk model for scour.

A greater explanation of these steps will be mentioned later on in section 2.3.

1.2 Objective

The goal of this research is to develop a risk assessment methodology for the quantification of the impact of scour to river crossings. The outcomes of the research will be the methodology of how to develop a fragility curve and a BBN risk model for scour at river crossings. The greater objective of this research is to provide information for managing and maintenance of river crossings that are exposed to scour. This will prevent the structure from collapsing, which is not only much safer, but also saves a lot of costs eventually.

2 RESEARCH PLAN

In this part of the project, the research objective, research questions and research method will be explained.

2.1 Research objective

The research will be part of the INFRARISK project which is a project for the European Union. For the European Union it is very important to minimize the risk and vulnerabilities of European operating infrastructure against natural extreme events, because they want to achieve energy and socio-economic sustainability. The objective of INFRARISK is to develop stress tests on European critical infrastructure, using integrated modelling tools for decision support. This will lead to higher resilience of the infrastructure against the natural events. It will also advance decision making approaches and better protection of existing infrastructure, while also more robust strategies for new infrastructure will be developed (The Free Library, 2013).

In the INFRARISK project, a couple of risks are apparent which are earthquakes, floods, landslides (earthquake triggered and heavy precipitation triggered), and scour at river crossings. This research will focus on scour. As scour can cause failure of river crossings, it is very important to have a clear view of how it occurs, how often and how we can determine the vulnerability of river crossings to scour. This vulnerability may even show that a river crossing is very likely to fail. Another output that is used to sometimes describe the vulnerability is therefore the probability of failure which also will be investigated.

In this research, existing mathematical models for scour prediction will be analysed and it will be explained how the vulnerability of river crossings potentially exposed to scour can be determined. Besides, graphical risk models will be formed, which will show which different independencies are contributing to the scour. In this research, these graphical models are as mentioned before a fragility curve and a Bayesian Belief Network (BBN). All the steps will be taken into account which are needed for risk assessment as seen before in Figure 1.

The aim of this research is to develop a risk assessment methodology which can quantify the impact of scour to river crossings. The outcomes can be used for further research, likely for developing risk management models and risk mitigation strategies (used for treatment of the problem).

2.2 Research questions

For the research there will be one main question with a couple of sub questions. All these questions are written below.

2.2.1 Main question

How can the impact of scour to river crossings be quantified?

Scour is a serious threat to river crossings, and as mentioned before, it is one of the most common causes of bridge failure in the United States. Therefore, proper research to this topic is necessary to reduce the damage river crossings may receive due to scour. In this research, the main question will be how we can quantify the impact (vulnerability) of scour to river crossings. With this information, further research to risk management models and risk mitigation strategies is possible. The answer on this main question will be given by the answer of three sub questions, which are written down below.

2.2.2 Sub questions

What is scour, how does it occur and how does it affect river crossings and eventually transport networks as a whole?

Scour is the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams and from around the piers and abutments of bridges or other foundational structures (Arneson, Zevenbergen, Lagasse, & Clopper, 2012). Scour does occur in different forms due to different situations. These forms will be explained in chapter 3 later on.

The loss of material from the bed and banks can cause the river crossing to fail because of the loss of bearing capacity of the material or by its own superstructure due to its ductility limit (because of movements of the river crossing due to the loss of material around the foundation). This can cause failure of the river crossing. Failure can occur in different modes. More information about this can be found in chapter 3.

Although the research is focused on one specific topic, scour to river crossings, it is important to determine the influence of this risk on the system as a whole. In this case, it is obvious that scour can lead to very undesirable situations for the whole transport network.

This shows that it is not only important to reduce the risks for the river crossings itself, but also for the transport network as a whole.

What are the vulnerabilities of river crossings systems against scour and how can these be determined?

Every river crossing does have a specific vulnerability to scour due to all the different factors that are apparent on each site. Therefore, the determination of the vulnerability of river crossings is very difficult and complex. Though, some models are developed which try to quantify or qualify the vulnerability of river crossings to scour. The models which give a quantitative outcome are preferred, as they will provide more useful information than qualitative models, which only give certain statements instead of real values.

In this report, an overview of the existing models will be given with the data useful for the research. These models will be discussed in chapter 4. With the analysis of these models, it will be clear what factors contribute to scour.

How can we determine the probabilities of failure of river crossings due to scour?

In the case of risk management and risk mitigation of river crossings to scour, the most important thing to know is the probability of failure of the river crossing due to scour. The probability of failure is a specific form of vulnerability, which indicates whether or not a structure is likely to fail. This probability of failure will be determined based on the information given by the vulnerability models. The outcomes will be a fragility curve and a risk model, developed by applying BBN.

Fragility curves most of the times have different damage states, such as slight, moderate, extensive and complete. Because of these different damage states, it is possible to adapt the management and mitigation to the state of the river crossing. If it turns out that there is slight damage, but the probability of failure is very low, no action is needed. More information about the fragility curves and the development of one for scour is mentioned in chapter 5.

A BBN risk model visualizes the contribution of all different variables to scour and the vulnerability of river crossings to scour with certain Bayesian probabilities. These are probabilities that mostly are determined based on expert knowledge instead of running trials. The fragility curve is a part of the BBN risk model, as the probabilities of failure that are determined for the fragility curve can also be found in the BBN risk model. Therefore, the outcomes of the fragility curve, such as the damage states, can be used for the development of the BBN risk model.

2.3 Research method

In this paragraph it is explained how the information for the research is gathered and which steps will be taken to answer the main and sub questions.

During the research a lot of information will be gathered. This information is needed to give answers to the main question and sub questions. The information will mostly come from previous research that has been done about scour, fragility curves and BBN. Combined with information from databases about previous scour events and other literature, sufficient information is gathered for fulfilling the research.

As already mentioned in the sections 1.2 and 2.1, the ultimate goal is to develop a fragility curve and a BBN risk model for river crossings exposed to scour. At first, scour will be explained and historic events of scour will be collected into a database. The database can be found in 8ATTACHMENT C. The next step is to find models which determine the vulnerability of river crossings to scour and to analyse these models. With these models, input for both the fragility curve and the BBN are generated. Therefore, the next step is to develop a methodology for fragility curves for scour. Lastly, a risk model developed by applying BBN will be developed from all the information gathered so far. This BBN won't include all the probabilities, but will show a general network which shows all the important variables and relations between them. In short, the following steps will be followed.

- Background study to scour;
- Analyse historic events;
- Evaluate vulnerability of river crossings to scour;
- Develop methodology for fragility curve for scour;
- Develop methodology for BBN risk model for scour.

In conclusion a summary will be given to show what can be done with the outcomes of this research and how it fits in the current way of risk management and risk mitigation strategies for river crossings.

3 SCOUR OF RIVER CROSSINGS

In this chapter, the general information about scour will be given what is the first step in the process of risk assessment (the risk identification). More detailed information can be found in 8ATTACHMENT D. The historic events that are collected can be found in 8ATTACHMENT C.

As mentioned before, transport networks are exposed to a lot of risks. As part of the INFRARISK project, earthquakes, floods, landslides and scour are the risks to look at. Earthquakes and floods both do have a great impact on the systems, as they cause a lot of damage, in structural and economic sense, not to forget the casualties. The same counts for landslides. These can be triggered by either earthquakes or heavy precipitation. Scour occurs at transport networks that cross a river, because it is an erosive action of flowing water. This will be explained in more detail later on in this chapter.

As a resource to research the vulnerability of transport networks to scour, the methodology and models of the other risks will be used. In Figure 2 a schematically transport network is drawn to illustrate how a transport network is exposed to the given risks. In this figure, the bridge and the telecom network could be affected by scour as they cross a river.

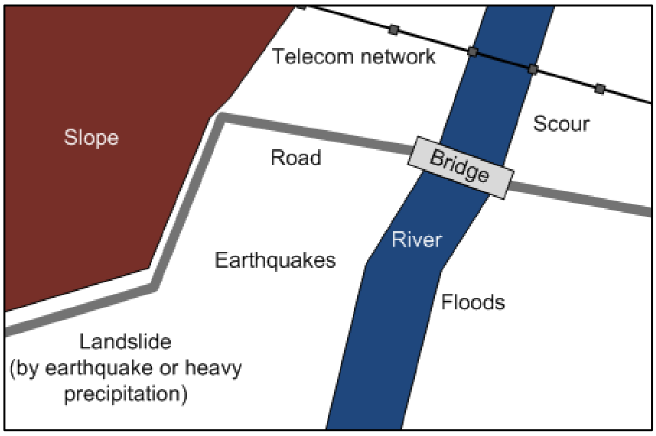


Figure 2 – Fictive example of transport network exposed to certain risks

Scour is the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams and from around the piers and abutments of bridges or other foundational structures (Arneson, Zevenbergen, Lagasse, & Clopper, 2012). Calm water does not have a big part in scour, as here the water flow is not strong enough to remove material from the bed and banks. Scour is the most common cause of highway bridge failure in the United States as 60 percent of the bridge failures since 1950 are due to hydraulics which includes scour (Landers, 1992).

Different materials scour at different rates. Materials such as loose granular soils are rapidly eroded, while cemented soils are eroded much slower. Although the process of scour is slower at cemented soils, the ultimate scour in cemented materials can be as deep as in loose-granular soils (Arneson, Zevenbergen, Lagasse, & Clopper, 2012). Scour occurs whenever the hydrodynamic bottom shear stresses are higher than the material's critical shear stress (Hughes, n.d.).

Figure 3 shows some typical scour failures. In this figure it can be seen that the removal of material because of scour often leads to a movement of the foundation into the scour hole. This can result in a deformation of the structure which can lead to a failure of the structure if the structure's ductility limit has been reached.

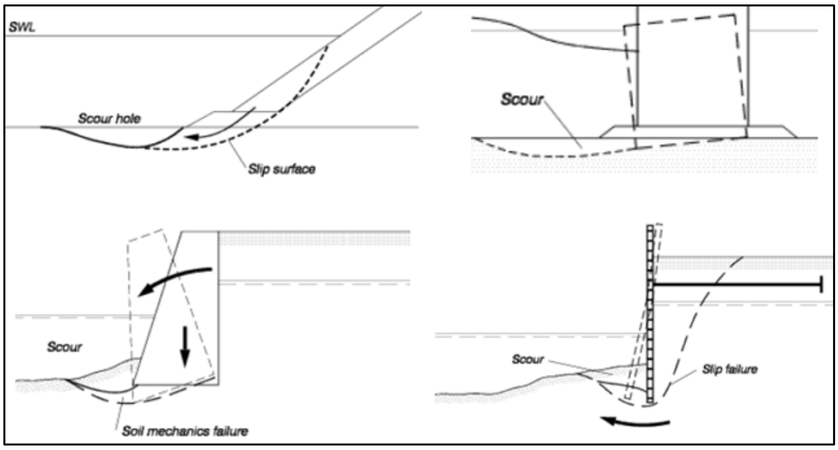


Figure 3 – Failure modes of scour (Hughes, n.d.)

Variables which are very important considering failure are the type of exposure (depth of foundation or length of buried asset exposed) and the aggressiveness of the environment (flow velocities and characteristics) (Roca & Whitehouse, 2012). Shallow foundations combined with heavy floods will for example easier lead to failure than a very deep foundation with calmer water.

For researchers and inspectors it may be complicated to determine the magnitude of the scour, because of the cyclic nature of its processes (Arneson, Zevenbergen, Lagasse, & Clopper, 2012). Scour can for example hardly be visible because of floodwaters that recede and scour holes that refill with sediment. Therefore, researcher and inspectors need to carefully determine the subsurface information at the specific site, so scour potential can be evaluated.

Though, scour is mostly estimated with laboratory experiments with limited field verification and mostly based on expert judgment (Roca & Whitehouse, 2012). These models tend to over predict scour in comparison to field measurements. This overprediction can result in overdesigned bridge foundation, which increases the costs. Because of the lack of understanding very complex physics of the scour process, this overprediction is still considered better than a possible failure of the river crossing. In chapter 4 the models which are used to estimate scour potential, will be discussed further on.

The effect of scour itself at river crossings is quite clear. Scour is one of the biggest threats to river crossings and therefore a serious problem. But scour is not only a problem to the river crossing, it is also a threat to the whole transport network. In case a river crossing fails that plays an important role in the network, the network as a whole will lose its functions too. Let's for example take a bridge. Failure of the bridge means people can no longer cross the river and have to take different routes. These routes are usually much longer causing user delay costs, might have less capacity, might be more dangerous et cetera.

As an example the failure of the CPR Bonnybrook Bridge in Calgary (CTVNews, 2013), Canada from last year will be taken. One of the four piers of this bridge collapsed because of the flood induced scour. The bridge's purpose was to let trains across the Bonnybrook River. Because of the collapse, no trains could cross the river anymore on that point of the river. This caused problems for the traffic and transport that normally used the bridge, so in this case, the transport system has failed.

Another example of scour is the Sava Jakuševac railway bridge in Croatia. Scour caused movement of the piers of the bridge as a lot of sediment was flown away in the past, especially on the sides of the river. The bridge didn't collapse, but one of the piers has started to fail and the bridge has experienced serious deformation, as can be seen in Figure 4a and 4b. Rehabilitation measures were taken into account to assure that no further damage would occur and train traffic was closed for almost a year (Engineering, 2010). In **Error! Reference source not found.**c, the strengthening measures taken to prevent the pier from further movement can be seen.


Figure 4a - Deformation


Figure 5b - Deformation


Figure 6c - Strengthening

Another possible threat for the network as a whole are the negative consequences that collapse of a river crossing may have. A bridge failure may for example block the river streams which can cause high water levels upstream the river and even flooding. This may damage nearby roads and other infrastructure or buildings.

4 SCOUR QUANTIFICATION MODELS

In order to develop risk management models and risk mitigation strategies it is very important to know whether or not a river crossing is vulnerable to scour. To determine the vulnerability of river crossings to scour, a couple of models are already developed. In this chapter, three of those models will be analysed.

- Tanasic, Ilic & Hajdin (2012);
- Park, Kwak, Lee & Chung (2012);
- Palmer, Turkiyyah, & Harmsen (1999).

In this chapter, a short overview of each model will be given. In the end, an assessment of the models will take place, whereby in the end, for each model the useful data for the development of the fragility curve and BBN risk model are presented. More detailed information about the models will be given in attachment 8ATTACHMENT E. This chapter is part of the risk identification concerning the three steps of risk assessment as the models are used to get a clear understanding about the variables that contribute to scour.

4.1 Model 1 - Vulnerability assessment of bridges exposed to scour (Tanasic, Ilic, & Hajdin, 2012)

Model created by Tanasic, Ilic and Haydin (2012) for the vulnerability assessment of bridges in the road network located in the south eastern of Serbia. Instead of bridge, here the term river crossing will be used.

The model describes the vulnerability of a bridge to scour. The resistance of a bridge to scour is described as the elastic-plastic behaviour of the superstructure and load bearing capacity degradation of the soil beneath foundation during the scouring event. The model calculates the probability of failure of a bridge given certain degree of scour, as well as the direct and indirect costs in case the of failure. The probability of failure and the direct and indirect cost multiplied by each other does form the vulnerability of a bridge to scour. More detailed information about this can be found in 8ATTACHMENT E.

The probability of failure in this model is based on the scour depth. For calculating the scour depth, the model uses the method used by Sheppard & Melville (Sheppard, Demir, & Melville, 2011) for local scour prediction equation.

$$\boldsymbol{y_s = 2{,}5a * f_1 f_2 f_3 K_t} \qquad \textbf{Eq. 1}$$

Where

- $f_1 = \tanh(\frac{y}{a^*})^{0{,}4}$
- $f_2 = 1 - 1{,}2\left(ln\left(\frac{V}{V_c}\right)^2\right)$
- $f_3 = \frac{\frac{a^*}{D_{50}}}{0{,}4\frac{a^{*1{,}2}}{D_{50}} + 10{,}6\frac{a^{*-0{,}13}}{D_{50}}}$
- $K_t = e^{-0{,}03\left|\frac{V_c}{V}\ln\left(\frac{t}{t_e}\right)\right|^{1{,}6}}$
- $t_e = 30{,}89\frac{a^*}{V}\left(\frac{V}{V_c}\right)\left(\frac{y}{a^*}\right)$

All parameters used in this model are explained in 8ATTACHMENT F. The most important parameters that are used in this model are the hydraulic depth, the flow velocity, median sediment diameter, bearing capacity and ductility limit.

With a Monte Carlo simulation of the Sheppard & Melville equation (1) from the available data and assumptions, a distribution of the maximum scour depth is yielded. For the vulnerability analysis the tail of obtained distribution is the point of interest.

The model assumes a simple yet accurate relationship between the magnitude of the flow Q and its duration t in a scouring event, what may develop bridge failure modes. The assumption is a simultaneous degradation of elastic and plastic soil parameters over time. Furthermore, this means that the bridge can fail due to either its superstructure (deformation capacity of superstructure is exhausted, in other words, ductility limit has been reached) or due to the loss of soil load bearing capacity (load bearing capacity of soil has been reached). The load bearing capacity of the soil under the pier foundation can be calculated by the friction angle φ and cohesion c. Collapse is eminent when the bearing capacity reaches the contact pressure (Tanasic, Ilic, & Hajdin, 2012). Therefore the degradation of the elastic and plastic soil parameters over time due to scour defines the failure mode.

In the model the maximum sinking of a pier is determined based on a specific kinematic model (different for each bridge), given the bearing capacity degradation. In the calculations, it is adopted that the maximum scour depth at the failure represents the soil cover height at the pier. This can be seen in part b of Figure 7. For the vulnerability assessment and determination of the probability of failure, the soil cover height of the pier, the median sediment diameter, equivalent pier diameter, the bearing capacity of the soil under the pier foundation, the contact pressure, the bridge structural properties, the flow characteristics and the time i.e. flood hydrograph for a certain return period at the investigated location are important.

In Figure 7 a probability of failure graph is shown, which shows the soil cover height distributed against the probability of failure. With no soil cover left, the probability of failure is over 60% and with a soil cover of 1,2m or more, the probability of failure is 0. More information about the model, refer to the original paper.

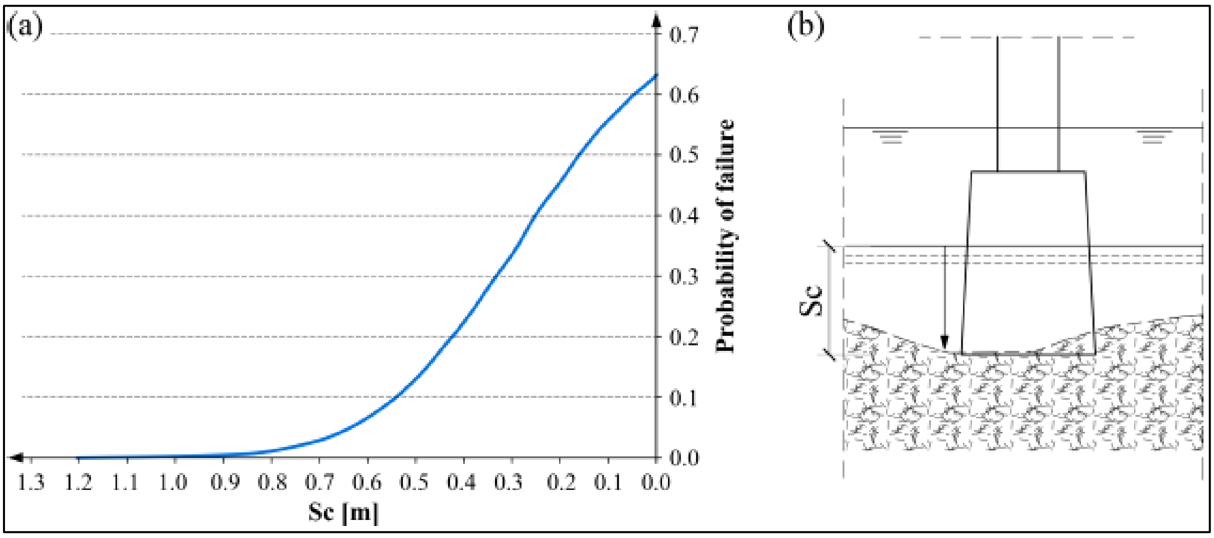


Figure 7 – Probability of failure graph given a certain soil cover height (Tanasic, Ilic, & Hajdin, 2012)

Although the model does represent the vulnerability of a pier to scour, it does not mention the actual depth of the foundation or the scour depth. Therefore, it is unknown how the actual situation is and the model doesn’t represent the actual situation completely.

4.2 Model 2 - Scour vulnerability evaluation of pile foundations (Park, Kwak, Lee, & Chung, 2012)

Model created by Park, Kwak, Lee and Chung (2012) for scour vulnerability evaluation of pile foundations during floods for national highway bridges.

In this model the method of evaluation of vulnerability to scour in case of spread footing is considering the bearing capacity change resulting from scour, as suggested by Federico et al. (2003). This method is both applicable to spread footing and pile foundation and provides sufficient preciseness to determine the vulnerability of foundations to scour reasonably. For this reason, this method is used by many bridge designers and is therefore already used for a large number of bridges.

Bridge vulnerability to scour can be explained in the concept of load bearing capacity safety factor as described in equation (2). In foundation design, the safety factor of a typical foundation-ground system is 3.0. Therefore, the safety factor of bridge foundation before scour can be defined as 3.0 and the safety factor decreases as scour progresses.

$$\xi = \frac{Q_u^{normal}}{Q_u^{scour}} = \frac{Q_a*(S.F.)_{normal}}{Q_a*(S.F.)_{scour}} = \frac{S.F._{normal}}{S.F._{scour}} \qquad \text{Eq. } 2$$

Where

- ξ = vulnerability to scour of a foundation
- Q_u^{normal} = ultimate bearing capacity of the foundation-ground system before scour
- Q_u^{scour} = ultimate bearing capacity of the foundation-ground system after scour
- Q_a = allowable bearing capacity of the foundation-ground system
- $S.F._{normal}$ = safety factor before scour
- $S.F._{scour}$ = safety factor after scour

This means that the vulnerability can be determined from the bearing capacities and the safety factor of foundation-ground systems as scour progresses.

In Figure 8 the different vulnerability grades are shown. Here B is the foundation width, Y_s the scour depth and Y_P the foundation embedment depth. In this figure can be seen that bridges are classified into four groups, grade 1, grade 2, grade 3 and grade 4. Grade 4 is the stable condition. Grade 1 is the unstable condition, in which it is likely to happen that the bridge will fail. Grade 0 is a conceptual approach, which states that there is no foundation embedment depth at all, what is of course very undesirable and will normally lead to failure.

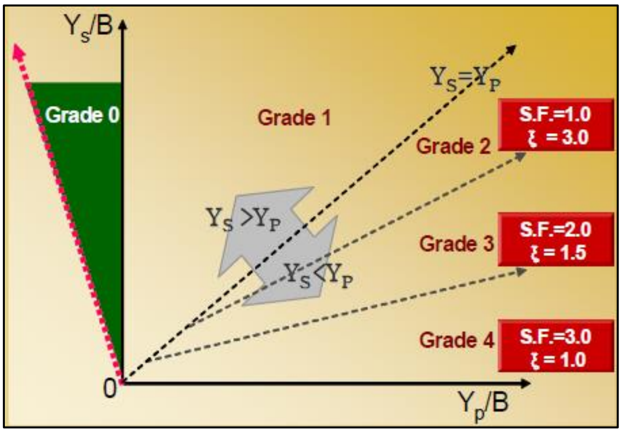


Figure 8 – Vulnerability grades (Park, Kwak, Lee, & Chung, 2012)

In the method potential future conditions are included. In order to estimate the scour depth around a bridge pier during flood events, potential future conditions about hydraulic and hydrological variables are needed, such as discharge, velocity and depth for the design flood. To predict these future conditions, the method uses a database to set up the hydraulic and hydrological variables.

Besides the hydraulic and hydrological variables, data about geotechnical and structural variables are also needed for the scour analysis. These contain the general structural condition of the bridge, the present degree of scour damage around bridge foundation and embankment, geomorphic properties of the watershed area, bed material properties (size, gradation, distribution and soil classification), and boring log information. In case rock exists, the rock depth was taken into account deciding the scour depth of the bridge.

The calculation of the scour depth in the method is done by a couple of different equations.

- CSU equation of HEC-18 (2001)

- Froehlich's Equation (1988)
- Laursen's Equation (1960)
- Neill's Equation (1973)

For the specific equations and parameters, the papers of these equations are given in the bibliography.

After determination of the scour depth that can occur, the assessment of the bridge vulnerability can be calculated. In the model this is done by the analysis of bearing capacity of foundation before and after scour. The equation that is used to estimate the bearing capacity is the general static bearing capacity method from Meyerhof (1976), as this method is very accurate in estimating the ultimate bearing capacity. The equation is:

$$\boldsymbol{Q_u = \left(c'_V N_q + cN_c\right)A_p + \sum f_s A_s} \qquad \textbf{Eq. 3}$$

In the model the scour vulnerability is estimated with comparing the scour depth with the foundation embedment depth. When expected scour depth is larger than the foundation embedment depth, the vulnerability is categorized as Grade 1 with potential scour condition. When expected scour depth is smaller than the foundation embedment depth, the vulnerability is categorized in Grade 2, 3 and 4. The specific way of how to determine in which class the vulnerability can be ranked, more info can be found in 8ATTACHMENT E.

Although the model says that it can be used for both pile and spread footing foundations, equation 3 only refers to pile foundations. Therefore, the model is not complete. However, that data provided is still useful considering the development of the fragility curve and the BBN risk model.

4.3 Model 3 - CAESAR (Palmer, Turkiyyah, & Harmsen, 1999)

Model created by Palmer, Turkiyyah and Harmsen (1999) for the evaluation of scour and stream stability under project of National Cooperative Highway Research Program (NCHRP).

The model is an expert system for Cataloging And Evaluation of Scour Risk and River stability at bridge sites (CAESAR). The system is a computer model which is developed in Microsoft Visual Basic and runs on a Windows 95 environment.

CAESAR includes two parts. First the user interface for information collection storage and retrieval. Second an evaluation model which presents recommendations with confidence values and suggestions for appropriate actions. The model aids bridge inspectors by the development of a database which includes a catalog of important features of a bridge, photographs, cross-section profiles and past inspections. Therefore, the model helps with the assessment of scour risks at a bridge and increase the accuracy of bridge scour screening processes.

CAESAR is based on a Bayesian Network. In the model the determination of scour risk is based by analysing three components of scour and stream stability. The three terms for scour are long-term aggradation and degradation, contraction and local scour. The three terms which indicates stream instability are lateral channel and thalweg (the line defining the lowest points along the length of a river, whether underwater or not) migration, vertical channel and thalweg degradation. In the model, the Bayesian Network incorporates the knowledge of experts from the field of hydraulic engineering, geotechnical engineering, geomorphology and structural engineering. Therefore, accurate and reasonable conclusions about the scour risks can be made.

The input of the model is split up in two sections: static information and dynamic information. Static information is information that does not change over time, such as the number of piers, type of abutments, foundation type, deck elevation pier locations, as-built channel elevation and pier shape. Dynamic information is information that may change from inspection to inspection, including information such as the cross-section profile, photographs and visual observations of the site. In Table 1 the static and dynamic information that is required by CAESAR can be found.

Table 1 – Static and dynamic information needed by CAESAR (Palmer, Turkiyyah, & Harmsen, 1999)

Static information	Dynamic information
Pier locations, foundation types, foundation elevations, pier shapes, as-built channel elevations	Abutment specific data: countermeasure presence, serious observables scour, historical scour problems.
Surface bed material	Instream bar location, size and vegetation
Subsurface bed material	Point bar location, size and vegetation
Notes about maintenance work, hydraulic problems or scour problems	Pier specific data: countermeasure presence, serious observables scour, historical scour problems
Historical inspection records	Erosion severity and location
	Site photographs
	Cross-section profile
	Presence of scour screamers

With the given input, the CAESAR model calculates several outputs, as pier and/or abutment evaluations, general site evaluations and conclusions. The pier and/or abutments evaluations are divided into three sections:

- Overall pier and/or abutment rating which describes the stability of the pier and/or abutment during future floods.
- Evidence/likelihood of scour at pier and/or abutment which describes the confidence that the abutment or pier will experience severe scour during the next flood, combined with experienced scour in the past.
- Apparent ability for pier and/or abutment to resist scour which describes the structural stability of the sub-structure foundation.

The general site evaluations are also divided into three sections:

- The potential or evidence of lateral migration which describes the likelihood of the channel migrating to the left or right.

- The potential or evidence of vertical stream instability which is a measure of the vertical channel or thalweg stability.
- The qualitative contraction scour which gives a qualitative estimate of contraction scour, which is based on expert system evaluation.

The conclusions that CAESAR gives are given in the form of a textual list which contains specific scour risk, potential threats to substructure elements and suggestion for mitigation methods.

4.4 Model assessment and selection

For this research, the most important outcomes are the development of the fragility curve and the BBN risk model, in where the fragility curve will be integrated. Therefore data and information is needed, which the models in this chapter can deliver. Not every model though suits the BBN and the fragility curve well. Therefore, in this section will be discussed if each model's information is useful or not for the development of the fragility curve and the BBN risk model.

The most important things from analyzing previously mentioned three are the understanding of the contributing parameters to the scour of river crossings and the inputs and outputs that the models generate. Therefore, the accuracy of the models is not from high importance in this thesis.

For the fragility curve the most important thing is that there is a clear relationship between an intensity measure on one side and the vulnerability/probability of failure on the other side. A model which gives the vulnerability to scour in terms of an intensity measure is therefore very desirable. For the BBN risk model it is important that we have a clear view of what the relations are between the different factors that contribute to scour. For the development of the BBN we also want to know what the probabilities of each of these factors are.

For each of the models a table is created in which the useful data is presented. More detailed information and explanation about data presented in the tables can be found in 8ATTACHMENT G.

4.4.1 Vulnerability assessment of bridges exposed to scour (Tanasic, Ilic, & Hajdin, 2012)

For the model of Tanasic, Ilic and Hajin (2012) the data which can be used for the fragility curve and the BBN risk model is given in Table 2.

Table 2 – Important issues from the model of Tanasic, Ilic and Hajdin (2012) for the fragility curve and BBN risk model

Fragility curve	BBN risk model
The outcomes of the model can be perfectly used as an intensity measure.	The used equations give a clear understanding in what factors contribute to scour.
The model calculates the how probable for a structure it is to fail considering the soil cover depth.	Debris potential is not mentioned in the model but is an important factor.
	Input is as well deterministic as probabilistic.
	Failure mode based on ductility limit of superstructure and bearing capacity of soil.

4.4.2 Scour vulnerability evaluation of pile foundations (Park, Kwak, Lee, & Chung, 2012)

For the model of Park, Kwak, Lee and Chung (2012) the data which can be used for the fragility curve and the BBN risk model is given in Table 3.

Table 3 – Important issues from the model of Park, Kwak, Lee and Chung (2012) for the fragility curve and BBN risk model

Fragility curve	BBN risk model
The outcomes of the model can be perfectly used as an intensity measure.	The used equations give a clear understanding in what factors contribute to scour.
Model calculates vulnerability but not probability of failure.	Input is as well deterministic as probabilistic.
	Failure mode based on bearing capacity of soil.

4.4.3 CAESAR (Palmer, Turkiyyah, & Harmsen, 1999)

For the model of Palmer, Turkiyyah and Harmsen (1999) the data which can be used for the fragility curve and the BBN risk model is given in Table 4.

Table 4 – Important issues from the model of Palmer, Turkiyyah and Harmsen (1999) for the fragility curve and BBN risk model

Fragility curve	BBN risk model
Vulnerability to scour is calculated but it's not clear how this can be transformed into a probability of failure.	No equations are given so the relations between all the different variables are not visible.
Intensity measure is not given.	Input all deterministic.
	No failure mode is given.

4.4.4 Conclusion

Based on the analysis of the models it turned out that all of the models can deliver input for both the BBN and the fragility curve. The model of Tanasic, Ilic and Hajdin (2012) delivers a lot of information for the BBN risk model, as with the equations the relations between all the variables become clear. Furthermore, its outcomes can be used as an intensity measure for the fragility curve and even the probability of failure can be determined. Downside is that is only mentions local scour.

The model of Park, Kwak, Lee and Chung (2012) delivers just as the model of Tanasic, Ilic and Hajdin (2012) a lot of information for the BBN, because of the equations that are given. The model only mentions one failure mode, but it does calculate outcomes that can be used as an intensity measure for the fragility curve. Furthermore, the vulnerability is calculated, but from these outcomes it may be difficult to determine a probability of failure.

The model of Palmer, Turkiyyah and Harmsen (1999) is a very complex model that is executed by a computer program. Therefore, the way the calculations are done is not clear. Though, the model does give a lot of variables that can be used for the BBN. The model does not give a clear intensity measure that can be used for the fragility curve and the vulnerability is calculated, but it's not clear how to transform this into a probability of failure.

For the development of the fragility curve and BBN risk model, most of the information will come from the models of Tanasic, Ilic and Hajdin (2012) and Park, Kwak, Lee and Chung (2012). But as they only provide information for local scour, model 3 will be used to cover this.

5 FRAGILITY ANALYSIS

In the previous chapter different vulnerability models were discussed. Each of these models describes the vulnerability of river crossings given a certain scour event. In some cases, the probability of failure was also determined, which can be considered as a specific form of vulnerability. With the information from these models, it is possible to describe the fragility of structures to scour in a more specific way. This will be done with 'fragility curves'. In this chapter, the data needed for fragility curves and the methodology to develop fragility curves for scour will be discussed. However, first some general information about fragility curves are given and second the useful data from the vulnerability models will be analysed. The part of the fragility analysis in the process of risk assessment is risk analysis.

5.1 General

Fragility curves describe the relation between a certain intensity measure or load and probability of failure, over the full range to which a system might be exposed. A fragility curve expresses the vulnerability over the load rather than give only an overall probability of failure (Schultz, Gouldby, Simm, & Wibowo, 2010). The intensity measures needed in case of scour are discussed in section 5.2.2. Fragility curves provide essential information for quantitative risk assessment studies as they allow the estimation of risk within a performance based network (Aristotle University of Thessaloniki, 2011).

Fragility curves are very useful graphical tools to give an expression about the probability of exceeding a given damage state under a certain hazardous event. They are often used when the structure under the damaging event is governed by important uncertainties. In this case of scour, important uncertainties such as the flooding events are present (Aristotle University of Thessaloniki, 2011). More general information about fragility curves can be found in 8ATTACHMENT H.

5.2 Fragility curves for scour

In this section, the methodology for the development of fragility curves for scour will be explained. First of all the input from the scour quantification models will be analysed to determine what specific data from each model can be used. At last, some examples of possible fragility curves for scour will be given, to give a clear understanding of the whole concept.

5.2.1 Input from scour quantification models

For fragility curves, a very important parameter that is needed is the intensity measure that is linked to the probability of failure. Intensity measures can also be seen as a sort of load that is applied to the structure. In the previously described vulnerability models, some very useful information for the determination of the intensity measure is provided.

Besides the determination of the intensity measure, it is also very important that it is clear in what way the intensity measure does affect the structure. In other words, how does the intensity measure affect the capacity of the structure to withstand the load. In this section, the useful data from the vulnerability models will be analysed.

- The outcomes that the model of Tanasic, Ilic and Hajdin (2012) generates are perfect to use as an intensity measure for the fragility curve. The model calculates scour depth (but uses soil cover height of the pier eventually), and furthermore provides information for the determination of the probability of failure based on scour depth.
- The same counts for the model of Park, Kwak, Lee and Chung (2012). This model also calculates the scour depth which can be used as an intensity measure. Furthermore, it describes the influence of scour depth on the load bearing capacity of the structure, and therefore the impact it has on the structural reliability and performance of the structure.
- The model of Palmer, Turkiyyah and Harmsen (1999) does not provide very useful information that can be used for the development of the fragility curve for scour as it is a computer program and therefore not very clear how the outcomes are exactly calculated. There is no specific outcome that can be used as an intensity measure.

So in short we see that the models of Tanasic, Ilic and Hajdin (2012) and Park, Kwak, Lee and Chung (2012) provide data that can be used for the determination of the fragility curve. Also information about how these intensity measures do affect the structure is provided and in model 1 even the probability of failure based on this intensity measure is described.

5.2.2 Methodology

As mentioned before, structures are often exposed to a lot of uncertainties. Because of these uncertainties, the potential extent of damage should be evaluated for different magnitudes of the hazardous event using probabilistic terms. Therefore representative damage states should be defined (Aristotle University of Thessaloniki, 2011).

For the development of fragility curves, three steps have to be taken. The first step is to determine the uncertainties and the intensity measure that will be used for the fragility curve. The second step is to estimate the intensity measure given the already found uncertainties with probabilistic terms. The second step also includes the determination of the damage states based on the uncertainties found in step 1. The third and final step is to translate these outcomes to a probability of failure and the fragility curve (Roca & Whitehouse, 2012). Here, also previous events and studies are considered in the calculation.

In Figure 9 this methodology with the illustration of the steps can be seen. It considers the change of the hazardous event happening. The probability is determined by information of previous studies and events. The certain events give a certain output, which in this case is the water discharge caused by different sort of floods. These outputs cause a certain amount of scour which gives in combination with the probability of failure of the bridge, the fragility curve.

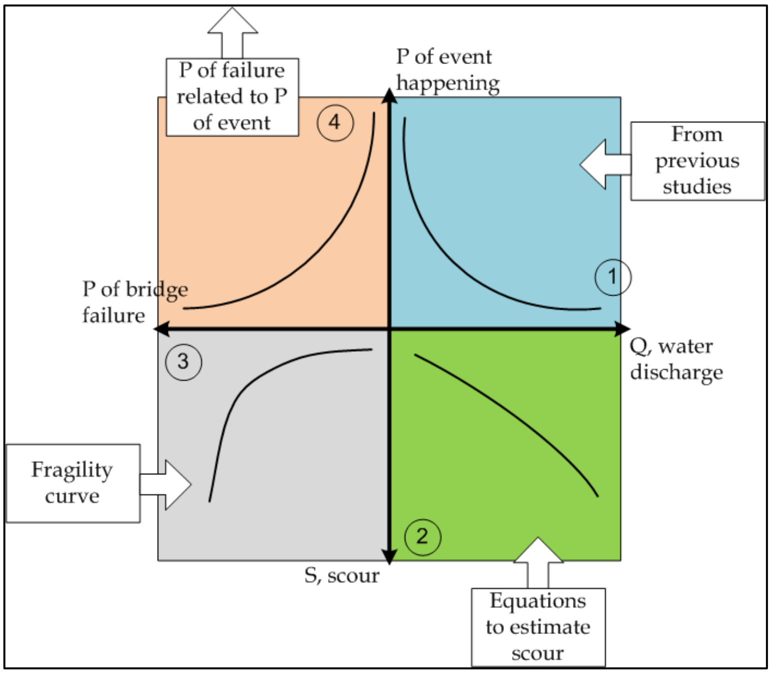


Figure 9 – Overview of methodology to determine probability of bridge failure (Roca & Whitehouse, 2012)

In Figure 9 it looks like the water discharge is the only factor that influences the scour but in the equations that calculate scour, also the geological and structural parameters are included.

If we follow the steps mentioned before to develop a fragility curve, the first step is to determine the uncertainties of the parameters that are needed for the calculations of the scour and possible impact on the river crossing. Therefore, data from the past will be attained. In case of the hydrological data, a lot of data can be obtained from hydrological studies at catchment or regional level or from national datasets (Roca & Whitehouse, 2012). In this case, the data about the probability of occurrence of different kind of floods is the most important data needed, since this is the most uncertain data. The geological and structural information are most of the time deterministic.

The intensity measure that will be used in the fragility curve for scour on river crossing will be the scour depth. This parameter is a common output of many vulnerability models and therefore a logical choice regarding scour. The scour depth will be calculated in the second step. Of course, other intensity measure can also be chosen, such as soil cover height which is used in one of the scour quantification models mentioned in chapter 4 and triggers like floods which cause high water discharges.

The second step is to determine the scour based on the information obtained by step 1. The calculation of scour can be done by different equations that are mentioned in chapter 4. This calculation also includes the different damage states that are possible. For the calculation of the potential impact of scour on river crossing, we will use the following damage states: slight, moderate, severe and complete damage. Here slight damage means the river crossing is fully serviceable, moderate damage means serviceable but impaired, severe damage means not serviceable and complete damage means the river crossing is collapsed (Aristotle University of Thessaloniki, 2011).

The third and final step is to evaluate the relation between the probability of an event and the probability of failure if such an event happens considering the intensity measure. These findings shall be integrated into the fragility curve, with the damage states defined in step two.

This all together should look like the fragility curve that can be seen in Figure 10. In this fragility curve, the damage done by landslides on buildings is calculated. This has been done for several speeds of the landslide, in this case 6m/s. The figure shows different diameters of rocks causing damage to buildings. The amount of damage determines if a certain damage state has been exceeded or not. For example, when a rock of a diameter of 1 m or more hits a building with the speed of 6 m/s, the damage state called 'low' already has been exceeded with a probability of 100%. The chance that the other damage states are exceeded in this example, are way lower and even 0% in case of the damage state called ' very high'.

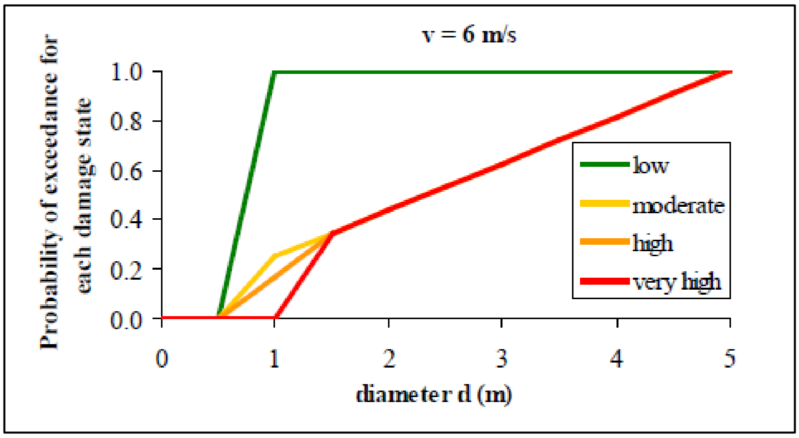


Figure 10 – Example of fragility curve for different rock velocities and diameters considering landslides (Aristotle University of Thessaloniki, 2011)

In 'Physical vulnerabilty of elements at risk to landslides: Methodology for evaluation, fragility curves and damage states for buildings and lifelines' (Aristotle University of Thessaloniki, 2011) a methology to determine the probability of each damage state is developed. We should thereby mention that for different damage states, different models are needed that determine what the probabilities of exceedence of each of these damage states are. Therefore, clear limit states of each damage state are needed.

For scour, the same sort of scheme can be developed. In Figure 11 this scheme can be seen. Though, the scheme only provides a framework and therefore values and numbers of parameters are of course not mentioned. It could also be that the amounts of choices given for each damage state are not correct, but the scheme is provided to give an impression of how it could look like.

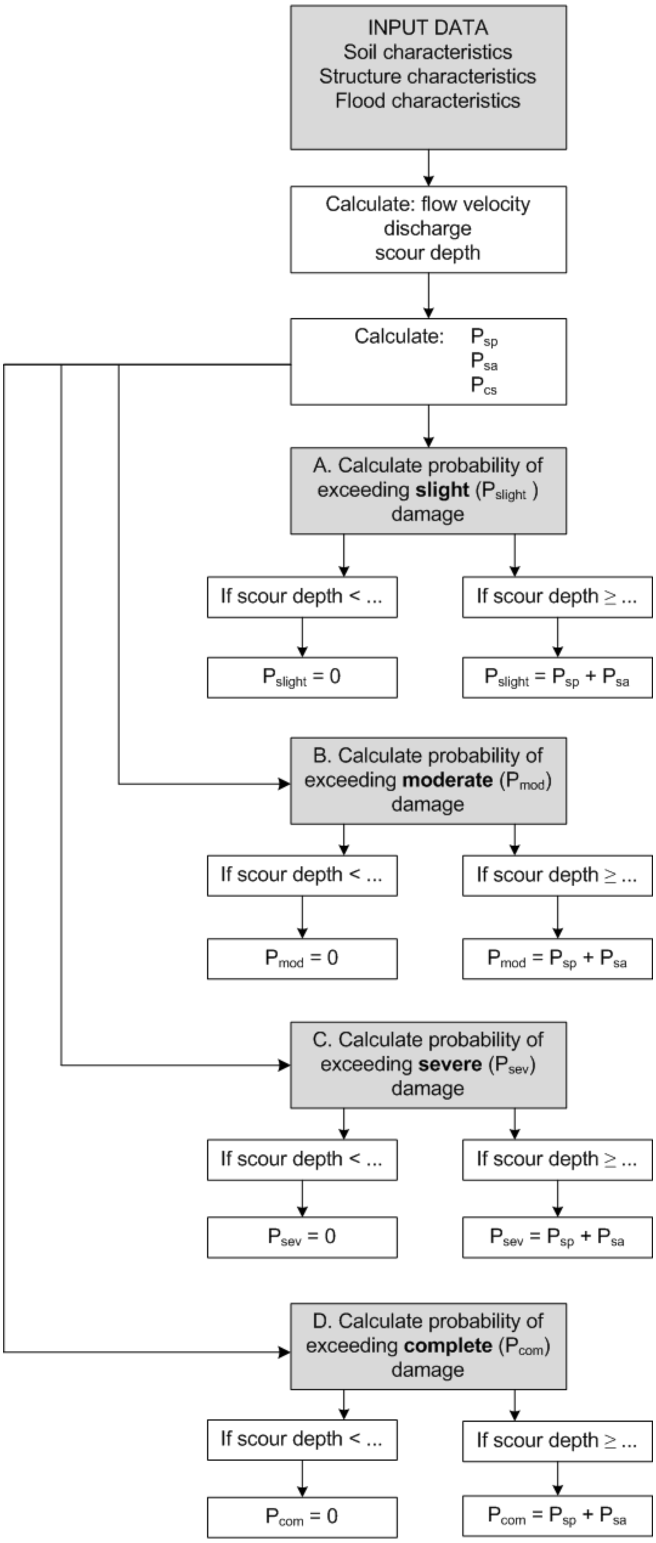


Figure 11 – Global algorithm for calculation of the probability of each damage states for scour

In this scheme, the flow characteristics combined with the structure and soil characteristics determine the amount of scour. The most important things to calculate are the flow velocity, discharge and eventually the scour depth. Scour is therefore separated in three types: scour at piers (sp), scour at abutments (sa) and contraction scour (sc). In the third box from above in Figure 11 the probability of occurrence of each of these types (P_{sp}, P_{sa} and P_{sc}) are calculated.

The amount of scour (scour depth) combined with the place where scour occurs (pier, abutment, and contraction) depends what the probability of each damage state is. Unfortunately, no data about the scour depth and probability of exceeding certain damage states is available. These calculations have to be done in case a fragility curve will be developed. Furthermore, different approaches are possible for the algorithm and the algorithm is very general, but this framework can be used for further development.

5.2.3 Example

With all the information given before, it is possible to develop an example of how a fragility curve for this research might look like. This means that there are no calculations included, so the fragility curve is just an impression of how it might look like in case of scour. As mentioned before, there are three steps that have to be taken into consideration when developing a fragility curve.

The first step is to determine the uncertainties in the parameters that are needed for the calculations of the scour and possible impact on the river crossing. In this research, this will not be done, but with data from the past it is possible to determine how often specific floods occur.

The intensity measure that will be used in the fragility curve for scour is the scour depth. As it has been explained before, this parameter is most of the time the outcome of the scour vulnerability models and therefore a good parameter to use as a intensity measure. Furthermore, the damage states used in the curve will be the ones also mentioned before: slight damage, moderate damage, severe damage and complete damage.

The second step is to calculate the scour based by the information gathered by step 1 and other information like the geological and structural characteristics. Because of the uncertainties in especially the flood characteristics all the possible outcomes have to be calculated. These outcomes eventually can be organized in the different damage states.

The third and final step will be to determine the relationships between the probability of a certain flood and the probability of failure if such an event happens. With the scour depth that is caused by the different types of floods, the probability of failure can be determined, or at least, the probability of a certain damage state can be calculated. As presented in Figure 11 based on the scour depth and the place where the scour occurs, the probability of exceedance of a certain damage state can be calculated. When all these steps are done, a fragility curve can be formed. To give an idea how a fragility curve for scour might look like, one example is given in Figure 12.

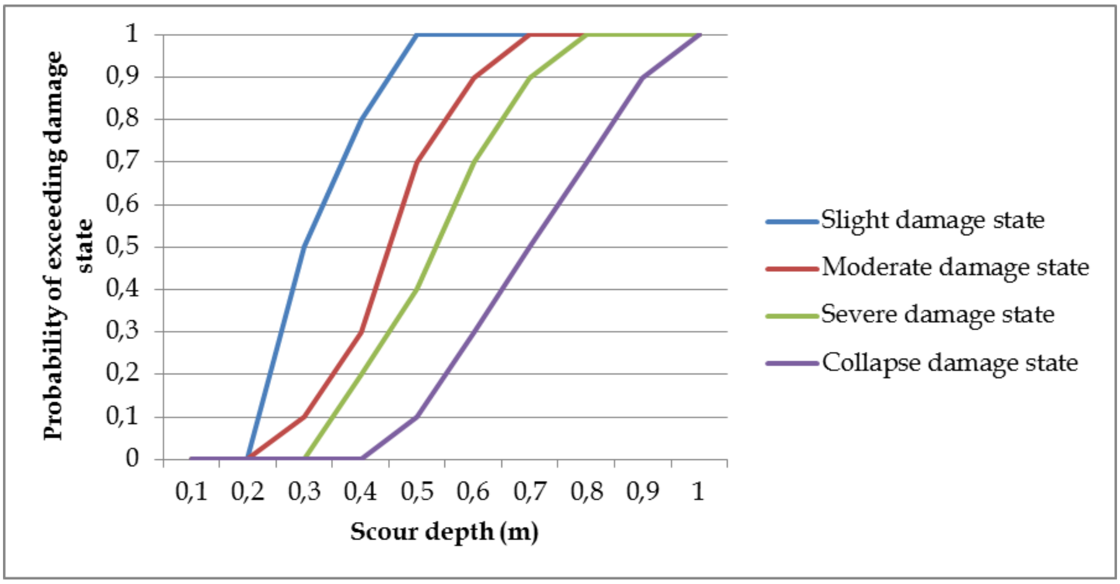


Figure 12 – Example of fragility curve for scour

6 BAYESIAN BELIEF NETWORK

In this chapter, the data found in the previous chapters considering the historic events and the vulnerability models, will be put together into one risk model, with the application of a Belief Network (BBN).

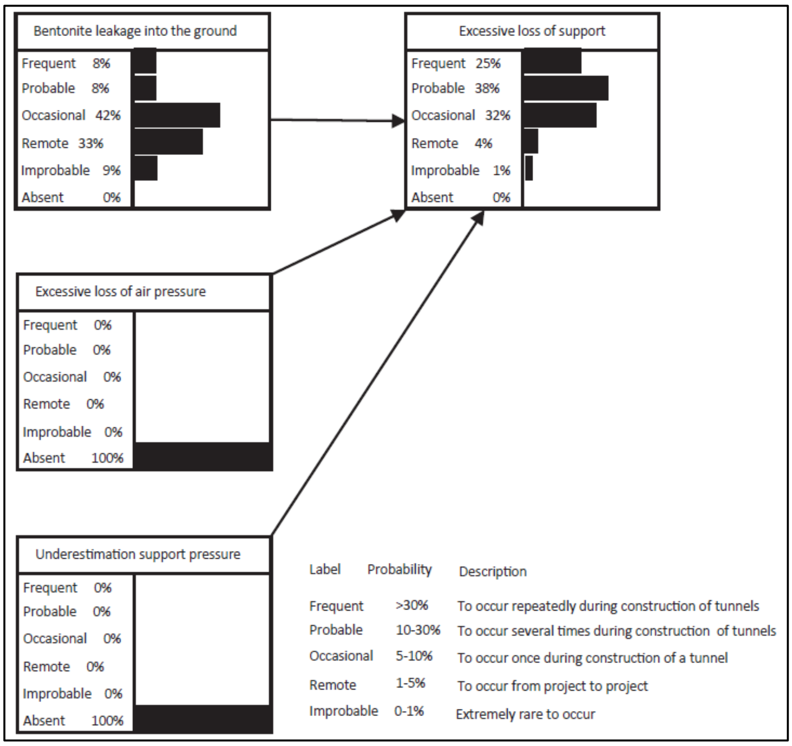
In this research, only the framework of the BBN risk model will be given. This means that the probabilities will not be calculated except the probabilities of the different types of floods, which give a good starting point for the rest of the BBN risk model. The reason for letting these probabilities out is that these probabilities are site specific and therefore not very useful to determine them in this research. The methodology of the development of the BBN risk model is just as the development of the methodology for the fragility curve part of risk analysis concerning risk assessment.

6.1 General

From the information obtained in the previous chapters, it has become clear that scour is a very big problem for river crossings. Therefore, management of this risk is very important to prevent the river crossing from future damage. Decision making in this management process is sometimes very difficult, because of the lack of knowledge. Probabilistic models such as Bayesian Belief Networks help with this by giving information about what the chances are that some undesirable events will happen.

The information in probabilistic models is represented by causal relations between the variables and their associated probabilities. BBN risk models make use of Bayesian probabilities. Bayesian probabilities use the degree of a person's belief that a specific event will occur. These probabilities are based on an expert's expertise in the field or domain of knowledge. The probabilities are from the person and not from the event itself. In this way, prior probabilities can be determined for each event without running repeated trials that are needed (Heckerman, 1996). In BBN, besides Bayesian probabilities, knowledge is blend with classical probabilities to try to get the model as accurate as possible. These probabilities rely upon repeated trials to determine the probabilities for particular events. This requires the processing of data which may not always be available. Therefore, it is easier to use Bayesian probabilities, but if available, classical probabilities may also be used to complement the Bayesian probabilities. BBN also makes use of as well prior probabilities as conditional probabilities. Because of these characteristics, BBN do have an advantage over classical probability techniques (Heckerman, 1996).

A BBN is a specific form of a belief network. Belief networks are graphical models that effectively model the knowledge domain. These models do provide useful information for inferring hypotheses with the probabilistic information from the data. BBN are a special form of belief networks. BBN are graphical models that use Bayesian probabilities to model the dependencies within the knowledge domain (Jensen, 1996). In Figure 13 an example of a BBN risk model about risks during tunneling projects (Cárdenas, Al-Jibouri, Halman, & Van Tol, 2013)can be seen. In this figure, the relations between the different variables and the probability of each variable can be found.



Label	Probability	Description
Frequent	>30%	To occur repeatedly during construction of tunnels
Probable	10-30%	To occur several times during construction of tunnels
Occasional	5-10%	To occur once during construction of a tunnel
Remote	1-5%	To occur from project to project
Improbable	0-1%	Extremely rare to occur

Figure 13 – Example of a BBN risk model (Cárdenas, Al-Jibouri, Halman, & Van Tol, 2013)

BBN determine the probability distributions for the variables of interest, based on the observed information. Because of this approach, it is possible to model the specific relations between variables and make predictions, even when direct evidence or observations are unavailable (Krieg, 2001). To develop a BBN risk model, the most appropriate network structure and probabilities must be determined. Developing a BBN involves the following steps (Heckerman, 1996):

- Identify the goals of the model;
- Identify all possible sources of data that may be relevant to achieving these goals;
- Select the data that are meaningful and worthwhile in the context of the model;

- Organize the selected data into variables that have mutually and collectively exhaustive states.

In the first part of this research, the first three steps are already done. The goal of the model is to determine how the different variables contribute to scour, what can lead to failure of river crossings. The data is collected from the historic events and different scour quantification models that are analysed. Besides, the data gathered for the fragility curve will be used (damage states, intensity measures et cetera). In this chapter, the fourth step will be done, including the determination of the relations between the different variables and the determination what probabilities are needed. Only the probabilities for the different type of floods will be determined.

6.2 Determine variables

To determine the variables needed for the BBN, the four steps mentioned before have to be done. This means that first of all the goal for the BBN should be clear. As mentioned in section 1.2 the BBN risk model will be developed to visualize the contribution of all the variables to scour and in general the vulnerability of bridges to scour. Furthermore, a BBN normally is developed to determine the probabilities of each variable to happen. In this research, only some data will be given concerning the types of floods and water quantities as scour is always a site specific phenomenon.

The data collected to develop the BBN is in short all the data presented in the previous chapters. The most important data needed for the BBN is the data collected from the vulnerability models and the fragility curve. The information gathered from both gives a clear insight in what variables are contributing to scour and furthermore they gave some information about the importance of each variable compared to other variables. The fragility curve probabilities can also be integrated in the BBN risk model.

From the information gathered so far, it is possible to determine the needed variables for the BBN. When considering scour, the most important factors are the flow characteristics, the soil characteristics and the structure characteristics. These factors include all the important parameters that are also used in the vulnerability models like the flow velocity, sediment diameter and pier dimensions. In Table 5 the most important parameters for each factor can be found.

Table 5 – Important parameters for each factor

Factor	Parameters
Flow characteristics	Hydraulic depth, mean flow velocity, critical velocity, peak flow duration, Froude number directly upstream from the pier, discharge in contracted area, discharge in upstream channel, depth in contracted channel, depth in upstream channel, Manning coefficient, bed material transport, acceleration of gravity, density of water, density of soil, unit weight of water, specific gravity of soil
Soil characteristics	Median sediment diameter, bearing capacity soil,

	initial foundation to soil contact pressure, limit of exhausting of bearing capacity, shear stresses, slope of every grade line, Shield's coefficient
Structure characteristics	Equivalent pier diameter, ductility limit, soil cover height, width of bridge pier, depth of foundation, shape of pier nose, length of pier

The parameters from Table 5 though won't be used in the BBN, as they are too many and it is more easy and clarifying to use only the three main factors (flow, soil and structure characteristics).

These factors (the three types of characteristics) however can be influenced by certain events that will eventually have a big impact on the scour. For each factor, different events are given in Table 6.

Table 6 – Overview of events that change the factors and therefore the parameters

Factor	Events
Flow characteristics	Heavy rainfall, large amount of outflow of water (from drainage basins or other instances)
Soil characteristics	Excavation, deforestation, long-term cultivation
Structure characteristics	Deterioration (caused by for example acid industry, organically contaminated water, chemically contaminated water, seawater of sewage, freezing and thawing)

Besides the three forms of characteristics and the events that influence these factors, other variables are present in the network. All of the variables that will be used in the BBN are written down below.

- Events:
    - Heavy rainfall;
    - Large amount of outflow of water;
    - Excavation;
    - Deforestation;
    - Long-term cultivation;
    - Deterioration;
- Location specific parameters:
    - Flow characteristics;
    - Soil characteristics;
    - Structure characteristics;
- Consequences:
    - Scour depth;
    - Bearing capacity of soil;
    - Ductility limit;
    - Damage states.

Taking a look at the variables, we see that the flow, soil and structure characteristics are influenced by certain events. Furthermore, these variables do have an impact on the scour depth. The failure modes due to scour occur because of too little bearing capacity or exceeding of the ductility limit of the structure. Therefore, these two define in what damage state the river crossing is.

Besides the variables, also the damage states defined for the fragility curves can be used in the BBN to clarify how the river crossing is affected by scour. These damage states were 'slight', 'moderate', 'severe' and 'complete damage'. These damage states from the fragility curves will be integrated into the BBN risk model. Also the calculations that are done to determine the probabilities from these damage states (not done in this thesis) can be used as they also are based on variables used in the BBN risk model. The next step in the development of the BBN is to determine how these variables relate to each other.

6.3 Determine relations and structure

Bayesian Belief Networks are used when we are interested in obtaining estimates of the uncertainties of events that are not observable or are observable but at an unacceptable cost. Therefore, it allows us to hypothesize the occurrence of the events that are interested. The events are because of this also called hypothesis events and correspond to the hypothesis nodes from the network (Krieg, 2001).

Additional information may offer more insight into the uncertainties of the various hypothesis events. This information can be incorporated into the network with the so called information nodes (Krieg, 2001). In the network, it is important to identify the types of information that are needed to reveal something about the hypothesis variables.

In the previous section 6.2 all the variables are identified. Now it is important to determine the causal structure between the variables, in particular, which variable causes a particular state in another variable (Krieg, 2001). Most of the time people are able to directly recognize the causal relations that are present between the variables. Important is that the relations between variables that influence each other are set up right.

In the network, there can be one-sided and two-sided relations between the variables. A one-sided relation means that between two variables, variable 1 influences variable 2, but variable 2 doesn't influence variable 1. With two-sided relations on the other hand, the variables get influenced by each other. We will now determine what relations between variables are there in the network and whether they are one-sided or two-sided.

The events that influence the soil, flow and structure characteristics do all have one-sided relations concerning the three main factors, flow, soil and structure characteristics. The events influence the factors but not the other way around.

The most important variables that influence the amount of scour that will occur are the flow, soil and structure characteristics. As seen in the vulnerability models, these factors contain all the different parameters used in the equations for the determination of scour depth. This means these characteristics do influence the scour depth and therefore a relation between these factors and the scour depth is present.

The relation between the soil and structure characteristics and the scour depth is one-sided. The soil and structure characteristics do influence the scour depth but not the other way around. In case of the flow characteristics, the relation could be two-sided, as some little changes in the flow occur when the scour depth grows. Overall however, this change is small and for that reason, a one-sided relation is chosen.

The soil and structure characteristics do not only influence the amount of scour, but the soil characteristics define the bearing capacity of the soil and the structure characteristics define the ductility limit of the structure. These relations are therefore one-sided. However, the scour depth is also influencing the bearing capacity of the soil and the ductility limit.

In section 6.4 the whole BBN risk model will be given, where the just mentioned relations between the variables can be seen. The relations in the network are visualized by directed links between the variables (Tesfamarian, 2013).

6.4 Determine probabilities

The probabilities used for the BBN can be either Bayesian probabilities or classical probabilities. As said before in BBN risk models, besides Bayesian probabilities, knowledge is blend with classical probabilities to try to get the model as accurate as possible.

In this research only the probabilities of the floods will be determined. Therefore, information from the Dutch organization Koninklijk Nederlands Meteorologisch Instituut (KNMI) (2013) is used. This organization is a meteorological organization that collects all the meteorological data from the Netherlands. This means the probabilities that will be developed are classical probabilities.

The data collected from the KNMI describes the amount of rain that can fall in a certain amount of time given the probability of occurrence. These (heavy) rainfalls cause floods and therefore provide very useful data in the probability assessment of the floods. In 8ATTACHMENT I the collected data can be found with the calculation of the probabilities of each flood. An issue that has to be named is the fact that only heavy rainfalls are included in the network, whereas it also might be that lighter rainfalls can cause scour.

6.5 Bayesian Belief Network risk model

The last step in this chapter is to present the BBN risk model based on the data collected in the previous steps. This means all the variables, relations and probabilities (in this case only for 'Heavy rainfall') are combined together in one network. This network can be seen in Figure 14.

In this network, all the variables that eventually lead to a certain damage state can be seen. To determine in what damage state the river crossing will be, the current bearing capacity of the soil and the ductility limit of the structure influenced by the scour depth are very important. Furthermore, as explained before, the scour depth is influenced by the soil, flow and structure characteristics, which are influenced by certain events.

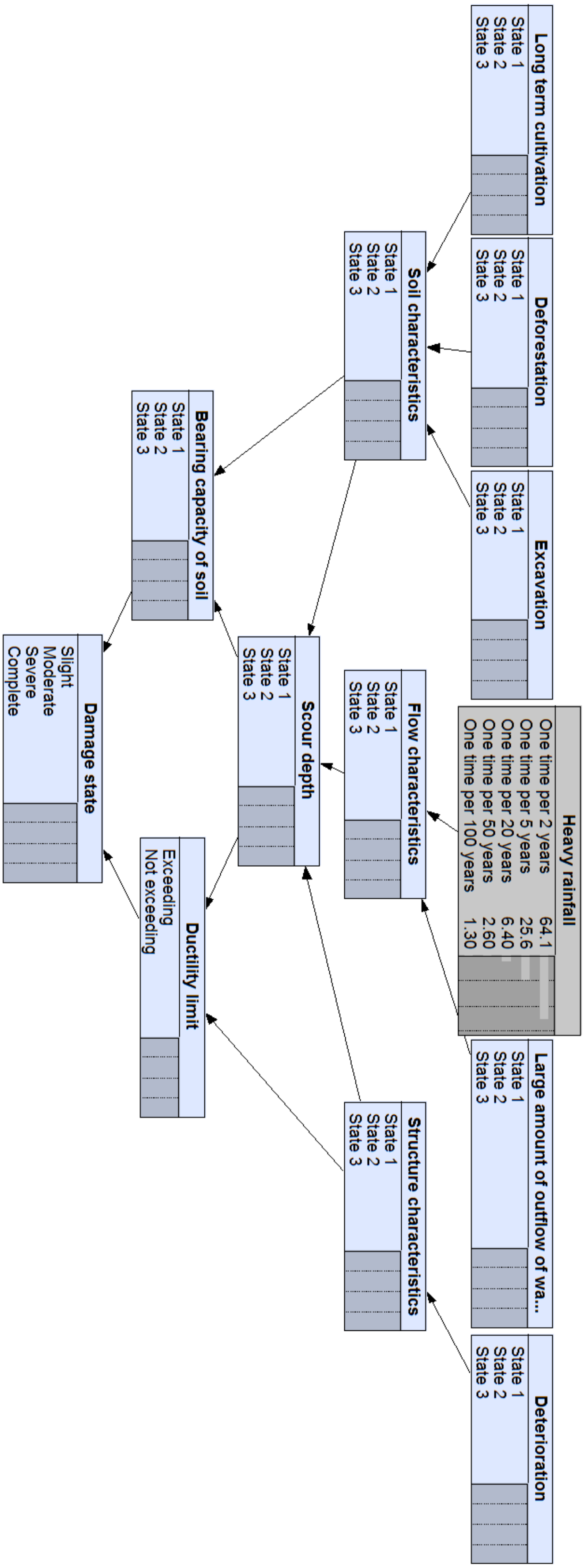


Figure 14 – Bayesian Belief Network for scour at river crossings

The BBN risk model only contains probabilities for heavy rainfall. This is because other information is very site specific, and therefore not useful to present now. The probabilities for heavy rainfall are general probabilities and can be used for several cases (in the Netherlands, as the data comes from a Dutch organization). The probabilities only apply to rainfall that occurs one time per two years or less. However, it might be that scour also occurs with floods that occur because of less heavy rainfall. Therefore, for river crossings that are vulnerable to scour because of floods induced by rainfall that occurs one time per two years, less heavy rainfall should also be taken into consideration.

In the network, most of the variables do have three states. Though, this does not mean that these variables need to have three states. In the filled in network, variables could have less or more states. Although, in the BBN risk model the damage states from the fragility curves are implemented, as a fragility curve can be seen as a part of the BBN risk model. The calculations done for the fragility curves considering the different damage states can also be integrated in the BBN risk model.

7 CONCLUSION

The main question in this research was how the impact of scour to river crossinsg can be quantified. In other words, how vulnerable are river crossings to scour. This question has been answered regarding the risk assessment process, which includes risk identification, risk analysis and risk evaluation.

For the quantification of scour, first of all the process behind scour have to be investigated. This is the phase of the risk identification. The general information about scour plus the different scour quantification models used in this report provided the information needed.

The information gathered during the risk identification is used during the next phase of risk analysis. The analysis of scour can be done in different ways. One of the most clear and informative ways to quantify the impact of scour to river crossings is to set up a fragility curve and/or a Bayesian Belief Network (BBN) risk model. The fragility curve and BBN risk model both provide information about the vulnerability of the river crossings against scour.

A fragility curve shows the probability of failure, a form of vulnerability, given a certain intensity measure. In case of scour, scour depth has been chosen. Most of the time fragilty curves have different damage states, which determine in what structural state the river crossing is like for example fully serviceable or not serviceable. For the development of a fragility curve, information about how the scour depth can be calculated, about how the probability of failure can be calculated and about the limit states of each damage state is needed.

A fragility curve can be seen as a part of BBN risk model, as it is a way of representing the probabilities of failure, which are also given in a BBN risk model. For that reason the outcomes of the fragility curves can be integrated into the BBN risk model. The example given in Figure 12 shows how a fragility curve for scour might look like.

BBN risk models provide a network where all the variables and relations between the variables can be seen, combined with the so called Bayesian probabilities. These probabilities show the probability of occurrence of each variable based on expert knowledge. These may be complemented with classical probabilities, which are based on historical data or the application of simulation models. To develop a BBN risk model for scour, a clear insight about scour is needed. All the variables have to be determined as well as the relations between them. Furthermore, the probabilities of each variable have to be calculated. This can be done based on information from the past (such as done with the probabilities of rainfall shown in this report) or based on simulation models. The example given in Figure 14 shows a BBN risk model for scour.

Considering the risk assessment of scour, in the report the first two steps are taking care of: risk identification and risk analysis. Risk evaluation, the last step, is not done because no data has been provided in the report so no evaluation was possible. However, about the methodology for the scour quantification, it can be said that when visual representations about the impact of scour to river crossings are needed, fragility curves and BBN risk models are an excellent choice.

Therefore, this report can be used as a guide for the development of fragility curves and BBN risk models for river crossings exposed to scour. It is a methodology that can be used in research about scour and the risk of scour to river crossings.

8 DISCUSSION

In this report, a methodology is shown of how to develop fragility curves and Bayesian Belief Network (BBN) risk models for scour. The set up of this report fits in the methodology of risk assessment.

However, the report does not provide any data except data for the heavy rainfall that is used in the BBN risk model. No further calculations were made during the research and therefore, when developing a fragility curve and/or BBN risk model, these steps still have to be taken. One of the reasons that no further calculations were made, is the fact that every river crossing is different and therefore most of the data is site specific. In general, this report should only be seen as a guide for risk assessment methodology and not as a complete network for the quantification of scour to river crossings.

In the literature, no examples of fragility curves or BBN risk models for scour can be found. Considering this, this report can be very useful in the development for these models, as it has turned out that not a lot of research has been done, concerning scour problems at river crossings. Especially when we take into consideration that scour nowadays has been recognized as a serious problem, this report could be very useful to determine the impact that scour may have on certain river crossings.

For this research, the fragility curve and BBN risk model are chosen to determine the impact of scour on river crossings. This has been done with information from differen scour quantification models and other literature information. However, not only other scour quantification models exist, also other methodologies to show the impact of scour may exist. This said, this report should not be seen as the only possible way to determine the impact of scour to river crossings.

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ATTACHMENT A **LIST OF FIGURES**

In this attachment, a list of figures that are present in this report is given.

ATTACHMENT B **LIST OF TABLES**

In this attachment, a list of tables that are present in this report is given.

ATTACHMENT C HISTORIC EVENTS

In this attachment a collection of events is given which are caused by scour. For each of the events, the year, name of structure, location, triggers and consequences (damage, fatalities and injuries) are given in Table 7.

Table 7 – List of historic scour events

CASE NO.	YEAR	EVENT	TRIGGERS	CONSEQUENCES		
				Damage	Fatalities	Injuries
1	2013	CPR Bonnybrook Bridge, Calgary, Alberta, Canada (CTVNews, 2013)	Flood caused one of the four piers to scour.	Partial collapse	0	0
2	2010	Railway Bridge Sava Jakuševac, Croatie (Engineering, 2010)	Scour caused movement of one of the piers.	No collapse	0	0
3	2009	Northside Bridge and Calva Bridge, Workington, England (BBC News, 2009)	Heavy floods lead to scour.	Complete collapse of bridges	0	0
4	2009	Railway Bridge RDG1, Feltham, England (Maddison, 2012)	Scour caused by obstruction of the river flow.	Arch of one span of the bridge partially collapsed	0	0
5	2009	Viaduct on Broadmeadow estuary, Malahide, Ireland (Maddison, 2012)	Seabed erosion/scour.	Partial collapse	0	0
6	2004	Ramu Bridge, Madang, Papua New Guinea (BridgeForum, 2014)	Soil erosion, landslides and heavy debris combined with poor design.	Complete collapse	0	0
7	2003	Beighton Railroad Bridge, Beighton, England (Maddison, 2012)	Contraction scour.	Pier and arch of one span of the bridge partially collapsed	0	0
8	2001	Steel Truss Bridge, between Castela de Paiva and Penafiel, Portugal (BridgeForum, 2014)	Flooding, scouring and deterioration.	Complete collapse	70	0
9	2001	Hintze Ribeiro Bridge, Entre-os-Rios, Castelo de	Fast waters and storm induced scour combined with	Partial collapse.	59	0

		Paiva, Portugal (BridgeForum, 2014)	decades of sand extraction.			
10	2000	Kaoping Bridge, Kaoping, Taiwan (BridgeForum, 2014)	Scour of the riverbed deepened by excessive gravel quarrying.	Partial collapse	0	22
11	1999	Covington Bridge, Covington, Tennessee, United States (BridgeForum, 2014)	Scouring and undermining of the foundations.	Partial collapse	0	0
12	1996	Walnut Street Bridge, Harrisburg, Pennsylvania, United States (BridgeForum, 2014)	Scour and ice damage.	Complete collapse	0	0
13	1995	Twin Bridges Interstate 5, Coalinga, California, United States (Wikipedia (1), 2014)	Scour of bridge foundations.	Complete collapse	7	0
14	1993	Five-Span Bridge, Forteviot, Great Britain (BridgeForum, 2014)	Scour of the gravel bed beneath the downstream face of the shallow founded pier, concrete bag scour protection washed away.	Partial collapse	0	0
15	1990	Holyhead Harbour, Holyhead, Wales (Maddison, 2012)	Scour caused by bed lowering and ship propellers.	Partial collapse	0	0
16	1989	Railroad Bridge Inverness, Inverness, Scotland (BBC News, 2009)	Scour caused by heavy floods.	Complete collapse	0	0
17	1989	Hatchie River Bridge, Tennessee, Covington, United States (Wikipedia (1), 2014)	Scour of the bridge foundations.	Partial collapse	8	0
18	1988	Staythorpe Railroad Viaduct, Staythorpe, England (Maddison, 2012)	Scour caused by changes to the course of the river.	No collapse	0	0
19	1987	Railroad Bridge Glanrhyd, Glanrhyd, Wales (Maddison, 2012)	Local and live bed scour caused by a period of heavy rain and channel instability.	Complete collapse	4	0
20	1987	Schoharie Bridge,	Flooding and storms	Partial	0	0

		New York, United States (Wikipedia (1), 2014)	lead to collapse of two spans after scouring of a pier.	collapse		
21	1987	Wassen Bridge N2-motorway viaduct, Switzerland (BridgeForum, 2014)	Flooding leads to scour of the pier foundations.	Partial collapse	0	0
22	1982	2-Span Truss Bridge, between Linz and Selzthal, Austria (BridgeForum, 2014)	Scour leads to loss of pier.	Partial collapse	0	0
23	1982	Multiple Stone Arches, between Milan and Bologna, Italy (BridgeForum, 2014)	Scour leads to loss of 2 piers.	Partial collapse (3 arches destroyed)	0	0
24	1977	Green Island Bridge, Troy, New York, United States (Wikipedia (1), 2014)	Flooding leads to scour which undermined the lift span pier.	Partial collapse	0	0
25	1972	2-Span Girder Bridge, Katerini, Greece (BridgeForum, 2014)	Flooding leads to scour combined with train load on bridge.	Partial collapse	1	0
26	1968	Countess Weir Bridge, Exeter, England (BridgeForum, 2014)	Scour under raft foundation.	Partial collapse	0	0
27	1966	Bridge between Antwerp and Luttich, Belgium (BridgeForum, 2014)	Flooding leads to scour.	Complete collapse	2	13
28	1965	Bridge near Charleston, South Carolina, United States (BridgeForum, 2014)	Scour leads to pier failure.	No collapse	0	0
29	1962	West Bridge Interstate 29, Sioux City, Iowa, United States (BridgeForum, 2014)	Flooding leads to scour.	Complete collapse	0	0
30	1953	Whangaehu River Bridge, Tangiway, North Island, New Zealand (Wikipedia	Lahar leads to scour combined with load of train.	Complete collapse	151	0

		(1), 2014)				
31	1938	Bridge AA-438, Prairie County, Montana, United States (Wikipedia (1), 2014)	Flooding leads to scour which undermined two of the central piers.	Complete collapse	47	75
32	1933	4-Span Beam and Slab Bridge, Anacostia River, United States (BridgeForum, 2014)	Flooding leads to scour combined with a lack of inspection.	Partial collapse	0	0
33	1926	3-Span Concrete Arch Bridge, Milcov River, Romania (BridgeForum, 2014)	Settlement of pier due to scour.	No collapse	0	0
34	1925	3-Hinge Concrete Arch Bridge, Aller, Germany (BridgeForum, 2014)	Flooding leads to scour.	Partial collapse	0	0
35	1923	Railroad Bridge Cole Creek, Converse County, Wyoming, United States (Wikipedia (1), 2014)	Heavy floods lead to scour.	Complete collapse	30	2
36	1914	Carr (masonry) Bridge, Baddenborg Burn, England (BridgeForum, 2014)	Heavy rain induced flooding leads to scour.	Complete collapse	5	10
37	1913	Concrete Arch Bridge, Deep, Germany (BridgeForum, 2014)	Flooding and gales lead to scour.	Complete collapse	0	0
38	1913	Truss Bridge near Prerow, Germany (BridgeForum, 2014)	Flooding and gales lead to scour.	Complete collapse	0	0
39	1882	Osijeg Bridge, Serbia (BridgeForum, 2014)	Flooding leads to scour combined with train load.	Partial collapse	0	0
40	1863	Chunky Creek Bride, Hickory, Mississippi, United States (Wikipedia (1), 2014)	Winter flooding leads to scour.	No collapse	0	0

ATTACHMENT D **BACKGROUND INFO SCOUR**

In this attachment, more information about scour, mainly about the different types of scour, is given.

Types of scour

Scour can in three different ways. These are natural scour, contraction scour and local scour. These all combined are called 'total scour' of a bridge. Besides the different types of scour, naturally occurring lateral migration of the streams within a floodplain may affect the piers and abutments. All of this will be explained below in more detail.

Natural scour (degradation and aggradation)

Natural scour can occur as degradation (erosion) and aggradation (deposition). Degradation scour is the general lowering of the streambed over a relatively long time, due to a deficit in sediment supply from upstream (Arneson, Zevenbergen, Lagasse, & Clopper, 2012). Although the lowering of the streambed because of degradation scour is a natural process, over a long time it may remove large amounts of sediment.

Besides degradation, aggradation can also occur. It involves the deposit of material eroded upstream of the bridge. Aggradation is not a type of scour, but can cause circumstances which contribute to scour. Deposits can cause a contraction of the water channel, which will lead to a higher stream velocity.

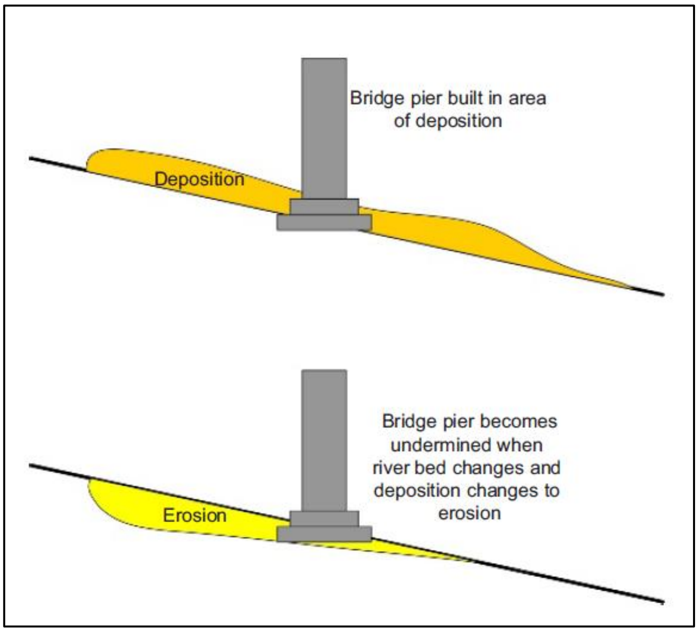

Figure 15 – Degradation and aggradation (Maddison, 2012)

Natural scour can lead to both changes in the plan and longitudinal section of the river. The effects on river crossings due to natural scour are undermining of the foundations and direct flows towards or behind the structure as seen in Figure 13Figure 13 – Degradation and aggradation .

As well degradation as aggradation is long-term and so may change over time. These changes may increase due to the result of natural processes like deforestation or human activities like urbanization. An engineer needs to carefully determine the current state of the stream and evaluate the potential future changes in the river system (Arneson, Zevenbergen, Lagasse, & Clopper, 2012).

Contraction scour (general scour)

Contraction scour is the process in which a channel narrows and the stream velocities increase (Kattel & Eriksson, 1998). It results in a lowering of the streambed across the stream or waterway bed at the bridge and so removes sediment from the bottom and sides of the river. The cause for contraction scour is the increase of speed of the streams, as it moves through a bridge opening that is narrower (contracted) than the normal river channel, the increase of the bed shear stress and therefore an increase in the frequency of bed movement (Maddison, 2012). This can be seen in Figure 14. (Kattel & Eriksson, 1998)

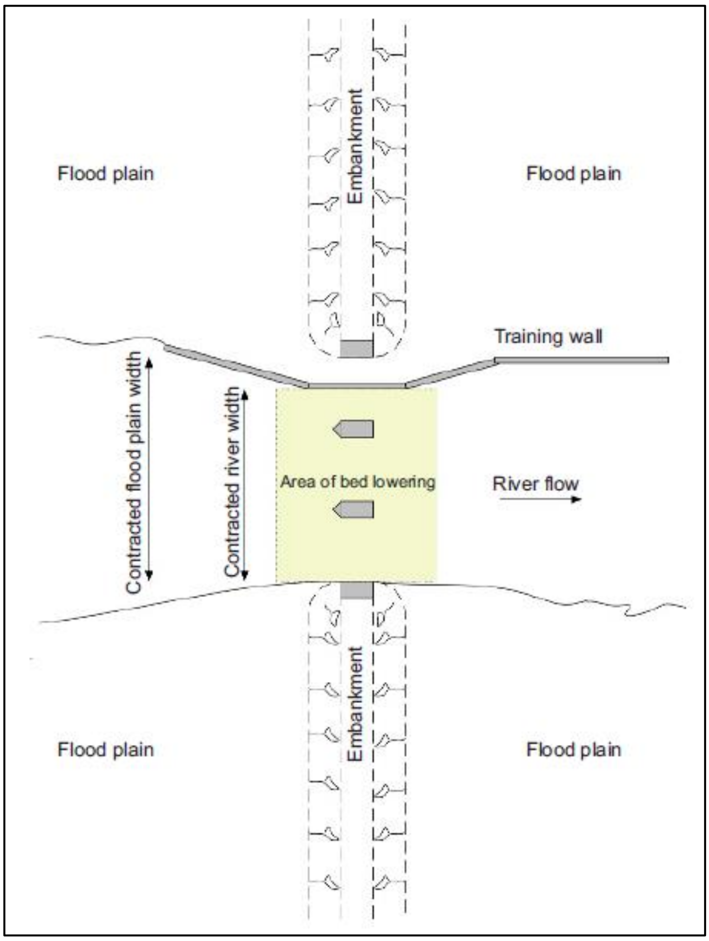

Figure 16 – Illustration of contraction scour (Maddison, 2012)

Contraction scour can occur because of three different ways: channel contraction, flood and plain estuary contraction and surcharging. Channel contraction is the width narrowing of the river channel because of the presence of a river crossing such as a bridge. With flood plain and estuary contraction run off from the flood plain is channeled through a bridge opening with a constant increase in flow velocity as the same quantity of flood water is channeled through a relatively small cross-sectional area. Surcharging happens when the soffit of the bridge is lower than the high water level during a flood period. Therefore, the water has a limited cross-section not only because of the narrowing of the bridge not only in his width, but now also in his height (Maddison, 2012).

Contraction scour does the same as natural scour, but the main difference is that contraction scour only occurs in the vicinity of the bridge, while degradation scour takes places over the whole river.

Local scour (or abutment scour)

Local scour involves removal of material from around piers, abutments, spurs, and embankments (Arneson, Zevenbergen, Lagasse, & Clopper, 2012). This type of scour is caused by an acceleration of flow past an obstruction and the subsequent turbulent water (vortices) (Kattel & Eriksson, 1998). The turbulence of the water will generally cause an uplifting effect at the nose, resulting in erosion of the bed. The material that is removed from this area is deposited behind the pier as the flow slows and turbulences are formed (Maddison, 2012). This can be seen in Figure 15.

At local scour, as the depth of scour increases, the strength of the turbulence of the water (vortices) is reduced, and thereby the amount of bed transport that takes place. This eventually ends up in equilibrium. For live-bed scour, this means that there is equilibrium between the bed material inflow and outflow and scouring ceases. For clear water this means scouring ceases when the shear stress caused by the vortices equals the shear stress of the sediment particles in the scour hole (Arneson, Zevenbergen, Lagasse, & Clopper, 2012).

Local scour can also occur because of rapid movement caused by boat propellers and water jet engines. This is a serious problem for harbour walls (Maddison, 2012).

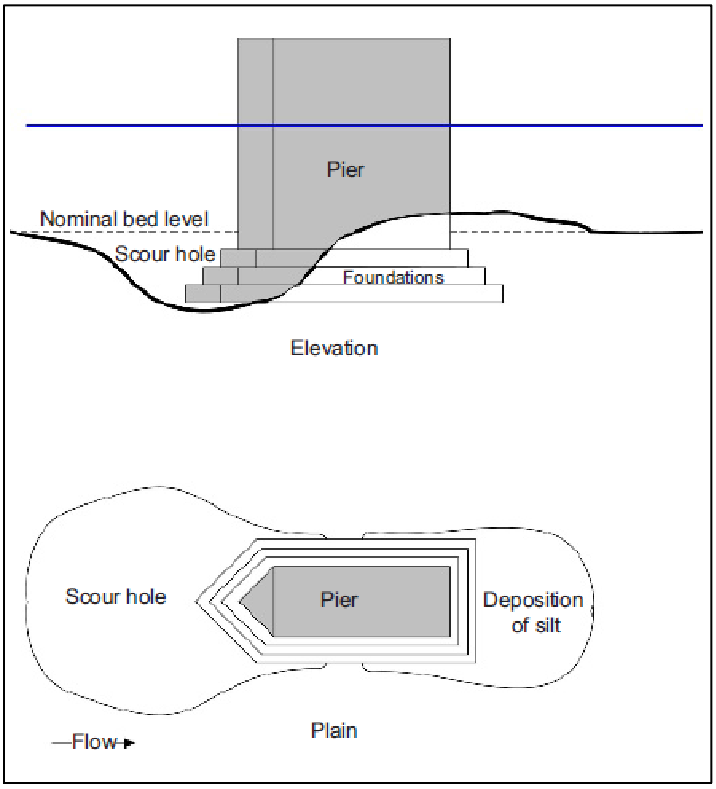

Figure 17 – Illustration of local scour (Maddison, 2012)

Lateral stream migration

Besides the different types of scour mentioned above, there is also a natural process which may affect the stability of the piers in a floodplain, erode the abutments, or change the total scour by changing the flow angle of attack the abutments and piers. Lateral stream migration is caused by factors that also have an effect on the stability of the bridge foundation. These factors are geomorphology of the stream, flood characteristics, characteristics of the bed and bank materials and location of the crossing on the stream. (Arneson, Zevenbergen, Lagasse, & Clopper, 2012).

Types of flow

For all three types of scour there are two conditions in which they can occur. These are clear-water and live-bed scour.

Clear-water

In case of clear-water, no sediment transport occurs upstream of the bridge. In other words, the water is clear. Although, there is also clear-water scour when the sediment upstream of the bridge is transported in suspension through the scour hole at less than the capacity of the flow (Arneson, Zevenbergen, Lagasse, & Clopper, 2012). At the bridge, bed material is removed because of the flow but no material is deposited from upstream. This results in scour holes that will remain present and can be seen by underwater inspection (Maddison, 2012).

Live-bed

In case of live-bed, sediment is transported from upstream the bridge through the contraction of the bridge. This type of scour is cyclic in nature which means that the developed scour hole during the rising stage of a flood is refilled again during the falling stage (Arneson, Zevenbergen, Lagasse, & Clopper, 2012). In the worst case, the bed underneath a pier foundation will become fluid. This type of scour may be very difficult to detect in contrary to clear water scour. When a diver wants to inspect the pier, the flow will have reduced the bed at a much higher level than the level of maximum scour during flood (Maddison, 2012).

Riverine versus coastal areas

Scour can occur in both coastal areas and riverine areas. The difference between these two areas lies in the types of flows that are present. In riverine areas, scour results from flow in one direction, which is downstream. In coastal areas, scour (may) result from flows in two direct, because of the tidal fluctuations that are present.

Besides the difference in the type of flows that occur in both areas, there is another big difference. Because of scour, in both areas the bed will lower resulting in an increase of the waterway. In tidal areas, this may result in an increase of the discharge. In riverine areas however, because of the principle of flow continuity, a constant discharge requires a velocity inversely proportional to the waterway will maintain (Arneson, Zevenbergen, Lagasse, & Clopper, 2012).

Soil, rock and geotechnical considerations

As mentioned before, different materials scour at different rates. Also mentioned before is that scour occurs when the hydrodynamic bottom shear stresses are higher than the material's critical shear stress. Therefore, hydraulic forces can be seen as a load and the engineering properties of the material as the resistance to it (Arneson, Zevenbergen, Lagasse, & Clopper, 2012).

The earth materials can be divided (in most general terms) in soil and rock. Soil can be cohesionless or cohesive. Cohesionless soils do erode particle by particle, and therefore scour occurs relatively rapidly. The maximum scour depth is reached within a period of a few hours to a few days, so some even say that in case of cohesionless soils, scour is not a function of time but occurs essentially instantaneously.

In case of cohesive soils, erosion also takes place particle by particle, but also block of particles by other particles as result of the cohesive properties of these soils. In contrary to cohesionless soils, the scour of cohesive soils is time dependent. After reaching the critical shear stress, the rate of erosion just increases slowly and is not, as in case with cohesionless soils, essentially instantaneously (Arneson, Zevenbergen, Lagasse, & Clopper, 2012). Scour can also affect rocks. In case of rocks, the rock density, abrasion resistance, slake durability and rock strength are important factors which contribute to scour in rock.

ATTACHMENT E INFO SCOUR QUANTIFICATION MODELS

In this attachment extra information about the vulnerability models explained in chapter 0 is given. For each model a couple of questions are answered and in some cases, extra model specific information is provided.

Model 1 - Vulnerability assessment of bridges exposed to scour (Tanasic, Ilic, & Hajdin, 2012)

Model specific information

As explained in chapter 0 this model calculates the risk of scour that a river crossing is exposed to. The risk is calculated by multiplying the probability of failure of the river crossing due to a scour event with the direct and indirect consequences as can be seen in equation 4.

$$\boldsymbol{R_i = P_{fi|S_e} * (DC_i + IC_i)} \qquad \textbf{Eq.4}$$

Where

- $P_{fi|S_e}$ = probability of failure due to a scour event
- DC_i = bridge_i – direct financial consequences
- CI_i = bridge_i indirect transport – related fail consequences
- R_i = vulnerability of bridge

The model is not clear in how it calculates the probability of failure, but clear is that it is based on the scour depth (equation 1). However, for the development of the methodology for the fragility curve and BBN risk model this is not very important. When realizing a real fragility curve or BBN risk model, it is.

The direct consequences are structural damage including repair costs required to return the damaged bridge to its original state as well as a loss in life and limb. The indirect consequences are the restricted or completely interrupted traffic flow for the road network users through analysed links including additional travel time and travel distance costs.

The indirect consequences can be calculated by calculating additional travel time costs, additional driving instance costs and changes in accident rates and associated total accident costs.

The additional travel time (TT) caused by a link failure is defined as:

$$\boldsymbol{\Delta TT_i} = \textstyle\sum_i \sum_{j \neq i} (\boldsymbol{c_{ij}^{(i)}} - \boldsymbol{c_{ij}^{(0)}}) \qquad \textbf{Eq. 5}$$

The additional travel distance (TD) caused by a link failure is defined as:

$$\boldsymbol{\Delta TD_l} = \textstyle\sum_i \sum_{j \neq i} (\boldsymbol{d_{ij}^{(i)}} - \boldsymbol{d_{ij}^{(0)}}) \qquad \textbf{Eq. 6}$$

The additional accident costs caused by a link are defined as:

$$\boldsymbol{\Delta AC = \sum(V_{m,t}^{(l)} - V_{m,t}^{(0)}) * ARC_t}$$

Eq. 1

In total the indirect consequences are then given by:

$$\boldsymbol{IC_i = \Delta TT_i * C_{TT} + \Delta TD_l * C_{TD} + \sum_t \Delta AC} \qquad \text{Eq. 7}$$

Is the model deterministic or probabilistic?
Data considered to the bridge geometry and soil characteristics may be considered as deterministic. Data considered to rainfalls that can cause floods and hydraulic data may be considered as probabilistic due to uncertainties and unavailability of the data.

What are the pros and cons of the model?
Pros:

- Does calculate the temporal aspect of scour (degradation of soil properties) instead of only using deterministic input.
- Model gives the probability of failure given the soil cover height at pier, what gives a more clear understanding then only mention the scour depth.
- The model is quite new.

Cons:

- Estimation of river bed level may highly differ from in situ conditions
- Debris potential is not mentioned in the method which may affect the realized scour depths.
- Only mention local scour.
- Not completely probabilistic.

How actual is the model (old – state of the art – state of science)?
The model is developed in 2012 so is really up to date.

Which programs are needed (open source, commercial, own programs)?
For the calculation of the scour depth distribution, a program which can perform Monte Carlo simulation is needed, such as Microsoft Excel. When interested in the risk of the bridge given scour, the program VISUM is needed to simulate a distribution of traffic flows.

What is the model accuracy?

- Errors can be made in estimating the parameters.
- Scour prediction is a very complex problem and therefore it is expected that most models will have a significant level of associated error

How much computation power is necessary?
Not much computation power is needed, as the only program that is used is VISUM and probably Microsoft Excel, which can run on almost every computer.

What data is needed?

- Data for calculating probability of failure.
- Data for calculating direct and indirect consequences.

Model 2 - Scour vulnerability evaluation of pile foundations (Park, Kwak, Lee, & Chung, 2012)

Model specific information

The model uses different equations for the calculation of scour as seen in chapter 0. When comparing the different equations, they all give different outcomes. The CSU equation predicts smaller scour depths in case large particle size exist at the river bed due to armouring effect. The Froehlich's equation considers inflow angle relatively larger than the Laursen's or Neill's equation does when calculating the scour depth. The Neill's equation at last considers only water depth and bridge pier with, and therefore the effect by the bridge pier width is relatively large. None of the equations was constantly giving larger or smaller values. The estimated scour depth in the end is calculated by taking the average of the four equations.

To determine in which specific class the vulnerability can be ranked, equation 2 has to be used. In this equation, as mentioned before, the vulnerability can be calculated with the safety factors or the bearing capacity. With the outcomes of equation 2, the scour vulnerability can be graded as each grade a specific value of the scour vulnerability (ξ) and safety factor after scour (S.F.) are needed. In Table 8, the values these parameters considering the grades are given.

Table 8 – Scour grading system

Grade 1	S.F. < 0	-
Grade 2	0 ≤ S.F. < 1	$\xi \geq 3$
Grade 3	1 ≤ S.F. < 2	$1,5 \leq \xi < 3$
Grade 4	S.F. ≥ 2	$1 \leq \xi < 1,5$

Is the model deterministic or probabilistic?

Data considered the geotechnical and structural characteristics may be considered as deterministic. This also applies to the data necessary for calculating the ultimate bearing capacity. Data considered the hydraulic and hydrological may be considered as probabilistic due to uncertainties and unavailability of data.

What are the pros and cons of the model?

Pros

- Model uses different equations for calculation of scour depth to get a more reliable outcome.
- Vulnerability can be calculated in different ways, which give the opportunity to check the models outcomes with each other.
- Include the temporal part of scour in fine-grained soil (degradation over time).

Cons

- Estimation of river bed level may highly differ from in situ conditions.
- Mainly focused on pier foundation (both spread footed and pile), while contraction scour is not mentioned.
- Meyerhof (1976) equation can only be applied to pile foundations.
- Not completely probabilistic.

<u>How actual is the model (old – state of the art – state of science)?</u>
The model itself is up to date, as it was developed in 2012. Some of the scour depth equations although, date from 1960, 1973 and 1988, which is relatively old. Though, the equations itself don't have to change over time, as scour back in those days was the same as now, so they are still very useful nowadays.

<u>Which programs are needed (open source, commercial, own programs)?</u>
The model does not need any specific program, although for the calculations, programs like Microsoft Excel or Matlab may be useful.

<u>What is the model accuracy? Any errors?</u>

- Errors can be made in estimating the parameters.
- Scour prediction is a very complex problem and therefore it is expected that most models will have a significant level of associated error.

<u>How much computation power is necessary?</u>
The model does not need specific programs that need a lot of computation power, so modern computers should be able to do the necessary calculations.

<u>Which data are needed?</u>
Data for calculating scour depth (specific parameters can be found in the papers):

- Hydraulic variables and hydrological variables (such as discharge, velocity and design for the design flood)
- Geotechnical and structural variables (such as general structural condition of the bridge, present degree of scour damage around bridge foundation and embankment, geomorphic properties of the watershed are, bed material properties (size, gradation, distribution and soil classification) and boring log information).

Data for calculating ultimate bearing capacity.

Model 3 - CAESAR (Palmer, Turkiyyah, & Harmsen, 1999)

<u>Is the model deterministic or probabilistic?</u>
In the model, only deterministic values are apparent, as the normally probabilistic hydraulic and hydrological parameters are not used in CAESAR.

<u>What are the pros and cons of the model?</u>
Pros:

- Can be used by field inspectors with little formal training in scour processes.
- Every evaluation is given in percentages, which gives a clear view about the current position of the bridge in general and against scour.
- Model does cover three components for scour and three components for stream instability.

Cons:

- Estimation of river bed level may highly differ from in situ conditions.
- Estimates of scour depth are not results of hydraulic engineering calculations.
- Model is completely deterministic.
- The temporal part of scour is not included.
- No data is given about the real scour depth that can occur.

How actual is the model (old – state of the art – state of science)?
The model dates from 1999 so it's quite old. Nevertheless, it is still useful for the determination of scour.

Which programs are needed (open source, commercial, own programs)?
The CAESAR model does have its own computer program.

What is the model accuracy? Any errors?

- No hydraulic or hydrological equations are included, which could affect the accuracy of the model.
- Errors can be made in estimating the parameters.
- Scour prediction is a very complex problem and therefore it is expected that most models will have a significant level of associated error.

How much computation power is necessary?
For the CAESAR model, a computer program is necessary, but as stated before, this program can already run in a Windows 95 environment and therefore not much computation power is needed to run it.

Which data are needed?
Static information needed for the CAESAR program in Table 9:

Table 9 – Static information required by CAESAR

Static information required by CAESAR	Primary use	System assistance with review or acquisition of information
Pier locations, foundation types, foundation elevations, pier shapes, as-built channel elevations	Inspectors use to determine critical foundation embedment level and to become familiar with the site. System uses information to determine severity of scour risk by analysing embedment, foundation location and change of embedment with time.	System help with photographs of foundation types, pier shapes and pier locations. Data are entered in a concise tabular format and a cross section is provided showing foundation locations, types and elevations.

Surface bed material Subsurface bed material	System uses as part of evidence factor for: foundation stability, contraction scour and long-term degradation.	System help with photographs with geologic surface and subsurface classifications.
Notes about maintenance work, hydraulic problems of scour problems	Inspectors use to determine if there are specific concerns noted by the maintenance staff or hydraulics staff.	Note: Editor feature allowing notes to be stores by dates: notes can be added, edited or deleted.
Historical inspection records	Inspectors use to identify changes at the bridge site by inspecting historical cross-section profiles, photographs, and site observables.	Cross-section plotting feature showing all historical cross-section profiles, site observables (including photographs) stored together for quick review.

Dynamic information needed for the CAESAR program in Table 10:

Table 10 – Dynamic information required by CAESAR

Dynamic information required by CAESAR	Primary use	System assistance with obtaining information
Presence of scour screamers	Program warns that scour screamers are serious problems and experts should investigate the bridge.	System help and background information about scour screamers.
Cross-section profile	Inspectors use to determine magnitude of lateral and vertical thalweg stability. System uses to determine severity of total scour, lateral stream migration, thalweg migrations and vertical stream degradation.	Cross-section plotting tool, allowing several reference points to be used as datum. Multiple cross-sections can be plotted simultaneously.
Site photographs	Inspectors use to visually record site conditions and compare with visual observations of previous inspections.	Photograph storage and retrieval feature providing photograph zoom ability.
Erosion severity and location	System uses to assess lateral stream migration and vertical stream instability.	System help with photographs of erosion severity.
Point bar location, size and vegetation	System uses to assess potential for lateral stream migration.	System help with photographs of point bar type and vegetation.
Instream bar location, size and vegetation.	System uses as part of evidence for: contraction scour and lateral stream instability.	System help with photographs of point bar type and vegetation.
Abutment specific data: countermeasure presence, serious observables scour, historical scour problems	System uses to assess scour risk and potential for scour at abutments.	System help with photographs of abutment conditions and severity.
Pier specific data: countermeasure presence, serious observables scour, historical scour problems	System uses to assess scour risk and potential for scour at piers.	System help with photographs of pier condition and severity.

ATTACHMENT F LIST OF VARIABLES

In this attachment a list of variables for model 1 and model 2 is given. Variables for model 3 are not mentioned as these are very general.

Vulnerability assessment of bridges exposed to scour (Tanasic, Ilic, & Hajdin, 2012)

- y_s = predicted scour depth (m)
- a^* = equivalent pier diameter (m)
- y = hydraulic depth (m)
- V = mean flow velocity (m/s)
- V_c = critical velocity (m/s)
- D_{50} = median sediment diameter (m)
- t = peak flood duration (h)
- f_1 = flow-structure interaction
- f_2 = flow-sediment interaction
- f_3 = sediment-structure interaction
- t_e = time to reach equilibrium scour depth (h)
- q_{max} = bearing capacity
- q_{ini} = initial foundation to soul contact pressure
- sf_1 = ductility limit
- sf_2 = exhausting of bearing capacity
- Sc = soil cover height
- $c_{ij}^{(i)}$ = travel time from origin *i* to destination *j* under normal network conditions
- $c_{ij}^{(0)}$ = travel time from origin *i* to destination *j* under modified network conditions
- $d_{ij}^{(i)}$ = travel time from origin *i* to destination *j* under normal network conditions
- $d_{ij}^{(0)}$ = travel time from origin *i* to destination *j* under modified network conditions
- AC = accident costs
- $V_{m,t}^{(l)}$ = volume on link *m* of type *t* in network conditions with link *l* severed
- $V_{m,t}^{(0)}$ = volume on link *m* of type *t* in normal network conditions
- ARC_t = accident costs per traffic volume on link of type *t*
- C_{TT} = the willingness to pay for a unit travel time reductions
- C_{TD} = the average costs for driving a unit distance

Scour vulnerability evaluation of pile foundations (Park, Kwak, Lee, & Chung, 2012)

- Q_u = ultimate bearing capacity
- c'_V = effective overburden pressure at pile tip with the depth limit to 20D (pile diameter)
- N_q = bearing capacity factor as function of friction angle (ϕ) of the soil
- N_c = bearing capacity factor for cohesion
- A_p = cross-section area of pile
- f_s = frictional resistance along the shaft of each layer

  - For cohesionless soils: $K_s c_V tan\partial$
    - $K_s = 1.4(1 - sin\phi)$
    - c_V = average effective overburden pressure along the shaft
    - ∂ = 20 degrees
  - For cohesive soils: ac_u
    - a = adhesion factor
    - c_u = undrained shear strength of soil
- A_s = pile shaft surface area of each layer

ATTACHMENT G **INFO MODEL ASSESSMENT**

In this attachment additional information concerning the model assessment discussed in section 4.4 is given.

Vulnerability assessment of bridges exposed to scour (Tanasic, Ilic, & Hajdin, 2012)
This model is a model that calculates the vulnerability of bridges with a couple of given equations. It even calculates the risks of bridges to scour, which means that the probability of failure of a bridge given a scour event is multiplied by the costs this failure will give.

To determine the vulnerability of bridges to scour, the model first of all calculates the scour depth, with the Sheppard & Melville equation (1) (Sheppard, Demir, & Melville, 2011). With a Monte Carlo simulation, a distribution of the maximum scour depth is calculated. The equation is pretty straightforward and the relations between the different factors are therefore clear. The inputs for the equations are both deterministic as probabilistic variables.

In the model the failure modes due to scour are caused by either the superstructure (deformation capacity is exhausted, in other words, ductility limit has been reached) or by the soil bearing capacity (bearing capacity of soil has been reached).

When looking at the pros and cons of the model, the most important con is that the model only mentions local scour. Still, the input that is given for local scour can be used for as well the BBN and the fragility curve.

Scour vulnerability evaluation of pile foundations (Park, Kwak, Lee, & Chung, 2012)
This model is a model that calculates the vulnerability of bridges to scour considering the change of bearing capacity of the soil resulting from scour. The model can be used for both spread footing foundations and pile foundation. The model does not calculate a probability of failure but gives an indication of how vulnerable a foundation may be to scour.

The vulnerability is divided into four grades, where grade 4 is not vulnerable and grade 1 very vulnerable. The bearing capacities are determined by hydraulic, hydrological and geotechnical variables. This also counts for the calculations of scour depth. For the determination of the vulnerability also structural variables are needed.

The model does provide the Meyerhof (1976) equation (3) for determination of the ultimate bearing capacity. For the determination of scour depth, four equations are given: CSU equation of HEC-18 (Richardson & Davis, 2001), Froehlich's equation (1988), Laursen's equation (1960) and Neill's equation (1973). Because of these different equations, the relations between the different factors that contribute to scour are very clear. The inputs for the equations are both deterministic as probabilistic variables.

When looking at the pros and cons of the model, the model only looks to local scour.. Contraction scour is not mentioned. Furthermore, the Meyerhof (1976) equation (3) can only be applied to pile foundations. Still, the input that is given for local scour can be used for as well the BBN and the fragility curve.

CAESAR (Palmer, Turkiyyah, & Harmsen, 1999)

This model is a model that calculates the vulnerability of bridges with a program called Cataloging And Evaluation of Scour Risk and River (CAESAR). This program generates a lot of output, such as the evidence/likelihood of scour at pier and/or abutments and the ability for pier and/or abutment to resist scour.

The input that the model needs is divided into static information and dynamic information. The static information includes information that does not change over time such as structural information and geotechnical information. Dynamic information is information that does change over time (in the model each time of inspection) such as the cross-section profile and the current state of erosion.

The model is based on a Bayesian Network. This means that the input that the model gets is input generated by engineers and inspectors. The input is based on the engineers and inspectors own 'belief'. The way the program calculates the vulnerability and other outputs is not clear. But what is clear, is that the estimations of scour depth are not results of hydraulic engineering calculations.

When looking at the pros and cons of the model it doesn't become clear how the model calculates the vulnerability, and therefore the relations between all the different variables are not known. Furthermore, no exact values for an intensity measure are generated.

ATTACHMENT H **INFO FRAGILITY CURVES**

In this attachment extra information about the fragility curves explained in chapter 5 is given. This contains more general information about fragility curves and the different approaches that can be taken for the development of fragility curves.

Additional general information

As this research concerns a risk-based approach, uncertainty is a key player. In models from chapter 0, the parameters are known, but the exact data values and the accuracy of the models are uncertain. Although these uncertainties, it is still possible to determine the sensitivity of river crossing to scour. Fragility curves are a useful tool to determine this sensitivity to variation of the different parameters (Roca & Whitehouse, 2012).

In contrary to deterministic approaches, fragility curves assume that there is no critical value where the probability of failure jumps from zero to unity. In reality a system such as a bridge may even fail when the critical value is not reached. Besides, it could also be that the system is not failing even though the critical value is reached (Aristotle University of Thessaloniki, 2011). Therefore, the shape of a fragility curve is S-shaped as seen in Figure 18. An S-shaped curve is appropriate when there is uncertainty in the system (Schultz, Gouldby, Simm, & Wibowo, 2010).

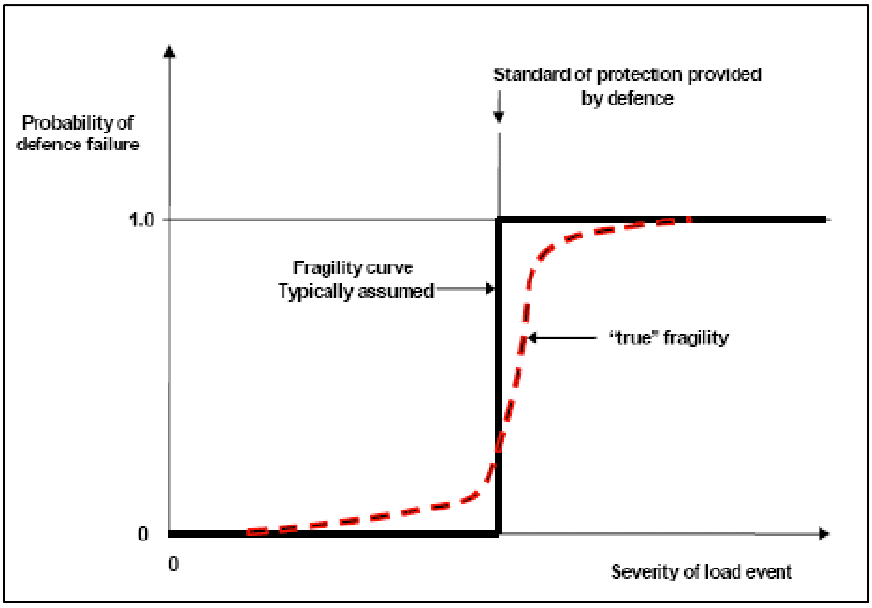

Figure 18 – Typically assumed fragility versus "true" fragility (Roca & Whitehouse, 2012)

Fragility curves can be based on expert judgment, analytical analysis and empirical data. Expert judgmental fragility curves are based on the expert's opinion. Here the reliability is questionable due to the dependence on the individual experience of an expert. Empirical fragility curves rely on data from previous events. The problem is the unavailability of statistical data. Analytical analysis fragility curves are mostly based on numerical modeling. A combination of these methods can also occur. What method is chosen depends on the scale of study area, the availability of data, the quality of the data and the local technology (Aristotle University of Thessaloniki, 2011).

The data needed for fragility curves depends on what type of intensity measure is chosen and what time of system is exposed to this. In this case, it would mean that for determination of the scour depth hydraulic, hydrological, geological and structural data is needed (Roca & Whitehouse, 2012).

An exceeding of critical value does not always mean that the system will fail like seen in Figure 18. In case of scour, exposure of the buried foundation does not always mean that failure will occur. When for example one pile of a pile footed foundation is exposed, the other piles can be still able to carry the load, and therefore, the foundation won't fail. Besides other structural conditions, the exposure can also be transient. This means that the probability of failure also depends of the time that the foundations are exposed (Roca & Whitehouse, 2012). Even though, the probability of failure that is mentioned in fragility curves still doesn't have to mean that the structure will collapse. The term failure is a relative term that means that the capacity of a structure provided to a certain designed level of service has been exceeded (sometimes probability is therefore called 'probability of unsatisfactory performance') (Schultz, Gouldby, Simm, & Wibowo, 2010). This is also called the serviceability limit state which describes the moment a structure fails to meet the technical requirements for use, even though it may be strong enough to remain standing (Wikipedia (2), 2014). In chapter 5 also can be found that different damage states can be seen as different serviceability states.

Following exposure to a load, structures may have mutually exclusive damage states based on local and global parameters of the structure. This is in order to identify the structure's performance (damage) state and to construct the fragility curve based on the relation between the damage index and intensity parameter. The damage index is the amount of damage that has been done to the structure regarding a certain amount of the intensity measure. The intensity measure is the trigger that will lead to damage to the structure. With these two combined, a fragility curve can be developed.

The damage states most of the times describe different fragility curves for slight, moderate, severe and complete damage (collapse) as mentioned in chapter 5 before. These damage states can vary for different topics, but in general the minimum is two and the maximum is six damage states (Aristotle University of Thessaloniki, 2011). Risk assessors are typically more interested in the probability that a structure will be in one of the several possible damage states rather than have only a probability of failure. An example of fragility curves with different damage states can be seen in Figure 19.

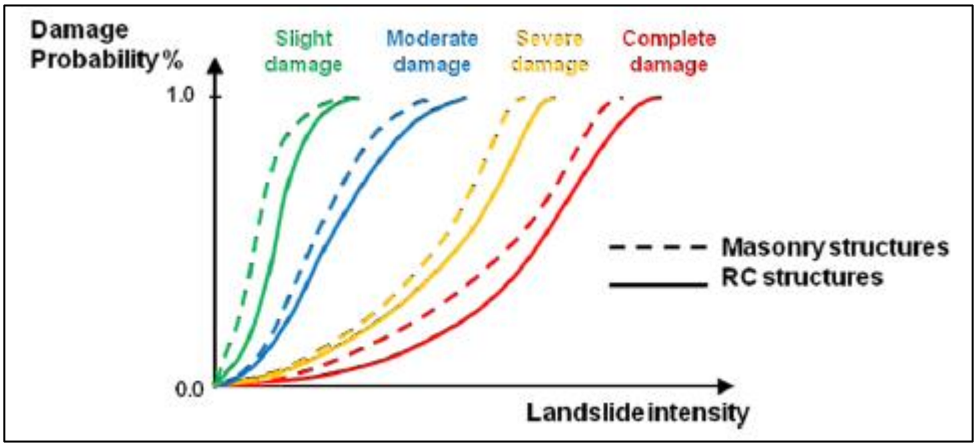

Figure 19 – Fragility curves for different damage states (Aristotle University of Thessaloniki, 2011)

Approaches for development of fragility curves

The approaches used for the development of fragility curves, as mentioned earlier, judgmental, empirical, analytical and a hybrid form. What approach is chosen, depends on the scale of study area, the availability of data, the quality of the data and the local technology (Aristotle University of Thessaloniki, 2011). In Table 11 (Schultz, Gouldby, Simm, & Wibowo, 2010)the main advantages and disadvantages of each approach are given.

Table 11 – Advantages and disadvantages of the different approaches to develop

Approach	Advantages	Disadvantages
Judgmental	Not limited by data or models. Fast and cheap method if consequences of potential inaccuracy are small. Useful check on other fragility estimates.	Difficult to validate of verify. Subject to biases of experts. Not auditable. Cannot improve over time.
Empirical	Data may come from either controlled or natural experiments. Useful and flexible if data are available.	Data can be scarce and source specific. Experiments can be expensive. Difficult to validate independently of the dataset. Difficult to extrapolate fragility curves to other structures.
Analytical	Based on physical models that can be validated and verified, enhancing transparency. Easier to extrapolate results to new situations. Facilitates a distinction between aleatory and epistemic uncertainty.	May be based on simplifications and assumptions. Requires the availability of data and models. More time consuming to implement. Requires a higher level of training.
Hybrid	Limitations of any particular approach can be overcome with a complementary approach. Modeling results and observations can be combined to improve the "robustness" of fragility estimates using Bayesian updating.	Limitations are the same as the individual approaches.

ATTACHMENT I **INFO BBN**

In this attachment extra information about the BBN explained in chapter 6 is given. This concern the determination of the probabilities of the heavy rainfall used in the BBN risk model.

Determination of probabilities of heavy rainfall

For the determination of the probabilities of heavy rainfall used for the BBN risk model, data from Koninklijk Nederlands Meteorologisch Instituut (2013) from the Netherlands is used. This data can be seen in Table 12.

Table 12 – Rainfall in the Netherlands in mm (Koninklijk Nederlands Meteorologisch Instituut, 2013)

		Full days				
		1	2	4	7	10
Chance of occurrence	10 times a year	15,5	20	0	0	0
	5 times a year	22	27	0	0	0
	2 times a year	29	36,5	46,75	60,25	70,5
	1 time a year	34,5	42,5	53,75	68,25	82,75
	1 time per 2 years	40,25	50	62,25	79	94,5
	1 time per 5 years	49	57,75	73,75	91,25	109
	1 time per 20 years	56	67,25	82,75	101,75	118,25
	1 time per 50 years	63,5	75,75	92,25	111,25	128,5
	1 time per 100 years	73,75	87,25	103,75	123,75	140,25

In the table can be seen that the probabilities are divided into nine probabilities of occurrence. However, floods are caused by heavy rainfall and not by light or moderate rainfall. For this reason, the rainfall that occurs one time per two years and less is taken into account for this research.

The amount of rainfall is furthermore determined for different amount of time it's raining. In Table 12 can be seen that the rainfall falling in one day, is always the most. When taking the average of the amount of rainfall of more days, we see that the rainfall per day is less. Therefore, in this research the amount of rainfall on one single day will be used for the determination of the probabilities of floods. To clarify what information will be used, the information can be found in Table 13.

Table 13 – Rainfall per day in mm used for the determination of probabilities for floods

		Rainfall per day (mm)
Chance of occurrence	1 time per 2 years	40,25
	1 time per 5 years	49
	1 time per 20 years	56
	1 time per 50 years	63,5
	1 time per 100 years	73,75

For the BBN, we use the probability of occurrence of each type of rainfall to determine the probabilities in our network. For the research, a single rainfall is interesting, as they induce floods. To determine the probabilities, for each type of rainfall is determined what the change of occurrence is per one year. As these chances of occurrence don't get up to 100% together, all of these chances are multiplied by a factor that does take the total up to 100%. These values will be uses in the BBN as seen in Figure 14. The data can be found in Table 14.

Table 14 – Chance of occurrence per year of each type of rainfall

		Chance of occurrence per one year	Chance of occurrence per one year for BBN
Chance of occurrence	1 time per 2 years	50%	64,1%
	1 time per 5 years	20%	25,6%
	1 time per 20 years	5%	6,4%
	1 time per 50 years	2%	2,6%
	1 time per 100 years	1%	1,3%