Scour risk assessment at river crossings

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Abstract

Transport networks are large infrastructure projects that traverse long tracks of land and normally include many stream crossings. One of the main natural risks to river crossings is scour of the riverbed. Scour may expose the foundations of bridges or other infrastructure, or buried assets, making them vulnerable to failure causing undesirable social, operational and environmental impacts.

This paper presents the framework and methods to develop a probabilistic scour risk assessment using fragility curves to account for uncertainty in input variables, prediction methods and performance of structures. Understanding the risks associated with possible movements of the riverbed, both in the vertical and lateral directions, is fundamental to provide an evidence base to define future management actions and strategies. The analysis includes the assessment of existing protection works, such as bed sills, and their impact in reducing the risk of scour.

Keywords

Scour, river crossing, bridge scour, risk assessment, probability of failure

1. Introduction

Assets in transport infrastructure systems such as roads, highways and railways, or in telecoms and power networks such as cables and pipelines, traverse long tracts of land and often include many stream or river channel crossings. The assets may cross over water with their foundations in, or adjacent to, the channel, or they may cross under the channel (tunnels, buried cables or pipelines). The flow hydraulics in active channels with erodible boundaries give rise to vertical and lateral movements of the channel that may undermine the foundations of bridges (Figure 1) or aerial crossings, or directly expose buried assets. The design process will engender each asset with functional requirements with respect to crossings which can be justified through calculation and/or monitoring.

Failures of the transport infrastructure may lead to severe disruptions of the network causing undesirable social, operational and environmental impacts. Examples of recent failures in Europe are the large number of bridges destroyed during the Cumbria floods in 2009 in UK causing loss of life and extensive traffic disruption, the Margarola bridge in Spain that failed in 2006 due to the interaction with the scour at a nearby bridge, causing two casualties, and the Hintze Ribeiro bridge in Castelo de Paiva in Portugal that collapsed in 2001 due to general degradation of the river bed, because of dredging, causing 60 casualties.

Figure 1: Example of failed bridge due to scour

The following classification provides an overview of the main mechanisms that may cause failures at river crossings. It takes account of the scale of the change, at stream, river crossing or structure scale, and whether the mechanisms depend or not on the presence of a structure in the river such as bridge piers, abutments or protection works. It is based on work presented in Melville and Coleman (2000) by those authors and Shen et al. (1981).

Table 1: Processes that may cause structure failure at channel crossings

	Stream scale	River crossing scale	Structure scale
Irrespective of the existence of a structure	Aggradation/degradation Change of stream pattern	Bend scour Confluence scour Bed-form migration	
Due to the presence of a structure		Contraction scour	Local scour

General scour includes several mechanisms mentioned in Table 1 that may occur at different spatial and temporal scales such as: aggradation and degradation, bend scour, confluence scour, scour related to bed-forms, bank erosion, etc. General scour occurs irrespective of the presence of any human-imposed structure although certain types of general scour such as degradation can be prompted by human interventions in the river such as mining or dredging. Development of general scour depends on river morphology and the discharge time-series.

The change of the stream pattern is related to the river morphology and includes all the changes that relate to the planform shape of the river, such as meander growth, cut-offs, river metamorphosis (change of river typology, for example, from meandering to braided), and avulsions (change of location of main channel in a valley).

The above two processes, general scour and the change of the stream pattern, may happen at long temporal scales (order of years) and also at shorter scales related to flood events. They may worsen the conditions at the vicinity of the river crossing; therefore, a not very extreme flood may have a larger impact than expected because of the previous gradual deterioration of conditions at the river crossing.

The presence of a bridge, river training works or any other structure at a river crossing may cause contraction scour if there is a restriction of the width of the stream.

Local scour occurs around piers, abutments and protection works. It develops due to the obstruction of flow caused by bridge foundation elements or by changes in flow structure and bed and bank characteristics caused by protection.

Foundations of structures or buried asset that become exposed unexpectedly are susceptible to impact damage, corrosion and a variety of hydraulic loading conditions that may lead to failure depending on variables related to:

- the type of exposure: such as the depth of foundation exposed or the length of buried asset exposed;
- the aggressiveness of the environment: such as flow velocities and characteristics (size, shape, density) of the material transported by the river;

Despite the undesirable consequences associated with structural failures at river crossings, it is rare that sufficient funds are made available to undertake all necessary improvement activities at river crossings. It is in the face of limited budgets that difficult decisions must be taken in order to decide how and where limited resources should be invested and, conversely, where intervention is not financially justified. Understanding risks along transport networks is fundamental to their operation and provides an evidence base to define management actions and strategies.

The aim of this paper is to present developments to create a general framework to quantify scour risks at river crossings in long transport infrastructures. Approaches to risk assessment for river channels are discussed by May et al (2002) and should form part of a clear approach to inform asset management. In the past, many assessments of risk of scour along transport networks have been based entirely on expert judgment. Such assessments by different experts may not be consistent given their background on hydraulics, engineering or geomorphology. In general, it is difficult to use such assessments to prioritize river crossings or to determine an absolute risk at a river crossing. The methodology developed to estimate the probability of failure due to scour at river crossings aims to be repeatable, as much as possible, independent of the user, and easy to update as more information or better knowledge becomes available. General statements about the application of the method are also provided.

2. Definition of risk concepts

The risk of failure of a structure at a river crossing can be defined [Porter et al, 2004] as the probability of failure multiplied by the consequences if that failure occurs (equation 1):

$$R = P \times C = H \times V \times C \qquad (1)$$

where R is the risk, P is the probability of failure, H is the hazard likelihood, V the vulnerability and C the consequences of the failure.

The hazard, H, describes the source of potential failure, in this case the scour related to the mobility of the river channel. The mobility of the river is a function of a range of factors with a probabilistic variation, such as water discharge, and others which have a deterministic description, such as sediment characteristics.

The vulnerability, V, is the susceptibility of the structure or, in other words, the chance of failure due to the impact of a given hazard (mobility of the river). In the particular case of bridges, vulnerability is defined by the bridge geometry such as location in relation to the river flow, depth and type of foundation. In the case of buried assets the vulnerability is defined by their material properties, the depth of foundation, the thickness of cover over the buried asset and set-back distance from the channel.

The consequences, C, of a failure may be expressed using different metrics such as:

- loss of life
- disruption time, expressed as the time that the structure (road or pipeline) remains closed
- delay time, the time to travel along an alternative route avoiding the river crossing
- replacement, repair and enhancement costs
- environmental impacts.

In this paper we present a method to evaluate the probability of failure, P. The consequences if such a failure occurs, necessary to formally evaluate the risk, are not included here.

Traditionally, design practice has estimated the scour risk at river crossings from a deterministic point of view and using some sensitivity analysis to give confidence in the selected design [CIRIA et al, 2007]. The deterministic approach uses single values for input variables, giving a single value as an output. When applying a sensitivity analysis, the above method is repeated with a range of input values. As it is stated in CIRIA et al (2007) a risk-based approach accounts for uncertainty instead of assuming that data values and prediction methods are known precisely. This type of approach does not require necessarily complex analysis. Fragility curves could be a useful tool to assess the sensitivity of failure to variation of different parameters.

Fragility curves (Figure 2) describe the relation between loading and probability of failure, in this case applied to a flood defence structure such as an embankment. The same principle can be applied to transport infrastructure performance. A deterministic approach assumes that there is a critical loading (e.g. a water discharge) for which any loadings below that critical value, the probability of failure is zero and for loadings exceeding that value the probability is unity. This is represented by the “simplified“ step function in Figure 2. In reality, a system (such as a bridge structure) might have a very small, but non-zero, probability of failing under a load smaller than the critical value with this probability increasing as the loading increases. Further, it may happen that a system does not fail even when the critical loading is exceeded. This means that the actual shape of the fragility curve is more likely to be S-shaped as indicated by the “true” curve in Figure 2.

The development of fragility curves can be based on empirical data, expert judgment or on structural reliability analysis including Monte Carlo simulations [HR Wallingford 2007]. For example, in the flood industry in the USA expert judgment fragility curves for a flood defence are established considering two critical water levels: the level for which the embankment is not very likely to fail with a 15% probability value of failure and the “probable failure point” for which the embankment has an 85% likelihood of failure.

Failure, defined as the inability to achieve a defined performance threshold, depends thus, on the loading conditions (hydraulic and morphological parameters) and the strength characteristics of the structure. It should be noted that the exposure of a foundation does not necessarily imply the failure of that foundation. An example is provided by buried assets: they can be exposed due to development of scour in a river crossing although this does not necessary imply that the asset will cease to function as expected or fail allowing ingress of sediment and water or a release of the product being transported. Parameters such as the length of exposed pipeline and the structural condition influence the final probability of failure. Exposure can also be transient, for example, due to scour developed during a flood event. Therefore the time that foundations or assets are exposed also influences the final probability of failure.

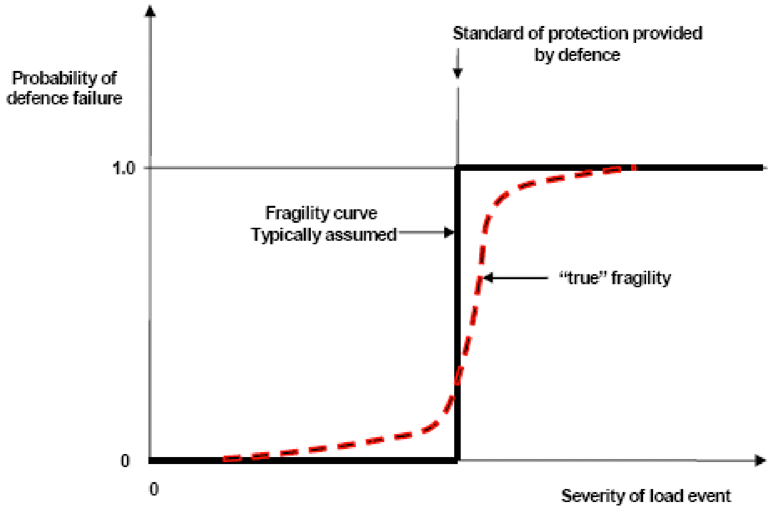

Figure 2: Example of a simplified and "true" generic fragility curve for flood defences

Traditional strategies for managing flood risk have been based on knowledge from historical floods events and focussed on reduction of flood hazard. The application of probabilistic techniques allowed a change of strategies where the desired safety levels are chosen based on acceptable probabilities of flooding [Roca and Glasgow, 2010]. In this context of flood risk, the Environment Agency in the UK has applied several probabilistic techniques at different levels to estimate the annual probabilities of flooding across the country in order to assess their management interventions. Following this approach, the methodology presented in this paper does not aim to estimate the risk associated with a particular event but, instead, to all possible events in order to obtain an annual probability of scour failure at each river crossing. This annual probability can then be compared to chosen thresholds to establish the necessary management strategies.

3. Overview of the method

The methodology to estimate the annual probability of scour failure at river crossings is summarized in Figure 3. The first step determines the relation between water discharge and the annual probability of such an event happening. Each water discharge is associated to a return period, T, thus, to a probability, p, of such discharge being exceeded in one year, $p = 1/T$. This information can be obtained from hydrological studies at catchment or regional level or from national datasets (such as the one developed by the Centre for Ecology and Hydrology (CEH) for the Environment Agency in UK).

In the second step, the main processes that contribute to the vertical mobility of the channel for each river crossing are identified (namely those described in Table 1) and scour is estimated for each event considering the specific equations and taking into account the hydraulic parameters of the flow and the geometric characteristics of the structure at the crossing. When applying the methodology to real examples, well-known and established equations are used. It is possible to update the equations to estimate scour and also to refine calculations as more information about the river crossing becomes available, for example detailed size composition of the bed material or an updated survey of the river channel cross-section.

The amount of scour calculated for each event is compared with the depth of foundation or thickness of cover and related to a probability of failure through a fragility curve. As mentioned in the previous section, fragility curves are developed to predict the probability of failure under the action of variable loadings.

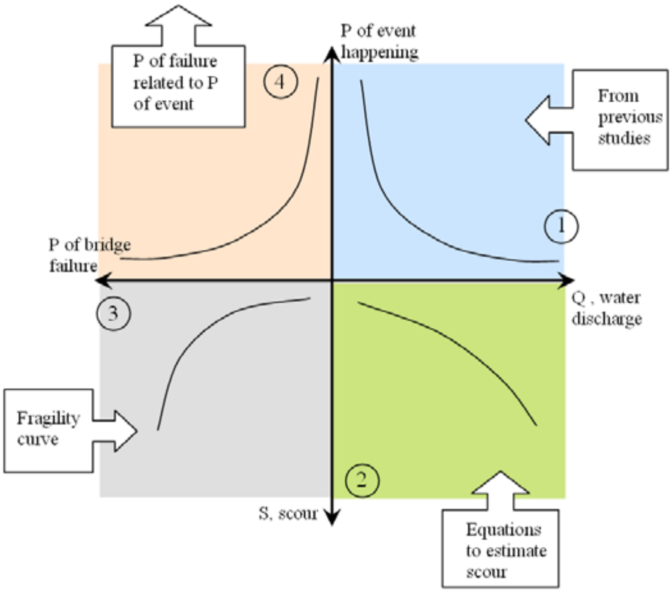

Figure 3: Overview of the methodology to estimate the annual probability of bridge failure

It is important to consider again that the probability of failure is also related, along with the hydraulic and morphologic parameters, to the structural parameters of the structure (type of bridge foundation such as spread foundations or piles or the material strength of the buried asset).

The final output of this calculation is a relation between the probability of an event and the probability of failure if such an event happens. The integration of that curve provides the annual probability of failure. Events with a very low water discharge but a high probability of occurrence have a low probability of failure. On the contrary, events with a high discharge but an exceedingly low probability of occurrence have a high probability of failure. The annual probability of failure at the river crossing is estimated by integrating the area below the curve (Figure 4). In this case the annual probability of failure is 0.14.

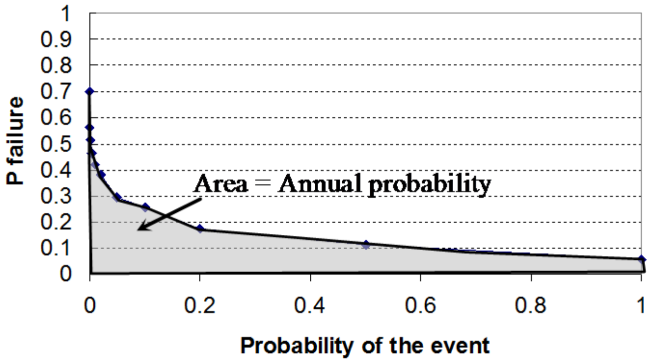

Figure 4: Annual probability of exposure

The overall annual probability of failure of the transport network is estimated considering the probability of failure at each river crossing and, assuming that possible failures at different crossings are independent, so the overall probability is calculated using equation (2) that shows how to combine the probabilities of two river crossings, A and B.

$$P(A \cup B) = P(A) + P(B) - P(A \cap B) = P(A) + P(B) - P(A)*P(B) \tag{2}$$

We note that this may not be the case where there are multiple crossings of the same reach of a river channel, in which case the failures on that reach may be dependent. The main inputs of the method are the usual ones to estimate the relevant flow parameters related to each return period: water discharges, obtained from hydrological studies, channel cross-sections and longitudinal bed slopes, obtained from surveys or known topography and roughness coefficients, based on photographs and field visits. The depth of foundations or cover in the case of buried assets should be known or estimated from surveys. Unfortunately, in the majority of the cases of bridges there is a lack of knowledge of the foundation depth. For example, Defra (2012) states that foundations of medieval road bridges and 19th century railway bridges, the most common bridge type in UK are generally unknown and so, also, is their vulnerability to scour.

4. Influence of protection works

The presence of protection works is designed to change the relation between scour and the probability of failure of the infrastructure, as protection “delays” the possible exposure of foundations or other buried assets by controlling the channel position and increasing the hydraulic load needed to fail the protection.

Failure of a protection structure is defined as a certain change of it’s state that is reflected in the contours of the structure (e.g. loss of foundation on a bank protection), the cross-section (e.g. loss of riprap on a bed sill) and integrity of constituent elements (e.g. deterioration of gabion wires). CIRIA et al (2007) have identified failure mechanisms of rock bank protections such as slope instabilities, sliding, movement of rock cover, migration of sub-layers, etc. Melville and Coleman (2000) identified four mechanisms of failure of bridge riprap protection that can also be common on bed sills:

- shear failure, whereby riprap stones cannot withstand the down flow;
- edge failure, whereby instability at the edge of the coarse riprap layer and the bed sediment initiates a scour hole beginning at the perimeter and working inward until it destabilizes the entire layer;
- winnowing failure, whereby the underlying finer bed material is removed through the voids in the riprap layer;
- bed forms, whereby fluctuations of the bed level caused by migrating bed forms under live-bed conditions undermine the riprap.

Most of these failure mechanisms are related to flow characteristics (such as discharge, flow velocity and water levels) and also to geotechnical characteristics (such as density of materials or pore water pressure).

The methodology developed to estimate the risks arising from scour at river crossings considers the influence of existing protection works in the field. So far, two failure mechanisms, shear stress and edge failure, have been considered in terms of resistance of protection to hydraulic shear and generation of a falling apron. In our experience they have been identified as the most common mechanisms of failure in many cases. Other mechanisms such as winnowing could be avoided with the proper design of filter layers or geotextile between the protection and bed material. Although not specifically assessed in our methodology the proper design of protection should always consider the specific requirements for underlayers that provide a filter function.

In a river crossing with protection works, the probability of failure of the protection is estimated in the first instance. This probability is then multiplied by the probability of failure due to scour (without protection) to obtain the total probability of failure. The same framework presented in Figure 3 can be used to estimate the probability of protection failure. In this case, instead of estimating scour related to each flood event, step 2 estimates different parameters that define the loading actions in the fragility curves used in step 3. The parameters consider whether the failure mechanism is shear stress or scour at the edge and whether the material of the protection is riprap or gabions and mattresses. The following table summarizes the parameters considered to define the probability of failure of protection works.

Table 2: Parameters to define probability of failure of protection works

	Type of Material	
Mode of failure	Riprap	Gabions and mattresses
Shear stress	D_{stable} / D_{field}	v_{field}/v_{stable}
Scour at the edge	V_{stable} / V_{field}	S/W_{field}

The subscript “field” indicates the real value of the parameter for a particular protection work in the field (or as designed) whilst “stable” indicates the required value of the parameter to be stable considering each flood event. D_{stable} is the stable diameter of riprap calculated with the Escarameia and May (1995) equation and D_{field} is the real diameter of riprap in the field. v_{field} is the flow velocity in the field and v_{stable} the threshold velocity for stable material defined by CIRIA et al (2007). When scour is developed at the toe of bed protection, the riprap material may roll down the slope and pave it (falling apron), preventing further erosion. For this to occur, the volume of material contained in the riprap bed sill, calculated as the length of protection multiplied by its thickness must be sufficient to spread along and cover the slope developed. In this case thus, V_{stable} is the volume of material need to pave the slope created when scour develops at the edge for each flood event and V_{field} is the existing volume of material in the field. If gabions or mattresses are used, the relation between the scour developed, S, and the width of the protection in the direction of the flow, W_{field}, is used to define failure.

Once the parameters defined in Table 2 are calculated, step 3 (in Figure 3) is taken to estimate the probability of failure based on fragility curves. In the case of riprap protection, the original experimental data from Escarameia and May (1995) has been used to develop the fragility curve of a riprap bed sill considering the flow shear stress as the loading condition. According to the fragility curve developed, there is a 50% probability of failure when the real diameter of the riprap is equal to the estimated stable size. The probability only reaches 100% when the real size is one third of the estimated stable size. Conversely, there is a 30% chance of the protection failing even when the real size is larger, i.e. 1.3 times, that of the estimated stable size of the riprap. The fragility curve of gabions and mattresses protection works have been developed based on information provided by Macaferri (2011), the experimental data reported in Escarameia and May (1995) and expert judgment. Fragility curves related to edge failure mechanism have been developed in a similar way to the ones related to shear stress failure.

5. Application of the method

The method has been developed and applied in FUTURENET which is a research project that addresses the issue of identifying vulnerabilities in transport infrastructure to climate change. The London-Glasgow transport corridor including highways and railways is the focus of the project. In such a corridor, the increased risk of bridge failure due to climate change is studied applying the risk approach detailed above.

In the first instance when performing a risk assessment, it is necessary to assemble all possible historical data about the different crossings. This has proved to be a very challenging exercise, for example, to determine the depth of foundations of several bridges. This exercise stresses the benefits of maintaining accurate data bases collecting all relevant data such as available reports, inspections observations, design and as-built drawings and photographs. Historical data can also be used to calibrate the fragility curves used in the method.

Water discharges associated with different probabilities (return periods), which are one of the main inputs required by the method, have been obtained from regional hydrologic studies and national data bases. Their uncertainties are likely to have a great impact on the results of the risk assessment. Geometric information about the river cross-section and longitudinal slope can be obtained from surveys or existing DTM. The most difficult information to obtain without field visits is the geometry of the structures (due to the lack of general databases with bridge information) and protection works.

When applying the methodology it is recommended to follow a tiered approach with different levels of analytical rigour. To avoid having to carry out detailed analysis on low risk rivers crossings, these crossings should be identified in the first level, using a simplified version of the probabilistic method, with minimum inputs and computation requirements. In the second level, the method detailed above is applied to the river crossings identified as having a risk higher than an agreed threshold. In a third level, river crossing having a potentially unacceptable risk are studied in more detail and possible options to reduce the risk are developed.

In the case of two contrasting crossings, the initial assessment at one crossing determined that failure was possible, which required a second level assessment. The combination of new input data confirmed the probability of failure as $8.4 \cdot 10^{-5}$ and it was decided to monitor for the next year. At the second crossing there were protection works in place. In their current condition they were demonstrated to have benefit as the probability of failure without the works was $6.8 \cdot 10^{-3}$ and this was reduced to $3.2 \cdot 10^{-4}$ with the protection.

In some cases the results of the risk assessment challenge existing conclusions and hence they provide a good basis for re-evaluating previously held knowledge and judgments.

The methodology appears to be useful in providing results that, together with other sources of information, helps to define future management actions and strategies. This includes structural maintenance or upgrading, maintenance or upgrading of scour protection and other river bed control structures, and monitoring against set targets for river channel position and profile.

6. Conclusions

The paper presents the framework and outline method to develop a probabilistic scour risk assessment using fragility curves to account for uncertainty. The methodology developed is a step forward to determine, in a quantitative and analytically rigorous way, the risks of scour failure at river crossings. However, the results of the probabilistic method should not be used in isolation but should be interpreted taking into account all the information available at each river crossing, including historical data.

The method presented evaluates the probability of failure. It does not yet take into account the consequences of such a failure. The methodology contains assumptions and limitations that could be improved in the future, such as fragility curves or the incorporation of more protection failure mechanisms. The methodology has been designed in a way that specific improvements or modifications can be easily incorporated.

The fragility curves to assess the probabilities of protection failure are based on laboratory data, existing information and expert judgment and further research will improve their reliability. The method does not take into account any deterioration of the protection, hence it considers that the main parameters of the protection do not change during the year.

The main value of the method developed is its ability to compare the relative risk of failure between crossings so providing both a means of identifying and prioritising the management activities.

7. Acknowlegments and thanks

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