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A framework for probabilistic assessment of clear-water scour around bridge piers

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ABSTRACT

Scouring at the base of bridge piers is the major cause of bridge collapses worldwide. Computing the scour risk of bridge foundations is therefore key for a correct management and allocation of resources for maintenance and scour mitigation works. Existing risk-assessment models compute the vulnerability of bridge foundations to scour by comparing the equilibrium scour depth associated with peak-flow discharges characterized by a given return period (usually of 100–200 years) with the critical foundation depth of the bridge. This approach neglects completely the history-dependent and time-dependent nature of scour. Yet, it is well known that bridge collapses can often be induced by the accumulation of scour during multiple flood events.

This study aims at developing a novel probabilistic framework for the computation of bridge-pier vulnerability to scour using a Markovian approach to account for memory effects in scour development. The paper focuses on the case of local pier scour occurring in clear-water conditions whereby cumulative effects are significant, well understood and known to be the cause of recent reported bridge collapses.

A simplified numerical example consisting of an idealised bridge pier in a canal is considered to clarify the application of the proposed framework and to shed light on the effects of some assumptions introduced to simplify the probabilistic scour assessment.

1. Introduction

Scouring of pier and abutment foundations has been widely recognized as the main cause of bridge collapse and damage, causing significant direct and indirect losses to the infrastructure system of rail and road networks [1]. In general, scour can be divided into different components: general aggradation-degradation (long term and short term), contraction, and local scour [2]. Local scour, which is the object of this paper, is caused by turbulent vortices forming at the base of bridge foundations impinged by a river current. Local scour can occur in so-called clear-water and live-bed conditions, which are characterized by the absence and presence of sediment transport in the undisturbed flow upstream of the bridge, respectively. Major floods usually tend to establish both types of scour, with live-bed conditions occurring at high flow rates and clear-water conditions occurring at low flow rates of an hydrograph [3–5]. Scour holes that develop under live-bed conditions are commonly subjected to refilling, before being eroded again during the recession limb of the hydrograph, when clear-water scour can be established.

In engineering-design practice, scour prediction is typically based on the evaluation of the equilibrium scour depth associated with a discharge of a given return period. The equilibrium scour depth is defined as the asymptotic scour depth that a pier (or an abutment) experiences after a long exposure to a steady flow. Typical design events adopted in US and in UK are those with a return period of 100 yrs or 200 yrs [1,6]. However, it should be acknowledged that during its service life a bridge is exposed to a large range of flood-hydrographs, some of which may have peaks exceeding the discharge corresponding to the assumed design-return period. Moreover, many others will be smaller but still capable of causing scour at the bridge within the service life.

In the last decades, several methodologies have been proposed for evaluating bridge vulnerability to scour (see e.g. [7,8]). Most of these frameworks are based on two strong assumptions: 1) the scour depth that results from exposure to a single flood event is independent from past events, 2) attainment, within a flood event, of the equilibrium scour depth for the given flood discharge, corresponding to assuming a stationary hydrograph of infinite duration

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[9–11]. However, a more rigorous assessment of vulnerability to scour should consider the fact that short duration floods or floods of minor intensity may not result in the critical scour depth of a system being exceeded, but they may cause partial erosions, making it easier to reach the maximum scour depth during the subsequent flood.

Very few studies have relaxed the assumption of independence of scour events by proposing a more accurate modelling approach that accounts for memory effects in the scour process. In this context, Van Noortwijk et al. [12] addressed stochastic modelling of scour accumulation but their work relies on the equally strong hypothesis of independent and stationary gamma-distributed scour increments from one flood to another. Johnson and Ayyub [13] and later Brandimarte et al. [14] and Briaud et al. [15] developed probabilistic frameworks for the scour temporal evolution that are based on the Monte Carlo simulation of a set of hydrographs for the service life of the bridge and the evaluation of the corresponding statistics of the scour depth. In Johnson and Ayyub [13], the sample storms are generated based on the information given by partial duration series and the scour formulae utilised in the model are targeted to sand and gravel beds. In Brandimarte et al. [14] and Briaud et al. [15] a stochastic process is fitted to the historic record and used to generate replicates of hydrologic series with the same statistical properties as the observed streamflow sequence. The SRICOS-EFA method [16], developed for cohesive soils, is then used to calculate the scour depth associated with each replicate of the hydrologic record and thus to derive the scour statistical distribution.

A simpler approach to the problem at hand could be based on Markovian modelling [17], i.e., on the assumption that the susceptibility to increase (or eventually decrease) scour during one event, given the features of the flood, depends on the scour level accumulated until the occurrence of the event itself, rather than on the entire flood and scour history. This paper follows this approach and illustrates a probabilistic framework for scour risk assessment which is capable of describing the scour progression over time by accounting for the occurrence of subsequent flood events. In particular, the scour progression is evaluated by combining the results of flood hazard analysis, providing the description of the uncertainty in the flood occurrence, intensity, and on the hydrograph shape, with that of hydraulic analysis, providing the information on the scour temporal evolution for an event of a given intensity. The proposed approach also allows accounting for the uncertainties in the scour prediction formula and in the measurement of the initial scour hole, which is useful when the scour risk of existing bridges needs to be evaluated.

In general, the aim of the study is to present a novel probabilistic approach that allows for the probabilistic assessment of scour by taking into account key temporal effects associated with scour evolution in time during a single flood event and scour accumulation as a consequence of multiple floods. The analysis is restricted to the case of local scour in clear-water conditions and this is justified by three reasons: firstly, multiple floods inducing clear-water conditions do lead to cumulative erosion as refilling processes do not take place as in live-bed conditions [3,18]. Secondly, during an individual flood event clear-water scouring evolves much more slowly than in live-bed conditions, whereby the attainment of the equilibrium scour depth associated with the peak flow is not such a stringent hypothesis [2–5,18]. Thirdly and most importantly, contrary to common belief, the scour accumulation associated with multiple floods having a very low return period, and hence presumably inducing clear-water scouring, have been documented as an important cause of multiple bridge failures [19], meaning that the problem investigated herein is very relevant from a practical point of view. Recent works in the literature have also stressed the fact that the problem of scour accumulation under multiple clear-water flood events has not received sufficient attention to date (see e.g. [20]). The rest of the paper is structured as follows. Next section illustrates the general framework for probabilistic scour assessment. Subsequently, the hydrologic, hydraulic and scour analysis steps are described in detail. Finally, a simplified numerical examples is considered to show the application of the proposed scour assessment procedure and evaluate the importance of some factors such as the initial scour state, temporal effects, and memory effects.

2. Framework for probabilistic scour assessment

The evaluation of the failure probability of bridges exposed to scouring can be cast in the form of a time-variant reliability problem, where one aims at estimating the first-passage probability of exceeding one or more limit states related to the bridge performance during the design life time. The performance function for a single limit state can be written as [21]:

$$G(t) = R - S(t) \tag{1}$$

where t denotes the time, whose initial value is assumed equal to zero, $S(t)$ is the time-variant random variable describing the scour depth at time t, and R is the bridge capacity, i.e., the critical level of scour that corresponds to the attainment of the limit state. If the collapse limit state is of interest, in the case of a bridge with shallow foundations R can be assumed to coincide with the foundation depth. More in general a structural analysis is required to obtain an accurate estimate of the effects of scour and of the critical scour levels that induce failure in bridges. This analysis is out of the scope of the present study, which focuses on the evaluation of $S(t)$, as discussed in the next section.

Under the assumption of deterministic capacity, the instantaneous probability of failure of the bridge at time t, can be expressed as [22]:

$$p_f(t) = P[G(t) \leqslant 0] = P[R \leqslant S(t)] = 1 - P[S(t) \leqslant R] = 1 - p_s(t) \tag{2}$$

where $p_s(t)$ denotes the survival probability at time t.

Flood events can be assumed to occur randomly in time. In particular, the time t can be discretized in intervals of fixed width equal to one year, and the probability of having $N = n$ flood events in the time interval $[0,t]$, i.e., $P[N(t) = n]$, can be described by an occurrence model. Accordingly, the probability of failure over the time interval can be expressed through application of the Total probability theorem as:

$$P_f(t) = 1 - \sum_{n=0}^{\infty} P\left[\max_{k=1,2,\ldots,n} S_k \leqslant R\right] \cdot P[N(t) = n] \tag{3}$$

where S_k denotes the scour depth at the time after the occurrence of the k flood event.

The evaluation of the probability of failure due to scour thus reduces to the computation of $P\left[\max_{k=1,2,\ldots,n} S_k \leqslant R\right]$. The relevant probability distribution can be obtained by combining the information provided by hydrologic analysis, hydraulic analysis of the flow in the channel, and scour analysis. Fig. 1 shows the conceptual flow chart of the probabilistic scour assessment through its intermediate steps. Hydrologic analysis provides the input to the hydraulic model, which in turn provides the input to the computation of scour. It is noteworthy that in some situations it may be important to account for the changes induced by scouring on the channel reach and bridge properties. For example, the development of a significant scour hole may induce also significant changes of the hydraulic parameters and flow profile for a given flow discharge. Such effects are neglected in the study, which focuses the analysis on local scour and hence assumes that the initial channel and