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A Stochastic Framework of Risk Assessment of Flooding on Stability and Serviceability of Bridges Under a Changing Climate

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Abstract. Over time, the Earth's climate has undergone significant changes due to a variety of natural processes. During the last century, global warming has drastically increased due to human activities, which has in turn increased the greenhouse gases in the atmosphere causing an increase in global average temperature. Under a changing climate, extreme events such as floods are expected to be more severe in intensity and frequency in some regions, which in turn, could significantly impact the performance and functionality of infrastructure assets. Particularly, the built environment (bridges, roads, buildings, etc.) surrounding rivers is impacted in some regions under a changing climate, increasing the risk posed to people and assets, posing challenges in maintaining the functionality of the built environment. To address this concern, proposing a comprehensive framework under a changing climate becomes essential to evaluate the stability of a bridge due to scour and the vulnerability of the surrounding areas due to overtopping floods under a changing climate. The approach involves flood frequency analysis to determine the flood levels, their respective return periods and annual exceedance probability, in addition to determining the scour estimates corresponding to these return periods under a changing climate. Subsequently, risk assessment protocols are implemented to evaluate the bridge's performance due to scouring and the surrounding areas' vulnerability in response to overtopping floods under a changing climatic conditions. Furthermore, employing stochastic methods, particularly the Poisson process, allows for the stochastic investigation of the bridge's probability of experiencing service disruptions due to scouring in a changing climate.

Keywords: Climate Change, Stochastic process, Floods, Scouring, Risk Assessment.

1 Introduction

Climate change signifies fundamental modifications in the Earth's climatic trends, resulting in global warming, rising sea levels, environmental impacts, and extreme weather events. In this context, river discharge values in some areas are expected to increase under a changing climate due to long-term shifts in weather patterns [1]. The weather changes (temperature and humidity), materials of construction, and degree of maintenance affect the lifespan of infrastructure assets. In this context, bridges could suffer a loss in their serviceability due to progressive deterioration (corrosion, fatigue, creep, etc.) [2,3] and they also might suffer a sudden loss in their serviceability due to shock-based deterioration (extreme events) [4].

Floods are the main cause of bridge failures due to a range of factors, e.g., scouring, hydrodynamic loads and pressures on the deck and piers, overtopping, and debris accumulation [5,6]. In the 20th century, floods were responsible for 6.8 million deaths from natural disasters across the world [7]. In this context, scouring is the main cause of bridge failures and is influenced by river discharge values, in which the removal of sediment around the piers reduces the stiffness and the bearing capacity of the bridge foundation, resulting in structural failure.

Bridges crossing rivers are designed to maintain their serviceability based on a design flood level of a pre-determined return period of historical floods which are determined using different probability distributions [8]. In this context, flood frequency analysis estimates the frequency of occurrence of extreme events, and relates the magnitude of extreme events to their frequency of occurrence [9]. In this context, floods are expected to increase in frequency and intensity in some regions under a changing climate, inundating floodplains and adjacent lands, leading to losses in agricultural lands and infrastructure assets.

This paper proposes a framework to approach stochastically the stability and serviceability of bridges in the face of floods under a changing climate. The objectives of this paper are as follows.

- Approach the random nature of floods occurrences.
- Evaluate stochastically the stability of bridges due to local scour under a changing climate.
- Evaluate stochastically the serviceability of bridges due to the interruption of traffic circulation due to floods under a changing climate.

This paper is organized as follows. Section 2 presents the methodology. Section 2.1 illustrates the local scour which is the structural failure mode applied in this study. Section 2.2 illustrates the flood frequency analysis applied to determine the evolution of the design flood level and under a changing climate. Section 2.3 illustrates the stochastic process applied in this study to consider the random nature of floods, presents the probability of the bridge being out of service and its probability of failure, and presents the risk assessment of floods. Section 3 introduces the case study. Section 4 presents a comprehensive analysis of the results of the applied methodology.

2 Methodology

The proposed methodology investigates stochastically the impact of floods on the structural failure of bridges due to local scour and the serviceability of bridges corresponding to the flood levels under a changing climate. Section 2.1 illustrates the flood frequency analysis method applied to the case study (Gumbel distribution), which was determined to be the best fit for the case study as determined recently in [10]. Section 2.2 illustrates the structural failure due to local scour.

2.1 Flood Frequency Analysis

Gumbel distribution [11] estimates the peak discharge values and probability of exceedance for return periods of extreme hydrological events, such as floods. The probability of flood event exceedance P_T for a given return period T , writes:

$$P_T = 1 - \left[e^{-e^{\ln\left[\frac{T}{T-1}\right]}} \right] = \frac{1}{T} \quad (1)$$

where Y_T is the reduced variate.

The annual peak discharge of a flood X_T for a return period T , writes:

$$X_T = \mu + \left[\sigma \times \left[\frac{Y_T - \mu_R}{\sigma_R} \right] \right] \quad (2)$$

where μ is the mean of the sample, σ is the standard deviation of the sample, μ_R is the reduced mean which signifies the location parameter, and σ_R is the reduced standard deviation which signifies the scale parameter. Detailed illustrations of the values of the reduced (mean and standard deviation) are discussed in [12].

The equation of frequency analysis $X_{T(UL,LL)}$ indicates the confidence limits CI for the annual peak discharge values of a flood X_T to account for the uncertainties of climate projections which are presented in mean and standard deviation, writes:

$$X_{T(UL,LL)} = X_T \pm [CI \times S_e] \quad (3)$$

$$S_e = \sqrt{1 + 1.3 \left[\frac{Y_T - \mu_R}{\sigma_R} \right] + 1.1 \left[\frac{Y_T - \mu_R}{\sigma_R} \right]^2 \left[\frac{\sigma}{\sqrt{N}} \right]} \quad (4)$$

where S_e is the probable error of the distribution which depends on the dispersion (standard deviation σ) of the sample, the sample size N , and the values of the reduced mean and reduced standard deviation.

2.2 Local Scour

The HEC-18 model was developed at Colorado State University [13] and is recommended by the United States Department of Transportation Hydraulic Engineering [14]. The local scour depth D_s , writes:

$$D_s = 2HK_1K_2K_3K_4 \left[\frac{b}{H} \right]^{0.65} \left[\frac{V}{[gH]^{0.5}} \right]^{0.43} \quad (5)$$

where H is the flow depth, b is the pier width, K_1 is the pier shape coefficient, K_2 is the angle of attack coefficient, K_3 is the bed condition coefficient, K_4 is the bed material coefficient, V is the mean flow velocity, and g is the gravity acceleration.

2.3 Risk Assessment

Stochastic Approach

The occurrence and magnitude of floods are random. Consequently, a stochastic Poisson process is used to simulate various scenarios of flood occurrences exceeding the design flood level under a changing climate. The number of floods $N = \{N_t: t \in [0, \infty]\}$ is defined as a Poisson process by supposing that floods are shocks of a sequence of independent, identically distributed random variables. The stochastic flood arrivals $f(t)$ simulates several flood scenarios occurrences with shock sizes ξ_i exceeding the design flood level. The stochastic flood arrivals, writes:

$$f(t) = \sum_{i=1}^{N_t} \xi_i \quad (6)$$

This approach is used to stochastically simulate and investigate the impact of climate change on the functionality and serviceability of the bridge as follows.

- The annual maximum river discharge value exceeding the magnitude of the design flood level.
- The structural failure due to local scour.

The probability of the bridge being out of service $P_s(t)$ considers the evolution of flood levels under a changing climate interrupting the bridge functionality in means of traffic circulation. The probability of bridge failure $P_f(t)$ considers the impact of local scour depth on the stability of the bridge.

$$P_{(s,f)}(t) = 1 - \sum_{t=1}^t \sum_{i=0}^n \frac{(\lambda t)^i}{i!} e^{-\lambda t}, n \in [0, t], \lambda \in [\lambda_s, \lambda_f] \quad (7)$$

where n presents the number of shocks, λ_s is the rate of flood arrivals exceeding the flood design level, and λ_f is the rate of scour depth exceeding the foundation depth under a changing climate.

Scour Risk Assessment

Scour risk assessment of bridges crossing rivers is determined by the priority rating. The scour risk assessment assesses the risk of scour based on a relation between the scour depth and foundation depth F_d , informing recommended actions to mitigate the likelihood of bridge failure due to scour.

The priority rating PR , writes:

$$PR = 15 + \ln \left[\frac{D_s}{F_d} \right] + R_T + F_T \quad (8)$$

where R_T is the river type coefficient and F_T is the foundation type coefficient.

Table 1. Scour risk assessment [15].

PR	Risk	Recommended action
16-21	High	Detailed Hydraulic Assessment. The structure is included in the flood warning plan or establishing protection works.
14-15.9	Medium	A repeat of assessment and underwater exams every 3 years (where necessary). The priority should be reviewed following the protection works.
10-13.9	Low	A repeat of assessment every 6 years and underwater exams every 3 years (where necessary). The priority should be reviewed following the protection works.

3 Application

3.1 Case Study Description

The case study is a dual-span bridge located in the United Kingdom with one pier of 2 m width and 1 m spread foundation depth. The bridge is designed to maintain its serviceability of a 200-year return period with a flood design level value of $114.19 \text{ m}^3/\text{sec}$ [16].

3.2 River Flow Projections

Optimistic (RCPs 2.6) and pessimistic (RCPs 8.5) projections scenarios from 2011 to 2095 are considered in this study to investigate the impact of climate change on the stability due to scour and serviceability due to floods causing interruption of circulation for the case study bridge. In this study, the KNMI-RACMO22E regional climate model is used to assess the impact of climate change on the stability and serviceability of the case study bridge.

4 Results and Discussions

4.1 River Flow Projections

Fig. 1 presents the optimistic (RCPs 2.6) and pessimistic (RCPs 8.5) climate change scenarios. The observations indicate a higher maximum annual river discharge values under more pessimistic climate change scenarios.

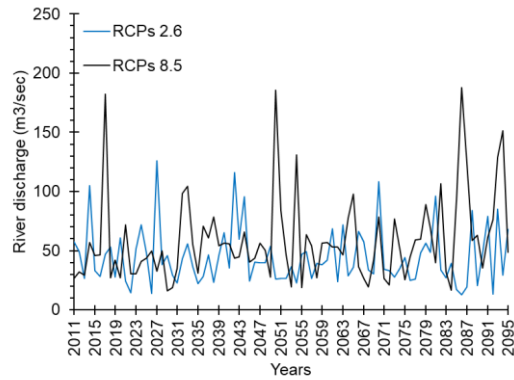


Fig. 1. River flow projections [10].

4.2 Flood Frequency Analysis

Fig. 2 presents the evolution of the maximum annual river discharge values, return periods, and annual exceedance probability. The results indicate the evolution of floods under a changing climate, in which higher flood levels with higher probability of exceedance are expected in the future under a changing climate.

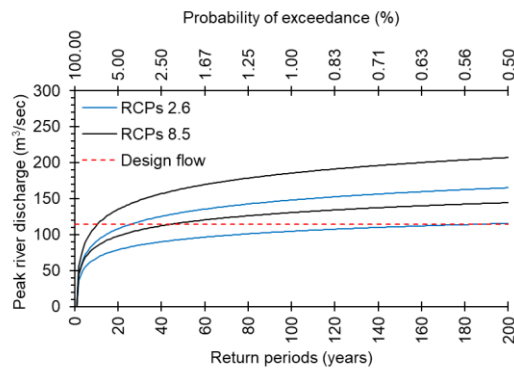


Fig. 2. Flood frequency analysis under a changing climate [10].

4.3 Scour Estimates

Fig. 3 presents the scour estimates under a changing climate, in which a higher occurrence rate (Table 2) is expected for more pessimistic scenarios. In addition, considering the 200-year flood levels, the scour estimates consistently exceed the foundation depth. This indicates that exceeding the design flood level, the bridge fails.

Table 2. Occurrence rate.

<i>Climate change scenario</i>	Occurrence rate
RCPs 2.6	0.02
RCPs 8.5	0.08

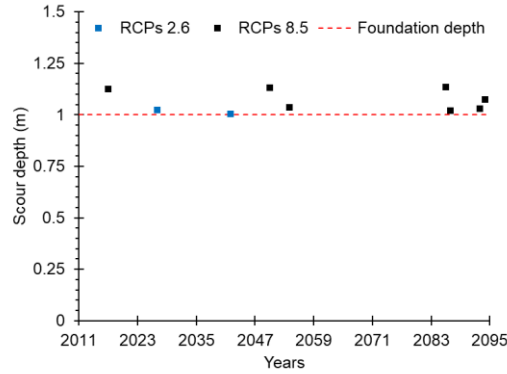


Fig. 3. Scour depth estimates.

4.4 Risk Assessment

Stochastic Results

Structural Failure

Scour estimates are stochastically simulated (Eq. (6)) based on the scour occurrences rate (Table 2) to consider the variability which is presented as Upper Limit (UL) and Lower Limit (LL) based on the quartile method [17] and to investigate the probability of failure due to scour depth exceeding the foundation depth (Eq. (7)). Table 3 indicates a higher failure rate for more pessimistic climate change scenarios.

Table 3. Failure rate.

<i>Climate change scenario</i>	Failure rate (λ_f)
RCPs 2.6 LL	0.01
RCPs 2.6 UL	0.02
RCPs 8.5 LL	0.05

Fig. 4 presents the likelihood of failure due to local scour (Eq. (7)). The results indicate a higher likelihood of failure due to scour for more pessimistic climate change scenarios.

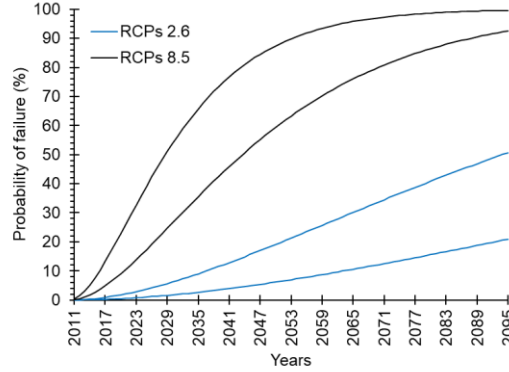


Fig. 4. Probability of failure due to stochastic scour estimates.

Serviceability

A stochastic investigation is performed to account for the random nature of floods based on their annual exceedance probability to represent their impact on the traffic crossing the bridge (Eq. (6)). Fig. 2 presents the probability of exceeding the design flood level (Eq. (7)), in which the serviceability of the bridge is impacted when exceeding the design flood level under more pessimistic climate change scenarios. The results of the stochastic simulations in Table 4 present a higher annual exceedance probability of floods exceeding the flood design level under more pessimistic climate change scenarios.

Table 4. Serviceability rate (%).

<i>Climate change scenario</i>	<i>Serviceability rate (λ_s)</i>
RCPs 2.6 LL	0.52
RCPs 2.6 UL	3.7
RCPs 8.5 LL	9.1
RCPs 8.5 UL	2.2

The probability of the bridge being out of service due to flooding events interrupting the traffic circulation due to exceeding the flood design level in Fig. 5, indicates a higher risk for more pessimistic climate change scenarios, in which the high variability in exceeding the design flood level is due to the high variability in the annual exceedance probability.

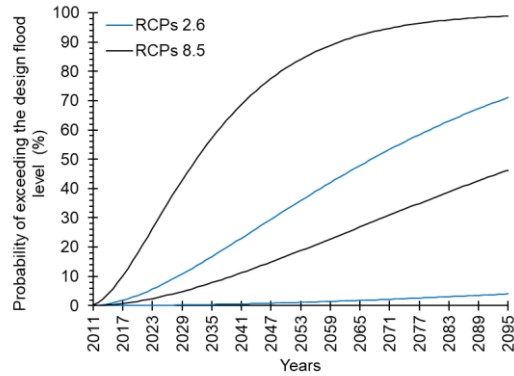


Fig. 5. Probability of exceeding the design flood level (Stochastic simulations).

Scour Risk Assessment

Exceeding the foundation depth as presented in Fig. 3 and as determined from the evolution of the 200-year flood levels under a changing climate, both results of scour estimates present a priority rating value of a range between 16 to 21 which indicates a high risk due to scour. In this context, the recommended actions are mentioned in Table 1.

5 Conclusions

Under a changing climate, the annual exceedance probability and flood levels are expected to increase for the case study. Exceeding the design flood level, a higher probability of failure and a higher probability of the bridge being out of service due to interrupting the traffic circulation are found under more pessimistic climate change scenarios.

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