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Shock Degradation Process to Assess the Reliability of Bridges Subjected to Scouring and Climate Change

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ABSTRACT: Climate change impacts the infrastructure in several ways. In the particular case of bridges crossing rivers, climate change may have a direct impact on the river discharge and, consequently, may modify the bridge scouring patterns. The significance of the scouring phenomenon is related to its effect on the reliability of the bridge since the structure's capacity rapidly decreases due to local scour causing sudden failure. Therefore, estimating the impact of climate change on the scouring risk is important within the context of bridge reliability analysis. This problem is addressed in this paper by introducing a Lévy process shock degradation model to present the changes within the scour depth of a typical bridge considering several Representative Concentration Pathways scenarios (RCPs). The scour depth is calculated using the HEC-18 Design model and the threshold of failure is considered the foundation depth. This paper presents the impact of climate change on the structure's safety, the results present the independent rapid decrease in the structure's capacity, the long-term availability, the expected lifetime of the bridge before failure, the probability of failure, and the Priority Rating Ratio of the bridge due to local scour.

1. INTRODUCTION

Reinforced concrete infrastructure systems are critical assets for the socio-economic development of any country, in which designing and maintaining these assets for a particular life span have been recognized as critical issues worldwide (Bastidas-Arteaga 2018).

The life span of infrastructure assets depends on their purpose, materials of construction, traffic flow intensity, and degree of maintenance. In the case of bridges, the life span may extend up to 100 years with a design that ensures high durability of the structure. However, the life span of infrastructure assets progressively decreases when the structures are subjected to different forms of deterioration, e.g., corrosion, fatigue, creep, etc. (Truong et al. 2023).

In addition, the life span of infrastructure assets is also affected by external forms of deterioration caused by natural hazards and extreme events.

Natural hazards and extreme events have the potential to significantly impact the structure's durability and are expected to increase in intensity and frequency due to climate change (Bastidas-Arteaga and Creach 2020). For instance, precipitation will be becoming more volatile and intense due to the increase in temperature, changes in aerosol patterns, and the shift of air and ocean currents will lead to more intense floods.

Over time, the climate has changed considerably due to a wide variety of natural processes, e.g., (Plate tectonics, volcanic activity, variations in the earth's orbit, and solar variability). Despite that, the changes within the natural processes were in a controlled chain, but since the 19th century, human activities have exceedingly produced greenhouse gas emissions. As a result, solar radiations became more concentrated in the earth's atmosphere causing global warming and climate change (Thomas et al. 2013).

The built environment could be also affected by changes in the sourrounding weather conditions. For example, climate change may modify the deterioration patterns of infrastructure assets and consequently will impact the risk assessment of infrastructure assets (Bastidas-Arteaga et al. 2020). In the particular case of bridges over rivers, climate change may impact the river discharge values causing more flood events to occur and consequently may modify bridge scouring patterns since precipitation patterns have become more volatile resulting in higher river flow velocity (Dikanski et al. 2017).

Scouring patterns are caused by the removal of the riverbed materials that are located around the bridge's pier. The outcome is known as local scour depth, in which the removal of the riverbed materials occurs when the velocity of the river flow is higher than the critical velocity that the riverbed materials can sustain (Liu et al. 2022).

The significance of the local scour depth around the bridge's pier is related to its impact on the stability of the bridge since the local scour depth reduces the stiffness of the bridge foundation as a result of the removal patterns of riverbed materials at the bridge foundations in which failure happens when the local scour depth surpasses the foundation depth (Design Manual For Roads And Bridges-BD 97/12 standard).

It is important to note that local scour develops rapidly and is considered an ambiguous factor of deterioration since this phenomenon is enhanced by flood events whereby the accumulation of the local scour depth is impossible to detect without underwater inspections. Subsequently, local scour is known to be one of the leading causes of bridge failure worldwide (Imam 2019; Malekjafarian and Prendergast 2020; Prendergast and Gavin 2014). In a sense, bridges collapse suddenly before their expected lifetime resulting in major repairs and replacement costs. In addition, estimating the impact of climate change on the local scour risk is important within the context of bridge risk assessment. This is implemented by considering the river flow projections of regional climate models.

Climate models are quantative mathematical methods that are based on the laws of physics, fluid, and chemistry. Climate models simulate the interaction of the climate drivers variables, e.g., jet streams, aerosols, atmosphere, ocean, land, ice, etc. The impact of climate change is considered within the climate models in terms of Representative Concentration Pathways scenarios (RCPs) which are possible changes in the predictions trajectories due to the possible changes in the greenhouse gases concentration in the year 2100 caused by global warming (Habeeb and Bastidas-Arteaga 2022).

In this paper, climate change impact is applied within the framework of the bridge stability and scour risk assessment by including the river flow projections, i.e., RCPs 2.6, RCPs 4.5, and RCPs 8.5 from the regional IMPACT-2C climate project as database within the HEC-18 design model. The Hec-18 design model computes the local scour depth considering the yearly river discharge values of the RCPs projections as flooding events for the design criteria. In addition, Lévy process shock degradation model based on the the Compound Poisson Process presents the computed local scour depth as independent identically distributed shock sizes which are defined as Poisson process with a rate of occurring based on each RCPs. The model computes the states of failure due to local scour depth, the long-term availability, the expected lifetime of the structure before failure, and the probability of failure due to local scour.

2. METHODOLOGY

The proposed methodology estimates the local scour depth using the HEC-18 design model, which considers the yearly river discharge values as flooding events for the design criteria (L.A. et al. 2012). The database used within the HEC-18 design model is the RCPs projections from the IMPACT-2C climate project, then a stochastic shock degradation model is proposed to estimate the scour risk assessment and stability of the bridge.

2.1. Local scour

The HEC-18 design equation computes the local scour depth. The HEC-18 design equation, writes:

$$\gamma_s = 2HK_1K_2K_3K_4K_w\left[\frac{a}{H}\right]^{0.65} Fr^{0.43} \tag{1}$$

$$Fr = \frac{V}{[gH]^{0.5}} \tag{2}$$

where γ_s is the local scour depth, H is the flow depth, K_1 is the coefficient of pier shape, K_2 is the coefficient of the angle of attack, K_3 is the coefficient of stream bed condition, K_4 is the coefficient of river bed material size, K_w is the coefficient of pier type, a is the pier width, Fr is the Froude number, V is the mean velocity of flow, and g is the gravity acceleration.

The coefficient of pier type K_w is applied under certain conditions, writes:

$$W_k = \begin{cases} 2.58\left[\frac{H}{a}\right]^{0.34} Fr^{0.65}, V < V_c \\ \left[\frac{H}{a}\right]^{0.13} Fr^{0.25}\;, \quad V \geq V_c \end{cases} \tag{3}$$

$$K_w = \begin{cases} W_k, \frac{H}{a} < 0.8,\ \frac{a}{D_{50}} > 50,\ Fr < 1 \\ 1, \frac{H}{a} \geq 0.8,\ \frac{a}{D_{50}} \leq 50,\ Fr \geq 1 \end{cases} \tag{4}$$

$$V_c = k_u H^{\frac{1}{6}} D_{50}{}^{\frac{1}{3}} \tag{5}$$

where D_{50} is the median bed material size, V_c is the critical velocity at which cohesionless particles initiate motion, and k_u is a unit correction factor (6.19) for SI units (m.kg.s).

2.2. Shock degradation

The applied model is a pure jump Lévy process with independent identically distributed shock sizes of a Compound Poisson process (CPP).

The Lévy measure π governs the timing and sizes of the jumps, as follows:

$$\pi(Y)_t = \mathbb{E}(N_t(Y)) \tag{6}$$

where $N_t(Y)$ is the number of shocks with shock sizes $y_i \in Y$ that occur at time t and is defined as a Poisson process with a rate λ.

The reliability of the structure is time-independent in which the damage to the system is a sudden shock with size y_i. The damage D at time t, writes:

$$D(t) = y_i \tag{7}$$

The capacity of the system suddenly decreases in which no safety precautions can be considered since the stability of the structure is governed by the shock size damage to the system. The capacity of the system, writes:

$$C_u(t) = \begin{cases} C_0, & C_0 - D(t) < k^* \\ 0, & C_0 - D(t) \geq k^* \end{cases} \tag{8}$$

where C_u is the capacity of the system at time t considering the ultimate limit k^* as an indicator of failure, and C_0 is the initial capacity of the system.

From another point of view, safety precautions can be applied with a serviceability limit by considering the capacity of the system to gradually decrease based on the mean time to failure $MTTF$. Consequently, the capacity of the system, writes:

$$C_s(t) = max\left[C_0 - \sum_{i=1}^{MTTF} \xi_i\,, k^s\right] \tag{9}$$

where C_s is the capacity of the system at time t considering the serviceability limit k^s as an indicator to implement maintenance procedures, and ξ_i is the damage on the system presented as a percentage with respect to the mean time to failure.

The system lifetime can then be defined by the relation between the capacity of the system and the serviceability limit. The system lifetime, writes:

$$L = inf\{t \geq 0 : C_s(t) \leq k^s\} \tag{10}$$

where L is the lifetime of the system.

When the system is maintained frequently by considering the serviceability limit, the long-term availability of the system, writes:

$$A_l = \frac{\frac{1}{\lambda_1}}{\left[\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right]} \tag{11}$$

where A_l is the long-term availability of the system, λ_1 is the rate of maintenance time, and λ_2 is the rate of the system being out of service.

The failure of the system takes place when the local scour depth surpasses the foundation depth. The probability of failure, writes:

$$P_f(t) = 1 - \sum_{i=0}^{n} \frac{(\psi t)^i}{i!} e^{-\psi t} \tag{12}$$

$$\psi = \frac{N_f}{MTTF} \tag{13}$$

where n is the estimated number of shocks before failure, ψ is the failure rate, N_f is the number of failures along the RCPs projections.

2.3. Risk assessment

The priority rating ratio PRR is used by the railway & highway authorities in the UK to categorize the scour risk assessment in Table 1. The scour risk assessment, writes:

$$PRR = 15 + ln\left[\frac{Y_s}{F_d}\right] \tag{14}$$

where F_d is the foundation depth.

Table 1: Scour risk assessment

PRR	*Score*	*Category*
17-21	*1*	*High*
16-16.9	*2*	*High*
15-15.9	*3*	*Medium*
14-14.9	*4*	*Medium*
13-13.9	*5*	*Low*
10-13	*6*	*Low*

3. APPLICATION

3.1. Case study

The DCL-7066 bridge is the case study within the framework of the bridge risk assessment subjected to local scour since the bridge was categorized as a structure of high priority for scour within the Scour Assessment Program. The bridge is located over the Cherwell River, 1.5 km to the west of Bletchingdon, United Kingdom.

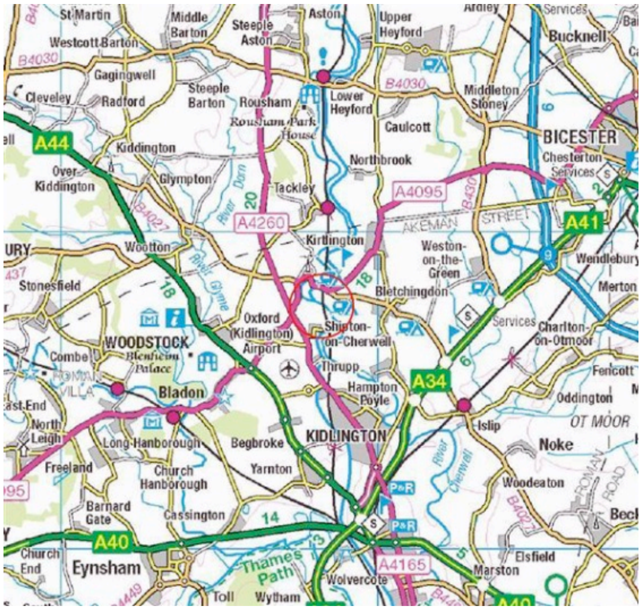

Figure 1: Location plan (Scale 1:200,000)

Table 2: Case study characteristics

longitudinal slope	*Flat*
Bed material size	*2 mm*
Foundation depth	*1 m*
Pier width	*2 m*
Pier shape	*Sharpe nose*
River width	*20 m*
Angle of flow	0°
K_1	*0.9*
K_2	*1*
K_3	*1.1*
K_4	*0.4*

3.2. Database

The database was produced within the IMPACT-2C climate research project. The database includes river flow projections, i.e., RCPs 2.6, RCPs 4.5, and RCPs 8.5 from 2011 to 2095.

4. RESULTS AND DISCUSSIONS

This section presents the impact of climate change on the stability of bridge subjected to local scour.

In Figure 2, the structure is assumed to fail when the local scour depth estimated from the HEC-18 design model exceeds the threshold value, i.e., foundation depth (1 m). The number of threshold exceedances for the RCPs 2.6, 4.5, and 8.5 are found as 9, 14, and 18, respectively.

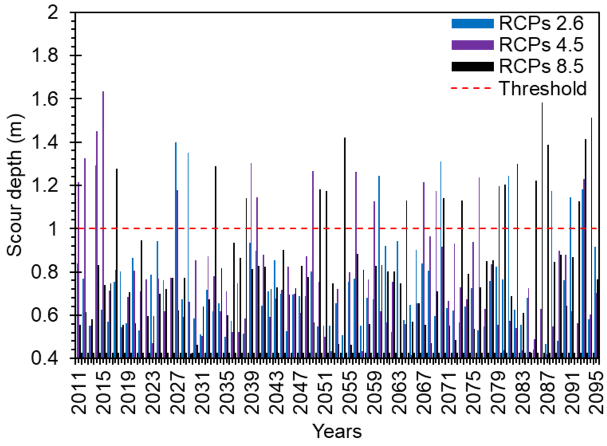

Figure 2: Local scour depth

In Figure 3, the capacity of the structure rapidly decreases indicating failure when the CPP shocks exceed the assumed threshold value resulting in a (0 %) of capacity. Otherwise, the capacity of the structure remains the same as the value of the initial condition (100 %). As explained in Eq. (8).

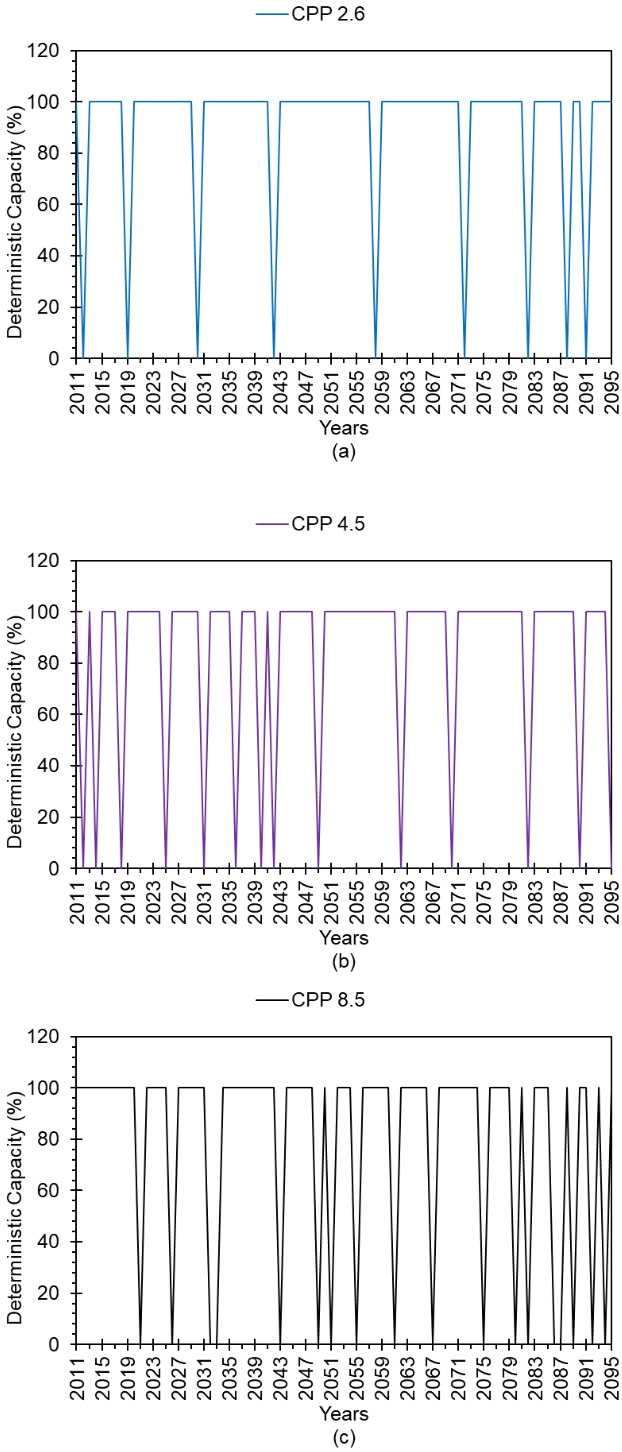

Figure 3: Deterministic capacity

The previously presented capacity suffers from the characteristics of the shock degradation process in which no safety precautions can be considered. This limitation is solved by considering the genuine capacity of the system which gradually decreases as explained in Eq. (9).

In Figure 4: Capacitysite inspections are considered to occur considering the RCPs 2.6, 4.5, and 8.5 every 9, 6, and 5 years, respectively.

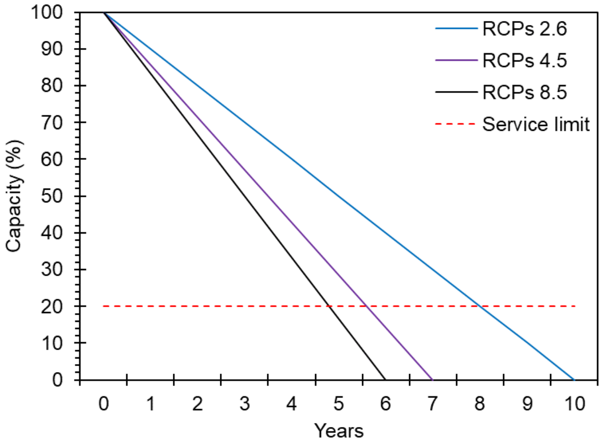

Figure 4: Capacity

In Table 3, the long-term availability of the structure is investigated from 2011 to 2095. The availability of the structure decreases gradually when considering the RCPs 2.6, 4.5, and 8.5, respectively.

Table 3: Long-term availability

RCPs	*Long-term availability*
2.6	*82 %*
4.5	*75 %*
8.5	*72 %*

In Figure 5, the probability of failure of the RCPs 2.6, 4.5, and 8.5 reaches a value of 90 % in the life expectancy of the structure before failure at every 14, 9, and 7 years, respectively.

In Figure 6, the scour risk assessment of the bridge is found to be with a maximum value of 15 since a local scour depth value of 1 m is the failure state. The results present higher PRR among the RCPs 8.5, 4.5, and 2.6, respectively. However, at the state of failure, all the RCPs are categorized as a structure of medium priority with recommended actions as follows: assessment and underwater exams should take place every 3 years. In addition to implementing protection works.

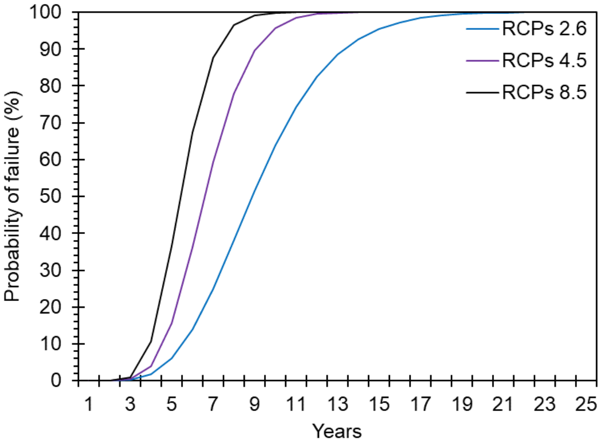

Figure 5: Probability of failure

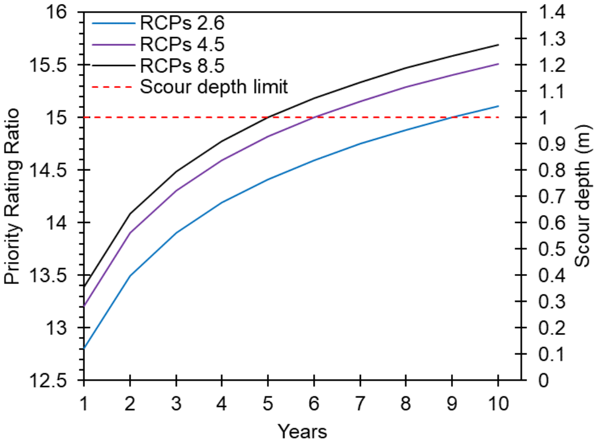

Figure 6: Scour risk assessment

5. CONCLUSIONS

This paper applies a stochastic shock degradation model within the framework of climate change impact on the states of failure of bridges over rivers due to local scour depth.

The main conclusions are summarized as follows:

- In a general manner, the CPP shock degradation model is capable of simulating failure states due to local scour depth. This is proved in terms of the mean time to failure and the number of failure states.

- The characteristics of the shock degradation process state that no safety precautions can be considered. However, this limitation is solved by considering the genuine capacity of the system which gradually decreases based on the mean time to failure for each RCPs.
- Climate change impact within the framework of bridges over rivers has been investigated in which the structure lifetime decreases when considering the RCPs. The analysis is presented in terms of the probability of failure, long-term availability, and scour risk assessment.

Future research should be devoted to the development of the HEC-18 design model since this model overestimates the local scour depth. In addition, the HEC-18 design model is a time-independent model. Consequently, the output can be only presented as shocks. Alternatively, local scour can be presented as an accumulation of progressive deterioration and shock degradation due to flooding events.

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