Shock Degradation Process in The Framework of Bridge Transportation Serviceability

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ABSTRACT

Infrastructure assets are designed to ensure a certain level of reliability. However, climate change may impact infrastructure assets in several ways affecting their reliability and availability. In the particular case of bridges crossing rivers, climate change may have a direct impact on the river discharge, leading to an increase in the frequency and magnitude of flooding events. This, in turn, is likely to result in an increased risk of bridge failure due to local scour, which is the removal of the bed material around the bridge's pier. The significance of the scouring phenomenon is related to its impact on the reliability of the bridge, as a result, the structure's capacity will rapidly decrease leading to a sudden failure. Consequently, it is essential to consider the impact of climate change on local scour when assessing the reliability of bridges crossing rivers, which can be represented by considering various Representative Concentration Pathways scenarios from climate models. This problem is addressed in this paper by proposing a Lévy process shock degradation model to study the impact of climate change on the structure's durability due to local scour. The results show the impact of climate change on the structure's long-term availability, an expected lifetime before failure, and the probability of failure. The outcome of the results indicates that the expected lifetime of the structure decreases by considering climate change.

Keywords Climate change, Bridge risk assessment, Local scour, Stochastic Lévy process, Shock degradation model.

I. INTRODUCTION

Bridges are an essential part of the infrastructure assets, providing vital transportation between communities. To ensure that bridges remain safe and functional for many years, they must be designed to ensure high durability. This can be achieved through the use of high-quality materials, proper construction techniques, and regular maintenance. Additionally, bridges should be designed to account for potential environmental factors such as flooding, earthquakes, and extreme temperatures. Subsequently, bridges can be designed to last for many years and provide safe and reliable transportation. However, climate change may have a significant impact on bridges causing the structure to be out of service. As a result of global warming, bridges are exposed to more extreme events, such as floods, storm surges, and hurricanes causing damage to the structure and leading to costly repairs or replacement. In addition, climate change threatens to fundamentally alter the intensity and frequency of natural hazards. For instance, precipitation will be becoming more volatile and intense due to the increase in temperature which leads to more intense floods, in turn, this can cause soil erosion of bed material around the bridge's pier over rivers, which in turn affects the stability of the foundation and causes sudden failure of bridges.

Climate change modifies the structural deterioration risks of bridges, such as corrosion (Bastidas-Arteaga et al., 2020). In addition, it has an indirect impact due to the potential changes in the removal patterns of riverbed materials at bridge foundations resulting in a sudden failure of the structure and is known to be one of the leading causes of bridge failure worldwide (Kallias and Imam, 2016). For example, a survey of U.S. bridge failures indicates that 84 percent of the bridges in the United States are over rivers and 60 percent of 823 failures surveyed were associated with local scour. Moreover, the annual cost for scour-related bridge failures in the United States is about $30 million and flood damage repair costs for Federal-aid highways are about $50 million (Mark N. Landers, 1992).

The available scour prediction models commonly in use can be classified into deterministic, probabilistic, and observation-based. Scour prediction models are mathematical models used to predict the rate of scour around bridge foundations. These models are used to assess the stability of structures in areas prone to scour. The HEC-18 model is widely used by engineers and researchers to predict local scour around bridge piers, the model is developed by the U.S. Army Corps of Engineers to predict local scour around bridge piers. The model takes into account the effects of turbulence and uses a variety of parameters, such as flow velocity, pier size, river flow, river dimension, flow depth, and sediment characteristics to estimate the depth of scour around a pier (Arneson et al., 2012).

The failure of a structure can be represented stochastically by using the probability distribution to represent the likelihood of different outcomes occurring. Stochastic Lévy shock degradation processes are mathematical models used to describe the progressive and shock degradation of a system over time due to random shocks following a Poisson distribution. These models are based on the Lévy distribution, which is a probability distribution that describes the probability of a random variable taking on a certain value. The system is assumed to degrade over time due to random shocks, and the Lévy distribution is used to describe the probability of the system experiencing a certain level of degradation. Those models can be used to predict the future state of a system, present different scenarios, and can also be used to optimize maintenance schedules and other system parameters (Sánchez-Silva and Klutke, 2016).

This paper investigates the reliability of a bridge over a river in the face of climate change-induced local scour. The HEC-18 model is used to compute the local scour, taking into account the impact of climate change by considering various Representative Concentration Pathway scenarios (RCPs) conducted from climate models. A stochastic Lévy process is then employed to simulate various states of failure over time due to local scour and to assess the impact of climate change on the structure's capacity, long-term availability, an expected lifetime before failure, and probability of failure. The reliability of the structure is related to the states of failure which are considered when the local scour depth exceeds the foundation depth of the bridge's pier.

The paper is divided as follows, Section II discusses the method used to evaluate the local scour and the applied stochastic Lévy process, Section III presents the case study and the database, and Section IV assesses the system's performance and presents a risk assessment by considering the impact of climate change.

II. METHODOLOGY

This paper computes the local scour using the HEC-18. This results in various forms of failures induced by local scour for each RCPs over the years 2011-2095 when the local scour depth exceeds the foundation depth, which are then represented stochastically using a Lévy process to account for shock deteriorations. This aims to stochastically represent the influence of the river discharge values variation on the local scour depth in the face of climate change. A probabilistic assessment is carried out in Section IV to assess the system's performance when considering climate change induced-local scour.

The HEC-18 design equation for local scour around bridge piers accounts for the effects of flow velocity, sediment size, channel geometry, pier shape characteristics, and bed material characteristics on the rate of scour. The HEC-18 design equation, writes:

$$\gamma_s = 2HK_1K_2K_3K_4\left[\frac{a}{H}\right]^{0.65} Fr^{0.43} \tag{1}$$

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

where γ_s is the local scour depth, H is the flow depth, a is the width of the pier, 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, Fr is the Froude number, V is the velocity of flow, and g is the gravity acceleration.

The depth of the local scour can vary based on the variations of the river flow, in which high river flow values can lead to a significant increase in the computed depth. To account for this, a stochastic Lévy process (Compound Poisson process) is proposed to simulate the shock deteriorations of local scour with shock sizes ξ_i that follows a Poisson process and the process also presents the damage on the structure at time t due to the computed local scour depth γ_s. For $t \in [0,\infty]$, the number of shocks N_t is defined as a Poisson process, supposing that shock sizes ξ_i are a sequence of independent, identically distributed random variables with a rate $\lambda \in [0,\infty]$. The damage on the system due to shock deterioration, writes:

$$D(t) = D_0 + \sum_{i=1}^{N_t} \xi_i\,, \quad t \geq 0 \tag{3}$$

where $D(t)$ is the damage at time t and D_0 is the initial state of damage on the system.

System lifetime is the period during which the system remains operational before it needs to be replaced or maintained, and therefore, it can then be defined as the relation between the capacity of the system and the threshold limit states k^s which in this study represents the foundation depth. The system lifetime, writes:

$$L = inf\{t \geq 0 : max[C_0 - D(t), k^s] \leq k^s\} \tag{4}$$

where L is the system lifetime and C_0 is the initial capacity of the system (nominal life).

The long-term availability of the system indicates the degree of availability of the system from a given period (2011 to 2095) in the face of climate change, it writes:

$$A = \frac{\frac{1}{\lambda_1}}{\left[\frac{1}{\lambda_1} + \frac{1}{\lambda_2}\right]} \tag{5}$$

where A 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 system fails when the local scour depth exceeds the foundation depth. Subsequently, the probability of failure at time t involves the concept of the failure rate. The probability of failure, writes:

$$P_f(t) = 1 - \sum_{i=0}^{n} \frac{(\propto t)^i}{i!} e^{-\propto t} \tag{6}$$

where $\propto$ is the failure rate and n is the number of years to failure.

III. Application

a. Case study

The DCL-7066 bridge was categorized as a structure of high priority for scour within the Scour Assessment Program (Wallingford, 1992). The bridge is located over the Cherwell River, 1.5 km to the west of Bletchingdon, United Kingdom. Location plan is presented in Figure 1. The bridge is a dual-span structure featuring a sharp-nosed pier with a width of 2 m. and has a bed-to-soffit height of around 4.5 m. Cross section of the bridge is presented in Figure 2.

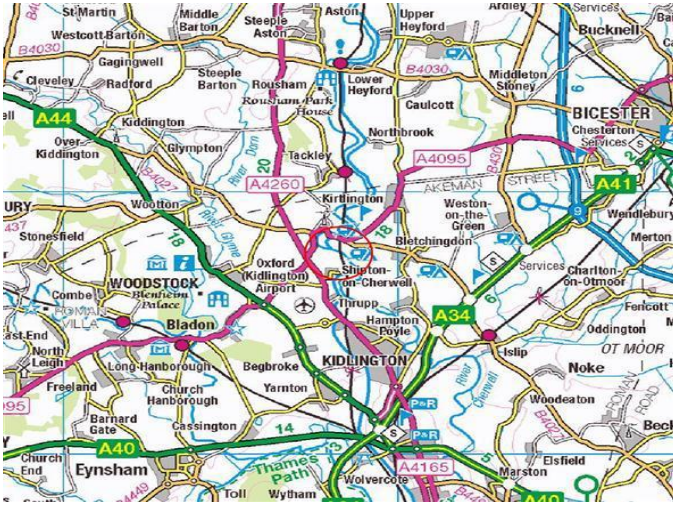

Figure 1. Location plan (Wallingford, 1992).

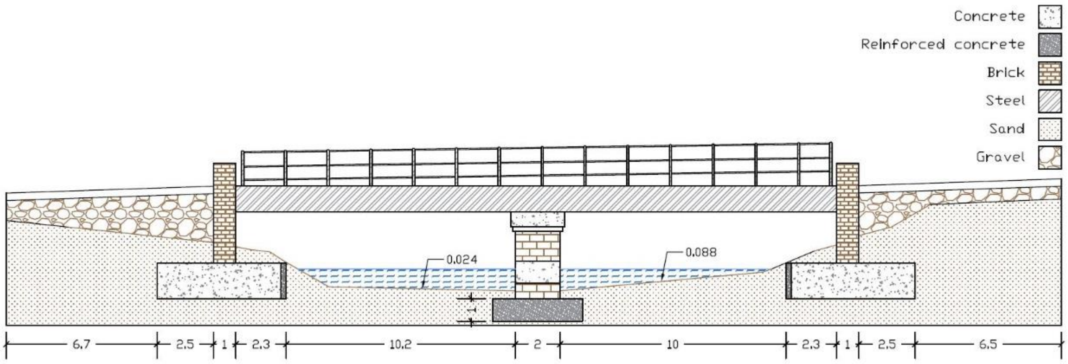

Figure 2. **Vertical cross section of the bridge.**

b. Database

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

IV. RESULTS AND DISCUSSION

This section presents the impact of climate change on the system's performance and probability of failure by including the river flow scenarios, i.e., RCPs 2.6, RCPs 4.5, and RCPs 8.5 from 2011 to 2095.

In Figure 3, the river discharge is expected to vary and increase in the future due to changes in precipitation and temperature. However, the magnitude of these changes varies depending on the region and the forcing factors of the RCPs of a specific model (Habeeb and Bastidas-Arteaga, 2022).

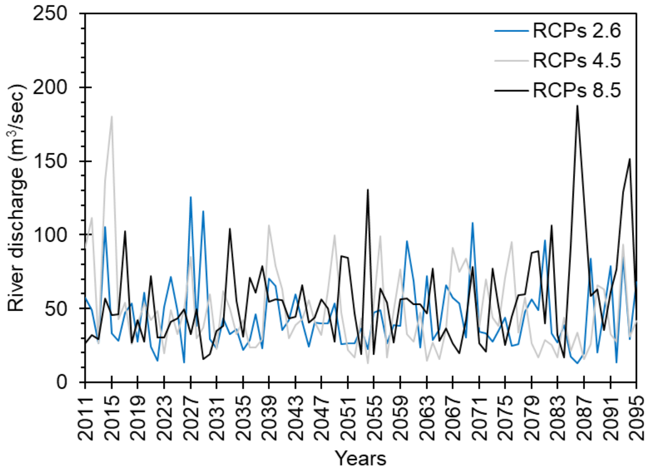

Figure 3. **River discharge variations.**

The response of river discharge variations of RCPs climate models to the formation of local scour is highly variable and depends on the specific characteristics of the river system and climate model driving factors. In general, climate models predict an increase in river discharge. This can lead to increased erosion and sediment transport, resulting in increased local scour. In Figure 4, the system is expected to fail when the local scour depth computed from the HEC-18 model exceeds the foundation (1 m). The number of local scour failures increases when considering a higher order of RCPs, in which the system is expected to fail 6, 8, and 11 times between 2011 and 2095 when taking into account the impact of climate change of RCPs 2.6, RCPs 4.5, and RCPs 8.5, respectively.

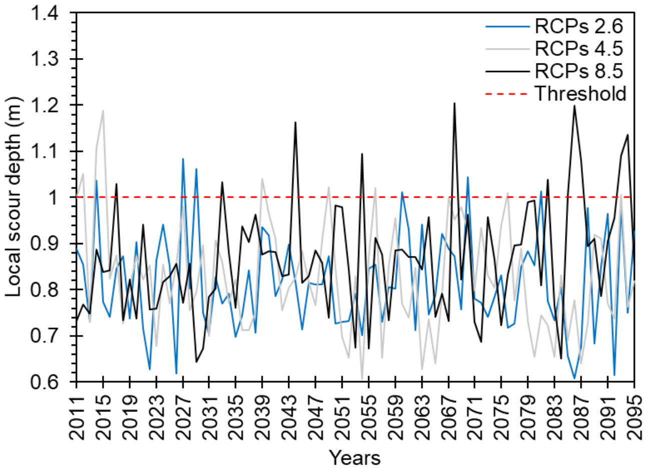

Figure 4. **Local scour.**

By implementing the stochastic Lévy process, it is possible to simulate various paths of failures based on the rate of failures estimated from the HEC-18 model and represent all the simulations with upper line (UL) and lower line (LL) of 95 % confidence levels. In Figure 5, Lévy simulations estimate the number of failures between 2011 and 2095. At the end of the simulations in 2095 (year 85), the number of failures considering both UL and LL integrate between 5-7, 6-10, and 8-14 for RCPs 2.6, 4.5, and 8.5, respectively.

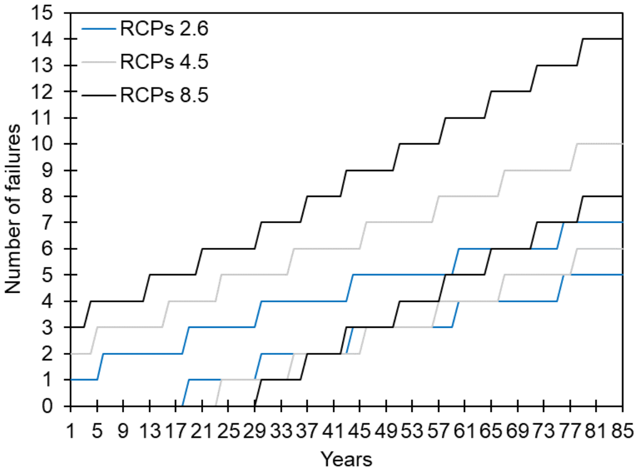

Figure 5. **Number of failures**

The lifetime of the system is the period during which the system remains operational before it needs to be replaced or maintained (Eq. (4)). The lifetime of the system is expected to decrease due to the impact of climate change as a result of the increased number of failures over the time interval between 2011 and 2095. In Figure 6 are presented the upper, lower, and average lifetimes of the system estimated over the time interval between 2011 and 2095 for three climate change scenarios. The system on average will no longer be available for service after every 14-18, 10-16, and 7-12 for RCPs 2.6, 4.5, and 8.5, respectively. The comparison of average values in Figure 6b confirms that RCPs 8.5 represents the pessimistic case scenario.

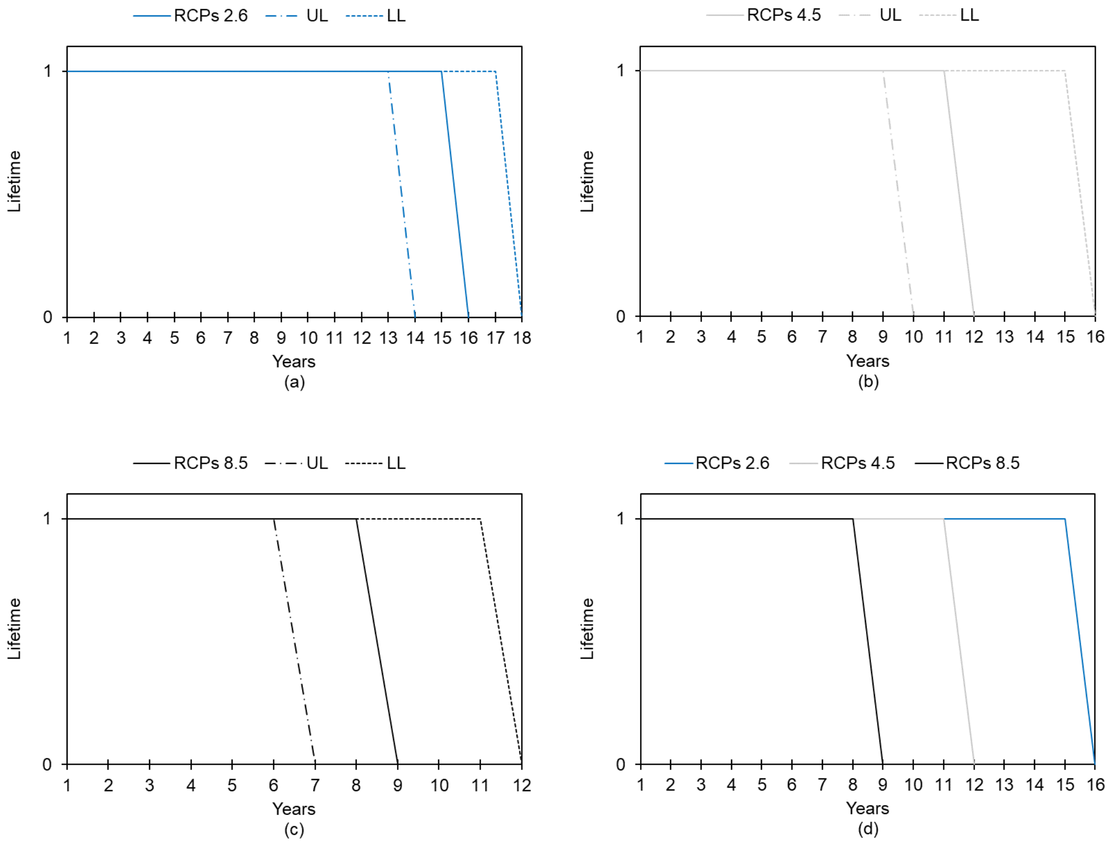

Figure 6. Lifetime of the system.

The long-term availability of the system (Eq. (5)) depends on the failure rate and the degree of maintenance. It is presented in Table 1 for each RCPs in terms of UL and LL. The results show that the long-term availability of the system is below the acceptable value of 95 % of availability for RCPs 4.5 and 8.5.

Table 1. Long-term availability

Climate scenario	UL	LL
RCPs 2.6	96 %	97.1 %
RCPs 4.5	94.5 %	96.6 %
RCPs 8.5	92.4 %	95.5 %

Figure 7 presents the probability of failure of the system due to the impact of climate change induced-local scour. The system is expected to fail with a higher probability of failure for RCPs 8.5, 4.5, and 2.6, respectively.

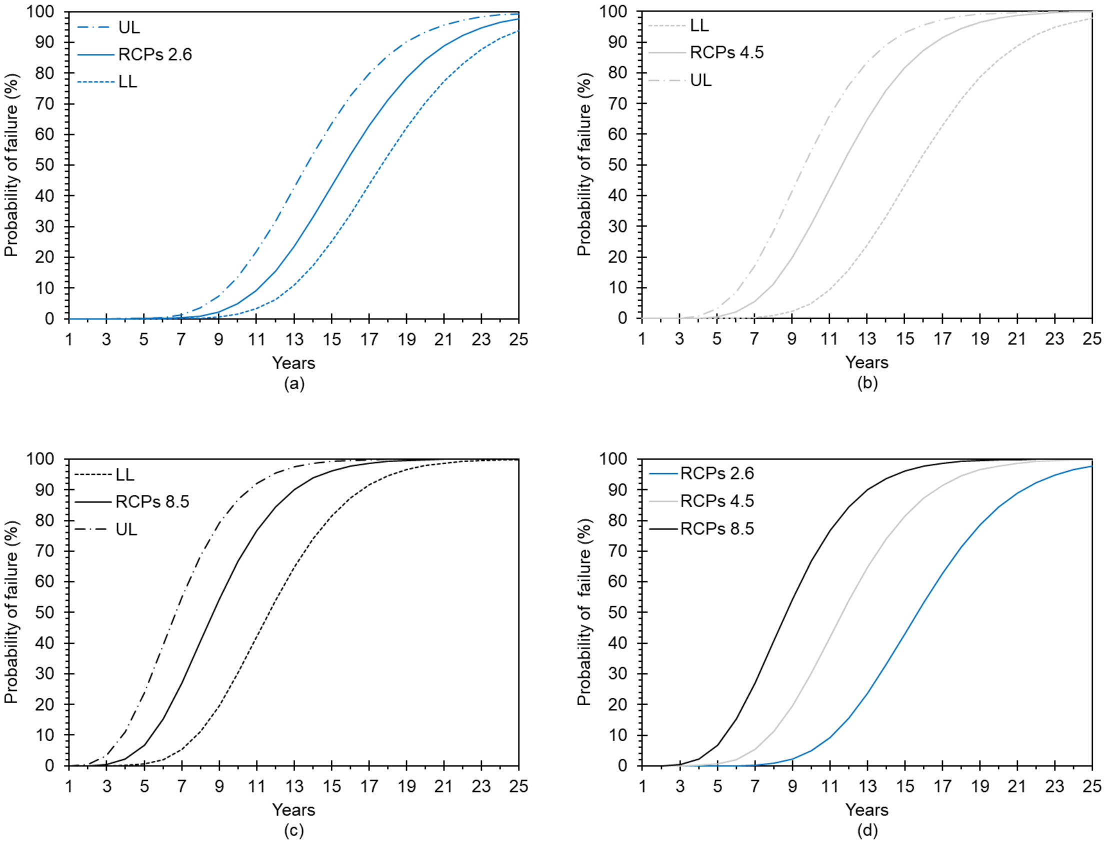

Figure 7. Probability of failure.

V. CONCLUSION AND PERSPECTIVES

The impact of climate change on the stability of bridges over rivers is highly variable. Herein, we present a stochastic approach to represent this impact stochastically by embedding the impact of climate change using RCPs from climate models on the induced-local scour. The results present a higher probability of failure of the system when considering higher Representative Concentration Pathway scenarios, i.e., RCPs of a climate model. In addition, the results are presented with upper and lower lines to represent the several simulations obtained by the Lévy process.

Future work should consider hydraulic constraints to define the years when there is a river discharge that can cause the sediments to be in a suspension motion. This is due to the fact that the HEC-18 model is used to design the systems over historical return periods. In addition, the HEC-18 design model is considered to overestimate the local scour, and therefore, a coefficient of filling could be applicable in the case where there are sediments transported with the flow.

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