A qualitative prioritization of the risks imposed on bridges due to climate change

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Abstract

Climate change and its impacts on infrastructures may seriously affect the functionality of societies. Despite the alarming potential consequences climate change pose, not enough effort has been directed towards averting these impacts or managing them in some other way (e.g. mitigation, reduction, etc.). Well-functioning infrastructure networks play a key role in societies' resilience and their ability to cope with climate-induced hazards. Therefore, ensuring the efficient performance of infrastructure networks, even during climate related emergencies, is central to the resilience of societies in the face of climate change. At the heart of a resilient transportation infrastructure network lays robust bridge structures. This paper builds on previous work where the potential risks from climate change on bridges were surveyed. Here, a qualitative risk prioritization scheme for bridges to rank these risks is presented. The aim of this work is hence to provide a tool for determining which of these risks are more worthy of closer investigation. The suggested framework is based on the basic elements of risk; i.e. hazard, exposure, vulnerability, and consequences. Several indices reflecting these four components and their different characteristics are introduced. Subsequently, a method for ranking the different risks based on these indices is presented. This framework can be used to optimize investments in adapting bridges to climate change.

Keywords: climate change; transportation; infrastructure; bridge; risk prioritization.

1. Introduction

There is an increasing amount of evidence indicating that significant changes to our climate have happened and are still taking place. According to [1] the following climate changes, among many others, are projected for the future:

1. Higher global mean surface temperature.
2. Heatwave events with higher frequencies and/or intensities.
3. An increase in precipitation intensity and frequency in some regions and a decrease in other regions.
4. Sea level rise

The impacts of the projected climate changes on bridges, among other infrastructures, can be substantial. The projected higher temperatures can increase the rate of material deterioration, heighten the risk of heat-induced damage to pavements and railways, raise the risk of wildfires, and elevate the risk of thermal-restrained stresses, among other risks. Furthermore, the increased precipitation frequency and intensity in some places can also increase the rate of material deterioration, further the risk of scour under bridge foundations, result in more frequent landslides; slope failures; rock falls; and debris flows, overwhelm drainage systems, increase the intensity and frequency of floods, and escalate the risk of vehicle-pier collisions. Possible changes in the intensity and frequency of wind storms is also another risk due to climate change. SLR also increases the risk of flooding and provides a higher launching level for storm surges hence rendering them more damaging to bridges. The risks induced by climate change on bridges are discussed in more detail in [2].

The conclusions made by [3], who studied the effect of climate change on concrete infrastructure deterioration, demonstrate the possible significance of these risks. For instance, their study predicted a four-fold increase in the risk of carbonation-induced damage to concrete infrastructure by the end of the century in some Australian cities. Nevertheless, up-to-now, only few similar studies have tried to quantify climate-change effects on infrastructure, e.g. [3], [4], [5], and [6].

The large number of possible climate change related risks to bridges gives rise to the question of criticality. For a specific bridge in a certain location, which of the potential risks are more critical and warrants higher attention? The answer to this question would be invaluable for bridge managers to efficiently direct their resources and climate change adaptation efforts. This paper addresses this objective and attempts to develop a qualitative climate-change risk prioritization framework that enables bridge managers to rank and prioritize these risks. To the best of our knowledge, this is the first attempt to develop a climate-change risk prioritization framework for bridges.

This paper starts with a literature review of some of the most relevant previous studies which have addressed risk prioritization and decision making for infrastructure management. The details of the proposed prioritization framework are then presented followed by concluding remarks and a brief discussion on the limitations of the proposed framework.

2. Literature review

Several previous studies have aimed at risk prioritization and the application of decision making methods in the context of infrastructure, see [7]. However, only few studies have tried to incorporate climate change in the prioritization and decision making processes in the context of infrastructure. In [8], which is one of the few exceptions, the authors tried to provide answers to two questions: which adaptation measure to select (i.e. whether to adapt infrastructure to precipitation only, temperature only, flooding only, or a combination of the three climatic effects); and which climate change scenario to design infrastructure for. [9] also introduced a methodology for prioritizing infrastructure projects in the light of a changing climate. In their methodology, a baseline prioritization was initially generated using a traditional multi-criteria analysis without including the effects of climate change. Two different climate change scenarios were then incorporated in the decision model to update the baseline prioritization; the first considered only climate conditions while the second considered climate conditions among other factors. In [10], a similar approach of first producing a baseline prioritization and then updating it is used to support the prioritization of transportation assets' adaptation to a changing climate. [11] developed a multi-criteria decision making method for prioritizing five options for watershed management considering climate change and urbanization.

Perhaps the most relevant previous work, in relation to the current paper, was done by [12]. In this study, the authors developed a method for climate change resilience ranking of highway bridges considering both direct costs (component failure and consequences to the bridge) as well as user costs. The authors demonstrated the methodology for five illustrative potential climate change impacts: abutment washout, pier scour, abutment erosion, deck flooding, and abutment permafrost stability. All of these factors were combined to calculate a single number, referred to as Bridge Resilience Indicator (BRI), for ranking bridges according to their resilience against climate change effects. There are, however, two limitations in the proposed method. Firstly, neither the probability of the climatic hazard (e.g. higher future temperatures) nor the probability of the relevant impact to the bridge (e.g. abutment permafrost stability problems), referred to as exposure in the present article, are considered. Not accounting for these probabilities may lead to the prioritization of bridges with low resilience but an overall low risk (due to lower probabilities of hazard and exposure) and the possible overlooking of those with average resilience but with an overall high risk (due to high probabilities of hazard and exposure). Secondly, the resilience measure against each of the five mentioned impacts was determined using only a single capacity measure (e.g. free board). Depending on only one parameter to judge the resilience of a bridge against these impacts may result in misleading conclusions. To the best of our knowledge, this is the only previous work attempting to incorporate the effects of climate change in bridge ranking. The framework presented in the current article is unique in that it overcomes the aforementioned limitations, incorporates uncertainty in the prioritization, and focuses on a single bridge with the aim of finding the most critical climate-change related risks threatening its performance and safety in the future.

3. Proposed framework

In this section the suggested framework with its main parts is presented. The framework depends on the four main elements of risk as described by the following equation:

$$R = P(H) \cdot P(E|H) \cdot P(D|E \cap H) \cdot C(D) \qquad (1)$$

Where P(H) is the probability of a hazard within a specific reference period, P(E|H) is the conditional probability of a specific exposure given the hazard, P(D|E∩H) is the conditional probability of a specific damage given hazard and exposure (herein referred to as vulnerability), C(D) is the consequences of damage, and R is the risk. In this study, a hazard refers to the projected climatic change (e.g. temperature increase) driving a relevant exposure which may affect a bridge (e.g. additional restrained thermal stresses). Vulnerability captures the probability of a bridge to sustain a certain level of damage from a specific exposure while the consequences account for the potential impacts inflicted by an exposure. The consequences are intended to reflect both the direct losses, due to damages to the bridge, as well as the indirect ones, due to the resulting disruptions to the transportation network.

Before prioritizing climate-change risks, preliminary steps for defining the scope are necessary. First, the time frame of interest for the prioritization must be defined, i.e. which climate changes are of interest; those projected in the 2030's; 2050's; or 2070's for example? Secondly, the potential climatic hazards at the chosen time frame should be determined and consequently the potential climate-change risks identified.

The proposed prioritization framework considers a number of relevant factors for each of the aforementioned elements of risk and later combines them. These factors, along with their aggregation to establish a ranking index, are described in the following sections.

3.1 Hazard

To be able to draw a rational and unbiased comparison between the different possible exposures, i.e. risks, the probability of the climatic hazards driving each exposure must be accounted for. This can be done by one of two alternatives. The first is to consider a predefined level of damage for all exposures and compare the estimated probabilities of the hazards causing this predefined damage level for each exposure. The second is to consider a predefined probability of occurrence for the hazards driving each exposure and then compare the subsequent severity of damages caused by each exposure due to this hazard level. Given the great difficulty, or even impossibility under current knowledge, in applying the first alternative, the latter choice is considered. In this study, we choose to use the 25th percentile probability value of hazard according to a low-emissions scenario (H_{low}), e.g. RCP 2.6, and the 75th percentile probability value of hazard according to a high-emissions scenario (H_{high}), e.g. RCP 8.5, to make the prioritization. This choice of scenarios and percentiles is made to represent a lower and an upper bound of the potential climatic hazards and can be changed by the decision maker.

Another aspect that affects the probability of an exposure to occur is the number of existing hazards, or hazard combinations, that are projected for the bridge location and can separately drive the exposure. For instance, higher temperatures, changes in relative humidity, and higher carbon dioxide concentration in the atmosphere can each separately result in a higher risk of deterioration of concrete bridges. A factor (N_h) is used to represent this effect as follows:

1.00= three or more hazards, or hazard combinations, that can separately drive the exposure.

0.67= two hazards, or hazard combinations, that can separately drive the exposure.

0.33= only one hazard, or hazard combination, that can separately drive the exposure.

Another important issue concerns the uncertainty of climate change models. The existing circulation models projecting the different climatic hazards can project these hazards with varying certainty. To represent this in the prioritization we consider a factor (C) reflecting the highest certainty among the hazards driving the exposure. The different values suggested for C are:

1.00= high uncertainty.

0.67= average uncertainty.

0.33= low uncertainty.

3.2 Exposure

This component of the framework is intended to reflect two characteristics of the different possible exposures. Firstly, the strength of the evidence supporting the increase of a certain exposure, as a result of the hazards projected at a specific bridge location, (E) is considered. The following values of E are suggested:

1.00= personal opinion of decision maker.

0.67= opinion of a group of experts, elaborated through e.g. expert elicitation; see, e.g., [13].

0.33= well-established and supported by scientific evidence.

Secondly, the framework considers the possible magnitude of exposure increase under the two previously mentioned hazard percentile values, i.e. H_{low} and H_{high}. These two exposure increase values are represented by the factors I_{low} and I_{high} respectively as follows:

$$I_{low} = min\left(100\%, \frac{e_{low} - e_i}{e_i}\right) \quad (2)$$

$$I_{high} = min\left(100\%, \frac{e_{high} - e_i}{e_i}\right) \quad (3)$$

Where e_{low} and e_{high} represent the exposure under H_{low} and H_{high} respectively and e_i represents the initial exposure without the effect of climate change. The fractions in Equations 2 and 3 represent the percentile increase of exposure. If models connecting the exposure to the relevant hazard are unavailable, these fractions can be evaluated qualitatively, either by a group of experts or by the decision maker, as discussed previously. The values of I_{low} and I_{high} are limited to 100% as we consider an exposure increase of

100% or more to belong to the group of highest exposure increase.

3.3 Vulnerability

The next element in the prioritization framework is concerned with assessing the vulnerability of the bridge to being damaged by each exposure. For representing the vulnerability, a number of bridge attributes that reflect its vulnerability to a specific exposure are selected and the possible alternatives for each attribute are given a score on a 0 to 1 scale, 0 being not vulnerable and 1 being highly vulnerable. Depending on the characteristics of the bridge under consideration, the bridge is assigned a score for each attribute. If the bridge at hand scores a 0 at any of the selected attributes, a Vulnerability Index (VI) of 0 is assigned to the exposure. Otherwise, VI is calculated as the average score for all the selected attributes. Table 1 shows the suggested bridge attributes for the risk of scour as an example. In case of the inability to develop and use such tables, due to either the lack of scientific knowledge or lack of information about the bridge characteristics, a value can be assigned to the vulnerability index qualitatively.

Table 1. Suggested bridge attributes for the calculation of the vulnerability index for scour

Sco-re	**Founda-tion type**	**Scour protection measure**	**Pier width**	**Soil type**
0.0		Sheet pile or cofferdam		Non-erosive
0.1	Long concre-te or steel piles (>6m)		<1m	
0.2				
0.3	Long timber piles (>6m)	Other properly designed and well-functioning protection measures	1≤w< 1.5m	Low erodibi-lity
0.4				
0.5				
0.6	Short piles (<6m)	Some protection	1.5≤w< 2.5m	Medi-um erodibi-lity
0.7				
0.8				
0.9				
1.0	Shallo-w found-ation	No prote-ction	3.0≤w	high erodibi-lity

3.4 Consequences

The last component of the proposed framework represents the likely consequences of each exposure. Consequences are divided into material costs; i.e. bridge replacement or repair costs, user costs; representing the cost of the additional distance travelled and the subsequent time loss due to the possible bridge closure, and life loss; representing the number of fatalities due to the partial or full collapse of the bridge. While material costs are only affected by the bridge damage state, user costs and the consequences associated with life loss are dependent on the size of traffic and the importance of the bridge under consideration. Accounting for these different consequence types, the suggested values for the consequence index used in the framework are presented in Table 2. The values in Table 2 are dependent on a factor i that is used to reflect the size of traffic served and the importance of the bridge. In this framework, the functional classification of the highway or the railway track that run along the bridge, according to e.g. Federal Highway Administration (FHWA) or Federal Railroad Administration (FRA) in the United States, is used as a representation of these two parameters. Table 3 shows the proposed values for the factor i for each FHWA highway class or FRA railroad class as an example. It is suggested that two consequence indices need to be determined for each exposure taking into account a pessimistic view (C_p), i.e. worst case scenario, and an optimistic view (C_o), i.e. best case scenario, to represent the uncertainty in consequences.

After calculating the consequence indices, it is necessary to normalize them to a scale from 0 to

1.0. This is done to ensure that all the indices are within the same range, i.e. 0 to 1.0, and no unintended hidden weights are introduced during the aggregation process. The normalized pessimistic and optimistic consequence indices, C_{pn} and C_{on} respectively, are calculated as follows:

$$C_{pn} = \frac{C_p}{2.0+4.0i} \tag{4}$$

$$C_{on} = \frac{C_o}{2.0+4.0i} \tag{5}$$

Table 2. The suggested values for the consequence index; SD: Slight Damage, MD: Moderate Damage, PC: Partial Collapse, and TC: Total Collapse; MSTL: Moderate Short-Term Loss, MLTL: Moderate Long-Term Loss, SSTL: Significant Short-Term Loss, and BC: Bridge Closure; MC: Material Costs, UC: User Costs, and LL: Life Loss

Conseq-uence index	**Damag e state**	**Loss of traffic state**	**Associated costs**
1.0	SD	None	
			MC
2.0	MD	None	
			UC
2.0+0.5i	MD	MSTL	
			UC
2.0+i	MD	MLTL or SSTL	
			UC+LL
2.0+2.5i	PC	BC	
			LL
2.0+4.0i	TC	BC	

Table 3. The proposed values for the factor i for each FHWA highway class and FRA track class

i	FHWA functional class of highway	FRA track class
4.00	Principal arterial - interstate	
3.50		9
3.00		8
2.50		7
2.25	Principal arterial - other freeway/expressway	6
1.75		5
1.50		4
1.25	Principal arterial - other	3
0.75	Minor arterial	2
0.50	Major and minor collector	1
0.25	Local	Excepted

3.5 Aggregation of indices, visualization of prioritization results, and the overall framework

3.5.1 Risk index

Many aggregation methods exist. Despite its transparency and intuitiveness, the weighted sum method is regarded as not suitable here as it can lead to mistaken conclusions. For instance, consider the situation of having two climate change risks, one scoring a 0 for VI but very high for the other indices and is consequently assigned a weighted sum risk index of, for example, 0.6 and the other scoring a 0.5 in every index and therefore assigned a weighted sum risk index of 0.5. In this case, the first climate change risk would be prioritized even though the second is clearly more critical. The weighted product method is selected in this study for its simplicity, ease of application, and because it resembles the basic risk equation, Equation 1, in multiplying the different risk elements. For the risk index, the upper and lower limits, UL and LL respectively, are calculated using Equations 6 and 7 as follows:

$$LL = N_h^{0.25} \cdot I_{low}^{0.25} \cdot VI^{0.25} \cdot C_{on}^{0.25} \tag{6}$$

$$UL = N_h^{0.25} \cdot I_{high}^{0.25} \cdot VI^{0.25} \cdot C_{pn}^{0.25} \tag{7}$$

It can be seen that the difference between LL and UL is caused by using I_{low} and C_{on} in the former, in contrast to using I_{high} and C_{pn} in the later. The same value for VI is used in both equations as the uncertainty in vulnerability is implicitly included in assessing C_{on} and C_{pn}. A neutral attitude is adopted in assigning the proposed weights in Equations 6 and 7. They are assigned keeping in mind that in the basic risk equation, Equation 1, each of the four main risk elements, i.e. hazard, exposure, vulnerability, and consequence, contribute equally to the risk value. Hence, each component is given a weight of 0.25. Depending on the preference of the decision maker these weights can be modified.

3.5.2 Uncertainty index

In the previous section, the uncertainty in the magnitude of each risk is represented in the values of UL and LL of the risk index. On the other hand, the uncertainty associated with climate projections and the strength of evidence supporting the increase of each exposure is reflected in the framework by an Uncertainty Index (UI) that is calculated as follows:

$$UI = C \cdot E \tag{8}$$

3.5.3 Ranking index and risk visualization

For ranking the risks, the decision maker may choose to use only the UL, the LL, or a combination of both depending on the information available at the time to guide their decision (e.g., which GHG scenario is more likely to unfold) and their preference. The UI and the difference between UL and LL may also play a considerable role in the prioritization depending on the decision maker's attitude. Visualization of the different indices may also facilitate the assessment of the criticality of the different risks. Figure 1 shows two possible visualization methods. The proposed framework is summarized in Figure 2.

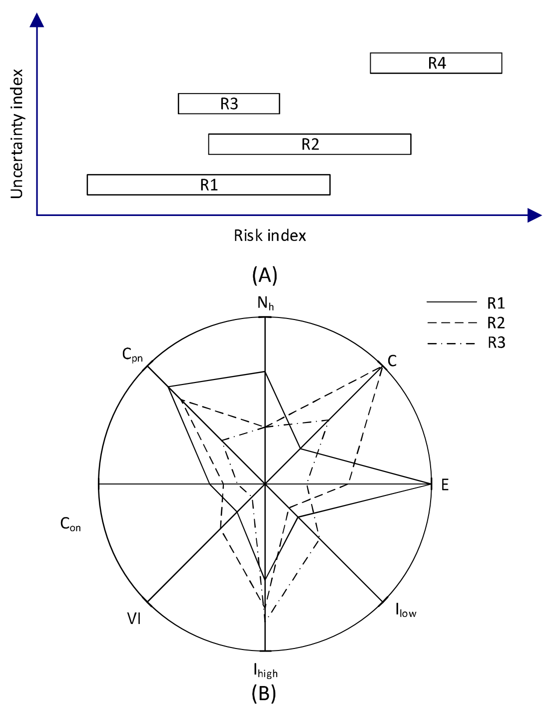

Figure 1. Two possible methods for the visualization of the risk and uncertainty indices (A) and prioritization indices (B)

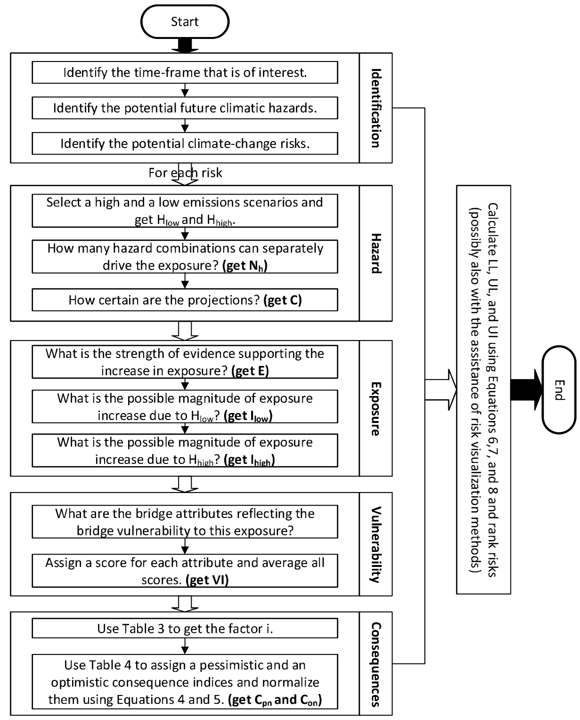

Figure 2. Flow chart of the proposed prioritization framework

4. Conclusions and limitations

In this work, a qualitative climate-change risk prioritization framework for bridges was proposed. Prioritization indices representing the main risk components are first defined. Afterwards, a method for aggregating these different prioritization indices into a single ranking index is presented.

Nevertheless, it is worth noting that, as any other decision making tool, the proposed framework has some limitations. First, the versatility of the framework across the different emissions scenarios is questionable. For example, if RCP 4.5 and RCP 6.0 were to be used instead of RCP 2.6 and RCP 8.5, how would the ranking be affected? Other limitations concern the proposed aggregation function. Firstly, it is obvious that two different combinations of the indices may result in the same risk index, i.e. the function is non-injective. This may imply that both climate-change risks are equally critical which is an erroneous interpretation. The defined uncertainty index and risk visualization methods can be helpful in such situations. Secondly, the proposed aggregation function is also non-surjective, which means that not all values of the risk index in the range from 0 to 1.0 are attainable. This is a result of using discrete values for some of the prioritization indices. Therefore, a climate-change risk assigned a risk index of 0.6 should not be interpreted as twice as risky as another that is assigned a 0.3 risk index. However, the problem at hand has such a high degree of uncertainty that any ambition of absolute objectivity could be counterproductive. Hence, these limitations are judged as minor and the proposed framework can well serve its purpose of providing a qualitative ranking of climate-change risks on bridges. The outcome of this work is a step forward towards an improved climate change risk management for bridges.

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