Climate change impact on safety and performance of existing and future bridges

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ABSTRACT: Recent decades have seen an increased attention towards the threat of climate change to our built environment and not least our infrastructure. Accounting for the different ways in which potential climate change scenarios can affect our infrastructure is paramount in determining appropriate adaptation and risk management strategies. This paper presents the initial findings of a new research project which is concerned with establishing an improved management of the risks to our infrastructure, especially bridges, in light of a changing climate. In this paper, a preliminary survey of the climate change related risks on bridges is conducted. Timely consideration of these impacts is of utmost importance to ensure a satisfactory performance of our bridges in the future. The interplay between the different risks and how the occurrence of one risk may influence other risks is also briefly discussed. The future stages of the project are mentioned as well.

1 INTRODUCTION

Climate change and its impacts on our infrastructure and built environment have gained considerable attention within the research community recently. Significant changes in our climate are already observed and climate change projections point to further changes in the not so distant future; changes which are likely to have a substantial impact on our built environment (IPCC 2014). The dire potential consequences of climate change necessitate prompt action not only in mitigating greenhouse gas emissions but also in adapting and preparing our infrastructure and built environment to these impacts. Furthermore, the design codes and standards for inspection and maintenance for the built environment need to be revised and updated to more appropriately treat the increased risks our future climate may impose.

The urgency for addressing these issues is further underscored by the fact that any proposed change to current engineering practices need to be strongly justified and well established before finding its way to the design codes and standards. As a general rule, stringent validation and testing of any suggested modification to the design codes and standards is necessary before these can be implemented. As an example, (Meyer 2008) mentions the lengthy process of introducing the Superpave program into pavement design specifications. Although it was in the early 1990's that a preliminary decision to implement the research findings was taken, it was not until 2005 that the new design standards and specifications were actually adopted.

In addition, it is important to consider that in planning major protection projects, e.g. storm surge barriers, there is often a lead time which is needed before these projects can be started. This period of time is required for gaining public support, securing the necessary funding for the project, making assessments, preparing designs, obtaining permits, etc. (Hill 2012). The MOSE project in Venice, Italy is a stark example of how long such projects can take. The project was prompted by the 1966 flood, almost 50 years ago, and is as of yet not operational. This project had a lead time of 37 years. Another example is the Maeslant storm surge barrier in Rotterdam, the Netherlands. In the wake of the 1953 flood, the Dutch government launched the Delta Works project with the Maeslant barrier as one of its main components. The construction of the barrier did not, however, start until 1989 and it was fully operational in 1997; corresponding to a 36 years lead time (Hill 2012).

This paper provides some preliminary results from the first stages of a new research project which is concerned with the treatment of climate-change related risks to existing and future bridges. The project, entitled 'Climate change impact on safety and performance of existing and future infrastructures' is being conducted as a PhD project at Lund University, Sweden, with primary funding from the Swedish

Transport Administration. Bridges are of particular and immediate relevance for climate change impacts as these structures are built with a considerably long service life, sometimes exceeding 100 years. Furthermore, as part of the transportation network, they represent a cornerstone of the resilience of communities through a complex interaction with other types of critical infrastructure. The research project aims to answer and/or provide insight to the following questions:

- What are the additional risks introduced by climate change to our bridge stock?
- Can we prioritize these risks? In other words, which of these risks are more critical and require closer investigation?
- Is it possible to quantify these critical risks?
- Are the current design, inspection, and maintenance practices adequate to ensure a satisfactory performance in the face of these risks?
- How can we improve the current design, inspection, and maintenance practices to better address future impacts and demands? What is the most cost-effective way of doing so?
- How can an adaptation framework be developed and demonstrated by application in case studies?

In this paper, which represents the very initial stage of the project, first the projected future climate changes are discussed. Afterwards, an attempt to link these climate changes to some of their potential consequences on bridges is made. This is done by reviewing the published literature on the topic and looking at documented cases of bridge failure. Some of the most pertinent risks are presented in more detail followed by a brief summary of some of the other possible risks. However, no inference about risk prioritization or the criticality of each risk should be made from the order and/or level of detail in which the different risks are discussed at this stage, more elaborate results are expected as the project progresses. Finally, the authors demonstrate some of the ways in which these risks may interact with one another together with some hints on risk prioritization. This study is only a preliminary overview of the potential impacts of climate change on bridges and is in no way comprehensive or all-inclusive; a more extensive study is planned in the future.

2 EMISSION SCENARIOS AND THE RELEVANT PROJECTED CLIMATE CHANGES

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2013, IPCC 2014) considers four different scenarios of Greenhouse gas (GHG) emissions. These different scenarios are described by their approximate values of Radiative Forcing (RF), in W/m^2, either at the year 2100, or at stabilization afterwards (if they stabilize after 2100), in comparison to the preindustrial levels, defined as the year 1750. Radiative forcing is a measure of the change in energy flux per surface area. A positive RF results in surface warming and vice versa (IPCC 2013).

The four scenarios introduced are RCP2.6 (Representative Concentration Pathway 2.6 (based on RF of 2.6 W/m^2)), RCP4.5, RCP6.0, and RCP8.5. The RCP 2.6 scenario represents a scenario in which stringent mitigation measures would be taken to limit GHG emissions in such a way that RF peaks at approximately 3 W/m^2 before 2100 and then declines. At the other end of the spectrum, the RCP8.5 scenario represents a scenario of unchanged current GHG emission trends by midcentury (IPCC 2014) in which RF reaches greater than 8.5 W/m^2 by 2100 (IPCC 2013). The range of scenarios considered by the IPCC is a reflection of the large degree of uncertainty concerning the predicted severity of long-term climate change impacts and highlights the importance of mitigating actions to minimize these effects.

The magnitude of climate change and the accompanying phenomena is strongly dependent on the considered scenario. Figure 1 presents the projected changes in global average surface temperature for the different scenarios as an example (IPCC 2013). However, projections for the different scenarios show an agreement on the following changes, which are of relevance to our infrastructure:

- Higher global mean temperatures. It should also be noted that temperature change will not be regionally uniform (IPCC 2013).
- Heat waves with unprecedented intensities and frequencies (The World Bank 2012).
- Increase in solar radiation due to stratospheric ozone depletion (Andrady et al. 2003).
- Increase in precipitation intensity and frequency in some regions, in other words many wet regions will become wetter (IPCC 2013).
- Decrease in precipitation intensity and frequency in other regions, in other words many dry regions will become drier (IPCC 2013).
- The contrast of precipitation between wet and dry regions will increase as well as that between wet and dry seasons (IPCC 2013).
- Increase in snowfall in some regions (IPCC 2013).
- Increase in surface specific humidity over land (IPCC 2013).
- Increase in intensity and frequency of extreme wind events (IPCC 2013).

- Higher soil salinity in some regions (Dasgupta et al. 2015).
- More violent and more frequent storms (IPCC 2013).
- More likely than not, an increase in the frequency of high-intensity tropical cyclones (IPCC 2013).
- Sea level rise (IPCC 2013)
- Higher carbon concentrations in the atmosphere and in the oceans (IPCC 2013).
- Higher ocean temperatures (IPCC 2013).
- Higher seasonal variations in wind speeds in some regions, more specifically faster speeds in winter and slower speeds in summer (Mideksa et al. 2010).

Aside from these changes, of particular interest for understanding some high-impact events are compound events when two or more anomalous, but not necessarily, extreme events occur simultaneously or in sequence. (van den Hurk et al. 2015) presents as an example an event with high precipitation over the river Rhine catchment area followed by a storm surge leading to extreme flooding along coastal areas in the Netherlands. Evidence for changes in such compound events is generally less robust than for individual extremes as the ones listed above.

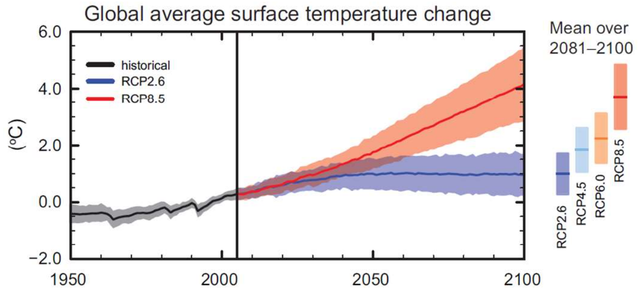

Figure 1. Changes in the global average surface temperature relative to 1986-2005 for the different emission scenarios (IPCC 2013).

3 CLIMATE-CHANGE IMPOSED RISKS ON BRIDGES

In this section, preliminary findings focusing on outlining some of the most pertinent risks to bridge infrastructure are presented.

3.1 *Accelerated degradation of structural and non-structural elements:*

Several aspects of the future climate tend to result in an increased rate of material degradation. As discussed in the previous section it is projected that in the future we will have higher temperatures, increase of precipitation in some regions, increase in surface specific humidity, and higher atmospheric carbon concentrations. All these factors may increase the risk of deterioration of the different materials used in bridges. In (Stewart et al. 2011), e.g., the authors assessed the risk of corrosion initiation and corrosion damage for concrete infrastructures in two Australian cities, Sydney and Darwin. The results of this study provide a clear example of how this risk may increase due to climate change. For instance, the study indicates that by the year 2100 the risk of carbonation induced corrosion may increase by more than 400% in some regions. It is reasonable to assume that bridges made of steel would be susceptible to an increased risk of corrosion as well.

On the other hand, timber bridges have their own set of problems that may result from changes in climatic conditions. Increased risk of photodegradation may be one of the relevant threats of climate change to timber bridges. According to (Andrady et al. 2003), photodamage to synthetic and naturally occurring materials is highly affected by the UV-B component of solar radiation. Materials that are especially sensitive to this risk are plastics, rubber, and timber (Andrady et al. 2003).

Biodegradation of materials due to climate change is also worthy of attention. Noting that this is already a well-known problem for timber structures, future climatic conditions may provide more favorable environments for the growth of organisms that cause biodegradation. The obvious climate changes that affect this are temperature, surface specific humidity, and precipitation. In addition, some bacteria that obtain carbon from carbon dioxide and energy from light may benefit from the increased abundance of carbon in the atmosphere (Moncmanová 2007). (Moncmanová 2007) also notes that, although the PH of freshly poured concrete is approximately 11-12.5 which prevents the growth of bacteria, this PH is gradually reduced to approximately 9-9.5 which can support the growth of bacteria. It is probable that climate change result in a faster rate of PH drop due to the excess carbon in atmosphere.

3.2 *Higher flood levels and more frequent flooding:*

Despite the fact that floods have always been a cause of concern for the safety of infrastructures, including bridges, several studies (Hoeppe 2015, GDV 2011, Batchabani et al. 2016) signal that the risk of flooding is very likely to increase significantly in the future. Climate change, specifically higher temperatures and the accompanying accelerated melting of ice sheets, lead to sea level rise. Moreover, more intense and more frequent precipitation, expected in some regions, further exacerbates this risk. Additionally, in a World Bank study (The World Bank 2012) it is mentioned that changes in ocean PH, water temperature, and intensity and frequency of tropical cyclones may have considerable negative effects on the growth of coral reefs; reefs which provide natural protection against coastal flooding (The World Bank 2012).

In a study conducted by the German Association of Insurers (GDV 2011) future insured losses due to flood events were modeled for Germany. In (Hoeppe 2015) the author notes that, one of the main results of the previously mentioned study (GDV 2011) is that extreme floods will be more frequent in the future. For example, the study states that a flood that currently has a 50 year return period will only have a 20 year return period within the next 30 years. In another study (Batchabani et al. 2016) the flood level rise as a result of climate change in the Riviere Des Prairies Basin, Quebec, Canada was simulated. It was shown that the flood levels for the projection period, from 2040 to 2060, will result in total submersion of two bridges in the studied area.

3.3 *Damage to pavements and railways:*

In (Meyer 2008) it is stated that pavements will possibly be most damaged by the projected changes in temperature. The author notes the damages which occurred during the Chicago 1995 heat wave that was reported in (Changnon et al. 1996) as an example. In (Changnon et al. 1996), the observed heat induced movement of rails was also determined to be one of the main causes of a train accident. Movements and deformations of rails on bridges may also induce higher lateral loads from passing trains. It is noteworthy that these rail deformations can have a significant influence on the bridge-train dynamic interaction. The effect of track geometric imperfections on the dynamic amplification of internal forces in railway bridges is discussed in (Amaral & Mazzilli 2017). The projected increase in precipitation intensity and frequency in some places are other factors which could increase the risk of pavement damage.

3.4 *Higher scour rates:*

Several studies have shown that a common initiating cause for bridge failure is hydraulic failure or scour. In (Taricska 2014) bridge failures during the period 2000-2012 in the United States were analyzed. In this study, it was found that bridge failures due to hydraulic causes represented around 50 percent of the studied cases; hydraulic causes were divided into floods and scour with the latter occurring more often. In (Cook et al. 2015), which analyzed bridge failures using the New York State Department of Transportation (NYSDOT) database for the period 1987-2011, scour was also one of the most frequent causes of failure.

In the future, higher scour rates in some regions are more likely for several reasons. First and foremost, significantly higher average annual runoff, due to higher precipitation, is projected over 47 percent of the world's land surface (Arnell & Gosling 2013). Consequently, considerably higher flow speeds are expected which will in turn substantially affect scour rates (Yazdanfar et al. 2017). Accounting for seasonal variations will further contribute to this effect. Furthermore, higher temperatures and snowmelt will result in higher water levels which may also affect scour rates, however to a lesser extent (Yazdanfar et al. 2017). Moreover, bridges located in areas where permafrost exists will probably be subjected to higher scour rates due to the additional runoff from the melting permafrost. In addition, several relationships for calculating the sediment critical shear stress, e.g. the equation suggested by (Soulsby & Whitehouse 1997), suggest that a decrease in the viscosity and/or density of water, which are both associated with the projected warmer climate, leads to smaller sediment critical shear stress and hence easier scour initiation. Both, general scour at the bridge site and local scour around bridge piers may be affected by the previously mentioned factors.

3.5 *Other risks:*

In the context of climate change, several other risks to bridges may arise or increase. Higher deformation capacities will be required due to the projected higher future temperatures. Considering that these deformations are not accounted for in the design of these bridges, additional restrained thermal stresses will arise. Due to higher temperatures more frequent wildfires, probably also more intense, are expected, putting bridges in the vicinity at higher risk.

More violent storm surges will also be a significant risk to bridges. In hurricane Katrina 2005, it was reported that storm surges resulted in lifting bridge decks off of their supports (Meyer 2008). This risk will be influenced not only by the more frequent more extreme hurricanes but also by sea level rise giving the surges a higher level to be launched from as well as the higher waves predicted for the future. A similar incident was reported during the 2011 Great East Japan Tsunami. The failure of the Utatsu highway bridge during this event was baffling. Although the unseating prevention devices connecting the deck to the abutments and piers were found to be undamaged after the event, some of the displaced decks were found flipped over (Bricker et al. 2012, Bricker & Nakayama 2014). The authors in (Bricker et al. 2012, Bricker & Nakayama 2014) point that the failure of the Utatsu highway bridge was the result of the unfortunate agglomeration of several factors including deck superelevation (due to the horizontal curve in the highway at the bridge location), presence of trapped air between bridge girders, and the presence of a seawall near the bridge. In (McGuire 2012), although contradicting other studies (e.g. (Hoeppe 2015)), the author suggests that climate change can, among other hazards (e.g. earthquakes and volcanos), trigger tsunamis. The risk of insufficient capacity of our drainage systems is also presumable due to the projected changes in precipitation.

The effect of climate change, more specifically changes in temperature and relative humidity, can substantially affect the loss of pre-stressing force in pre-stressed bridges. Similarly, the stressing force of stress-laminated timber decks in timber bridges can be affected (Leonardo da Vinci Pilot Project TEMTIS 2008). Another potential risk for timber bridges that warrants consideration is related to the Mechanosorptive effect. With an increasing frequency of wetting and drying cycles, timber elements exhibit excessive deformations leading to failure under significantly smaller loads when compared to the initial design load. Taking into account that the seasonal contrast in precipitation is projected to increase, this is a reasonable concern.

In (Toll et al. 2012) the authors present ways in which soil can bring about a number of additional risks in the context of climate change. Depending on the region, the Ground Water Table (GWT) may either be expected to rise or drop as a result of changes in precipitation. In the case of a GWT drop, an increase in the effective stresses will result in higher consolidation settlement. One may think that this risk is exclusive to bridges on shallow foundations; however, bridges on pile foundations can also be affected. In pile foundations, the settlement of the surrounding soils results in negative skin friction thus possibly overstressing the piles beyond their capacity. GWT lowering can also pose an additional risk on wooden piles as it makes the top of these piles exposed to aerobic conditions and biodegradation can start. Loss of buoyancy force and the subsequent increase in pile stresses can also be a problem. On the other hand, in (Toll et al. 2012) it is demonstrated that GWT rise comes with its own set of risks.

The stability of side slopes is jeopardized by the rise of GWT; the potential death of some vegetation species due to the elevated future temperatures may further aggravate this problem. This is due to the loss of the contribution of vegetation to slope stability, see for example (Wu et al. 1979, Chok et al. 2004). Also, more frequent extreme winds, beside the potentially higher risk of aeroelastic instabilities (Seo & Caracoglia 2015), can result in faster erosion of side slopes and increase the risk of slope failure. Increased risk of landslides can also be expected. GWT rise can also lead to collapse settlement. Soils in which particles are bond together with forces that are sensitive to water, e.g. suction forces in the pore water and inter-particle cemented bonds, collapse after coming in contact with water due to GWT rise and consequently settlement occurs. Higher hydrostatic pressure behind abutments and retaining walls as a result of GWT rise is also plausible (Meyer 2008). In seismically active regions, GWT rise can considerably raise the risk of soil liquefaction (Arab et al. 2011).

As can be seen, a broad range of risks is foreseeable, however further research is needed before any conclusive remarks about their severity, or even plausibility, are made. Figure 2 provides an overview of the risks presented in this study with the projected climate changes which affect them. Different line types are used to connect the different elements of climate change to their potential risks.

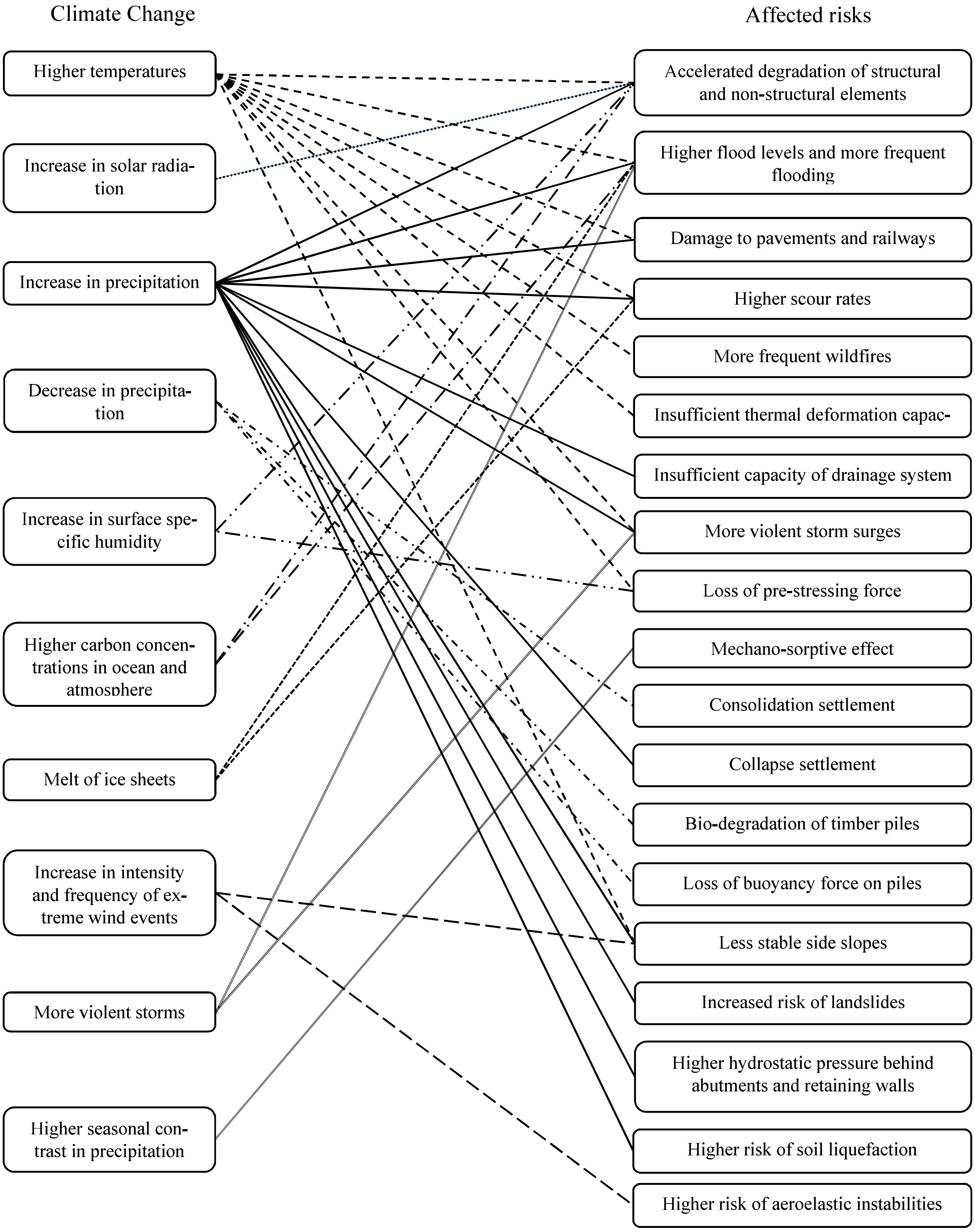

Figure 2. Increased risks on bridges due to climate change, examples.

4 THE INTERCONNECTEDNESS OF RISKS AND RISK PRIORITIZATION

Bridge failure is in most cases attributed to the combined effect of multiple causes (Hong et al. 2012). It is therefore extremely important to address the different potential risks in a holistic way rather than in isolation from one another. As an example, if collapse settlement takes place, due the rise of GWT, in a region that is flood prone an increased risk of flooding is presumable. In addition, if a landslide happens there is the possibility of closure of expansion joints in bridges which will consequently further decrease the bridge deformation capacity. This problem may be compounded for bridges sensitive to restrained cracking as a result of thermal actions. The Deer Creek bridge, Saskatchewan, Canada is an incidence where expansion joints closure of 13-80 mm was recorded due to an active landslide (Kelly et al. 1995). There are many ways in which such compound risks can contribute to bridge failure.

Many factors come into play when risk prioritization is aimed for. For a meaningful prioritization of risks for a given bridge, several important questions should be answered. Where is the bridge located? Does it cross a waterway? Is it located in a seismically active zone? Is the region flood prone? Will the likelihood of compound events to occur change with a changing climate? What is the structural material? What is the foundation type? What is the bridge type (structural system)? What is the soil type? Etc. The scour risk, for example, will be ranked higher on the prioritization list for a bridge on a shallow foundation compared to one on a deep foundation. Other factors that will also play a role in the severity of the scour risk are the geometry of the foundation, bed material, and bed protection (armoring) among others (Björnsson 2015). In addition, the potential consequences of each risk should also be considered in risk prioritization. Risks that pose a threat to the serviceability of the bridge should have a lower ranking than those that may result in a bridge failure. This task will be addressed in detail in a later stage of this project.

5 CONCLUSIONS

The projected future changes in our climate can seriously affect the performance and safety of our built environment. Due to their relatively long service life, bridges are one of the most relevant infrastructure elements in this regard. Nevertheless, the effects of climate change on the safety and performance of bridges have, up to now, received very limited attention. As an attempt to fill this void in scientific literature, a project was started with the aim of ensuring a reliable performance of bridges in the light of climate change.

As an initial stage of the project, this paper presents a preliminary survey of the climate-change imposed risks on bridges. Timely consideration of these impacts is of utmost importance to ensure a satisfactory performance of our bridges in the future. The possibility of interaction between the different risks and how the occurrence of one risk may influence other risks was also briefly discussed.

The first stage of this research project, initiated by this study, is to thoroughly survey the potential increase of risks on bridges due to climate change. Then, a qualitative risk assessment will be carried out for different types of bridges in order to rank and prioritize these risks. Afterwards, a more detailed quantitative risk assessment of the most critical risks is planned. Building on the previous stages, an adaptation framework will then be developed. Finally, as a project capstone, several case studies are used to demonstrate the applicability of the developed framework.

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