A review of the potential impacts of climate change on the safety and performance of bridges

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An overabundance of evidence, both observational and from model projections, indicate that changes to the climate system are taking place at unprecedented rates. Although the magnitudes of these changes involve large uncertainties, the fact that our climate is changing is unequivocal. To ensure an unimpaired functionality of our societies, with an acceptable level of safety and performance it is therefore of crucial importance to study the potential impacts of these changes on the different sectors of infrastructure. Taking into account that bridges have a considerably long service life, sometimes surpassing 100 years, it is of direct relevance to ascertain their reliable performance against climate change risks. This paper synthesizes the findings of over 190 research articles to identify the potential risks climate change may pose on bridges. Over 30 potential risks, supported by pertinent previous bridge damage (or failure) cases, are identified, categorized, and linked to the projected future climate changes. The identified risks can be used as a basis for future risk prioritization by bridge managers.

Keywords: climate change; risk; bridges; infrastructure safety

Introduction

The more we proceed towards the future, the clearer it becomes that significant changes to our climate are taking place. Not only is it being observed that our climate is changing in an unprecedented pace in comparison to the preindustrial climate but also, further changes, potentially with even faster rates than the ones observed so far, are consistently being projected by Global Circulation Models (GCMs). Such changes may induce unforeseen, or increase currently existing, impacts on several sectors including, but not limited to, the different elements of the infrastructure. The potentially severe climate impacts on infrastructure necessitate timely and unfaltering measures, not only to mitigate Greenhouse gas (GHG) emissions by introducing international environmental agreements, e.g. the 2015 Paris agreement (UNFCCC, 2015), but also in terms of adapting existing infrastructure and increasing its resilience against such impacts. In addition to adaptation, reforming maintenance and inspection manuals in order to accommodate the effects of climate change is also relevant for existing infrastructure. With regards to infrastructure to be built in the future, a revision of the design codes to account for the effects of climate change is essential.

The imperativeness for studying the effects of climate change on infrastructure is also highlighted by several other factors. For instance, any proposed alterations to the currently accepted engineering practice must be strongly supported by research results; well-established; and critically scrutinized by the engineering community prior to being considered for adoption in codes of practice. Considering how lengthy this process may be, the urgency for addressing climate change effects can be easily comprehended. As an example, Meyer (2008) refers to the prolonged process of implementing the Superpave program in the pavement design standards. Despite an initial decision to introduce the program in the standards in the early 1990s, it was only in 2005, i.e. approximately 15 years after the initial decision, that the standards were actually updated to include the amendments. Two other stark examples are mentioned in Borges (1997). Although the principle ideas were articulately introduced in a 1926 thesis titled “The Safety of Constructional Works and its Design According to Limit States Instead of Permissible Stresses” by Mayer (1926), it was not until the mid-1940s that limit state methods first found their way into codes of practice of the former Soviet Union. The time needed to introduce these methods into other design standards was even longer. Moreover, the partial safety factors design method currently used in most codes of practice was not implemented until 1963 in the CEB recommendations (Comité Europeen du Beton, 1963), even though the foundation for this method was already laid in the late 1940s in the pioneering work of Freudenthal (1945) and Torroja & Paez (1949).

Another argument for the urgency of addressing climate change risks to Infrastructure is presented in Hill (2012). Hill (2012) observes that major protection projects, e.g. storm surge barriers, often require a considerable period of lead time for gaining public support, securing the necessary funding for the project, making assessments, preparing designs, obtaining permits, etc., before their construction is even initiated. Two examples of extended lead time are the MOSE project in Venice, Italy, and the Maeslant storm surge barrier in Rotterdam, the Netherlands. Although the former was triggered by the 1966 flood in Venice, close to 50 years ago, it is as of the time this research is conducted not yet operational. This project had a lead time of 37 years, i.e. it started in 2003. The latter project was launched by the Dutch government in the wake of the 1953 Rotterdam flood as an essential element of the Delta Works project. The construction of the barrier, which has been fully operational since 1997, did not, however, start until 1989; i.e. it had a lead time of 36 years.

Despite all these considerations, to date, only few studies have addressed the potential impacts of climate change on infrastructure (e.g., Kumar & Imam, 2013; Meyer, 2008; Mondoro, Frangopol, & Liu, 2018; and Schwartz, 2010). The purpose of this paper is to address this gap in scientific knowledge by investigating the potential risks climate change may induce, or increase, on bridges. Taking into account the fact that bridges have a considerably long service life, sometimes surpassing 100 years, it is of direct relevance to ascertain their reliable performance against climate-change risks. Furthermore, considering that climate change is projected to increase the frequency and intensity of some extreme events (e.g. floods) the importance of having resilient bridges that are able to maintain at least a minimum level of their functionality during these events and quickly recover afterwards is highlighted. This puts bridges at the forefront of climate-change relevant infrastructure. The paper synthesizes a broad list of the potential risks climate change may impose on bridges, independent of their likelihood or the consequences of their occurrence. Identifying all the rationally possible risks, irrespective of how low/impact or improbable they may seem, is vital to avoid leaving out critical risks that may appear trivial at first sight. The importance of developing an as complete as possible list of the potential risks at this stage of risk analysis, i.e. the risk identification stage, has been highlighted by several researchers; see, e.g., Chapman (2001), Kaplan, Haimes, & Garrick (2001), and Raspotnig & Opdahl (2013). Ruling out the uncritical and prioritizing the more serious risks will be addressed in further work. Although bridges are the main focus of the current paper, many of the identified risks can affect other infrastructure elements as well. This paper starts by providing an overview of the projected changes in the future climate. Next, the method used for identifying the potential impacts of these changes to bridges is outlined. The identified risks are then presented followed by a section highlighting some of the ways these risks may interact. Lastly, a section dedicated for discussing the implications of this study and further research directions is introduced.

Emission scenarios and the relevant projected climate changes

Numerous climate change scenarios have been defined in literature. However, in its fifth, and most recent, Assessment Report (AR5), the Intergovernmental Panel on Climate Change (IPCC) refers to four different scenarios, RCP 2.6 (Representative Concentration Pathway 2.6), RCP 4.5, RCP 6.0, and RCP 8.5 (IPCC, 2013; and IPCC, 2014). The number identifying each scenario represents the approximate Radiative Forcing (RF), in W/m^2, either at the year 2100, or at stabilization afterwards, in comparison to the year 1750; representing the preindustrial levels. Radiative forcing is a measure of the change in energy flux per surface area. Surface warming is a result of positive radiative forcing while negative radiative forcing results in surface cooling (IPCC, 2013).

The RCP 2.6 is a relatively optimistic scenario in which stringent mitigation policies would be implemented to limit GHG emissions. This scenario is characterized by a peak of 3 W/m^2 in RF that occurs before 2100 followed by a decline to a value of 2.6 W/m^2 at 2100 (IPCC, 2014). A rapid decline in oil consumption, a world population of approximately 9 billion by the year 2100, and a significant increase in the use of bio-energy are among the assumptions associated with this scenario (Van Vuuren et al., 2011). Under this scenario a warming of 0.3ºC to 1.7ºC by the end of the century is projected. At the other extreme, the RCP 8.5, a scenario of comparatively high greenhouse gas emissions, results in a RF of approximately 8.5 W/m^2 by 2100 (Van Vuuren et al., 2011). This is a highly energy-intensive scenario which assumes rapid population growth, with a population close to 12 billion by the year 2100, a modest income growth, and a low rate of technological development (Riahi et al., 2011; and Van Vuuren et al., 2011). The IPCC special report on global warming of 1.5ºC (IPCC, 2018) maintains that even pathways reflecting the current nationally stated mitigation ambitions, i.e. in the Paris agreement, would not limit global warming to 1.5ºC. According to Rogelj et al. (2016), such pathways imply a median warming of 2.6ºC to 3.1ºC by 2100. Regardless of which scenario the future unfolds (i.e. even in a 1.5ºC world), the future climate will be significantly different from that of today (IPCC, 2018).

Looking at the range of these scenarios and the many assumptions associated with them, the large degree of uncertainty involved in projecting the future climate becomes easily appreciable, not to mention the uncertainty added by the GCMs themselves. Therefore, the selected scenario strongly influences the magnitude of climate change and its different parameters or phenomena. For instance, Figure 1 illustrates the projections of the global average surface temperature for the four scenarios (IPCC, 2013). It should be noted, however, that there exists an agreement between the projections of the four scenarios on the trend of change of many climate parameters and phenomena. The climate changes relevant to this study are presented in Table 1.

In addition to the changes in Table 1, so-called compound events may also be influenced by climate change. Compound events are defined as instances where two or more events that are not necessarily themselves extreme happen simultaneously or shortly after one another leading to an extreme impact (IPCC, 2012). In January 2012, a near-flooding event took place in the Netherlands as a result of such compound events. An intense precipitation event over the Rhine catchment area followed by a storm surge resulted in this high-impact event (Van den Hurk, Van Meijgaard, De Valk, Van Heeringen, & Gooijer, 2015). However, changes in the patterns of such compound events due to climate change are generally supported by less robust evidence.

Method

In this work, close to 200 research articles were reviewed to construct a broad list of the potential impacts of climate change on bridges. The presented impacts were identified in three ways. Firstly, some of the presented risks were cited in previous literature as potential climate change risks, see; e.g.; Hultén, Andersson-Sköld, Ottosson, Edstam, & Johansson (2007); Kumar & Imam (2013); Meyer (2008); Schwartz (2010); and Stewart, Wang, & Nguyen (2011). Other risks were identified by reviewing documented cases of bridge malfunction, damage, or failure and investigating possible connections between these incidents and the climatic parameters that are projected to change in the future. Lastly some of the risks were identified considering the climatic parameters projected to change and attempting to elaborate scenarios in which they can affect the performance and/or safety of bridges. The last two methods for identifying climate change impacts are analogous to the two methods of risk identification described in Kaplan (1997); i.e., identifying possible end states and finding their possible causes (method 2) and identifying initiating events (a change in a climatic parameter in our case) and finding their possible consequences. The method used for identifying the presented risks is shown in Figure 2.

Climate-change imposed risks on bridges

In this section, a review of the potential risks on bridges as a result of climate change is presented. Although bridges are the main focus in this study, most of the mentioned risks can be extended to other types of infrastructure assets and systems. A total of 31 risks are identified and discussed. The different risks are grouped into seven main categories as follows:

- Durability (risk group D),
- Serviceability (risk group S),
- Geotechnical (risk group G),
- Increased demand (risk group I),
- Accidental loads (risk group A),
- Extreme natural events (risk group E), and
- Operational risks (risk group O).

Although most of the identified risks are a direct impact of climate change on bridges, a few only may affect bridges indirectly, i.e. they involve other external factors beside the climate and the bridge system; e.g., risk group A and risk O3. In addition, most of the discussed risks can, in the worst case, affect the safety of bridges, however some only concern the serviceability (e.g., risk S1 and risk I5) or operation (e.g., risk group O) of bridges.

Risk group D: Durability risks

Risk D1: Accelerated degradation of superstructure

One very relevant risk that climate change poses to existing bridges, and infrastructure in general, is an increased rate of material deterioration and degradation; see, e.g., Kumar & Imam (2013). Projected climate change like higher temperatures, increased precipitation in some regions, increase in relative humidity in some regions under some scenarios, and higher carbon concentrations in the atmosphere all promote accelerated deterioration. This observation is supported by a number of studies (e.g., Bastidas-Arteaga, Schoefs, Stewart, & Wang, 2013; Bastidas-Arteaga & Stewart, 2015; Chaves, Melchers, Peng, & Stewart, 2016; Köliö, Pakkala, Lahdensivu, & Kiviste, 2014; Stewart et al., 2011; and Wang, Stewart, & Nguyen, 2012). For instance, a recent study by Stewart et al. (2011) quantitatively assessed the risk of corrosion initiation and damage to concrete infrastructure under future climatic conditions in the cities of Sydney and Darwin, Australia. One of the conclusions of this study was that over a 400% increase in the risk of carbonation-induced damage is presumable by the year 2100 for some regions in Australia. Another study by Köliö et al. (2014) considered the effects of the higher carbon concentration and higher precipitation on corrosion initiation and the duration of active corrosion (after which the structure is assumed to have reached a predefined limit state) for concrete buildings in Finland. The results of this study showed that both corrosion initiation and the duration of active corrosion were likely to be adversely impacted by climate change. For instance, it was indicated that in Lapland a change in the duration of active corrosion from 37.5 years, for the 1980-2009 climate, to only 19.7 years is probable for the projected 2100 climate. However, as indicated in Bastidas-Arteaga & Stewart (2015), the potential drop in relative humidity, which is projected for many regions, can have some positive effects on the deterioration rate of concrete structures. It is reasonable to assume that this risk is also relevant to steel, and other metallic, elements as well. Examples of previous bridge failures that were, at least partly, attributed to corrosion are the Silver Bridge, Ohio, USA in 1967 and the I-95 over the Mianus River Bridge, Connecticut, USA in 1983 (Cook, Barr, & Halling, 2015; Lichtenstein, 1993).

The possible increase in solar radiation in some places raises concern for another degradation type risk, namely, photodegradation; see, e.g., Andrady, Hamid, & Torikai (2003), Chin, Nguyen, & Aouadi (1997), and Kumar & Imam (2013). According to Andrady et al. (2003), the increase in the UV-B component of solar radiation significantly affects light-induced damage of synthetic and naturally occurring materials. In this study it is pointed out that plastics, rubber, and timber are especially sensitive to this risk. Composite materials are also prone to degradation initiated by solar radiation (Chin et al., 1997; and Kumar & Imam, 2013).

Biodegradation of materials may also be influenced by the projected future climate changes (e.g., Kumar & Imam, 2013; and Moncmanová, 2007). The growth of organisms causing biodegradation is supported by the higher temperatures, higher relative humidity in some regions under some scenarios, and higher precipitation projected in the future. Timber is especially susceptible to this type of deterioration (e.g., Shupe, Lebow, & Ring, 2008). Furthermore, Moncmanová (2007) notes that higher atmospheric carbon concentrations may enhance the activity of some bacteria types that obtain carbon from carbon dioxide and produce energy from light. The author of the study points out that although concrete has a pH value of 11-12.5 when it is freshly poured, which prevents the growth of bacteria, the pH of concrete drops with time to reach a value of 9-9.5 which offers a more favorable environment for bacterial growth. It can be argued that, the increased abundance of atmospheric carbon, characteristic of the future climate, may accelerate this pH drop subsequently leading to faster biodegradation. Similar to biodegradation, it has also been noted that degradation of timber structures resulting from insect attacks may increase due to future climatic conditions, e.g. shorter and warmer winters that provide less harsh environments for these insects (Schwartz, 2010).

Further relevant risks include faster deterioration of concrete or steel structures as a result of either a more frequent application of de-icing salt (Cady & Weyers, 1984; and Darwin, Browning, Gong, & Hughes, 2008) in regions where snowfall is projected to increase or a possible increase in freeze and thaw cycles (Meyer & Weigel, 2011; and TRB, 2008). Regarding the latter risk, it can be noted that Pakkala, Köliö, Lahdensivu, & Pentii (2015) did not find a significant increase in the number of freeze and thaw cycles in southern Finland due to climate change. However, trends may be different in other regions (Meyer & Weigel, 2011; and TRB, 2008).

Risk D2: Accelerated degradation of substructure

Similar to the risk of accelerated degradation of superstructure elements, several aspects of the future climate can result in a more aggressive environment to bridge foundations. The projected higher future temperatures, change in relative humidity, lower ocean pH value (ocean acidification), higher soil salinity in some places (salinity intrusion), and higher carbon concentrations in ocean and atmosphere, all potentially contribute to a more corrosive environment. The extent of this problem is also dependent on the

Ground Water Table (GWT) level. In Mallick, Tawil, & Shibani (1989), e.g., it is stated that chemicals (e.g. sulfates and chlorides) in their dry state do not significantly increase the foundation deterioration rate. However, when these chemicals are present in the form of a solution in the ground water, a much faster deterioration is expected. As a result, the projected higher precipitation in some regions, which may lead to a higher GWT, further aggravates the risk of foundation deterioration.

On the other hand, the potential GWT drop, possibly occurring in regions of lower precipitation and/or increasing evaporation, may come with its own negative impacts on the foundation material (Toll et al., 2012). Wooden piles under the GWT are not exposed to aerobic conditions, and are therefore not susceptible to biodegradation. As soon as the GWT lowers, the part of the pile above water becomes exposed to aerobic conditions and biodegradation can start (Klaassen, 2015; Toll et al., 2012). This risk is also relevant to steel piles; see, e.g., Cheung, Walsh, Campbell, Chao, & Beech (1994).

It can also be mentioned that, taking into account that the corrosion rate is highest in the splash and low water zones, substructures supporting bridges in marine environments are often provided with additional corrosion protection over the length exposed to these zones; see, e.g., Corus Construction & Industrial (2005). This measure is taken to counteract the accelerated corrosion in these zones and reach the desired service life for which the bridge is designed. However, the projected Sea Level Rise (SLR) in the future implies that the length over which the substructure is exposed to the splash and low water zones will possibly shift upwards exposing unprotected portions to higher corrosion rates.

Risk group S: Serviceability risks

Risk S1: Heat-induced damage to pavements and railways

It has been argued that, the projected temperature rise and more frequent heatwaves may have significant impacts on both pavements and railways (Schwartz, 2010). Meyer (2008) references the Chicago 1995 heatwave event and the damage associated with it as an example. As reported in Changnon, Kunkel, & Reinke (1996) the heat-induced movement of rails was a main factor contributing to a train accident during the Chicago 1995 heatwave. Gudipudi, Underwood, & Zalghout (2017) studied the impact of the projected future temperature on the structural performance of pavement in the United States. The results of their study indicate that earlier pavement failure and/or greater distress are likely under future climate conditions. Another study by Anyala, Odoki, & Baker (2011) indicates that the expected cumulative rut depth in pavements may increase threefold by 2050 due to the projected temperature increases. The projected increase in precipitation in some regions may also affect this risk. In a case study for the UK, Hudson (2004) indicated that an increase of as much as 60 times in the annual road maintenance costs by the 2080s is possible due to climate change. For further reading on the possible effects of climate change on highway pavements, the reader is referred to Jeong, Kim, Kim, & Kim (2017), Kumlai, Jitsangiam, & Pichayapan (2017), Mallick, Jacobs, Miller, Daniel, & Kirshen (2018), Qiao (2015), and Willway et al. (2008).

Risk S2: Risk of increased long-term deformations

This subsection addresses the risk of long-term deformations, i.e. creep, which is not to be confused with the risk of increased demand on deformation capacity addressed under risk I4. It is well established in the literature that one of the factors governing long-term deformations of concrete, i.e. creep, is the ambient environmental conditions. The projected lower relative humidity over land, along with higher temperatures are identified in the literature as resulting in a higher creep rate for concrete; see, e.g., Bažant & Panula (1978), England & Ross (1962), Geymayer (1972), Nasser & Neville (1967), Razak (1986), and Vandamme et al. (2013). In a recent study by Bažant, Hubler, & Yu (2011) it is noted that creep problems are of considerable significance for bridges. The authors of this study demonstrate that, although mainly a serviceability problem, creep may lead to serious consequences. As an example, the authors cited the 1996 collapse of the Koror-Babeldaob Bridge in Palau (a segmentally erected prestressed box girder bridge with a world-record span of 241 m) which is said to have occurred as a result of excessive creep. The failure of this bridge draws attention to yet another potential risk; namely, the possible loss of prestressing force (risk I8). Measurements revealed that this bridge had on average a 50% loss of prestress due to excessive deformations (Bažant et al., 2011). In this study it is reported that 56 other bridges were identified to exhibit similar excessive creep deformations and it is stated that many more likely exist.

Timber is also susceptible to creep problems and, similar to concrete, the higher future temperature is likely to contribute to accelerated creep. However, moisture content also significantly influences the creep behavior in timber. A higher moisture content leads to higher creep rates and vice versa; see, e.g., Carll & Wiedenhoeft (2009). Noting that the moisture content increases with lower temperatures and higher relative humidity (e.g., Carll & Wiedenhoeft, 2009), the future climatic conditions may result in increased or decreased timber moisture content depending on the location. Another behavior that distinguishes timber from other materials is related to the mechano-sorptive effect; see, e.g., Holzer, Loferski, & Dillard (1989), and

Mårtensson (1994). Timber displays considerably higher deformations under the same stress level if exposed to more frequent and/or higher magnitude moisture content cycling. Therefore, a more frequent and/or higher magnitude of change in relative humidity will increase the risk of excessive deformations, possibly leading to serviceability problems under loads that are significantly smaller than the original design load (Honfi, 2013). The higher seasonal contrast in precipitation for some regions, projected in AR5 of the IPCC, may plausibly imply a higher contrast in relative humidity as well. Similar to the loss of prestress in prestressed concrete elements, stress-laminated timber bridge decks, which are mainly supported by pre-stressing forces connecting the timber laminations, are also susceptible to loss of pre-stressing forces due to changes in temperature and timber moisture content (Bell, 2008).

Risk group G: Geotechnical risks

Risk G1: Higher scour rates

Scour problems have been repeatedly demonstrated to be one of the most common initiating causes for bridges failure. Cook et al. (2015) surveyed bridge failures from the New York State Department of Transportation (NYSDOT) database for the period 1987-2011 and found scour to be one of the most common causes of failure. Many other studies reaffirm this conclusion; see, e.g., Arneson, Zevenbergen, Lagasse, & Clopper (2012), Briaud, Brandimarte, Wang, & D'Odorico (2007), Briaud, Gardoni, & Yao (2014), Flint, Fringer, Billington, Freyberg, & Diffenbaugh (2017), Kattell & Eriksson (1998), Stein, Young, Trend, & Pearson (1999), Stein & Sedmera (2006), and Taricksa (2014). Several empirical equations for predicting scour depths exist; see, e.g., Deng & Cai (2010). These empirical equations often link scour depths to the approach water depth, flow velocity, and the water kinematic viscosity; see, e.g., Froehlich (1989), Neil (1964), and Shen, Schneider, & Karaki (1969). According to these equations higher scour rates are associated with higher flow depths, higher flow speeds, and lower kinematic viscosity.

Considering climate change, higher future scour rates are likely for a number of reasons (RSSB, 2003; DoT, 2005; TRB, 2008; and Kumar & Imam, 2013). Arnell & Gosling (2013) studied the impacts of climate change on river flow regimes at the global scale. In their study, they concluded that over 47 percent of the world's land surface is projected to experience significantly higher average annual runoff. As a result, higher flow speeds, resulting in a substantial increase in scour rates, are expected. Another local factor that may lead to higher flow speeds is the additional runoff from the melting permafrost in places where they exist. Furthermore, due to sea level rise and increase in precipitation, higher future flow depths and/or velocities that may lead to faster scour rates are possible at many locations. Moreover, a warmer future climate results in a decrease in the kinematic viscosity of water and therefore the scour risk could be further increased. These factors of the future climate can affect the local scour around bridge piers and abutments as well as the general scour of the river bed at the bridge site. Several recent studies addressed the impact of climate change on this risk; see, e.g., Dikanski, Hagen-Zanker, Imam, & Avery (2016), Dikanski, Imam, & Hagen-Zanker (2018), and Kallias & Imam (2016).

Risk G2 and risk G3: Higher risk of bridge side-slope failure and higher risk of landslides

Due to their similar failure mechanisms and driving forces, this subsection discusses both the higher risk of bridge side-slope failure and landslides. However, these are presented as two separate risks as they may have totally different consequences. It is well established that one of the main triggering mechanisms of slope failure and landslides is intense rainfall events; see, e.g., Chen, Lee, & Law (2004). Kristo, Rahardjo, & Satyanaga (2017) studied the effect of variations in rainfall intensity on the slope stability in Singapore and observed a significant reduction, especially in the first half of the century, in the factor of safety of slopes due to the projected more frequent intense precipitation events. In Hultén et al. (2007) the impact of increased precipitation on the slope failure risk was assessed for two case study areas in Sweden; one in the south west, the Göta Älv valley, and one in the north, Krokvåg. It was concluded that, for all types of slopes in the studied areas, a reduced safety is to be expected. Several other studies also indicate that climate change will negatively impact slope stability and potentially lead to more frequent landslides (Ciabatta et al., 2016; Komori et al., 2018; and Robinson, Vahedifard, & AghaKouchak, 2017). It should be pointed out, however, that the results of some studies (e.g., Wu, Shih, Li, Su, & Chen, 2016) provide contradictory conclusions to the aforementioned risk of increased frequency of landslides as a result of climate change.

There are also other aspects of the projected future climate that may influence the stability of slopes and the occurrence of landslides. For example, the potential death of some vegetation species due to the elevated future temperatures may further jeopardize the stability of slopes. This is due to the loss of the contribution of vegetation to slope stability (Chok, Kaggwa, Jaksa, & Griffiths, 2004; and Wu, McKinnell III, & Swanston, 1979). Additionally, changing wind climate and faster water flows, as discussed under risk G1, can result in a faster rate of erosion of side slopes and consequently further increase this risk.

Risk G4: Higher risk of foundation settlement

A GWT rise, due to the increase in precipitation, or drop, due to the decrease in precipitation, may result from the projected changes in the future precipitation patterns.

As discussed in Toll et al. (2012), both changes in the GWT can heighten a number of settlement related risks. An increase in the soil effective stresses is a direct outcome of the drop in GWT due to the associated decrease in the pore water pressure. Therefore, higher consolidation settlement, as a result of this increase in effective stresses, is predictable. On the other hand, a rise in the GWT increases the risk of collapse settlement. Some soils are supported by water-sensitive forces between their particles, e.g. suction forces in the pore water or inter-particle cemented bonds. When these soils come in contact with water, which may result from GWT rise, these forces are lost, and the soil structure can no longer be supported by them which leads to settlement of the foundation. GWT rise can also increase the moisture content of clayey soils leading to a decrease in the modulus of deformation which in turn can significantly increase the settlement of clays. Furthermore, the formation of sink holes for soils in karstic conditions can also be affected by climate change. Caverns are formed when soluble rock formations, e.g. limestone and dolomite, get dissolved due to ground water flow. As long as these caverns remain full of water they are provided with a support preventing their collapse. However, when GWT drops these caverns collapse forming sink holes, which can seriously impact any structure in the region. Considering projected higher contrasts in seasonal precipitation in some regions, and the stronger seasonal fluctuations in GWT it may cause, this risk is of relevance to climate change. Lastly, permafrost melt due to the increase in temperature also increases the risk of settlement for bridges in such regions (Meyer, 2008).

Risk G5: Higher risks of rockfalls, debris flows, and snow avalanches

Similar to the risks of slope stability and landslides, higher risks of rockfalls, debris flows, and avalanches can be predicted; see, e.g., Collins & Stock (2016), Harris et al. (2009), and Stoffel, Tiranti, & Huggel (2014). In addition to the mechanisms mentioned for risks G2 and G3, melting permafrost can induce less stable rock slopes and cause debris flows (Stoffel et al., 2014). Furthermore, the higher future temperatures may also trigger rockfalls (Collins & Stock, 2016) and increase the risk of avalanches (Harris et al., 2009). The reader is referred to Gruber, Hoelzle, & Haeberli (2004), Harris et al. (2009), Stoffel & Huggel (2012), and Stoffel et al. (2014) for further reading on the risk of mass movements due to climate change. A textbook example of a bridge with a severe rockfall risk is the bridge at the Glenwood Canyon, Colorado, USA on the I-70 highway, where large rockfalls happened in 2005; 2010; and 2016. It is worth noting that the 2010 rockfall left the bridge deck punched. Another example is the Chediguan Bridge, China (He, Yan, Deng, & Liu, 2018). Due to an earthquake-triggered rockfall in May 2008 the bridge was destroyed. The bridge was then rebuilt and reopened for traffic almost one year after the incident. However, on July 2009, only 2 months after being reopened, the bridge was again destroyed due to a rainfall-triggered rockfall. On the other hand, the Ri di Rialp road Bridge in the Swiss Alps, which collapsed during a snow avalanche in 1998, highlights how consequential can the impacts of an avalanche be. Margreth & Ammann (2004) is referred for a further read on the latter incident.

Risk G6: Higher risk of soil liquefaction

Soil liquefaction is one of the main mechanisms causing damage to bridges during earthquakes (e.g., Youd, 1993). The failure of the Showa Bridge in the 1964 Niigata earthquake in Japan is often cited as a classical example; see, e.g. Youd (1993). Several studies (e.g., Nath et al., 2014; Nath et al., 2018; Obermeier, 1996; and Yilmaz & Bagci, 2006) show that shallower GWT are associated with higher liquefaction risk during an earthquake. This is explained by the reduction in the effective confining stresses resulting from the higher GWT which creates a more favorable condition for triggering liquefaction (Nath et al., 2018). Noting that a higher GWT is a possible consequence of climate change at some locations, a higher risk of soil liquefaction during earthquakes at seismically active regions is a plausible concern. In addition, some studies (e.g., Ekström, Nettles, & Tsai, 2006; Hampel, Hetzel, & Maniatis, 2010; McGuire, 2012; and Usman, 2016) argue that climate change can increase the frequency of earthquakes themselves, nevertheless other studies contradict this claim; see, e.g., Hoeppe (2015).

Risk G7: Additional loads on piles that may overstress them

The projected future climate changes may result in additional loads on piled foundations (Toll et al., 2012). Toll et al. (2012) gives two possible mechanisms for inducing these additional loads. Firstly, if the soil surrounding a pile settles, see G4, a downdrag force, referred to as negative skin friction, is exerted on the pile due to the friction between its shaft and the surrounding soil. This force can potentially overstress piled foundations and cause failure. Secondly, GWT lowering due to the decrease in precipitation can lead to the loss of buoyancy force and further overstress the piles.

Risk G8: Damage due to clay shrinkage and swelling

Shrinkage and swelling of clays during the dry and wet seasons respectively has been reported as a common cause of damage to buildings (Crilly, 2001; Sanders & Phillipson, 2003; and Toll et al., 2012). For instance, during the 1990s drought years in the UK over £1.6 billion of economic losses were linked to clay shrink/swell movements. Similar to buildings, bridges are also susceptible to this risk. The projected increase in seasonal contrast in precipitation, as well as the higher future temperatures that lead to additional evapotranspiration, may increase the severity of the drying and wetting cycles leading to more serious shrinkage and swelling damages (Capon &

Oakley, 2012; and Toll et al., 2012). In support of the effect of climate change on shrink/swell damages, Corti, Muccione, Kollner-Heck, Bresch, & Seneviratne (2009) attributes the observation that shrink/swell damages in France in the period 1989-2002 were double of those in the period 1961-1990 to climate change.

Risk group I: Increased demand risks

Risk I1: Higher wave impact on piers and abutments

In the IPCC (2013) report, several factors of the future climate, most importantly the faster winds in some regions, are projected to increase the frequency and height of extreme waves. Considering that wave impact is an important parameter in the design of bridge components, e.g. piers and abutments (Meyer, 2008), this increase in extreme waves can affect the safety of bridges.

Risk I2: Higher risk of wind-induced loads

The projected faster future winds in some locations pose a serious threat on our built environment in general and bridges in particular (Meyer, 2008). The effect of wind on bridges is described by a number of mechanisms; namely wind static loading, wind buffeting, vortex shedding, galloping, flutter, wake-induced loading, rain-wind instabilities of cables, and dry galloping of cables (Nikitas, 2011). Despite that the notorious failure of the Tacoma Narrows Bridge, Washington, USA in 1940 prompted intensive research on wind-induced loading, a lot of these mechanisms, and the parameters affecting them, are not yet fully understood. However, the intuitive assumption that higher wind speeds correspond to higher actions on bridges is generally true for many of these mechanisms; see, e.g., Nikitas (2011). Aside from the higher future wind speeds, the more frequent precipitation events increase the risk of rain-wind cable instabilities. Additionally, buffeting is also affected by wind turbulence intensity which may as well be influenced by climate change. In Seo & Caracoglia (2015), it is demonstrated that climate change can influence the flutter risk for long-span bridges. In another relevant study, Ryan, Stewart, Spencer, & Li (2016) studied the effect of climate change on wind failures of timber power pole networks. In this work, it is shown that, under a high-emissions scenario, approximately a 60% increase of wind failures in Brisbane, Australia is predictable for the period until 2070. A number of other studies also assessed the effect of climate change on this risk; see, e.g., Mudd, Wang, Letchford, & Rosowsky (2014a, 2014b), Rosowsky (2018), and Salman, Li, & Bastidas-Arteaga (2017).

Risk I3: Additional snow loads on covered bridges

The projected increase in snowfall intensity in some locations can put covered bridges at risk. Many covered bridges are still in operation, e.g. the Hartland Bridge in Hartland; New Brunswick; Canada and the Holzbrücke Bad Säckingen Bridge connecting Germany and Switzerland. Although most covered bridges are nowadays only open for pedestrians, some are still being used as traffic bridges, e.g. the Conwy Railway Bridge, North Wales, UK.

Risk I4: Higher risk of thermally-induced stresses

The projected temperature changes in the future climate may place an increased demand on the deformation capacity of bridges and potentially increase the restrained thermal stresses (Holper, Lucy, Nolan, Senese, & Hennessy, 2007; Karl, Melillo, & Peterson, 2009; Schwartz, 2010; TRB, 2008). This risk is demonstrated by the case of DuSable Bridge, Chicago, USA. During the July 2018 heatwave, this movable bridge that opens its decks to allow navigation in the Chicago River could not be opened due to the heat-induced closure of its joint. Thermally-induced stresses are of particular importance to bridges. For example, Hejnic (1988) found that the tensile stresses due to temperature gradients were larger than those due to the whole live load for the Klement Gottwald Bridge, Prague, Czech Republic. Furthermore, the possible higher solar radiation in some places may increase the temperature gradient between the top and bottom of bridge decks and result in stress increases.

Risk I5: Additional demand on drainage capacity

The projected increase in precipitation in some locations will place an increased demand, and possibly overwhelm, the drainage system of bridges. This risk is relevant to the whole urban drainage system and is not only particular to bridges; see, e.g., Berggren (2007), and Olofsson (2007).

Risk I6: Higher hydrostatic pressure behind bridge abutments

As discussed previously, precipitation is projected to increase in many locations in the future. Meyer (2008) notes that this increase in precipitation may result in a higher GWT in these locations leading to additional hydrostatic pressure building up behind bridge abutments.

Risk I7: Increased load on bridges with control sluice gates

Flood protection barriers, e.g. the Morganza spillway in Louisiana; USA (e.g., Balaguru & Gopu, 2016 and Rupnow, 2010), and flow control structures for irrigation purposes, e.g. Chamravattom Regulator cum Bridge and Koottayi Regulator Cum Bridge in Kerala; India (e.g., Abdul Hakkim, Praveena, Rakhi, & Ajay Gokul, 2013; and Ajith & James, 2016), are sometimes designed to serve as highway or railway bridges as well. The higher precipitation in some regions and SLR will increase the water head these structures are demanded to support and as a result additional loads on the abutments and piers of these structures will be introduced. This risk is also relevant for other hydraulic structures; see, e.g., Ankum (2002), Chanson (2004), Novak, Moffat, Nalluri, & Narayanan (2014), and Zevenbergen, Arneson, Hunt, & Miller (2012).

Risk I8: Increased stresses due to the faster loss of prestressing force

Loss of prestress is divided into immediate losses and time-dependent losses. Two major components of the time-dependent loss of prestress force are those related to creep and shrinkage; see, e.g., Aalami (1998), Hernandez & Gamble (1975), and Zia, Preston, Scott, & Workman (1979). As discussed in risk S2, several future climate changes may lead to increased creep and subsequently increased creep losses. On the other hand, shrinkage losses are also increased by the projected lower relative humidity (e.g., Aalami, 1998; Bažant & Baweja, 1995; Hernandez & Gamble, 1975; and Zia, Preston, Scott, & Workman, 1979).

Risk I9: Higher ice-induced loads

Ice affects bridges located in environments subject to ice covers in a number of ways; see, e.g., Beltaos, Burrel, Miller, & Sullivan (2003), Fransson (1988), and US Army Corps of Engineers (2006). Firstly, the temperature variations of the ice cover cause thermal ice expansion or contraction which exerts a lateral pressure on bridge piers (Fransson, 1988). Several bridges have been damaged by thermal ice pressure; e.g., the bridge at Kusforsen in Skellefte River, Sweden in 1980 (Fransson, 1988). Vertical forces on piers can also result from the vertical movements of the ice cover due to water-level fluctuations (US Army Corps of Engineers, 2006). Moreover, after ice cover break-up the dynamic force from ice floes collision with bridge piers, which is dependent on floe size and ice strength (Beltaos et al., 2003), can be significant. Lastly, ice jams under bridges can impose pressure on the piers, damage bridge superstructure; e.g. Honeymoon Bridge over the Niagara River, Ontario, Canada in 1936 and the Perth-Andover Bridge over the Saint John River, New Brunswick, Canada in 1987; increase the scour rate under bridge piers, or even cause severe floods (Beltaos et al., 2003).

Climate change may considerably influence river ice regimes (Beltaos, 2004) and consequently affect the severity of the mentioned impacts. A higher seasonal temperature contrast, which is projected by some studies at some locations (e.g., Imada et al., 2017), can increase the risk of thermal ice pressure. Increase in water level fluctuations, indicated in some rivers e.g. (Úbeda et al., 2013), may also increase the vertical forces on piers. Moreover, more severe ice jams may be assumed due to the higher temperatures and precipitation in the future. For instance, Beltaos & Burrel (2003) and Beltaos (2004) suggest that climate change can cause more frequent and more severe spring and mid-winter ice jams along many Canadian rivers. On the other hand, a lower dynamic impact from ice floes can result from climate change as the higher future temperatures can cause a decrease in the thickness (Prowse et al., 2011) and strength (US Army Corps of Engineers, 2006) of ice flues. The analysis of the Confederation Bridge, New Brunswick, Canada sensor readings (Brown, Tibbo, Tripathi, Obert, & Shrestha, 2010) supports this suggestion.

Risk group A: Accidental loads risks

Risk A1: Higher chance of water vessel collisions

It is well established that higher liquid water content leads to lower visibility during fogs (Houghton & Radford, 1938). This is again underscored by more recent studies, (e.g., Wu et al., 2007). Noting that under the projected future warming the in-cloud liquid water content of marine fogs is projected to increase (Kawai et al., 2016), a higher risk of ship collisions can be reasonably inferred. Qu, Wang, Zhang, Yang, & Gao (2015) maintains that climate change is at least partly responsible for the observed steady decrease in winter visibility over eastern China. The projected higher future waves in some places, as discussed in risk I1, can lead to more difficult navigation and further increase this risk. The 1980 Almö Bridge incident in Sweden, in which the bridge collapsed due to a water vessel collision, illustrates this risk. Another example, which happened in 1980 as well, is the collapse of a 396 m section of the Sunshine Skyway Bridge, Florida, USA due to a ship collision (Cook et al., 2015; and Wuttrich, Wekezer, Yazdani, & Wilson, 2001).

Risk A2, risk A3, and risk A4: Higher chance of vehicle-pier collisions, vehicle accidents, and train-pier collisions

Similar to risk A1, the reduced visibility during fogs increases the risk of vehicle-pier collisions. Furthermore, the projected increase in precipitation in some places leads to more slippery roads and increases the chance of such accidents. These two climatic factors can also lead to the risk of more frequent vehicle accidents. Although at first sight this risk may seem insignificant, more frequent vehicle accidents, as well as more frequent vehicle-pier collisions, increase the chance of bridge damage due to fire that may result from these accidents. According to Woodworth (2013), the risk of bridge fire exposure is strongly dependent on the likelihood of vehicle accidents to take place at the bridge. Lastly, a higher chance of damage to pavements and rails, as discussed in risk S1, can increase the occurrence of train derailments and consequently increase the chance of train-pier accidents, as well as vehicle-pier collisions and vehicle accidents. For more on the probabilistic analysis of vehicle-pier and train-pier collisions the reader is referred to Björnsson (2015).

Risk group E: Extreme natural events risks

Risk E1: Increase in intensity and/or frequency of floods

Flooding is known to be one of the most damaging natural hazards to Infrastructure, including bridges. Jevrejeva, Jackson, Grinsted, Lincke, & Marzeion (2018) maintain that one of the costliest effects of climate change could be the possible increase in the intensity and frequency of floods. Several studies (e.g., Batchabani, Sormain, & Fuamba, 2016; GDV, 2011; and Hoeppe, 2015), establish that a significant increase in the risk of flooding under the future climatic conditions is likely. In GDV (2011) for instance, it is stated that a flood that currently has a 50 year return period may only have a 20 year return period within the next 30 years. The projected SLR and increase in precipitation can aggregate causing higher and more frequent floods. Moreover, in The World Bank (2012) it is suggested that the projected decrease in ocean pH, increase in ocean temperature, and increase in the intensity and frequency of tropical cyclones can negatively impact the growth of coral reefs; reefs that naturally decrease the impact of floods. Beck et al. (2018) show that the annual expected damages from flooding would double without coral reefs. As an example of how devastating the impact of future floods to bridges can be, Batchabani et al. (2016) studied the effect of climate change on flood levels in the Riviere Des Prairies Basin; Quebec; Canada and found that flood levels for the period 2040-2060 will totally submerge two bridges in the study area.

In addition to exacerbating the risk of flooding, SLR can also pose considerable threats on existing and future bridge assets as well as other infrastructure; see, e.g., Meyer & Weigel (2011), Mondoro et al. (2018), and TRB (2008). For instance, Wu, Najjar, & Siewert (2009) estimated an inundation area of up to 3800 km^2 for the Mid- and Upper-Atlantic region of the United States by the end of the century. Furthermore, Mondoro et al. (2018) draws attention to the possibility that many coastal bridges, despite not being inundated by water, may become unusable as a result of the permanent submersion of roadways in coastal zones. Gornitz, Couch, & Hartig (2002), McInnes, Walsh, Hubbert, & Beer (2003), and Titus, & Richman (2001) are examples of other studies which address the potential impacts of SLR.

Risk E2: Increase in intensity and/or frequency of storms

The IPCC (2013) maintains that it is virtually certain, i.e. more than 99% probability, that since the 1970’s intense tropical cyclones have increased over the North Atlantic and it is more likely than not, more than 50% probability, that further increases will be observed in the future. Schwartz (2010) states that a storm event that had a 100 years return period in the past may now have a return period of only 20 years.

The devastating effects of storms to bridges have repeatedly been reported. In hurricane Katrina 2005, lifting and unseating of bridge decks due to storm surges was one of the main observed failure mechanisms (Meyer, 2008; and Padgett et al., 2008). In addition to the stronger and more frequent storms, the higher surge launching level offered by SLR and the projected higher future waves further exacerbate this risk.

Risk E3: Increase in intensity and/or frequency of wildfires

A considerable increase in the frequency and/or intensity of wildfires in some locations is predictable under the future higher temperatures and decreased precipitation in some locations; see, e.g., Kerr, DeGaetano, Stoof, & Ward (2018), Lozano et al. (2017), Song & Lee (2017), Strydom & Savage (2017), and Stambaugh, Guyette, Stroh, Struckhoff, & Whittier (2018). This increase places bridges, and other infrastructure, in the vicinity at an elevated risk. The damage of the famous Royal Gorge Bridge, Colorado, USA in the 2013 wildfire exemplifies this risk. Another incident that is arguably attributable to brushfires is the failure of the railroad bridge in San Saba, Texas, USA also in 2013

(Brun, Giaccu, Movchan, & Slepyan, 2014). In addition to changes in temperature and precipitation, the projected faster winds in some locations may further aggravate this risk by increasing the fire spread (Song & Lee, 2017).

Risk group O: Operational risks

Risk O1: Additional operational costs for snow removal

The projected increase in snowfall in some locations may result in an increase in the costs associated with snow removal or even increase the occurrence of bridge blockages. On the other hand, a reduction in such costs and occurrences can be expected at locations where a decrease in snowfall is projected as a result of climate change; see, e.g., Karl et al. (2009) and TRB (2008).

Risk O2: More frequent temporary bridge restrictions

If sustained fast wind speeds are observed for a considerable period of time, e.g. 10-15 minutes, restrictions on which vehicles are allowed to cross the bridge are applied. These restrictions cause detours for some vehicles and result in additional user costs. Considering that faster winds are projected for some locations in the future more frequent bridge restrictions can be expected. Moreover, if climate change increases ice accretion on bridge members more frequent bridge closures may be expected (Kleissl & Georgakis, 2010). For instance, Kleissl & Georgakis (2010) reports that the Øresund Bridge connecting Denmark and Sweden has had to close 5 times between the years 2001 and 2010 due to ice accretion. Similar observations have been noted for other North European bridges (Kleissl & Georgakis, 2010). Nevertheless, such bridge restrictions may be decreased at some locations due to some of the projected climatic changes, e.g. a reduction in wind speeds or warmer conditions reducing the risk of ice accretion.

Risk O3: Increased risk of power shortage

Several factors of the projected future climate may threaten the availability of energy. The future wind energy can be affected by changes in wind speeds and, for some areas such as Scandinavia, atmospheric icing (Mideksa & Kallbekken, 2010). Carvalho, Rocha, Gómez-Gesteira, & Silva Santos (2017), Davy, Gnatiuk, Pettersson, & Bobylev (2018), Gonçalves-Ageitos, Barrera-Escoda, & Baldasano (2015), and Soares, Lima, Cardoso, Nascimento, & Semedo (2017) predict a reduction in wind energy output during some seasons in some regions. The higher future temperatures are expected to reduce electricity production from thermal power plants (Mideksa & Kallbekken, 2010). The decrease in precipitation in some places accompanied by the increased evaporation due to the higher temperatures may adversely impact the output of hydropower plants. Furthermore, more power outage events due to the increased frequency of extreme events, e.g. storms, is expectable.

This increased risk of energy shortage can affect the operation of bridges, as well as all other Infrastructure, in many ways. Most trains depend on electricity for their operation and therefore railway bridges operation is affected. Inoperative traffic and road lights may hinder the flow of traffic on highway bridges. The operation of movable bridges is also dependent on power. Lastly, the operation of structural health monitoring systems is also impacted by power outages. A detailed investigation of the consequences of power outages on different Infrastructure is presented in Petermann, Bradke, Lüllmann, Poetzsch, & Riehm (2011).

The interconnectedness of risks

Rarely can one single cause be identified as the only reason for a bridge failure. Bridge failure often happens due to the unfortunate aggregation of several factors going wrong simultaneously (Hong, Chiew, Lu, Lai, & Lin, 2012). Hence, it is rather important to view the previously mentioned risks holistically instead of in isolation. Most of these risks may add up to one another to cause bridge failures. For instance, the increased hydrostatic pressure behind bridge abutments, risk I6, can combine with the risk of accelerated scour rates, risk G1, and the durability risks, risk group D, to cause failure.

Furthermore, some of the previously mentioned risks are interdependent, i.e. the occurrence of one risk may affect the criticality of another risk. For instance, the occurrence of a landslide, risk G3, may lead to the closure of expansion joints of bridges in the vicinity and consequently aggravate the risk of thermally-induced stresses, risk I4. This can be highlighted by the case of the Deer Creek bridge, Saskatchewan, Canada (Kelly, Sauer, Christiansen, Barbour, & Widger, 1995; and Toll et al., 2012). Due to an active landslide, a 13-80 mm closure of the bridge expansion joints was observed. Another example of risk interdependency is that if collapse settlement happens in a region, this region becomes more susceptible to flooding (Charles and Watts, 1996; and Toll et al., 2012). Furthermore, the occurrence of a wildfire event in a region causes the formation of a water-repellant soil layer below the surface, which increases the surface run-off, and burns the roots of vegetation. Consequently, the criticality of flash floods, debris flows, and landslides risks increase following a wildfire event; see, e.g., Cannon & DeGraff (2009), Elliott & Parker (2001), Kean, Staley, & Cannon (2011), Moody & Martin (2001), Neary, Gottfried, & Ffolliott (2003), and Shakesby & Doer (2006). As an example, Elliott & Parker (2001) cites the floods that followed the May 1996 Buffalo Creek, Colorado, USA forest fire. Moreover, heat-induced damage to pavements can increase the risk of vehicle accidental loads. Lastly, the risk of scour is elevated during a flooding event, referred to as pressure flow scour. Many other such interdependencies between the identified risks may exist.

Discussion and further work

In this work, a review of the potential risks of climate change on bridges was made. In total, 31 potential climate change risks to bridges were identified and presented. Some of the possible ways in which the presented risks may interact were also briefly discussed. Although this review was intended to be as comprehensive as possible, the list of identified risks and/or their possible interactions should be updated as better information become available in the future.

Figure 3 and Table 2 summarize the risks identified in this paper. The inner most circle in Figure 3 shows the different risk groups. Moving outwards, the risks within each of these groups are then presented, followed by the climatic parameters driving each of them on the outermost part of the figure. In addition, the risk interdependencies presented in the previous section are represented by arrows connecting the interdependent risks. As indicated by Table 2, the projected increase in precipitation in some regions and the projected future increase in temperatures seem to be the two most attention worthy climatic parameters in terms of the number of risks they may influence. While each of the two climatic parameters may contribute to 18 potential risks, the two climatic drivers combined can affect 25 of the 31 investigated risks. If increase in wind speeds is added to these two climatic drivers, 28 potential risks are foreseeable. Figure 3 and Table 2 can be augmented to include other risks, and/or interdependencies, not presented in this work. Such display items can be used to effectively communicate the results of climate-change risk identification processes for Infrastructure for further consideration in subsequent risk assessments, e.g. risk prioritization.

As can be seen from this study, a wide range of impacts are predictable. However, depending on the specifics of a certain bridge (i.e., geographical location, site characteristics, structural system, etc.) the potential climate change impacts and their possible consequences will vary. For instance, scour will only concern bridges crossing waterways, liquefaction will only be a potential risk if the bridge is located in a seismically active region, permanent inundation due to SLR is only relevant for coastal bridges, and wind-induced instabilities are particularly relevant for slender (i.e., suspension and cable-stayed) bridges. Further research is needed before any conclusive remarks about the severity, likelihood, or even plausibility of the identified risks are made. Therefore, no claims about which climate-change risk, or climatic parameter, is more critical can be made based on the results of this study. A study with the aim of developing a climate-change risk prioritization framework for bridges is planned in the future.

For the purpose of performing such a prioritization, characteristics identifying each risk need to be considered. For instance, some of the investigated risks, e.g. D1; D2; G1; G4 and E1, can be separately driven by a large number of climatic parameters while others can be driven by only one parameter, e.g. G6; I1; and I3. Furthermore, the fact that climate models can project the different climatic parameters with varying certainty should be considered in the prioritization. Additionally, the strength of evidence supporting the occurrence of each risk as a result of climate change is relevant. Other factors such as the bridge vulnerability and the size of potential consequences are also of significance.

Conclusions

The effects of climate change on the performance and safety of Infrastructure, although potentially severe, have, up to now, been mostly overlooked in both practice and research. This work attempts to draw more attention to the potential risks climate change may pose on an essential part of modern infrastructure; bridges. The findings of over 190 research articles were synthesized to identify the presented risks. The method used in the paper can be used for updating the list of climate change risks as better information become available in the future. In total 31 potential climate change risks have been identified, categorized, and presented in this paper. The results of this review indicate that the two climatic parameters that may cause the highest number of risks in the future are the higher future temperatures and the increase in precipitation in some regions. However, no claims about which climate-change risk, or climatic parameter, is more critical can be made based on this research article. Further research is needed before any conclusive remarks about the severity, likelihood, or even plausibility of the presented risks are made. Developing a holistic climate-change risk prioritization framework for bridges will be the aim of future research. This review can be of high value for bridge managers in better managing the risk of climate change to existing infrastructure. Although this paper specifically addresses bridges, many of the mentioned risks may also affect many other infrastructure types, e.g., tunnels, dams, underground pipes, etc.

Acknowledgements

The authors acknowledge the financial support provided by the Swedish Transport Administration and the strategic innovation program InfraSweden2030, a joint effort of Sweden's Innovation Agency (Vinnova), the Swedish Research Council (Formas) and the Swedish Energy Agency (Energimyndigheten). Any opinions, findings, or conclusions stated herein are those of the authors and do not necessarily align with those of the financiers.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Swedish Transport Administration and the strategic innovation program InfraSweden2030.

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Table 1. Projected future trends of different climate parameters/phenomena.

Climate parameter/phenomenon	Trend of change	Reference(s)
Temperature	- Higher global mean (T↑) - Higher seasonal contrast in some locations (T↔)	IPCC (2013) Imada et al. (2017)
Heatwaves	- Increased intensity and/or frequency (HW↑)	The World Bank (2012)
Solar radiation	- Possible increase in some regions (SR↑)	McKenzie et al. (2011) Ohunakin, Adaramola, Oyewola, Matthew, & Fagbenle (2015)
Precipitation	- Increase in intensity and/or frequency in some regions (P↑) - Decrease in intensity and/or frequency in other regions (P↓) - Increase in contrast between wet and dry regions and seasons (P↔)	IPCC (2013)
Snowfall	- Increase in intensity and/or frequency in some regions (SF↑)	IPCC (2013)
Relative humidity	- Decrease in relative humidity over land for most regions. (RH↓) - Increase in relative humidity over land for some regions under some scenarios (RH↑)	IPCC (2013)
Wind	- Increase in speed in some regions during some seasons (W↑) - A decrease in speed during other seasons (W↓) - Increase in intensity and/or frequency of extreme wind events (W↑)	IPCC (2013) Cradden, Harrison, & Chick (2006) Bloom, Kotroni, & Lagouvardos (2008)
Soil salinity	- Increase in some regions (SS↑)	Dasgupta, Hossain, Huq, & Wheeler (2015)
Storms	- Increase in intensity and/or frequency in some regions (S↑)	IPCC (2013)
Sea level	- Sea level rise (SLR)	IPCC (2013)
Carbon concentrations in the atmosphere and oceans	- An increase in carbon concentrations in the atmosphere and in oceans (CC↑)	IPCC (2013)
Ocean temperature	- A rise in ocean temperature (OT↑)	IPCC (2013)
Run-off	- Higher annual mean run-off in some regions (RO↑)	IPCC (2013)
Near surface permafrost area	- Decrease in near surface permafrost area (PF↓)	IPCC (2013)
Ocean surface pH	- Decrease in global ocean surface pH (PH↓)	IPCC (2013)
Fog	- Increase in the in-cloud liquid water content of marine fogs (F↑)	Kawai, Koshiro, Endo, Arakawa, & Hagihara (2016)
Water level in rivers	- Increased water level fluctuation for some rivers (WL↔)	Úbeda et al. (2013)

Table 2. Relevant climate change parameters and the affected risks. [a]

	Climate-change parameter																				
	P↑	T↑	W↑	SLR	P↓	RH↓ & RH↑	PF↓	P↔	F↑	CC↑	SR↑	OT↑	PH↓	SF↑	S↑	HW↑	T↔	RO↑	W↓	WL↔	SS↑
Affected risks	D1	D1	G2	D2	D2	D1	G1	S2	A1	D1	D1	D2	D2	I3	E1	S1	I4	G1	O3	I9	D2
	D2	D2	G3	G1	G4	D2	G4	G4	A2	D2	I4	E1	E1	O1	E2	I4	I9				
	S1	S1	I1	I7	G7	S2	G5	G7	A3												
	G1	S2	I2	E1	E3	I8	G7	G8													
	G2	G1	A1	E2	O3																
	G3	G2	E3																		
	G4	G3	O2																		
	G5	G4																			
	G6	G5																			
	G7	G8																			
	I2	I4																			
	I5	I8																			
	I6	I9																			
	I7	A2																			
	I9	A3																			
	A2	A4																			
	A3	E3																			
	E1	O3																			
Σ	18	18	7	5	5	4	4	4	3	2	2	2	2	2	2	2	2	1	1	1	1

a D1: accelerated degradation of superstructure, D2: accelerated degradation of substructure, S1: heat-induced damage to pavements and railways, S2: increased long-term deformations, G1: higher scour rates, G2: bridge slope failure, G3: landslides, G4: foundation settlement, G5: rockfalls; debris flows; and snow avalanches, G6: soil liquefaction, G7: additional loads on piles, G8: clay shrinkage and swelling, I1: higher wave impact, I2: wind-induced loads, I3: additional snow loads on covered bridges, I4: thermally-induced stresses, I5: drainage capacity, I6: hydrostatic pressure behind abutments, I7: loads on bridges with control sluice gates, I8: loss of prestressing force, I9: ice-induced loads, A1:water vessel collisions, A2: vehicle-pier collisions, A3: vehicle accidents, A4: train-pier collisions, E1: floods, E2: storms, E3: wildfires, O1: snow removal costs, O2: temporary bridge restrictions, O3: power shortage; P↑, P↓: higher and lower precipitation in some regions respectively, T↑: higher temperatures, W↑: more frequent/intense extreme winds, SLR: sea level rise, RH↑, RH↓: increase and decrease in relative humidity respectively , PF↓: permafrost melt, P↔: increase in precipitation contrast, F↑: higher in-cloud liquid water content of marine fogs , CC↑: higher carbon concentrations, SR↑: higher solar radiation, OT↑: higher ocean temperature, PH↓: decrease in global ocean pH, SF↑: higher snowfall, S↑: increase in storms intensity/frequency, HW↑: increase in intensity/frequency of heatwaves, T↔: higher temperature seasonal contrast, RO↑: higher run-off, W↓: decrease in wind speeds, WL↔: increased water fluctuations in rivers, SS↑: higher soil salinity.

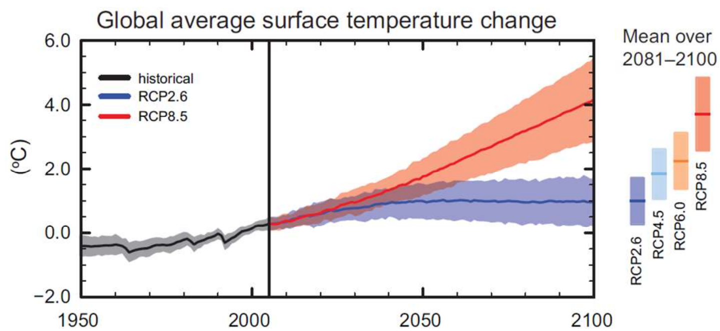

Figure 1. Changes in the global average surface temperature relative to 1986-2005 for the different emission scenarios (IPCC, 2013).

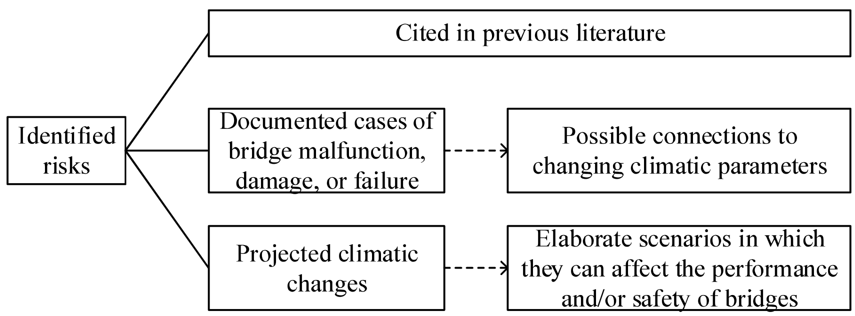

Figure 2. Method of risk identification.

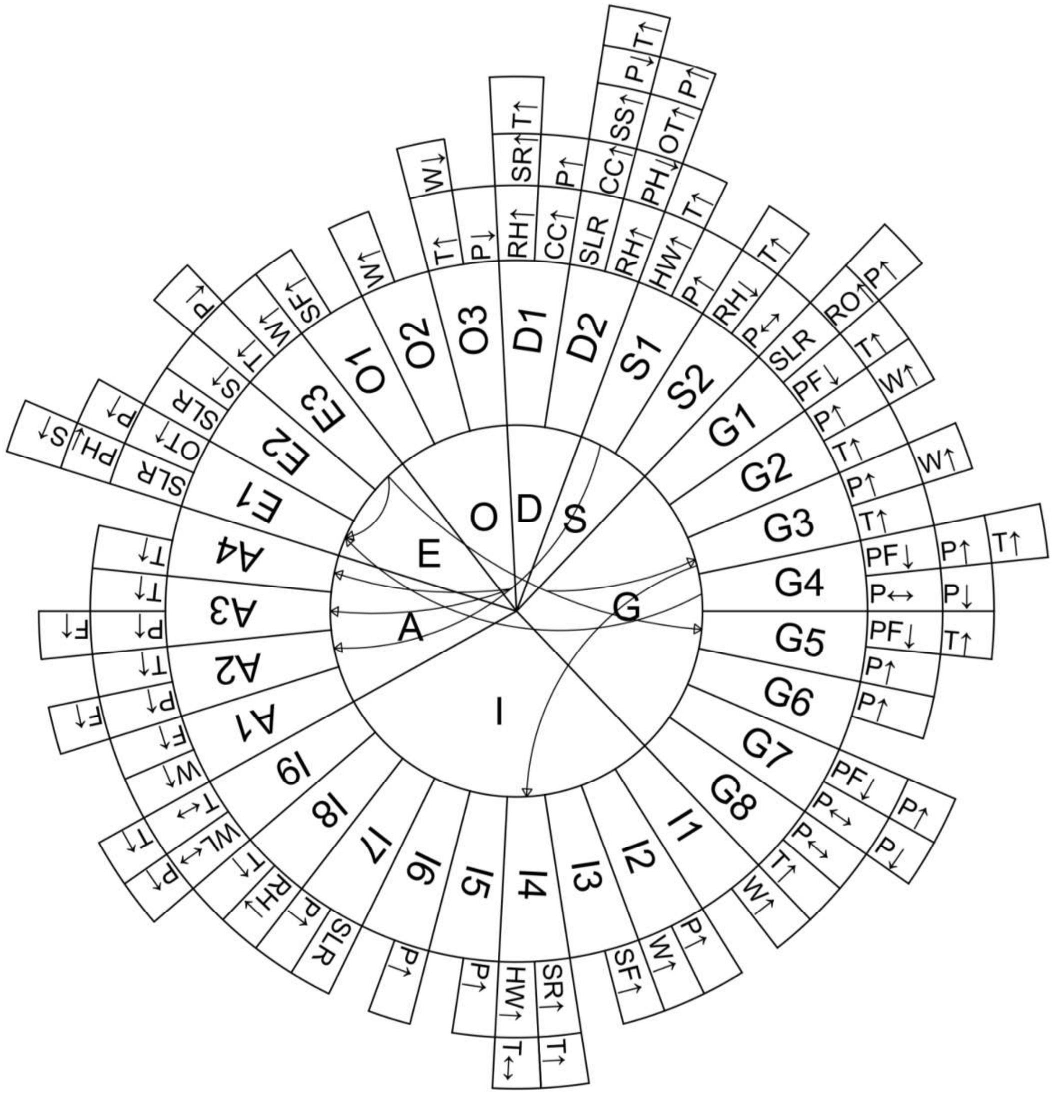

Figure 3. Identified climate-change risks on bridges and the climate changes affecting them. Inside to outside: risk group, identified risk, responsible climatic change parameters. Arrows connecting the different risks represent the discussed interdependencies. [b]

[b] D1: accelerated degradation of superstructure, D2: accelerated degradation of substructure, S1: heat-induced damage to pavements and railways, S2: increased long-term deformations, G1: higher scour rates, G2: bridge slope failure, G3: landslides, G4: foundation settlement, G5: rockfalls; debris flows; and snow avalanches, G6: soil liquefaction, G7: additional loads on piles, G8: clay shrinkage and swelling, I1: higher wave impact, I2: wind-induced loads, I3: additional snow loads on covered bridges, I4: thermally-induced stresses, I5: drainage capacity, I6: hydrostatic pressure behind abutments, I7: loads on bridges with control sluice gates, I8: loss of prestressing force, I9: ice-induced loads, A1:water vessel collisions, A2: vehicle-pier collisions, A3: vehicle accidents, A4: train-pier collisions, E1:

floods, E2: storms, E3: wildfires, O1: snow removal costs, O2: temporary bridge restrictions, O3: power shortage; P↑, P↓: higher and lower precipitation in some regions respectively, T↑: higher temperatures, W↑: more frequent/intense extreme winds, SLR: sea level rise, RH↑, RH↓: increase and decrease in relative humidity respectively , PF↓: permafrost melt, P↔: increase in precipitation contrast, F↑: higher in-cloud liquid water content of marine fogs , CC↑: higher carbon concentrations, SR↑: higher solar radiation, OT↑: higher ocean temperature, PH↓: decrease in global ocean pH, SF↑: higher snowfall, S↑: increase in storms intensity/frequency, HW↑: increase in intensity/frequency of heatwaves, T↔: higher temperature seasonal contrast, RO↑: higher run-off, W↓: decrease in wind speeds, WL↔: increased water fluctuations in rivers, SS↑: higher soil salinity.