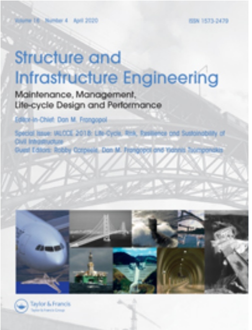

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Bridges in a changing climate: a study of the potential impacts of climate change on bridges and their possible adaptations

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ABSTRACT

Climate change may have multifaceted impacts on the safety and performance of 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. Despite gaining some attention among researchers in recent years, this research area is still largely uninvestigated. Several studies have indicated bridges to be especially susceptible to the effects of climate change. This article presents the potential impacts of climate change on bridges and combines the findings of close to 70 research articles to construct a broad list of their possible adaptation techniques. Although this study focuses on bridges, many of the presented climate change impacts and their adaptations are of relevance also to other types of infrastructure.

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Climate change; risk; bridges; adaptation; infrastructure safety; climate change impacts; climate-related risks; climate change adaptation; adaptation options

1. Introduction

Climate-related hazards can have serious impacts on the safety and functionality of infrastructure systems. In its most recent assessment report (AR5), the Intergovernmental Panel on Climate Change (IPCC) maintains that climate change will have substantial impacts on a wide range of infrastructure systems (IPCC, 2014, p. 538). Numerous examples of previous climate related events which seriously affected the infrastructure exist. For instance, between the years 1999 and 2007, i.e. a period less than a decade, three damaging storms hit the southern part of Sweden (Wallentin & Nilsson, 2014). The second of these storms, storm Gudrun, was the most consequential storm in centuries (Brodin & Rootzén, 2009; Enander, Hede, & Lajksjö, 2009; Nohrstedt & Parker, 2014). Storm Gudrun, which occurred on the 8th of January 2005, had far-reaching effects including damages to the transportation network, the electricity and telecommunications infrastructure, and water supply infrastructure (Broman, Frisk, & Rönnqvist, 2009; Enander et al., 2009; Nohrstedt & Parker, 2014; Nyberg & Johansson, 2013; Strandén, Krohns, Verho, & Sarsama, 2011). It is estimated that 730 000 individuals did not have access to electricity due to this devastating event (Nohrstedt & Parker, 2014; Strandén et al., 2011). These conditions lasted for eight weeks in some areas (Enander et al., 2009) and the total cost inflicted on the society was potentially in the order of 2 billion Euros (The Swedish Civil Contingencies Agency, 2010). Other neighbouring countries were also severely impacted by this event (e.g. Suursaar & Sooäär, 2006).

Noting that some studies suggest a possible increase in storm activity, over e.g.; the North Atlantic (IPCC, 2013); and the North Sea (Lindner & Rummukainen, 2013), and in wind speeds, over e.g.; the Baltic Sea (Kjellström, Nikulin, Hansson, Strandberg, & Ullerstig, 2011; Lindner & Rummukainen, 2013), due to a changing climate, it is crucial to ascertain the safety of our infrastructure against the potential impacts of climate change. Furthermore, Nasr et al. (2019a) mentions the usually prolonged process of updating standards and codes of practice (Auld et al., 2010; Meyer, 2008) and the considerable delay associated with the construction of major protection projects (e.g. storm surge barriers) (Hill, 2012), both of which may be necessary as a response to climate change, as two compelling arguments for an expedited consideration of the potential impacts of climate change on infrastructure.

Considering that in the aftermath of storm Gudrun, as in many similar incidents, the impaired transportation network was the root cause of many of the cascading effects impacting other infrastructure systems (e.g. slowed down restoration of electricity supply and disruptions in water supply, sewage, and heating systems) (Nyberg & Johansson, 2013), this study focuses on one of the main elements of road network infrastructure; bridges. Taking into account their relatively long service life, which in some cases exceed 100 years, bridges are one of the most climate-change

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relevant elements of the road infrastructure (Meyer & Weigel, 2011; Smith, 2006) and their adaptation responses are not to be delayed (Vicroads, 2015).

The aim of this article is to present the potential impacts of climate change on bridges and develop an extensive list of the possible adaptation strategies to counteract these impacts. To date, a small number of studies have addressed the risks imposed on bridges by climate change and their possible adaptations (e.g., Kumar & Imam, 2013; Meyer, 2008; Mondoro, Frangopol, & Liu, 2018; Schwartz, 2010; Nasr et al., 2019a). However, this study is unique in that it provides a broad list of the possible adaptation techniques in response to the risks identified in literature. This is done by identifying and reviewing close to 70 research articles relevant to the topic. Such a comprehensive review of the possible adaptations of bridges in response to climate change is missing from existing literature. This article starts by presenting the projected future climatic conditions with a focus on Sweden and the Nordic region as an example. This is followed by a discussion of the potential impacts of climate change on bridges mentioned in literature. A section presenting a broad review of the possible adaptations for managing the potential climate change impacts is then introduced. Finally, the last section discusses important considerations for adaptation and presents some concluding remarks.

2. Projected climatic changes

Globally, climate models project continued warming in the future (IPCC, 2018). Also, they project an intensification of the hydrological cycle resulting in wet areas, in the tropics and at mid- and high latitudes, generally getting wetter, and dry areas, in the subtropics, getting even drier (IPCC, 2013). The regional and local changes in temperature and precipitation resulting from global warming are modulated by local and regional feedback processes, for instance involving soil-moisture changes and/or changes in sea ice and snow cover. Also, changes in the large-scale circulation of the atmosphere play an important role in determining the local and regional climate change signal (Kjellström et al., 2018). The climate in northern Europe is highly variable on interannual and decadal time scales, to a large extent governed by variability in the large-scale atmospheric circulation. Notably, any changes in the large-scale circulation and/or the frequency or intensity of the mid-latitude low pressure systems or in high-pressure blocking situations can have a strong impact on the climate in this region (IPCC, 2013).

For Scandinavia, a warming considerably higher than the global average is projected (IPCC, 2013; The Swedish Commission on Climate and Vulnerability, 2007) as a result of the positive feedback induced by reduction in sea ice and snow cover in a warmer climate. Consequently, future warming is most pronounced in winter when snow and sea ice retreats. One of the most prominent changes in temperature is the strong reduction in frequency of very cold winter days (Kjellström, 2004). Furthermore, winters not only get milder, but also shorter. For southern Sweden, this generally means less days with freezing and days with both freezing and thawing. In northern Sweden, wintertime warming contrastingly leads to more days with freeze-thaw cycles in the future when the temperature increases from well below to close to zero degrees. Future summers get longer and hotter in Sweden resulting in a longer vegetation period (Kjellström et al., 2016).

For Europe, climate projections show more precipitation in the north and less in the south on an annual mean basis (Christensen & Christensen, 2007; Jacob et al., 2014). Sweden is projected to get increased precipitation, most notably during winter (Kjellström et al., 2016). In summer, however, it is more uncertain as to what extent there will be an increase in precipitation or not, especially in the southern parts of the country being closer to the areas in southern and central Europe that are projected to become drier. The larger amounts of water vapour in a warmer atmosphere imply that single precipitation events can become more intense. Such increases have been reported for daily precipitation by Christensen and Christensen (2003) and Nikulin et al. (2011). For short-term, hourly or sub-hourly time scales, there exist no comprehensive climate change projections specifically for Sweden. There are, however, good reasons to assume that there will be strong increases in intense precipitation events in a warmer climate based on results for other regions, like the UK (Kendon et al., 2014).

Another important aspect of climate change relates to changes in snow fall and snow cover. Warmer conditions in general will result in a shorter snow season but at the same time precipitation will increase. Based on a set of regional climate model simulations at 50 km horizontal resolution, Räisänen and Eklund (2012) found that milder winters will result in less snow on the ground despite of more wintertime precipitation. An exception was parts of northern Sweden, where cold-enough conditions lead to at least as much, or even more, snow on the ground as today during parts of the season.

Changes in the wind climate are uncertain mainly as a result of the large natural variability of the atmospheric circulation. Some projections show increasing wind speed over parts of Western Europe including southern Scandinavia while others do not (e.g. Kjellström et al., 2018). It is therefore difficult to draw general conclusions about changes in the wind climate in the region. This also holds true for the frequency and intensity of high wind speeds related to wind storms. One consistent feature in climate projections is found in areas that are covered by sea ice in today's climate. Future warmer ice-free conditions in these areas, including parts of the Baltic Sea, lead to less frequent calm conditions and thereby higher average wind speed.

Climate models project considerable year-to-year and decadal variability also in a future warmer climate. The large variability on longer, decadal, timescales makes it difficult to assess to what extent climate may change over certain time periods. It may well be that there are longer periods with for instance warmer, or colder, conditions than what would be expected from a pure linear increase in temperature. Such, natural, or internal, variability is one of the key uncertainties in projecting future changes in the regional climate

(Hawkins & Sutton, 2009). For some variables, like seasonal mean precipitation or wind speed, the large natural variability is so large that it is not certain that any forced long-term changes will become detectable, even at the end of this century (Kjellström et al., 2013).

3. Climate-change imposed risks on bridges

In this section, the potential impacts of climate change on bridges are discussed. Four of the potential risks are presented in more detail followed by a subsection outlining other potential risks. However, no inference about the criticality of each risk should be made from the order and/or level of detail in which the different risks are discussed. Future studies should aim at developing methods for ranking the potential impacts of climate change on bridges. The risks discussed in this section are largely based on Nasr et al. (2018).

3.1. Accelerated material degradation

It is expected that a changing climate will have a negative effect on the degradation of construction materials and accelerate the process. The projected higher temperatures, increased precipitation, and relative humidity in some areas, and higher carbon concentrations in the atmosphere may all contribute to an increased risk of deterioration of bridges. An Australian study (Stewart, Wang, & Nguyen, 2011) assessed the risk of corrosion in concrete structures in two cities, namely Sydney and Darwin, indicating a possible increase in this risk as an effect of a changing climate. 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. Similar trends are reasonably expected concerning steel bridges.

Apart from concrete and steel, a large number of bridges involve timber as a construction material. There is evidence that suggest that these might as well be susceptible to changes in climatic conditions. For example, Andrady, Hamid, and Torikai (2003), describe that damage in wood is affected by the UV-B component of solar radiation, which may increase in some regions under future climate conditions (McKenzie et al., 2011). Furthermore, other materials used in bridge construction, such as plastics and rubber are affected by this risk (Andrady et al., 2003).

Another possible risk with timber bridges relates to biodegradation (Shupe, Lebow, & Ring, 2008), as future climates may provide more favourable environments (increasing temperature, relative humidity, and precipitation) for the growth of organisms attacking wood. Biodegradation may also affect the structural performance of bridge components made of concrete. Moncmanová (2007) 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. The excess carbon in atmosphere due to a changing climate may result in a faster rate of pH drop. Other degradation mechanisms, e.g. due to the potential increase in the number of freeze and thaw cycles, may be affected by climate change; see, e.g., Nasr et al. (2019a).

3.2. Higher flood levels and more frequent flooding

Floods have always been a cause of concern for the safety of infrastructure, including bridges. Several studies (e.g., Batchabani, Sormain, & Fuamba, 2016; GDV, 2011; Hoeppe, 2016) suggest that a significant increase in the risk of flooding is expected in the future. Sea level rise, caused mainly by the higher temperatures and the accompanying thermal expansion of ocean water, and the increase in precipitation projected for some regions contribute to an increased flooding risk. Furthermore, changes in ocean pH, water temperature, and intensity and frequency of tropical cyclones may have considerable negative effects on the growth of coral reefs which provide natural protection against coastal flooding (The World Bank, 2012).

A study of the German Association of Insurers (GDV, 2011) maintains that extreme floods will be significantly more frequent in the future. As an example, the study suggests that a flood that currently has a 50-year return period will only have a 20-year return period within the next 30 years. A potential impact of increased risk of flooding on bridges is that it could actually lead to total submersion. A numerical simulation predicts that increased flooding due to climate change will totally submerge two bridges on the Riviere Des Prairies Basin, Quebec, Canada between 2040 and 2060 (Batchabani et al., 2016).

3.3. Damage to pavements and railways

An important component of bridges that is likely to be affected by climate change is their pavement according to Meyer (2008), who refers to the damages during the Chicago 1995 heatwave reported in Changnon, Kunkel, and Reinke (1996) as an example. Besides temperature, the projected increase in precipitation intensity and frequency (in some areas) are other factors which may contribute to an increased risk of damage to pavements. Heatwaves can also significantly impact rails which lead to increased risk of train accidents or service disruptions, due to, e.g. lateral buckling of railroad tracks resulting from constrained thermal expansions. Rail deformations on bridges may also induce higher lateral loads from passing trains and alter the bridge-train dynamic interaction with potential negative effects on the structural behaviour. For a more detailed discussion on the effect of track geometric imperfections on the dynamic amplification of internal forces in railway bridges the reader is referred to, e.g. Amaral and Mazzilli (2017).

3.4. Higher scour rates

A common triggering event for bridge failure is hydraulic failure or scour. Taricska (2014) studied bridge failures between 2000 and 2012 in the US and concluded that bridge failures due to hydraulic causes represented about half of the investigated cases. Another study identifying scour as one of the most important bridge failure causes was done by Cook, Barr, and Halling (2015), who looked at bridge failures using the New York State Department of Transportation (NYSDOT) database for the period 1987–2011. This finding is supported by numerous other studies (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).

In some regions, a negative effect of climate change concerning the risk of scour is expected due to a number of reasons (RSSB, 2003; DoT, 2005; NRC, 2008; Kumar & Imam, 2013). One of the most important reasons is that, due to higher precipitation, significantly higher average annual runoff is projected over 47% of the world's land surface (Arnell & Gosling, 2013). Therefore, the velocity of stream flows will increase which will result in higher scour rates; see, e.g., Froehlich (1989), Neil (1964), and Shen, Schneider, and Karaki (1969). Another reason is that higher temperatures and snowmelt will result in higher water levels which will also affect scour rates; see, e.g. Froehlich (1989), Neil (1964), and Shen et al. (1969). In addition, in some areas, where bridges are built on permanently frozen ground additional runoff from the melting permafrost due to climate change may also result in a higher scour risk. Finally, as suggested by, e.g., Soulsby and Whitehouse (1997) 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. The aforementioned aspects may affect both general scour at the bridge site and local scour around bridge piers.

3.5. Other risks

Several other risks to bridges may be influenced by climate change. Higher demand on deformation capacity, causing additional restrained thermal stresses, may be introduced by the projected higher future temperatures and further exacerbated by the potential increase in solar radiation (NRC, 2008; Schwartz, 2010). Bridges existing in wildfire-susceptible areas may be threatened by the expected increase in the frequency and intensity of wildfires; see, e.g. Kerr, DeGaetano, Stoof, and Ward (2018), Lozano et al. (2017), Song and Lee (2017), Stambaugh, Guyette, Stroh, Struckhoff, and Whittier (2018), and Strydom and Savage (2017).

Climate change is expected to render storm surges more violent. In addition to the projected more frequent very intense hurricanes, a higher launching level offered by sea level rise as well as the projected higher future waves may combine to aggravate this risk. One of the most common bridge failure mechanisms observed during Hurricane Katrina 2005 was the lifting of bridge decks off of their supports due to storm surges (Meyer, 2008). This failure mechanism was also observed for the Utatsu highway bridge during the 2011 Great East Japan Tsunami. Although the deck to abutment unseating prevention devices of the bridge were found to be undamaged after the event, some of the displaced decks were found flipped over (Bricker, Kawashima, & Nakayama, 2012; Bricker & Nakayama, 2014). Bricker et al. (2012), and Bricker and Nakayama (2014) suggest that the unfortunate agglomeration of several factors including deck superelevation, presence of trapped air between bridge girders, and the presence of a seawall near the bridge caused this failure mechanism. It has been suggested that climate change can trigger tsunamis, among other natural hazards (e.g. earthquakes and volcanos) (McGuire, 2013). Other studies, however, contradict this suggestion (e.g. Hoeppe, 2016).

Changes in temperature and relative humidity can substantially affect the loss of prestressing force in prestressed bridges and stress-laminated timber decks (Bell, 2008). Another potential risk for timber bridges that warrants consideration is related to the mechano-sorptive effect; see, e.g. Holzer, Loferski, and Dillard (1989), and Mårtensson (1994). 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 the possible increase in precipitation seasonal contrast in some regions, this may be a reasonable concern. The risk of insufficient capacity of drainage systems is also presumable due to the projected changes in precipitation.

Several ways in which climate change may introduce geotechnical risks are presented in Toll et al. (2012). Due to the projected regional changes in precipitation patterns, the Ground Water Table (GWT) may either be expected to rise or drop depending on the region. In the case of a GWT drop, an increase in the effective stresses will result in higher consolidation settlement. In addition to affecting bridges on shallow foundations, this settlement can overstress pile foundations due to the additional forces introduced by negative skin friction. The loss of buoyancy force resulting from GWT drop can also overstress pile foundations. Lastly, as a result of GWT lowering the upper part of wooden piles becomes exposed to aerobic conditions and biodegradation can initiate.

On the other hand, Toll et al. (2012) demonstrated several ways in which GWT rise can cause geotechnical risks. GWT rise can negatively affect the stability of side slopes. Considering the potential death of some vegetation species, due to the elevated future summer temperatures and the extended drought periods, and the subsequent loss of their contribution to slope stability (e.g. Chok, Kaggwa, Jaksa, & Griffiths, 2004; Wu, McKinnell III, & Swanston, 1979), this risk is further highlighted. Additionally, more frequent extreme winds, beside the potentially higher risk of aeroelastic instabilities and wind-induced loads (e.g. Seo & Caracoglia, 2015), can result in faster erosion of side slopes and increase the risk of slope failure. Similarly, an increased risk of landslides is presumable. Collapse settlement is another potential effect of GWT rise. Soils in which particles are bond together with water-sensitive forces, e.g. suction forces in the pore water and inter-particle cemented bonds,

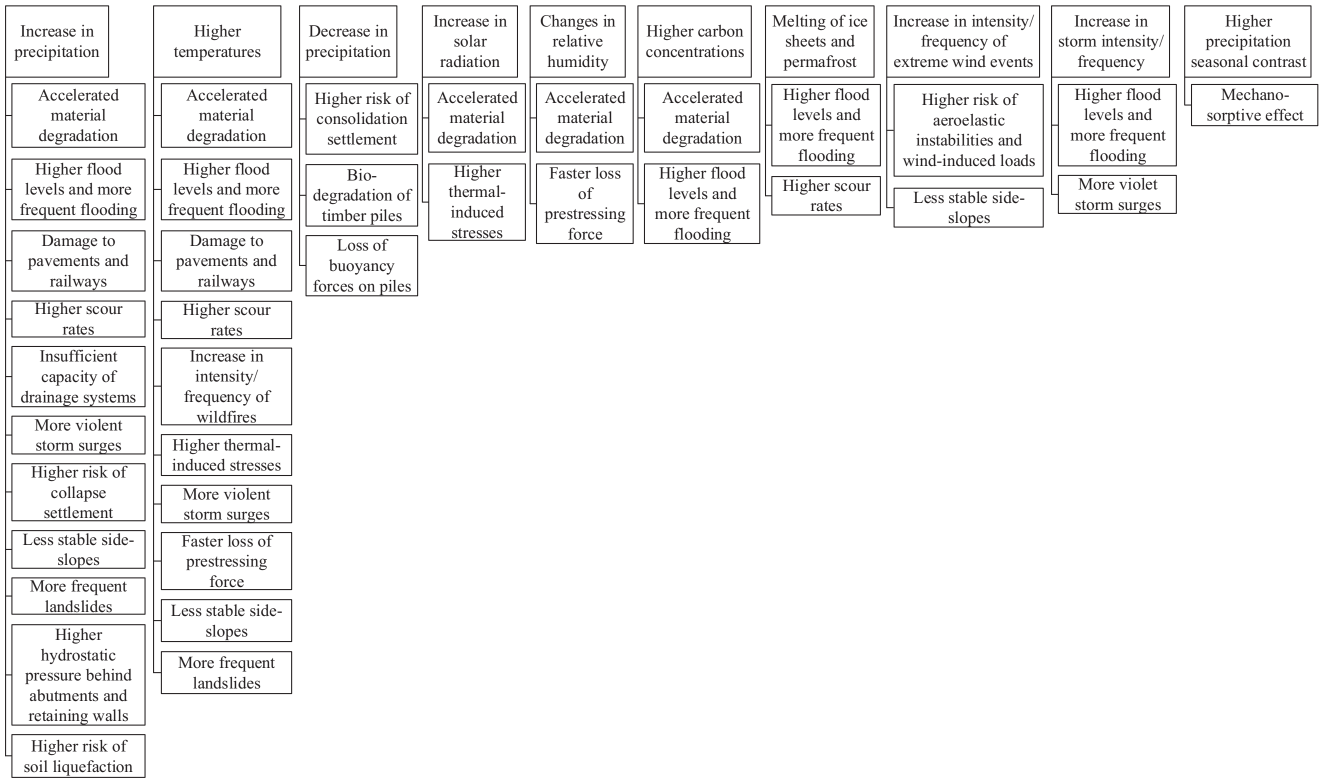

Figure 1. Climate change risks on bridges, examples.

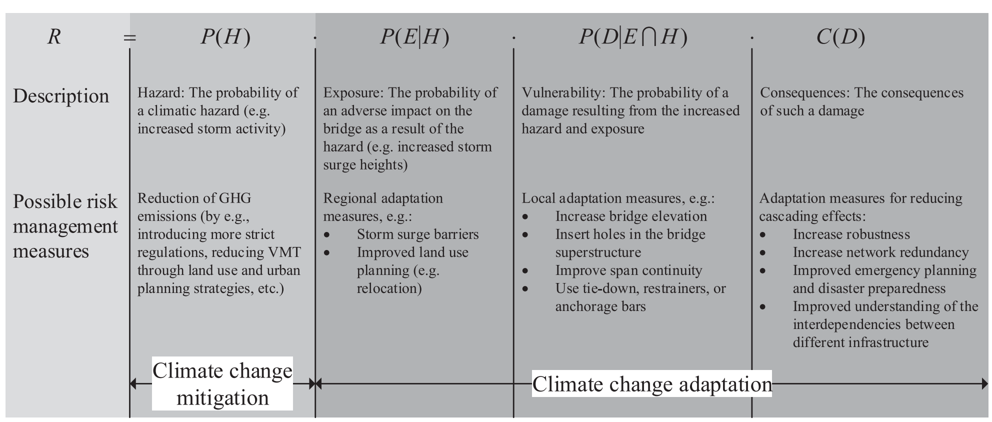

Figure 2. Different ways for managing climate change risks.

collapse after coming in contact with water due to GWT rise and consequently settlement occurs (Toll et al., 2012). A build-up of hydrostatic pressure behind abutments and retaining walls can also result from GWT rise (Meyer, 2008). Lastly, several studies (e.g. Nath et al., 2014; Nath et al., 2018; Obermeier, 1996; Yilmaz & Bagci, 2006) link shallower ground water tables to an increased risk of soil liquefaction in seismically active regions.

As can be seen, a broad range of risks is foreseeable, however further research is needed before any conclusive remarks about their severity, likelihood, or even plausibility, are made. Figure 1 provides an overview of the risks presented in this study with the projected climate changes which may affect them. A more detailed discussion of the potential impacts of climate change on bridges is presented in Nasr et al. (2019a).

4. Possible adaptation techniques

As has been discussed in the previous section, climate change may impose considerable impacts on bridges. Nevertheless, measures to reduce the probability and/or consequences associated with such impacts can, and should, be taken. The risk of such impacts can be represented as shown in Figure 2 (Nasr et al., 2019b). As presented in Figure 2, climate change impacts can be controlled in two general ways; mitigation and adaptation. Firstly, mitigating GHG emissions, by e.g. reducing vehicle miles travelled (VMT) through land use and urban planning strategies (e.g., Hamin & Gurran, 2009), can significantly decrease the potential impacts of climate change. However, Füssel (2007) gives several arguments why mitigation alone is insufficient and prompt adaptation actions are, in many cases,

Table 1. Potential climate change risks and their possible adaptations.

Potential impact	Adaptation
Accelerated degradation of material	Cathodic protection (Stewart et al., 2012; Vicroads, 2015); Increase in concrete cover thickness, improve quality of concrete (strength grade), protective surface coatings and barriers, use of stainless steel, galvanized reinforcement, corrosion inhibitors, electrochemical chloride extraction (Stewart et al., 2012); Protection by design, preservative treatment and the use of modified wood for timber bridges (Mahnert & Hundhausen, 2017); More frequent inspection and maintenance
Heat-induced damage to pavements and rails	Use of polymer modified binders (Vicroads, 2015); Development of new heat resistant paving materials (FHWA, 2009; NRC, 2008); More frequent maintenance(ATSE, 2008; FHWA, 2009; FHWA, 2013; Lindgren et al., 2009); Use of concrete railroad ties instead of wood ties (Delgado & Aktas, 2016); More expansion joints in pavements and rails (Meyer & Weigel, 2011); Introducing speed restrictions (Mehrotra et al., 2011).
Increased long-term deformations	Improved monitoring and inspection of bridges (Mahnert & Hundhausen, 2017)
Increased scour rate	Use of riprap (FHWA, 2009; Mondoro et al., 2018; Nemry & Demirel, 2012; NRC, 2008); Partially grouted riprap, concrete block systems, gabion mattresses, grout-filled mattresses; Upstream walls and obstructions, collars, etc. (Mondoro et al., 2018; NRC, 2008); Use of sacrificial embankments (Brand, Dewoolkar, & Rizzo, 2017); Increased use of sonars to monitor streambed flow and bridge scour (FHWA, 2009; NRC, 2008); For further scour protection measures see e.g., Arneson, Zevenbergen, Lagasse, and Clopper (2012); and Chen and Duan (2014)
Side-slope failure and Landslides	Adequate slope stabilization measures, river bank protection works (FHWA, 2009; NRC, 2008; Regmi & Hanaoka, 2011); Relocation, modification of slope geometry, drainage, retaining structures, internal slope reinforcement (see, e.g., Chen & Duan, 2014, p. 337)
Foundation settlement	Relocate facilities to more stable ground (Meyer & Weigel, 2011); Incorporate increased ground subsidence in the design of infrastructure (Meyer & Weigel, 2011); Remove permafrost before construction, crushed rock cooling systems, insulation/ground refrigeration systems (CCSP, 2008; Mehrotra et al., 2011; Meyer & Weigel, 2011); Use of different types of passive refrigeration schemes, e.g., thermosiphons, rock galleries, and "cold culverts", to prevent settlement due to permafrost melt(NRC, 2008); Replacement of ice-rich soils with gravel (Bastedo, 2007)
Rockfalls	Energy dissipating protective structures for bridge piers (He, Yan, Deng, & Liu, 2018); Attenuator fence system and combined wire mesh and cable net drapery, soil berm to provide protection for piers (Graham, Turner & Axtell, 2016); Embankments and ditches, rockfall protection galleries (cushion layer, structural elevation), flexible protection systems (Volkwein et al., 2011).
Snow avalanches	Relocation, early warning systems, flow deflection (e.g., earthfill deflectors) and deceleration methods, structural protection measures (e.g. avalanche sheds), artificial release by explosives, afforestation (Decaulne, 2007; Ganju & Dimiri, 2004; Höller, 2007; Rheinberger, Bründl, & Rhyner, 2009)
Debris flows	Terrain alteration, soil bioengineering, debris flow breakers, debris flow deflectors, etc. (see, e.g., Huebl & Fiebiger, 2005)
Liquefaction	Stone columns (Adalier, Elgamal, Meneses, & Baez, 2003; Adalier & Elgamal, 2004); Gravel and rubber drainage columns (Bahadori, Farzalizadeh, Barghi, & Hasheminezhad, 2018); Chemical grouting, passive site remediation techniques (Gallagher, 2000); Ground improvement methods (grouting), Vibro systems, buttresses and surcharge fills, containment and reinforcement, drains, underpinning with mini-piles, deep dynamic compaction and deep blasting (Cooke & Mitchell, 1999)
Additional loads on piles	For negative skin friction: Treatment of subsiding soils, removal of subsiding soils, sleeve liner to allow the soil to settle without causing downdrag, bitumen coating of piles (Davisson, 1993)
Clay shrinkage and swelling	Wet compaction and lime stabilization (Kasangaki & Towhata, 2009); Geofiber reinforcement (Viswanadham, Phanikumar, & Mukherjee, 2009)
Higher wave impact	Surface coatings, pile wraps, pile jackets, etc. (Mondoro et al., 2018)
Wind-induced loads	Use of guide vanes (Larsen, Esdahl, Andersen, & Vejrum, 2000; Larsen & Larose, 2015); Streamlining the bridge deck cross section for suppressing vortex shedding excitations (Larsen & Larose, 2015); Use of damping devices (e.g., tuned mass dampers, tuned liquid dampers) (Chen et al., 2004; Dieng, Helbert, Chirani, Lecompte, & Pilvin, 2013; Larsen & Larose, 2015; Main & Jones, 2001)
Additional snow load	See the general strengthening and retrofitting measures at the end of the table
Higher risk of thermally-induced stresses	Increased ongoing maintenance (CCSP, 2008); Design for higher maximum temperatures in replacement or new construction (NRC, 2008); Greater use of expansion joints (Meyer & Weigel, 2011; Regmi & Hanaoka, 2011); Paint the bridge white to introduce an albedo effect and reduce overheating (Delgado & Aktas, 2016)
Additional demand on drainage capacity	Upgrading drainage systems (Karl, Melillo, & Peterson, 2009; NRC, 2008); Increases in the standards for drainage capacity for bridges (FHWA, 2009, NRC, 2008); Increase in pavement sloping and grooving (FHWA, 2009); Increase in monitoring of drainage systems (Mehrotra et al., 2011; NRC, 2008)
Higher hydrostatic pressure behind abutments	The use of anchors to stabilize abutments (e.g., Truong-Hong, Laefer, & Ba, 2013; Wade & Davies, 1993); Enlargement of abutment components (Truong-Hong et al., 2013)
Increased loads on bridges with control sluice gates	See the general strengthening and retrofitting measures at the end of the table
Loss of prestressing	More frequent inspection maintenance and retensioning
Ice-induced loads	Scour protection measures to prevent scour damage; Pier protection against the impact from ice flues; Strengthened connections, improved span continuity, and increased elevation to prevent the damage of superstructure from ice accumulation
Water vessel collisions	Fender systems, pile-supported systems, Dolphin protection systems, island protection systems, floating protection systems (see, e.g., Chen & Duan, 2014)
Vehicle-pier collisions	Speed control (Mehrotra et al., 2011), Pier protection (e.g., Williamson & Winget, 2005), Pier strengthening
Vehicle accidents	Speed control (Mehrotra et al., 2011)
Train-pier collisions	Speed control (Mehrotra et al., 2011); Pier protection (e.g., Williamson & Winget, 2005); More frequent wheel truing and maintenance of rails (Delgado & Aktas, 2016)
Floods	Relocation or flood-proofing (Mehrotra et al., 2011; Meyer & Weigel, 2011); Flood control seawalls, dikes, and levees (Stewart & Deng, 2015); Elevation of bridges, strengthening and heightening of existing levees, increase in real-time monitoring of flood levels, restriction of most vulnerable coastal areas from further development, increase insurance rates to help restrict development (NRC, 2008); Channel alteration and stabilization, diversion and storage of floodwaters (e.g., Dunne, 1988); Regulate the flow of water through dams (Batchabani, Sormain, & Fuamba, 2016)

(*continued*)

Table 1. Continued.

Potential impact	Adaptation
Storms	Elevate critical infrastructures, insert holes, tie-down, restrainers, anchorage bars, etc., concrete shear tabs etc., connect adjacent spans, cladding (e.g., toe nails, hurricane straps, etc.) (Mondoro et al., 2018); Strengthened connections, improved span continuity, modified bridge shape, increased elevation (Cleary, Webb, Douglass, Buhring, & Steward, 2018); Relocation and restriction of development in vulnerable regions (Meyer & Weigel, 2011; NRC, 2008); Strengthening and heightening existing storm surge barriers and building new ones (NRC, 2008)
Wildfires	Vulnerability assessments incorporated into infrastructure location decisions, use of fire-resistant materials and landscaping (Meyer & Weigel, 2011); Installing monitoring systems, installing on site firefighting equipment, implementing structural fire design for bridges, fire proofing main structural elements (Naser & Kodur, 2015); Vegetation management strategies (i.e. control operating situation around the structure by regularly removing vegetation in the vicinity of bridges) (NRC, 2008; Wright, Lattimer, Woodworth, Nahid, & Sotelino, 2013); Bigger expansion gaps, passive fire protection, active fire suppression (e.g. wet pipe water systems, dry pipe water systems, total flooding agents, foam deluge systems) (Wright et al., 2013)
General strengthening and retrofitting measures	
Addition of steel cover plates, shear reinforcement (e.g., external, epoxy injection and rebar insertion), jacketing of timber or concrete piles and pier columns (modification jacketing), post-tensioning various bridge components, developing additional bridge continuity, use of CFRP (Carbon Fiber Reinforced Polymers) strips (see, e.g. Chen & Duan, 2003)	

necessary. For instance, as a result of the inertia of the climate system, the coming decades are projected to exhibit a substantial increase in the rate of climate change regardless of the emissions scenario (Füssel, 2007). Furthermore, unlike mitigation, adaptation measures are not contingent on the actions of others and can induce direct benefits on the regional and local scale.

From a Swedish perspective, the Swedish Transport Administration has already developed a climate adaptation strategy which provides a list of general activities for adapting to a changing climate. These activities, for instance, include adapting new and existing infrastructure, and developing methods for determining when and where such adaptations would be cost-effective (Liljegren, 2016). Several cases where adaptation measures have already been implemented exist. For instance, in the wake of storm Gudrun tree-free zones were established on high priority parts of the railway network to prevent the blockage of railways with fallen trees during future storms (Lindgren, Jonsson, & Carlsson-Kanyama, 2009). However, according to Lindgren et al. (2009) it is unclear whether this was done with the intention of adapting to future climate change or not. Other cases of climate change adaptation in Sweden can be found on the Swedish climate adaptation portal (http://www.klimatanpassning.se).

Future bridges can be adapted to climate change in several ways. For instance, Auld et al. (2010), Connor, Niall, Cummings, and Papillo (2013), Gibbs (2012), Mondoro, Frangopol, and Liu (2018), and Pietro et al. (2016) among many other studies emphasize the need for regularly updating codes and standards to accommodate a changing climate. Examples of updating codes and standards in response to climate change already exist; e.g. including adjustment factors for design floods and design rainfalls in several European guidelines (Madsen, Lawrence, Lang, Martinkova, & Kjeldsen, 2014), and introducing a cyclone uncertainty factor in Australian standards (Connor et al., 2013). It is worth noting that this adaptation measure of regularly updating codes and standards has been categorized as a no-regret adaptation strategy (Auld, Maclver, & Klaassen, 2006) which is considered robust irrespective of the future climate scenario and therefore should be implemented without delay. Restrictive land use planning, by e.g. increasing insurance rates in hazardous coastal zones (FHWA, 2009; NRC, 2008), has also been identified as a no-regret adaptation strategy (Hallegatte, 2009). Furthermore, the development of new materials and/or technologies that are more resistant to the impacts of climate change (e.g., the development of new heat-resistant paving materials (FHWA, 2009; NRC, 2008)) has been mentioned in literature as a possible adaptation technique. Another important aspect for adapting future bridges to climate change is opting for designs which are flexible to any adaptations that may be needed in the future to enhance the resilience of the transport infrastructure.

Several measures to adapt existing bridges to climate change have been cited in literature. Stewart, Wang, and Nguyen (2012) mentions increasing the concrete cover thickness, the use of protective surface coatings and barriers, galvanized reinforcement, corrosion inhibitors, electrochemical chloride extraction, or cathodic protection as possible adaptation techniques for controlling the potential increase in the corrosion of concrete infrastructure as a result of climate change. Mondoro et al. (2018) suggests the use of riprap, concrete bock systems, and gabion mattresses as possible adaptations against an increased scour rate and the use of anchorage bars, concrete shear tabs, and increasing continuity as adaptations against deck unseating during storms. Table 1 presents an extensive list of the measures presented in literature as possible adaptations against climate-change imposed risks. In addition, adaptations that have not been previously identified as climate change responses but are judged as suitable measures to decrease climate change related impacts are also presented. For the sake of completeness, the presented adaptation techniques are not limited to the risks discussed in the previous section but also include climate change relevant risks identified in other studies (e.g., Nasr et al., 2019a).

Considering the large number of possible adaptations (as demonstrated by Table 1), two crucial questions that need to be considered are which adaptation option to choose and when to implement it. It has been repeatedly suggested that a cost-benefit, risk-based, life cycle analysis is most suitable for answering such questions (e.g. ATSE, 2008; CEN, 2016; Gibbs, 2012; Stewart, Val, Bastidas-Arteaga, O'Connor, &

Wang, 2014). For this purpose, Stewart et al. (2014) identifies three criteria that may be used for such analysis, namely, the Net Present Value (NPV); the probability of cost effectiveness; and the Benefit-to-Cost Ratio (BCR), and demonstrates the procedure for a number of case studies.

5. Conclusions

In this study, a presentation of the potential climate-change impacts on bridges and a review of their possible adaptation measures was made. In the context of adapting bridges, and other infrastructure, to a changing climate a number of issues need to be taken into consideration. Firstly, the different ways in which the potential impacts are interconnected and can influence one another (Nasr et al., 2019a) should be taken into account.

In addition to limit the possibility of maladaptation, i.e.; implementing adaptations which are inappropriate, opting for adaptation options which incorporate sufficient safety margins and are robust, reversible, and flexible is recommended (e.g., IPCC, 2014). Noting the large number of potential climate change impacts, the effect of adapting to one risk on the vulnerability to other risks should be carefully regarded. For instance, although channel alteration measures, e.g. increasing channel slopes, can control the risk of flooding, such measures can simultaneously heighten the risk of scour. Such examples of conflicting adaptations need to be identified and cautiously examined before implementation. Lastly, considering how GHG mitigation efforts may affect adaptation (ASCE, 2015) and recognizing that mitigation policies and adaptation options may in some cases be in conflict (e.g., Füssel, 2007) is crucial.

Despite focusing on bridges, many of the potential risks discussed in this work and their possible adaptations are of relevance to other infrastructure types. This study is a step forward towards an efficient management of bridges in a changing climate and can be of considerable benefit to bridge managers and transport administrations in adapting their assets to the future climate conditions.

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