DOI: https://doi.org/10.14256/JCE.3756.2023

Građevinar 9/2023

Primljen / Received: 30.3.2023.
Ispravljen / Corrected: 21.7.2023.
Prihvaćen / Accepted: 23.8.2023.
Dostupno online / Available online: 10.10.2023.

Climate change effect on durability of bridges and other infrastructure

Authors:

Petra Milić, MCE
BBR Adria, Croatia
petramilic7@gmail.com

Assist.Prof. **Marija Kušter Marić**, PhD. CE
University of Zagreb
Faculty of Civil Engineering
marija.kuster.maric@grad.unizg.hr
Corresponding author

Subject review

Petra Milić, Marija Kušter Marić

Climate change effect on durability of bridges and other infrastructure

Climate change has significant implications for structures which will continue to increase in the future, particularly bridges and other strategic infrastructure with longer service life exposed to aggressive environments. In this paper, a projection of climate change for Croatia for periods up to 2040 and up to 2070 is presented with potential impacts on bridges and other structures. By reviewing scientific research results, the impact of climate change on the durability and seismic capacity of concrete structures as well as effects on loads on structures is presented. Research into and a better understanding of the effects of climate change on structures will enable the development of adaptation measures to future conditions, not only in the design of new structures, but also in the appropriate maintenance of existing structures, as well as in procedures for rehabilitation, renovation, etc.

Key words:

climate change, durability of structures, seismic capacity, reinforcement corrosion

Pregledni rad

Petra Milić, Marija Kušter Marić

Utjecaj klimatskih promjena na trajnost mostova i druge infrastrukture

Klimatske promjene imaju značajan utjecaj na konstrukcije koji će u budućnosti biti još veći, naročito za mostove i drugu stratešku infrastrukturu dužeg uporabnog vijeka izloženu agresivnom okolišu. U radu je prikazana projekcija klimatskih promjena u Hrvatskoj za razdoblje do 2040. odnosno 2070. godine s mogućim posljedicama na mostove i druge građevine. Kroz pregled rezultata znanstvenih istraživanja prikazan je utjecaj klimatskih promjena na trajnost i seizmički kapacitet betonskih konstrukcija te na djelovanja na građevine. Istraživanje utjecaja klimatskih promjena na konstrukcije i njihovo bolje razumijevanje omogućit će i razvijanje prilagodbe na buduće uvjete, ne samo pri projektiranju novih konstrukcija, već i za adekvatno održavanje postojećih, kao i postupke pri sanacijama, renovacijama i sl.

Ključne riječi:

klimatske promjene, trajnost konstrukcija, seizmički kapacitet, korozija armature

1. Introduction

The highest temperature ever recorded in Europe was 48.8 °C in the summer of 2021. (Floridia, Italy: 48.8 °C, date: 11.8.2021.) [1]. Record-breaking temperatures of up to 50°C were also measured in Canada, resulting in a large number of human fatalities. In Europe, the summer of 2022 has been the warmest ever [2]. The African continent has experienced the worst drought in the last 40 years, and for the same reason, many countries worldwide have introduced restrictive water-use measures [3]. For the first time, a level red heatwave warning was issued in the UK, where deformation of railway tracks due to extreme temperatures was detected [1]. By contrast, Central European countries were hit by devastating floods that caused damage and destruction on a large scale. China, India, and Pakistan have struggled with severe floods in August 2022. Croatia, Turkey, Spain, the USA, Canada, and Russia have experienced catastrophic fires, whereas Antarctica has experienced record temperatures and precipitation [3].

This is only a part of the phenomenon recorded in the last two years, confirming the seriousness of the situation and the impossibility of denying climate change. In the future, extreme weather conditions will occur more frequently, the risk of natural disasters will increase, and their intensity and frequency will continue to increase. The Republic of Croatia is one of the three most vulnerable countries in the European Union, with an estimated largest share of damage from extreme weather and climate events in relation to gross national product [4]. In early August 2021, the Intergovernmental Panel on Climate Change (IPCC) published the latest 6th Assessment Report and warned that we are approaching a 'no turning back' scenario in terms of global warming. They called for urgent action and stated that the current practices and adaptations were inadequate [5].

Adaptation to climate change includes the prediction of its negative impacts of climate change and the use of appropriate measures to prevent or reduce potential damage from climate change [4]. Existing and future buildings will certainly be affected by climate change. To enable infrastructure adaptation, it is necessary to study the impacts of climate change on structures. These impacts can be seen as changes to the properties of existing structures, reductions in load-bearing capacity and reliability, and changes in external influences on the structures. For example, changes in carbon dioxide concentration, temperature, and relative humidity affect corrosion processes, which are the most common causes of damage to reinforced concrete structures. Bridges are engineering structures that are particularly exposed to climatic and environmental influences and are therefore potentially at high risk. This study presents a projection of climate change in Croatia for the period until 2070, with potential impacts on structures. The effects of climate change on external actions are presented, as well as its effects on the material properties, capacity, and usability of structures, with special reference to the corrosion of reinforcement and seismic resistance.

2. Projection of climate change in Croatia for the period up to 2040 with an outlook to 2070

2.1. Climate and climate change

Climate change is undoubtedly occurring and represents one of the greatest threats to the 21st century. The last three decades have been the warmest since 1850; with rising ocean temperatures, higher salinity areas have become saltier, and lower salinity areas continue to lose salinity. From 1901 to 2010, sea levels rose by 0.19 m worldwide [6]. Heatwaves are becoming more frequent, as are heavy rainfalls. Over the last two decades, the ice sheets of Greenland and Antarctica have lost mass, and glaciers continue to shrink.

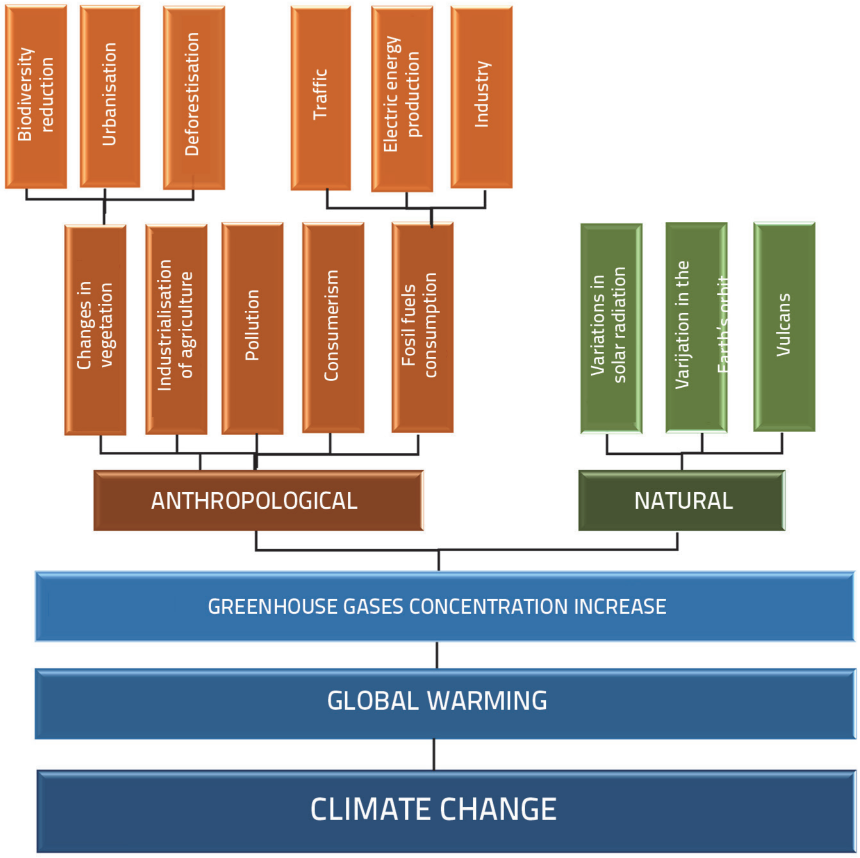

Figure 1. Causes of climate change

The causes of climate change can be divided into natural and anthropological causes (Figure 1). Natural causes include variations in solar radiation, the Earth's orbit, and volcanic eruptions. However, natural causes did not have a major impact on the climate over the observed periods of 100–200 years. According to [7], science claims with 95 % certainty that human activities are the main cause of global warming since the mid-20th century. Although not yet officially confirmed, scientists first used the term Anthropocene in 2000 to refer to a new geological period of the Earth that began in the second half of the 20th century. The main features of the Anthropocene are the acceleration of erosion and sedimentation rates, chemical disruption of carbon and nitrogen cycles, climate change, and major changes in the biosphere [8].

The dominant factor in changing the Earth's energy balance are greenhouse gases that absorb long-wave radiation from the Earth's surface. Part of this radiation directed back towards the Earth contributes to the heating of the lower parts of the atmosphere and the Earth's surface. This effect is known as the greenhouse effect. Some of the greenhouse gases occur naturally, however, the increase in their concentration in the last 250 years is mainly due to human influences, primarily through the consumption of fossil fuels [9]. Human influence is also manifested in changing the Earth's surface. For example, deforestation (removal of forests) reduces carbon storage in vegetation, increases carbon dioxide in the atmosphere and changes the reflective power of the surface, the rate of evapotranspiration and energy emissions [7, 9].

2.2. Climate change adaptation

The Intergovernmental Panel on Climate Change (IPCC) was founded in 1988 under the United Nations (UN). The IPCC aims to collect and summarise scientific data on climate change. These data are published in reports that undergo rigorous review procedures and can serve as a basis for the development of climate policies.

The international fight against climate change began in 1992 when the United Nations Framework Convention on Climate Change (UNFCCC) was signed. The Kyoto Protocol, the first agreement on greenhouse gas emissions, was signed in 1997. The Republic of Croatia is one of the three most vulnerable countries in the European Union, with the highest share of damage caused by extreme weather and climate events in relation to the Gross Domestic Product (GDP) [10]. As a Party to the UNFCCC, Croatia submits, among other things, periodic reports on adaptation to climate change. The Strategy for Adaptation to Climate Change in Croatia [11] for the period to 2040 with a view to 2070 was adopted by the Croatian Parliament on 7 April, 2020. The strategy was adopted based on the "Green and White Book" [10, 12] prepared by experts in the fields of climate modelling, water and marine resources, hydrology, agriculture, forestry, biodiversity, fisheries, tourism, spatial planning, and management of coastal areas, construction, health, and risk management. The strategy provides 80 measures for 10 sectors and three general measures of major importance. Table 1 shows the measures by sector for which the Ministry of Physical Planning, Construction and State Assets (MPCA), the Ministry of Sea, Transport and Infrastructure (MSTI), or the universities (U) are responsible and which are relevant for the entire infrastructure, i.e., the construction sector. Thus, the long-term goal of the adaptation strategy is to reduce the vulnerability of social and natural systems to the negative impacts of climate change; that is, to strengthen their resilience and capacity to recover from these impacts.

Most of the measures in the adaptation strategy are non-structural measures, that is, measures that focus on increasing awareness and knowledge of climate change, risk monitoring, and the need for adaptation. Only a small portion of the measures consist of structural measures, including the construction of mitigation facilities and other technical measures that are closely linked to the construction sector. These measures primarily focus on hydrology, water and marine resource management, and spatial planning.

The risks associated with flooding and extreme hydrological conditions caused by climate change pose major threats to society and the economy. In civil engineering, this requires an increase in the capacity for the construction, reconstruction, and upgrading of systems to protect against the harmful effects of water. This includes the construction, reconstruction, and modernisation of protective embankments, thresholds, dams, retention systems, accumulation systems, and other hydro-technical facilities and protection systems. Increased protection against the damaging effects of rising sea levels on infrastructure includes the reconstruction of water and utility infrastructure and the relocation of water intake points. Due to the consequences of adverse hydrological conditions, there is a need to reduce water supply losses, strengthen drainage systems, and build water treatment systems.

Adaptation measures include not only construction and strengthening measures but also the development of rehabilitation projects for vulnerable buildings, particularly important buildings and cultural assets.

The strategy refers to the development of "green infrastructure" and its integration into spatial planning. Green infrastructure involves the application of natural solutions to environmental, economic, and social challenges. For example, watercourse sections are designed to provide natural lowland areas for controlled flooding and reduce large water bodies.

It is also important to implement erosion control measures when cultivating soil and strengthen its ability to absorb excess water. Deforestation is one of the main causes of the increase in greenhouse gas concentrations. Therefore, spatial planning and land conversion play important roles in climate change adaptation [11].

As mentioned above, most measures belong to the so-called "non-structural" measures. This is because adaptation to climate change must be considered over the long term, with great uncertainty. Therefore, it is necessary to work on raising awareness, conducting research, and creating good databases to be able to adequately analyse the situation, decide on the

Table 1. Measures of the strategy of the Republic of Croatia for adaptation to climate change relevant to the construction sector (adapted from [11])

Measure label		Name of the measure	Responsible institution		
			MPCA	MSTI	U
Water resources	HM-01	Implement non-structural protection measures against the negative impacts of water and water regulation during extreme hydrological conditions whose intensity and frequency of occurrence are increasing due to climate change			
	HM-03	Strengthen technical, research, and management capacity for assessing the occurrence and risk of adverse climate change impacts and adaptation of freshwater and marine water systems under existing and future climate conditions	✓		✓
	HM-04	Strengthening the capacity of the competent institutions to act in the event of extreme hydrological conditions	✓		
	HM-05	Reduce the adverse impacts of sea level rise due to climate change on coastal water supply infrastructure and coastal water resources (non-structural measures)	✓	✓	
	HM-06	Strengthening the resilience of urban areas to anthropogenic pressures caused by climate change	✓		
Bio-diversity	B-07	Improve sustainable management and reduce anthropogenic impacts on (pre-) natural ecosystems, habitats, and wild species mainly through sustainable development measures using nature-based solutions	✓		
Energetics	E-03	Strengthening the resilience of existing capacities for the generation of electricity and thermal energy	✓		
Tourism	T-04	Strengthening the resilience of tourism infrastructure to various weather extremes	✓	✓	✓
Health	ZD-06	Increase in the number of safe points in the event of extreme weather conditions	✓		
	ZD-07	Strengthening the surveillance system for allergenic species		✓	✓
Spatial planning and arrangement	PP-01	Strengthening the knowledge base and monitoring and evaluation systems	✓		✓
	PP-02	Strengthening the technical and institutional capacities of professional actors in the system of spatial planning and development	✓		✓
	PP-03	Integration of adaptation measures into the system of spatial planning and development	✓		✓
	PP-04	Raise awareness and sensitise the public and decision-makers at all levels	✓		✓
	PP-05	Preparation of rehabilitation programs and projects	✓	✓	✓
Risk management	UR-02	Multisectoral and sectoral risk assessment for different threat/risk scenarios related to climate change	✓	✓	✓
General measures	KM-01	Strengthen professional and technical capacities for the implementation of research and applied and operational activities encompassing the field of climate modelling and predictive technologies for forecasting weather and environmental conditions and related warnings of hazardous conditions, as well as the analysis and interpretation of observed and expected climate changes and the hazardous weather phenomena they cause		✓	✓
	OM-01	Improve knowledge and capacity for monitoring climate change impacts, risk assessment, and adaptation to climate change			✓
	RP-01	Developing indicators for the impact of the implementation of adaptation strategies			✓

necessary measures, and react in time. These include defining floodplains and natural retention areas, conducting hazard analyses, and monitoring groundwater.

The reason for the lower number of structural measures related to construction is that experts in the construction field were not involved in the preparation of Croatia's Strategy for Adaptation to Climate Change. For this reason, the construction sector, both in Croatia and globally, needs to systematically reflect on the impact of climate change on structures and, consequently, on measures to adapt and reduce the impact of climate change.

According to worldwide building practices and scientific findings, there is a need for more durable structures that can better withstand weather conditions. However, more durable buildings preclude more frequent demolition and new construction cycles; that is, they reduce material consumption and decrease the carbon footprint. Finally, it is necessary to develop appropriate and accurate systems for monitoring and maintaining the buildings themselves because climate change has many consequences for the safety and durability of structures, which are explained in more detail in the following chapters.

2.3. Projection of climate change in the Republic of Croatia

The regional climate model RegCM4 was used for climate simulations within the framework of a Climate Change Adaptation Strategy in the Republic of Croatia. The current "historical" climate covers the period 1971–2000 and constitutes the reference period marked P0. The change in climate variables in relation to the reference climate is presented and discussed for two time periods: 2011–2040, i.e., P1 (immediate future) and 2041–2070, P2 (climate in the middle of the 21st century) [13]. Two climate scenarios were considered in the preparation of an adaptation strategy for the Republic of Croatia, RCP4.5. and RCP8.5., representing a future in which mitigation and adaptation measures are foreseen, in which GHG (greenhouse gases) concentrations increase until 2040 and then decrease (RCP4.5); and a future in which no significant mitigation and adaptation measures are foreseen, that is, a continuous increase in GHG concentrations (RCP8.5) [12].

According to [12], the optimistic scenario of RCP4.5. in the Republic of Croatia predicted a smaller increase in total precipitation in winter and spring and a decrease in autumn and summer with an increase in dry periods. Observations in the period 1961–2010 showed a trend towards increasing air temperatures over the entire territory of Croatia. An almost uniform increase in mean annual air temperature is expected until 2040, with a further increase until 2070. The increase in maximum air temperature could reach 2.3 °C by 2070. The largest increase in the minimum temperature occurred in winter in the coldest region of Gorski Kotar. The increase in hot days is between six and eight days in most parts of Croatia and will further increase to 12 days by 2070, which would mean almost a doubling of hot days for the mountainous regions. In the area with the strongest wind in the reference climate, a decrease in the maximum wind speed was expected in winter. Evapotranspiration will increase and soil moisture will decrease. Humidity increases throughout the year, particularly in summer in the Adriatic region. The decrease in snow cover in the Gorski Kotar region was approximately 50 % of the reference value. The sea level rise estimates were not determined by the RegCM model, but the results were taken from the IPCC AR5, and the conclusions were drawn based on research by local authors and observations of the current trend of changes in the mean water level of the Adriatic Sea. According to the results of the global models, the expected rise in mean global sea level by the mid-21st century is 19–33 cm under RCP4.5 and 22–38 cm under RCP8.5. However, it should be emphasised that these estimates are subject to considerable uncertainties, which we are already aware of when calculating sea levels for the historical climate. More detailed projections of climate parameters for the Republic of Croatia under scenario RCP4.5 scenario with possible impacts of climate change on infrastructure, especially bridges, are presented in Table 2.

Climate change has led to more frequent or intense phenomena that cause damage and pose a direct threat to structures. This will lead to greater loads on the structure but will also have an impact on the properties of the materials, usability, and safety of

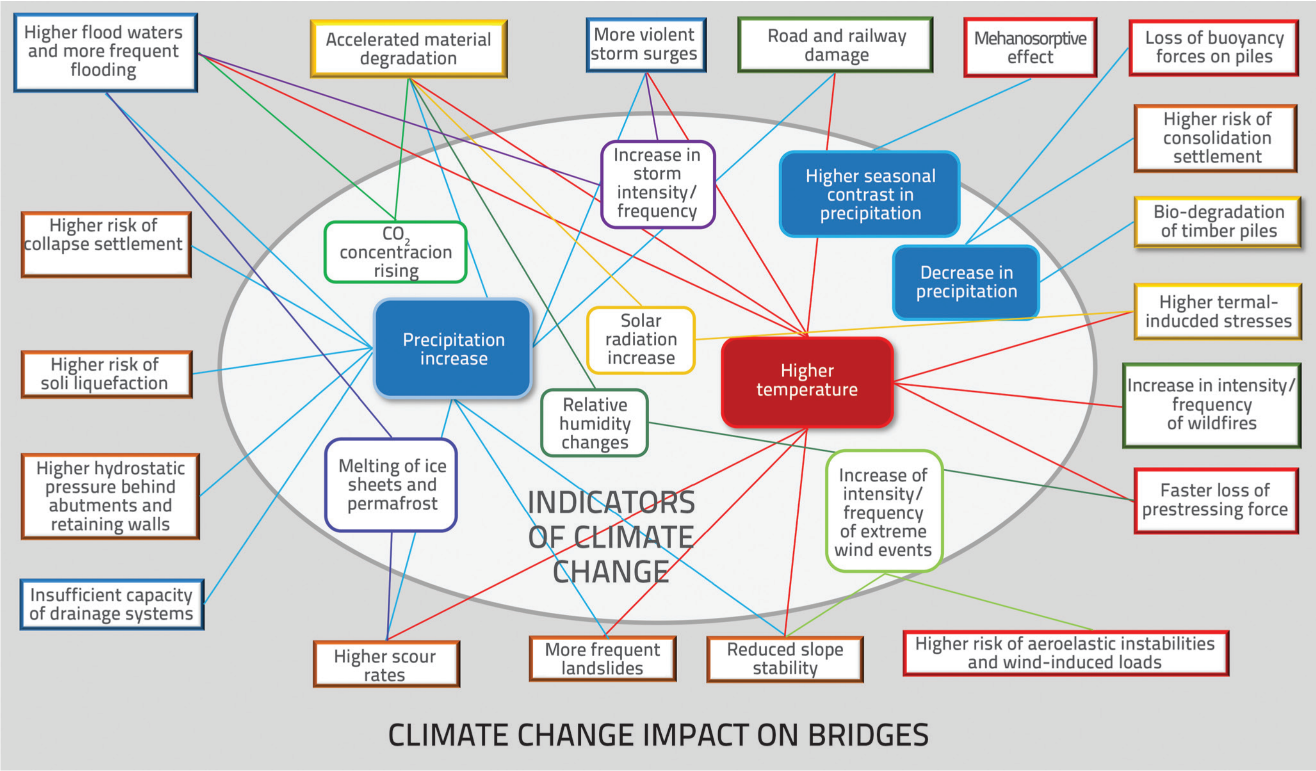

Figure 2. Impact of climate change on bridges [14]

Table 2. Projections of climate parameters for the Republic of Croatia according to the RCP4.5 scenario with respect to the period 1971–2000 (adapted from [12])

Climate parameters		Projections of the future climate according to the RCP4.5 scenario in relation to the period 1971–2000 obtained by climate modelling		Possible impact on infrastructure
		2011 – 2040	**2041 – 2070**	
Precipitation		Slight decrease in the average annual amount (apart from a smaller increase in NW Croatia)	A further trend of reducing the average annual volume (up to 5 %) except in the NW parts of the Republic of Croatia	Decrease in precipitation: loss of buoyancy forces on piles, biodegradation of timber piles, higher risk of consolidation settlement Higher seasonal contrast in precipitation: mechano-sorptive effect Precipitation increase: higher flood waters and more frequent flooding, higher risk of soil liquefaction and collapse settlement, higher hydrostatic pressure behind abutments and retaining walls, insufficient capacity of drainage systems, higher scour rates and storm surges, more frequent landslides, road and railway damage, accelerated material degradation, reduced slope stability
		Seasonal total: in winter and spring in most parts of Croatia smaller increase (5–10 %); in summer and autumn decrease (maximum 5–10 % in South Lika and South Dalmatia)	Seasonal total: up to 10 % decrease (mountains and southern Dalmatia) except in winter (5-10 % increase in southern Croatia)	
		Decrease in the number of rainy periods (except in central Croatia, where there is a smaller increase). Increase in dry periods.	Prolongation of the dry season.	
Surface runoff		No major changes, except in the highlands and hinterland of Dalmatia, where there is a decrease of up to 10 %	Reduction of runoff throughout Croatia (especially in spring)	Loss of buoyancy forces on piles, biodegradation of timber piles, higher risk of consolidation settlement
Evapotranspiration		Increase in spring and summer 5 – 10 % (outer islands and W Istria > 10 %)	An increase of up to 10 % for most of Croatia, up to 15 % on the coast and inland, and up to 20 % on the outer islands	Loss of buoyancy forces on piles, biodegradation of timber piles, higher risk of consolidation settlement
Air temperature		Mean: Increase of 1 – 1.4 °C (all seasons, all of Croatia)	Mean: increase of 1.5–2.2 °C (all seasons, all of Croatia, especially the mainland)	Higher thermal-induced stresses, increase in intensity/ frequency of wildfires, faster loss of prestressing force, reduced slope stability, more frequent landslides, higher scour rates and storm surges, higher flood waters and more frequent flooding, accelerated material degradation, road and railway damage
		Maximum: increase in all seasons 1 – 1.5 °C	Maximum: Rise to up to 2.2 °C in summer (up to 2.3 °C on the islands)	
		Minimum: highest rise in winter 1.2 – 1.4 °C	Minimum: the greatest increase on the continent in winter 2.1 – 2.4 °C. and 1.8 – 2 °C in the coastal regions	
Solar radiation		In summer and in autumn increase; in spring increase in the north and decrease in the west of Croatia; in winter decrease in the whole of Croatia	Rise in all seasons except winter (highest rise in the mountains and central Croatia)	Higher thermal-induced stresses, accelerated material degradation.
Snow cover		Reduction (largest in Gorski Kotar, up to 50 %)	Further reduction (especially in mountainous regions)	Higher scour rates, higher flood waters, and more frequent flooding
Air humidity		Year-round increase (highest in summer on the Adriatic)	Year-round increase (highest in summer on the Adriatic)	Faster loss of prestressing force, accelerated material degradation
Soil humidity		Decrease in northern Croatia	Reduction throughout Croatia (mostly in summer and autumn)	Loss of buoyancy forces on piles, biodegradation of timber piles, higher risk of consolidation settlement, mechano-sorptive effect
Extreme weather conditions	Days with Tmax > +30 °C)	Increase of 6 to 8 days (reference period: 15–25 days per year)	Up to 12 days more than the reference period	Higher thermal-induced stresses, increase in intensity/ frequency of wildfires, faster loss of prestressing force, accelerated material degradation, road and railway damage
	Days with Tmin < -10°C)	Further reduction and an increase in the Tmin value (1.2–1.4 °C)	Further reduction	
	Nights with Tmin ≥ +20 °C)	Increasing	Increasing	
Wind	Mean speed at 10 m	In summer and autumn on the Adriatic, increase up to 20-25 %	Winter and spring largely unchanged, but trend of increasing in summer and autumn in the Adriatic	Reduced slope stability, higher risk of aeroelastic instabilities, and wind-induced loads
	Max. speed at 10 m	Reduction in winter in the southern Adriatic and hinterland of Dalmatia	Reduction for all seasons except summer; biggest decrease in winter in the southern Adriatic	
Mean water level		2046. – 2065. :19–33 cm (IPCC AR5)	2081.–2100.:32–65 cm	Material degradation (corrosion of reinforced and metal structures), higher scour rates and storm surges, higher flood waters, and more frequent flooding

the structure, and geomechanical conditions. Figure 2 shows the effects of climate change on bridges and the associated causes.

The impact of climate change on structures is evident in all areas of civil engineering, from hydraulic engineering, geotechnical engineering, and load-bearing structures to building materials, construction organisation, and management.

Changes in the intensity and quantity of precipitation and temperature are the most evident signs of climate change and, at the same time, the causes of the most negative impact on structures. The most unfavourable impact of the increase in the amount and intensity of precipitation is higher flood levels and more frequent flooding, leading to a greater risk of the collapse of structures due to soil washout and erosion around piers, that is, damage and/or collapse of piers and roads due to the activation of landslides, erosion, and soil liquefaction. Other impacts of altered precipitation affect the usability and durability of structures, that is, they lead to the deterioration of materials, insufficient capacity of the drainage system, and damage to roads and railways.

Because many bridges are located near or over watercourses, they are particularly vulnerable to flood hazards with the hydraulic risk of scour. Scour leads to soil erosion around bridge piers. This results in a larger area of the pier being exposed to hydrodynamic forces [15]. According to [15], the greatest scour depth is reached during a flood. Scour and erosion are among the most common causes of bridge collapse. In combination with other stressors, emergencies, and climate change, this risk continues to increase and can have catastrophic consequences [16-18]. To address the risk of bridge scouring, early flood warning systems and infrastructure management must be integrated and a hydraulic component must be included in bridge inspections. Climate change also leads to changes in the groundwater and geomechanical conditions. Changes in groundwater lead to changes in soil strength, which increase the risk of landslides and reduce slope stability. In addition to seismic activity, the most common causes of landslides are extreme weather conditions, high precipitation, and flooding. Increased wind loads also contribute to reduced slope stability and accelerated terrain erosion [19].

A rise or fall in groundwater leads to the settlement or elevation of the ground surface and differential ground settlement, which are particularly problematic for structures. In some cases, water saturation leads to collapse owing to settlement, as the water weakens the internal bonds between the particles, and a loss of stability occurs. This has proven to be particularly serious in the artificial fields. In seismically active areas, soil liquefaction is associated with decreased groundwater content [18].

The effects of climate change are also evident in deep foundations and piles. This is because the sinking of the soil around the piles causes negative friction on the casing, which increases the stress in the piles and can lead to collapse. In the case of piles, a decline in groundwater also causes the upper part of the pile to be exposed to aerobic conditions and the material to degrade [18, 19].

The next most important indicator of climate change is an increase in air temperature. The standards for the design of bridges provide for a wide range of temperature loads, which are considered when calculating the load-bearing capacity of a structure so that the stability of the bridge is not compromised. However, an increase in temperature negatively impacts infrastructure durability and usability. For example, one of the direct consequences of global warming is the buckling of rails owing to temperature extremes, rendering the infrastructure unusable during heat waves. In addition, high temperatures can affect the dynamics of the structure, especially for steel bridges, but can also lead to cracks in the concrete owing to excessive stresses. Frequent and severe fluctuations in temperature stress increase the risk of cracking and damage and can significantly shorten the life of a structure, especially in an aggressive environment.

Increases in temperature and relative humidity have a significant impact on the durability of reinforced concrete bridges, which is discussed in more detail in the next chapter. As an increasing proportion of concrete structures are made of prestressed concrete, especially bridges, the effects of climate change on the reduction of the prestressing force are also very significant. Long-term losses of prestressing force are closely related to concrete shrinkage and creep, which are influenced by environmental conditions. Changes in relative humidity and an increase in temperature increase the creep and shrinkage of concrete, which can lead to large deformations. In dozens of cases, a significant reduction in prestressing force of up to 50 % has been observed owing to large deformations [19, 20].

3. Impact of climate change on the durability of concrete structures

Figure 2 shows that at least five indicators of climate change (increases in CO2 concentration, precipitation, solar radiation, and temperature and a change in relative humidity) influenced the accelerated degradation of building materials. These findings become more significant when considering that material degradation is already one of the most common causes of damage, deterioration, shortening of service life, and failure of structures, particularly bridges (Figure 3) [13]. The most commonly used materials in modern structures are reinforced concrete, steel, prestressed concrete, timber, and brick. As far as bridge construction is concerned, reinforced or prestressed concrete is by far the leader, accounting for more than 85 % of bridges on state roads in the Republic of Croatia [21]. Bridges, as engineering structures, have a required service life of up to 100 years. This service life is often difficult to achieve in concrete structures. Concrete structures exposed to mechanical stress and the conditions of an aggressive environment are not durable, and without proper planning for the durability and maintenance of the structure, they cannot achieve the expected service life [22]. According to [23], material deterioration was found to be the main cause of failure in approximately 15 % of the more than 600 bridges studied. The main causes of failure due to deterioration are the corrosion of the reinforcement in the concrete, age, and atmospheric influences. Similar results were obtained in [24], as shown in Figure 3.

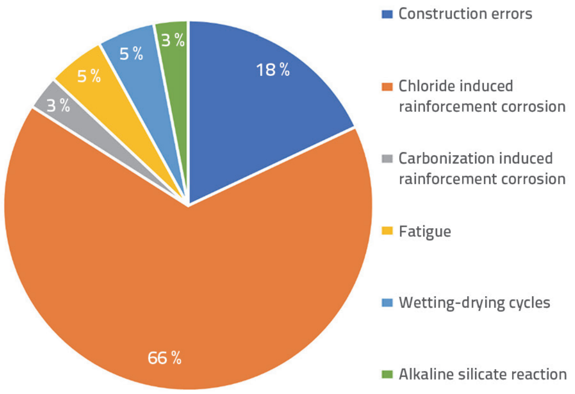

Figure 3. Causes of deterioration of concrete structures [13]

According to some statistics, corrosion damage is responsible for more than 80 % of all damage to reinforced concrete structures [25]. The rehabilitation of these problems is also associated with significant economic costs. Corrosion negatively affects concrete structures through several mechanisms. This leads to a reduction in the cross-section of the steel bar, reduces the adhesion of the reinforcement and concrete, and because the corrosion products have a much larger volume than the original volume of the reinforcement, leads to high stresses and the opening of cracks. Aggressive substances can penetrate the reinforcement through cracks and further accelerate the corrosion process [25, 26].

3.1. Impact of climate change on corrosion

Carbonation and chloride ingress are influenced by climatic factors. The temperature and relative humidity are among the most important factors.

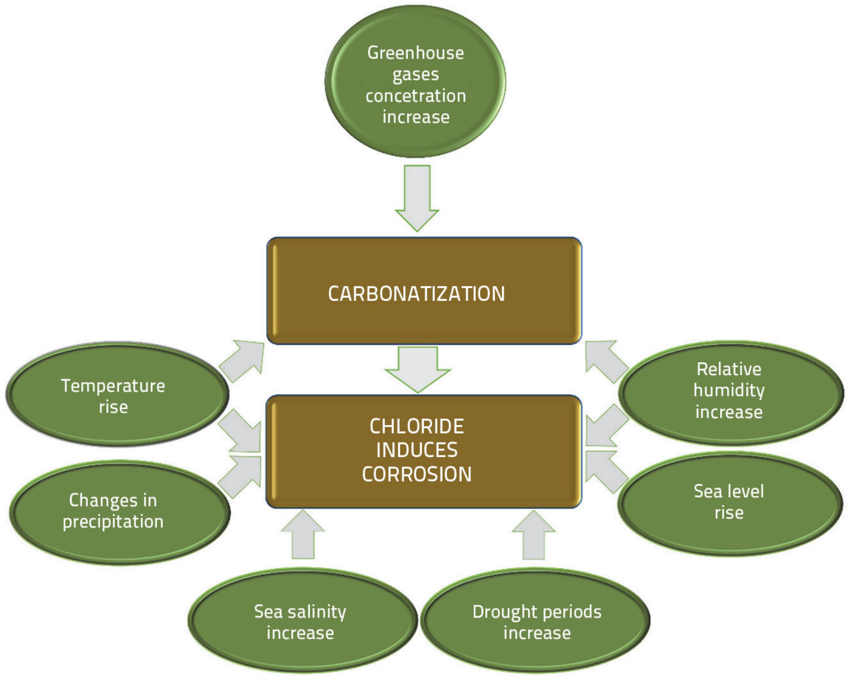

Figure 4. Climate change impact on reinforcement concrete corrosion

The carbon dioxide diffusion coefficient during carbonation increased with increasing temperature. Filling the pores with water slows down the carbonation process because CO$_2$ (gas in general) has a low diffusion coefficient in water, whereas chloride ions behave the other way around as the humidity increases [27]. It has been shown that carbonation is strongest at a relative humidity of 50 % to 70 % because, at higher relative humidity, the carbon dioxide diffusion coefficient decreases significantly, and at lower values, there is not enough moisture for the carbonation process [28]. The presence of chloride in the environment varies with changes in precipitation, sea salinity, prolonged periods of heat and drought, and sea level rise, resulting in a greater and longer-lasting presence of chloride on the surface of the structure (Figure 4). In addition, changes in temperature and relative humidity affect the processes of diffusion, convection, migration, absorption, and thermodiffusion, which cause chloride to penetrate the material [29]. There is also evidence that the carbonation of concrete accelerates chloride penetration, implying that chloride corrosion is also indirectly influenced by the CO$_2$ concentration [28].

The effect of climate change on concrete corrosion has been the subject of numerous studies. Yoon et al. [30] conducted one of the first studies to confirm that an increase in the CO$_2$ concentration affects carbonation. The results of Wang et al. [28] showed that with the predicted changes in carbon dioxide (CO2) concentration and temperature by 2100, the probability of damage increases by 20-40 % after the first 20-30 years of service life. Compared with the reference scenario (without an increase in carbon dioxide concentration), the probability of damage increased by up to 460 %. For the year 2100, the results for the area of China predict an increase in carbonation depth of up to 50 % for the most severe scenario compared to the year 2000, but the predictions showed an increase of up to 18 % for the medium scenario RCP4.5 [31]. As for corrosion due to chloride penetration, studies on bridges in China predict a 6-15 % increase in chloride concentration at the reinforcement level [32]. Depending on the possible scenarios and exposure conditions, service life may be reduced by 2 %-18 % due to chloride penetration [30-33]. Khatami D. [34] showed that changes in temperature, relative humidity, and surface concentration of chloride reduced the corrosion initiation time by up to 39 % and increased the crack width by up to 29 %. The results are presented in comparison with a reference scenario in which climate change was not considered. In general, carbonation is more sensitive to projected climate change than chloride intrusion processes. According to French studies, carbonation is more sensitive to relative humidity than to temperature changes [35]. It was also concluded that the protective layer of concrete is the most important factor in testing the reliability of the structure, with a much greater influence than other parameters such as porosity, diffusion coefficient, and permeability, all of which have a similar influence. In the Boston area, existing protective coatings will not be sufficient for the next 50 years. This is more likely to be exceeded by chloride-induced corrosion (2055 years) than by carbonation (2077 years) [36]. It has also been shown that the protective layer has the greatest influence on the probability of damage, whereas the compressive strength of concrete has negligible influence [37]. According to [38], when considering chloride penetration into concrete under different climate change scenarios, the corrosion initiation time, i.e., the time to reach the critical chloride concentration at the reinforcement level, decreased from 13 % to 31 % compared with the reference scenario without climate change. It should be noted that the models for chloride penetration into concrete mentioned here do not consider the processes of drying and wetting concrete, which is one of the main features of the existing weather conditions as well as climate change projections. In [39], it was shown that by including the seasonal processes of drying and wetting cycles and the application of de-icing salt only in the winter months in numerical models, the depassivation time was reduced by up to 60 % compared to numerical models that do not take into account the drying and wetting cycles and the non-uniform chloride distribution on the surface during the year. It should also be remembered that CO_2 concentrations in urban and developed environments are approximately 14 % higher than the global average reported by the IPCC[37].

3.2. Impact of corrosion on seismic resistance of structures

Currently, seismic design does not assume that the seismic resistance of a structure changes over time. It is considered constant throughout the life of the structure [40, 41]. Thus, the effects of the environment on the structures, material deterioration, the influence of previous earthquakes, and damage were not considered [42]. This means that the seismic capacity of a structure at the beginning of its life, which is not corroded or undamaged, is equated with a structure that is at the end of its life and is under the long-term influence of corrosion, climate, other environmental conditions, damage, and others. From a seismic design perspective, the consequences of corrosion are the reduction of bearing capacity and deformability, as well as the reduction of energy dissipation capacity, changes in the dynamic properties of the structure, ductility, and collapse mechanisms [26, 27, 30, 43]. Indeed, the immediate consequence of the formation of corrosion products is a reduction in the cross-section of the reinforcement, as well as a reduction in the ductility of the reinforcing bars [44-47]. A smaller cross-section of the reinforcement reduces the load-bearing capacity of the structure, that is, it reduces the load-bearing capacity for bending, shear, and fatigue strength. Furthermore, not only the ductility of the reinforcing bars is reduced, but also the stiffness of the structure, the redistribution of internal forces, and the load-bearing capacity of a statically indeterminate system [48, 49].

Pitting corrosion can significantly reduce the cross-section of the reinforcement, affect the load-bearing capacity and fatigue strength, and can lead to brittle fracture of high-strength steel cables for concrete prestressing [50]. The danger of localised corrosion is also reflected in the fact that the degree (depth) of damage can progress considerably before the signs become visible on the surface of the concrete [24].

Further volume growth of the corrosion products, which is significantly greater than the original volume of the reinforcement, (causes additional stresses in the concrete, leading to cracking and possible fracturing of the concrete. This leads to a reduction in the cross section and protective layer of the concrete. If concrete spalling occurs on the compression side of the cross section, the arm of the internal forces, and thus the bending moment, is reduced. Cracks and spalling of the concrete in the area of the reinforcing bars lead to a reduction in the bond between the concrete and reinforcement and a reduction in the shear strength. Cracks in the concrete in the tensile zone indicate that the tensile strength of the concrete has been reached, and any additional tensile stress leads to the enlargement of existing cracks or the formation of new cracks in the concrete [49]. Cracked concrete reduces the protection of the reinforcement and allows easier and more direct passage of aggressive substances into the reinforcement, thereby reducing the load-bearing capacity of the structure in the long term. Depending on the direction of the cracks, they can also affect the stiffness and distribution of internal forces in a structure [49-51].

The results of studies on the influence of corrosion on seismic capacity confirm that the assumption that the capacity of a structure remains constant throughout its life is incorrect, especially on the safety side. The importance of these findings increases when it is known that there are currently a significant number of earthquake-prone structures designed before modern seismic standards, and as such, pose a hazard owing to the additional deterioration of the material over time [52]. The most common method for assessing existing bridges is visual inspection, where corrosion of the reinforcement can only be detected when it is already advanced [53]. Dizaj et al. [52] developed a model to predict the residual load-bearing capacity of corroded reinforced concrete structures. They related the cross-sectional loss as a measure of corrosion and the associated crack width to the remaining load-bearing capacity. This establishes a relationship between the visually perceptible damage and the remaining load-bearing capacity of the structure at that time, which underlines the importance of visual inspection of the building. The results showed that corrosion changes the failure mechanism from ductile (yielding of reinforcement) to brittle (concrete crushing), which is always less desirable. This was confirmed in [54]. As the ductility decreases, the capacity values of the structure in terms of the peak ground acceleration and the corresponding return period of the earthquake also decrease. Comparing the values for the uncorroded and the corroded structures, a lower capacity in terms of peak ground acceleration of up to 93 % was observed. The return period decreased from 968 years for the non-corroded structure to 232 years for the most severe variants. In general, corrosion has a greater effect on ductility than on flexural capacity. According to [52], neglecting the negative effects of the environment and climate throughout the life of a structure significantly underestimates the probability of failure. For example, at a peak ground acceleration of a_g = 1.0g, the probability of failure of the structure increases from 20 % to 50 % when the negative effects of climate and environment are taken into account. Bridges are located in extremely aggressive environments; often, marine environments with chlorides and/or de-icing salts are also present as part of the transport infrastructure. Simultaneously, the entire structure and its parts are exposed to negative environmental effects. The effects of an aggressive marine environment on seismic resilience have been demonstrated in studies [55] on three bridges in Japan with different seismic hazards and exposures to chlorides. After 50 years of service, the bridge closest to the coast had the highest probability of collapse although it originally had the lowest seismic hazard. Furthermore, these results were compared with those in which the influence of the environment was not considered. This indicates that the change in the seismic capacity of the structure was caused by the major influence of the maritime environment.

Similar to other structures, corrosion affects the ductility of bridges. According to [56], the destruction of concrete in a corroded element occurs at significantly lower deformations. At a corrosion-related mass loss of 20 %, these values decreased to 80 %. Studies [57-60] show similar results regarding the influence of material deterioration on the seismic behaviour of bridges: a reduction in ductility with increasing corrosion, a lower load-bearing capacity, and a general increase in the probability of collapse over time, that is, with the development of corrosion.

According to [60], the influence of corrosion can be neglected for smaller peak accelerations (< 0.1 g). For higher peak accelerations, the reduction in capacity was not significant for either corroded or non-corroded bridges up to a service life of approximately 25 years. However, as a bridge ages, the probability of its collapse under corrosion becomes increasingly different from that at the beginning of its service life.

It should be noted that in these studies, the effects of corrosion were mainly represented by the loss of the cross-sectional area of the reinforcement. The reduction in adhesion between the concrete and steel and pitting corrosion is often not considered in the models. In addition to these and other uncertainties compared to the real situation, there is a possibility that the real results will be less favourable than those obtained from the research presented.

The influence of reinforcement corrosion in concrete on the reduction of structural capacity, and thus, seismic resistance, is a challenge, even without considering climate change. Using examples of large Adriatic bridges exposed to sea salt and bridges in mountainous regions exposed to deicing salts, it has been shown that the active phase of corrosion, in which there is a significant reduction in the diameter of the reinforcement bar, occurs after only 15 to 20 years [41, 61-64]. Thus, even without considering climate change, ensuring the durability of structures and preventing or slowing down aggressive substance penetration and active corrosion are challenges that have not yet been fully solved for both new and existing structures. However, climate change can further accelerate the corrosion process, thereby reducing the durability and load-bearing capacity of structures.

4. Climate change impact on actions on structures

Buildings are directly influenced by the environment, atmospheric conditions, and weather, and climatic effects have a large share of the action loads on structures. Climate change also changes individual action loads on structures. This may manifest itself as a change in the intensity of loads (e.g.,, an increase in temperature, precipitation intensity, and wind speed, but also an increase in the frequency of extreme weather conditions, such as floods, heat waves, and extreme winds).

Some of these consequences may prove more favourable in terms of the load on the structures. According to [65], the snow load values for Norway in the period of 2070–2100. g could be reduced in most parts of the country. However, for smaller inland areas, the load is predicted to increase. The situation is similar across Europe. While a decrease in snow depth and area was estimated for the Alps and the Carpathians, an increase in snow load was predicted for the Mediterranean, the Apennine Peninsula, the UK, and Sweden. However, although a decrease in annual maximum snow cover is possible in some places, more frequent extreme precipitation events are expected, particularly in higher mountainous regions [66].

For bridges, extreme snow conditions are of greater importance for the serviceability or accessibility of roads and bridges, and for the durability of the structure. For example, a snowstorm at the end of February 2023 led to the complete disruption of road traffic

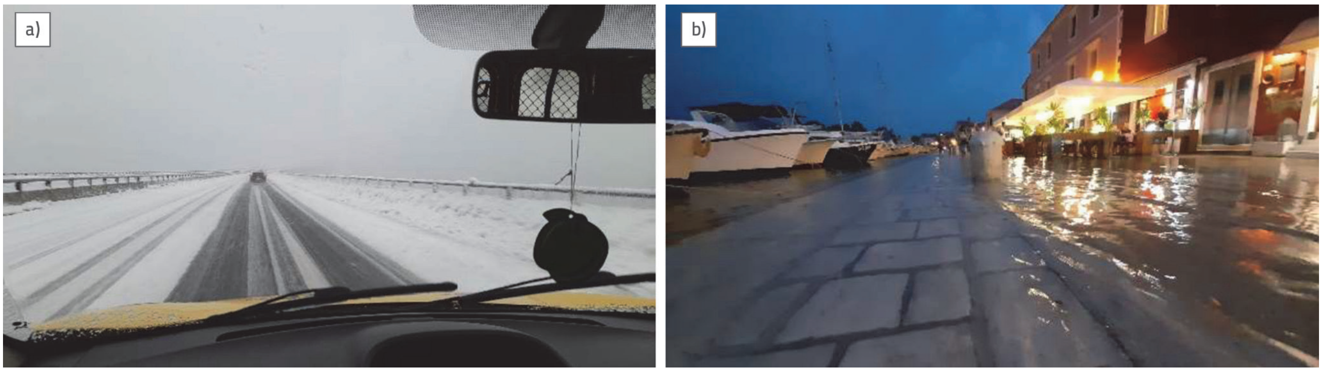

Figure 5. a) Viaduct Zečeve Drage during a snowstorm at the end of February 2023; b) Flood of promenade and buildings due to high tide in Starigrad on Hvar Island in August 2020.

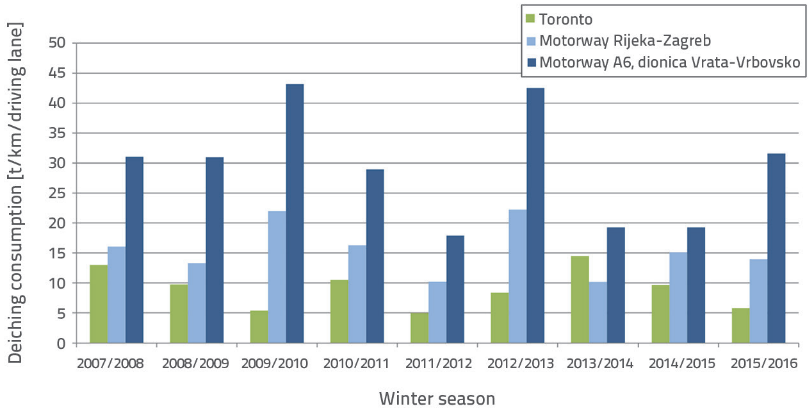

Figure 6. Seasonal consumption of de-icing salts per kilometre per lane on Croatian and Canadian motorways (according to [63]

between the coast and the Croatian mainland (Figure 5a). Within 24 hours, 47 cm of snow fell in Gospić and 3300 tonnes of de-icing salt were used on the mountain section of the Zagreb – Rijeka motorway [66, 67].

Research on the consumption of de-icing salt on Croatian and Canadian roads led to an interesting result: on the Rijeka–Zagreb motorway, especially on the mountain section Vrata–Vrbovsko, salt consumption was higher than that on the urban highway in Toronto (Figure 6) [63]. It should be noted that the salt consumption in Figure 6 is given per lane and per kilometre of the road so that the data can be directly compared. Based on 10 years of data, no statement can be made regarding the trend in road salt consumption, and data for longer periods are not available. Additionally, Croatian roads and highways have adopted a conservative approach to road salt consumption to ensure passenger safety during the winter months [62], which is one of the reasons why salt consumption is higher in the mountainous regions of Croatia than in Toronto. While climate change generally brings warmer weather and less snow, in mountainous regions, it also means more frequent changes in the freeze-thaw cycle, which does not reduce salt consumption. This freeze-thaw cycle leads to degenerative changes in concrete structures, usually in the form of cracks, while the large amount of de-icing salts used increases the risk of reinforcement corrosion in concrete.

Flooding is one of the most noticeable effects of climate change in Croatia and Europe. It has already been established that extreme events with a return period of 100 years occur much more frequently, even every few years [65, 68]. Indeed, it is predicted that by 2080, events with a hundred-year return period will have a 30-year return period. In addition to an increase in frequency, the intensity of such events is expected to increase. Numerous factors influence the occurrence of floods. For example, urbanisation and an increase (density) in the population density significantly increase the risk of flooding. Changes in rainfall also affect the risk of bridge collapses. According to [69], in the UK, depending on location and other parameters, bridge scour could increase from 5 % to 50 % by 2080.

Temperature increases in expected averages and extreme events (e.g., more intense and prolonged heat waves) can lead to a range of consequences, from damage to roads and railways to more frequent and intense forest fires. Research [70] has shown that a 2.9 °C increase in average temperature by 2100 could lead to a reduction in the service life of bridge elements by up to 25 years due to fatigue problems.

Rising sea levels as a result of climate change contribute to an increase in many risks. Higher sea level increases the likelihood of flooding. A tsunami, which is a consequence of tectonic events, can have far more catastrophic consequences when combined with higher sea levels, and this effect certainly Therefore, further detailed studies are required. Sea level rise values are subject to many uncertainties and vary greatly from region to region. Therefore, local predictions of future conditions are of great importance. According to some predictions, it ranges from 9.8 to 25.6 cm in the Mediterranean [65]. The Adriatic coast is already experiencing flooding of the shore and coastal buildings owing to high tides and strong southerly winds (Figure 5b). Although such phenomena do not affect the stability or load-bearing capacity of the structures, they have a strong impact on their durability and serviceability.

In general, these projections show the potentially significant influence of climate change on (climate) load. An increase in the frequency and intensity of extreme weather conditions significantly affects structures. It should be emphasised that it is currently difficult to estimate new characteristic load values owing to a lack of data on temporal and spatial distributions. Further research will also lead to a reduction in uncertainties related to climate modelling and climate change, which are still noticeable. Indeed, the prediction of changes in wind load is still subject to significant uncertainties, mainly because of insufficient knowledge and data from previous observations, such as the sea level, which are largely location-dependent. However, according to the European Committee for Standardisation (CEN), an increase in the occurrence of extreme wind storms is expected in northern and central Europe. For this reason, the CEN calls for the continuous development and monitoring of climate change guidelines, at least every 15 years, and stresses that further knowledge is needed to limit uncertainties, both static and modelling.

5. Conclusion

Research and a better understanding of the effects of climate change on structures will enable the development of adaptation measures for future conditions, not only in the design of new structures but also in the appropriate maintenance of existing structures, as well as in procedures for rehabilitation, renovation, etc.

As outlined in this study, climate change has multiple effects on bridges and other structures. In addition to the changes in the intensity, frequency, and nature of the external loads acting on the structure, they also lead to changes in the material properties, internal processes in the materials, and their acceleration or deceleration. It can be said that climate change negatively impacts the structures in two directions. Not only do they require higher values for the load-bearing capacity of the structure owing to more negative impacts than those for which they were designed, but at the same time they also further reduce the existing load-bearing capacity because they affect material properties and accelerate degradation processes. Therefore, climate change must be considered when planning, designing, and maintaining new and existing structures.

To determine future conditions as accurately as possible and enable an appropriate response, and considering that climate modelling is regionally sensitive, further improvements are needed in both climate modelling and structural design and management systems. Furthermore, the lengthy process of setting standards has an additional impact on the slowness of adopting standards that consider climate change.

An explicit design approach is recommended until standards that considered climate change are introduced. This design is based on the structural behaviour and includes degradation models with time-dependent processes and variables. According to the current standards in the Republic of Croatia [71, 72], the durability calculation includes only an implicit (descriptive) procedure from which certain requirements for the design, construction, and maintenance of the structure are derived. For example, the required values for the water-cement ratio, minimum depth of concrete cover, method and schedule for the inspection of the structure, maintenance work, etc. These values are primarily based on practical experience. If these requirements are satisfied, the durability of the structure is considered ensured. The standard HRN EN 206 [73] only mentions certain cases where an explicit design might be appropriate, such as structures with a demanding service life that differs significantly from 50 years and structures in particularly aggressive environments. Bridges are examples of such engineering structures of significant importance. The calculation of service life includes models of all relevant degradation mechanisms calibrated to the exploitation conditions [28]. Such comprehensive models of degradation mechanisms provide more accurate requirements for the design and construction of structures and allow for the improvement of maintenance procedures. This leads to more reliable structures and a reduction in costs over their service life. However, a more precise use of the model to calculate the service life of structures (degree of complexity, types of degradation mechanisms, verification procedures, etc.) has not yet been clarified in the current standards.

REFERENCES

[1] BBC News, bbc.com , 27.07.2022.

[2] The Copernicus Climate Change Service (C3S), Copernicus, 18.2.2023,

[3] WMO - World Meteorological Organization, https://public.wmo.int/en, 29.08.2021.

[4] DOOR - Društvo za oblikovanje održivog razvoja, https://door.hr/, 29.08.2021.

[5] IPCC - The Intergovernmental Panel on Climate Change, https://www.ipcc.ch/, 14.7.2021.

[6] Cubasch, U., Wuebbles, D., Chen, D., et al.: Introduction. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

[7] Stocker, T.F., D. Qin, G.-K. Plattner, M. et al.: Summary for Policymakers.. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA, Cambridge University Press, Cambridge, IPCC, 2013

[8] Subcommission on Quaternary Stratigraphy (SQS), Anthropocene Working Group, http://quaternary.stratigraphy.org/working-groups/anthropocene/, 14.07.2022

[9] Solomon, S., Qin, D., Manning, M., et al.: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, IPCC, 2007

[10] Ministarstvo zaštite okoliša i energetike: Radna verzija Strategije prilagodbe klimatskim promjenama u Republici Hrvatskoj za razdoblje do 2040. godine s pogledom na 2070. godinu (Zelena knjiga) (poglavlje), Jačanje kapaciteta Ministarstva zaštite okoliša i energetike za prilagodbu klimatskim promjenama te priprema Nacrta strategije prilagodbe klimatskim promjenama, mr.sc. Trumbić I., Zagreb, 2017

[11] Strategija prilagodbe klimatskim promjenama u Republici Hrvatskoj za razdoblje do 2040. godine s pogledom na 2070. godinu. Zagreb: Narodne novine d.d., NN 46/2020

[12] Ministarstvo zaštite okoliša i energetike: Nacrt Strategije prilagodbe klimatskim promjenama u Republici Hrvatskoj za razdoblje do 2040. godine s pogledom na 2070. godinu (Bijela knjiga), Jačanje kapaciteta Ministarstva zaštite okoliša i energetike za prilagodbu klimatskim promjenama te priprema Nacrta strategije prilagodbe klimatskim promjenama, mr.sc. Trumbić I., Zagreb, 2017

[13] Ministarstvo zaštite okoliša i energetike: Rezultati klimatskog modeliranja na sustavu HPC Velebit za potrebe izrade nacrta Strategije prilagodbe klimatskim promjenama Republike Hrvatske do 2040. s pogledom na 2070. i Akcijskog plana (Poglavlje), Jačanje kapaciteta Ministarstva zaštite okoliša i energetike za prilagodbu klimatskim promjenama te priprema Nacrta strategije prilagodbe klimatskim promjenama, dr.sc. Branković Č., Zagreb, 2017 .

[14] Kušter Marić, M., Mandić Ivanković, A., Srbić, M. et al.: Utjecaj klimatskih promjena na mostove u morskom i planinskom okolišu, 8. sabor hrvatskih graditelja, Vodice, 2021.

[15] Harasti, A., Gilja, G., Potočki, K., Lacko, M.: Scour at Bridge Piers Protected by the Riprap Sloping Structure: A Review. Water 2021, 13, 3606. https://doi.org/10.3390/w13243606

[16] Bačić, M., Kovačević, S.M., Librić, L. et al.: Utjecaj klimatskih promjena na sustav zaštite od poplava: primjer projekta oVERFLOw, 8. sabor hrvatskih graditelja, Vodice, 2021.

[17] Kosič, M., Prendergast, L.J., Anžlin, A.: Analysis of the response of a roadway bridge under extreme flooding-related events: Scour and debris-loading, Engineering Structures, 279 (2023), 115607, ISSN 0141-0296, https://doi.org/10.1016/j.engstruct.2023.115607.

[18] Toll, D.G., Abedin, Z., Buma, J. et al.: The impact of changes in the water table and soil moisture on structural stability of buildings and foundation systems:systematic review CEE10-005 (SR90), 2012, Technical Report. Collaboration for Environmental Evidence.

[19] Nasr, A.E., Björnsson, I. et al: Bridges in a changing climate: a study of the potential impacts of climate change on bridges and their possible adaptations, Structure and Infrastructure Engineering, 16 (2020) 4, pp. 738-749, https://doi.org/10.1080/15732479.2019.1670215

[20] Bažant, Z.P., Hubler, M.H., Yu, Q.: Pervasiveness of excessive segmental bridge deflections: Wake-up call for creep. ACI Structural Journal, 108 (2011) 6, pp. 766–774.

[21] Puž, G., Radić, J., Tenžera, D.: Visual inspection in evaluation of bridge condition, GRAĐEVINAR, 64 (2012) 9, doi: https://doi.org/10.14256/JCE.718.2012

[22] Stipanović Oslaković, I., Bjegović, D., Mikulić, D.: Matematički modeli za proračun uporabnog vijeka armiranobetonskih konstrukcija, GRAĐEVINAR, 59 (2007) 9

[23] Milić, I., Mandić Ivanković, A., Syrkov, A., Skokandić, D.: Bridge failures, forensic structural engineering and recommendations for design of robust structures, GRAĐEVINAR, 73 (2021) 7, pp. 717-736, doi: https://doi.org/10.14256/JCE.3234.2021

[24] RILEM 2022: Benchmarking Chloride Ingress Models on Real-life Case Studies—Marine Submerged and Road Sprayed Concrete Structures, Koenders E., Imamoto K., Soive A., Springer Cham. 2022, https://doi.org/10.1007/978-3-030-96422-1

[25] Cairns, J., Plizzari, G.A., Du, Y., et al.: Mechanical Properties of Corrosion-Damaged Reinforcement, ACI Materials Journal, 102 (4), pp. 256-264, 2005.

[26] Franciškovič, J.: Corrosion protection in reinforced-concrete structures, GRAĐEVINAR, 56 (2004) 12

[27] Böhni, H.: Corrosion in reinforced concrete structures, Woodhead Publishing Limited, Cambridge, 2005.

[28] Wang, X., Stewart, M.G., Nguyen, M.: Impact of climate change on corrosion and damage to concrete infrastructure in Australia. Climatic Change 110 (2012), pp. 941–957. doi: 10.1007/s10584-011-0124-7

[29] Nguyen, P., Bastidas-Arteaga, E., Amiri et al.: An Efficient Chloride Ingress Model for Long-Term Lifetime Assessment of Reinforced Concrete Structures Under Realistic climate and Exposure Conditions, International Journal of Concrete Structures and Materials 11 (2017) pp. 199-213, doi: 10.1007/s40069-017-0185-8

[30] Yoon, I., Copuroglu, O., Park, K.: Effect of global climatic change on carbonation progress of concrete, Atmospheric environment, 41 (2007) 34, pp. 7274–7285, doi: 10.1016/j.atmosenv.2007.05.028

[31] Peng, L., Stewart, M.G.: Climate change and corrosion damage risks for reinforced concrete infrastructure in China. Struct Infrastruct Eng., 12 (2016) 4, pp. 499–516.

[32] Xie, H.B., Wang, Y.F., Gong, J. et al.: Effect of Global Warming on Chloride Ion Erosion Risks for Offshore RC Bridges in China. KSCE Journal of Civil Engineering 22 (2018) 9, pp.3600–3606 doi: 10.1007/s12205-018-1547-8

[33] Gao, X., Wang, X.: Impacts of Global Warming and Sea Level Rise on Service Life of Chloride-Exposed Concrete Structures, Sustainability, 9 (2017) 3, pp. 460; doi:10.3390/su9030460

[34] Khatami, D.: Impast of climate conditions on deteriorating reinforced concrete bridges in the US Midwest region, J. Perform. Constr. Facil., 35 (2021) 1. DOI: 10.1061/(ASCE)CF.1943-5509.0001528

[35] Larrard, T., Bastidas-Arteaga, E., Duprat, F et al. Effects of climate variations and global warming on the durability of RC structures subjected to carbonation, Civil Engineering and Environmental Systems, 31 (2014) 2, pp. 153-164. doi: 10.1080/10286608.2014.913033

[36] Saha, M., Eckelman, M.J.: Urban scale mapping of concrete degradation from projected climate change. Urban Climate, 9 (2014) pp. 101-114, doi: 10.1016/j.uclim.2014.07.007

[37] Orcesi, A., O'Connor, A., Bastidas-Arteaga, E., et al.: Investigating the Effects of Climate Change on Material Properties and Structural Performance, Structural Engineering International, 32 (2022) 4, pp. 577-588, doi: 10.1080/10168664.2022.2107468

[38] Bastidas-Arteaga, E., Schoefs, F., Stewart, M.G., Wang, X.: Influence of global warming on durability of corroding RC structures: A probabilistic approach, Engineering Structures. 51 (2013), pp. 259–266.

[39] Kušter Marić, M., Ožbolt, J., Balabanić, G., et al.: Chloride Transport in Cracked Concrete Subjected to Wetting – Drying Cycles: Numerical Simulations and Measurements on Bridges Exposed to DE-Icing Salts. Front. Built Environ. 6 (2020) :561897. doi: 10.3389/fbuil.2020.561897

[40] Titi, A., Biondini, F.: Probabilistic seismic assessment of multistory precast concrete frames exposed to corrosion, Bulletin of Earthquake Engineering, 12 (2014) 6, pp. 2665–2681, doi:10.1007/s10518-014-9620-2

[41] Skokandić, D., Vlašić, A., Kušter Marić, M., Srbić, M., Mandić Ivanković, A.: Seismic Assessment and retrofitting of Existing Road Bridges; State of the Art Review, Materials, 15 (2022) 7, 2523,23 doi:10.3390/ma15072523

[42] Karapetrou, S., Manakou, M., Bindi, D., Petrovic B., Pitilakis, K.: Time-building specific seismic vulnerability assessment of a hospital RC building using field monitoring data, Engineering Structures, 112 (2016), pp. 114-132, doi: 10.1016/j.engstruct.2016.01.009

[43] Sousa, M.L., Dimova, S., Athanasopoulou, A., et al.: Expected implications of climate change on the corrosion of structures, EUR 30303 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-20782-5, doi:10.2760/05229, JRC121312

[44] fib Task Group Bond Models: Bond of Reinforcement in Concrete – State-of-art report, fib Bulletin 10 (2000), Lausanne, International Federation for Structural Concrete, doi:10.35789/fib.BULL.0010

[45] Cairns, J., Plizzari, G.A., Du, Y. et al.: Mechanical properties of corrosion-damaged reinforcement, ACI Materials Journal, 102 (2005) 4, pp. 256-264.

[46] Du, Y.G., Clark, L.A., Chan, A.H.C.: Effect of corrosion on ductility of reinforcing bars, Magazine of Concrete Research, 57 (2005) 7, pp. 407-419.

[47] Du, Y.G.; Clark, L.A., Chan, A.H.C.: Residual capacity of corroded reinforcing bars, Magazine of Concrete Research, 57 (2005) 3. pp. 135-147.

[48] Rodriguez, J., Ortega, L.M., Casal, J.: Load carrying capacity of concrete structures with corroded reinforcement, Construction and Building Materials, 11 (1997) 4, pp. 239-248.

[49] Zandi Hanjari, K.: Structural Behaviour of Deteriorated Concrete Structures. PhD thesis.Gothenburg, Sweden: Chalmers University of Technology – Department of Civil and Environmental Engineering – Division of Structural Engineering, Concrete Structures, 2010

[50] Kušter Marić, M.: Service life prediction of reinforced concrete bridges exposed to chlorides. PhD thesis, University of Zagreb, Croatia, 2013.

[51] Kušter Marić, M., Radić, J., Ožbolt, J. et al.: Analysis on durability of reinforced concrete bridges in maritime environment, Annual 2015 of the Croatian Academy of Engineering, 22 (2016), pp. 57-78.

[52] Afsar Dizaj, E., Madandoust, R., Kashani, M.M.: Modelling the effect of corrosion on failure modes of RC columns subject to lateral seismic loading, Proceedings of the 16th European Conference on Earthquake Engineering, 2018.

[53] Kušter Marić, M., Mandić Ivanković, A., Vlašić, A., Bleiziffer, J., Srbić, M., Skokandić, D.: Assessment of reinforcement corrosion and concrete damage on bridges using non-destructive testing, GRAĐEVINAR, 71 (2019) 10,pp. 843-862, https://doi.org/10.14256/JCE.2724.2019

[54] Karapetrou, S.T., Fotopoulou, S.D., Pitilakis, K.D.: Seismic Vulnerability of RC Buildings under the Effect of Aging, Procedia Environmental Sciences, 38 (2017), pp. 461–468, doi: 10.1016/j.proenv.2017.03.137

[55] Akiyama, M., Frangopol, D.M., Matsuzaki, H.: Life-cycle reliability of RC bridge piers under seismic and airborne chloride hazards, Earthquake Engng Struct. Dyn. 2011; 40:1671–1687. DOI: 10.1002/eqe.1108

[56] Biondini, F., Camnasio, E., Palermo, A.: Lifetime seismic performance of concrete bridges exposed to corrosion, Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, 10 (2014) 7, pp. 880-900, doi:10.1080/15732479.2012.761248

[57] Afsar Dizaj, E., Kashani, M.M.: Numerical investigation of the influence of cross-sectional shape and corrosion damage on failure mechanisms of RC bridge piers under earthquake loading. Bull Earthquake Eng ,18 (2020), pp. 4939–4961, doi:10.1007/s10518-020-00883-3

[58] Cheng, H., Li, HN., Yang, Y.B. et al.: Seismic fragility analysis of deteriorating RC bridge columns with time-variant capacity index. Bull Earthquake Eng 17 (2019), pp. 4247–4267, doi:10.1007/s10518-019-00628-x

[59] Zanini, M.A., Pellegrino, C., Morbin, R. et al.: Seismic vulnerability of bridges in transport networks subjected to environmental deterioration, Bull Earthquake Eng, 11 (2013), pp- 561–579, doi:10.1007/s10518-012-9400-9

[60] Deng, P., Zhang, C., Shiling, P., Jin, Z.: Modeling the Impact of Corrosion on Seismic Performance of Multi-Span Simply-Supported Bridges, Construction and Building Materials, 185 (2018), pp. 193-205. doi:10.1016/j.conbuildmat.2018.07.015

[61] Kušter Marić, M.; Ožbolt, J., Balabanić, G.: Reinforced concrete bridge exposed to extreme maritime environmental conditions and mechanical damage: Measurements and numerical simulation, Engineering structures, 205 (2020), 110078, 12 doi:10.1016/j.engstruct.2019.110078

[62] Kušter Marić, M., Ožbolt, J., Balabanić, G., et al.: Chloride Transport in Cracked Concrete Subjected to Wetting – Drying Cycles: Numerical Simulations and Measurements on Bridges Exposed to DE-Icing Salts. Front. Built Environ. 6 (2020) :561897. doi: 10.3389/fbuil.2020.561897

[63] Kušter Marić, M., Mandić Ivanković, A., Vlašić, A. et al.: Assessment of reinforcement corrosion and concrete damage on bridges using non-destructive testing, GRAĐEVINAR, 71 (2019) 10, pp. 843-862, doi: 10.14256/JCE.2724.2019

[64] Kušter Marić, M., Ivanković, A.M., Srbić, M., et al.: Assessment of Performance Indicators of a Large-Span Reinforced Concrete Arch Bridge in a Multi-Hazard Environment" Buildings 12, no. 7: 1046. https://doi.org/10.3390/buildings12071046

[65] Orcesi A., O'Connor A.: Diamantidis D. et al., Investigating the Effects of Climate Change on Structural Actions, Structural Engineering International, 32 (2022) 4, pp.563-576 doi:10.1080/10168664.2022.2098894

[66] DHMZ, meteo.hr, 28.2.2023.

[67] Hrvatske autoceste, hac.hr, 28.2.2023.

[68] Forzieri, G., Bianchi, A., Marin Herrera, M.A., et al.: Resilience of large investments and critical infrastructures in Europe to climate change. Joint Research Centre (European Commission); 2015. p. 175. ISSN 1831-9424.ISBN 978-92-79-54003-5. DOI: 10.2788/171858.

[69] DEFRA. Annual report. ISBN, 9781474146265; 2016.

[70] Farreras-Alcover, I., Chryssanthopoulos, M.K., Andersen, J.E.: Data-based models for fatigue reliability of orthotropic steel bridge decks based on temperature, traffic and strain monitoring. International Journal of Fatigue. 95 (2017), pp.104–119, doi:10.1016/j.ijfatigue.2016.09.019

[71] HRN EN 1990:2011 Eurokod: Osnove projektiranja konstrukcija (EN 1990:2002+A12005/AC:2010)

[72] HRN EN 1992-1-1:2013 Eurokod: Projektiranje betonskih konstrukcija -- Dio 1-1: Opća pravila i pravila za zgrade (EN 1992-1-1:2004+AC:2010) Hrvatski zavod za norme, Zagreb, 2013

[73] HRN EN 206-1:2021 Beton: Specifikacije, svojstva, proizvodnja i sukladnost (EN 206:2013+A2:2021), Hrvatski zavod za norme, Zagreb, 2021