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Research on the Vulnerability and Resilience of Bridges to Climate Change and Disasters: The Current Practice in Serbia

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ABSTRACT

Timely response to the impact of climate change is a big challenge for the whole world, especially for developing countries. Within the framework of a country's transportation system, bridges play a crucial role in maintaining an efficient and well-connected road network. Ensuring their functionality is of paramount importance. However, climate change poses serious risks to the damage of bridge structures, jeopardizing traffic safety and potentially causing complete traffic interruptions. The aim of this paper is to present the current practice in Serbia regarding vulnerability analysis of bridges and the implementation of measures to enhance resilience.

1. Introduction

Due to the impact of climate change, an increase in the frequency and intensity of extreme weather events such as droughts, heatwaves, floods, landslides, storms, and wildfires is expected. To ensure the uninterrupted functionality of nations, it is essential to study the potential impacts of climate change. Furthermore, responding to the effects of climate change represents a challenge for the entire world.

Bridges, aside from facilitating traffic flow over obstacles, play a crucial role in meeting human needs. These civil structures are carefully planned, designed, constructed, and maintained to ensure the functionality of the roadways they serve and simultaneously contribute to social and economic benefits. Building a bridge requires a deep understanding of structural theory and material characteristics, but both the past and the future indicate the necessity of considering the impact of climate change. A complete or temporary interruption of traffic caused by bridge damage or collapse can disrupt normal economic and other flows, leading to significant economic consequences. Maintaining bridges in an acceptable condition is key to ensuring a high level of service and safety for users.

Changes in environmental conditions, caused by climate change, can lead to harmful effects on bridge structures and the materials from which they are built. Such impacts can be short-term and intense if they are caused by extreme weather conditions, and long-term and slow when they are caused by a change in average climate conditions. The impacts of climate change can cause many potential risks. Only a moderate number of research studies have dealt with the risks that climate change causes for bridges, including their possible adaptations [1-5]. The traffic infrastructure is mainly considered in its entirety without distinguishing the individual elements of the structure.

Serbia is one of the countries in Southeastern Europe where climate changes are evident, and their manifestations are becoming more frequent and intense. As a consequence of climate change, floods are more frequent and intense, landslides and erosion are more active, and dry periods are more frequent and longer. In 2022 and 2023 alone, a dozen heavy rains caused local impacts in the form of flooding, damage to slopes and bridge supports, etc. The effects will be different depending on the observed area because of differences due to the composition and characteristics of the road network, the type of changes, topographic and hydrological conditions, but also the level of development achieved, and financial and institutional capacities.

The aim of the paper is to present the current practice in Serbia regarding the assessment of the condition of bridges, their vulnerability, and improvements aimed at protecting against the adverse effects of climate change and natural disasters. Additionally, a methodological framework utilized by European Union (EU) member states is presented, which can be adopted on the entire road network and within all infrastructure facilities.

2. Climate change impact to bridge

Transport infrastructure is affected by different types of climate change that can threaten life, level of service, maintenance budget, etc. Potential risks can have direct and indirect effects of climate change on bridges. Indirect influence, in addition to the climate and the bridge system, includes other external factors. Also, major damages can occur due to factors that appear at the same time.

Nasr et al. [5] and Meyer and Weigel [6], in their studies on the impact of climate change on bridges, indicate that bridges are particularly susceptible to the effects of climate change. They are vulnerable to extreme precipitation, temperatures, and storm events, which can damage the bridge structure and carriageway. The occurrence of extreme precipitation and destructive storms increases the risk of flooding, leading to bridge closures and the need for repairs, reconstructions, and in extreme cases, the construction of entirely new bridges. Rising temperatures affect thermal expansion and movement of bridge joints, increasing the stress on the bridge structure. A significant difference between minimum and maximum temperatures can lead to more frequent freeze/thaw cycles, thereby affecting the damage to expansion joints on bridges.

Based on a review of research articles, a list of potential risks from climate change to which bridges are exposed was formed. Risks were identified based on the literature [1-3, 7, 8], by reviewing documented cases of damage or failure on bridges, as well as by research on the possible links between damage and climate change. Some of the risks are identified in relation to climate parameters that are predicted to change and the possibility that these changes will lead to events that can affect the structure of bridges.

A total of 31 potential risks from the impact of climate change were presented, which Nasr et al. [5] described in detail. The greatest number of risks in the future can be caused by increased temperatures and precipitation. However, it cannot be concluded which risk of the impact of climate change is more critical, further research is needed that would give final determinations about the seriousness of the results obtained so far. Potential risks to bridges (Table 1), which are a consequence of climate change, can be divided into seven major categories [5]:

- durability (risk group D),
- serviceability (risk group C),
- geotechnical (risk group G),
- increased demand (risk group I),
- accidental loads (risk group A),
- extreme natural events (risk group E),
- operational risks (risk group O).

Table 1. Potential risks from climate change [5]

risk group		description
D	D1	accelerated degradation of the superstructure
	D2	accelerated degradation of the substructure
S	S1	heat-induces damage to pavements and railways
	S2	risk of increased long-term deformations
G	G1	higher scour rates
	G2,G3	higher risk of bridge side-slope failure and higher risk of landslides
	G4	higher risk of foundation settlement
	G5	higher risks of rockfalls, debris flows, avalanches
	G6	higher risk of soil liquefaction
	G7	additional loads on piles that may overstress them
	G8	damage due to clay shrinkage and swelling
I	I1	higher wave impact on piers and abutments
	I2	higher risk of wind-induced loads
	I3	additional snow loads on covered bridges
	I4	higher risk of thermally induced stresses
	I5	additional demand on drainage capacity
	I6	higher hydrostatic pressure behind bridge abutments
	I7	increased load on bridges with control sluice gates
	I8	increased stresses due to the faster loss of prestressing force
	I9	higher ice-induced loads
A	A1	higher chance of water vessel collisions
	A2,A3,A4	higher chance of vehicle-pier collisions, vehicle accidents, and train-pier collisions
E	E1	increase in intensity and/or frequency of floods
	E2	increase in intensity and/or frequency of storms
	E3	increase in intensity and/or frequency of wildfires
O	O1	additional operational costs for snow removal
	O2	more frequent temporary bridge restrictions
	O3	increased risk of power shortage

The level of climate change impacts is uncertain, especially over the long time periods for which bridges are designed. The frequency of climate change and the intensity of natural hazards are increasing, and the vulnerability of bridges is getting bigger. Therefore, consequences such as accelerated deterioration of materials, damage from floods and fire (Figure 1), and increased temperature stresses appear. Ignoring sudden and potentially catastrophic damage can cause increased economic costs or lead to the need to rebuild permanent facilities.

Figure 1. Flood damage and wildfire impact [9,10]

Given the large number of potential impacts of climate change, it is necessary to carefully analyze how adapting to one risk may affect vulnerability to other risks. Climate factors that can impact infrastructure require timely and decisive measures in terms of adapting existing infrastructure and enhancing its resilience to these influences.

3. Worldwide methodological approaches

Responding to impacts arising or increasing with climate change requires an appropriate selection of adaptation strategies. At the same time, strategies are proposed and chosen based on a previous assessment carried out according to a specific (official) methodology. Such a methodology must allow the inclusion of consideration of climate change impacts when designing new bridge structures or within the assessment of existing ones.

The framework defined by the United States Agency for International Development (USAID) can facilitate climate change risk management using a five-step methodology [11]:

1. Defining the service that the infrastructure will provide when facing the future climate change. It is necessary to collect research and information to understand the baseline and planned traffic conditions, travel patterns and distribution by means of transport (car, truck, bus, bicycle, pedestrian). Also, it is necessary to identify the impact of climate change and the expected changes in the patterns of natural hazards;
2. Consideration of the level to which a particular infrastructure (or facility) may be exposed to hazards and identifying hazards that require detailed investigation in step 3;
3. Consideration of risk when the vulnerability of the bridge is determined. Only those bridge elements identified as vulnerable in step 2 should be analyzed for risk. Conducting a risk assessment includes defining the probability of the occurrence of specific climate impacts, understanding the consequences of climate impacts, conducting risk analyzes and preparing a risk level matrix, determining the possibility of accepting the appropriate level of risk, defining the need for adaptation;
4. Once the degree of vulnerability is determined and the most significant risks are identified, a decision can be made to respond to the risks;
5. The last step is the implementation of activities, through which it is necessary to: ensure constant monitoring and development to consider the change of risk status, identify and develop examples of best practice for application in future design processes, conduct consultations and transparent communication with all involved, interested parties to promote acceptance and better understanding of the local context.

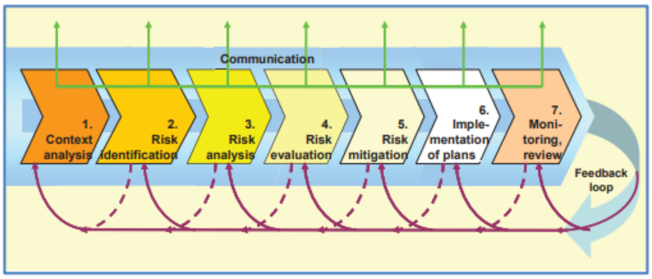

Figure 2. RIMAROCC framework [12]

The EU applies a specific methodological framework for modeling dynamic interactions between climate, long-term behavior of road structures, maintenance interventions, rehabilitation, and life-cycle costs. The RIMAROCC (Risk Management for Roads in a Changing Climate) framework presents the steps (Figure 2) needed to assess climate change risks for roads in a changing climate. It consists of seven basic steps [12], through which one goes from the effects of climate change to vulnerability and socio-economic assessments:

1. Context analysis - the authority responsible for climate change risk management defines external and internal parameters that should be taken into account during risk management, sets the scope and risk criteria for the remaining process;
2. Risk identification - identification of risk sources, identification of possible consequences;
3. Risk analysis - establishment of risk chronology and scenarios, determination of risk impact, occurrence assessment, risk review;
4. Risk assessment - prioritization of risks, comparison of climate risks with other types of risks, evaluation of risk acceptability;
5. Risk mitigation - identification of options, assessment of options, negotiation with financial agencies, presentation of action plans;
6. Implementation of action plans - development of action plans for each level of responsibility, implementation of adaptation plans;
7. Monitoring, re-planning and capitalization of knowledge and experience - regular monitoring and review, re-planning in case of new data or delays in execution, capitalization based on accumulated experience of climate events and implementation progress.

The number of steps within the RIMAROCC methodology can be considered complicated and difficult to perform, and for this reason, in 2015, within the ROADAPT project [12], another procedure was introduced (Figure 3) which determines all the basic aspects that should be considered during climate change risk assessments. The ROADAPT guidelines consist of five parts:

1. Guidelines on using climate data for the current and future climate;
2. Guidelines for quick assessment (QuickScan) of climate change risks for roads;
3. Guidelines for detailed vulnerability assessment;
4. Guidelines for assessing socio-economic impacts;
5. Guidelines for the selection of an adjustment strategy.

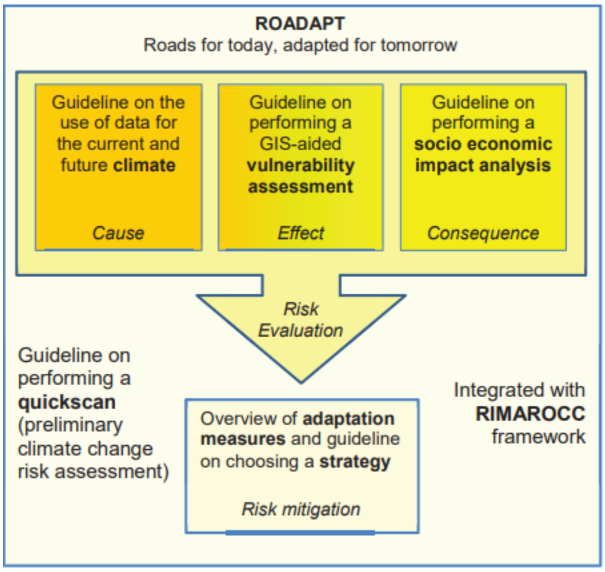

Figure 3. ROADAPT risk assessment guidelines [12]

Climate change brings various challenges that can be successfully addressed through two key approaches: reducing emissions to mitigate the impact of climate change and adapting our systems and societies to better cope with its consequences. Adaptation involves updating legal and regulatory frameworks to accommodate changing climate conditions, planning sustainable land use with an emphasis on increased resilience in high-risk areas, and developing materials and technologies that are climate-resistant [13].

The use of materials that are resistant to the effects of climate change is one type of adaptation to climate change. Less than 40% of countries in the world [14] apply modern materials, such as Carbon Fiber Reinforced Polymer (CFRP), Glass Fiber Reinforced Polymer (GFRP) and Ultra High-Performance Fiber-reinforced Concrete (UHPFC), for the protection of bridge structures.

Table 2. Examples of possible adaptation in relation to the potential impact of climate change [13]

Potential impact	Adaptation
accelerated degradation of material	cathodic protection; 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; protection by design, preservative treatment and the use of modified wood for timber bridges; more frequent inspection and maintenance
increased long-term deformations	improved monitoring and inspection of bridges
floods	relocation or flood-proofing; flood control seawalls, dikes, and levees; 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; channel alteration and stabilization, diversion and storage of floodwaters; regulate the flow of water through dams
higher risk of thermally-induced stresses	increased ongoing maintenance; design for higher maximum temperatures in replacement or new construction; greater use of expansion joints; paint the bridge white to introduce an albedo effect and reduce overheating
liquefaction	stone columns, gravel and rubber drainage columns; chemical grouting, passive site remediation techniques; ground improvement methods (grouting), vibro-systems, buttresses and surcharge fills, containment and reinforcement, drains, underpinning with mini-piles, deep dynamic compaction and deep blasting
debris flows	terrain alteration, soil bioengineering, debris flow breakers, debris flow deflectors, etc.

4. Activities in Serbia

Understanding the inventory of the road network and all its components, including infrastructure objects, is crucial for efficient management of that network. This process entails not only basic data about the objects but also regular monitoring of their current condition. Through careful documentation of the state of bridges, it is possible to carry out activities that will ensure the planned lifespan of these bridges, enable continuous traffic flow, and reduce the risk of serious damage or collapse.

The bridge management system (BMS) provides a rational and systematic approach to all activities related to bridge management both at the individual and network level. In many countries of the world, for the needs of high-quality bridge management, bridge databases have been created, which can provide all the necessary information about the requested bridge. In a smaller number of countries, as an upgrade, BMS have been developed, which make it possible to forecast the condition of bridges, determine priorities for various interventions, and work programs.

Serbia's road network comprises approximately 17,000 kilometers of highways and regional roads, with a significant number of bridge structures, specifically around 3,000, with a total value amounting to an impressive 114 billion dollars [15]. Although in the last century there were activities on defining the database on bridges and collecting data, active work on the introduction of BMS has been done only since 2001 in Serbia. It is interesting to emphasize that, as the manager of the state road network, the Public Company Roads of Serbia prepared a database of bridges, which defines all the elements of the bridge under examination, an assessment of the condition, load capacity of the bridge and a list of existing damages [16]. However, a unique BMS has not yet been established [17]. Achievements at the local level are far less, where many local managers do not even have basic information about the assets they manage, not to mention monitoring its condition or planning activities. In such conditions, most of the actions take place in the domain of reactive activities, which are usually reduced to absolutely necessary interventions to keep the bridge functional or to repairs/reconstructions of an unusable (destroyed) structure. Problems increase with the size of the network, the growth of traffic load, the change of means of transport, the different sensitivity of structures and the environment, as well as due to the historical legacy that is reflected in the outdated methods of design and construction, rehabilitation, reconstruction, and maintenance [18].

In Serbia, the presence of climate change is evident, and its manifestations have become increasingly frequent and intense over the past years [19]. These changes have led to more frequent and severe floods, landslides, and soil erosion, heightened wind impacts, as well as prolonged and more frequent periods of drought. It is worth noting that heavy rains often cause flooding and landslides along major watercourses and smaller rivers, especially in hilly and mountainous areas.

During the last 15 years, Serbia was repeatedly affected by medium and large floods and landslides. Bridges over torrential rivers are most at risk, which was confirmed during the May 2014 floods on most of Serbia's road network. Damage to bridges and roads threatened access to markets and made access to agricultural land difficult. A total of 304 bridges were damaged then. Damages included erosion of support elements and access embankments, undermining of foundations, and the collapse of bridges. Also, about 2,000 landslides were recorded, of which 135 endangered the road network (blocking numerous roads and demolishing parts of the road structure) [20].

Figure 4. Rehabilitation of bridge after floods, EU donation [9]

However, natural disasters and catastrophes in Serbia are often talked about at the time of occurrence and later when work is done on long-term remediation of the consequences of natural disasters (Figure 4), instead of implementing measures to reduce the risk of the impact of potential disasters. Although there is awareness that climate change can affect the road network and traffic infrastructure in general, a critical mass has not yet been reached that would result in a significant volume of activities that would affect the identification and implementation of strategies to solve the problem. Actions to repair the damage are still dominating, while the need to strengthen the capacity of the existing infrastructure in relation to climate change and natural disasters is only shyly emerging as a preventive possibility when a disaster occurs. Such an opportunity is quickly lost between requests for repairs of damages or in general for reconstructions/rehabilitation of bridges in poor condition.

It is important to emphasize that there is no comprehensive or partial assessment of network vulnerability and general identification of measures to improve the resilience of the road network and its components (e.g. bridges). This is also the immediate priority of activities - assessment of the network and assessment of vulnerability to climate change, to create conditions for adapting the road network to climate change.

5. Conclusion

In general, the risk of disasters decreases as the society's capacity and preparedness to deal with them increase. Therefore, it is crucial that everyone, from high-level government institutions to infrastructure managers and individuals, be prepared to adequately cope with natural disasters arising from climate change. When it comes to management, the impacts and risks of climate change and natural disasters are becoming increasingly complex. Regular monitoring of bridge elements allows for timely interventions, ensuring greater resilience and durability of the structure. As climate change represents the greatest threat to today's economy, it is necessary to use the available funds in an efficient way , considering that the budget is generally limited.

Efficiency can only be ensured by understanding the capital being managed (which includes bridge structures), assessing risks, namely the vulnerability of structures to the impacts arising from climate change, and considering the relevance and cost-effectiveness of climate adaptation activities. In this regard, the Bridge Management System (BMS) must also include a suitable component that enables the assessment of the bridge in the context of climate change risks and the consequences that may arise if the bridge collapses or experiences damage that would lead to traffic restrictions or interruptions. Timely response to potential impacts of climate change, methodology improvement, climate adaptation, and damage remediation result in significant cost savings, enable the structure to withstand its intended service life, and ensure the safety of traffic participants.

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