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COMBINING MULTIRISK REGIONAL ASSESSMENT OF CIVIL INFRASTRUCTURES WITH MATERIAL DEGRADATION. A BRIEF REVIEW

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Abstract

Civil infrastructures are naturally subjected to multifaceted risks derived from internal or external causes, natural or human-made. This brief discussion investigates the effect of exogenous and endogenous threats on the structural integrity of bridges and viaducts in Mediterranean areas at the network level. In this region, the most likely risk sources derive from earthquakes and hydrogeological effects. The immediate and catastrophic damage induced by such exogenous threats is often combined with endogenous risks, involving intrinsic factors, such as material degradation, design flaws, and construction deficiencies. Again, these pose significant challenges to the longevity of bridge structures on their own; yet, they also facilitate structural failures triggered by seismic or extreme weather event.
Nevertheless, the current scientific literature lacks established methodologies for jointly assessing seismic and hydrogeological risks considering also degradation and wearing of road infrastructures. The discussion provided herein emphasizes the need for holistic, comprehensive risk assessment and proactive maintenance strategies to mitigate these threats and ensure the resilience and structural safety of civil infrastructures, also propagating the risk at the regional level.

Keywords: Civil infrastructures, Multi-risk assessment, Ageing, Maintenance, Structural degradation.

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1 INTRODUCTION

Civil infrastructures encompass all kinds of transportation networks, from roads to railways and others. These networks are intended to facilitate economic growth, social connectivity, and overall quality of life for all their users. However, these complicated systems face multifaceted challenges arising from natural and man-made hazards, ageing materials, and increasing demand (with related traffic-induced loads and fatigue effects). All these external actions can compromise their functionality and safety in the long run. Even more importantly, transportation networks comprise several utilities and portions but are generally characterized by critical artworks such as bridges, viaducts, and tunnels. These strategic points are the key vulnerabilities of these backbones of modern society, as even one disruption may cause a cascade effect throughout the whole network, generating and amplifying the negative impacts. Therefore, addressing these challenges necessitates a holistic, multi-scale, and multidisciplinary approach to ensure the resilience and sustainability of critical civil infrastructures.

In this context, "resilience" can refer to the ability to anticipate, withstand, adapt to, and/or rapidly recover from disruptions, according to the specific needs and aims. 'Sustainability', on the other hand, specifically requires meeting these present needs without compromising the ability of future generations to meet theirs. Integrating resilience and sustainability not only ensures robustness against immediate threats but also adaptability to long-term changes, such as evolving environmental conditions (e.g. climate change) and societal demands.

In this perspective, a holistic approach involves considering the complex interdependencies within infrastructure systems and their interactions with the surrounding natural and built environment. Traditional siloed methodologies often fail in capturing the systemic nature of infrastructure vulnerabilities. For instance, the disabling of a single critical component on a critical road or rail axis can disrupt transportation networks, economic activities, and emergency response operations [1]. Therefore, an holistic framework should integrate technical/engineering considerations with social, economic, and environmental factors for effective risk assessment and management.

Multi-risk assessment methods, widely applied in Industrial Engineering applications -see e.g. [2] and [3]- should be inherited in Civil Engineering for infrastructure management, accounting for higher uncertainties compared to industrial facility environment. Furthermore, risks need to be georeferenced [4]. At the detail level, different domain experts are required to address the specific components of the multi-risk analysis -e.g. hydraulic and environmental engineers for floods, scouring, etc. geotechnical engineers for land- and rock-slides- or even complex risks that involve different fields at once (e.g. rain-induced landslides or mudflows).

Importantly, a multi-risk assessment is not limited to a multiplicity of hazards -such as earthquakes, fires, extreme weather, and so on- and scenarios [5] but also to a variety of possible vulnerabilities and the corresponding outcomes. Partial non-structural collapse, or minor structural damage, can exceed the serviceability limit state and cause long term disruption even if the structural system is far from collapse. Such interruption, or even just a reduction of service (e.g. speed and/or lane reduction), can be highly impactful if excessively prolonged. However, even very short closures can significantly affect the immediate aftermaths of a catastrophic event such as an earthquake, due to the rapid need of emergency transportations [6].

Lastly, incorporating multi-scale analysis is crucial, as transportation infrastructures operate over long distances and across various spatial and scales. Local material degradation can have network-wide implications if not addressed promptly. Similarly, regional factors like peculiar weather patterns can exacerbate infrastructure vulnerabilities otherwise under control elsewhere (e.g. snow-induced risks). A multi-scale approach should, thus, enable the identification of both localized issues and broader systemic risks, facilitating targeted interventions that enhance overall system resilience, both at the regional and at the network levels (or subpart of them).

In Conclusion, these analyses will need to convey into a general yet adaptable framework, due to the need for local analyses – according to the site-specific seismic activities, hydrogeological effects, and material degradation due to the region's specific environmental conditions. Given this overview of all the aspects at play here, this contribution will assess the key risk typologies involved in the assessment of road and rail infrastructures, considering both rural and urbanized environments. The remainder of this brief paper is organized as follows. Firstly, the two main typologies of risk are introduced and discussed separately in Section 2. The degradation issue is detailed in Section 3. Multirisk assessment strategies, considering different combinatorial approaches, are reported in Section 4. Finally, the propagation of these multiple risks from the single structure to the road network level is examined in Section 5, and Conclusions follow.

2 MULTIRISK ASSESSMENT

The seismic evaluation of existing constructions in the Mediterranean region is often conducted without considering prior damage caused by other factors, such as slow-moving settlements. In this area, natural hazards like landslides and earthquakes can impact structures over time, usually occurring years apart rather than simultaneously. To ensure a more accurate seismic assessment of existing constructions, it is essential to account for these additional hazards, as they may have altered the stress-strain response or caused structural damage.

Previous damage at the time of seismic evaluation can result from various factors, including landslides, subsidence, and excavations. Additionally, a key consideration in seismic assessment is that many structures are at or beyond their intended design lifespan. The research community has made significant efforts to incorporate multiple hazards and their interactions into numerical models for assessing seismic vulnerability, rather than focusing solely on individual hazards. Various studies have proposed methodologies for multi-hazard analysis in different types of constructions, such as earthquake-fire and earthquake-landslide interactions. Additionally, research has explored specific hazards that should be considered alongside earthquakes in multi-risk assessments [7–14]. The novelty of these approaches is in showing the importance of the safety assessment in a multi-hazard analysis, cumulating the actions coming from two or more different hazards. For example, with landslide/subsidence that affect the structures before earthquake, these approaches can be easily repeated to quantify in different time frames the effect of the active slow-moving precedent settlements on the seismic assessment of the buildings. Moreover, in a fragility analysis framework, the updated fragility curves, with respect to single hazard fragility, help to understand the influence of the other hazards, based on their specific configurations.

Finally, damage to a single infrastructure component can have widespread consequences across the entire transportation network, leading to rerouting, congestion, and increased strain on alternative routes. This impact becomes especially clear after major disasters like earthquakes and landslides. Then, a comprehensive resilience framework for addressing these broader effects is very important and one of the most discussed issues in the civil engineering research field [6].

In this work, a specific focus is dedicated to seismic and hydrogeological risks and then to ageing and degradation. Clearly other man-made events can affect the built environment, such as fire, overloading and increased traffic volume/traffic loads, incidents, explosions.

2.1 Seismic Risk

Seismic risk, determined by the combination of hazard, vulnerability and exposure, is the measurement of the damage expected in a specific time period, based on the type of seismicity, the resistance of buildings and anthropisation (nature, quality and quantity of assets exposed).

Many buildings/infrastructures in seismically active regions were constructed without proper seismic detailing, making them highly vulnerable to earthquakes. Accurately determining their performance levels is crucial for effective seismic assessment and classification. In this regard, analytical structural fragility evaluation plays a key role in modern performance-based engineering.

Methods for assessing structural fragility at a given limit state vary from simple approaches -such as analyzing an equivalent single-degree-of-freedom model's response- to complex nonlinear dynamic analyses using structural models subjected to multiple ground-motion records [15]. Among these advanced methods, several techniques are available for establishing the relationship between Engineering Demand Parameters (EDPs) and Intensity Measures (IMs), as well as for deriving fragility curves based on recorded seismic data. These techniques include Incremental Dynamic Analysis (IDA), Multiple-Stripe Analysis (MSA), and Cloud/Modified Cloud Analysis [16–18].

As highlighted before, the literature about seismic assessment is full of methodologies and approaches at different scales. In this work, a focus is given to the multi-hazard assessment. In fact, the seismic assessment of structures around Mediterranean area is commonly carried out neglecting potential previous damage induced by other phenomena, for example those related to the actions of slow-moving settlements. In this area, the natural hazards, such as landslides or earthquakes, can affect structures throughout their existence, generally not occurring simultaneously, but spaced over the years.

2.2 Hydrogeological risk

Hydrogeological risks encompass a range of site-specific, natural hazards that significantly impact civil infrastructure, particularly in regions prone to extreme weather conditions. These risks include floods, scouring, avalanches, and rainfall-induced landslides, each posing unique challenges to the integrity and longevity of structures such as bridges and viaducts, as well as potential risks at the tunnel entrances.

As the name suggests, the main factor is a deleterious interaction between the infrastructure and/or the soil beneath or around it with running water. However, this issue is hardly due to direct hydraulic actions on e.g. the piers or the deck of a riverine bridge. More commonly, soil-water-structure interaction is the main factor of risk, leading to up to 80% of all bridge collapses worldwide [19].

Importantly, these risks can manifest in two forms with different time scales: immediate and long-term. Immediate risks involve extreme events that directly threaten the structural integrity of a system, such as water uplift and horizontal forces acting on piles during a flood [20], potentially causing instant failure. In contrast, long-term risks involve gradual, cumulative damage -either direct or indirect- affecting structural integrity over time. These effects may eventually reach a critical threshold, either leading to direct failure or creating conditions that predispose the structure to collapse. In such compromised states, even unrelated or less severe events could trigger a failure that would not have occurred if the structure were in a healthier condition. The key phenomena can be summarized as follows:

Subsidence: Excessive groundwater run-offs and wash-outs can cause land subsidence, leading to ground-level lowering. This subsidence can damage buildings, roads, and underground utilities, and increase the risk of flooding in affected areas, affecting the stability of bridges as well as of the road pavement. The gradual nature of these landslides necessitates continuous monitoring to detect subtle ground movements before they cause substantial damage. Techniques such as satellite-based interferometric synthetic aperture radar (InSAR) and ground-based measurements are employed to track displacement rates and patterns.

Slow-moving landslides: characterized by gradual ground displacement over extended periods, pose significant challenges to civil infrastructure and communities. Unlike rapid landslides, their subtle progression often leads to underestimation, resulting in cumulative damage that can be extensive and costly. Early detection enables the implementation of mitigation strategies to prevent or minimize damage. However, geographically-informed methodologies should be defined, considering e.g. the specificities of the Mediterranean area [21].

Floods: Intense rainfall or, in rarer occurrences (especially in the Mediterranean area) rapid snowmelt, can lead to flooding. As already mentioned before, this can subject river-crossing bridges and viaducts to both uplifting forces on the deck intrados and horizontal pressures on the piers. These forces can compromise the stability of bridge decks and substructures, especially when water levels rise swiftly. The increasing frequency and intensity of such events, exacerbated by climate change, underscores the need for adaptive management strategies.

Scouring: floodwaters can erode the soil surrounding bridge foundations, a process known as scouring. This erosion undermines the support of piers and abutments, potentially leading to structural failures. Scouring is, by far, the leading cause of bridge collapses, both during and after flood events, highlighting the necessity for regular inspection and maintenance of foundation elements. More in detail, scouring can be further categorized as pier- and abutment-localized scouring [22] or bank erosion due to river lateral migration [23].

Rainfall-Induced Rapid Landslides and mud or debris flows: Prolonged or heavy rainfall saturates soil layers, reducing their shear strength and triggering landslides. Such landslides can obstruct roadways, damage structures, and disrupt transportation networks. The unpredictability of these events makes them particularly hazardous, requiring comprehensive risk assessments and, even more than their slow-moving counterparts, the implementation of early warning systems [24]. This will be even more accentuated in the next years, due to climate change and perceptible topicalization of the Euro-Mediterranean basin, which will induce more frequent and more intense rain events [25].

These hydrogeological risks have increased in frequency and amplitude in the last decades due to changing weather and rain patterns [26]. To be properly assessed, they demand a multidisciplinary approach that integrates structural, geotechnical, hydrological, and environmental engineering. Additionally, a holistic approach is needed as the risks both affect and are affected by the built and natural environment – for instance, a highly forested area can be prone to clogging due to tree accumulations between piers, obstructing the water flow and thus dramatically increasing the risk of collapse due to water pressure-induced horizontal forces [27]. Hence, effective early warning systems and flood-risk mapping [28] will be instrumental are crucial for better preparedness and risk management.

3 AGEING AND DEGRADATION

In recent years, the increasing number of bridge and viaduct collapses has been largely attributed to structural degradation and inadequate maintenance. Many existing bridges are now approaching the end of their designed service life (e.g. most of Italian bridges were built within 1960-1980). As a result, the topic of building materials' durability is increasingly acquiring paramount importance both in scientific community and practical engineering, because of the need to detect failure mechanisms in load-bearing elements of existing structures due to degradation. This issue is even more crucial when dealing with critical transport infrastructures, whose failure may lead to human and economic losses, not only due to direct damage but also because of service disruptions.

In recent years, numerous studies have examined the impact of environmental factors on the degradation of reinforced concrete structures. Steel rebar corrosion, concrete cracking propagation and long-term effect on mechanical properties are mostly examined in the literature [29–31]. A deal of attention is paid to those phenomena which can lead to brittle failure modes of structural elements, such as Gerber half-joints (widely employed in RC bridges) [32], which can trigger so-called disproportioned collapses [33].

Among the main challenges in predicting the long-term performance of complex structures like bridges and viaducts is assessing the impact of carbonation- and chloride-induced corrosion on their mechanical response. This is due to the high number of parameters ruling such phenomenon, as well as on their uncertainty. An effective examination of corrosion process often requires demanding analytical modelling of localized phenomena on rebars/tendons [34], which can hardly be extended to global analysis of structures. Furthermore, chloride penetration and carbonation are highly susceptible to concrete mixture and to weather conditions, which vary across space and time, requiring long-term experimental data to support theoretical prediction [35]. Lastly, a strong interplay exists between concrete cracking and corrosion penetration and rate in reinforcement. Recent studies proposed accurate modelling of the distribution of corrosion-induced cracks in concrete, based on machine learning methods and advanced numerical modelling [36,37].

Despite the high accuracy of the developed models and frameworks for analyzing local corrosion-induced aspects, performance degradation of structures at global level often requires simplified approaches. As well known, the degradation of reinforcing steel is generally described by defining two parameters, namely the triggering time, t_{tr}, and the corrosion rate, $v_{c,u}$. Most of existing formulations for the evaluation of t_{tr} account for a number of weather parameters, concrete cover and composition, and the geometry of the considered element (e.g. equation (1) in Fib Model Code [38]).

$$t_{tr} = \left(\frac{C(t_i)}{\sqrt{2k_e \cdot k_c \cdot R_{NAC,0}^{-1} \cdot C_s \cdot W(t)}} \right)^2 \tag{1}$$

Past studies also proposed simplified formulations to compute corrosion-induced cracking time of concrete, due to expansive products of corrosion after triggering time is achieved [39].

Corrosion rate after triggering time also depends on weather parameters, such as relative humidity and average temperature, as well as on concrete cover thickness. The value of $v_{c,u}$ is physically represented by the current flow within the anodic-cathodic half-cell reaction generated after steel depassivation. However, mechanical-oriented approaches address $v_{c,u}$ as the mass loss of corroded rebar, which is directly related to mechanical performance decay of both steel and concrete [40,41].

Considering the nature of corrosion-induced degradation, its interaction with additional long-term phenomena, such as concrete creep and shrinkage, should be considered. This statement applies particularly to large span bridges, for which simplified creep models often lead to unconservative prediction of actual displacement response [42].

Modified mechanical models of materials accounting for aging effects are employed in reliability and life-cycle analyses of structural elements or systems, aiming to estimate performance evolution over time [43,44], generally represented through functionality curves. In such approaches, uncertainties play a key role on the results and their influence should be accurately evaluated. For instance, concrete cover affects the triggering time, after which performance decay rate significantly increases. Hence, uncertainties in evaluating the actual value of concrete cover, as well as on its variation among structural elements, may change the expected failure time or functionality loss time of the structure.

Additionally, highly reliable models employed for the evaluation of mechanical response of structural elements (e.g. fiber-based non-linear approaches, Figure 1) in un-degraded conditions may fail in effectively simulating the response in case of degradation. Corrosion may indeed lead to failure mechanisms generally neglected in traditional models, such as concrete-rebar slip [45] and longitudinal rebar buckling due to loss of confinement caused by cover spalling [46].

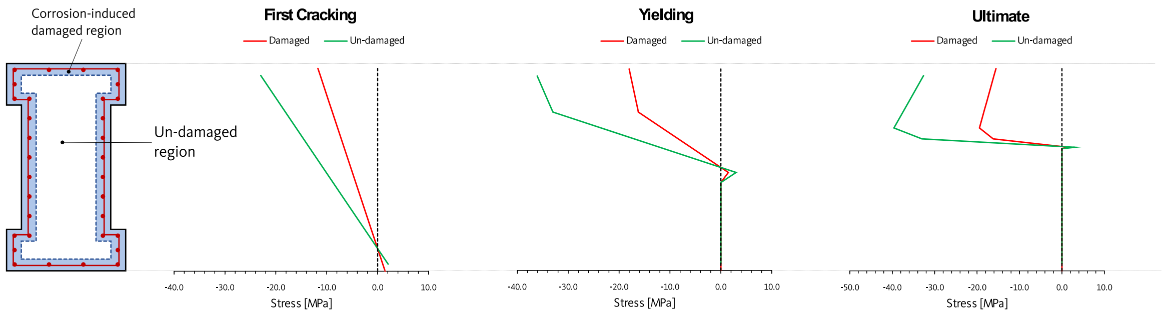
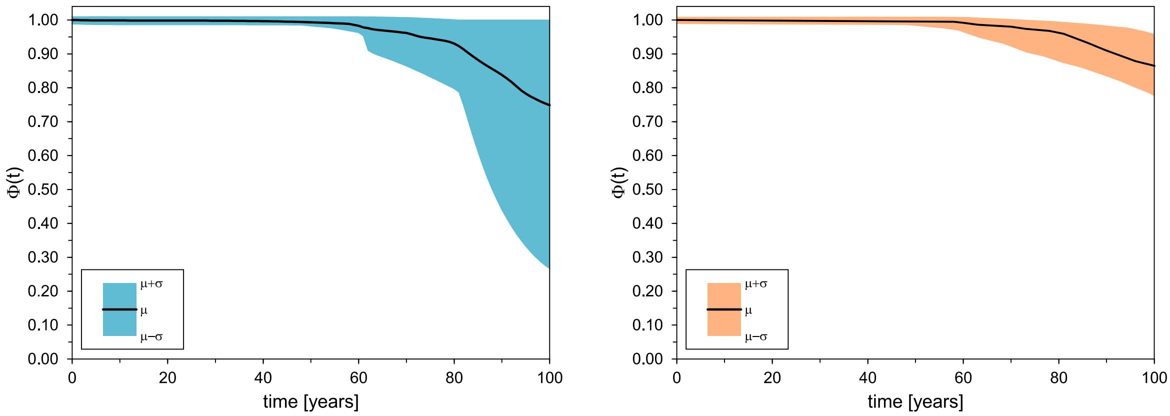


Figure 1. Fiber-based computation of resisting moment of RC elements at different performance levels.

Lastly, analytical models for computing mechanical performance decay should also consider uncertainties in weather parameters computation at each time interval, alongside their average value variation with time (e.g. due to climate change). A qualitative example of the influence of weather parameters is depicted in Figure 2.

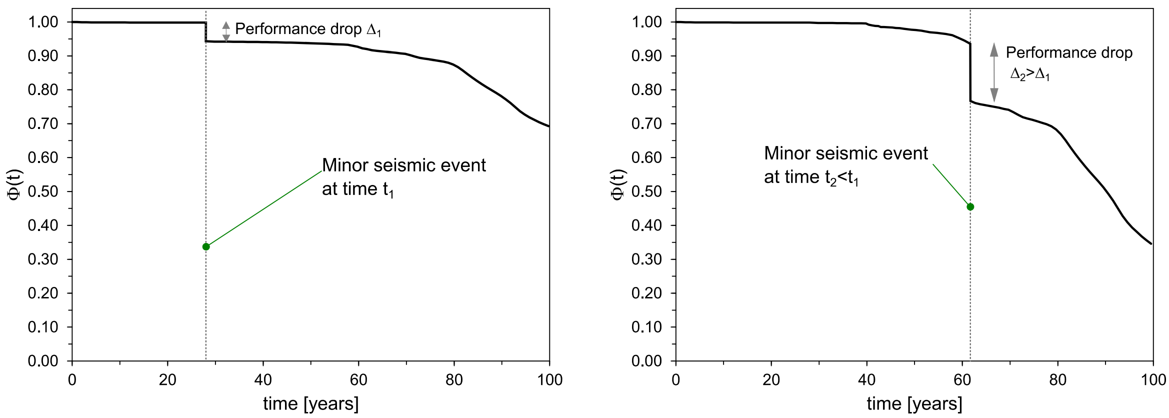


(a) (b)

Figure 2. Computation of performance evolution over time for RC bridge elements (a) accounting and (b) neglecting weather parameters uncertainties.

4 JOINT RISK ASSESSMENT

The performance decay caused by long-term phenomena and material degradation also affects the response of the structures to exceptional events. As per seismic action, this aspect is generally neglected in modern building codes when computing seismic capacity of lateral load resisting elements, such as bridge piers. Moreover, a mutual influence between exceptional events and aging can be observed in high seismic hazard zones, where minor structural damage due to low intensity seismic events may accelerate carbonation and chloride penetration. This could result in a long-term chain effect characterized, on the one hand, by an increase of degradation rate due to seismic damage and, on the other hand, by seismic capacity decay caused by degradation (an example is illustrated in Figure 3).



(a) (b)

Figure 3. Mutual influence between seismic events and degradation: (a) seismic event occurring in early stage, causing minor performance decay and slightly affecting degradation rate and (b) seismic event occurring in advanced stage, causing major performance decay and greatly affecting degradation rate.

The influence of the condition of the structure on its seismic response was addressed in the literature to obtain state-dependent fragility functions [47]. However, such studies mainly focus on the structural response in case of subsequent earthquakes occurring during its service life and aging and degradation-induced damage is mostly neglected. The inclusion of degradation requires the adoption of more complex approaches (e.g. [48]), in which both damage rate and time need to be discretized in order to express the probability of achieving a specific damage state within a specific time unit given the initial damage state and time. Such approaches generally require a great computational effort and, consequently, simplified models in which detailed modelling of degradation could be hardly implemented.

5 RISK PROPAGATION TO THE NETWORK LEVEL

Damage to a single infrastructure component can have widespread consequences across the entire transportation network, leading to rerouting, congestion, and increased strain on alternative routes. This impact becomes especially clear after major disasters like earthquakes and landslides. Ensuring the continued functionality of at-risk assets requires assessing their resilience. Road networks, in particular, play a critical role during emergencies, facilitating evacuations and the delivery of relief supplies. Evaluating their resilience involves not only analyzing their vulnerability but also improving risk assessments by considering the compounded disruptions caused by damaged infrastructure in their surroundings. Another key factor is recovery time, which significantly influences decisions regarding post-disaster repairs and rehabilitation.

The most important point is the definition of a framework for evaluating the engineering efficiency of a road network (RN). Such approach analyzes the capacity of an RN and its surrounding built environment to sustain functionality following a seismic event. Simple relationships are developed and examined to quantify RN efficiency in relation to seismic occurrences, highlighting their potential application in conventional urban disaster management. The distinctiveness of this framework lies in its independence from temporal constraints and its ability to incorporate multiple factors affecting RN efficiency. Consequently, RN performance is evaluated both prior to the event and by assessing the number of disrupted road segments after an earthquake, along with the overall damage to buildings and bridges. Figure 4 proposes a flowchart of a general procedure for road network efficiency assessment. The proposed framework integrates RN modeling, hazard analyses, and vulnerability assessment into a comprehensive evaluation RN efficiency. Clearly this procedure can be declined under different specifications for the different hazards and for multi-hazard analyses.

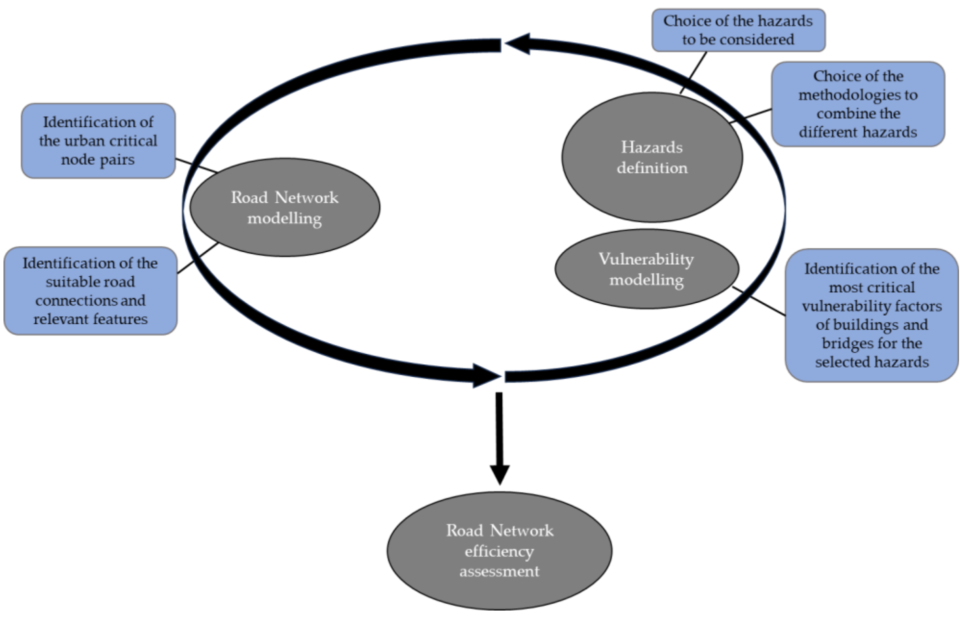


Figure 4. Flowchart of a general procedure for road network efficiency assessment.

6 CONCLUSIONS

Proactive assessment and mitigation of the risks addressed herein are crucial for ensuring transportation networks resilience. A multi-risk assessment should combine hazards and scenarios with a variety of possible vulnerabilities and the corresponding outcomes. Minor damage of critical infrastructural assets may have major effects on society due to disruption even if structural performance is almost intact. On the other hand, even temporary service interruption after natural or human-made events could lead to catastrophic consequences due to emergency chain inefficiency.

To this regard, multi-scale risk assessment is fundamental, particularly for main infrastructures which operate over long distances and across various spatial and scales. Such approaches should cover, on the one hand, prompt estimation of local material degradation, to avoid network-wide consequences and, on the other hand, the influence of regional parameters, such as extreme weather conditions, which increase infrastructure vulnerabilities. The complexity and multi-disciplinarity of such frameworks, in turn, facilitates targeted interventions aimed at enhancing resilience at both the regional and network levels, including specific infrastructure assets.

This study aims to lay the basis for the definition of comprehensive multi-risk assessment frameworks for critical infrastructure management, which could allow a more reliable service disruption or structural failure prediction and accelerate decision making process. The plethora of aspects addressed alongside the wide review of the risk assessment methods is meant to contribute to identifying their interaction, in a view of effective resilience analyses.

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