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The Methodologies and Main Challenges of Assessment the Multi-Hazard Interaction and Risk Management Associated with Roads Infrastructures and Dam Safety: A Review

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Abstract: The idea of multi-hazard interactions and risk assessment, particularly in relation to both natural hazards and hazards triggered by anthropogenic processes, has been widely used, especially in recent decades. Numerous areas worldwide, as well as various sectors, face exposure to multiple hazards. These hazards encompass natural phenomena like floods, earthquakes, hurricanes, and more. In comparison, the human-induced or anthropogenic processes associated with infrastructure development, along with other potential human activities such as, land and cover use change, contribute to the overall hazard landscape. Both natural hazards and anthropogenic-induced directly led to infrastructure collapse and loss of functionality with other consequences for human lives, economy, beside the environment impacts. Limited studies have been conducted on the implementation of the comprehensive multi-hazard interaction approach, which is globally or regionally required, along with detailed studies on the interaction between different multi-hazard sources and their interrelationships in short-term or long-term scenarios. The current research aims to review previous literature and studies on the multi-hazard interaction approach, methodologies of visualization and classification, as well as explores the potential of multi-hazard associated with road networks, infrastructures, and dams. The research utilizes simulation various models and tools such as, Geographic Information System (GIS) beside Remote Sensing (Rs) techniques. The current study concludes that using multi-hazard maps, hazard matrix, and fragility curves represents highly valuable and very useful and flexible tools for implementing and visualization hot spot areas exposure by multi-hazard consequences and vulnerability analysis for short and long-term scenarios. In addition, the current review highlighted for development a holistic conceptual framework for multi-hazard and risk assessment associated with hydraulic structures such as dams, road networks and infrastructures with hazard exposure analysis to be used as tools for a decision support system (DSS) in order to develop urban resilience, risk management and hazard mitigations.

Keywords: Multi-hazard interaction, anthropogenic processes, roads and infrastructures, multi-purpose dam, hazard matrix, fragility curves, multi-hazard maps

1. Introduction

The multi-hazard framework is widely used by institutions, agencies, and stakeholders in various sectors, including municipalities, industrial, agricultural, and the environment. Floods and seismic represent the main natural hazards

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threatening people's lives, properties, and economic losses. Besides, extreme climate events with climate change subsequently increase the probabilities of successive floods or drought years.

The rapid population growth, socioeconomic development, and urbanisation increased the demand for new road networks and infrastructures to meet the various stakeholder's requirements, increasing the multi-hazard associated with multiple projects and infrastructures inside and outside cities. In recent decades, the global incidence of people impacted by natural hazards and anthropogenic processes has seen a significant increase worldwide [1]- [3].

Flash floods are the most dangerous and consequential of global natural disasters. During 2007 and 2014, heavy rainfall in the United Kingdom directly affected infrastructure and road networks, resulting in an estimated cost of millions of pounds. This incident highlights the significant economic consequences and damage caused by flooding events [4]- [6]. The development of the multi-hazard interaction framework aims to enhance the understanding of both single and multi-hazard sources by incorporating the combined interaction between natural and human impacts; besides, the consequences of these hazards can initiate cascades of interactions among the multi-hazard.

The United Nations Disaster Risk Reduction Office (UNDRR) defines the multi-hazard as (i) the identification of several significant hazards that a country encounters, (ii) certain conditions under which potential risk events can occur concurrently, leading to cascading or cumulative effects over time, and (iii) the recognition of potential interrelated impacts [7]. Seven worldwide targets and four tasks for action have been recommended to reduce the present risks of catastrophe per the Sendai Framework for Reducing the Probability of Disaster (2015-2030). In particular, through deep understanding and strengthening disaster risk governance with planning for disaster reduction, resilience, and suitable disaster risk management. In addition, it is crucial to enhance disaster preparedness by focusing on "Reconstructing Back Better". This approach highlights the significance of implementing measures that strengthen resilience and improve conditions beyond pre-disaster [8]. Infrastructure and road transport, e.g., bridges and tunnels beside the highways, are essential to urban transportation systems.

The multi-purpose dam plays a vital role in water resources management and supply for various stakeholders. However, large dams are susceptible to multiple extreme natural events such as flash floods or devastating earthquakes and the impacts of ageing or human-induced factors besides inadequate operation and poor maintenance of dams, which further compound these risks [9]. These combined natural or anthropogenic impacts increase the probability of dam failure, which leads to catastrophic flooding in downstream areas. Therefore, it is crucial to develop a dam safety framework that addresses the interactions of multiple hazards to mitigate risk and protect cities and communities living behind the dam.

The infrastructures and other roadway networks were vulnerable to catastrophic damage caused by a combination of natural and human-induced, such as extreme rainfall leading to flood and submerged roads and railways in London in 2017, as an example of the railway network impacted by flash floods shown in Fig. 1.

Fig. 1 - Railway networks flooding [10]

The extreme earthquake events, especially in the last decades, directly impacted the roads, dams, and infrastructures. For instance, the Loma Prieta earthquake 1989 caused a hundred fatalities due to bridge damage to the transportation infrastructure, which is about $1.8 billion as direct damages [11]. Nevertheless, the climate variability associated with impacts of climate change (e.g., heavy storms, increasing precipitation intensity, and extreme temperatures) leads to successive flood events and directly impacts road networks' and infrastructure's performance and operation.

Inadequate assessments of flood return periods and infrastructure vulnerabilities contribute to flash floods being a leading cause of infrastructure damage, endangering lives and resulting in economic losses across various regions worldwide. On the other hand, during major earthquake events that cause damage to infrastructure worldwide, such infrastructure, including bridges, road networks, and dams, while the design criteria for infrastructure foundations and soil liquefaction play a crucial factor in determining the performance of roads and other infrastructures during natural hazards [5].

Road networks and railways have been extensively damaged during earthquakes, for instance, in real case studies such as Loma Prieta in 1989, Kobe in 1995, Canterbury in 2011, and Sulawesi in 2018. Also, the soil liquefication led to irregular settlement and further contributed to the destruction of infrastructure [12].

2. Multi-Hazard and Risk Assessment: Literature Review Summary

In recent decades, various international initiatives and research studies have focused on assessing and evaluating the multi-hazard interaction approach. Based on the initial research, it is recommended that the various risks that exist in the environment be investigated. The researchers propose the idea of the "hazardousness of a place", which considers the local ecology of destructive events. Additionally, the current study reviews and presents the previous literature on flood hazards and earthquake hazard losses, considering past global disasters and suggesting various potential responses for each risk [13].

Limited studies and research are implementing the comprehensive multi-hazard interaction approach, which is required to define and thoroughly describe the interaction between various multi-hazard sources and their interrelationships for short or long-term scenarios. Lewis [14] emphasised the multi-hazard concept in a regional study of the historical multi-hazard events in Antigua. Kappes et al. [15] defined and reviewed the main challenges of multi-hazard risk. Docherty et al. [8] carried out a review inventory of the research articles, including the word or concept of multi-hazard. The results showed a higher percentage in the research articles, while fewer included or set specific case studies. The study indicated that after 2010, there was a gradual increase in the rate of published research and articles adopting the multi-hazard concept, as shown in Fig. 2.

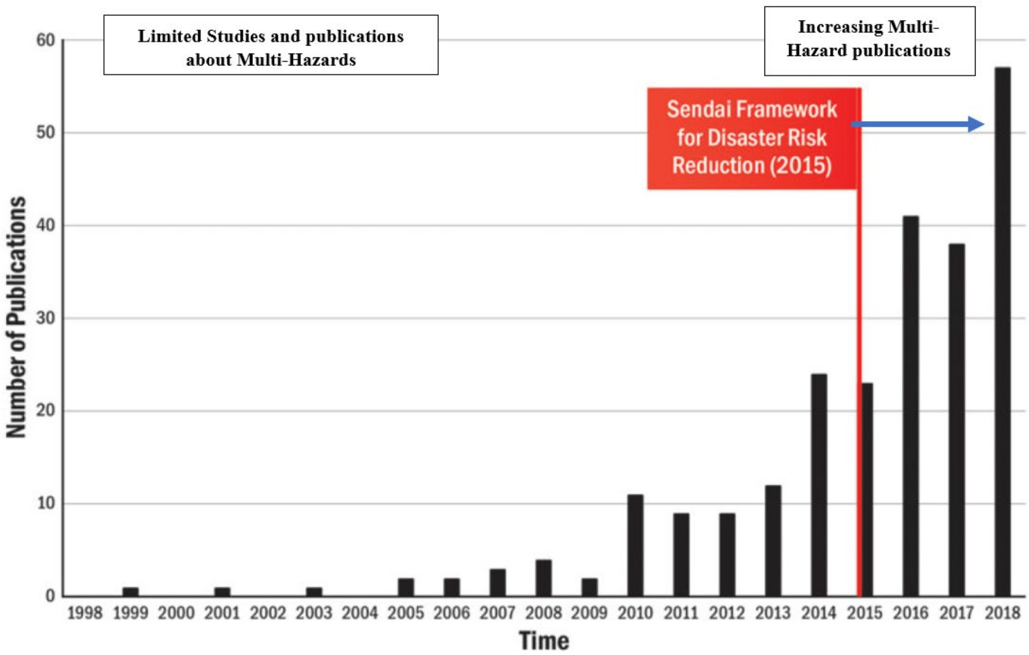

Fig. 2 - The annual inventory of historical multi-hazard publications [8]

The escalation of natural crises in the past two decades, primarily driven by extreme climate events, has prompted researchers to intensify their focus on natural hazard studies. The significance of this research was further emphasised internationally with the introduction of the Sendai Framework for Risk Reduction in 2015. This framework stresses the adoption of a multi-hazard within the layout of disaster risk reduction. As a result, researchers have significantly contributed to studies, research, and articles integrating multi-hazard.

Joel Gill & Malamud [16] reviewed and visualised various natural multi-hazard interactions. Their research classified twenty-one different natural hazards into six distinct categories: geographical, atmospheric, space, earth, bio-physical and hydrological scheme hazards. Building upon this research, Joel Gill & Malamud [16] extend multi-hazard studies by incorporating cascade hazard interactions. They proposed a synthesis framework implementing natural and anthropogenic processes besides technologies to address the challenges of hazard disasters.

Pescaroli & Alexandar [17] submitted a holistic framework through the physical model with network analysis to address compound, interconnected, interacting complex risks. Also, the British Geology Survey in the year 2018, supported by the National Hazard Partnership (NHP) and Environmental Risks to Infrastructure Innovation Program (ERIIP), released a “Review Report for Multi-Hazard Research and Risk Assessments" [18]. This report emphasised the recognition and understanding of multi-hazard events, highlighting the valuable insights gained from contributions by various stakeholders, including academia, engineering, industry, strategy, and policy-making. These collaborative efforts aim to promote a multi-disciplinary approach and address multi-hazard challenges.

Liu Baoyin et al. [19] developed and classified a hazard interaction based on the geophysical of various environments for natural hazards. It involved four trigger factor types and was applied to assess typhoon and flood risks in the Yangtze River basin. Docherty et al. [8] presented a novel water-hazard framework, the methodologies based on information and data set collection followed by analysis and with assistance tools such as (GIS). These methodologies aimed to expand the knowledge for both people and places affected by the multi-hazard scenarios and reduce the social vulnerability to these multiple- hazards.

De Angeli et al. [1] introduced and utilised multi-hazard modelling to assess the impacts of hazards on various spatial and temporal scenarios. The study investigated the multi-hazard scenario in Italy, along Po Valley, which experienced a 6.1 MW earthquake, causing levee damage in May 2012. Subsequently, heavy rainfall occurred. Furthermore, the research also involved assessing the potential consequences of hypothetical scenarios of levee collapse and subsequent flooding, employing quantitative hazard analysis techniques. In recent decades, researchers have done various studies to assess the consequences of multi-hazard events, which require additional efforts in various fields, such as industry, policy, and civil engineering. The primary objective of these research efforts is to obtain diverse datasets encompassing a broad spectrum of potential natural and anthropogenic impacts.

The following research studies were focused on combined multi-natural hazards with possible interactions for spatial and temporal resolution with the trigging possibility of connecting one hazard, which led to other singular or multiple hazards, such as in the case of earthquakes led to the increased probability of future landslides, especially in the hilly areas, which may be causing another future extra land sliding. On the other hand, human-induced such as land use, land cover change, and extreme climate events due to climate change scenarios led to increased runoff and changing infiltration processes due to urbanisation and road construction, which directly increase the hazards of flashing flood inside cities, as an example floods in various regions inside Germany in 2021.

3. The Multi-Hazard Holistic Framework

The interaction of multi-hazard methodologies was summarised in the previous literature review, as shown in Fig. 3, which is, includes (i) Identifying probable hazard sources and their interaction, (ii) Multi-hazard simulation modelling and integrating with GIS and Rs techniques, (iii) Spatial and temporal analysis with risk impact assessment, (iv) Interacting, risk compound, communication, and cascading risks, (v) Evaluation of the multi-hazard and re-assessing the impacts, (vi) Risks measurement and vulnerability analysis, and (vii) Risk management and decision support.

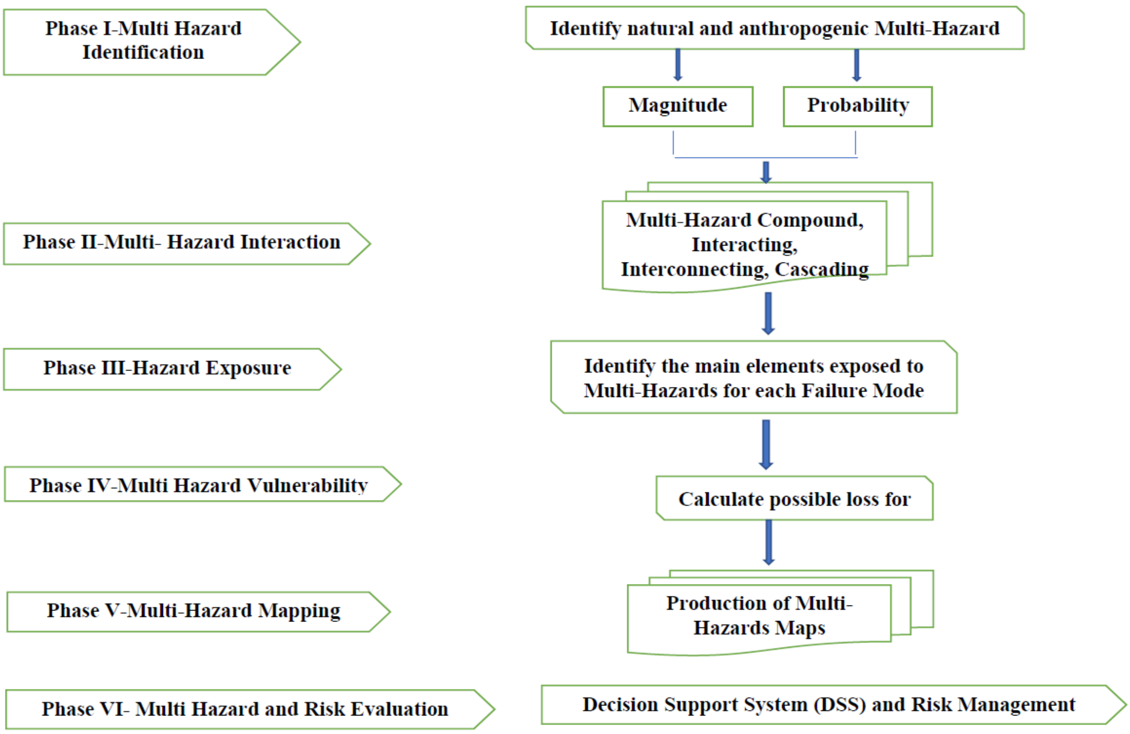

Fig. 3 - The holistic framework for evaluating multi-hazard [1], [16], [18]

4. Multi-Hazard Risk Assessment Methods

The current research reviews and summarises the previous literature with case studies of the applications of various methods of compound multi-hazard and risk assessment associated with roads, infrastructures, and dams impacted by multiple hazards, such as seismic and flood hazards. Furthermore, assessing interaction and hazard trigging with various tools such as GIS and Rs techniques.

4.1 Narrative Descriptions (Qualitative)

The qualitative risk assessment narrative simplifies and classifies risks, clearly understanding the current status and identifying multi-hazard. Furthermore, characterises the potential multi-hazard in a specific location [18]. Collins Brian & Randall [20] investigated and assessed the potential landslide hazards due to the impact of the earthquake in Nepal in 2015, which led to landslides and associated flooding. Jinliang et al. [21] conducted qualitative-narrative hazard descriptions and classifications to assess geo-hazard consequences in China. The primary hazards were earthquakes and rainstorms, which lead to secondary hazards, landslides, and debris flow; the study recommends further research focusing on geotechnical, hydrology, and failure mode with a simulation model to predict the probability or assess the safety factor with the aid of GIS tools.

4.2 Hazard Indices

The hazard indicators represent a simplified method for identifying each hazard component and reflect the environmental situation and impacts; as an application, indicators of multiple weather hazards. Araya et al. [22] conducted a study in Chile, employing a semi-quantitative concept to identify multi-hazard scenarios. They used a fuzzy logic approach to evaluate the risks and catastrophic consequences of extreme climate events, and the research findings indicated the municipalities most affected by these hazards.

Neha Bansal et al. [23] evaluate the index of urban flood hazard in Dehradun, India, utilising a decision-based multi-criteria approach. They classified the area into four hazard zones based on various indices parameters, including slope, land cover, and distance from the water bodies. The study utilised GIS and Rs techniques to visualise the results. Integrating the hazard index with simulation models, such as the hydrological model, becomes more realistic as it incorporates historical data and predicts probable scenarios under various conditions. This improves the accuracy and usefulness of the index for risk assessment and planning.

4.3 Hazardous Events Trees Scenario

Neri et al. [24], [25] carried out probability trees for future scenarios based on quantitative and expert judgments. The case study on Italy at the volcano Vesuvius and the Philippines assesses possible eruption modes and the frequency of secondary hazards. The event tree was used to implement the initial starting hazards of the volcanic eruption events and extended to other consequences events and impacts on the human and other infrastructure. Developing a comprehensive parameterisation event tree with detailed quantitative multi-hazard and risk evaluation, integrating with multi-hazard mapping and simulation models, can be applied in various scenarios and evaluation consequences of multi-hazard and anthropogenic processes for both short and long-term scenarios. An event tree with a simple form can be used as an example for multi-hazard and risk assessment related to infrastructure, road networks, or multi-purpose dam operations. It helps implement various possible scenarios, as shown in Fig. 4.

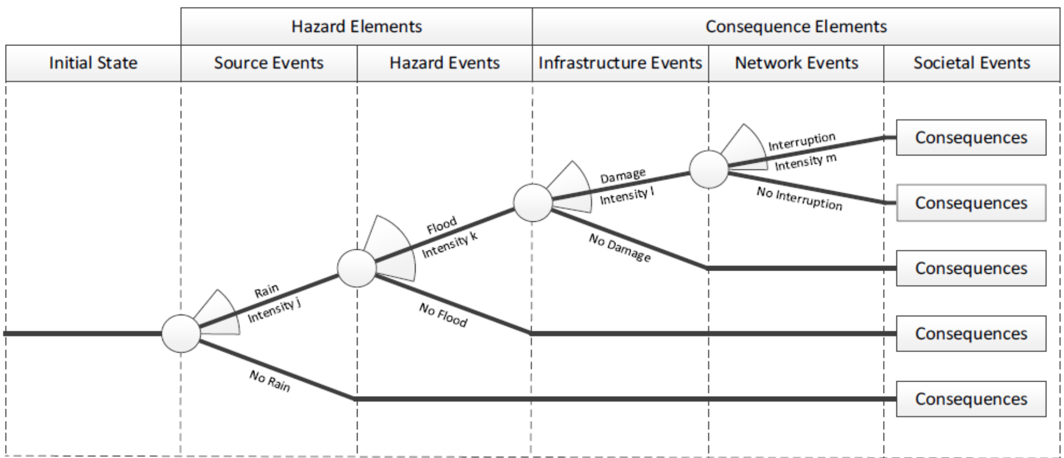

Fig. 4 - Simple method of event tree for evaluating risk [26]

4.4 Hazard Wheels

The coastal hazard in wheel form is designed to help visualise the hazardous situations, which can be utilised to support decision-making on both regional and national scales [18]. Appelquist & Kirsten [27] carried out qualitative hazard wheels with a case study in Karnataka, India, and the research implemented flood hazard and erosion developed for coastal management and the possible options applied for biophysical hazard circles classification.

4.5 Hazard Matrix and Diagrams

Hazards Matrix represents a simplified tool for visualisation interaction and consequence trigging between primary and secondary hazards. The matrix cells visualise through various paths and colours to interpret the relationship between hazard sources (stimuli) for triggers and other probable secondary multi-hazard. Tarvainen et al. [28] studied the spatial variation of interactions between multiple European hazards. They employed binary matrices, diagrams, and hazard maps to categorise potential natural hazards, including flash floods, earthquakes, and fire hazards, based on the typology of regions. The hazards were then visualised using multi-hazard interaction maps. De Pippo et al. [29] carried out a descriptive matrix for identifying natural and human-induced interaction hazards in the Northern Campanian region of Italy's coast. In addition to presenting a matrix depicting triggering relationships among assessed multi-hazard events (such as earthquakes, flash floods, snow avalanches, and landslides). Kappes et al. [15], [30] significantly emphasised the shift from considering single hazards to embracing the concept of multi-hazard risk.

The qualitative hazard network diagram represents a simplified tool for implementing triggering interaction and connecting the multi-hazard through network diagram nodes. Van Western et al. [31] presented the hazard-triggered network diagrams in European mountainous environments to visualise possible interactions that multi-hazard triggered consequently, such as earthquakes and extreme meteorological events, which led to landslides, flooding, and land degradation. The current review highlights the concept and research by Joel Gill et al. [16] through four case studies in Japan, the USA, the Philippines, and Guatemala. The first study explores the eruption of Mount Unzen in Japan in 1792, which triggered the collapse with a large landslide and increased volumes of material deposited near the ocean. Consequently, a tsunami was generated, crossing the ocean and threatening nearby communities, leading to significant economic losses.

The second case study was in Alaska, USA, where a 9.2-magnitude earthquake occurred in 1964. Meanwhile, the earthquake triggered submarine and subaerial landslides with tsunamis; secondary hazards also triggered further tsunami waves with regional subsidence and floods. Flooding and mass displacement occurred in Guatemala City after an extreme tropical storm hit the country's Pacific coast in May 2010. The drainage system was already degraded by debris from the volcanic ash. As a result, ground collapse and structural damage occurred throughout the city [16].

The general approach includes visualising the interactions of various multi-hazard by categorising them into primary and secondary hazard groups. The cascaded hazard interactions network is built upon three main categories: natural, anthropogenic, and technological hazards. This framework enhances our understanding of how these hazards interact and enables us to comprehend the potential cascading impacts better. The hazard matrix concerning primary and secondary connecting hazards can demonstrate the possible multi-hazard interaction scenarios associated with dam operation. Moreover, interaction-triggering relationships for various probable are multiple natural hazards or anthropogenic processes. For instance, an earthquake (ET) event is probable to cause landslides (LA), Subsequently leading to flooding (FL) and future Ground Collapse (GC). Ground Collapse (GC) can be a triggering consequence of the additional flash flood (FL), as shown in Fig. 5.

As an example, human activities can trigger natural hazards. For instance, the expansion of road networks can destabilise slopes and initiate landslides in the case of land use change through deforestation, which can contribute to an increase in floods and landslides. Additionally, technical hazards like dam breaches can result in catastrophic floods.

4.6 Multi-Hazard Maps

Hazard maps can effectively visualise the key features of multi-hazard in specific regions, encompassing road networks, multi-purpose dams, and other infrastructures. These maps serve as simplified tools, utilising GIS and Rs techniques to convey and interpret the complex interactions of multiple hazards, considering the wide range in intensity, frequency, and spatial distribution impacts, along with their potential human and economic consequences. Numerous researchers have developed accurate terrain maps, such as flood hazard maps, using various GIS and Rs techniques tools on global and regional scales.

Johnson et al. [32] carried out multiple hazard and vulnerability maps of Hong Kong districts in 2016 to determine the hot spot location hazard with the legend of risk concentration. The research produced various hazard maps with vulnerabilities within urban areas, which provided spatial hazard distribution inside and outside urban regions. Bell & Glade [33] carried out hazard maps in Bíldudalur, Iceland, by visualising the natural hazards and life and economic risks. They integrated single-risk maps into various or multi-hazard risk maps, highlighting severe threats from hazards such as rockslides and debris flows. The risk assessment associated with road networks and other infrastructures can easily integrate qualitative and semi-quantitive cartography through multi-hazard maps with the aid tools of GIS and Rs techniques. These tools enable the integrating of spatial data and analysis, providing valuable insights for assessing and managing risks associated with various hazards.

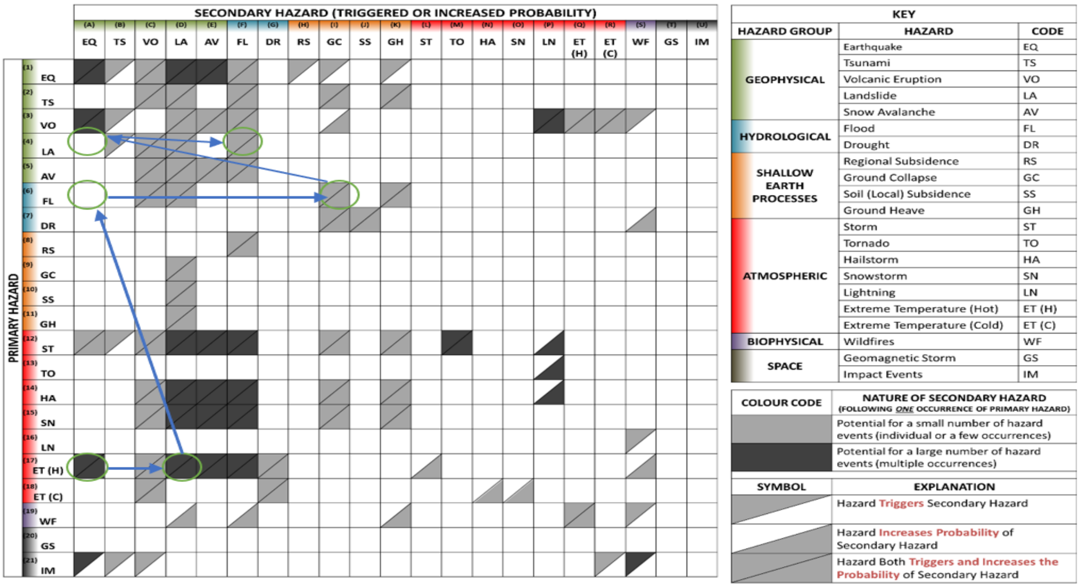

Fig. 5 - The multi-hazard interaction matrix [16]

Karatzetzou Anna et al. [11] conducted a study to develop unified hazard models for assessing the vulnerability of transportation networks to multiple hazards. The study focused on a specific area in Greece and examined the condition of the road network following heavy rainfall and flooding in 2019, as well as the impact of the Crete earthquake in 2021. The research utilised a qualitative intensity of the hazard colour cell matrix (4×4) with assigned code numbers, categorising the hazards into four risk levels for flooding and seismic activity. The study also quantified the intensities by referencing the return period of flood and seismic hazards. The researchers calculated the probabilistic seismic risk using a return period Tms=475 years. They also considered flood scenarios with five hundred years of return periods.

The research listed the seismic and flood hazard events mentioned earlier in Greece, directly affecting various infrastructures (e.g., bridges, tunnels, and road network systems). The combination of risk hazard maps for both seismic and flood is shown in Fig. 6.

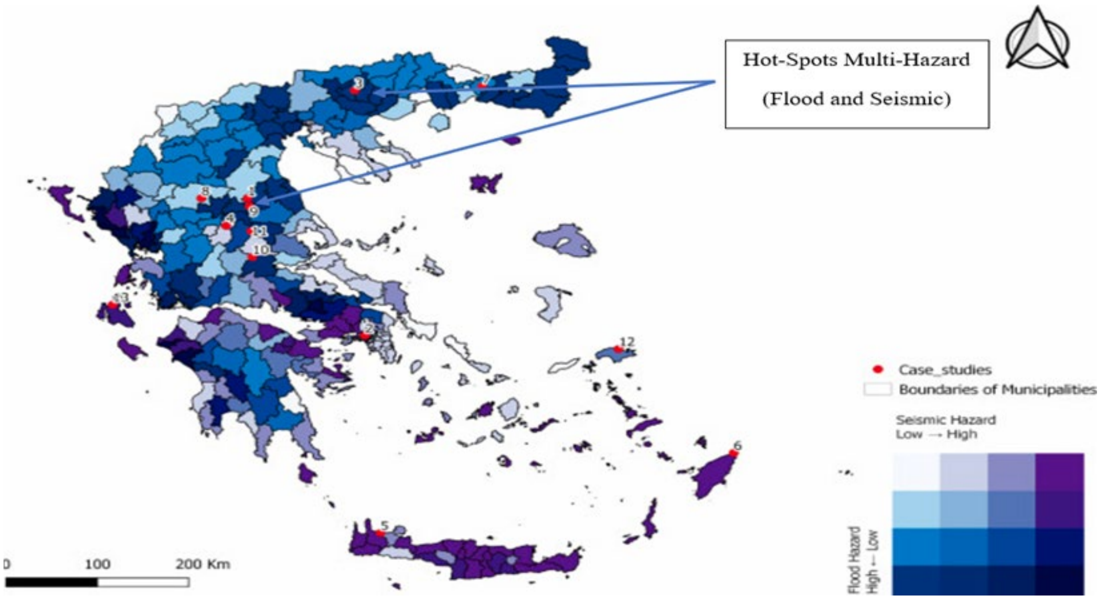

Fig. 6 - Flood and seismic hazard map in Greece [11]

In this example, the study categorised the Farkodona Bridge as experiencing multiple hazards, including moderate seismic activity and severe flood risks. The bridge was affected by an earthquake in 2020, resulting in moderate damage. Subsequently, flash floods occurred three weeks later, causing erosion at the pier and abutment, thereby exacerbating the level of damage, as shown in Fig.7(a). In addition, the study focused on identifying and categorising the hazards that affected the twin railway Othrios tunnel, Greece's second-longest train tunnel. Due to heavy rainfall and landslides, debris flows impeded passage through the tunnel in 2020. Additionally, the study investigated the consequences of flood events on the Athens-Thessaloniki railway line during the same year, as shown in Fig.7 b) and Fig. 7(c).

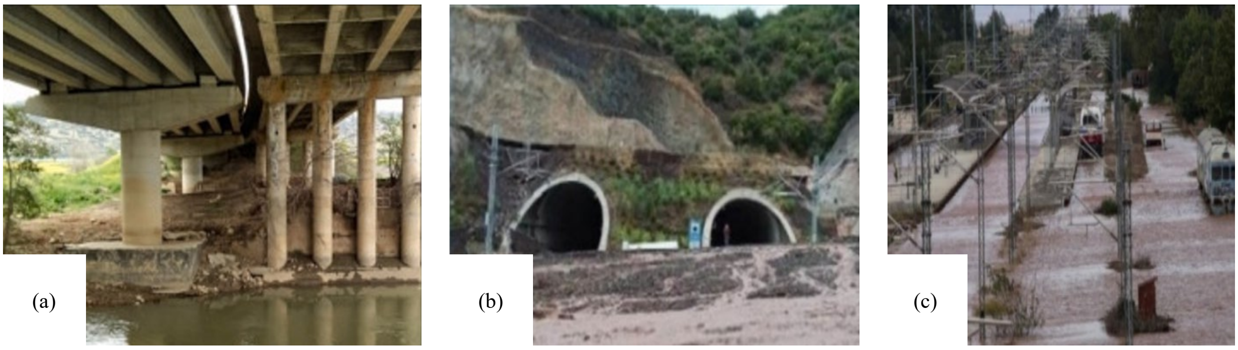

Fig. 7 - (a) Bridge at Farkadon, 2021, (b) Othrios Tunnel Greece, 2020, and (c) Athens-Thessaloniki Railway Line, 2020 [11]

The multi-hazard mapping visualises and interprets the current and probable future hazard scenarios associated with road network elements and other infrastructures. Furthermore, the spatial distribution of the hot spot areas is exposed to multi-hazard. Subsequently, required hazard prioritisation with realistic development for supporting decision-makers and emergency action plans to mitigate the hazards and reduce the losses.

Koks et al. [12] carried out a worldwide multi-hazard and risk assessment of the transportation network's assets, including roads and railways. The research collected a global dataset encompassing various natural hazards such as flash floods, cyclones and earthquakes. Regarding the road and railways information, the study utilised the Open Street Map (OSM) dataset. It categorises countries into income levels. Transport infrastructure exposure to multi-hazard was classified into five levels, as shown in Fig. 8.

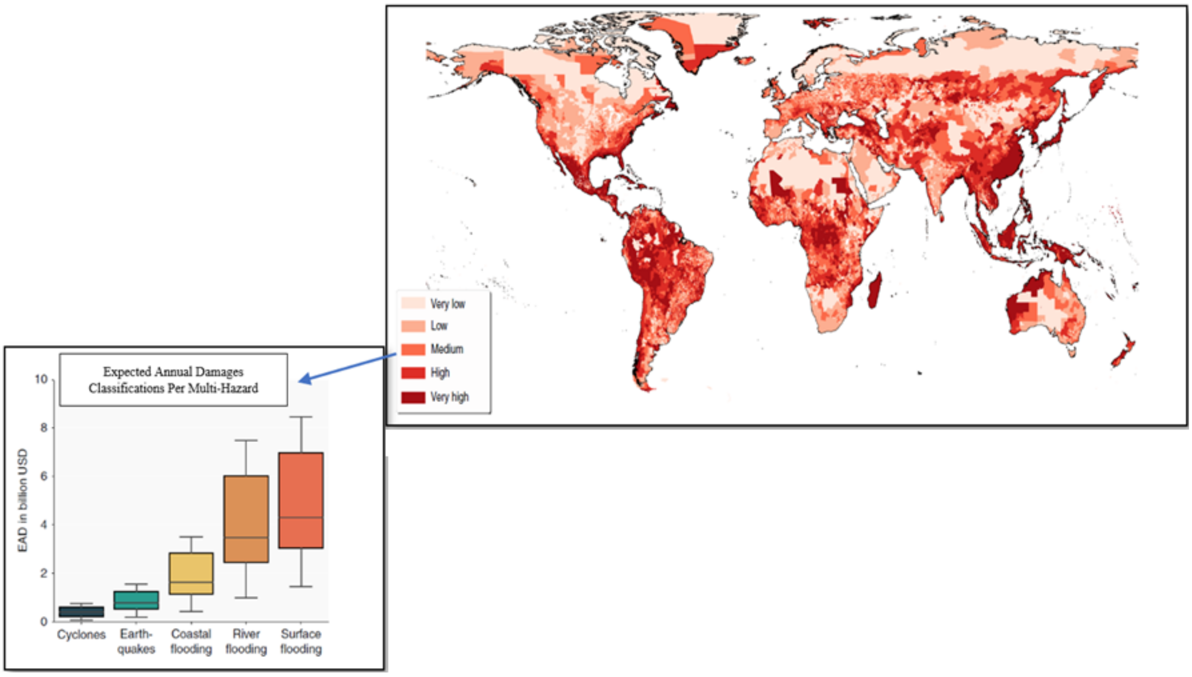

Fig. 8 - Global expected annual damage (EAD) to transport infrastructure assets among multi-hazard [12]

The study results showed fewer kilometres of road infrastructure exposed to flood due to higher priorities of protection structure standards in high-income countries. In contrast, a high percentage of exposure in Africa is due to frequent flooding.

The research methodologies indicate valuable information for exposing roads and infrastructure to various risks by expected annual damage (EAD) to transport infrastructure assets. The methodologies implemented the necessary financial resources relevant significantly to the country's gross domestic product (GDP) with the required maintenance and rehabilitation of road networks and other infrastructures. However, it is essential that natural hazards such as cyclones and earthquakes substantially influence the infrastructure of both higher and middle-income countries due to their geographical occurrence.

The study estimated the higher percentage of the total expected annual damage (EAD) caused by floods with less impact due to earthquake and cyclone hazards. Nevertheless, mitigation of flood hazards can be achieved by improving hazard management practices, which involve implementing preventive measures and various protection actions such as barriers or increased drainage capacity. These activities aim to enhance flood protection under different road scenarios. Strengthening the fragility curves for natural multi-hazard events and impacts resulting from human-induced activities can reduce the uncertainty associated with damage and cost estimation. Hence, this is particularly valuable, especially in regions with limited information or data-set availability for multi-hazard assessments.

4.7 Physically-Based Model (Quantitative)

The physical model provided comprehensive details for interaction multi-hazard approaches through the multi-process connecting with the data set. Machine learning, artificial neural networks, and fuzzy logic can easily connect with models and represent an assistance tool for connecting multi-hazard interactions for various trigging processes.

Chen et al. [34] The study conducted an assessment of multi-hazard using a physically-based model. This approach was implemented along a highway and in close proximity to the areas of the 2008 earthquake epicentre. The multi-risk analysis indicated that slope failures were triggered by a storm event, resulting in heightened channel erosion and an increased debris flow volume. These hazards posed a significant threat to people along the road network, particularly in the event of a high-magnitude earthquake.

Pilkington & Mahmoud [35] used artificial neural networks and machine learning to evaluate multi-hazard in the USA impacted by various meteorological hazards and tropical cyclones. Xiaodong et al. [36] presented a framework for quantitative multi-hazard applied in London and downstream the estuary of the Thames. The study utilised a 2D hydrodynamic model to simulate floods and generate probabilistic inundation maps. These maps were integrated with a quantitative risk assessment model. The study methodology can be utilised for analysing other potential natural hazards, such as extreme floods and earthquakes, while enhancing the physical model to predict the possible multi-hazard impacts by considering the climate impacts and human-induced processes on short- and long-term scenarios.

5. The Assistance Tools and Techniques Used for Assessment of the Multi-Hazard

Various assistant tools and fragility analysis methods were employed in the multi-hazard assessment of road networks and dam operations. The current review highlighted using the GIS and Rs techniques with different applications for detecting exposure to multi-hazard in various regions. This involved evaluating the displacement of both vertical and horizontal infrastructures before and after the hazard events.

5.1 Methodology for Detection the Ground Motion Areas by DInSAR Techniques

The Differential Interferometry Synthetic Aperture Radar (DInSAR) technique is utilised to investigate and analyse ground motion and terrain deformation in relation to infrastructures and road networks. This involves integrating field survey data or comparing satellite images for various periods using GIS and Rs techniques. These approaches facilitate understanding the spatial dynamics and changes occurring in the studied areas, contributing to improved assessment and risk management related to infrastructure and dams.

The application includes acquiring the satellite dataset to evaluate the spatial displacement and estimate safety infrastructures. The DInSAR satellite monitoring technique investigates the difference between at least two synthetic aperture radar (SAR) images [37], [38]. The concept of DInSAR through remote sensing techniques by satellite sensors, passing polar orbits, between 500 to 800 km from the earth, for global spatial resolution in both ascending or descending orbits with opposite directions to the ground surface and then capturing images from different perspectives relative to the earth's surface.

The DInSAR method is highly effective in monitoring complicated topographic regions, particularly in complex topographic regions such as hilly areas, as it enables lower costs and facilitates the monitoring process with flexible equipment requirements. By utilising DInSAR techniques, the metadata of thematic maps can provide valuable information for assessing ground displacements relative to predefined reference points (benchmarks) on key structures such as bridges, roads, and dams. The final step of the process involves visualising the hot spot-risk areas through the production of risk maps using GIS and Rs techniques, which can accommodate different temporal and spatial resolutions and consider multiple hazard scenarios.

Troisi Roberta & Castaldo [37] researched to develop a theoretical framework for risk management associated with roads and infrastructure in Rome, Italy. The study examined two scenarios: the first involved long-term coordination among different stakeholders, while the second focused on a fragmented system with flexible compound sharing and local autonomy. The study utilised approximately 5 million monitoring points in the ascending orbit and 3.7 million points in the descending orbit. These data were processed within a GIS system to obtain velocity measurements and horizontal and vertical displacement on grid cells 3×3 meters covering the road network system and subsystem.

The risk maps were generated using high-resolution SAR sensor satellite images captured between July 2011 and March 2019, utilising the DInSAR and GIS tools. Nevertheless, the risk levels were determined by calculating the discrepancy between vertical and horizontal displacements and dividing it by the size of each cell. The resulting risk map categorised the levels of risk into six groups: various from very high to negligible risk levels, as shown in Fig. 9. These risk maps provide valuable insights into the varying levels of risk across the studied area, considering different spatial and temporal resolutions.

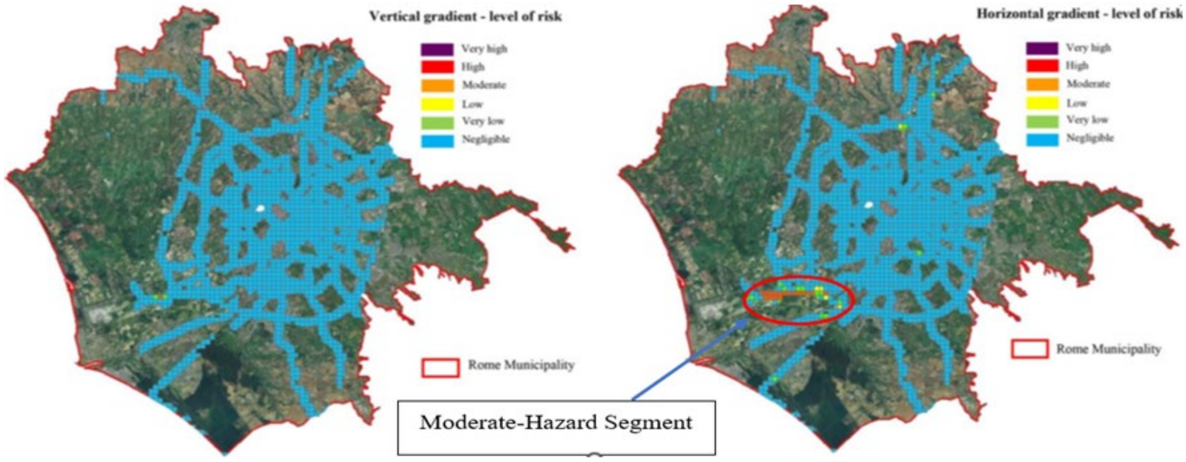

Fig. 9 - Infrastructure network risk maps, Italy, Roma [37]

The results indicated that the risk levels were generally insignificant in most areas, except for moderate to low risk observed in certain interconnected elements. The production of thematic maps using DInSAR and GIS techniques and many low-cost spatial monitoring points proved valuable in obtaining information about road conditions and safety. Furthermore, it enhances our knowledge of risks across various safety aspects.

DInSAR enables decision-makers to allocate and prioritise resources effectively, implement planned measures, and mitigate infrastructure and dam operation risks. This approach supports risk management efforts and ensures the infrastructure's safety and functionality within the system and subsystem. DInSAR tools are precious for regions in high-risk zones potentially impacted by multiple hazards, as they aid in identifying areas that require maintenance or rehabilitation, allowing for targeted interventions to enhance infrastructure resilience and mitigate potential hazards. The limitation of using DInSAR techniques includes the accuracy with uncertainty due to the scatters with specific infrastructures [37].

The Rs techniques require ground-truthing with real field survey datasets and information to achieve more accurate results and reduce the errors associated with sensor and satellite images. This process is essential for specific spatial and temporal resolutions, particularly within infrastructures, road networks, and dam sites. In addition, ground truthing is similar to the process of model calibration. Significantly incorporating ground-truth data allows remote sensing images to be adjusted and aligned with physical ground features, resulting in a more precise and reliable assessment.

Al-Husseinawi et al. [38] investigated the constancy of the Darbandikhan Dam inside Iraq after the Sarpol-e Zahab earthquake in the Iran-Iraq Zagros zone on November 12, 2017. The study utilised InSAR techniques and analysed sixty-eight images from the Sentinel-1 satellite from 2014 to 2018. The study results indicated a maximum displacement rate of approximately 4 mm/year at various point locations along the dam crest following the earthquake. The highest rate of creep displacement was observed near the centre of the dam crest, reaching approximately 17 mm/year between the period from November 19, 2017, to March 7, 2018, as shown in Fig. 10. These findings provide valuable insights into the post-earthquake behaviour of the dam and contribute to its ongoing stability assessment.

In addition, the study also investigated displacement by utilising the Global Positioning System (GPS) with a real survey dataset of level observations taken at various points on the dam crest and near the dam spillway. The relative analysis results indicate a horizontal displacement of approximately 0.12 m for the right dam abutments and about 0.14 m for the left abutments. In comparison, the relative vertical subsidence displacement was approximately 0.5 m for the central part of the dam, while the relative vertical displacement measured around 0.15 m and 0.45 m at the left and right dam abutment points, respectively. Furthermore, the ultimate relative horizontal displacement was 0.27 m at the downstream dam site, as measured by GPS.

The seismic event resulted in multiple transverse cracks along the length of the Darbandikhan dam at the crest dam, as shown in Fig. 11. The author demonstrated that the maximum deformation in the dam's crest centre could occur in accordance with the Earthfall dam mechanism. Additionally, potential movement scenarios following subsequent earthquakes were examined.

In terms of monitoring post-seismic deformation, the InSAR techniques yield satisfactory results. However, when it comes to high levels of deformation caused by successive earthquakes, terrestrial geodetic survey techniques are still considered more suitable and accurate [38]. The current review significantly emphasises the utilisation of GIS besides remote sensing techniques for assessing the safety of infrastructure and dams. These techniques are successfully applied to estimate regional subsidence in dams caused by various multi-hazard impacts, whether natural or human-induced. Milillo et al. [39] conducted space geodetic monitoring of the Mosul dam to evaluate deformation at the dam site. The study utilised a dataset from multiple satellites using Synthetic Aperture Radar (SAR) to measure and assess the deformation. The study processed sixty-two images captured within the geometry of an ascending track to measure ground deformation between 2012 and 2015. Additionally, the researchers analysed six interferograms from the Envisat satellite to monitor the destabilisation process from 2004 to 2010. Furthermore, they acquired 32 images from the Sentinel-1A sensor, covering 18 months from October 2014 [39].

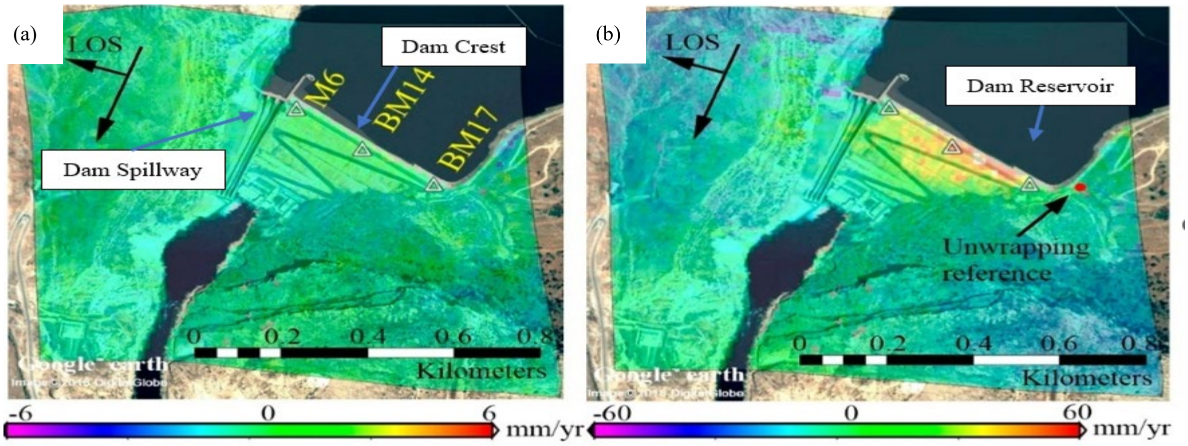

Fig. 10 - Maps of Linear velocity (mm/year) (a) before the year 2017, and; (b) post-2017 earthquake, Darbandikhan Dam, Iraq [38]

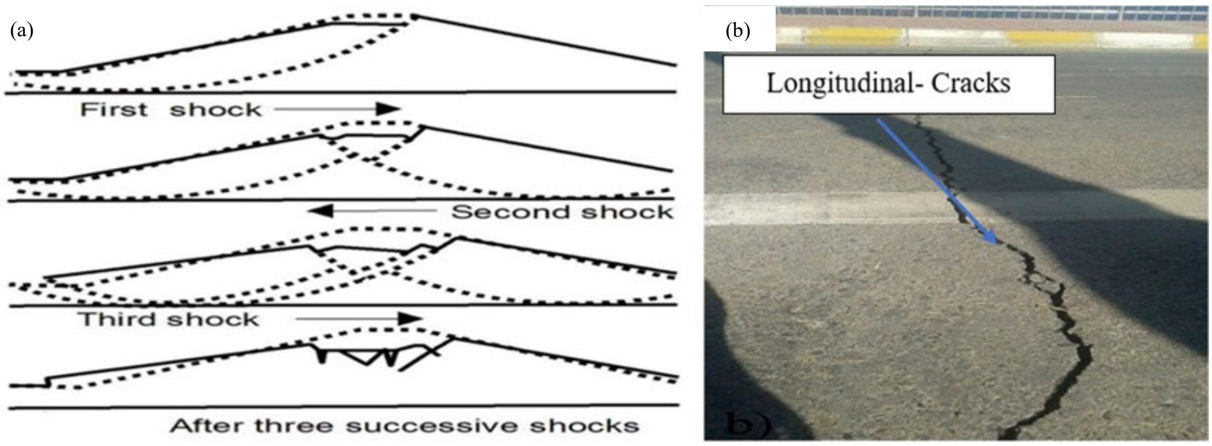

Fig. 11 - (a) The behaviours of the embankment dam during earthquakes, and; (b) cracks on the road of Darbandikhan Dam crest after the earthquake of November 12, 2017 [38]

The foundations of the Mosul Dam are situated in layers of limestone and gypsum, which have a high propensity for dissolution. As a result, from the operation of the Mosul Dam in 1988 until the present day, grouting operations have been carried out. These operations involve the mixture of cement and bentonite to mitigate the dissolution of the gypsum layers and to enhance the connection between the rocks and the underlying layers beneath the dam's foundation [9].

The dam safety requires continuous monitoring to assess the dam situation, especially for the Mosul dam foundation issues. This involves the constant measurement of vertical and horizontal displacement. This study calculated the subsidence rate in millimetres per year across three distinct periods. The findings, derived from the subsidence rate analysis, reveal that the dam experienced rapid deformation from 2004 to 2010, followed by a slowdown between 2012 and 2014. Subsequently, after 2014, the deformation increased again when grouting operations were stopped [39], as shown in Fig. 12.

The regional subsidence in Mosul dams is attributed to various natural impacts, including gypsum dissolution beside the anhydrite layers under the dam foundation [9]. Furthermore, it is human-induced, leading to increasing dam stability hazards. The probable multi-hazard can be visualised and connected through a hazard matrix or network hazard interaction diagram developed by Gill & Malamud et al. [16].

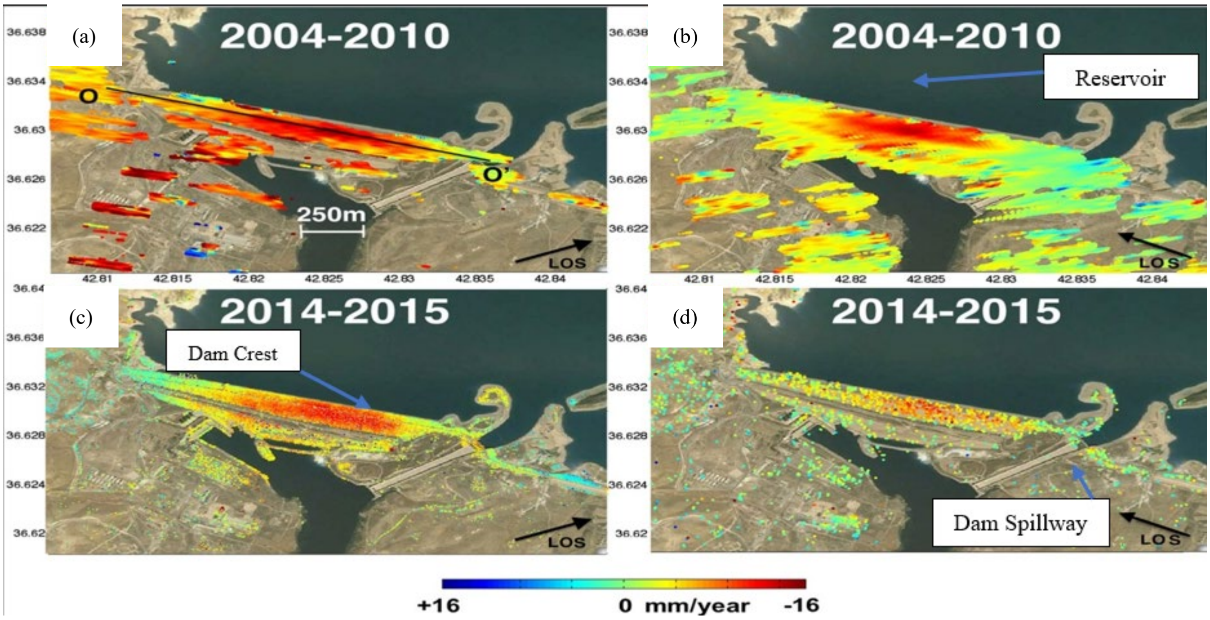

Fig. 12 - Subsidence rates for Mosul Dam, Iraq [39]

5.2 The Fragility Assessment of the Compound System to Multi-Hazard

It is crucial to gather detailed information regarding the topology of infrastructure and transport assets to enhance the assessment of multiple hazards associated with infrastructures. This includes various elements such as road networks, culverts, bridges, embankments, tunnels, retaining walls, and more. The collection of such information is vital in supporting risk management efforts and effectively mitigating multiple hazards.

Argyroudis Sotirios et al. [5] reviewed the fragility of critical transport infrastructures concerning geotechnical and climatic hazards. The research methodology involved selecting specific engineering demand parameters for each infrastructure component to determine different damage states. Therefore, obtaining detailed information about the infrastructure is crucial during the design, operation, and maintenance stages. Furthermore, the researchers developed a numerical fragility function using systems of assets for transport systems impacted by various hazards [5].

Transport infrastructure hazards and risks in hilly or mountainous areas include faults and extreme rainfall, triggering landslides, rockfalls, and debris flow. Meanwhile, slow-moving floodwaters may persist for an extended period in lowland areas. The wider floodplain in such sites can lead to the scouring of foundations and soil softening due to saturation, as shown in Fig. 13.

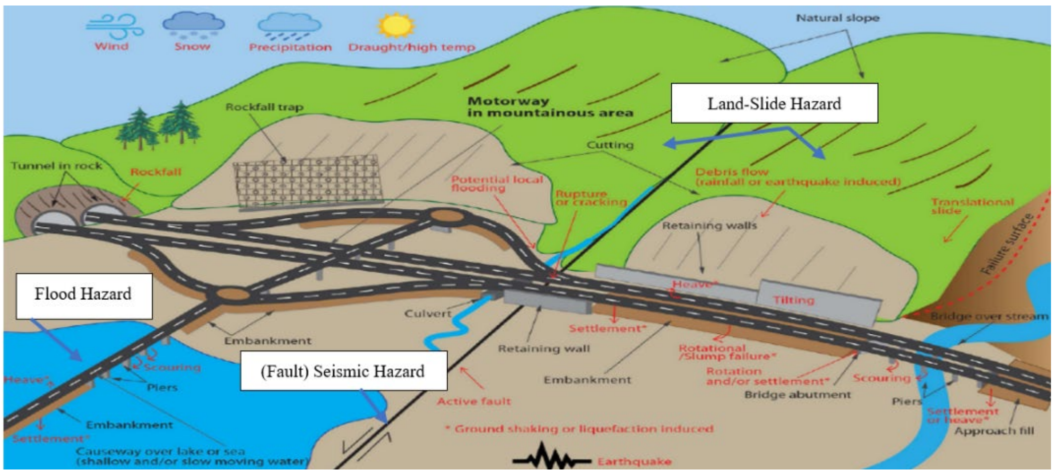

Fig. 13 - The multiple hazards associated with transport infrastructure in mountainous areas [5]

Gehl et al. [40] conducted analyses of losses for a virtual case-study network of roads and infrastructure in another study concerned with fragility assessment to multi-hazard associated with road networks. The study aimed to harmonise multiple hazards and derive hazard-specific components, such as fragility curves. These curves were categorised and used to quantify the frequency of numerous potential failure mechanisms across various scenarios. The fragility function methodology for multiple-hazard represents very suitable supporting tools for investigating a particular target area. It offers enhanced accuracy through an engineering-based approach combined with simulation modelling technology. This methodology enhances the analysis of hazard impacts on roads and infrastructure assets by incorporating intensity measurements. In addition, it contributes to developing strategies for adaptation and mitigation of hazard and decision support systems (DSS).

6. Conclusions

The current study reviews the main principles and methodologies of hazard interactions and risk assessment, encompassing natural hazards and anthropogenic processes associated with road networks, dams, and other infrastructures. The current review highlights and concludes the following items below:

- Numerous studies have international initiatives concerning multi-hazard interaction, such as the framework of SENDAI for reduced risk (2015-2030).
- The holistic framework for multi-hazard and risk assessment was developed, including various phases of multi-hazard interacting, compounding, and cascading risks exposure and vulnerability analysis for both natural and human-induced [1], [15], [16], [18], [37].
- The multi-hazard interaction relationship can be categorised into three main scenarios. Firstly, there is hazard triggering, where one hazard triggers another. Secondly, there is the amplification of hazard probability, which increases the likelihood of other hazard events. The third scenario encompasses compound hazards, where multiple hazards interact and compound their effects [15], [17].
- Various tools and models, including hazard matrices, network diagrams, hazard wheels, and physical-based models, are utilised for multi-hazard assessment, besides enhancing risk mitigation and management.
- Integrating multiple hazard maps with GIS and Rs techniques can serve as valuable visualisation tools and enhance our understanding of how multi-hazard propagate across specific spatial and temporal resolutions.
- The changes in vulnerability due to the interaction of various hazards are directly proportional to the impact of the hazards or disasters, posing a threat to the population or infrastructure. This assessment considers the residual damage and system recovery, as well as the evaluation of potential hazard consequences. [1].
- The fragility function methodology for multiple potential hazards is vital for examining systems within certain regions. It incorporates engineering-based approaches to understand and address the impacts of various hazards associated with infrastructures and dams.
- The current review highlights applying a theoretical risk assessment framework for monitoring and evaluating risks in the system and subsystem of road infrastructures and dam safety. This is achieved through various assistance techniques, including GIS, DInSAR, and Rs.

The current review listed the main gaps and limitations associated with multi-hazard interactions and risk assessment associated with roads and infrastructures:

- The multi-hazard analysis and assessment were applied with limitations globally and between neighbouring countries due to border restrictions and limited information exchange.
- The knowledge and potential of multi-hazard extend beyond the immediate consequences and impacts.
- Due to the heterogeneity of interactions, establishing a standardised framework for multi-hazard procedures has required various analysis procedures. Global and regional multi-hazard dataset availability and accessibility.
- The stability of geophysical environmental factors plays a significant role in determining the distribution of hazards alongside the triggering factors for multiple induced hazards [19].
- Uncertainty in hazard parameters introduces challenges when comparing different phenomena within a hazard chain besides the probability and magnitude and the hazard's spatial and temporal propagation [16].
- The limitation of assistance tools for multi-hazard interactions such as multi-criteria analysis mainly depends on judgment opinion for deciding weight per hazard. Nevertheless, machine learning requires an intensive and realistic input dataset [6].
- Addressing uncertainties in assessing residual damage from cascade disasters caused by multiple hazards. [1].
- Determine the range or span of safety associated with multi-hazard and risk management [37].
- Dealing with uncertainty in estimating multi-hazard fragility function curves and assessing losses [5], [12].
- Assessing the impacts of climate change, particularly those associated with the operation of infrastructure, including road networks and dams.

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